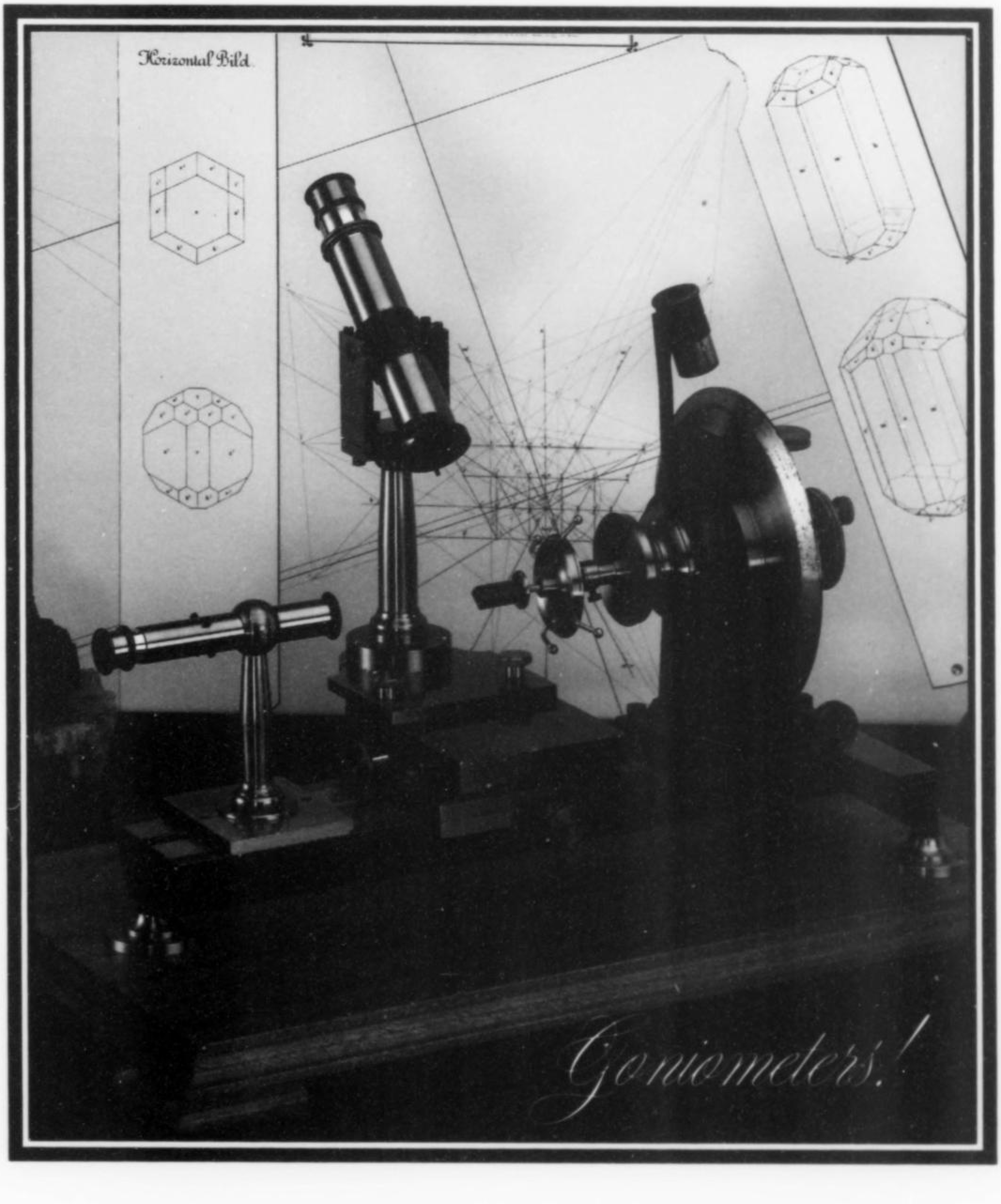
Mineralogical Record



November-December 1998 • Volume 29 Number 6 • $15

KRISTALLE

Wayne & Dona Leicht, 875 North Pacific Coast Highway, Laguna Beach, CA 92651
(714) 494-7695 . . . 494-5155 . . . FAX (714) 494-0402
Open Tues.-Sat. 10-5. (Closed Sun.-Mon.)

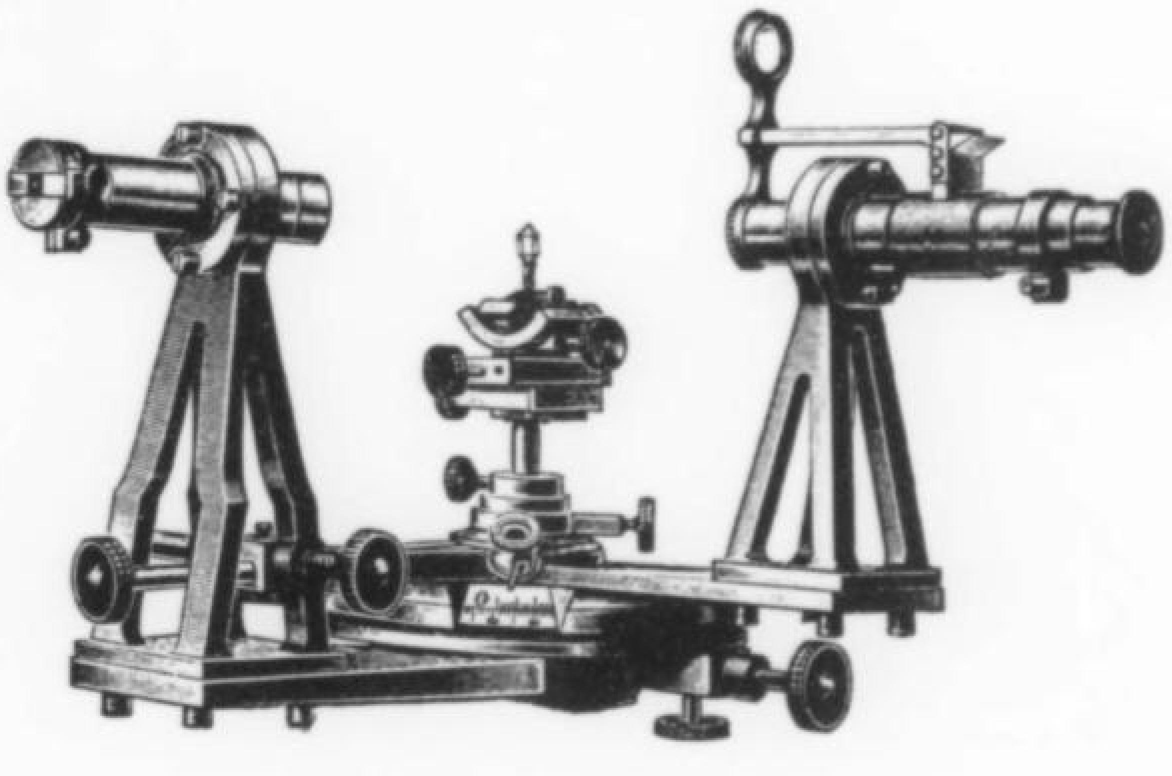
photo by Harold and Erica Van Pelt, Los Angeles

NOTE: Please call ahead for our travel schedule–we would hate to miss your visit!
WEB: http://www.kristalle.com
E-mail: leicht@kristalle.com

THE
MINERALOGICAL
RECORD
November–December 1998 Volume Twenty-nine, Number Six

Editing, advertising
4631 Paseo Tubutama
Tucson, AZ 85750
520-299-5274 • FAX: 520-299-5702
E-mail: minrec@aol.com
Subscriptions
(Subscriptions, back issues, reprints, book sales, shows)
P.O. Box 35565
Tucson, Arizona 85740
520-297-6709 • FAX: 520-544-0815
E-mail: minrec@aol.com
- **Individuals (U.S.):** $47 for one year; $90 for two years. (First-class mailing available; write to circulation manager for rates.)
- **Individuals (outside the U.S.):** $51 for one year, $98 for two years. (Airmail mailing available; write to circulation manager for rates.)
- **Libraries, Companies and Institutions (worldwide):** $120 for one year.

*Continued on p. 514



* * *

HISTORY OF THE DEVELOPMENT OF THE CRYSTALLOGRAPHIC GONIOMETER

by
Ulrich Burchard

* * *

COVER: Hirschwald's microscope goniometer with regular observation telescope. Signed: R. Fuess, Berlin, ca. 1900. Photograph by P. Kubath. (See page 527.)

The Mineralogical Record
(ISSN 0026-4628) is published bi-monthly for $42 per year (U.S.) by Mineralogical Record, Inc., a non-profit organization, 7413 N. Mowry Place, Tucson, AZ 85741. Periodicals postage paid at Tucson, Arizona and additional mailing offices. POSTMASTER: Send address changes to: The Mineralogical Record, P.O. Box 35565, Tucson, AZ 85740.

notes from the EDITOR

THIS ISSUE

Now and then we like to devote an issue to some especially significant aspect of the history of mineralogy, particularly if prime mineral-related collectibles are also involved. So it is with this special issue on the history of the *goniometer,* one of the most elegant, beautiful and technologically fascinating of all collectible scientific instruments. The goniometer, which is unique in its application to studying *only* euhedral, free-growing crystals, was the central device for mineralogical/crystallographic research from the time of Haüy in the late 1700's until the discovery of X-ray diffraction in the early 20th century. Author Uli Burchard has been researching his monograph on the subject for more years than I can remember. The result, presented here, is a truly superb and wholly original piece of scholarship. Next issue we'll be back to *minerals, minerals, minerals!*

GERMAN TRANSLATION AVAILABLE

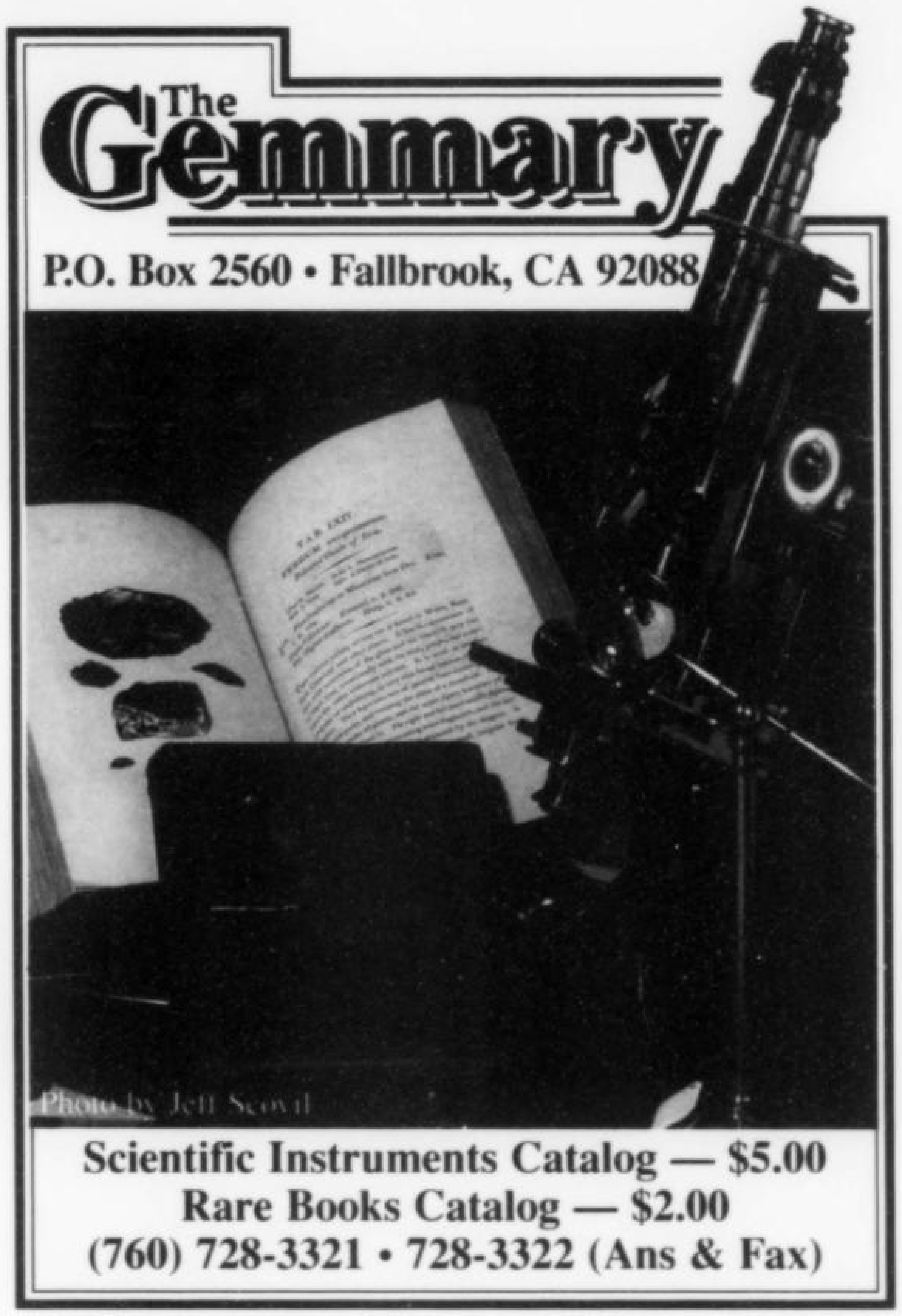
For readers more fluent in German than English, the full text of this issue is available **in German** at no charge from the Circulation Manager.

ANNUAL INDEX

Due to space limitations in this issue, the annual index for 1998 will appear in the January–February 1999 issue.

YEAR-END SALE

Check the special supplement pages attached to the mailing cover sheet in the envelope with this issue, and you'll find some ideas for Christmas gifts along with a little gift of our own: a 10% discount if the order form is used. Offer good until January 1 (but we give our non-U.S. subscribers a little longer to respond).



Advertising Information
All advertising in the Mineralogical Record must be paid in advance of the closing date. Telephone orders not accepted. Write to the editor for rates.

Closing dates:

Jan.-Feb. issue	Oct. 15
March-April issue	Dec. 15
May-June issue	Feb. 15
July-Aug. issue	April 15
Sept.-Oct. issue	June 15
Nov.-Dec. issue	Aug. 15

An additional 20 days past the closing date are allowed in which advertisers may make changes (excluding size changes) in ads already paid for.

Design
Wendell E. Wilson

Graphic Production
Capitol Communications
Crofton, MD

Printing
Cadmus Journal Services,
Easton, MD

Foreign Payments
Remittance may be made in local currency, at *prevailing exchange rates,* without surcharge, to the following people:

Belgium
Paul Van Hee
Marialei 43
B-2900 Schoten

Canada
Mrs. J. W. Peat
36 Deepwood Crescent
Don Mills, Ontario M3C 1N8

Great Britain
Paul Lowe
"Endsleigh"
50 Daniell Road
Truro, Cornwall TR1 2DA

Italy
Renato & Adriana Pagano
P.O. Box 37
I-20092 Cinisello Balsamo MI

Japan
Bon Earth Sciences
Tsukasa Kikuchi
Nagata Bldg. 201
19-10 Kitaotsuka 2-chome
Toshima, Tokyo 170

Netherlands
W. J. R. Kwak
Kabeljauwallee 23
6865 BL Doorwerth (Gld)

Norway & Sweden
Geir Wiik
N-2740 Roa
Norway

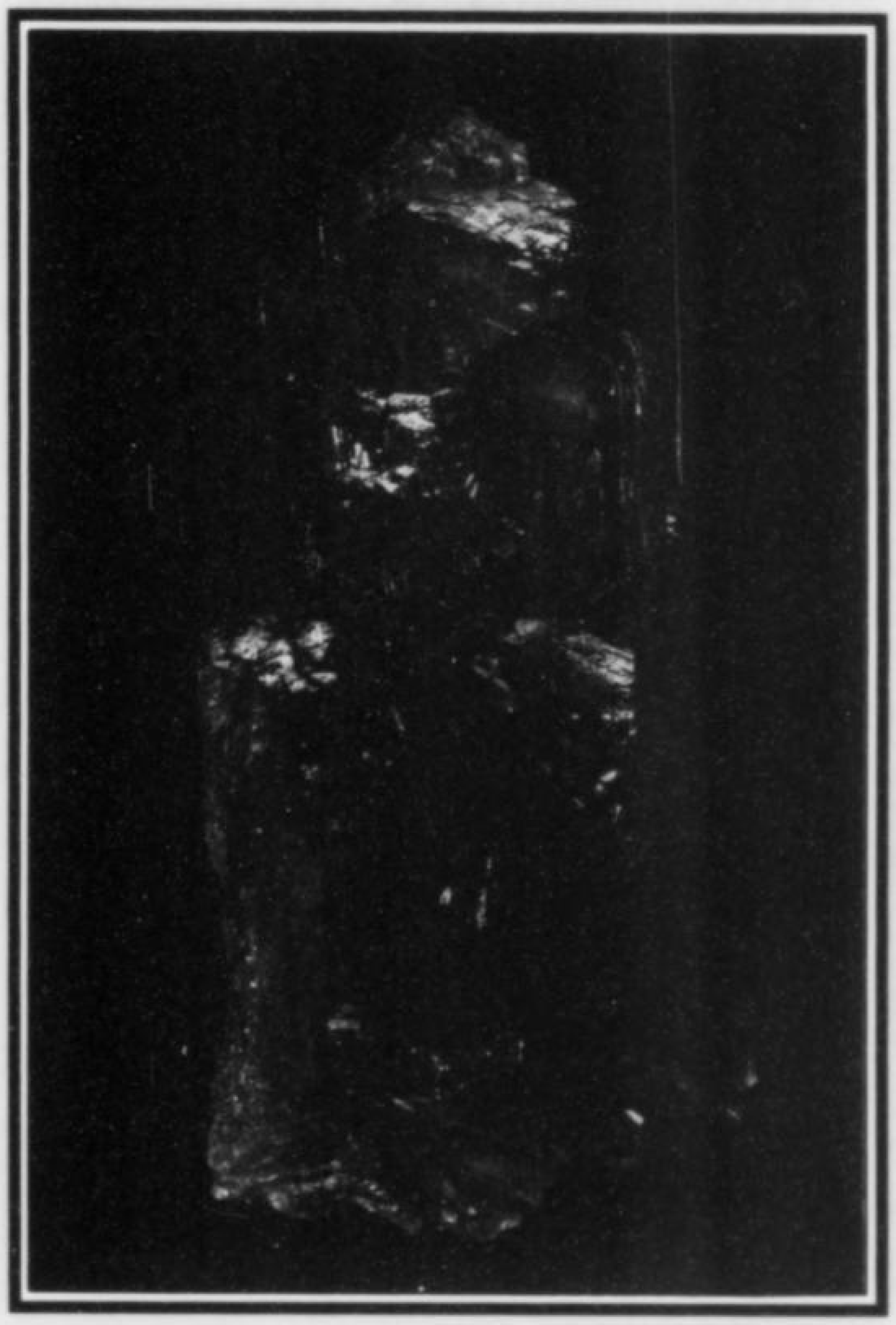
South Africa
Horst Windisch
30 Van Wouw Street
Groenkloof, Pretoria

Germany
Christian Weise Verlag
Oberanger 6
D-80331 München 2

THE 45th ANNUAL

TUCSON

GEM & MINERAL SHOW



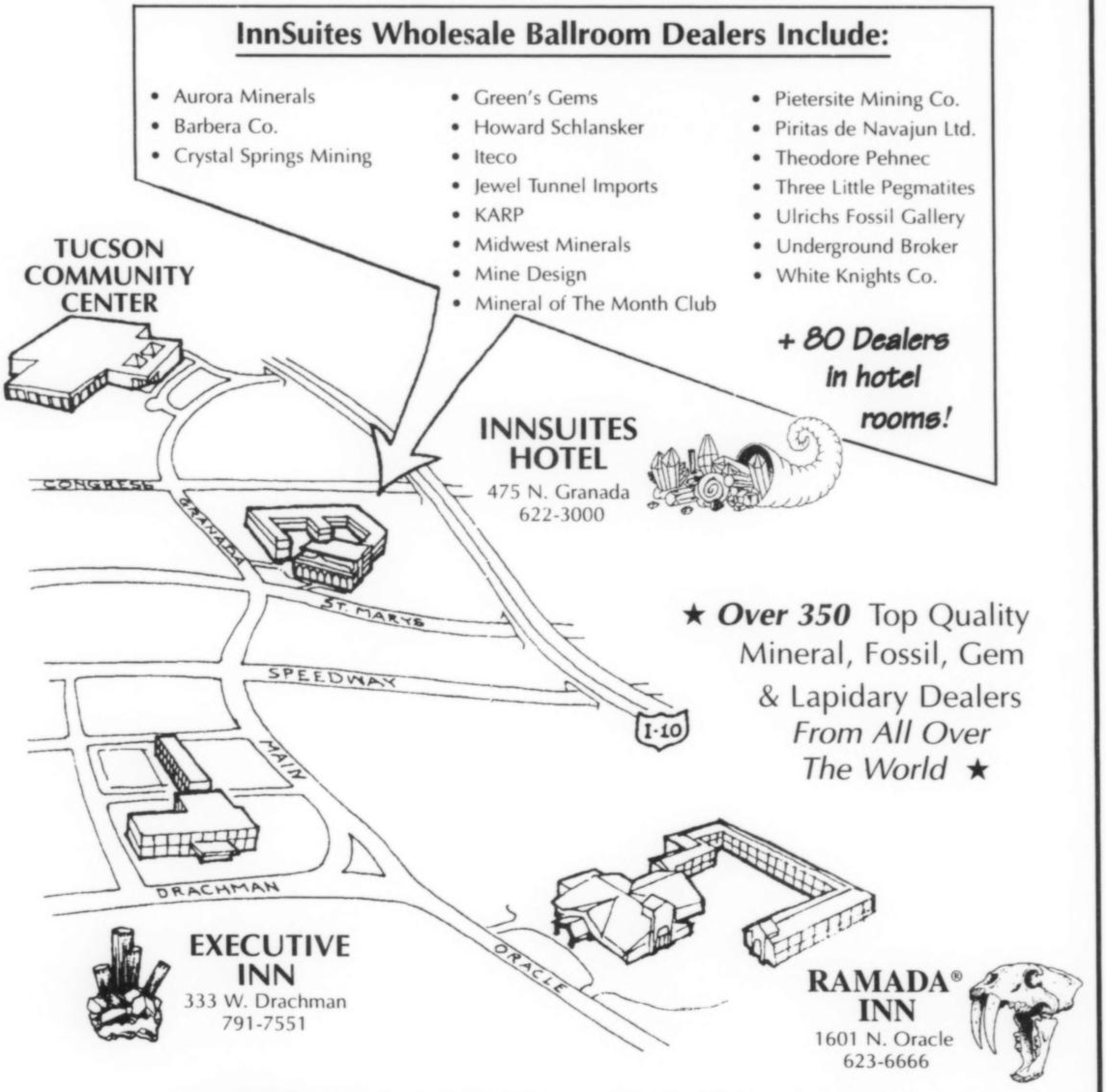
FEB. 11–14, 1999

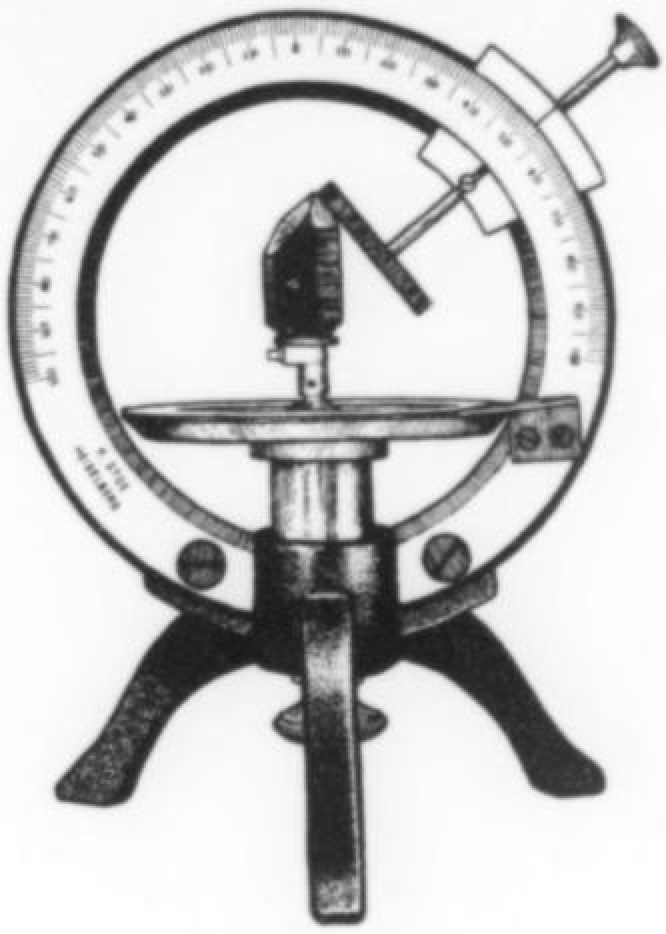
This year Mexican minerals will be the featured species at the Tucson show; the exhibits are sure to be spectacular. If you've been thinking about making a trip to see the world-famous Tucson Show, this is the year to do it! Besides the extraordinary exhibits from museums and private collections worldwide, you'll see the world's top mineral dealers, publishers and program lecturers. Make your arrangements now to attend the greatest mineral event of the year. **Use Church Street or Granada Avenue Entrance!**

Tucson Convention Center, Downtown Tucson • See: Competitive exhibits • the Arthur Roe Memorial Micromount Symposium • Mineral Photography Seminar • Meet the Authors hour • Symposium on Mexican Minerals (sponsored by FM, FMS, MSA, and TGMS) • Great Saturday Night Program • And the world's finest dealers in minerals, mineral books and magazines, and mineralogical antiques! HOURS: Thurs.-Sat. 10–6, Sun. 10–5. Admission $5 per day.

TUCSON GEM & MINERAL SOCIETY SHOW COMMITTEE
P.O. BOX 42543 • TUCSON, AZ 85733 • (520) 322-5773 • FAX (520) 322-6031

PHOTO: LUDLAMITE, Santa Eulalia, Mexico, 3.5 cm. Photo by Wendell E. Wilson.


CONGRESS
GRANADA
ST. MARYS
SPEEDWAY
MAIN
DRACHMAN
ORACLE
I-10



HISTORY OF THE DEVELOPMENT OF THE CRYSTALLOGRAPHIC GONIOMETER

Ulrich Burchard
Schlosstrasse 6
D-85354 Haindlfing, Freising
Germany

Instruments for the measurement of the angles between crystal faces have been constructed in an astonishing variety of types and degrees of complexity. They range from the pocket-size contact goniometers, as first designed by Carangeot in 1782, up to gigantic three-circle reflecting goniometers constructed around 1900. While in the first half of the 19th century it was mainly English and French precision mechanics and opticians who manufactured goniometers, the firm of R. Fuess in Berlin attained world fame and an almost monopolistic position from about 1875 to 1925. Today these beautiful devices are coveted as fascinatingly elegant reminders of the era of classical mineralogy.

Introduction

> *Even if instruments are incomplete, the diligent use of them for measurements is much more useful to science than if they were stored away in a cabinet.*
>
> W. K. Haidinger, 1845

The scientific discipline of crystallography evolved over the course of two centuries. Initially it was just a supplementary aid to mineralogy, but it matured into an independent science which today still has vital importance, especially in electronics and material science.

The crystallographer's most important instrument prior to the invention of X-ray diffraction was the *goniometer* (from Greek: *gonio* = "corner," or, roughly, "angles"), which is used to measure the angle between two crystal faces. Although the term "goniometer" is used almost exclusively to describe these crystallographic measuring instruments, there are also geodetical or radio-locating devices and demonstration apparatus (e.g., for Snell's law) that are similarly named; these will not be treated in this article. Projection goniometers and so-called cutting goniometers that were used in the production of crystal models will likewise not be discussed here.

The evolution of crystal study is closely allied with the development of the goniometer. Precision mechanics and optical instrument makers, in close cooperation with important scientists, invented ever more complex and accurate goniometers capable of more precise crystal measurements, creating fresh knowledge, so that ultimately crystallography became an independent science. In the course of time, simple contact goniometers evolved into highly complex three-circle reflecting goniometers, and the construction of individual custom-made instruments gave way to mass production. The development of the goniometer reflects not only the history of an exact science but also that of technology and industry.

The diversity of goniometer models is comparable to that of microscopes and theodolites. It is remarkably difficult to classify the amazing variety of different types. Therefore, the descriptions of individual instruments will allude also to historical advances in the level of crystallographic knowledge and to the scientists who carried out the research. At times, when necessary (e.g., to explain different techniques of goniometric measurement), the historical sequence will be disregarded.

Although goniometers are still used today, for example in the examination of new mineral species, their importance has been dramatically reduced since the discovery of X-ray crystal structure analysis in 1912.

Historic Roots of Crystallography

The earliest descriptions of external forms of crystals were made by the Roman scholar **Pliny the Elder** (24 AD–79 AD), who was killed observing an eruption of Mt. Vesuvius. In his *Historia naturalis*, Pliny mentions a six-sided quartz crystal:

Figure 1. **Imagined portrait of Pliny, from an early printed edition of his *Historia naturalis.***

> *Quare sexangulis nascatur lateribus non facile ratio inveneri potest, eo magis quad neque mucronis eadem species est.*

Throughout antiquity, astrological-alchemical speculations regarding crystal structures were rife. No crystallomorphological discoveries were made during the Middle Ages because of the era's preoccupation with jewels and their supposed healing and magical powers.

After Pliny, over one and a half millennia passed before the Belgian **Anselmus Boetius de Boodt** (1550–1632) engaged in the study of the geometric forms of crystals. De Boodt, who was Emperor Rudolph II's personal physician at the Royal Court in Prague, curated the emperor's gem and mineral collection. In his work *Gemmarum et lapidum historia libri V* (1609), de Boodt refers explicitly to *"Lapides, qui hebent figuram certam mathematicum"*; the earliest crystal drawings of quartz crystals (Fig. 2) are also found here.

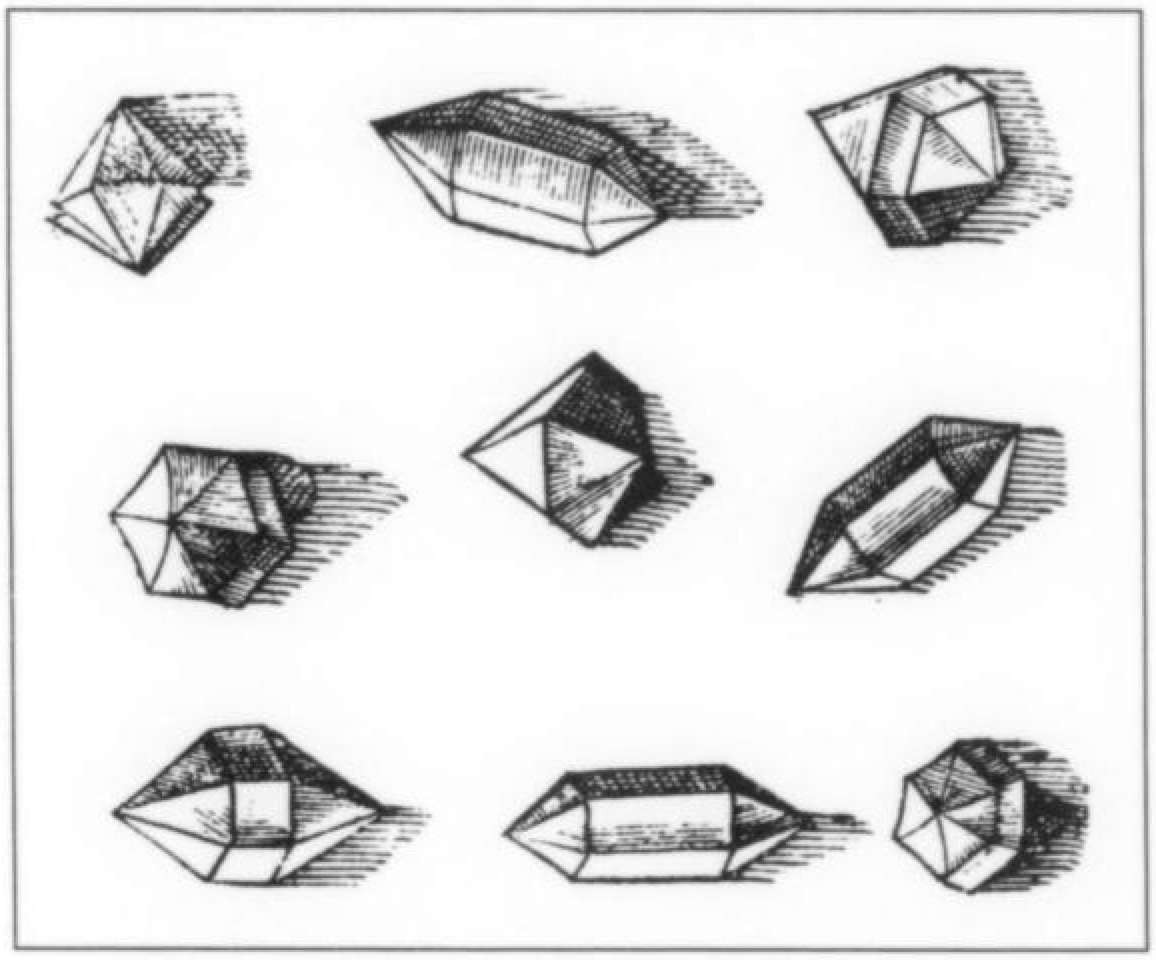


Figure 2. **Earliest drawing of quartz crystals (Boetius de Boodt, 1647).**

At the beginning of the 17th century, the first optical instruments, the telescope and the microscope, came into use almost simultaneously. The pioneering work *Micrographiá* (1665) by **Robert Hooke** (1635–1703), the inventor of the compound microscope, contains numerous illustrations and descriptions of crystals that he observed under the microscope (Fig. 3). Many sketches of

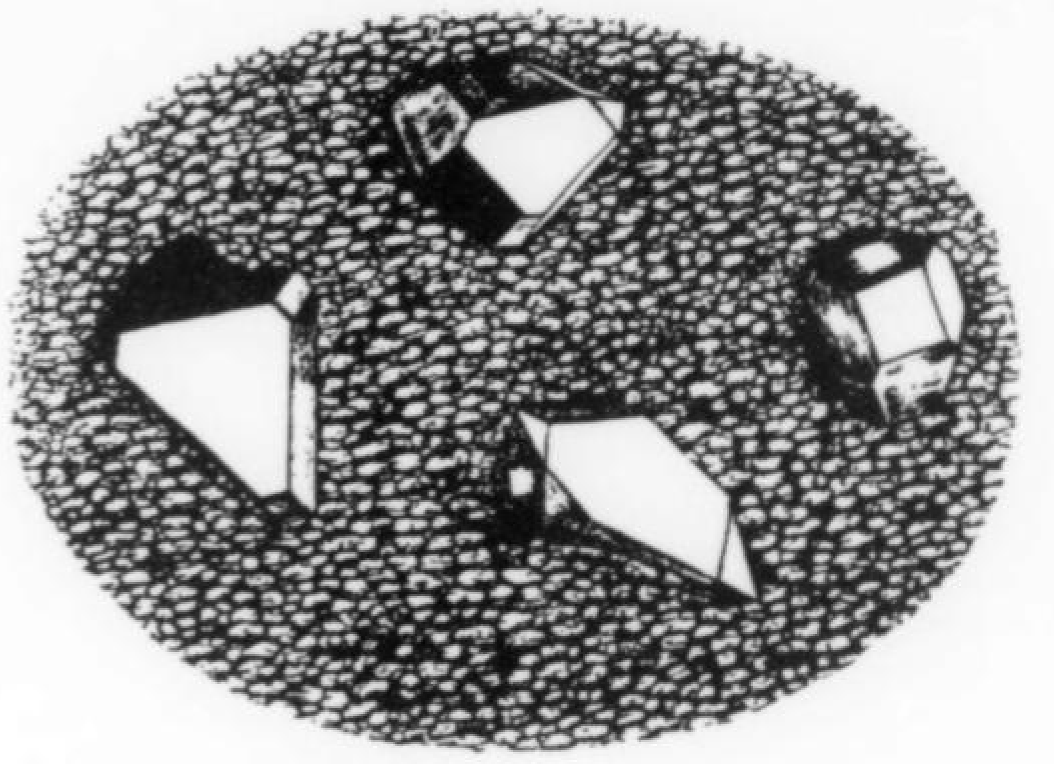


Figure 3. **Drawing of "gravel of urine" (Hooke, 1667).**

crystal forms are contained in the famous letters that the Dutch microscopist **Antony van Leeuwenhoek** (1632–1723) wrote to the Royal Society of London between 1678 and 1685. This tradition was later continued by the Englishman **Henry Baker** (1698–1774) in his essay *Employment of the Microscope* (1753), with dozens of detailed descriptions and drawings of crystalline substances. All these works paved the way for exact and reproducible mathematical observations based on scientific crystallography.

Mieleitner (1923) remarked:

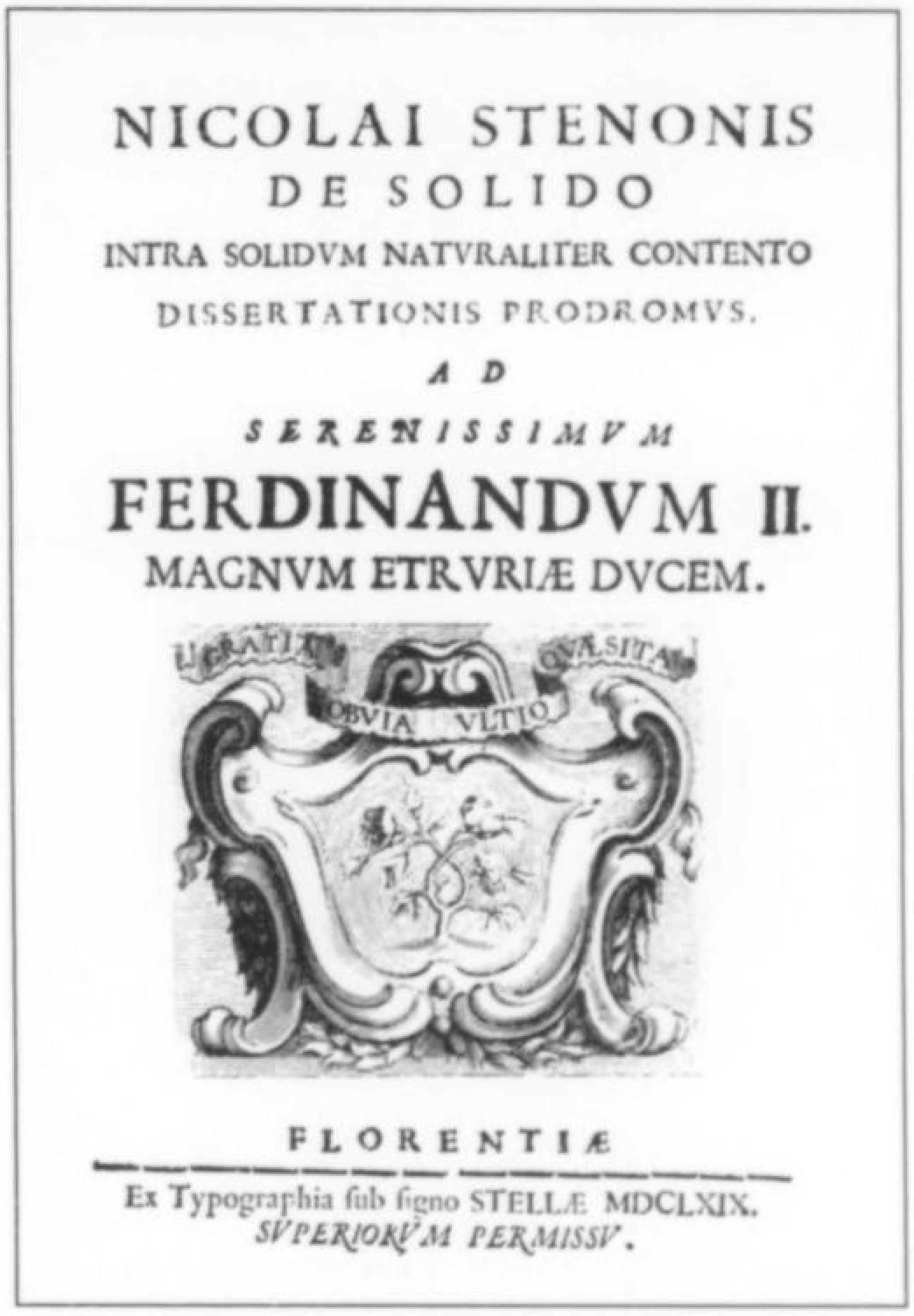
> *The year 1669 should be considered as the birth year of scientific crystallography, in which Erasmus Bartholinus's* Experiments with doubly refracting Iceland crystal *and Nicolaus Steno's work* About solid bodies, which are enclosed within other solid bodies *appeared. In the first work double refraction is discovered and crystal optics established; in the latter the law of the constancy of interfacial angles is proposed, and the growth as well as the origin of the crystals is examined.*

In addition, it may be noted that Bartholinus also first described blowpipe experiments on minerals, so that 1669 can also be considered as the birth year of chemical mineralogy.

The Dane **Nicolaus Steno** (Stensen, Stenonis, 1636–1686) was physician to the Medicis in Florence. In his chief work, *De Solido intra Solidum naturaliter contento, Dissertationes Prodromus* (1669) (Fig. 4), the section which describes quartz in detail is of particular interest. Steno explained the phenomenon of crystal growth through layered deposits of material on the crystal faces. In his explanation of the outline sketches of the "rock crystal" of quartz (Fig. 5), Steno mentions rather casually that, of course, even though the positions of the sides and their number can change, the angles between the faces remain constant, since the new crystal growth material accumulates in parallel layers: *In plano axis laterum et numerum et longitudinem varie mutari, non mutatis angulis.*

Both Burke (1966) and Fabian (1986) explicitly state that Steno recognized the constancy of the angles of quartz correctly, but that he did not generalize this observation to include other crystalline substances. How Steno determined the crystal angles is not clear. It is likely that he placed the crystal sections on paper and traced the outlines.

Steno's compatriot, the mathematician and physician **Erasmus Bartholinus** (1625–1698), described the double-refracting Icelandic calcites in his book *Experimenta Crystalli Islandici Disdiaclastici*—which was also published in Copenhagen in 1669.



NICOLAI STENONIS
DE SOLIDO
INTRA SOLIDVM NATVRALITER CONTENTO
DISSERTATIONIS PRODROMVS.
AD
SERENISSIMVM
FERDINANDVM II.
MAGNVM ETRVRIÆ DVCEM.

FLORENTIÆ
Ex Typographia ſub ſigno STELLÆ MDCLXIX.
SVPERIORVM PERMISSV.

Figure 4. **Title page of Steno's (1669)** ***De solido intra solidum naturaliter contento.***

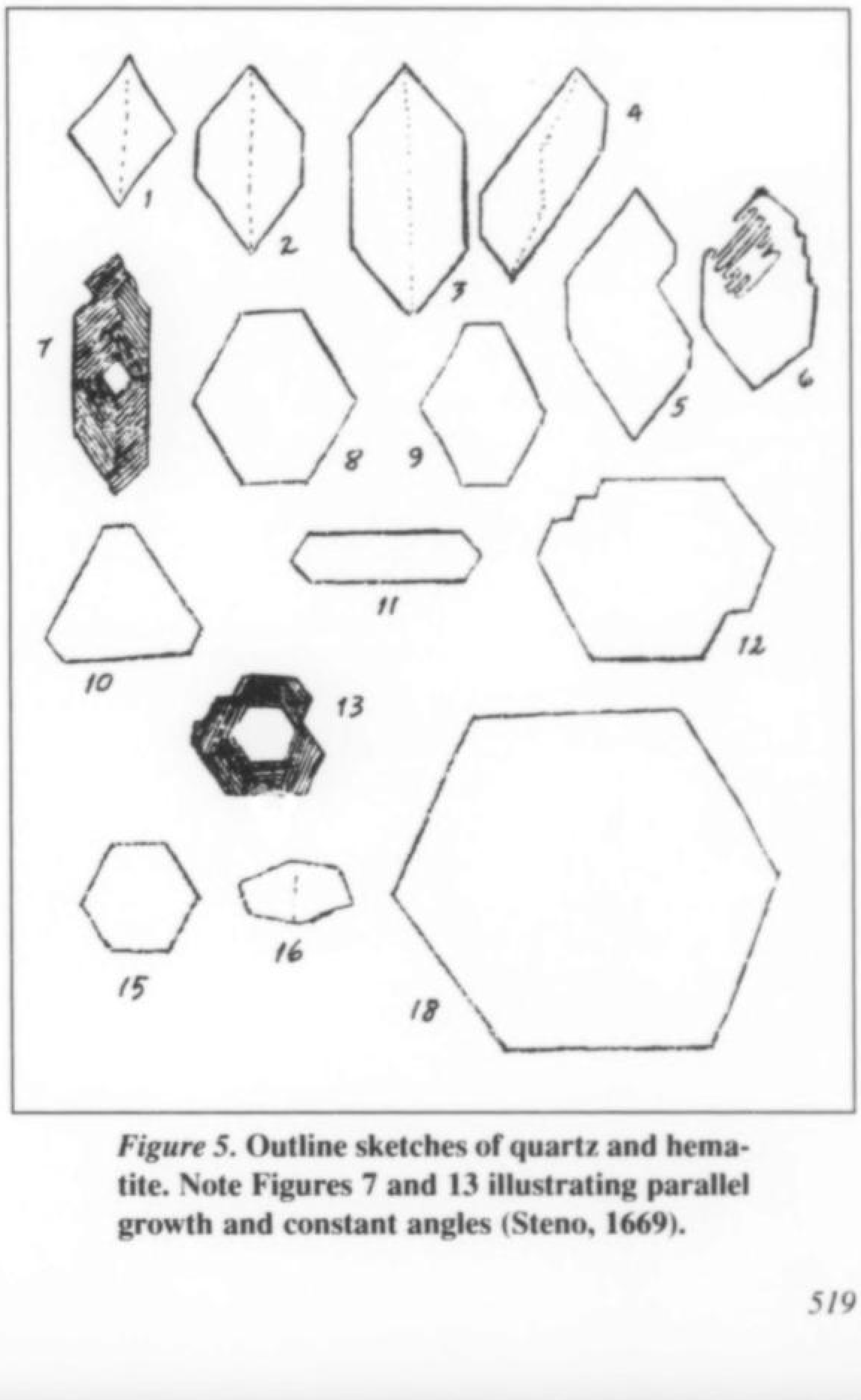


Figure 5. **Outline sketches of quartz and hematite. Note Figures 7 and 13 illustrating parallel growth and constant angles (Steno, 1669).**

Furthermore, he determined more accurately than ever before that the angles of the calcite rhombohedron are 101° and 79°. It is strongly probable that he used a mechanical means of measurement, possibly a contact instrument such as a carpenter's protractor.

The Dutch physicist **Christian Huygens** (1629–1695) continued the work of Bartholinus. In his work *Traité de la Lumière* (1690), Huygens indicated the interfacial angles of the calcite rhombohedron to be 101°52′ and 78°8′; these angles were mathematically determined from the bevel of the opposite edge of the rhombohedron (105°). Huygens examined mineral samples from Iceland as well as crystals "of the same kind" from France and Corsica. Although he did not emphasize it explicitly, Huygens clearly accepted the principle of the constancy of interfacial angles in crystals of the same species.

Almost 100 years were to pass, however, until Romé de l'Isle formulated a *universal* law of the constancy of angles. During this period, surprisingly few scholars engaged in crystal measurements. Burke (1966) suggests that the reason for this evident disinterest was that the prevailing beliefs of the scientists of the time were in simple mathematical laws, and a constant interfacial angle of such an "odd" dimension as 101°52′ was hard to accept. It is also true that precise, easy to use instruments were not available to produce the necessary reliable results.

The Italian scholar **Domenico Guglielmini** (1655–1710) in his *Riflessioni filosofiche dedotte dalla Figuri de Sali* (1688) differentiated four crystal forms in salt: cube, prism, octahedron and rhombohedron. He ascertained that, despite incomplete formation of the crystals, ideally, "the relation of the planes and the angle is always constant." Although Guglielmini postulated this constancy of angles in salt crystals, he did not generalize his theory for all crystalline substances.

The next documented crystal measurements are those of the Frenchman **Gabriel de la Hire** (1677–1719), who, studying the outline forms of calcite and gypsum, determined for the former an angle of 101°30′ (*Observations sur une espèce de talc qu'on trouve communément proche de Paris au-dessus les bancs de pierre de plâtre*, 1710).

The Swiss physician **Moritz Anton Cappeller** (1685–1769), in his work *Produmus Crystallographiae de Crystallis improprie sic dictis commentarium* (1723), introduced for the first time the term *crystallography* = crystal description. According to Fabian (1986), "Cappeller moved the geometric form as a qualitative feature of a crystal to the foreground," and tried to use this form in mineral identification.

Simple Contact Goniometers

Early geometry-oriented discussions of crystals limited themselves to the few mineral species (quartz, calcite) for which the constant interfacial angles were known. The fact that a suitable device for measuring such angles was not built until the end of the 18th century cannot be attributed positively to the lack of technical knowledge. **Philippe Danfrie** (d. 1606), as early as 1597, built a surveying instrument, the *graphometer*, which was similar in shape to a contact goniometer; it had one fixed and one movable diopter straightedge mounted on a semicircular protractor. The main technical problem, namely the precise division of a circle into equal parts, was solved through the invention of the circle-dividing machine by **Georg Friedrich Brander** (1713–1783), **John Bird** (1709–1776) and **Jesse Ramsden** (1731–1800). But the diagnostic importance of interfacial angles in crystals had not yet been recognized; theoretical and technological lines of research had yet to come together.

Franz von Kobell (1864) noted:

> *The progress of each science depends especially on the production of new means for investigation; a single apparatus, a single instrument has often contributed more than all study and interpretation with simple speculation and philosophy. And so also has the invention of an instrument for the measurement of angles of inclination afforded completely new points of view.*

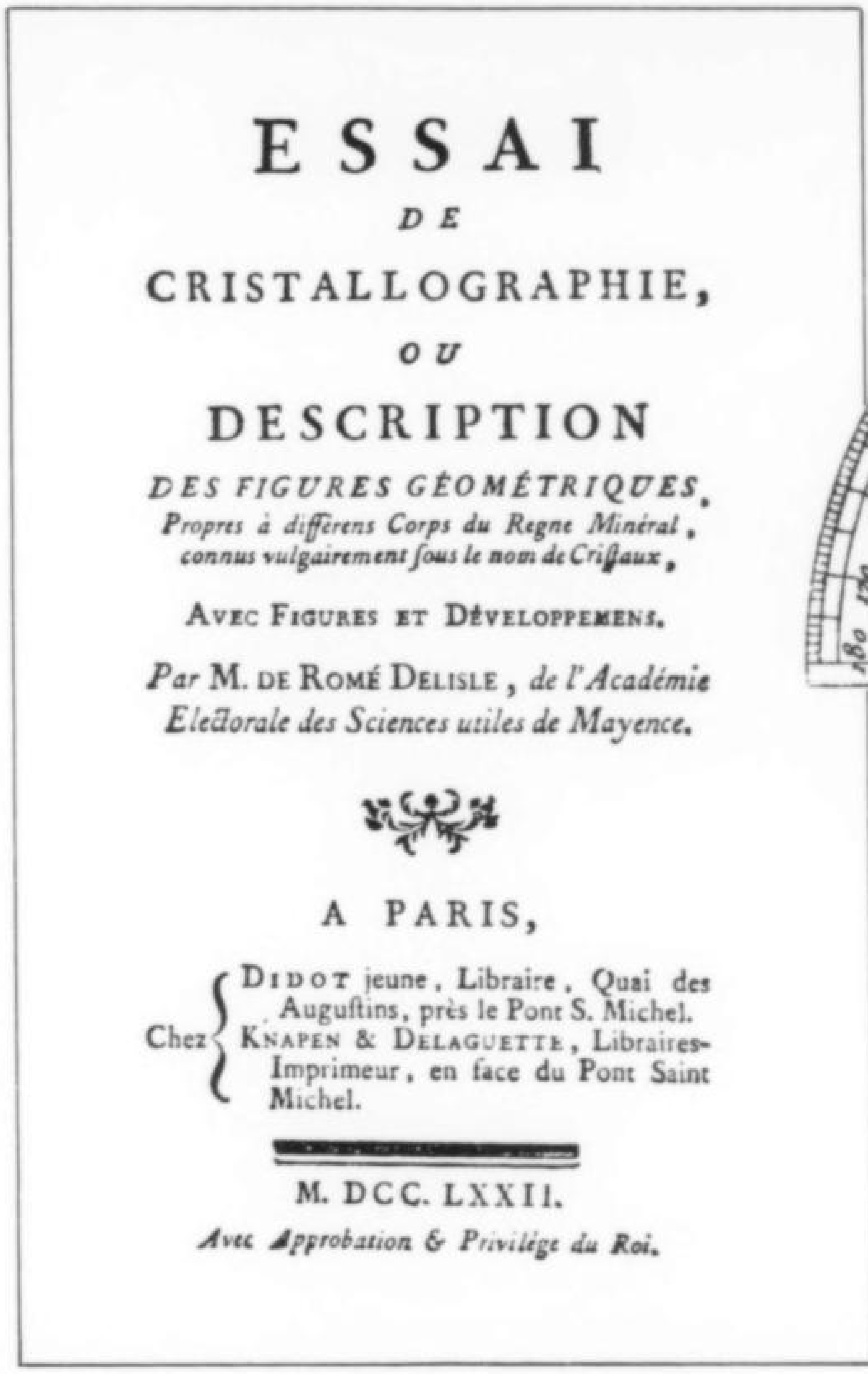
W. Miller (1856) wrote:

> *[The fact that] by putting the simplest form of such scissors [contact goniometers] on paper and inserting a crystal between the legs one can determine the angle of the latter with help of a partial circle, is found mentioned even earlier than Delisle, in the* Systema mineralogicum *of Wallerius I, pg. 255.*

Indeed, Brezina (1884) also refers to **Johann Gottschalk Wallerius** (1709–1785), page number 225. The relevant text, however, cannot be found in either the 1772 Stockholm, Paris or Vienna editions.

Setting aside this early ambiguity, the invention of the first goniometers is unusually well documented because the persons involved immediately recognized the significance of the new instrument for crystallography. The French scientist **Jean Baptiste Louis Romé de l'Isle** (1736–1790) (Fig. 6) published his first book, *Essai de Crystallographie* (Fig. 7), in 1772. The work contained drawings of 110 crystal forms, but almost all angles described are plane angles. For the only angles formed by two planes, in gypsum and calcite, whose values are given, the values were probably copied from de la Hire. As research material for the planned expanded second edition of his book, Romé de l'Isle assembled a private crystal collection, and in about 1780 hired the

***Figure 6.* Jean Baptiste Romé de l'Isle (1736–1790), the founder of crystallography.**



ESSAI

DE

CRISTALLOGRAPHIE,

OU

DESCRIPTION

DES FIGURES GÉOMÉTRIQUES,
Propres à différens Corps du Regne Minéral,
connus vulgairement ſous le nom de Criſtaux,

AVEC FIGURES ET DÉVELOPPEMENS.

Par M. DE ROMÉ DELISLE, de l'Académie
Electorale des Sciences utiles de Mayence.

A PARIS,

Chez { DIDOT jeune, Libraire, Quai des Auguſtins, près le Pont S. Michel.
KNAPEN & DELAGUETTE, Libraires-Imprimeur, en face du Pont Saint Michel.

M. DCC. LXXII.
Avec Approbation & Privilége du Roi.

Figure 7. **Title page of Romé de l'Isle's (1772) *Essai de cristallographie.***

engraver Francois Louis Swebach des Fontaines to draw and reproduce 452 crystals. To make his drawing work easier, Swebach requested clay models of the selected crystals. This request probably gave Romé de l'Isle the idea of manufacturing such small crystal models of clay, wood or brass, and offering them to buyers of his book to explain the two-dimensional drawings. Commercial interests almost certainly had an influence, since the first crystal model collections were well received.

Romé de l'Isle authorized two of his pupils, **Arnould Carangeot** (1742–1806) and **Claude Lermina** (1749–1806), to construct an instrument for the measurement and reproduction of crystal angles; Carangeot, accordingly, designed the prototype of a contact goniometer. **Nicolas Vincard** was entrusted with constructing the actual instrument. Interestingly enough, Vincard considered himself a pupil and successor of Canivet (?–1774), from whose workshop many graphometers have survived.

On April 11th, 1782, Carangeot demonstrated this first goniometer to a circle of scientists and the editor Pahin de la Blancherie; six days later it was reported in the *Nouvelles de la Republique des Lettres et des Arts.* Romé de l'Isle's four-volume work *Cristallographie*, appearing in 1783, contained in its preface a description of Carangeot's goniometer, along with the first illustration of it (Fig. 8). A sentence stating the fundamental idea of the science of crystallography is also contained here:

> *Les faces d'un cristall peuvent varier dans leur figure, et leurs dimensions relative, mais l'inclinasion respective de ces mémes faces est constante et variable dans chaque espèce.*

With this, Romé de l'Isle was the first to express the law of the constancy of angles in its universally valid form. Mineral species could be identified and systematized by the angles of inclination, and angular measurements would become the indispensable basis of crystallography.

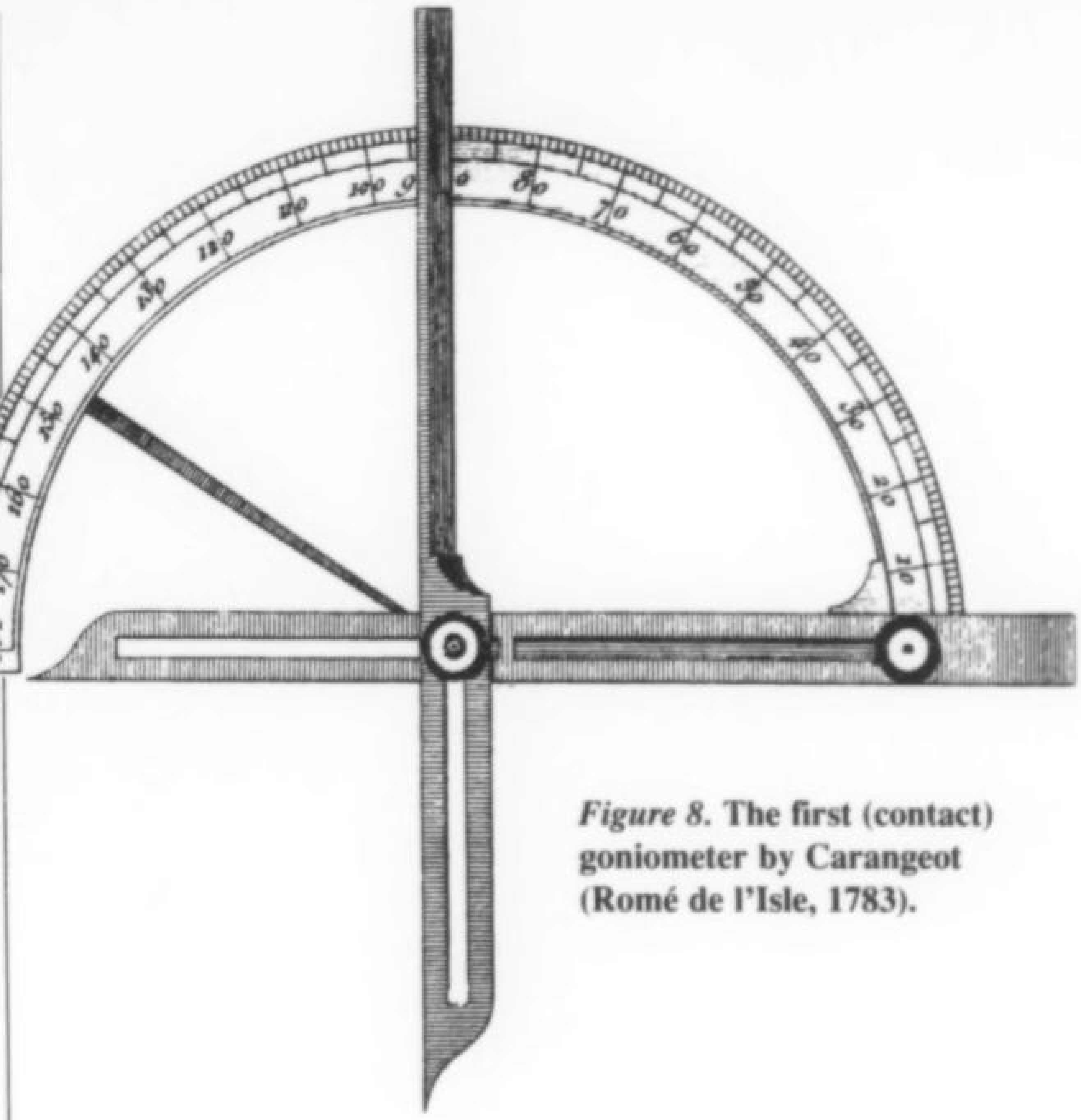


Figure 8. **The first (contact) goniometer by Carangeot (Romé de l'Isle, 1783).**

Naturally Carangeot was fully aware of the significance of this cornerstone of crystallography, and he fought to be recognized as at least a co-discoverer of the law of the constancy of angles. As early as 1783, the year of the publication of Romé de l'Isle's *Cristallographié*, Carangeot described the history of the discovery from his viewpoint. He stated that he had precisely determined different angles of several quartz crystals with his contact goniometer, had recognized the constancy of the angles between comparable crystal faces, and had related these observations to Romé de l'Isle. Romé de l'Isle, Carangeot claimed, had only realized the general principle after Carangeot had repeated these measurements on other species. Again in 1787, Carangeot repeats his claim and writes of his discovery:

> *J'ai donné par example le cristal de roche, qui m'avoit occasioné la découverte de cette proprieté si interessante & particulière aux cristeaux, de la constance de leurs angles solides dans ceux d'une méme espèce.*

Carangeot's fight for recognition met with little success; Romé de l'Isle's reputation as discoverer of the constancy of angles was secured in the literature. After Carangeot's death, only René Just Haüy the adversary of Romé de l'Isle and the real father of crystallography, indicated that Carangeot was involved in the discovery.

The prototype of the contact goniometer invented by Carangeot consists of a graduated semicircular arc whose diameter also serves as the stationary measuring limb. The second limb rotates around the center of the circle. The left half of the arc is not connected with the diameter. Both limbs are equipped with internal slots, so that the pointed ends can arbitrarily be shortened and extended through parallel sliding.

The method of measuring with all contact goniometers is simply to place the crystal edge to be measured between both measuring limbs such that these stand exactly vertical on the crystal faces

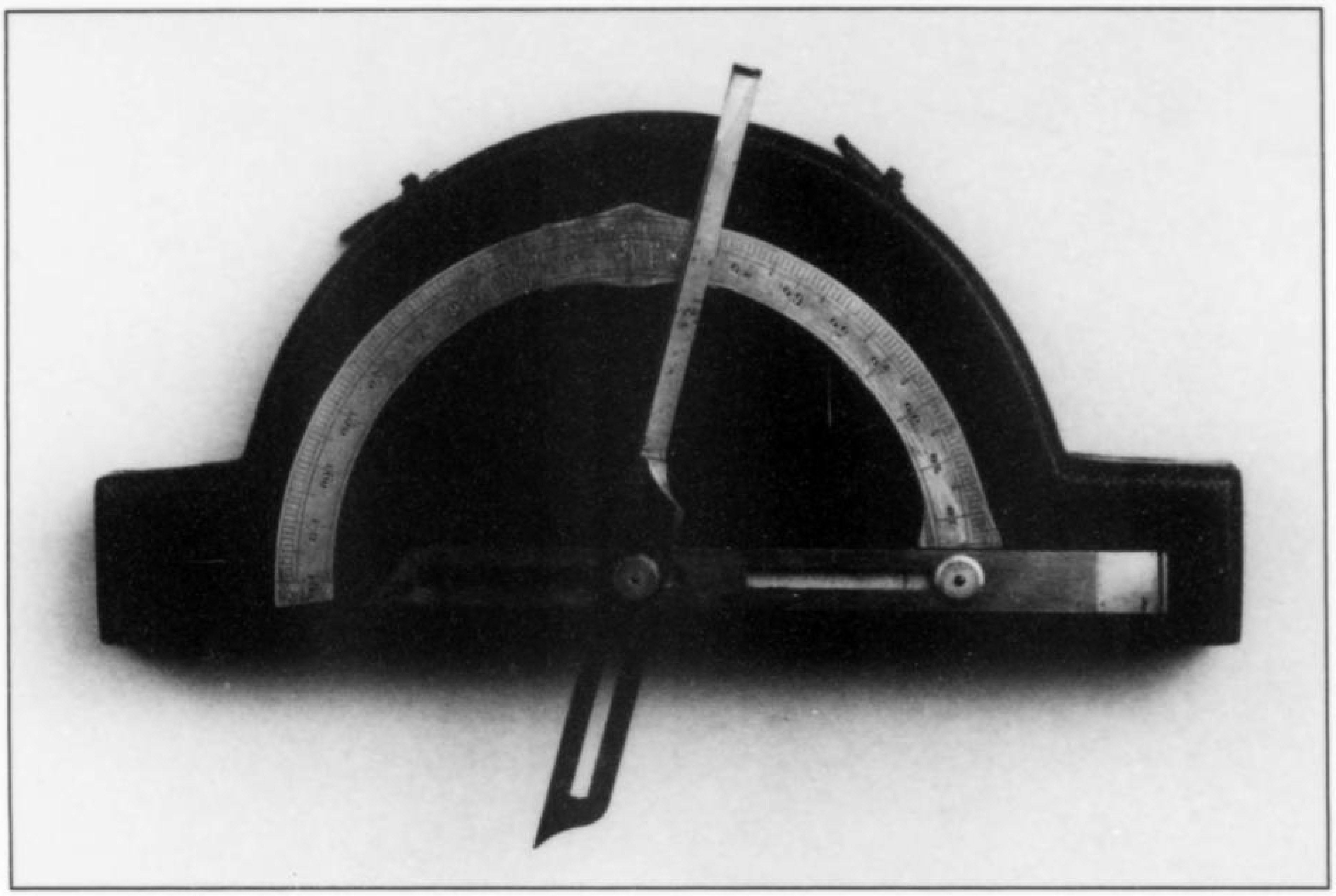


Figure 9. **Improved model of the Carangeot contact goniometer hinged at the 90° graduation. Signed: "Ferat à Paris," ca. 1790.**

which meet to form the edge. The crystal edge must be held directly at the scissor opening. A contrasting background facilitates the measurement, because no background should be visible between the goniometer measuring limbs and the crystal when the limbs are snug against the faces. The angle being measured is read directly from the scale.

It was difficult with the prototype to measure crystals which were parts of crystal groups, or to measure crystals on matrix, because the extraneous masses would interfere with proper positioning; in 1786, therefore, Carangeot developed an improved model. By means of a hinge at the 90° mark, the left half of the semicircular arc could be folded away, so both points of the straight-edge arms could be advanced freely to the crystal faces (Fig. 9). An additional radial arm secured by mill-headed screws was mounted behind the 140° mark to stabilize the instrument and allow freedom of rotation.

The instrument maker Ferat was entrusted with the completion of this improved model. Ferat worked in the workshops of Vincard, and up to Vincard's death in 1788 he sold his goniometer under the name of his employer. Each of the models from the workshop of Vincard & Ferat was sold in two versions, one in copper (brass?) and the other in silver. Prices for the original models in 1786 were 18 livre for copper and 36 livre for silver; for the improved models, 36 and 54 livre respectively. Of the last of these, at least two examples are known.

Between 1781 and 1784 the genius who was the founder of crystallography, **René Just Haüy** (1743–1822), developed his *laws of decrement*, expressing complex ideas about crystal structure. In principle, Haüy postulated, all crystal shapes can be traced back to a few simple building blocks. All secondary forms can be derived from primitive (simple) forms by a regular stripping away (decresence = decrease) or, in the reverse process, a regular accumulation of molecules or rows of molecules. For example, a rhombic dodecahedron can be built up from small cubes. The surfaces of the secondary forms are not perfect planes but stepped, layered lamellae. Haüy designed hundreds of wooden crystal models to illustrate and further his theory. His stepped models with manuscript labels are famous (Fig. 10). In the atlas of his main work *Traité de Minéralogie* (1801), he published the surprisingly versatile and precise results of his crystal measurements. Haüy worked exclusively with a contact goniometer, and in Fig. 11 he is pictured with such an instrument, incidentally illustrating the way the instrument is used. But the invention of the reflecting goniom-

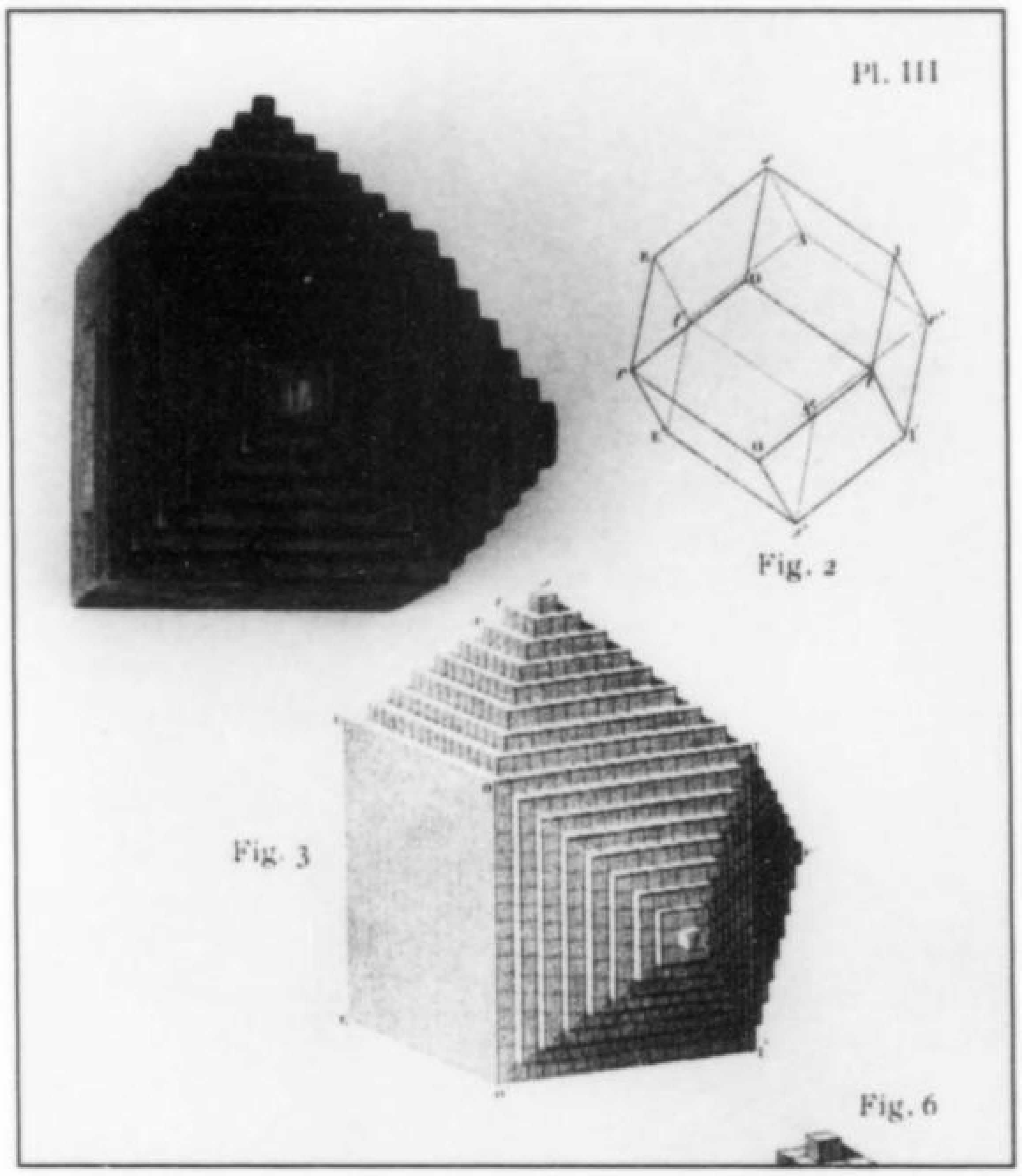


Figure 10. **Haüy's (1809) illustration of a rhombo-dodecahedron composed by simple cubes. Original wooden model with Haüy manuscript label ca. 1810.**

Figure 11. **René Just Haüy (1743–1822), genius of crystallography, depicted with his contact goniometer measuring the angle of a calcite rhombohedron.**

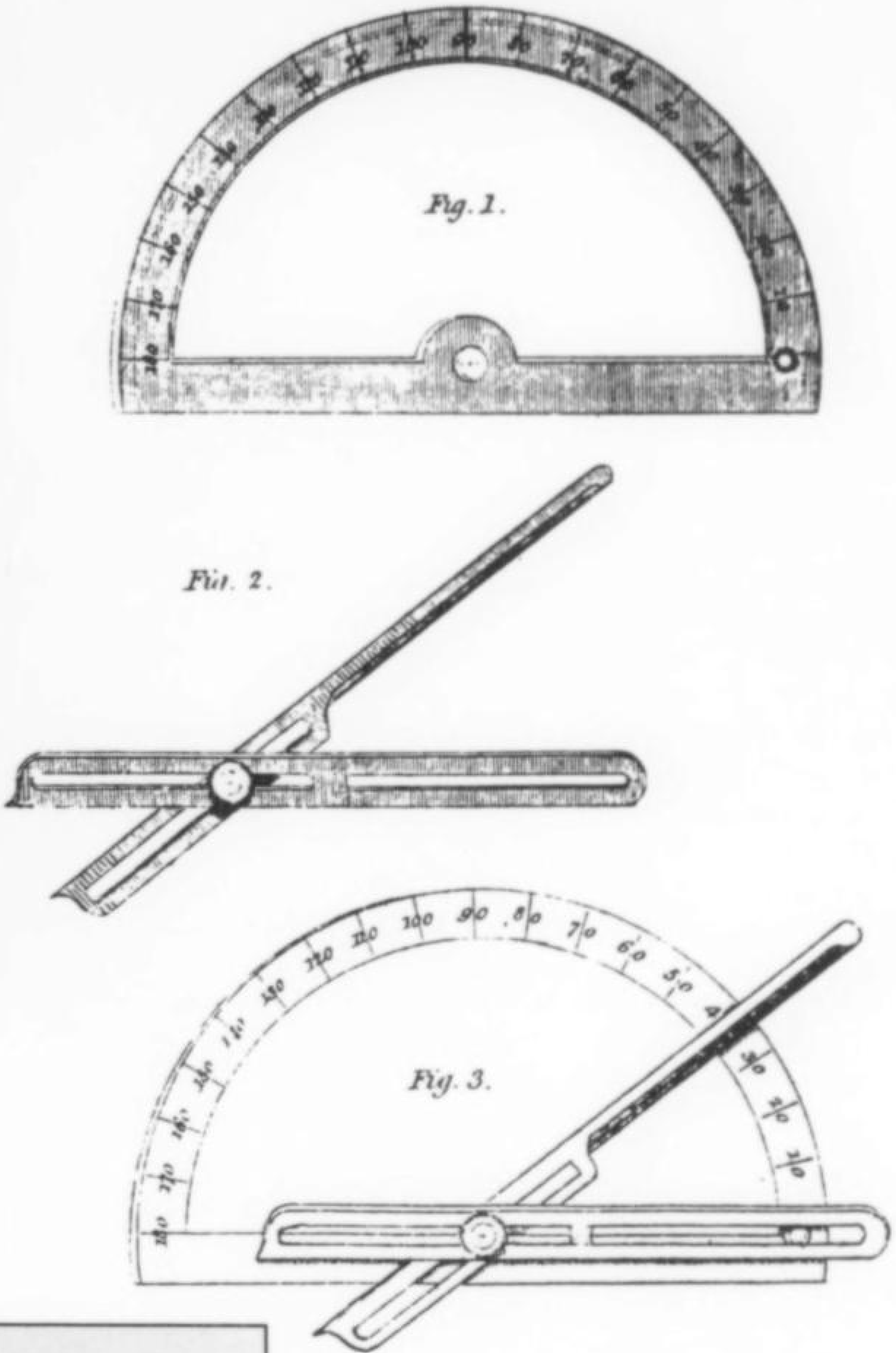


Figure 12. **Improved contact goniometer with detachable slotted radii (Bancks, 1805).**

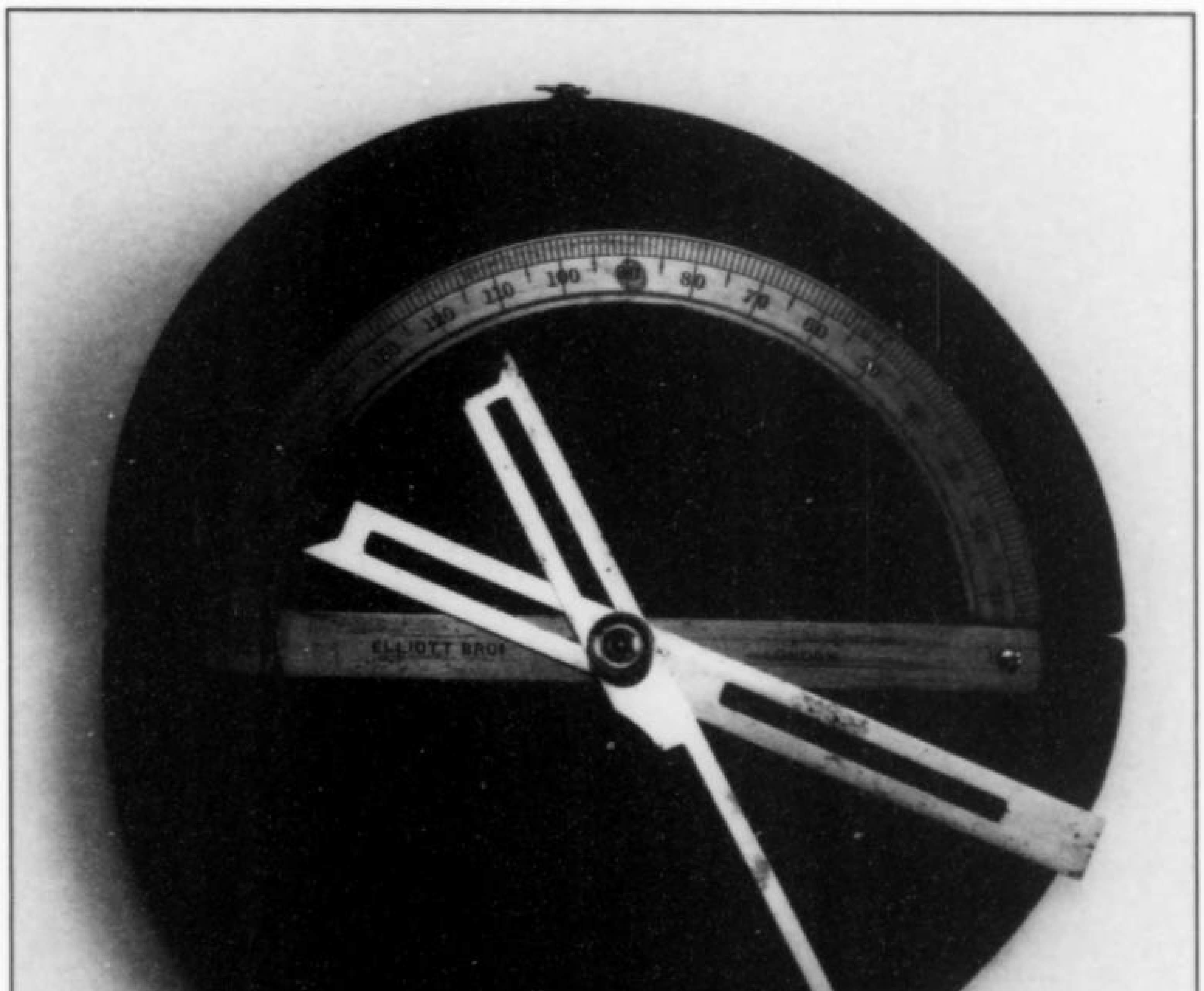


Figure 13. **Simple contact goniometer with firm frame; signed: "Elliot Bros. London," ca. 1890.**

eter by W. H. Wollaston in 1809 allowed more precise crystal measurements than obtainable with the contact goniometer; the results cast some doubt on Haüy's theories, doubts against which Haüy fought.

It is not surprising that early attempts were made to simplify and lower the cost of contact goniometers and to introduce them into universal use. A decided improvement was proposed by **Robert Bancks** (1805) (Fig. 12). Interestingly, Bancks called his instrument a "Graphometer," although Carangeot (1783) had used the name *"goniomètre ou mesure angle."* Bancks's model, because of its simplicity and ease of use, was widely disseminated, and became the standard contact goniometer. It has several advantages over the Carangeot model: (1) The diameter of the semicircle is not interrupted, making the instrument more stable; (2) The two scissor-like slotted straight-edge bars can be removed and replaced in the exact center of the circle with the help of a pin; (3) After the measurement, the opening of the arms is fixed with a pivot screw, and one arm, with the help of a notch, is placed exactly on the zero line corresponding with the diameter (Fig. 13). It is to be noted at this point that both Dufrénoy (1856) and Miller (1856) gave the Frenchman Alexandre Brogniart the credit for construction of a goniometer with detachable arms.

Most authors (Haüy, 1818; Dana, 1878; Groth, 1876) indicated an accuracy of between 15 minutes and 1 degree for measurements made with the contact goniometer. To improve the accuracy of readings, **Francois Pierre Nicolas Gillet de Laumont** (1747–1834) (see Beudant, 1830) extended the radius of the circle and added seven concentric inner circles. He connected the full degree graduating marks at the inner and outer edges of the semicircle with diagonal lines (Fig. 14). If the edge of the measuring limb aligns fully with the degree mark on the outer or inner circle respectively, one can read a full degree. However, if the edge of the measuring limb lies on one of the diagonal intersections of the second to sixth semicircles, one can read off a multiple of 10 minutes. The relatively complicated Laumont contact goniometer appears to have found little if any acceptance; the author knows of no existing examples of this type.

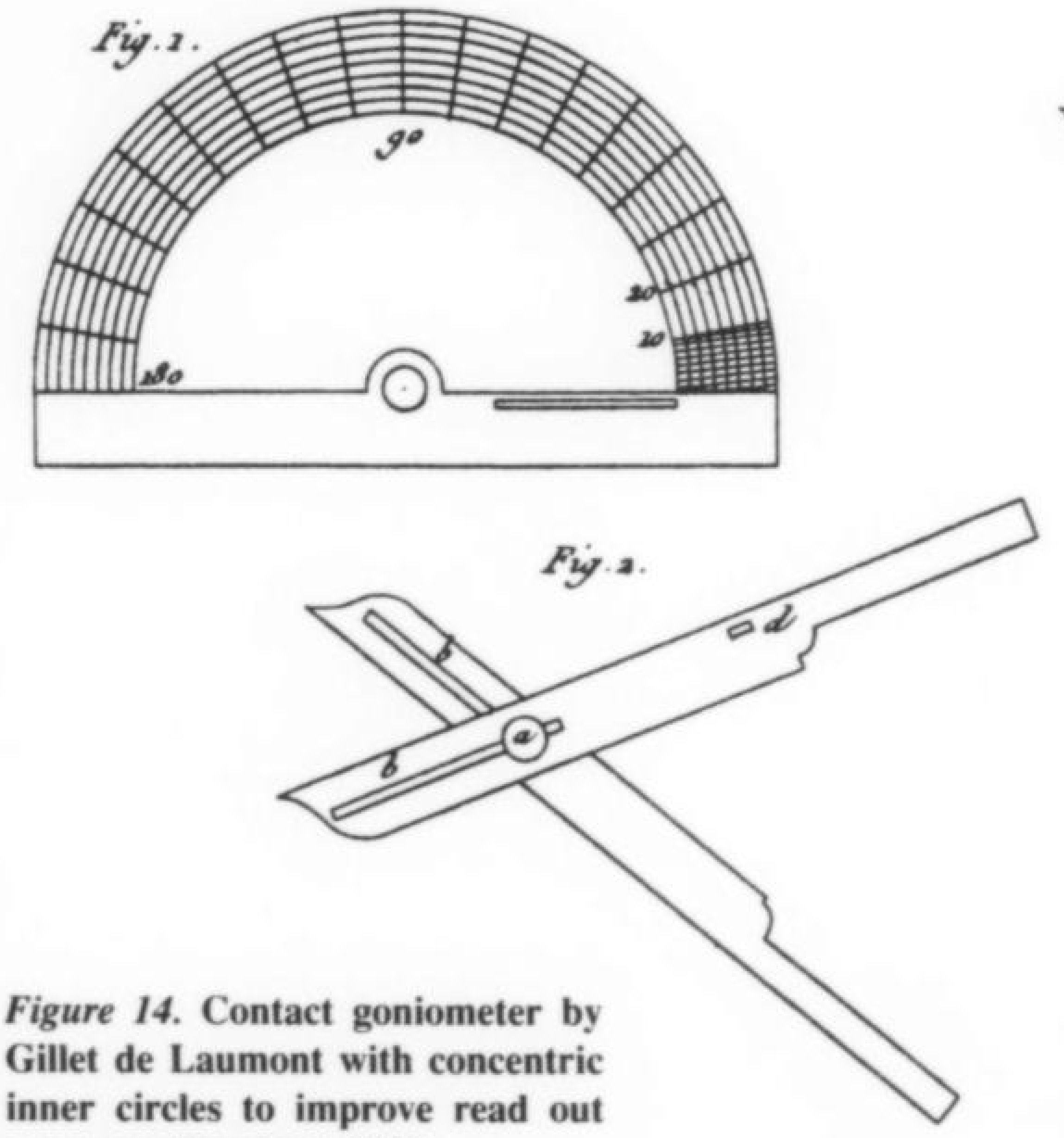


***Figure 14.* Contact goniometer by Gillet de Laumont with concentric inner circles to improve read out accuracy (Beudant, 1830).**

While all the above described contact goniometers used a graduated semicircular arc, quarter-circle and full-circle contact goniometers were also designed. **E. J. Burrow** (1809) contrived a scissor-like device with a graduated quarter circle that soon fell into oblivion (Fig. 15). Only in 1899 did Leiss again construct this type. To increase the stability, a limb is firmly joined to a quarter-circle track. The second limb is mounted on the track of the quarter-circle and can be moved within it. The Fuess company sold this model for 30 Marks in 1909.

A full-circle contact goniometer also originated in the Fuess workshops. Its date of introduction cannot be found in the literature, but Groth (1876) describes it as "today's usual form." It is not known for what purpose this instrument was designed, but it can be assumed that, by using both readings on a full circle, any errors could be averaged out (Fig. 17).

To round out the picture, it is to be noted that Adolf Bär tried to give new impetus to the principle of contact through his investigations of "new contact goniometers for measurement, calculation and drawings of crystals" in 1933. Bär's relatively simple ideas were never implemented. He suggested a so-called plane goniometer which would work as does a Carangeot goniometer. Since the exact contact with the crystal faces is of utmost importance, Bär suggested the use of two flat plates joined by a hinge and opening as a book does, instead of the scissor-like limbs.

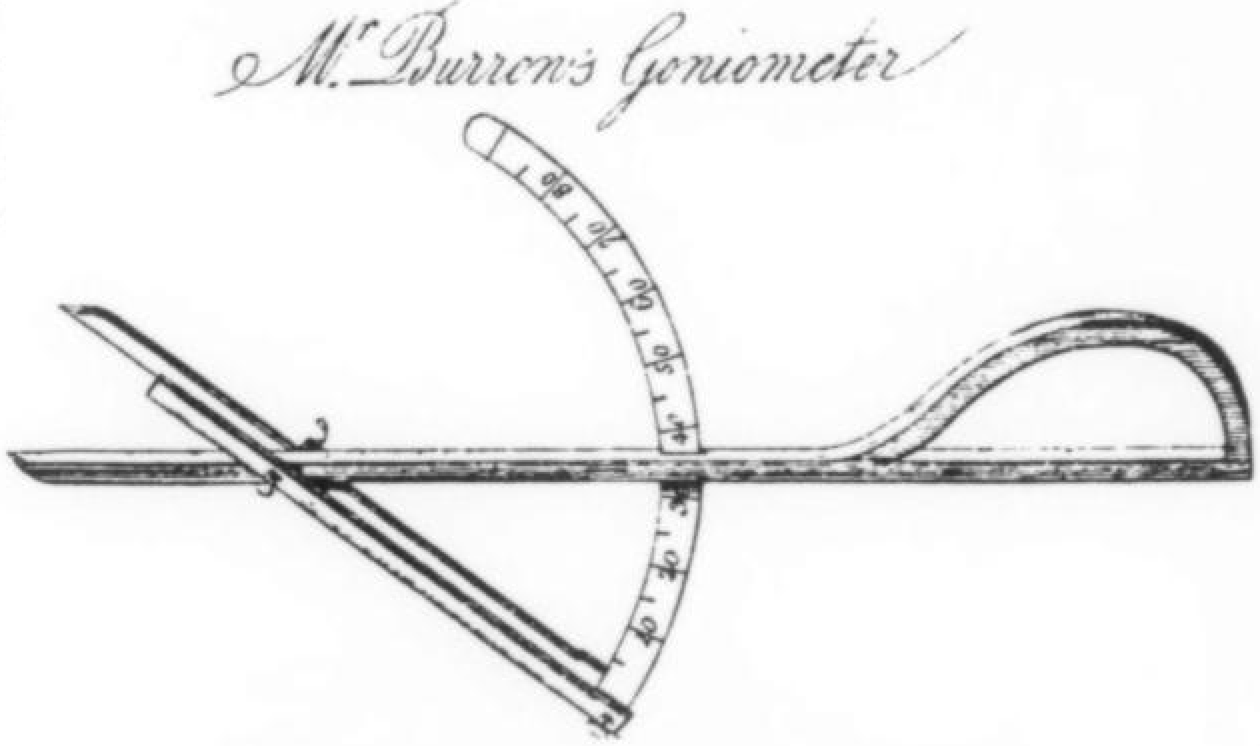


***Figure 15.* Quarter-circle contact goniometer by Burrow (1809).**

Because of their simplicity, contact goniometers were produced by a multitude of manufacturers, most of which used a diameter of around 8 cm, and rarely up to 15 cm. Gilbert (1815) noted: "The University technician F. Apel of Göttingen sells a nice, clean-worked, cased goniometer for 6 Thaler." Prices of 8 Marks can be found in a Fuess catalog (Groth, 1876). In 1900 a dramatic reduction in price was brought about with the introduction of cardboard and celluloid models made by (and named after) Samuel Lewis Penfield (1856–1906) (Fig. 18). At the turn of the century these cost 50 cents; Goldschmidt (1934) listed them at 1.20 Reichsmark.

Fabian (1986) wrote about the simplest forms of the goniometer:

> *Even though the contact goniometer still didn't allow precise measurements, its invention entirely revolutionized crystallography, transforming it from the description of the crystal form to exact measurements. After Romé de l'Isle, serious crystallography without consideration of angle measurements was no longer conceivable.*

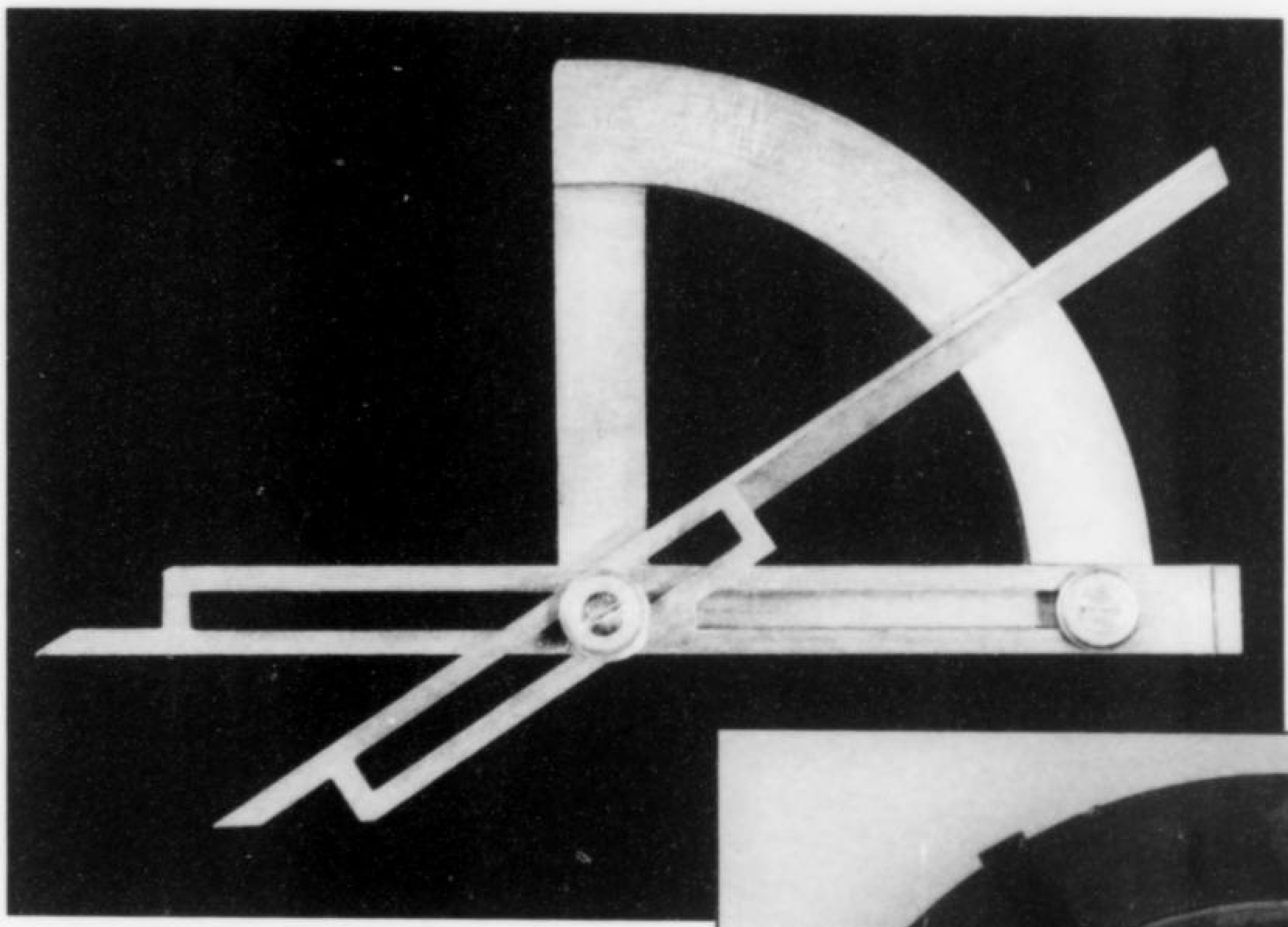


Figure 16. **Quarter-circle contact goniometer, unsigned, ca. 1870. Berlin Natural History Museum collection.**

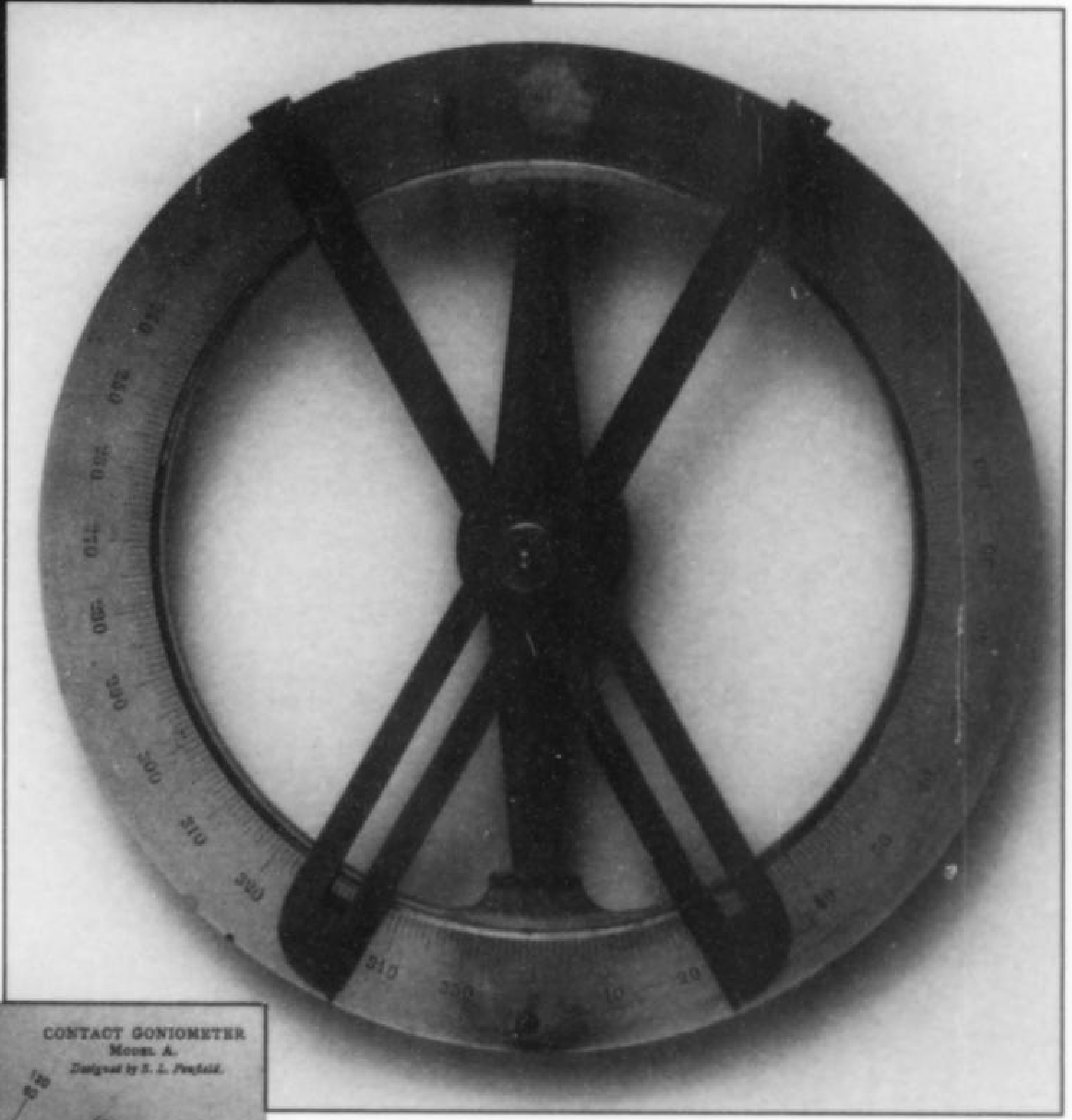


Figure 17. **Full-circle contact goniometer, unsigned but probably by R. Fuess, Berlin, ca. 1920.**

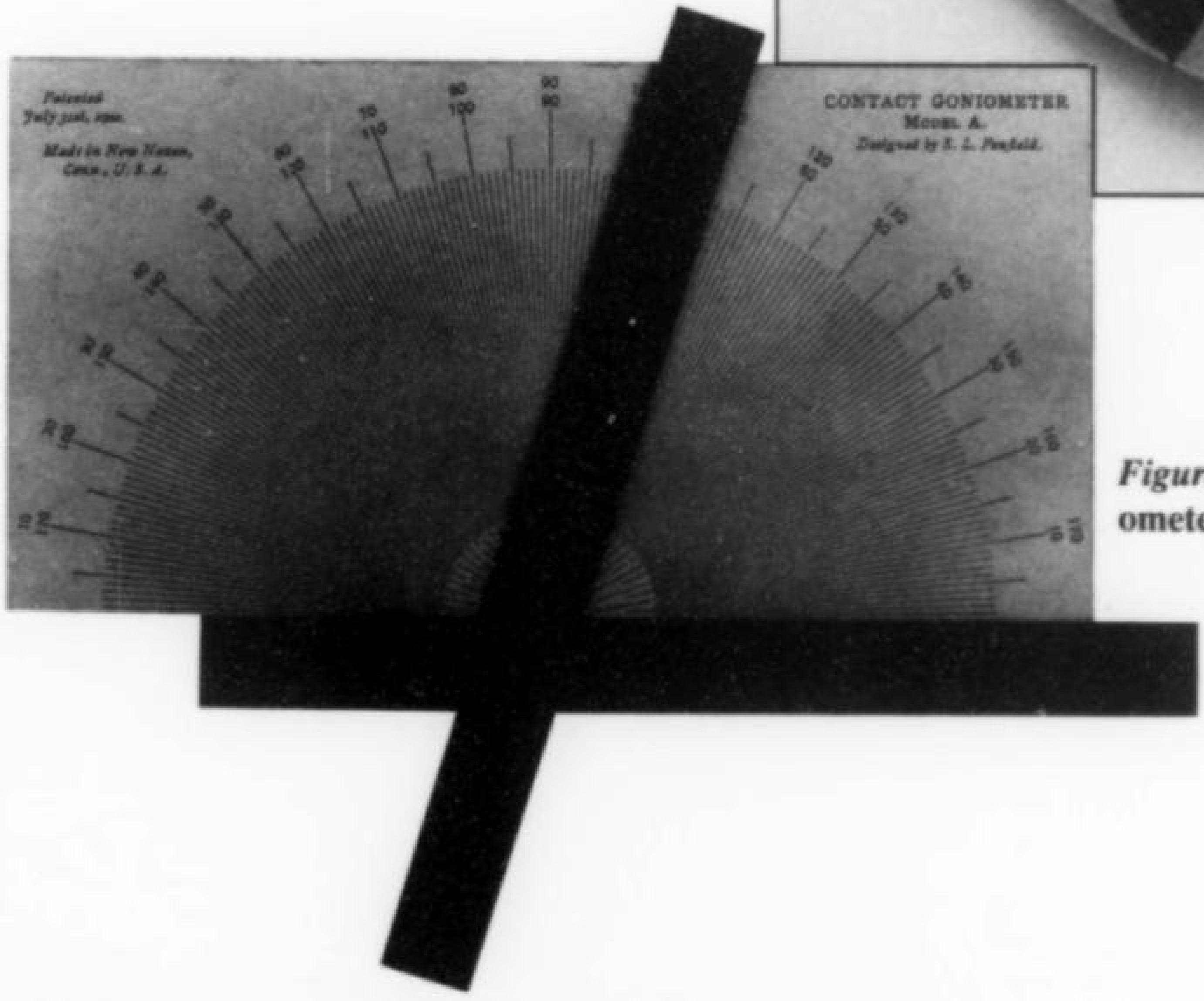


Figure 18. **Cardboard "Penfield" contact goniometer, ca. 1910.**

Stationary Contact Goniometers

All contact goniometers are burdened with inherent sources of error. Most of these difficulties originate at eye level, as one hand holds the crystal and the other hand must place the measuring arms exactly perpendicular to the crystal faces. Additionally, the crystals must be of sufficient size to permit measurement, and must have even surfaces. To eliminate at least some of these problems and to free both hands for repeated measurements, a series of stationary contact goniometers was developed. **The fundamental measuring principal is that the crystal face must be horizontal.** This is achieved either through a mechanical contact or through optical sighting to bring the crystal faces into an exactly horizontal position.

ADELMANN'S CONTACT GONIOMETERS

The earliest stationary contact goniometer was described in 1824 by **Jacques-Louis Compte de Bournon** (1751–1825). The chaos of the French Revolution forced Bournon, an advocate of Haüy's theses, to flee to England. There he cataloged and arranged different important collections of minerals, Lord Charles Greville's and Sir Abraham Hume's among them. His main work, *Traité complet de la chaux carbonatée et l'aragonite* (1808), contains an exact description of all variations of calcite and aragonite crystals known up to that time. His famous collection of wooden crystal models of calcite is located at the Natural History Museum in London. After the Bourbons had returned to power, Bournon became director of King Louis XVIII's mineral collection. Bournon ordered the construction of a goniometer by his staff member Adelmann, whom he described as follows:

> *Le gardien aide-minéralogiste de la Collection minéralogique particulaire du Roi, placée sous ma direction, M. Adelmann, homme extremement intelligent, adroit et modeste, vient d'inventer un goniomètre . . . .*

Bournon produced a scale drawing of Adelmann's goniometer. The drawing was also published in works by Francois-Sulpice Beudant (1830) and Antoine-Cesar Becquerel (1845) (Fig 19).

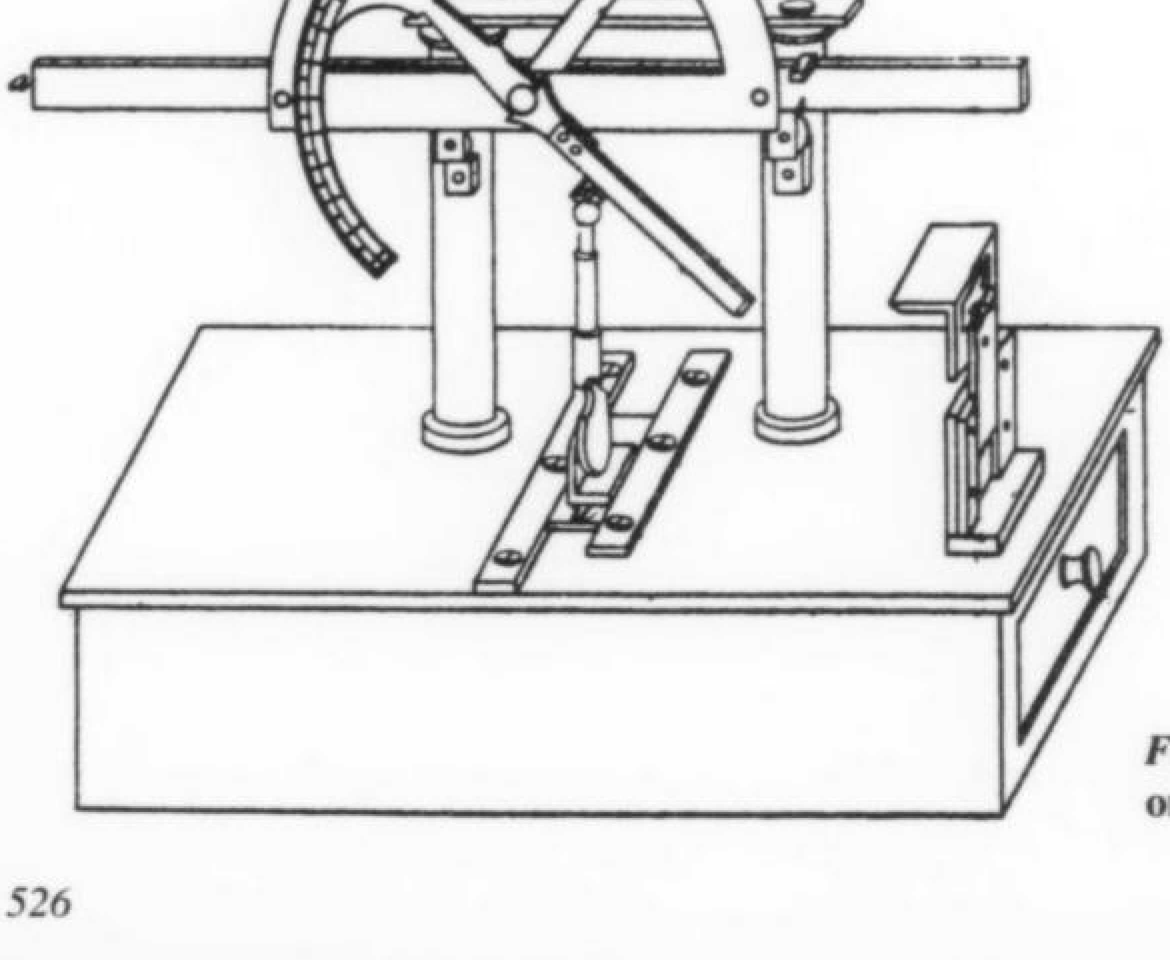


Figure 19. **Adelmann's stationary contact goniometer (Bournon, 1824).**

The instrument is fastened on a 15 x 30-cm mahogany box. Two columns carry a horizontal track which can be rolled from right to left. A 16-cm semicircle is fastened on top. A radial limb revolves around the horizontal axis of the semicircle, and at its outer end are a vernier and a locking screw. A second radius is likewise revolvable around the axis and carries a contact limb below it and a semicircular protractor above it. The crystal is attached on a carrier that is adjustable for height and originates from below the measuring instrument. By means of an adjustment mechanism (shown in the drawing on the right), and with the help of a guide rail for the crystal holder, the crystal edge to be measured can be oriented exactly horizontal and parallel to the axis of the semicircle. The straight-edge with the mounted measuring apparatus is moved far enough so that the contact arm, after rotation around the axis, rests flat on a crystal face. Thereupon the vernier is adjusted with the indicator so that the zero point of the protractor is marked. After the same operation is executed for the second plane, the angles can be read directly.

Bournon renounced all claims of high precision. Both Beudant and Becquerel indicate an accuracy of three to four minutes of arc, a value which seems somewhat optimistic by today's standards. Bournon refers to the maker: "ce goniomètre a été fait avec beaucoup d'exactitude et de perfection, par M. Rochette le jeune, opticien, quai de l'Horloge." The author knows of no surviving instruments of this type.

A further development in this type of contact goniometer was presented by Ours-Pierre-Armand Dufrénoy in his book *Traité de minéralogié* (1856), which contains a construction sketch as well (Fig. 20). The year of introduction of this type remains unknown, but was probably after 1845, since Becquerel made no mention of the instrument. Dufrénoy writes:

> *M. Adelmann, attaché aux collections de l'Ecole impérial des mines, a rèuni dans un seul instrument les deux méthodes de mesure.*

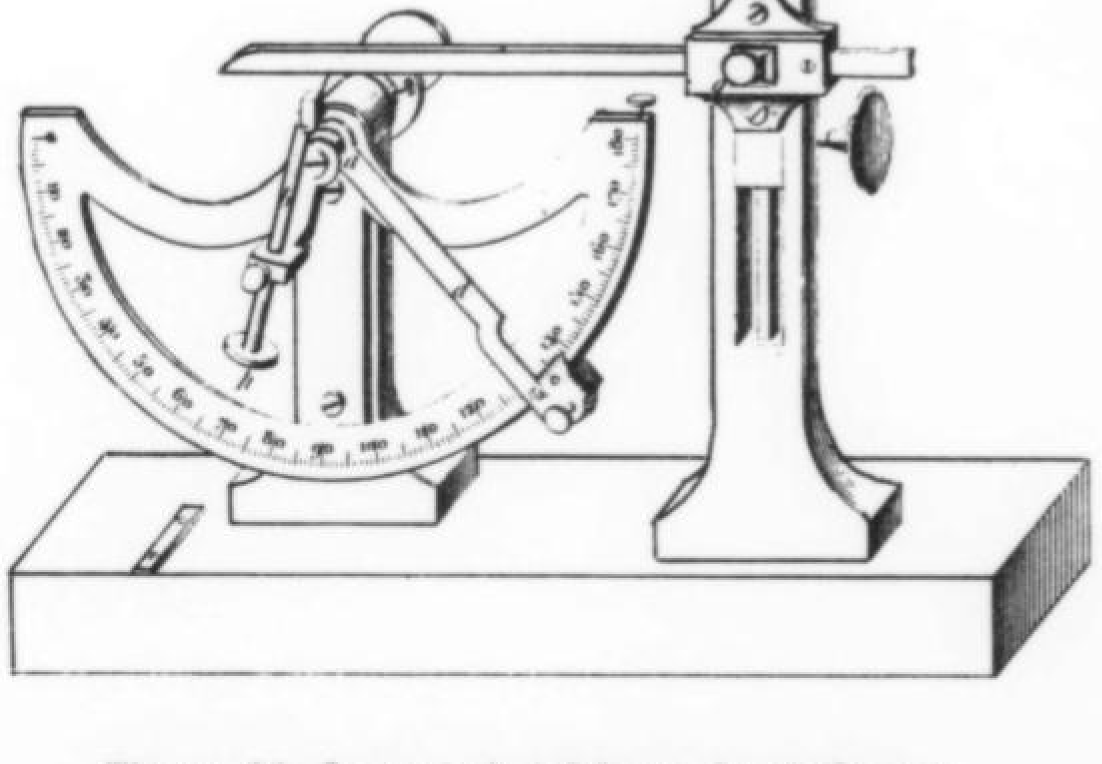


Figure 20. **Improved Adelmann's stationary contact goniometer (Dufrénoy, 1856).**

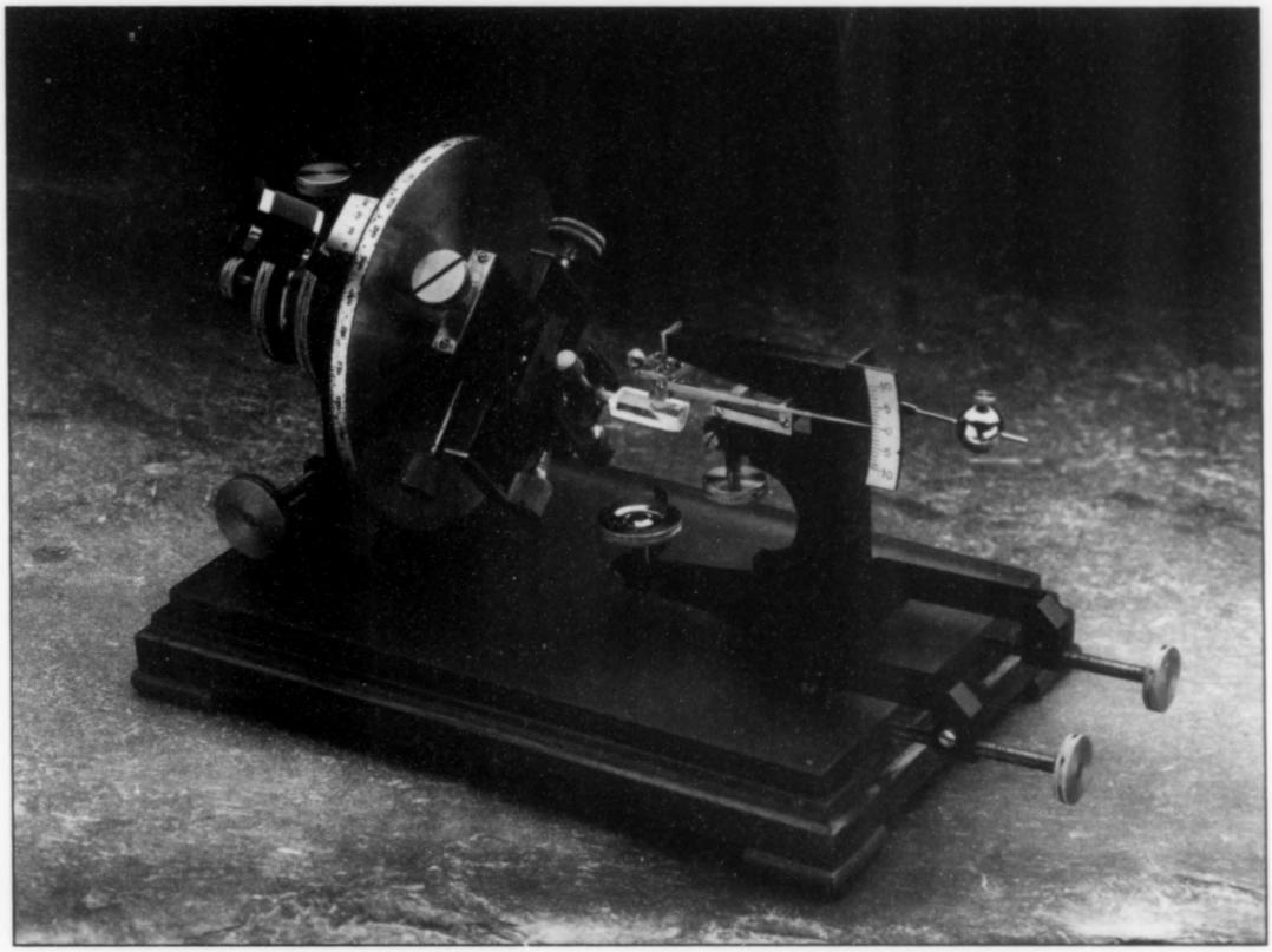


Figure 21. **Lever-arm goniometer by R. Fuess, Berlin, purchased in 1909. University of Innsbruck collection.**

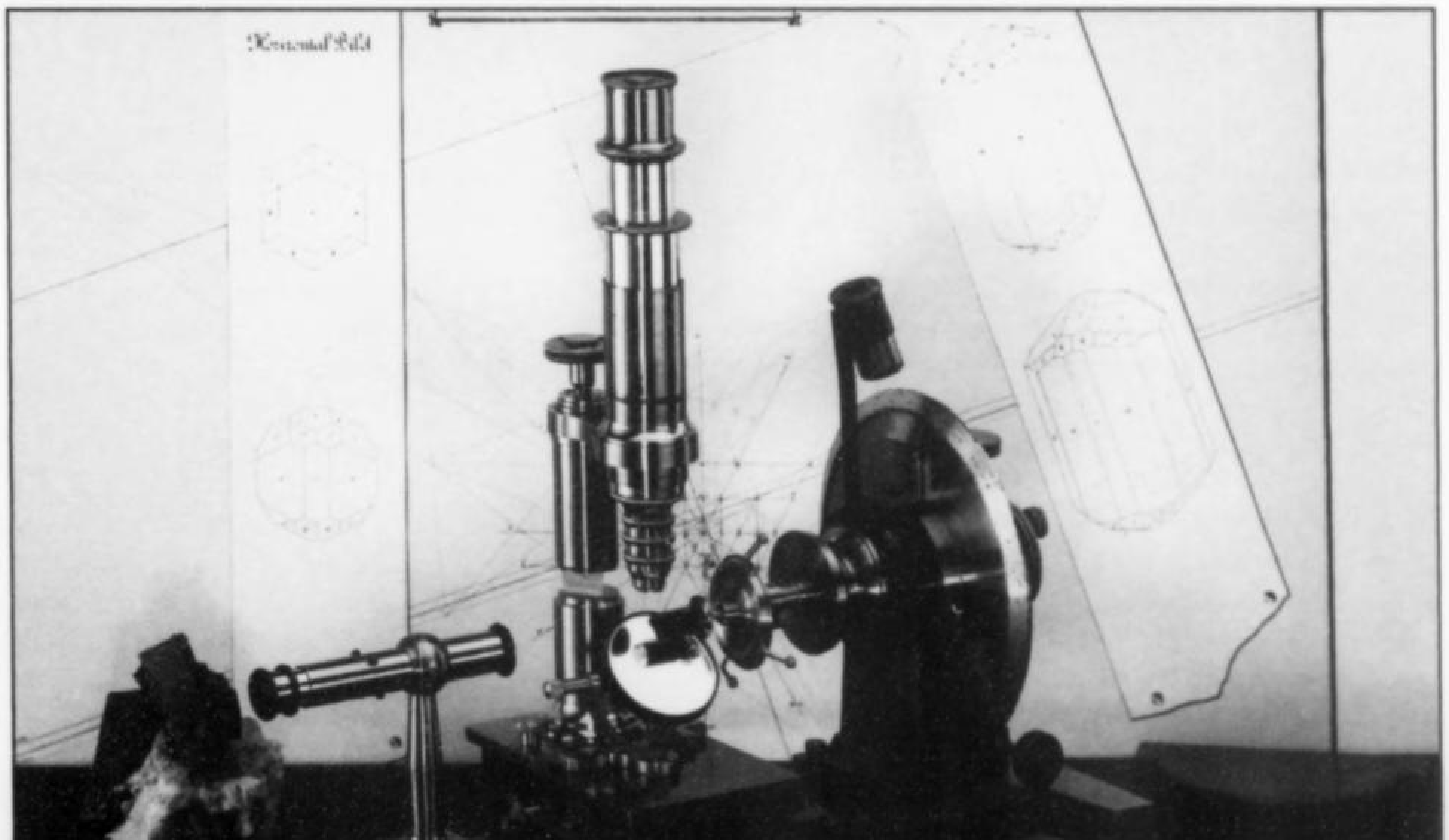


Figure 22. **Hirschwald's microscope goniometer, signed: "R. Fuess, Berlin," ca. 1900. In the background is a gnomonic projection of the goniometric data for an amphibole crystal, by V. M. Goldschmidt.**

The apparatus likewise consists of a semicircular protractor on a vertical column. In the center of the circle, two nested cylindrical axes are found, one joined firmly with the crystal holder, the other with an indicator with a vernier mounted at its end. Both can be rotated individually as well as coupled around the axis of the circle. A new component, a horizontal straightedge contact plane which can be adjusted for height, is positioned close to the axis of the semicircle. This contact plane version of the straightedge replaces the contact lever of the old model. For measurement, a crystal edge is adjusted to be perpendicular to the circular plane (parallel to the circular axis). One crystal face is rotated horizontally, its position to be established by the straightedge contact plane. The vernier is set to zero, and both axes are coupled by a screw. The second crystal face is brought to a horizontal position by common rotation of indicator and holder arms, and the angle can be read directly.

Dufrénoy mentions that the straightedge contact must be removed in order to use the instrument as a reflecting goniometer. This principle will be explained later. Dufrénoy mentions no manufacturers; however, he indicates that an Adelmann goniometer is less expensive than a Wollaston goniometer. This claim is refuted by a price comparison in the A. Krantz catalog of 1853: 3p 3s for a Wollaston instrument and 5p 5s for an Adelmann goniometer. The author knows of no surviving instruments of this type.

FUESS'S LEVER-ARM GONIOMETER

The basic idea of Adelmann's contact goniometer was reintroduced 30 years later by the Berlin firm of **Rudolf Fuess.** In place of the contact straightedge, a sensitive lever arm, originally conceived for the determination of coefficient of expansion of solid bodies, was introduced. The instrument was presented for the first time at the Berlin trade fair of 1879 and was described by Theodor Liebisch. Alexander Schmidt (1884) described in detail the testing of the instrument, and some of its incorrect measurements, and Paul Groth (1895) made some minor suggestions for improvements.

The instrument is composed of a frosted, completely smooth, ground glass plate (14 x 22 cm). On it stands a graduated circle with its plane exactly perpendicular to the plate glass base (Fig 21); the axis of rotation of the graduated circle is thus exactly parallel to the base plate. The rotatable axis carries the crystal-holder, mounted on an adjustment and centering device which will be described in a later paragraph. The graduated circle is revolvable on the axis alone or coupled with the crystal-holder axis. Through a locking screw and a tangential micrometer screw a precision adjustment can be made, and the position of the circle can be read (aided by a loupe) to arc-minutes on a vernier.

The crystal edges to be measured can be adjusted and centered on the axis of the goniometer with the help of an auxiliary apparatus consisting of a sharp horizontal steel knife-edge mounted on a carrier. Through rotation of the graduated circle, first one, then the other crystal face can be brought horizontal (parallel to the base-plate), and the interfacial angle can be read. Groth (1905) remarks:

> *This measurement deals with exactly checking the parallelism of the plane of the crystal face mounted on the goniometer with the horizontal base-plate.*

This is done by means of the lever arm connected to a brass stand placed on the base-plate. Greatly simplified, the extremely complex mechanics consists of an amplifying lever system which allows the slightest deviation of the ivory point contacting the crystal face to be read on a scale by means of a 7 cm long pointer. A deviation of only 0.0005 mm of the ivory point is readable! To check the horizontality of a crystal face, the ivory point is moved along with the entire lever apparatus. This movement is facilitated through the action of two long screws mounted on the underside of the brass stand and contacting the outer edge of the glass base plate which is likewise accurately ground, serving as a guide rail. The crystal has to be oriented so that as little deviation as possible occurs when the arm is moved over the whole surface of the crystal face. Since the crystal faces can be uneven, the system has a micrometer screw on the interior underside of the stand so that the point can be adjusted in height and freely skimmed over the crystal. Through suitable selection of smooth crystal faces and lowering of the ivory point, uneven crystals can also be examined in the horizontal position. Liebisch (1879) calculated a measuring accuracy of the instrument of 2 arc-minutes. The Fuess company of Berlin was the only manufacturer, as will be discussed later. In 1905 the price of the goniometer and the associated apparatus (delivered in a separate box) totaled 350 Marks (in 1912, 400 Marks). Goniometers of this type were used mostly to measure unreflective crystal faces. They are relatively rare today.

HIRSCHWALD'S MICROSCOPE GONIOMETER

Even though the microscope goniometer cannot be considered a mechanical instrument, it will nevertheless be discussed at this point, because in its operation the principle of keeping the horizontal position of the crystal face remains the same. In lieu of a contact edge or lever arm an "optical" contact is used, namely the focal adjustment of a microscope. Under strong magnification the complete crystal face will appear clearly only when the face is exactly perpendicular to the axis of the microscope tube. This apparatus assembly was conceived by Hirschwald in 1879 and was shown at the Berlin Trade Fair the same year (Liebisch, 1879). Its creator, **Julius Hirschwald** (1849–1928), was professor of mineralogy and geology at the Technical University of Berlin. He conducted mainly crystallographic research, and he won world fame in the area of building stone testing.

The microscope goniometer (Fig. 22) is composed of three parts fastened on a brass base plate: a goniometer, a microscope, and a centering telescope. The *goniometer* has a vertical graduated circle, a fine adjustment and vernier read-out, and an adjustment device for the crystal holder. The *microscope* is assembled on a double-rail cross-slide and can be moved both parallel and perpendicular to the goniometer axis. It is therefore possible to view the entire crystal face which is to be oriented horizontally. The microscope tube can be raised and lowered by means of a micrometer screw, on which a movement of 0.004 mm is readable. The lens system has one 350X magnification, and in a later model (Hirschwald, 1880) a 500X magnification. The ocular contains a thread parallel to the goniometer axis, allowing the examination of the exact adjustment of the crystal edge. One of the mirrors mounted on the track below the objective serves to illuminate transparent crystals. Opaque crystals are illuminated from above by means of a separate condensing lens. The *centering telescope* is oriented on a track of the base-plate exactly in line with the goniometer axis, and serves exclusively to provide an exact adjustment of the crystal edge on the crystal holder.

After the resulting axial parallel adjustment and centering of the crystal edge, the microscope is moved on its track, perpendicular to the axis of the goniometer, over the entire surface of the crystal face. The height adjustment of the tube remains unchanged, and a sharp focus is attained solely by a gentle turn of the goniometer's fine adjustment. This procedure is repeated for the second plane. It is recommended that transparent crystals be dusted with finely powdered lindenwood charcoal, and opaque crystals with gum arabic. For ideal conditions, Hirschwald calculates a measuring accuracy of 1 to 3 arc-minutes. L. Calderon (1880), in a small commentary, called into question the usefulness of this measuring method, since observers have different optical abilities and the focus follows subjective criteria. Indeed, Calderon used an improvised apparatus combination without mechanically exact synchronization of the single units. Calderon's criticism was severely attacked by Hirschwald (1880).

The microscope goniometer was manufactured by the Fuess company in Berlin; in 1895 the cost was 500 Marks, but the instrument was no longer being offered in the 1912 catalog. It could be rebuilt for measurements using the reflecting principle by replacing the microscope with an observation telescope (see cover photo). Because of the high costs and the complicated measuring technique, demand for these instruments was very limited, and they are now therefore very rare.

Loupe-goniometers and Microgoniometers

Numerous microscope attachments were developed for the measurements of plane angles, i.e., the angle formed by two crystal edges of a horizontal crystal plane, and for determining the angles of very small crystals. A comparison reticle is alternately brought into congruence on both of the edges. Under magnification only the crystal sections lying on one plane, which is perpendicular to the optical axis, can be clearly observed. The vertex is shortened to a point and must lie respectively in the center of the optical axis and in the intersection of an ocular cross-hair. The measurement of the plane angle can be accomplished through two measurement techniques: (1) a graduated circle at the ocular (the ocular reticle is turned until both facial edges align), or (2) the graduated circle is found at the object stage and is turned along with the crystal.

Though he does not cite specific references, Pistor (1820) gives **David Brewster** (1781–1868) the priority as developer of the first microscope goniometer. Schrauf (1866) remarked about Brewster's instrument that "the achieved precision is slight and cannot be properly judged." The earliest description (1816) of a microgoniometer comes from the astronomer and geodesist **Johann Gottlieb Friedrich Bohnenberger** (1765–1831) of Württemberg. This microscope apparatus, invented by Mr. Gundler of Esslingen, featured a spiderweb hair in the main tube and in the revolving ocular, which was provided with an external vernier. For the measurement, the tube reticle was brought into line with one edge of a crystal that was firmly attached to the object stage, and the ocular reticle was brought into coincidence with the second edge. The physics professor **Moritz Ludwig Frankenheim** (1801–1869) of Breslau, as early as 1836, used a reticle in the ocular, and used a micrometer carriage to center the vertex on the object stage. **Karl Ernst Heinrich Schmidt** (1822–1894), the lecturer for chemistry at the University at Dorpat (now Tartu, Estonia), received his education in Berlin through Heinrich Rose (1795–1864) and Friedrich Wöhler (1800–1882); Schmidt engaged in physiological studies, principally concerning crystalline substances in urine, blood and milk. In 1846 he introduced a new accessory for the microscope of the Schiek Company in Berlin. The upper end of the tube carries an 8-cm-wide flat disc whose outer rim is divided by a graduated circle. The insertable ocular along with the reticle is firmly connected to a vernier that tightly rotates around the entire graduated circle. This construction principle of an ocular with a reticle, with one cross-hair rotatable around the center, became the model for many microscopes.

Figure 23. **Drawings of an ocular goniometer and object stage microgoniometer as attachments for microscopes, with photos of actual instruments, by R. Fuess, Berlin, ca. 1900.**

As early as 1848 the Englishman **H. B. Leeson** conceived a special ocular which contained a doubly refractive prism made of Iceland spar (calcite) or quartz. The disturbing dispersion was eliminated in later models by an equally strongly dispersing glass prism mounted in reverse position. The observer sees all objects doubled through the prism. Through rotation of the prism the double view can be put parallel to the crystal outlines, and the amount of rotation can be read on a vernier (Fig. 23).

For the measurement of plane angles it is, in principle, irrelevant whether the optical contact results from rotation of the reference reticle or of the crystal mounted on the object stage. Measurement by the latter method apparently was first done by **Nordenskiöld** in 1821. He fastened his crystal centered on the axis of an "astronomical circle" and observed the crystal outline and the vertical edge through a microscope within whose tube a "micrometer wire" was stretched. The microscope remaining unchanged, the circle was rotated, and the measurement made at the graduated circle of the stage.

In 1857, geology professor **Friedrich Pfaff** (1825–1886) of Erlangen invented a quite original apparatus that can be considered a loupe or compass goniometer (Fig. 24). A horizontal arm has a holder in which a 2 to 10-power loupe may be inserted; a simple silk thread is stretched directly underneath. Below is a base-plate with one freely movable box; therein is a compass and a primitive device for the horizontal positioning of a crystal face, the crystal being held by flexible pins.

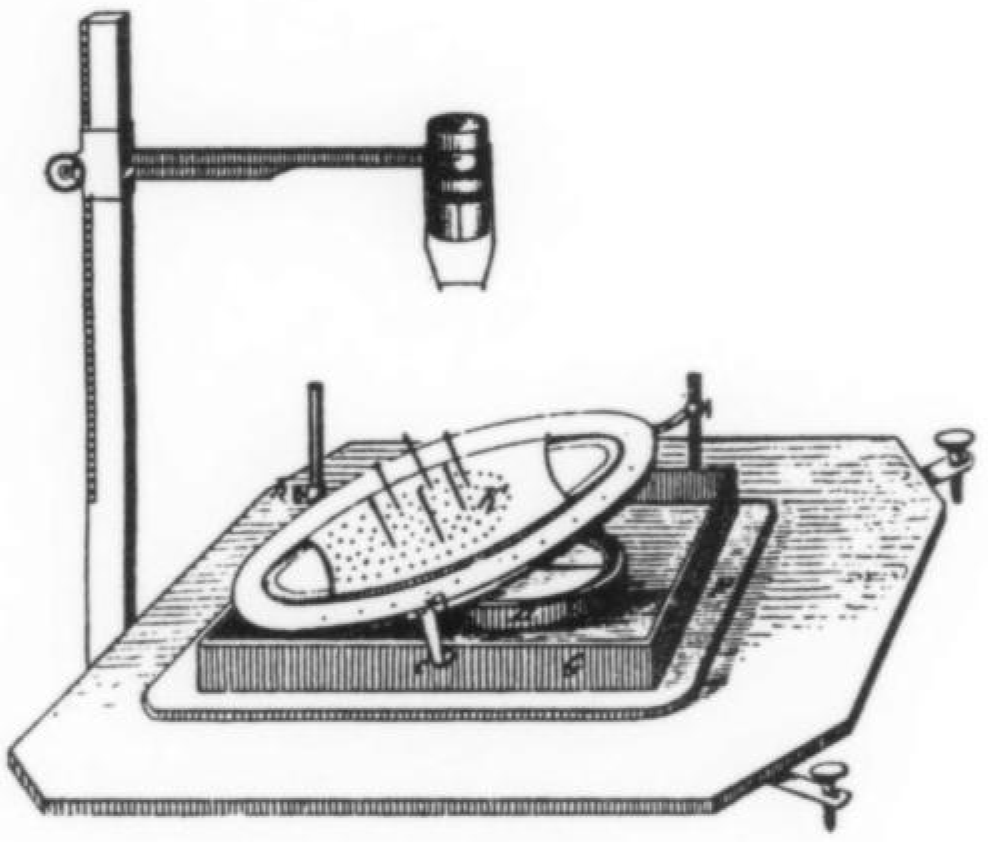


Figure 24. **Loupe or compass goniometer by Pfaff (1857).**

For the measurement the crystal face is placed horizontally, an edge brought into congruence with the reticle, and the compass needle's position noted; this process is repeated for the second edge. No rotation around a centered vertex is necessary, since the compass is turned simultaneously with the crystal.

Over time, the method of rotating the object with the object holder, with its graduated perimeter, prevailed. A requirement of the instrument is that the axis of rotation of the object holder coincide with the axis of the optic system. To facilitate adjustment of the crystal faces, Leeson (1848) designed a primitive stage micro-goniometer (Fig. 23) which was later greatly improved. This method is frequently used in determining angles in crystal outlines in petrographic thin sections. **Evgraf Stepanovich Fedorov**'s (1853–1919) universal stage, revolving in all three dimensions, makes the parallel positioning of the optical axis and crystal axis possible, so that color changes in polarized light and interference figures may be noted.

Although really a graphic approximation technique, one suggestion made by **Wilhelm Karl Haidinger** (1795–1870) can also be added to the history of loupe goniometers. The first director of the geological survey of the Austrian Empire in Vienna, Haidinger was a pupil of Mohs and the inventor of the dichroscope. In two articles in 1854 and 1855 he described a process in which a crystal is mounted on a genuflexed piece of wax, the wax holder mounted on a thicker glass plate, and this mounted on a piece of paper. After the crystal edges to be measured are adjusted by eye to the vertical, a straight edge is brought as parallel as possible to both faces successively and the positions checked with a loupe. Both straight edge positions are drawn with pencil on paper, and the angle read with a regular protractor.

Ocular goniometers and stage micro-goniometers are essentially special parts for microscopes and were offered by all important makers of petrographic microscopes: Smith & Beck, Powell & Lealand, Chevalier, Hartnack, Fuess, Zeiss, Swift and others.

In the Fuess catalog of 1912 the ocular goniometer with iris diaphram cost 65 Marks, and the stage goniometer 36 Marks (Fig. 23).

Mirror Goniometers

The instrument proposed in 1822 by **Andreas Ritter von Baumgartner** (1793–1865) was a hybrid between a contact and a reflecting goniometer. Baumgartner was director of the royal porcelain factory, and from 1851 president of the Viennese Academy of Sciences. His measuring technique rests on the principle that the image of a crystal face reflected in a mirror is reduced to a line if the planes are exactly perpendicular to the mirror surface. The instrument consists essentially of a plane mirror and a horizontal metal rod rotatable on its axis. A stirrup-shaped crystal holder is attached to one end of the rod, and on the other is a radial indicator with a vernier (Fig. 25). The extension of the axis of the rod lies exactly in the plane of the mirror surface. A graduated quadrant is positioned perpendicular to the mirror.

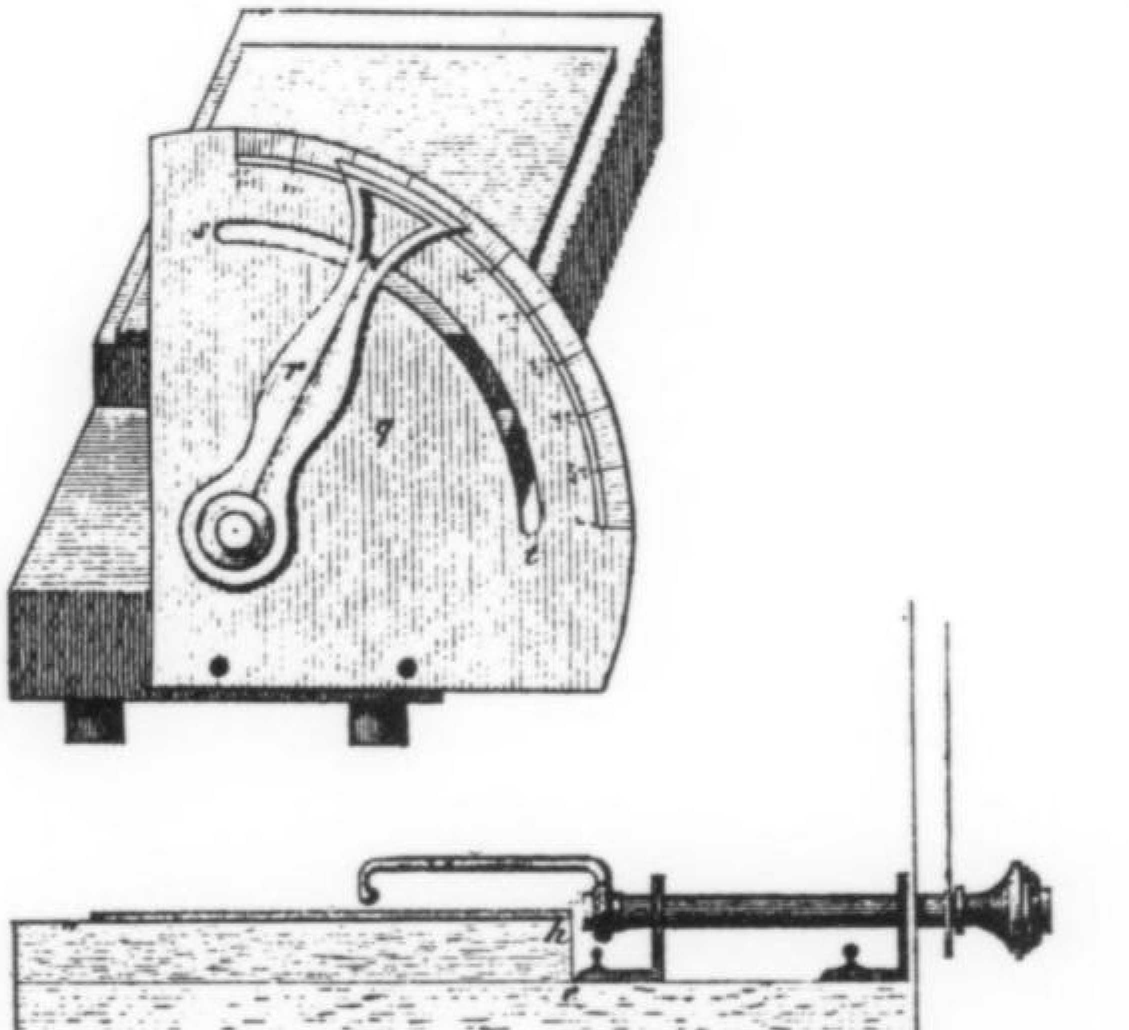


Figure 25. **Mirror goniometer by Baumgartner (1822).**

For measurement, one crystal surface is laid flat on the mirror and the crystal edge perfectly parallel to the axis. In his remarks on Baumgartner's description, the publisher Ludwig Wilhelm Gilbert

(1769–1824), proposed scratching an orientation line with a diamond on the mirror at the axial extension. In this position one fastens the crystal to the stirrup with wax or a clamp. The crystal is then rotated with the radius indicator around the axis of rotation, until the second plane is exactly vertical on the mirror. The measured angle is the one complementary to 90°. Baumgartner indicates separate, easily modified adjustment techniques for obtuse and acute plane angles. It is not known if this goniometer was ever built, and no source gives its measuring accuracies. The difficulties of the precise centering of the axis and of fixing the crystal edge on the stirrup, and the eccentricity of the rod, would seem likely to render the instrument's accuracy problematical.

As early as 1811 the French instrument maker **Robert Agalae Cauchoix** (1776–1845) constructed a similar reflecting goniometer. According to Biot (1811), this is *"antérieur au goniomètre de M. Vollaston et à celui de M. Malus"*; however, Cauchoix failed to establish priority. He specialized in the construction of optical instruments, and he experimented with so-called crown and flint glasses. One could manufacture achromatic telescope objectives by assembling these various glass lenses in the correct sequence. To experiment with these glass types one required prisms cut with sharply defined angles, and for measuring these angles Cauchoix's instrument proved superior. According to the description of Biot (1821), this goniometer consists of a vertical circle with a horizontal mirrored glass in its center (Fig. 26). Through set screws and a mountable box level a precisely horizontal position can be achieved.

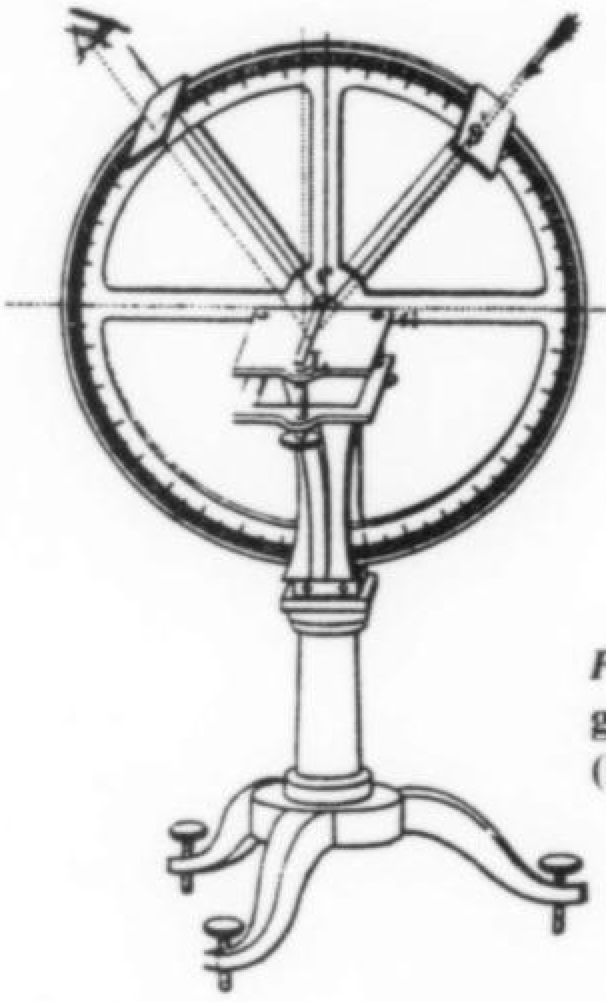


***Figure 26.* Reflecting goniometer by Cauchoix (Biot, 1821).**

The mirror is needed mainly for purposes of adjustment, and other experiments. There is a knife edge mounted at the end of the circular axis, much as on Baumgartner's goniometer. Rotatable around the graduated circle are two alidades that have small plates mounted at perpendicular angles to their extremities and perforated at the same distance from the plane of rotation. For measurement a crystal face is put on the mirror with the edge parallel to the axis of rotation. The light shining through the small hole in one alidade is reflected from the second crystal face. The second alidade is rotated until coincidence is perceived by the observer's eye. The sought-for angle is the arc between the vertical and the perpendicular plane (half the angle between the two alidades). Surprisingly, this very early reflecting goniometer survived; it has a semicircular graduated circle (Fig. 27), although it is not so shown in Biot's drawing (1821).

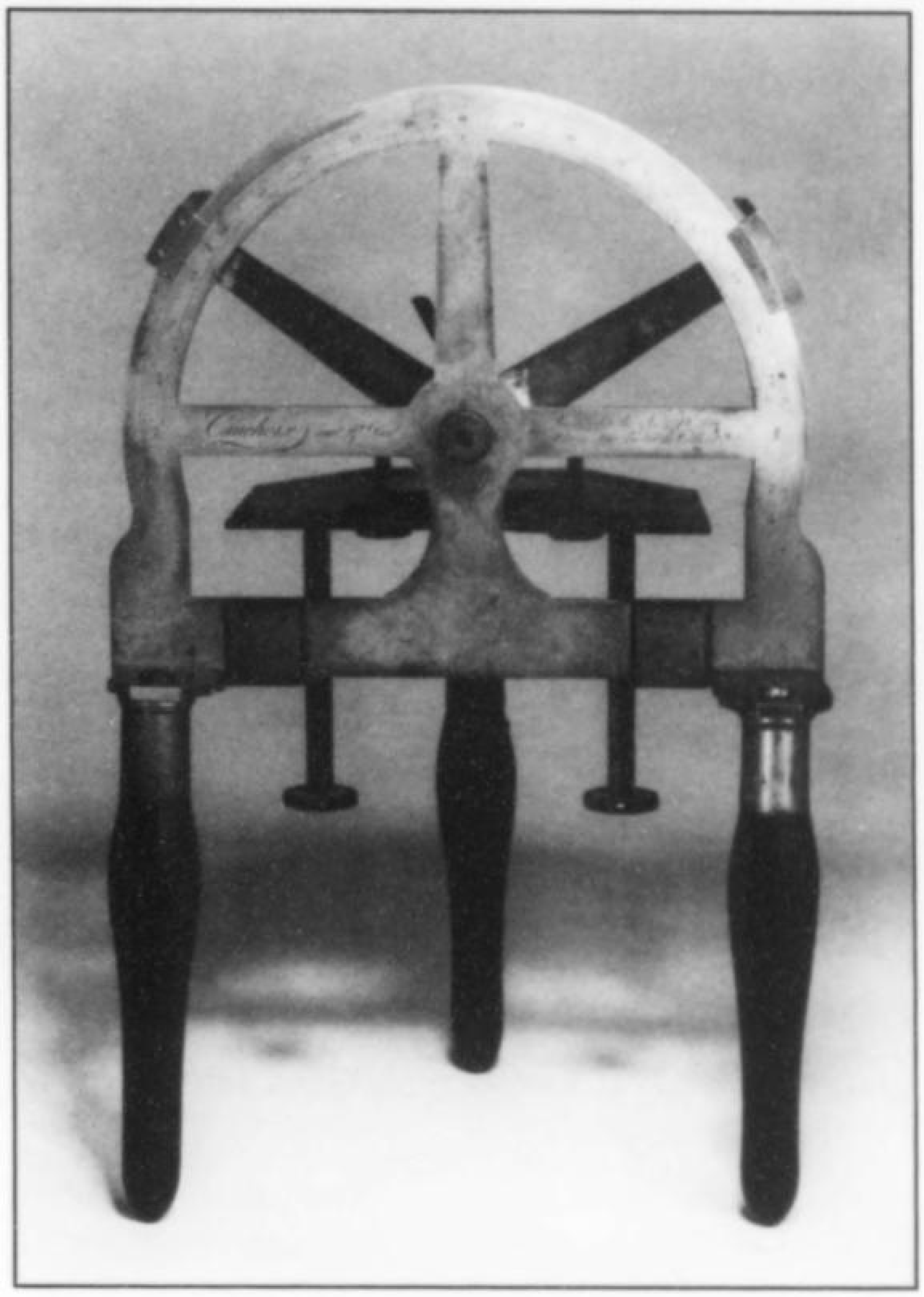


***Figure 27.* Reflecting goniometer, signed: "Cauchoix invt. & Divt.," ca. 1825.**

Reflecting Goniometers

MEASUREMENT TECHNIQUE

The measurement of angles with a reflecting goniometer is based on the physical laws of the reflection of light from a plane mirror with equal angles of incidence and reflection: the incident light is reflected from smooth crystal faces. With these instruments, the angles between any two crystal faces, even in very small crystals, can be measured, even if the faces do not meet at a common edge. In principle, the reflection of a signal from one crystal face is observed, then the second face is rotated into exactly the same position (the same plane) as the initial position of the first face. This position is given respectively when the *bisectrix* between incoming and reflected light rays stands perpendicular to the crystal face. These imaginary lines are also known as *normals* to a crystal face. The angle of rotation required to bring the two faces, one after the other, to the reference position is measured on the divided circle. The interfacial angle equals the angle between the normals of the two faces. Figure 28 elucidates the method of measurement.

On a divided circle (plane of the circle = drawing plane) a crystal with the planes EC and CD is mounted. In the drawing the planes are represented by lines, and their common edge by the vertex C. This edge must be placed exactly in the center of the circle, i.e., both planes of the crystal must stand perpendicular to the plane of the circle, and the common edge must lie exactly along the extension of the axis of the graduated circle. A remote signal O is reflected on the crystal surface CD as close as possible to edge C as seen by the eye of the observer in A. The crystal is now turned in the direction of the arrow along with the measuring circle, which turning does not affect the position of the axially centered edge C. If the plane EC arrives in the position E′C, therefore in the extension of the initial position CD, its (E′C) reflection is, to the observer's eye, at an unchanged position close to C. As the diagram clearly shows, the rotated angle ECE′ is the supplement of the angle ECD to 180°. This *supplementary angle* is also called the *normal angle* since it equals the angle between the normals of the two faces—the imaginary lines perpendicular to each face. The real internal dihedral angle ECD accordingly totals 180° minus the normal angle.

Besides precise workmanship in making the goniometer, the following conditions must be met for accurate crystal measurements with reflecting goniometers:

(1) There must be smooth, reflecting crystal faces. To achieve them, when necessary, thin glass plates can be glued onto dull surfaces, or the faces can be coated with varnish.

(2) The crystal edges must be adjusted and centered parallel to the axis. Appropriate mechanical devices facilitate the exact positioning.

(3) The rays of light must strike parallel. Thus on older machines the chosen source of the signals was distant: the cross members of a window frame, for example. On advanced instruments, parallel light is admitted to the crystal face through a collimating tube.

(4) To avoid parallax errors, the imaginary plane formed by the signal, the reflecting crystal face and the observer's eye must be kept parallel to the plane of the divided circle throughout the measurement procedure.

The latter condition, i.e., the unchanged position of the observer, can be fulfilled through a threefold measurement procedure:

(1) Along an extension of the direction of the reflected signal (CA in the illustration, Fig. 28) the observer fixes a distant point (O′) and brings both to convergence. In practice a horizontal window mullion or a slit in an otherwise darkened window serves as a signal, the goniometer's axis being placed parallel to the distant window. A chalk line made on the floor underneath the window serves as the reference line.

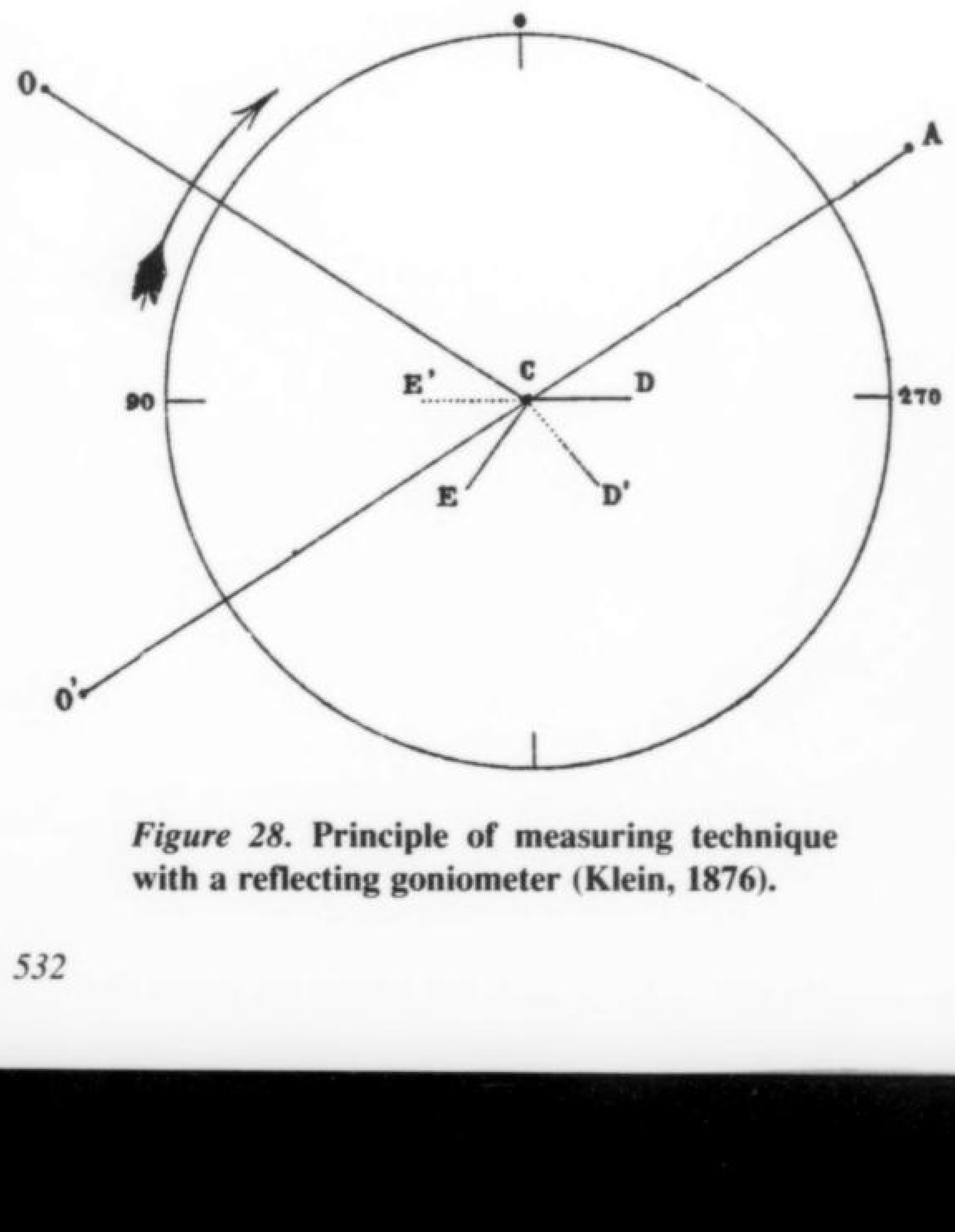


Figure 28. **Principle of measuring technique with a reflecting goniometer (Klein, 1876).**

(2) Instead of the reference point O′ the signal can be simultaneously reflected by an auxiliary mirror and by the crystal face, the mirror signal serving as reference line. The blackened glass mirror is carried by the goniometer base just underneath the crystal. The tiltable mirror surface must be placed in a fixed position parallel to the axis of the circle.

(3) The signal is observed through a telescope whose axis lies parallel to the plane and perpendicular to the axis of the circle. The use of a telescope guarantees a steady position of the observer's eye. A reticle facilitates the determination of the coincidence with the reflected signal.

There have been numerous theoretical and practical investigations into different possible sources of error and how they might be eliminated. Especially worthy of mention in this regard are *Preisschrift ueber genaue Messung der Winkel an Krystallen* (1825) and the *Handbuch der rechnenden Krystallonomie* (1831) by Adolpf Theodor Kupffer (b. 1799), who taught at the Academy in St. Petersburg. But the geologist and mineralogist Karl Friedrich Naumann (1797–1873) also mentioned sources of error in his *Notiz ueber die Fehler der Excentrität der Kante bei Messungen mit Wollaston's Goniometer* (1831).

It is clear that in this technique the spatial orientation of the graduated circle is irrelevant for the measurement of crystal angles by the reflection principle. As long as all other conditions are fulfilled, the plane of the measuring circle can lie horizontally or vertically, or the circle may be turned in the hand as for a nautical instrument. Yet in the literature a differentiation of types of the reflecting goniometer according to the position of the graduated circle exists, the types being named after the respective designers:

(1) **The Wollaston-Mitscherlich goniometer** with a vertical graduated circle.

(2) **The Malus-Babinet goniometer** with horizontal graduated circle.

Since the Babinet goniometer is hand-held for crystal measurement, it is incorrectly defined in any case: the classification of goniometers by position of the graduated circles is purely historical and of no real consequence. It is more meaningful to classify goniometer types by their auxiliary equipment, although, because there are so many different construction details, this classification method is somewhat difficult to apply consistently.

WOLLASTON'S GONIOMETER

The prototype of all reflecting goniometers was invented by **William Hyde Wollaston** (1766–1828) (Fig. 29) in 1809. The further development of this instrument, with which one could measure very small crystals, yielded pioneering knowledge in

Figure 29. **William Hyde Wollaston (1766–1828), inventor of the reflecting goniometer.**

crystallography. The British astronomer **John Frederick William Herschel** (1792–1871) remarked about it in his *Preliminary Discourse of the Study of Natural Philosophy* (1830):

> *What an important influence may be exercised over the progress of a single branch of science by the invention of a ready and convenient mode of executing a definite measurement, and the construction and common introduction of an instrument adapted for it, cannot be better exemplified than by the instance of the reflecting goniometer! This simple, cheap and portable little instrument has changed the face of mineralogy and given it all the characters of one of the exact sciences.*

Wollaston was an ingenious naturalist with a great many interests. He investigated the chemistry of the platinum-group metals, discovered the elements rhodium and palladium, and developed a process for the production of malleable platinum. His trade in platinum laboratory ware made him economically independent. But he also made pioneering advances in optics, and he discovered the lines of the solar spectrum that were later named after **Joseph von Fraunhofer** (1787–1826).

In the field of crystallography Wollaston acquired great fame. As early as 1802 he presented a method to determine the refractive indices of Iceland spar by way of total reflection. In his essay *On the Oblique Refraction of Iceland Crystal* (1802) he writes: "I measured with care, an angle at which two surfaces of the spar are inclined to each other, and found it to be 105°5′." This value corresponds exactly with modern measurements. Unfortunately it remains unknown by which instrument or technique Wollaston determined the exterior angles of the calcite rhombohedron. It appears, however, that no early form of the reflecting goniometer was available, since in 1809 Wollaston commented on his new invention: "A means of remedying this defect has lately (!) occurred to me." It is astonishing that Wollaston, with his reflective goniometer, ascertained an angle for the calcite rhombohedron which was less exact than his measurement of seven years earlier: "very nearly, if not accurately 105°." Wollaston attacked Haüy's doctrine directly without referring to him by name:

> *The inclination of the surfaces of a primitive crystal of carbonate of lime is stated, with great appearance of precision, to be 104°28′40″, a result deduced from the supposed position of its axis at an angle of 45° with each of the surfaces, and from other seducing circumstances of apparent harmony by simple ratios.*

That the angle of the calcite rhombohedron is 105°5′ was confirmed in the following year by the French physicist **Etienne Louis Malus** in his famous work *Théorie de la double réfraction de la Lumière* (1810). This indisputable difference of over half a degree from Haüy's theoretical value was one of the first cracks in the edifice of the ideas of Haüy, who, by the way, declined to use the reflecting goniometer.

Burke (1966) remarked on the fact that Haüy did not react to the criticism of his colleagues:

> *But the most important factor in Haüy's decision to ignore these observations was that their acceptance would destroy a simple mathematical relationship which, to Haüy, had the character of a limit. . . . Simplicity, Haüy asserted, was demanded by science.*

Although Wollaston invented the measuring instrument and paved the way to more exact angular measurements, he was not ready to perform the necessary series of tests. He left this task to the London mineralogist and geologist **William Phillips** (1775–1828) (Fig. 30), who had compiled what was then the most complete collection of data regarding crystal angles.

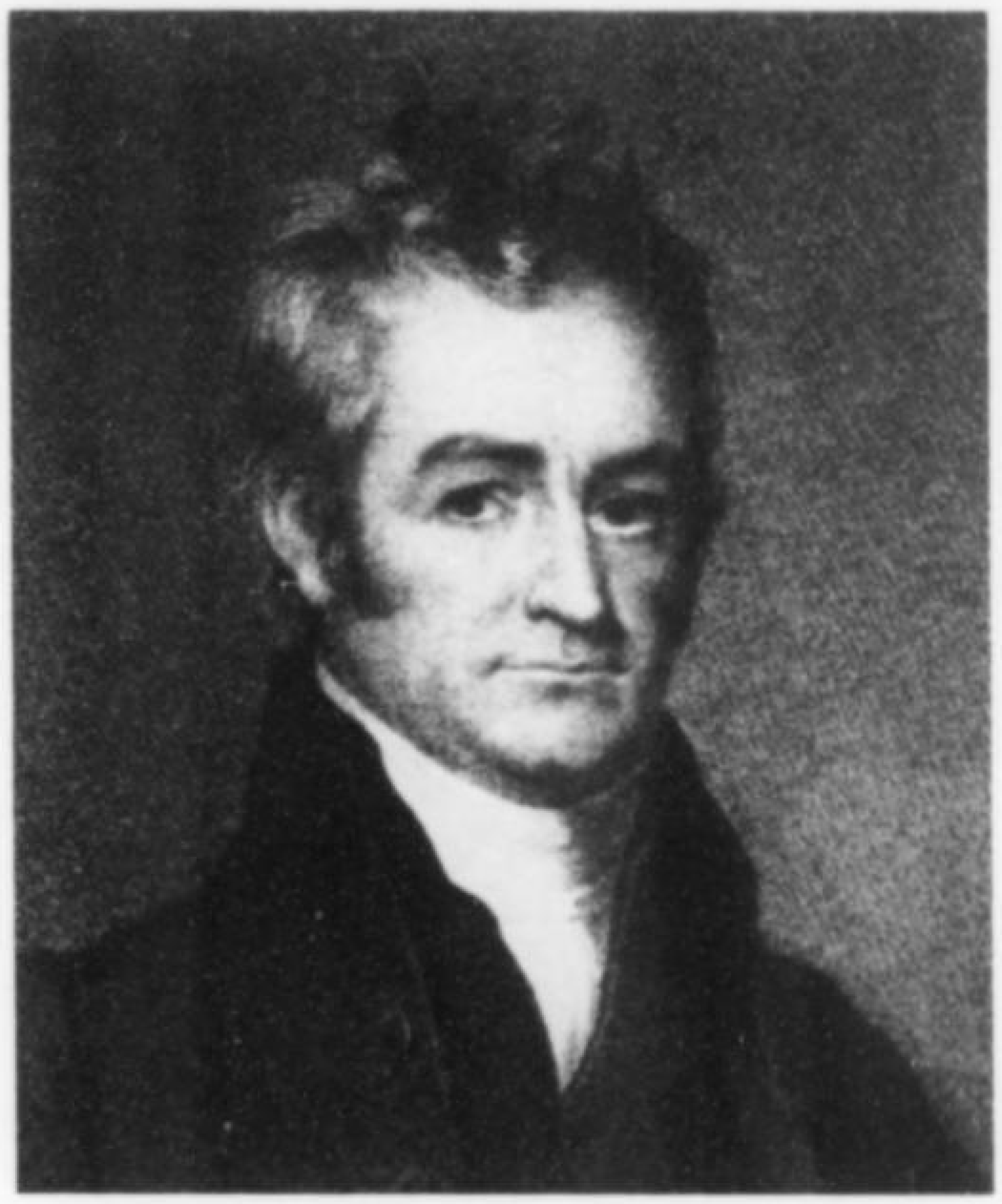
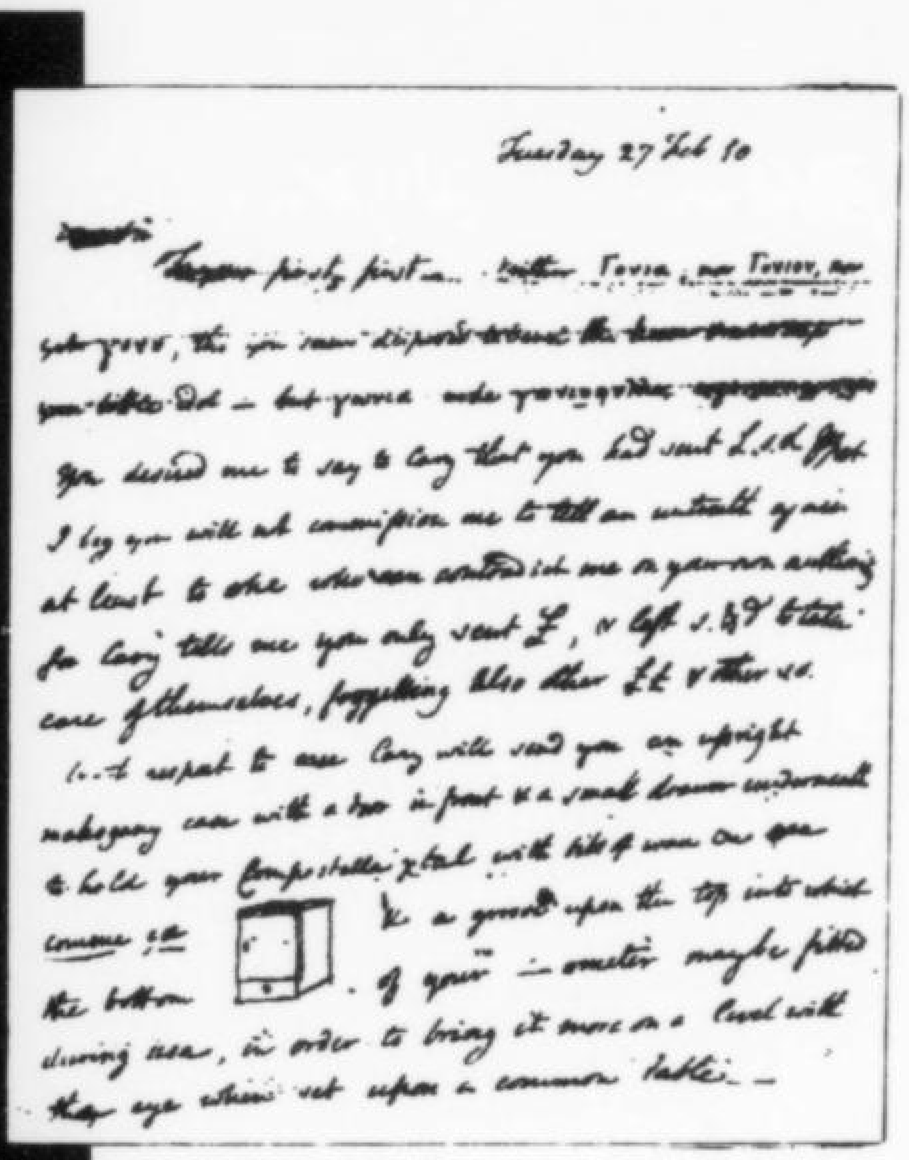


Figure 30. **William Phillips (1775–1828), compiler of goniometric data obtained using Wollaston's instrument.**

The Wollaston goniometer (Fig. 31) consists of a vertically mounted graduated circle; on the side is attached a vernier affording measurements to arc-minutes. The horizontal axis is joined firmly with the circle and can be rotated by means of a flanged disk. There are two nested axes: an outer axis and an internal axis which has a geniculated stirrup ending with the crystal mount and which can be turned by means of a smaller milled screw. Both axes are so arranged that a single as well as a coupled rotation is possible. The original model had a small notch at the 0° and 180° positions which, with the help of a small spring, would stop the circle at these points. Later models dispensed with this device.

The adjustment and centering mechanism is relatively primitive. There is a platelet on which to mount the crystal with wax; this crystal mount is clamped to a pin which is mounted to a turnable and movable semicircular stirrup. This stirrup is joined firmly with the internal axis of the graduated circle; a joint makes the rotation around another axis possible. One can imagine the difficulties of centering and adjusting the crystal edge.

The actual measurement is accomplished as described in the preceding chapter. The axis of the graduated circle is arranged parallel to the window level and close to the opposite wall, with a window mullion, for example, serving as the signal. The window sill or a chalk line on the baseboard below the window serves as a reference line. The graduated circle is now placed at the 0° or 180° mark, and the viewer places his eye a few centimeters away from the crystal. With the milled screw of the internal axis a crystal face is turned into position until the signal and reference line are congruent. The eye of the observer remains stationary, while one brings the circle, along with the crystal holder, through simultaneous rotation of both axes to a position where the second crystal face also displays the signal and reference lines in congruence. The sought-after supplemental angle can be read directly off the vernier. The more reflective the crystal faces are, the more remote the objects (e.g., a steeple cross) which can be chosen as a signal.



Tuesday 27 Feb 10

Figure 31. **Letter from Wollaston to Rev. Daniel C. Clarke, dated Feb. 27, 1810, with small sketch of case box. H. Obodda collection.**

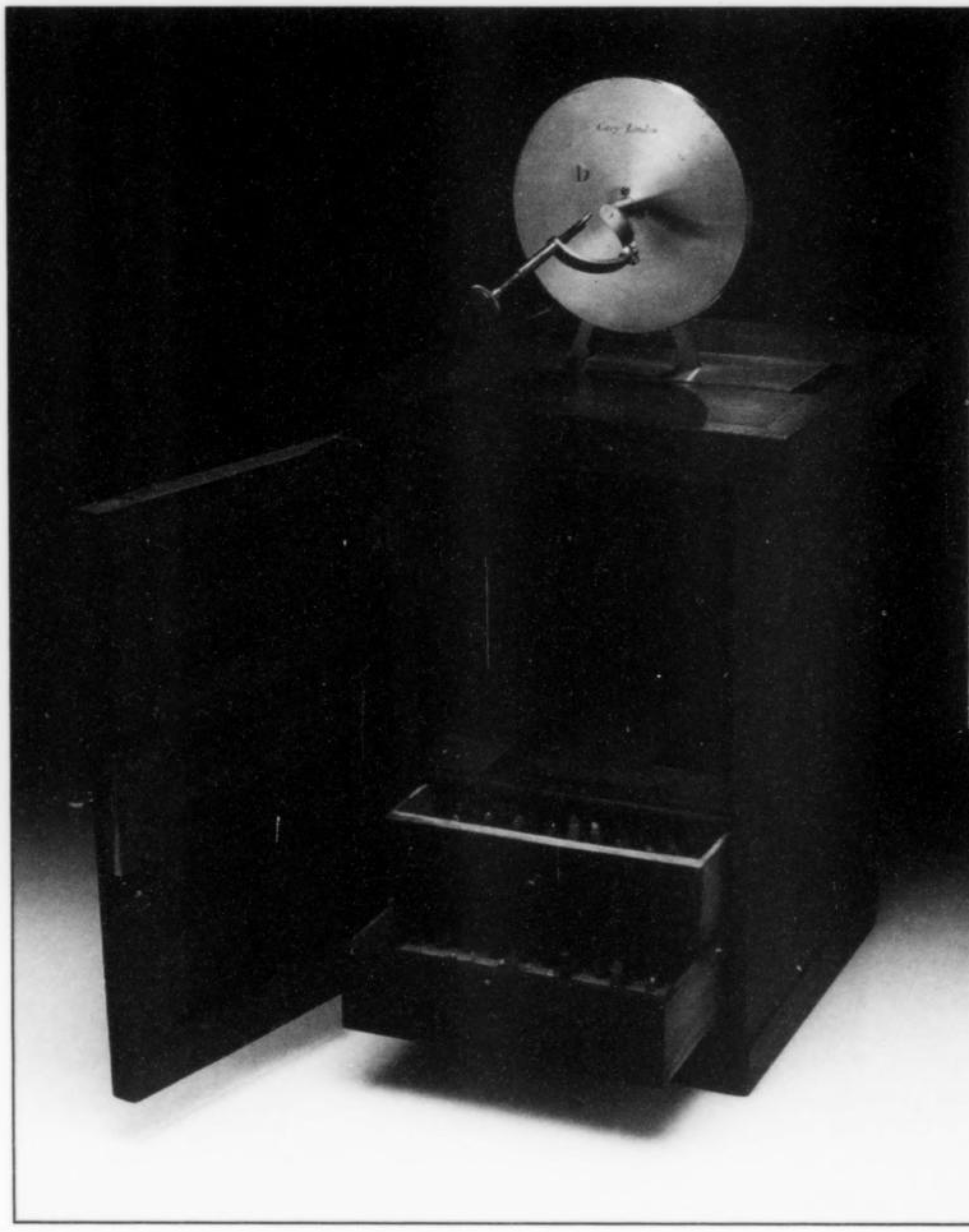


Figure 32. **Wollaston goniometer by Cary, London, ca. 1815, mounted on its case. H. Obodda collection.**

If the planes reflect poorly, a closer signal, e.g., a heated metal wire, must be used.

Ours-Pierre-Armand Dufrénoy (1792–1857) described (1856) a goniometer designed by **Friedrich Mohs** (1773–1839) which was similar in its measuring technique to that of Wollaston, but with the circle in a horizontal position. This device is not otherwise mentioned in the literature, and its originality is doubtful, since as early as 1810 Malus constructed a horizontal circle goniometer with observation telescopes.

Wollaston (1809) does not name the maker of his goniometers. Because he worked closely with William Phillips one can assume that they used either the same instrument or instruments from the same maker. In his work *On the Oxide of Tin* (1814) Phillips writes about an improved scale arrangement: "and I have obtained one graduated to half a minute, from Mr. Carey, whose ingenuity led him to add to it some apparatus with the view to precision in its use."

Further reference to Cary is contained in an important letter by Wollaston to Rev. C. Clarke of Cambridge dated Feb. 27th, 1810. This autograph is preserved in the collection of H. Obodda. In the opening line Wollaston ridicules the addressee who obviously mistook the Greek letter "omikron" for a Greek "omega," a peculiarity of the Greek language having two "O"s. The word gonio spelled with the letter omikron has some phallic meaning and consequently Wollaston states, "You seem disposed to bend the knee & worship your little idol." Later Wollaston continues, "With respect to case, Cary will send you an upright mahogany case with a door in front and a small drawer underneath to hold your compostella x-tal with bits of wax or be comme, & a groove upon the top into which the bottom of your -ometer [*sic*] may be fitted during use, in order to bring it more on a level with the eye when set upon a common table."

The reflecting goniometer in its original form appears to have been manufactured predominantly by English makers. The catalogs of W. Cary (1827), F. West (approx. 1920), Troughton & Simms (1830), T. C. Robinson (1830), and A. Krantz (1853) all list the Wollaston goniometer at a price of 3 pounds and 3 shillings. The graduated circles have diameters of 4 to 4.5 inches (only exceptionally 6 inches), and are always manufactured from a solid brass disk. Gilbert (1815) mentions a Wollaston goniometer by Pistor of Berlin for 18 Thalers, although the catalog of Pistor and Schick (1829) indicates 24 Thalers. The English engineer R. Graves (1833) built a slightly modified instrument from wooden parts.

James Ballantine Hannay (b. 1855) in 1877 suggested one of the most ludicrous instruments for the "do-it-yourselfer." The stand is made from test tubes, the connections and axes from cork, and the graduated circle from a mica sheet (Fig. 33).

Mitscherlich (1843), who has a type of goniometer named after him, describes a small *travel goniometer* (circle diameter 2.5 inch) of the Wollaston type stored in a brass cylinder which also serves as a base (Fig. 35). It was manufactured by the Oertling factory in

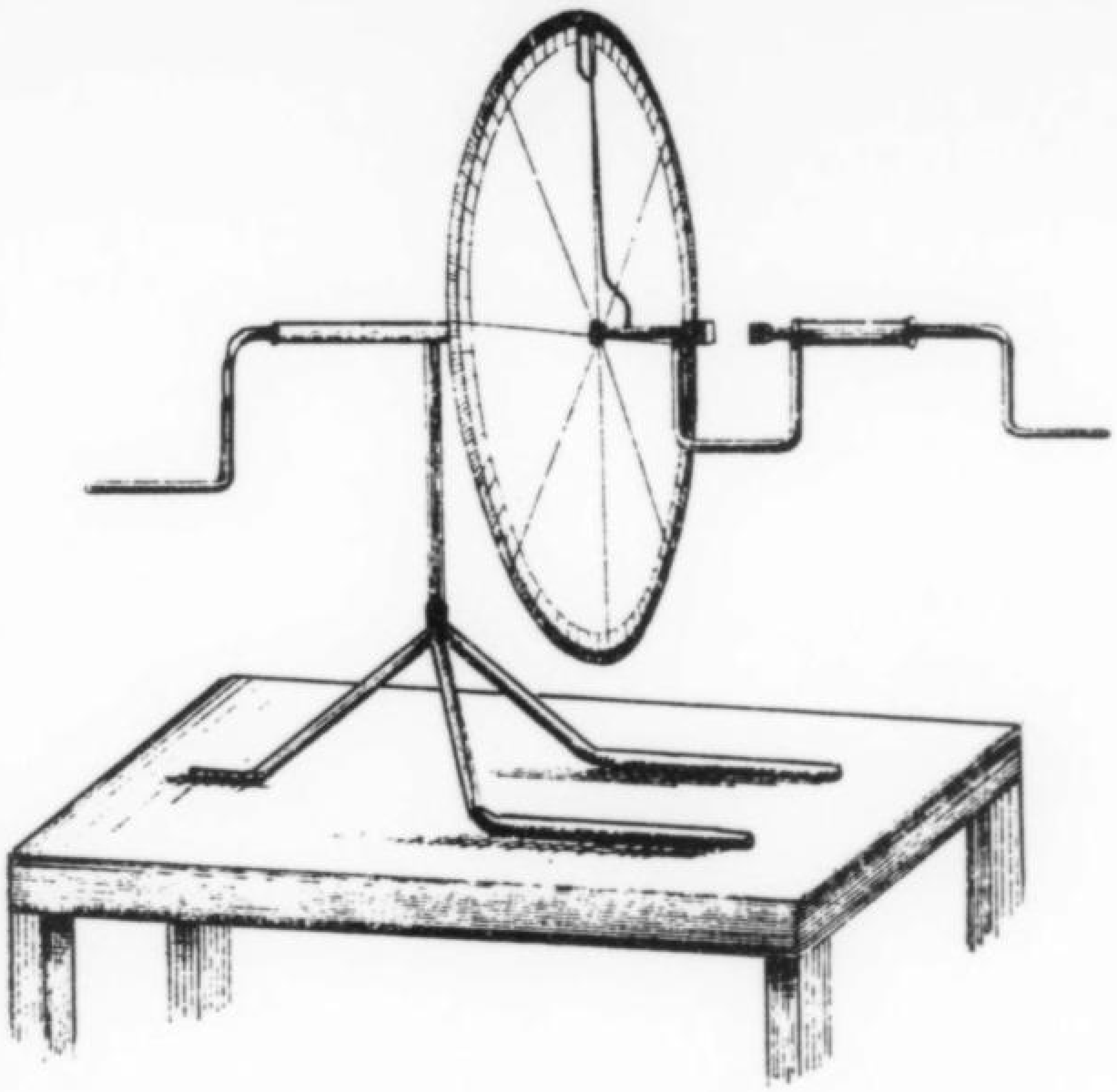


Figure 33. **"Do it yourself" goniometer proposed by Hannay (1877).**

Berlin. A very similar travel goniometer was built by the Fuess company of Berlin until 1914. It is only slightly modified so that the position of the crystal edge could be observed through a loupe in an appropriate hole bored through the axis of the circle. In 1876 the price of this travel goniometer was 48 Marks, in 1914 68 Marks.

One of the most extraordinary and exotic goniometer designs was suggested by **Joseph Patrick O'Reilly**, professor of mineralogy in Dublin (?) in 1872 (Fig. 34). The general measuring technique of Wollaston is retained; however, the use of the graduated circle is replaced by measurement along a straight line. The crystal is mounted with wax directly on a central axis. This is built in a spiral, which will keep the precise pitch of the screw thread. A tubular cylinder with a narrow slit along its longitudinal

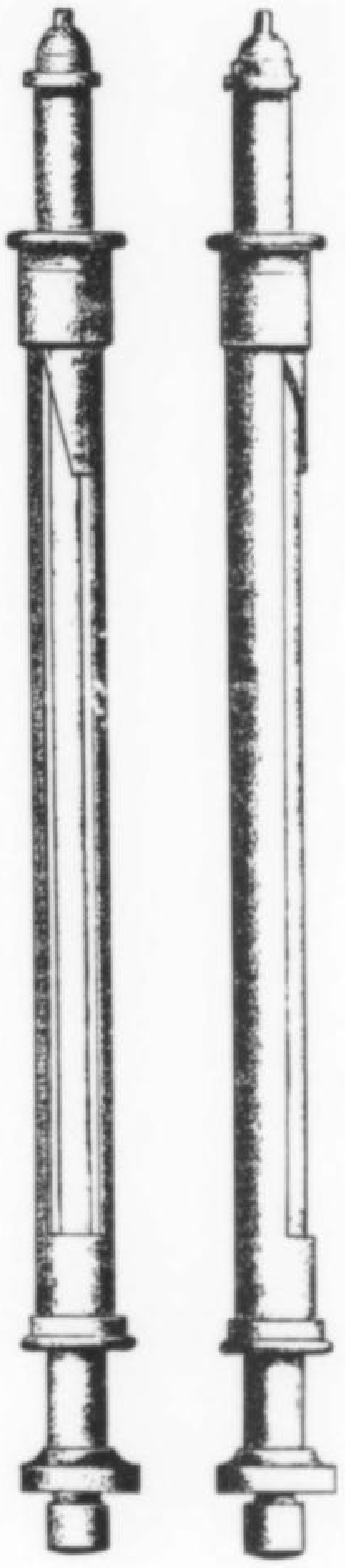


Figure 34. **Axial goniometer by O'Reilly (1872).**

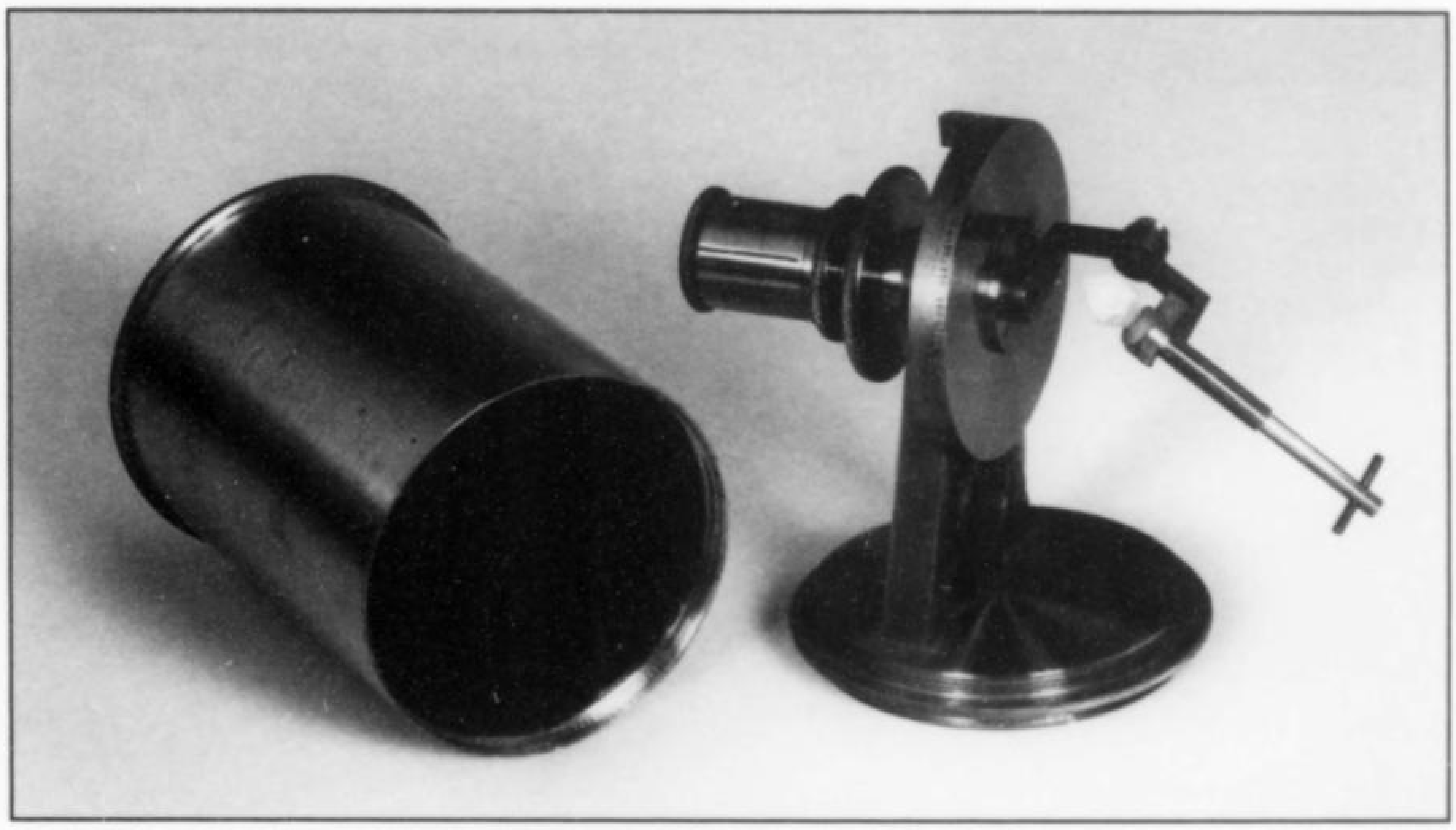


Figure 35. **Travel goniometer with transport cylinder by R. Fuess, Berlin, ca. 1900. Natural History Museum, Berlin collection.**

axis can be rotated about the central axis. The rotation angle can be read with the aid of an appropriately placed vernier and a straight graduated scale. The very compact instrument should only be 18 to 25 cm long and 2.5 cm in diameter. It is hand-held and designed especially for making measurements in the field. It is not known whether instruments of this design were actually manufactured.

In 1857, **P. Casamajor** (b. 1831) proposed a graphic method of angular measurement which relied on the principle of reflection. He dispensed completely with the goniometer and fastened the crystal on a straightedge resting horizontally on a piece of white paper. For adjustment and measurement the eye is brought close to the crystal, observing a vertical signal and a reference line. The ruler, together with the crystal, can be rotated around a central point. For both crystal faces a line is drawn with the straightedge at signal congruence, and the supplementary angle is measured with a protractor.

As already mentioned, the position of the circle is insignificant. The protractor can also be positioned horizontally, the crystal mounted on the vertical axis, and a vertical signal used. Dufrénoy (1856) refers to a horizontal-circle reflecting goniometer without accessories named after the mineralogist Friedrich Mohs (1773–1839), but Dufrénoy offers no proof or citation The author does not know of any example of such a Mohs goniometer.

The accuracy of the Wollaston goniometers without accessories, using repeated measurements, is rated differently by various authors; however, to judge by the graduation of the circle, it lies between 1 and 6 arc-minutes.

BREWSTER'S GONIOMETER

Priority in the invention of reflecting goniometers was claimed exclusively for himself by the Scot **David Brewster** (1781–1868) in 1813. Brewster made great advances in the understanding of the refraction and polarization of light, as well as in optical mineralogy, but seems not to have been publically honored for his scientific accomplishments. Brewster's goniometer resembles Wollaston's, but its construction is more complicated. He claimed to have invented the principle of the reflecting goniometer as early as 1807, two years before Wollaston, and this is confirmed by Alexander Tilloch in his *Philosophical Magazine* (1807), in a sentence under "List of patents and inventions": "M. D. Brewster, of Edinburgh, has invented a . . . goniometer for measuring the angles of crystals."

In his description of the design, Brewster (1813) writes:

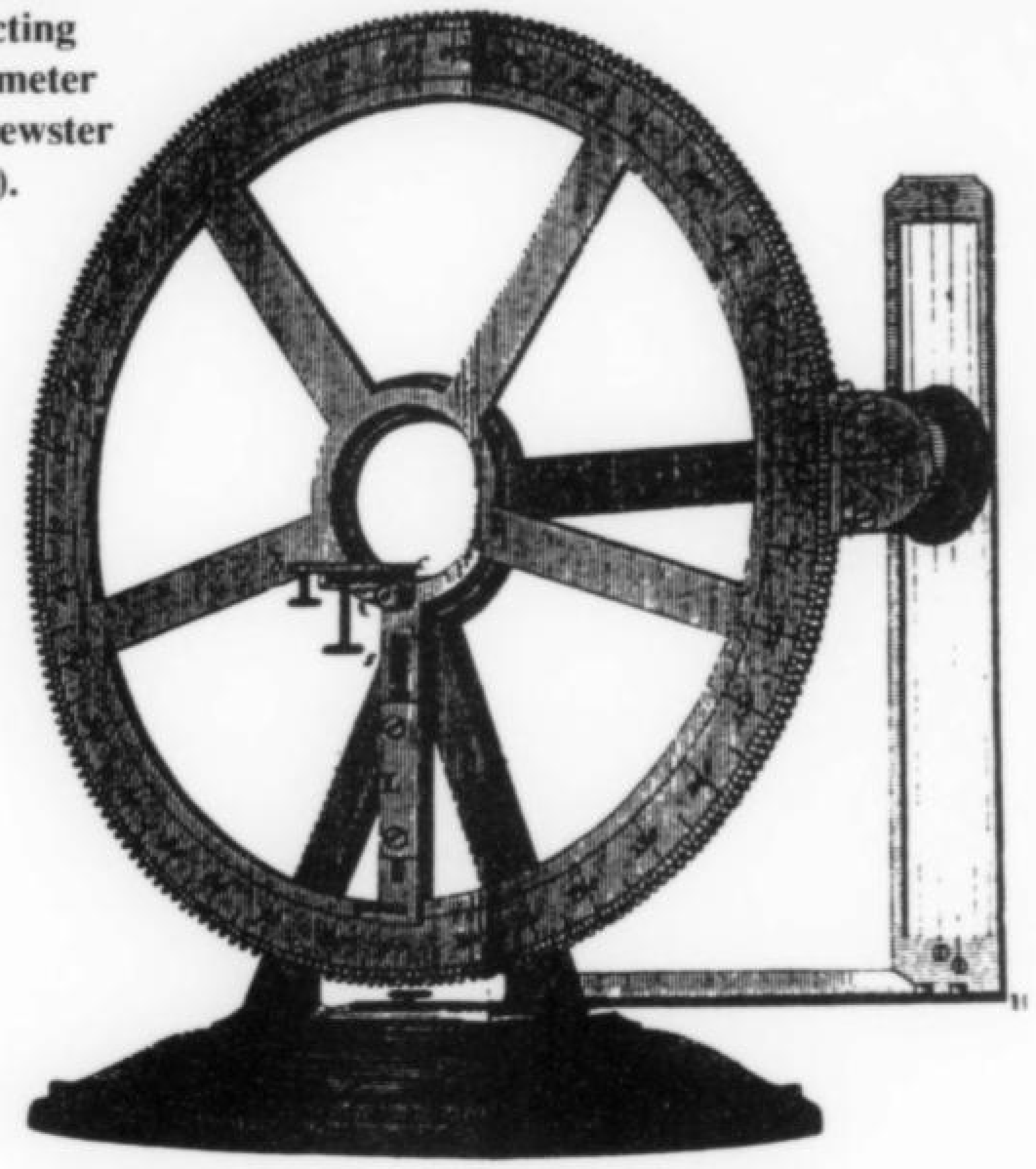
> *On the 3rd of February 1809 I gave directions to Mr. Harris to construct for me a goniometer, . . . I shewed this goniometer to several of my friends in London . . . in the beginning of April it was exhibited to the mathematical class of Cambridge university. . . . At this time I got at addition made to the instrument by Mr. Adie . . .*

The truth appears to be that in 1809 the reflecting goniometer was built independently by Wollaston and Brewster. There is a similar chronological coincidence about the invention of the two-circle goniometer: in the years 1882–1883 three crystallographers constructed, independently of each other, the so-called *theodolite goniometer,* which will be discussed later.

Brewster's instrument (Fig. 36) was constructed as follows:

The reversed V-shaped holder ends in a ring-shaped hollow-axis center. Firmly joined with this is a radius which has a vernier mounted on the outside. The vertical, 6-inch graduated circle is joined by 5 spokes to the axis; the perimeter is geared and can be rotated with a drive screw in the area of the vernier. The crystal holder, mounted in a track that is adjustable for height, is firmly attached to one of the spokes. The actual crystal holder is mounted on a bearing revolvable perpendicular to the plane of the graduated circle; the holder can be positioned parallel to the circle axis by a small joint. Therefore, the axis of the graduated circle is not identical with the axis of the crystal holder, although the latter cannot be turned independently of the graduated circle.

Figure 36. **Reflecting goniometer by Brewster (1813).**

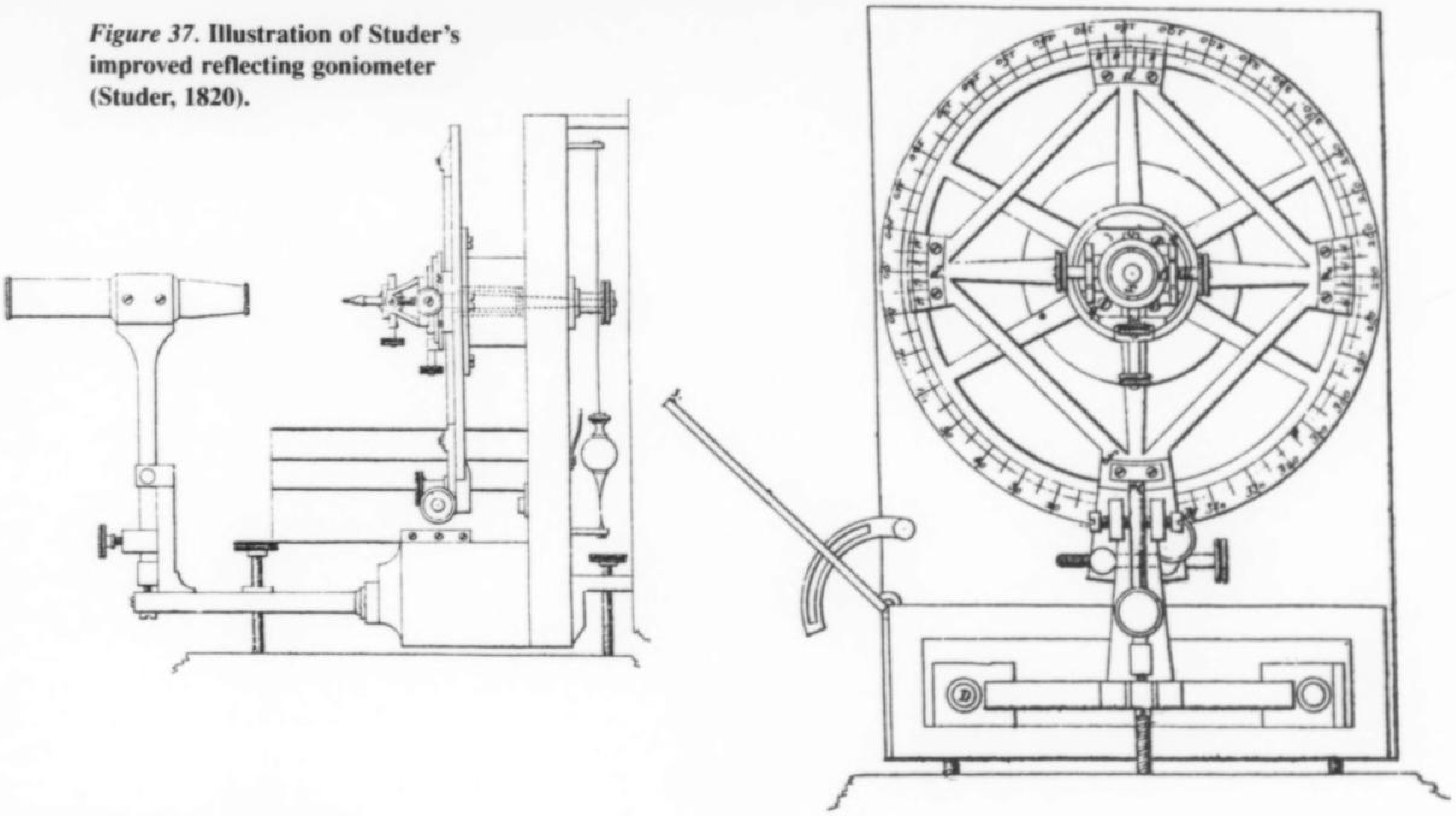


Exact centering of the crystal axis is not necessary. Brewster's adjustment instructions anticipate that the instrument will be set up like a Wollaston goniometer. This means that the instrument is leveled so that the axis of the circle lies parallel to the level of a window. The crystal holder is manipulated until the reflection of a vertical (!) window mullion appears as an exactly vertical line on both crystal faces. This assures that the crystal faces lie perpendicular to the graduated circle. For the actual measurement the instrument is turned 90° until the circle axis is perpendicular to the level of the window and the crystal edge points in the direction of the window. That means that the eye of the observer looking at the crystal edge through the ring-shaped opening forms a plane with the crystal and a vertical (!) window mullion. Coincidence of the edge parallel reflection and vertical window mullion is achieved through rotation of the circle, and the process is repeated for the second crystal face.

The instrument can also be used without an external signal. For this purpose a 20 to 25-cm arm is fastened to the base plate. This arm has a vertical frame whose plane lies parallel to the plane of the circle. In this frame are stretched three pairs of thin silver wires, whose reflection one observes on the crystal faces. In this configuration the instrument can be hand-held and used in any position in the room. For matte, non-reflecting crystal faces, Brewster suggests covering them with glass or other reflective plates. He makes no comments on the accuracy of his goniometer.

The instrument was built in 1809 by William Harris, No. 47 (later No. 50) High Holborn, London. The additional assembly for the wires evidently originated with Alexander Adie, No. 96 Nicholson St., Edinburgh. It does not appear to have survived the competition with the Wollaston goniometer, and no examples of it are known to the author. Brewster's original instrument was destroyed by fire in 1903 (P. Embrey, personal communication, 1984).

Figure 37. **Illustration of Studer's improved reflecting goniometer (Studer, 1820).**



STUDER'S GONIOMETER

The goniometer described in 1820 by **Johann Gotthelf Studer** (1763–1832) was similar in construction and operation to Wollaston's. However, it already displays a series of pioneering improvements and accessories, which are repeated in later models.

First of all it is to be emphasized that Studer, although he studied at the Mining College in Freiberg, was an instrument maker, not a scientist. He received his education from Jesse Ramsden (1731–1800) in London and from Johann Christian Breithaupt (1736–1799), the founder of the famous, and still extant, workshop for geodetical instruments in Kassel. He was related to Breithaupt through marriage with his daughter. In 1791, as a mining 'mechanikus' in Freiberg, Studer founded his own workshop, from which the firm of Lingke (later called Hildebrandt) emerged. He later became Court Instrument Maker, and from 1813 Mint Master, in Dresden.

Studer presumably exchanged ideas with scientists in Freiberg, a common practice of the time. **Friedrich Mohs** (1773–1839), successor to **Abraham Gottlob Werner** (1749–1817) as professor and chairman for mineralogy in the Mining College of Freiberg (Mohs held this position from 1818 to 1826) was Studer's possible mentor. During his time in Freiberg, Mohs dedicated himself to the study of the external symmetry of crystals and their systematic arrangement, as will be discussed later. The fact that Studer's intricate goniometer still exists today at Freiberg supports the hypothesis that it was conceived for research at this facility. The construction drawing is shown in side view (Fig. 37); the actual instrument is depicted in Figure 38. Following are its principal novelties in comparison to, and its improvements over, the Wollaston goniometer.

(1) The 8-inch graduated circle of Studer's instrument is no longer rotated by an axial gear, but can be coupled by means of a clamp to a tangential precision drive, making very exact adjustments possible.

(2) The readings can be made on any of three verniers. This goniometer has the advantage that repetitive measurements can be made on the entire circle; individual inaccuracies are reduced through averaging (the sum of the measurements divided by the number of readings).

(3) The crystal holder is mounted on a complicated adjusting and centering mechanism. This construction principle remains almost unchanged to this day, and therefore will be described in some detail: Two cross slides mounted at right angles, one on top of the other, can be shifted with the aid of rapid adjusting screws (later equipped with a resisting spring), affording minute transverse movements of the crystal during its centering. On these flat traversing boxes a hemisphere is located, containing within it two mutually perpendicular screws which can be used to tilt the crystal mount in an arc from the vertical to the horizontal. The crystal edge can be put parallel to the axis of rotation. In later models the adjustment apparatus consists of two curved, segmented cradles, superimposed at right angles. With these traverse and tilt movements the edge of the crystal may be precisely aligned with the prolongation of the axis of the divided circle. This precision mechanical wonder, the actual "heart" of every goniometer, is called the *goniometer head* (Fig. 39).

(4) A centering microscope, with the center of its cross-hairs on the graduated circle's axis, allows the exact adjustment of the crystal edge. This centering mechanism is used solely on goniometers manufactured by the Breithaupt company, the only exception being the already mentioned Hirschwald microscope goniometer made by the Fuess company.

(5) An exactly horizontal position of the instrument is achieved by means of a pointed pendulum with a corresponding stationary point and three adjustable leveling screws.

(6) The divided circle of the goniometer can be positioned vertically as well as horizontally. Studer suggests that for the adjustment of the crystal the instrument should be positioned horizontally, allowing one to look down vertically through the centering microscope in order to perform the necessary manipulations.

(7) The most important innovation is a white board mounted sideways below the circle (see construction designs; today it is missing on the original instrument). This board is mounted perpendicular to the plane of rotation and may be folded up and down by

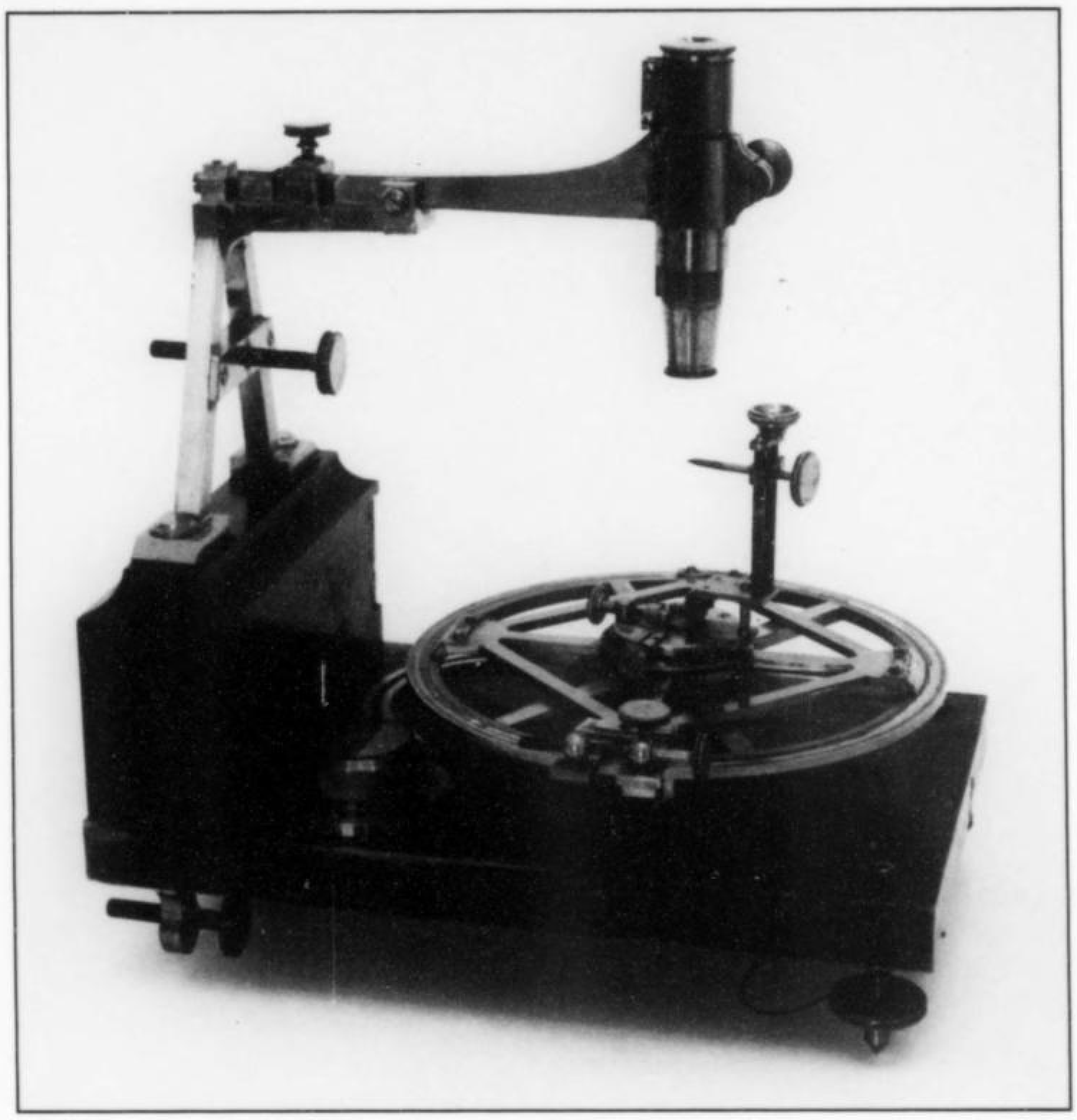
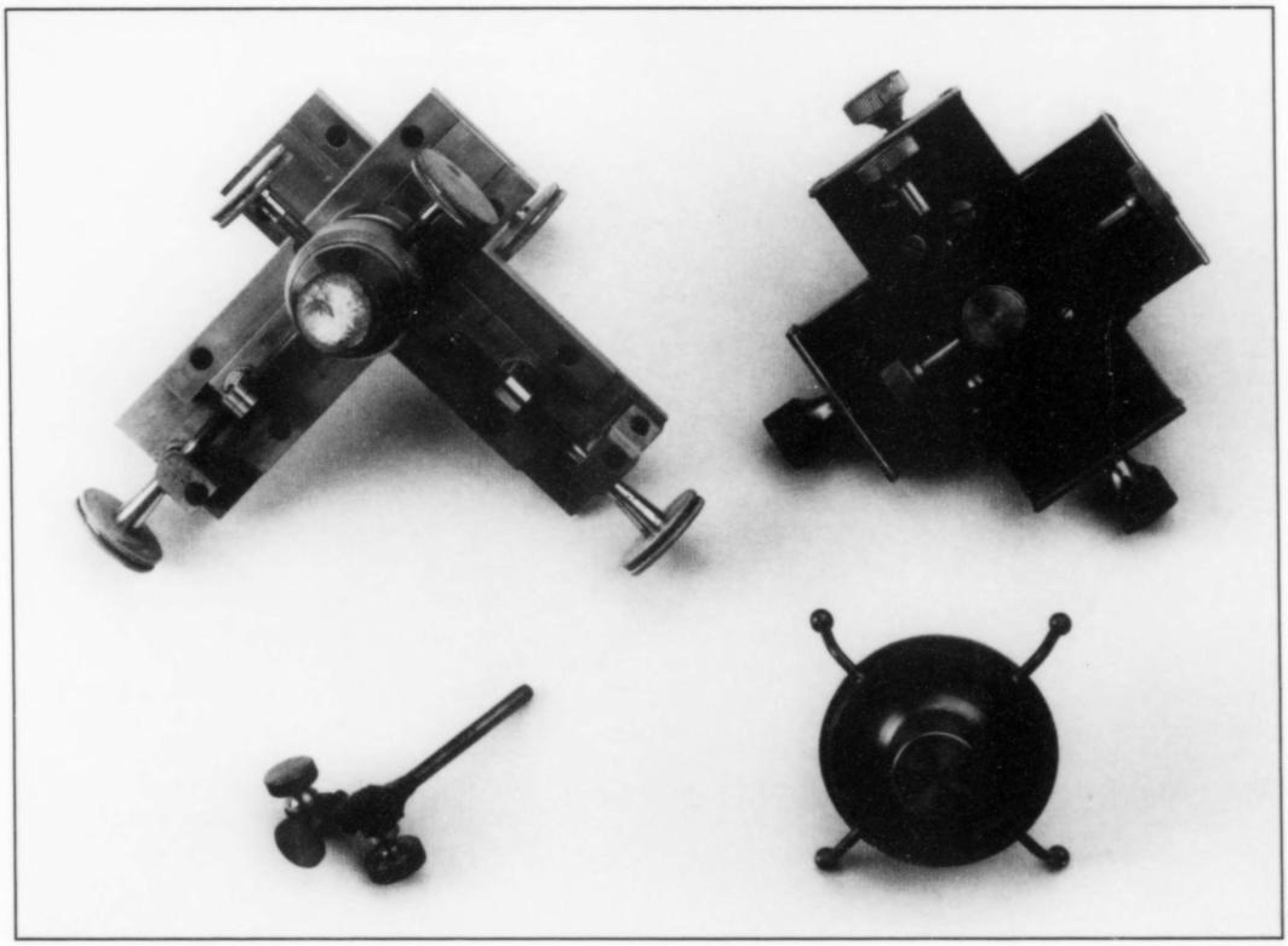


Figure 38. Goniometer by Studer, unsigned, ca. 1820. Mining academy of Freiberg, Saxony collection. Photograph by M. Knopfe.

Figure 39. Various types of goniometer "heads"—devices to adjust and center the crystal edge. Counter-clockwise from lower left: simple type used on old Wollaston goniometers; Petzval type; modern Fuess type with cross slides and segmented cradles; Studer type with cross slides and hemisphere.



means of a hinge. The board is divided by three small, parallel, inlaid, black ebony lines. One of these can be used as a reference line and brought into coincidence with the image reflected on the crystal edge. This board clearly is the precursor of the later auxiliary mirror attachments! Studer used a smooth rope stretched horizontally over a windowpane as a signal.

Studer's description does not clearly explain which accessories originated with him and which with Breithaupt:

> *The Court and Mint "Mechanikus" Breithaupt in Cassel has mounted an ingenious addition to this goniometer, the centering and adjusting attachment. I have described the goniometer, with the information as received from Breithaupt. The instrument was of excellent manufacture . . . and the divisions made on silver were not only very precise but well mounted.*

However, the board, the pendulum and the attachments for use in horizontal positioning appear without doubt to have been invented by Studer. He repeatedly says that his instrument is accurate to within 1 arc-minute! The author knows of only one extant example: the above-mentioned one in Freiberg.

GONIOMETERS WITH MIRROR ATTACHMENTS

While making measurements with the Wollaston goniometer it was often difficult to bring the distant signal into coincidence with a similarly distant reference point. Only with this coincidence can it be guaranteed that the light rays fall parallel on the crystal faces, so as to render negligible any potential error resulting from an irregularity on the crystal edge, or an error in measuring the parallax between the plane of the divided circle and the imaginary plane formed by signal, reflecting crystal face and the observer's eye. The measuring technique used with a Wollaston goniometer also assumes an absolutely stationary instrument, as the slightest movement during measurement will result in considerable errors.

To minimize these problems, a method was developed which made it possible to use only one signal point. A blackened mirror mounted under the crystal on an otherwise unmodified Wollaston goniometer was suitable for this purpose. The plane mirror is exactly parallel to the axis of the circle and is tiltable parallel to that axis. The mirror is so positioned that the observer sees a distant object, e.g., a horizontal lightning rod wire, reflected on the crystal face, and allows it to come into congruence with the same object reflected in the mirror. This works particularly well with small crystals.

The mirror produces the impression that the object and the reference point are equally distant to the observer's eye during the measurement of the angle. The mirror must not be moved after making this adjustment. As Figure 40 illustrates, the observer perceives congruence when the crystal face OA is adjusted so that it is exactly parallel to the plane of the mirror MM. The second face OB is brought parallel to the plane of the mirror by rotation of the circle; the angle of rotation is the supplemental angle.

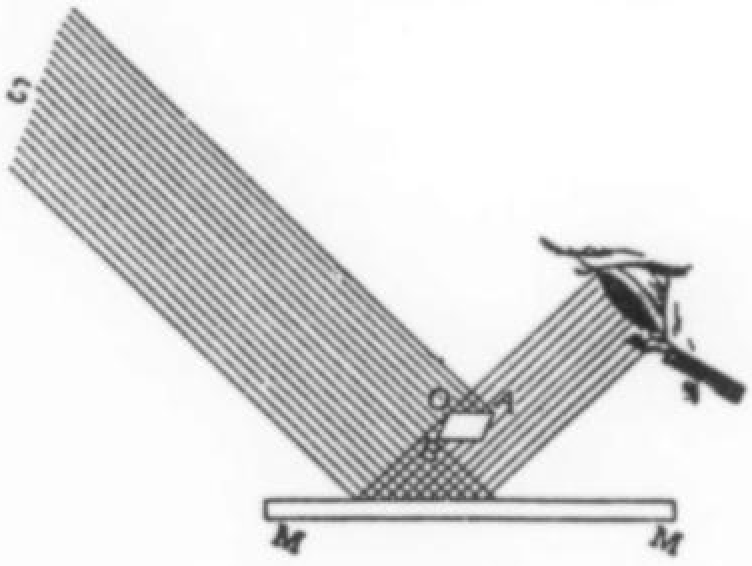


Figure 40. **Principle of measurements with the reflecting goniometer and mirror attachments (Miers, 1902).**

This technique was first introduced by **J. B. Emmet** of Cambridge in 1817 to determine the angle of a sextant prism: "Being in some respect more convenient, and certainly capable of measuring an angle with a greater degree of precision than most goniometers at present in use, it may not perhaps be unacceptable to the mineralogist," he said.

As for a Hadley sextant, Emmet fastened a small mirror to the

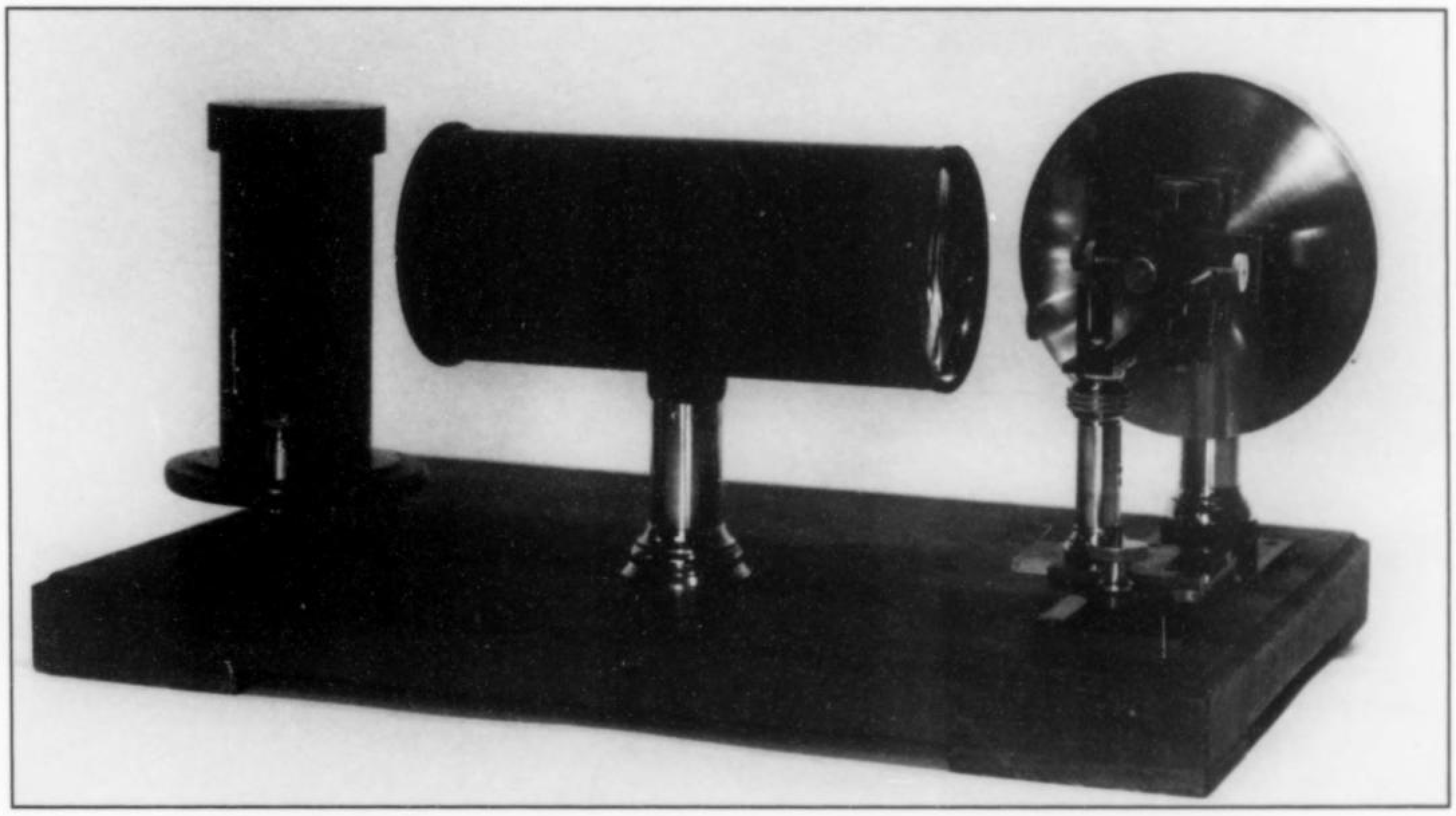


Figure 41. **Mallard-type configuration. Note: mirror attachment close to crystal holder. With artificial light source and condensing lens system. Signed: "Pellin, Paris," ca. 1910.**

center of the axis of a graduated circle; a crystal face was to be adjusted until parallel to it. This small instrument was hand-held (Fig. 41).

In 1817 as well, an article by **Etienne Louis Malus** (1775–1812) appeared which, according to the report of the reviewer Arago, was read before the Societé de Arcueil on June 30th, 1810. In it, Malus described for the first time an observation telescope (see the following paragraph), as well as a "metallic" mirror: *"Au moyen de ce mirroir, on peut se dispenser, à la rigueur, de placer l'instrument sur un pied fixe, et on peut faire les opérations avec la mème facilité que celles du sextant. Cet instrument a été exécute par M. Fortin."* The mirror was placed opposite to the telescope and was not used for the actual measurement, but aided in the adjustment of the telescope.

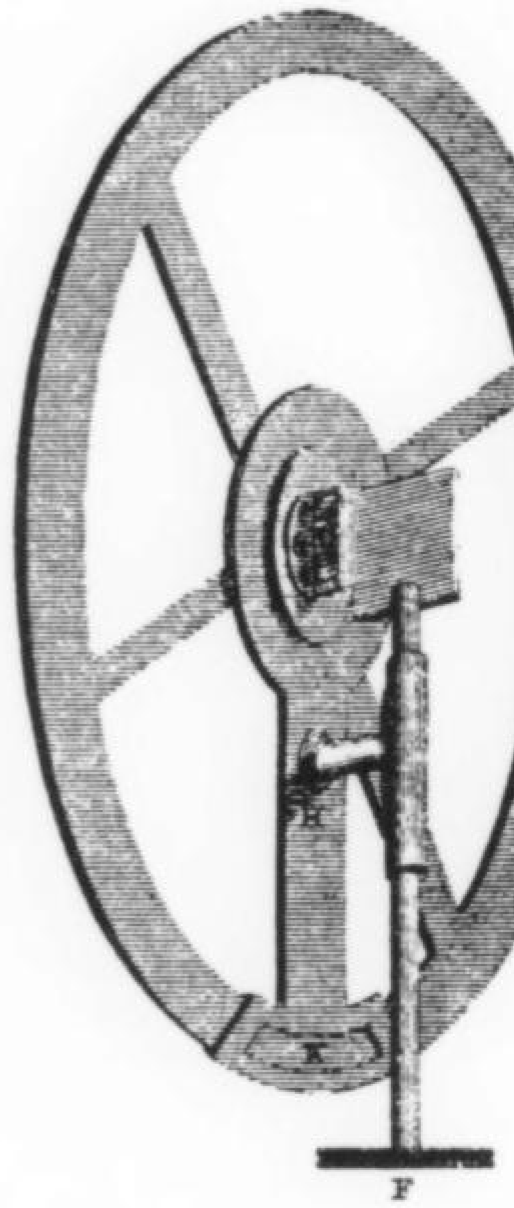


Figure 42. **Hand-held goniometer by Emmet (1817).**

In his *Preisschrift ueber genaue Messung der Winkel an Kristallen* (1825) **Adolph Theodor Kupffer** grasped the same idea: "in the meantime I have allowed a single distant object such as a steeple or chimney to be reflected on a completely flat black mirror."

In German technical literature (Liebisch, 1879; Leiss, 1899) the construction of the mirror was credited to **August Friedrich Enst Degen** (1802–1850), professor of physics and chemistry in Stuttgart, who in 1833 observed in his notes: "another advantage is that a small movement of the instrument during measurement does not cause any meaningful error. One could even hold the instrument in the hand as one would a sextant."

In English literature the priority of invention is given to **Edward Sang** (1805–1890), mathematics professor in Edinburgh, who worked for many years on improving the Wollaston goniometer, publishing his suggestions in 1837: "The surface of the permanent reflector must not be too bright, otherwise the light from it will be too strong and prevent the distinct vision of the other image." Sang also suggested that the 0° and 180° stops on the graduated circle be removed: "In conclusion, I remark, that the steps affixed to the instrument, as ordinarily made, impede much of the work, on which account I would recommend their removal from it."

In 1825 Kupffer had already written: "In sunny weather I use the sun as a distant object and protect my eye from too strong a light by means of a black glass." Later, an investigator typically worked in a darkened room, with an open slit to admit sunlight. With the use of a heliostat the sunlight could be kept at an even level and used throughout the day.

Figure 43 illustrates the manner in which the goniometer is used. In the foreground a vertical cardscreen is so positioned that it blocks the light which falls from the signal upon the mirror, but not that which falls upon the crystal.

Poor weather may mean that there are no distant signals to use, or the crystal faces are not reflective enough: in 1887 the Parisian mineralogy professor **Ernest Mallard** (1837–1894) solved these problems by moving the black mirror to a distance of 2–3 cm from the crystal (Fig. 41 and 44). The mirror and crystal faces were

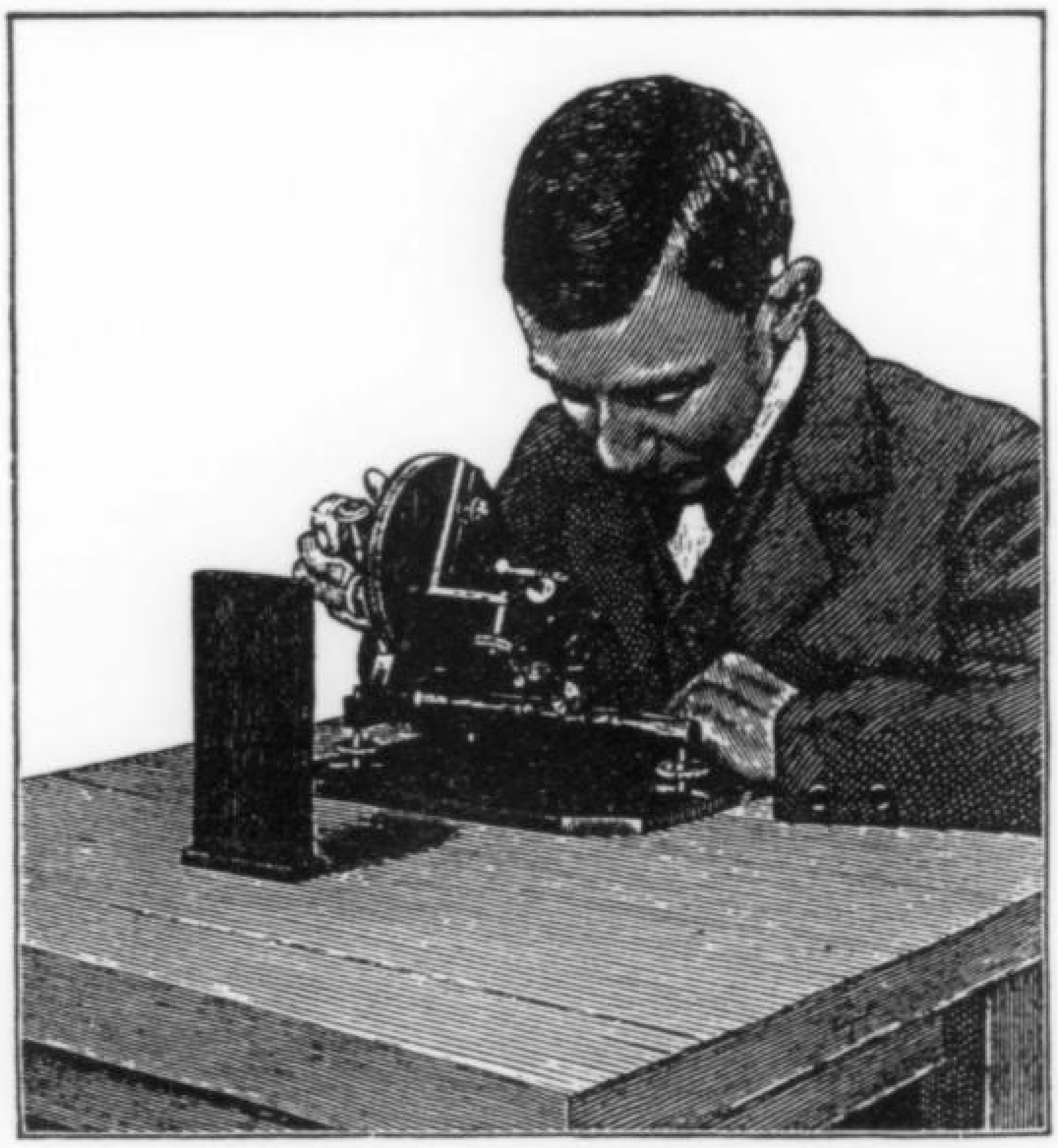


Figure 43. **Actual use of the reflecting goniometer with mirror attachment (Miers, 1902).**

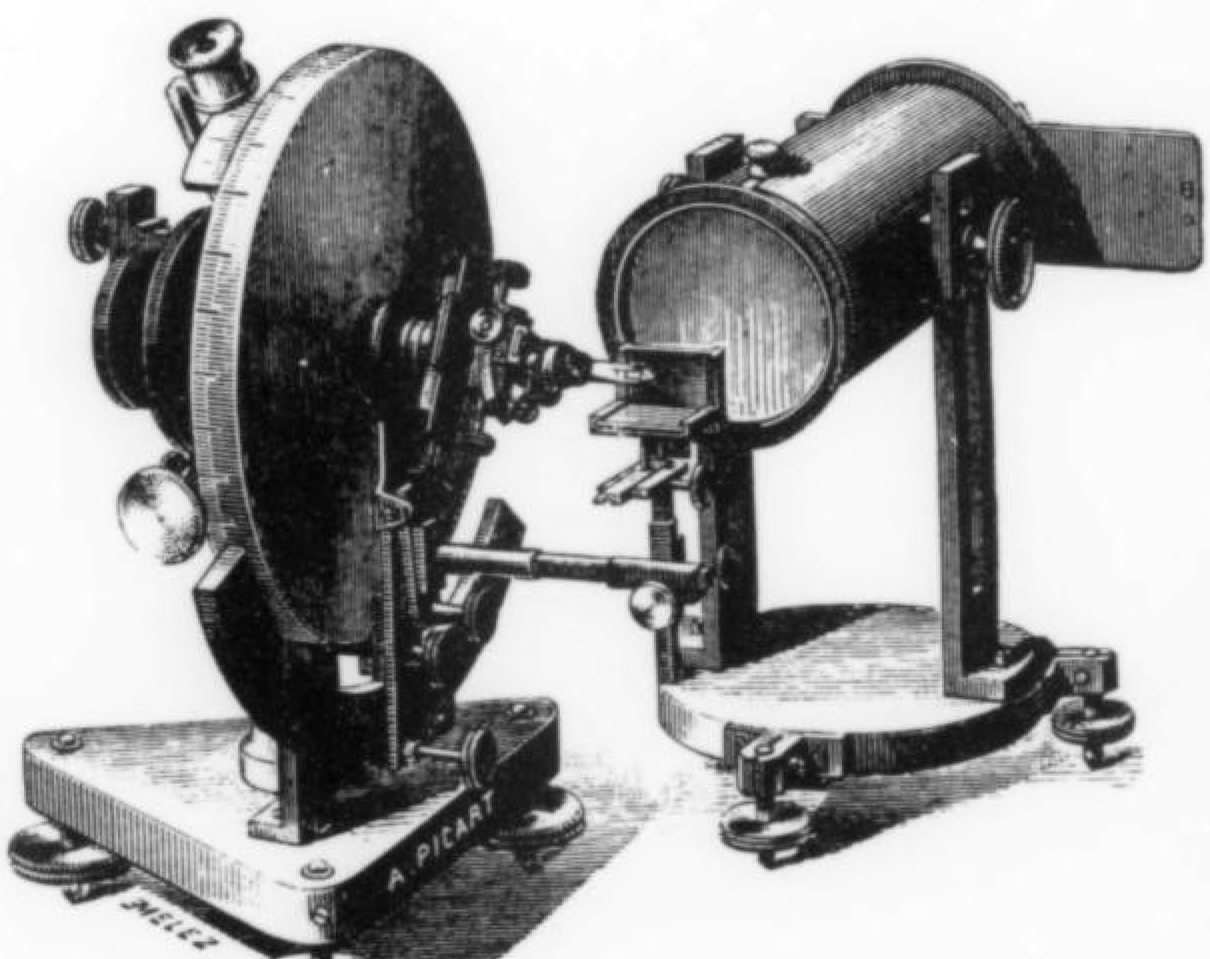


Figure 44. **Wollaston-type goniometer as modified by Mallard, with collimated artificial light source; sold by Picart, Paris.**

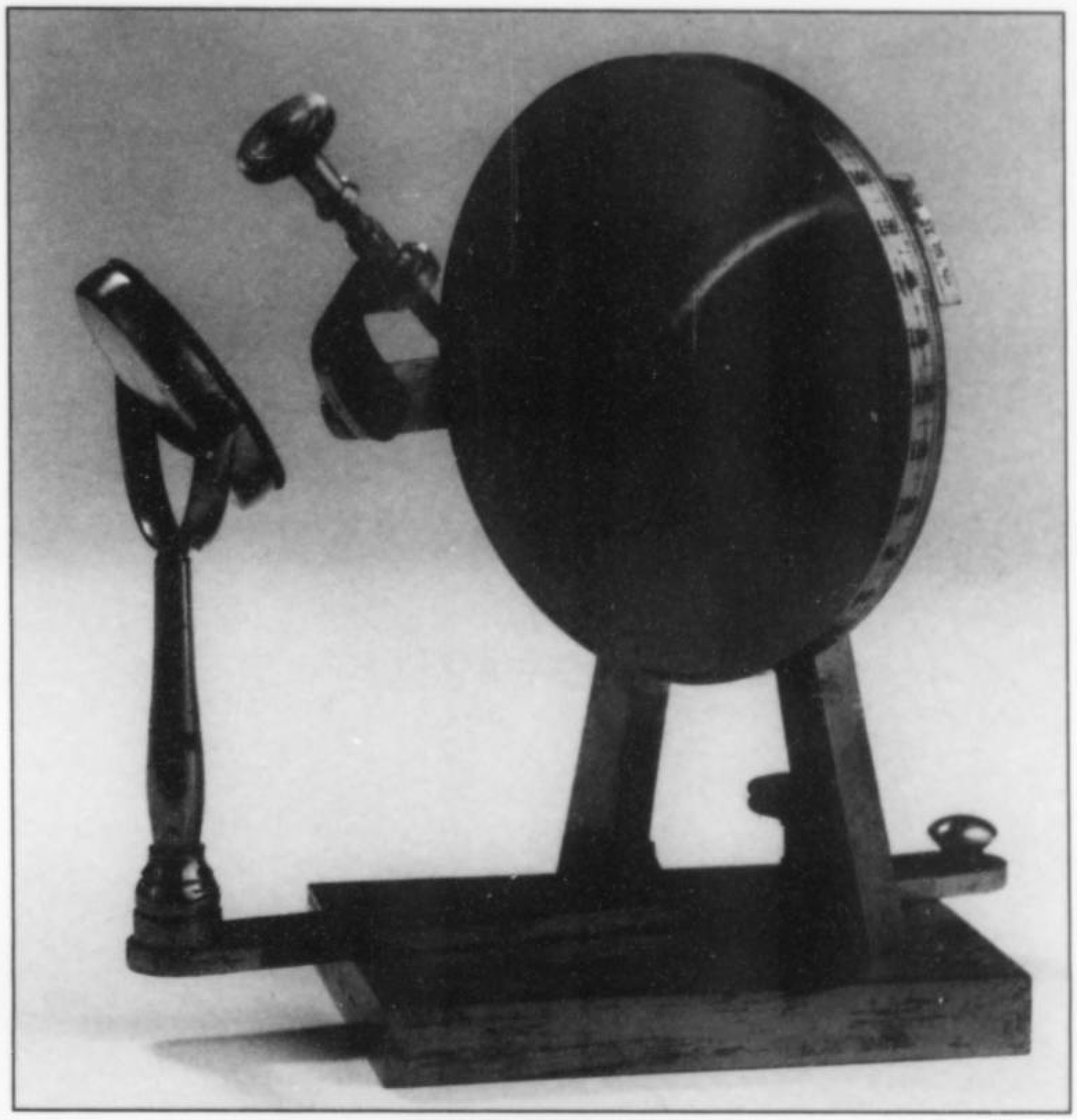


Figure 45. **Reflecting goniometer with nonstandard mirror configuration. Signed: "Duffey, Philadelphia," ca. 1850.**

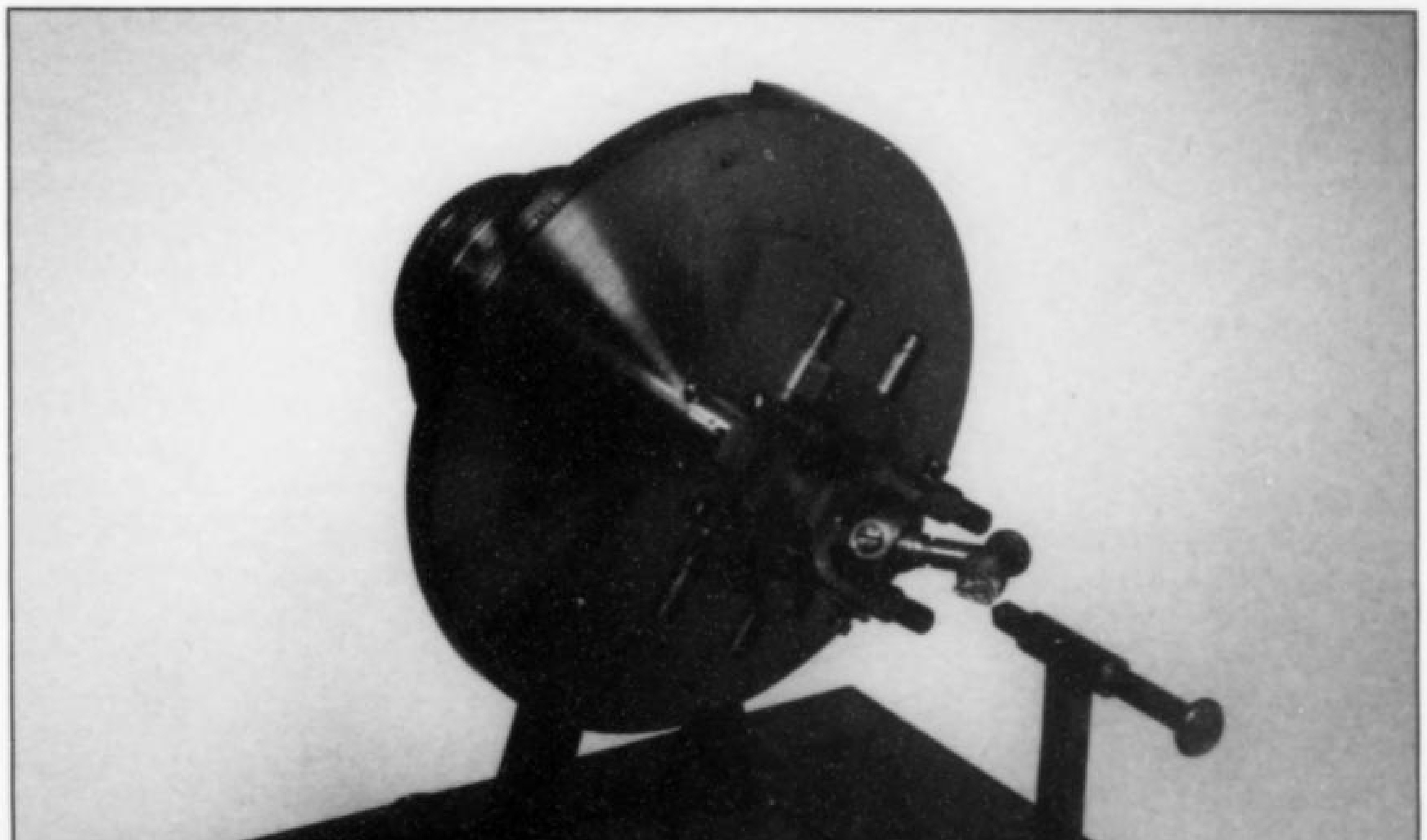


Figure 46. **Reflecting goniometer with unique form of goniometer head and mirror attachment. Signed: "A. Stadler in Linz," ca. 1850. Collection of the Abbey of Kremsmünster, Austria.**

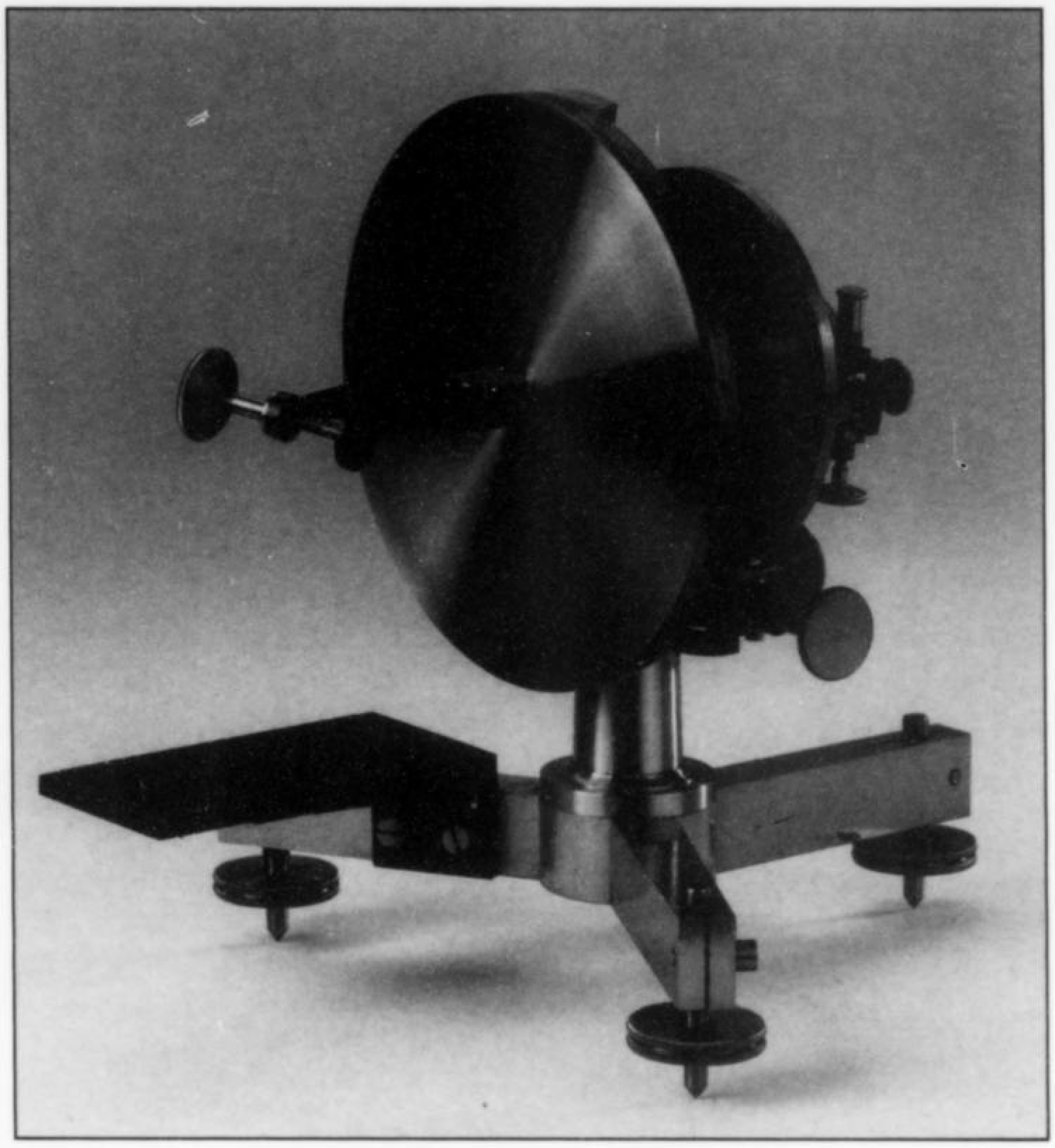


Figure 47. **Reflecting goniometer with mirror attachment; signed "Brunner, Paris," ca. 1900.**

illuminated simultaneously by parallel light rays provided by an artificial light source. To the side of the crystal Mallard placed a tube with a large achromatic double lens, and at the focus of the lens an opaque cap with a horizontal slit. By this means, light from an electric lamp arrived parallel at the crystal and mirror. Because the signal reflected from a crystal face is considerably weaker than that reflected from a mirror, the latter light was purposely weakened by putting a colored glass in front of it.

Most goniometers with mirrors are of the Wollaston type; that is, they have a vertical circle. As already mentioned, however, the measuring technique is workable for circles in any position. Of all surviving goniometers the most common and widespread type is that with a vertical circle and mirror. Early examples of Wollaston goniometers (e.g., those made by W. & S. Jones, London, or by Duffey, Philadelphia) have a round mirror that is not mounted parallel to the circular axis but rather as an extension of it. The mirror is fastened on a vertical column which is mounted on a horizontal bar that is adjustable to a few degrees out of alignment with the circle axis (Fig. 45). The conditions for accurate measurement, mentioned earlier, are not met by this construction; measurement can only be made, as with a Brewster goniometer, with a vertical signal and orientation of the crystal edge. Perhaps a description of this unusual type has been published, but, if so, the publication remains unknown to the author, despite intensive research.

Goniometers built after 1830 meet the measurement conditions (Fig. 46). The rectangular (3 x 5 cm) flat mirrors are mounted in a fixed position, or may be slid in a track parallel to the axis of the 4 to 6-inch circle. Between 1850 and 1880 the French (Dubosc, Pellin or Brunner, for example) particularly preferred to build this type of instrument (Fig. 47). The so-called student goniometers described by **Henry Alexander Miers** (1858–1942) in 1892 and **George Frederic Smith** in 1919 also used this principle of construction. These were manufactured by the firms of J. H. Steward Ltd., London, and Troughton & Simms, New Charlton (Fig. 48). Mallard's instrument, with the mirror directly at the crystal and lighting unit, seems to have been built exclusively by French craftsmen. In Germany, it seems, goniometers with accessory mirrors were rarely manufactured. No goniometer with a horizontal circle and mirror is known to the author, but Mallard illustrated one in 1879, and professor **William Hallowes Miller** (1801–1880) of Cambridge, for whom the currently used crystal indices ("Miller indices") are named, published a description of such a goniometer, manufactured by Troughton & Simms, in 1876. The circle lies horizontally and the vertical mirror is attached to the side. Miller also mentions a collimator, so the importance of the mirror would have been secondary.

MUNCKE'S SIGHTING GONIOMETER

Before discussion of the further development of geometrical crystallography and of other optical accessories for the Wollaston goniometer, a relatively complicated non-stationary goniometer must be mentioned. This goniometer, described by the Heidelberg physics professor **Georg Wilhelm Muncke** (1772–1847) in 1818, utilizes the principle of the double reflection of light. The construction plans mention a round brass holder mounted in a wooden handle that is held in the left hand during measurement (Fig. 49). This holder is conically bored, and the hole within which the crystal is to be mounted is filled with wax. The holder is solidly connected to a cross beam which rests on a 14-cm diameter graduated circle. Contained within is a smaller inner circle held by four spokes and fitted with a vernier and micrometer screw. The latter allows movement of the inner circle in relation to the outer one. Mounted on one of the spokes is a dioptic ruler equipped with

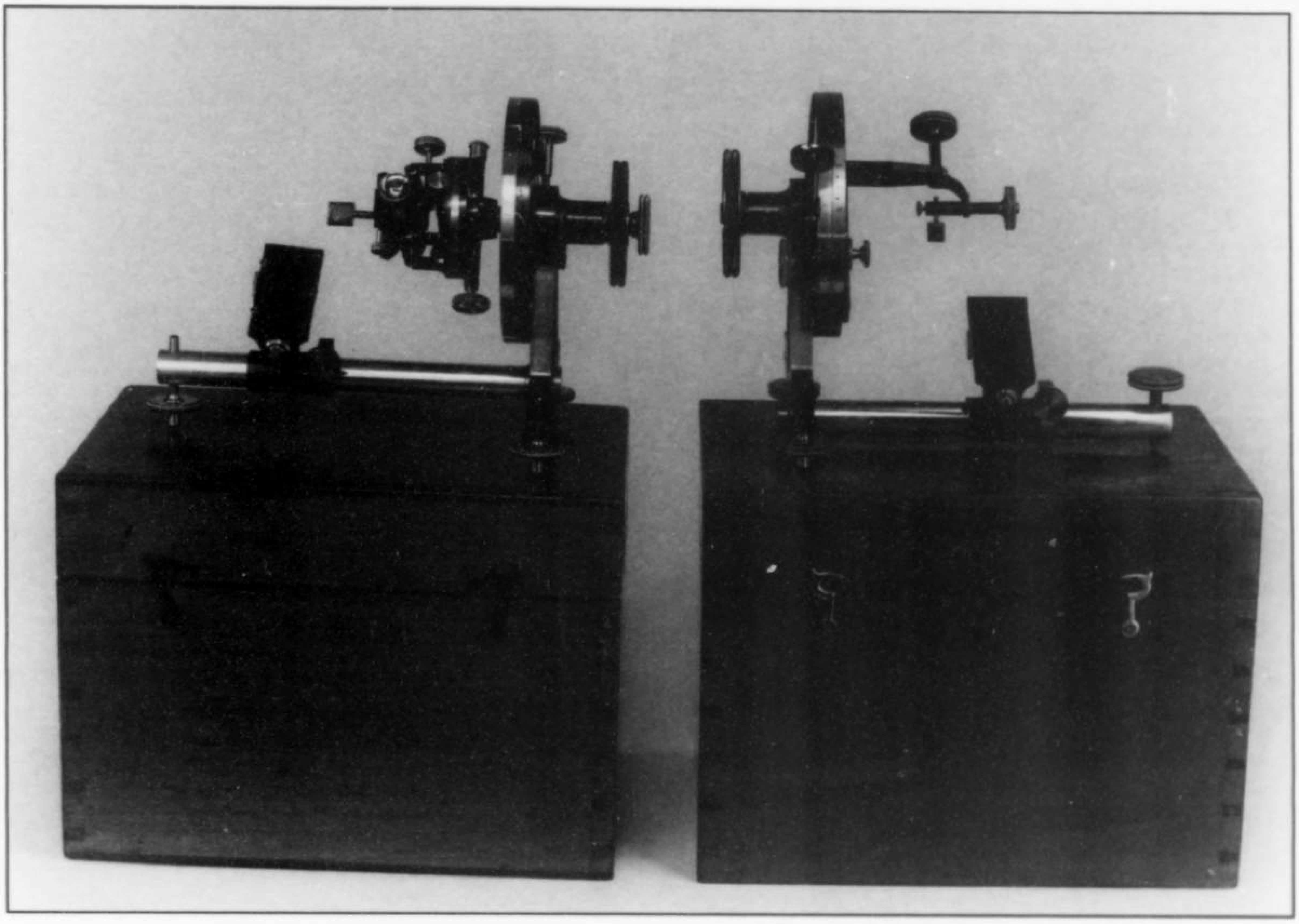


Figure 48. **Two similar reflecting goniometers with differing crystal holder. Both signed: "Troughton & Simms, London," ca. 1900.**

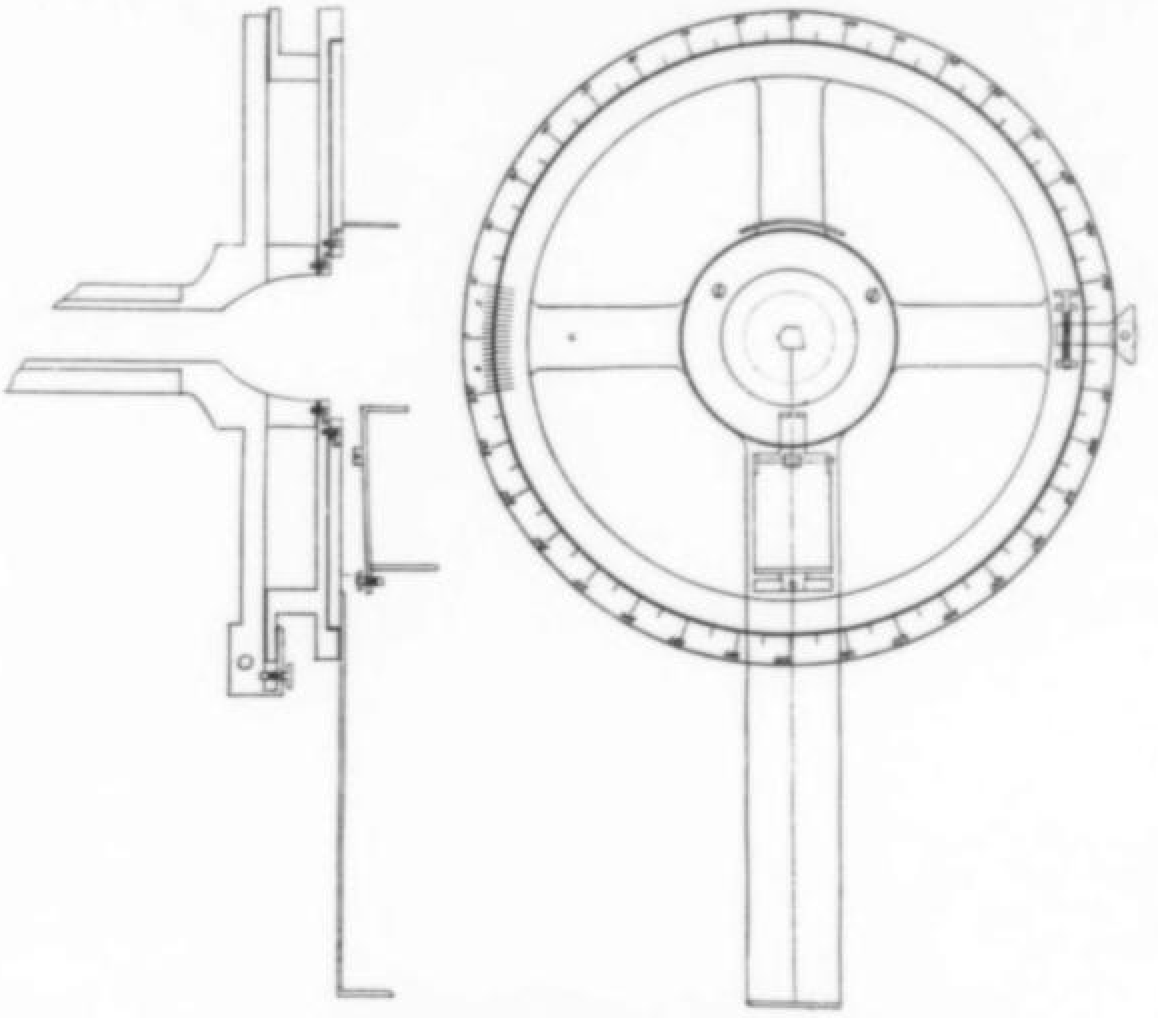


Figure 49. **Sighting goniometer by Muncke (1818).**

an external aperture and an internal vertical silver wire. Above this apparatus four small screws hold a horizontal plate which has mounted on its outer edge a vertical concave mirror whose focal point lies in the center of the axis of the circle. On the inner side of the plate is a vertical slit. It is understood that the hole of the diopter, the silver wire, the slit, the focal point of the concave mirror and the axis of the circle all lie on one plane. On the opposite spoke a blackened shade is mounted to protect the crystal from direct light.

For measurement, the crystal is pressed into the wax, roughly parallel to the axis (precise centering is not necessary). The light of a candle or low sun is focused by the concave mirror and projected through the slit onto a crystal face. If this face lies exactly perpendicular to the incoming signal, a sharp vertical line appears on the crystal face and can be brought into congruence with the dioptric rule. This step is repeated for the second face to determine the crystal angle.

While describing his instrument Muncke gives only simulated exemplary measurements, and refers explicitly to preliminary attempts with a concave and flat mirror. He recommends construction of the instrument by the "best German Artists," and names Georg Reichenbach (1772–1826), Joseph Liebherr (1767–1840) and Theodor Baumann. It is very doubtful that this relatively complex goniometer was ever built.

C. S. WEISS AND FURTHER DEVELOPMENTS

The understanding of the elementary laws of crystallography was significantly advanced by two students of Abraham Gottlob Werner (1749–1817), namely **Christian Samuel Weiss** (1780–1856) and **Friedrich Mohs** (1773–1839). Through his translation of Haüy's *Traité de Minéralogie*, Weiss familiarized himself with Haüy's hypotheses, recognized defects in the work and critically commented on them.

Contrary to Haüy, Weiss dispensed with the investigation of molecular structure and instead defined each crystal face with reference to an imaginary three-axis coordinate system, the axes intercepting the crystal faces at a certain length from the common origin. Nevil Story Maskelyne (1876) commented on Weiss's work:

> *As the originator of the idea, though incomplete, of symmetry in respect to axes as the ruling feature in a crystal, Weiss gave a new standing-point to the science: he designated the crystallographic systems upon this principle, and instituted a mode of crystallographic notation simpler and more easily intelligible than that of Haüy. In this notation we first (1816) have the faces of a crystal referred, not to its external edges for geometrical comparison, but to axes (parallel to certain of these edges) internal to the crystal; while paramentral ratios, as we now term them, were recognized in the relative distances along these axes at which some chosen face would intersect them. Simple coefficients of these axial lengths, or parameters, gave the distances at which any and every other face of the crystal would, if continued, meet the axes. Here, therefore, in asserting the integral character of the numbers representing these coefficients (or indices) belonging to every face of the crystal was the fundamental law of crystallography laid down on a purely geometrical basis.*

Weiss's notations are essentially the reciprocals of the Miller indices. Weiss not only introduced the crystallographic axes but also recognized the vectorial principle of crystal growth as well as the law of zones. A zone defines the sum of all crystal faces parallel to an axis. In his treatise *Uebersichtliche Darstellung der verschiedenen natuerlichen Abteilungen der Krystallisations systeme* (1818), Weiss attempted to establish a system of crystals. It was imperfect in two regards. First, Weiss insisted on a rectangular axis coordinate system and thus could not properly accommodate the monoclinic and triclinic systems. Second, Weiss couldn't free himself from his idea that the axial ratios were derived through the square roots of whole numbers. In 1810 Weiss became professor of mineralogy in the newly established Humboldt University in Berlin. **Gustav Rose** (1798–1873), **Adolph Theodor Kupffer** (b. 1799) and **Franz Ernst Neumann** (1798–1895) were among his numerous students who later became prominent scientists and further developed his ideas.

After Werner's death in 1817, **Friedrich Mohs** (1773–1839) took charge of the mineralogy department in Freiberg. He published his *Elements of Mineralogy* in 1822 and 1824. In this work he proposed a theoretical model similar to Weiss's, which led to charges of plagiarism, but Mohs recognized the oblique axial angles of the monoclinic and triclinic systems. Mohs was supported in his measurements by **Wilhelm Karl Haidinger** (1795–1871) in particular, and after Mohs took a position offered to him in Vienna in 1826, **Karl Friedrich Naumann** (1797–1873) took over Werner's former department in Freiberg. Naumann dealt in detail with crystals with oblique axes, and confirmed Mohs' ideas.

Through the development of more accurate goniometers, Kupffer, Neumann and later Eilhard Mitscherlich partly revised Weiss's theories. With the publication of *Beitraege zur Kristallonomie*, **Franz Ernst Neumann** (1798–1895) followed in the footsteps of Weiss, his teacher and mentor. He showed how the zones and directions could be illustrated in a picture through the use of a special type of spherical projection.

The description of seven crystal systems and 32 crystal classes was first proposed by **Moritz Frankenheim** (1801–1869) in 1826, and shortly thereafter in 1830 by **Johann Friedrich Christian Hessel** (1796–1871). The French naval officer **Auguste Bravais** (1811–1863), in his work of 1849, *Mémoire sur les polyèdres de forme symétrique*, completed the theoretical ideas and analyzed all possibilities of symmetry through reflection and rotation.

MALUS'S GONIOMETER

As already discussed in the section reviewing the elementary principles of measuring with a reflecting goniometer, accurate measurements depend on a constant, unchanged position of the observer's eye, as well as on the parallelism of the graduated circle plane and that of the imaginary plane formed by the signal, the reflecting crystal face and the observer's eye.

Measuring conditions were vastly improved by the introduction of an observation telescope, as the straight line of the signal reflected by the crystal face could be adjusted with a cross hair in the ocular of the telescope. There is a general confusion in the literature with regard to the order of priority and naming of goniometers with telescopes, especially since the reflecting goniometers with vertical circles were in use until about the middle of the 19th century, and instruments with horizontal circles were increasingly built after that. The techniques and principles of measurements are independent of the position of the circle; however, vertical circle instruments have the following faults:

(1) A crystal mounted in wax on a vertical circle can, through its own weight, move out of position, and therefore only small crystals are suitable for measurement.

(2) Through the exclusively downward pressure placed on the conical axis by the relatively heavy goniometer head, the former becomes worn and the rotation becomes eccentric.

(3) Accessory observation devices and signal telescopes cannot be rotated in the area of the goniometer base, and the area of measurement is thereby restricted.

All of these disadvantages can be avoided by the use of a horizontal circle.

Strictly for historical reasons, the introduction of observation telescopes in vertical and horizontal circle goniometers will be described separately: Malus's goniometer first and Mitscherlich's second. But it must be emphasized again that there is no difference in principle between the processes of crystal measurement using any reflecting goniometer.

Without doubt, the French physicist **Etienne Louis Malus** (1775–1812) was the first to describe a goniometer with observation telescope. Malus engaged principally in the study of optics and of the nature and polarity of light. Unfortunately there is no illustration accompanying his short description of the goniometer:

> *Il est composé d'une lunette fixe placée parallelement a un cercle mobile qui est diversé, et qui porte une alidade et des verniers comme le cercle répétiteur.*

Although the description was first published posthumously in 1817, it can be assumed from Arago's footnote that the instrument already existed in Paris on June 30, 1810.

Dominique Francois Jean Arago (1786–1855) asserted in 1817 and again in 1853 that the idea of using the reflection of light to measure angles belonged to the famed physicist **Johann Heinrich Lambert** (1728–1777).

The Malus goniometer has a horizontal circle, and a straightedge, rotatable about the circle axis, on which the crystal is actually mounted. The telescope is mounted on the side of the goniometer, fixed on a support. The axis of the telescope lies parallel to that of the circle plane (i.e., horizontal) and directed at the axis of the circle. The reflected image of a vertical signal is brought into congruence with the cross-hair in the observation scope.

A simple sketch (Fig. 50) that exactly matches Malus's description is first found in an 1816 work by Jean Baptiste Biot (1774–1862). Biot remarked that the instrument was "used" by Mr. Charles. Various 20th century biographies cite **Jacques Alexandre César Charles** (1746–1832) as an inventor of this type of instrument, but they probably used an inaccurate source.

In 1820, **André Jean Francois Marie Brochant de Villiers** (1772–1870) published a sketch of a goniometer almost identical to that of Biot but did not credit it to any one person.

In his *Preisschrift ueber genaue Messungen der Winkel an Kristallen* Kupffer deals in detail with Malus's goniometer and is convinced that it is not as well built as his Wollaston goniometer. Nevertheless he used Malus's method by fastening a telescope mount firmly on the table at the side of his goniometer. In Kupffer's instrument the observation scope is freely movable in any position. By means of a blackened plate initially mounted on the crystal holder prior to actual measurement, Kupffer guarantees parallelism of the plane of the graduated circle and the plane formed by the signal, the reflecting crystal face and the telescope.

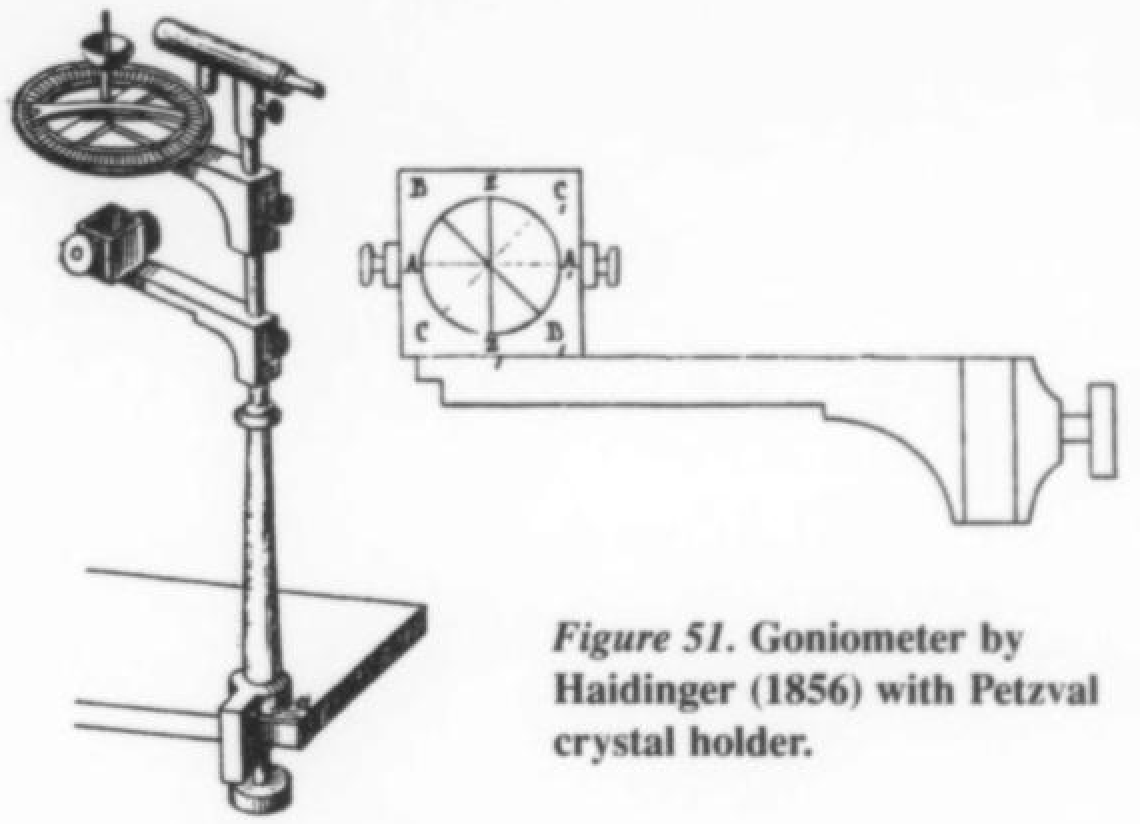


Figure 51. **Goniometer by Haidinger (1856) with Petzval crystal holder.**

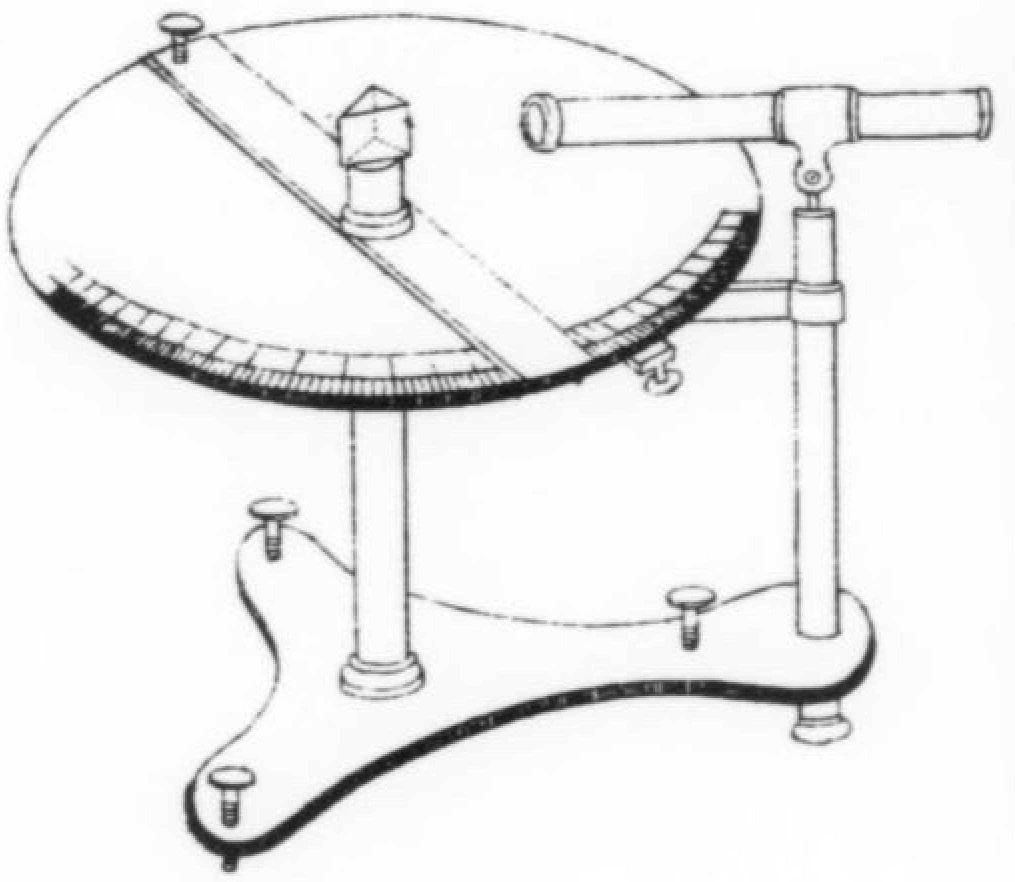


Figure 50. **Malus goniometer with observing telescope (Brochant, 1820).**

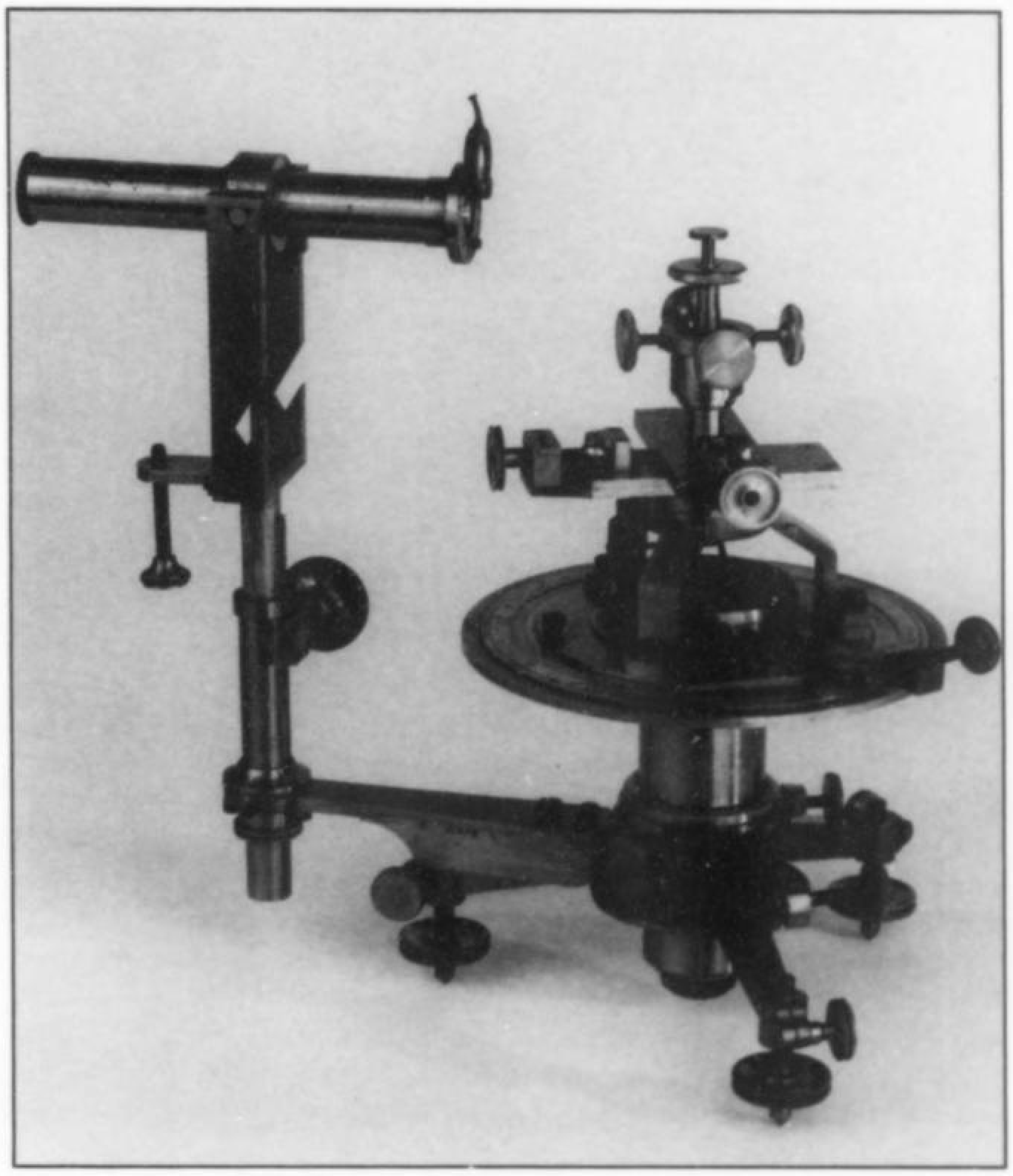


Figure 52. **Malus type goniometer. Unsigned but probably by Breithaupt, Kassel, ca. 1850.**

A very extraordinary method of measuring crystal angles with the use of a theodolite also originates with Malus. He fastened the crystal edge to be measured on a suitable base. At a distance of about 20 to 30 cm the exactly leveled theodolite was set up, and once during the measurement it was moved sideways a few centimeters. In this way the angles of two 1200-meter distant vertical signals in opposite directions and their reflections on the crystal faces were measured. The crystal angles were then computed trigonometrically.

In 1837 **Gustav Suckow** (1803–1867), mineralogy professor at Jena, ordered a similar instrument to be built by the court "Mechanikus" Koerner; however, the telescope is fastened to the alidade and positioned opposite to the vernier. Suckow dispensed entirely with the reflection of a signal and sighted the crystal edge in question with the aid of the telescope; from his description it is not possible to ascertain if the latter was equipped with a reticle.

Wilhelm Karl Haidinger's (1795–1870) "optical mineralogical screw-on goniometer" of 1856 is identical in principle to that of Malus, but it can be converted to a universal apparatus so that it can also be used to determine indices of refraction as well as to measure the position of optical axes. Haidinger mounted his crystal on a holder designed in 1846 by the Viennese professor **Joseph (?) Petzval** (1807–1891). This holder consisted mainly of two hollow hemispheres that could be moved within another, making precise adjustment possible (Fig. 51).

Malus's goniometer was constructed by the Fortin company in Paris, but the history of this prototype is unknown to the author. Horizontal-circle goniometers equipped with an added observation

Figure 53. **Eilhard Mitscherlich (1794–1863), famous chemist and mineralogist.**

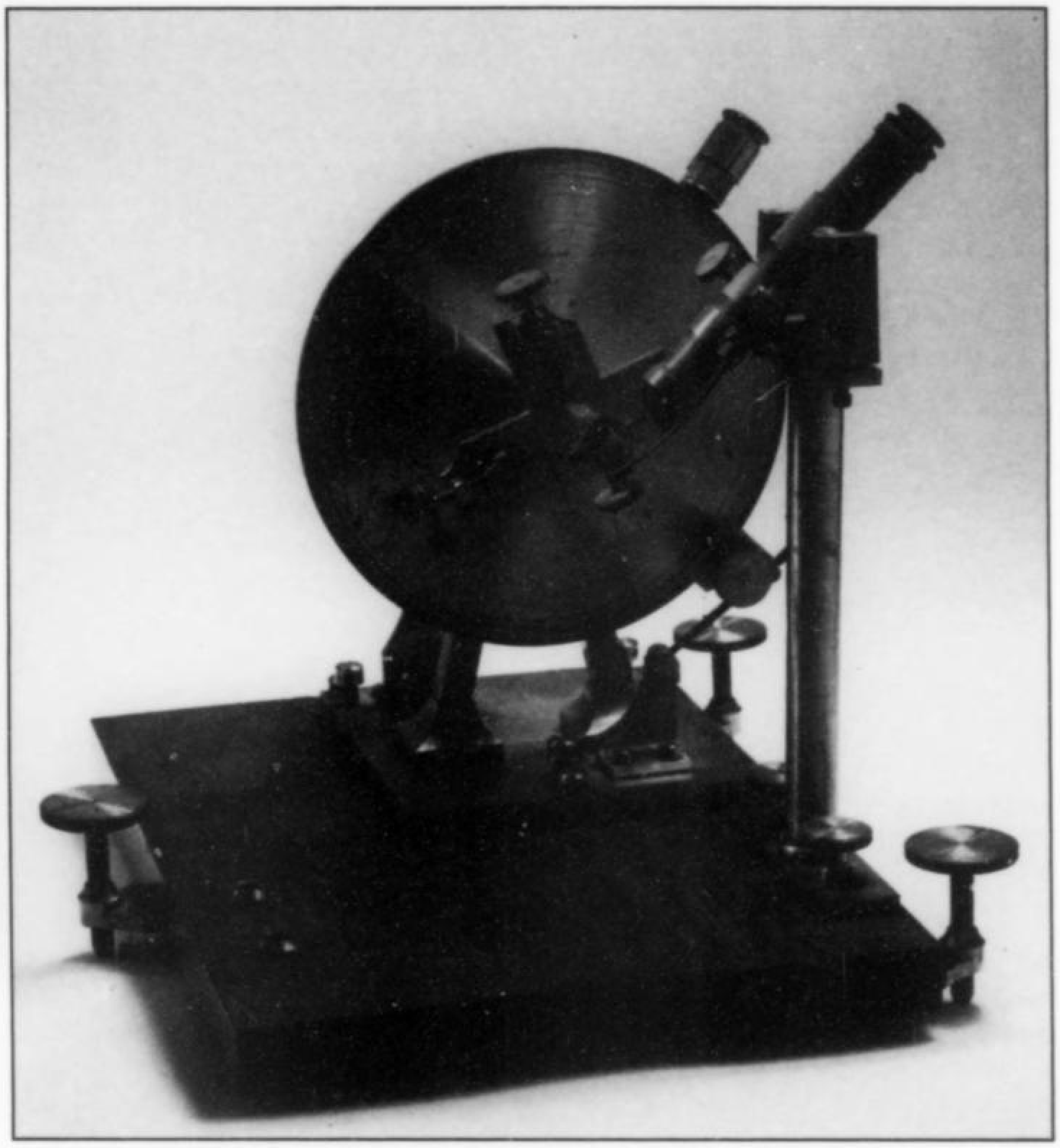


Figure 54. **Original goniometer of Mitscherlich, signed: "Pistor & Schiek, Berlin," ca. 1830. Courtesy of Deutsches Museum, Munich.**

scope seem to be extraordinarily rare. The author knows of only two, which are identical and were made by the same person. They are unsigned, but either Studer in Freiberg or Breithaupt in Kassel may have been the maker (Fig. 52).

MITSCHERLICH'S GONIOMETER

The measurement principles of the goniometer constructed by **Eilhard Mitscherlich** (1794–1863) (Fig. 52) are the same as those of Malus; however, the telescope is directed at the horizontal axis of the vertical circle. In literature, the term "Mitscherlich goniometer" mostly refers to a costly, extremely well-built instrument that could make very precise measurements. Sometimes the designation also includes instruments with observation as well as signal scopes. Mitscherlich's sketches of his goniometer do not show a signal scope, but he mentions the possibility of a supplementary signal scope, and his original surviving instrument suggests that a second brass support, now absent, was attached to the wooden base (Fig. 54).

According to Rose (1864), Mitscherlich ordered the construction of two similar instruments, of which the older had no signal telescope but the newer did. Independent of the presence of one or two telescopes, a characteristic construction feature that can be found on all Mitscherlich goniometers is that the telescope support(s) are always solidly mounted on the base plate, unattached to the circle and not movable around it.

In 1822, Mitscherlich was appointed professor of chemistry at the University of Berlin. He is recognized as the discoverer of *isomorphism*, *bimorphism* and *polymorphism* in crystals, and he established the foundation of a chemical-crystallographic mineral system. He recognized that potassium phosphate crystallized in the same form as potassium arsenate. With Gustav Rose, he was able to prove that the same laws applied to other salts.

Only in the 20th century, through the use of X-ray structure analysis, has it been realized that the atomic lattice types, ion radii and equality of formula types are requirements for the phenomenon of mixed crystal formation of two salts. On the other hand, Mitscherlich observed that chemically identical substances such as calcite and aragonite could take different crystal forms. With the example of rhombic and monoclinic sulfur he was able to challenge Haüy's theory that the crystal angles for any substance were a constant characteristic.

Mitscherlich also worked with the unequal expansion of crystal angles at different temperatures. By chance he ascertained that his series of measurements on Iceland spar varied by about 20″, depending upon whether the determinations were made in the morning or afternoon, in the presence or absence of the sun, and over a temperature difference of 3° Reaumur. He extended these investigations to other minerals and constructed a special heatable mercury bath from which only one crystal face was exposed for measurement.

It was easily understood that a normal Wollaston goniometer would be inadequate for precision measurements of this sort. Thus, according to G. Rose (1864), in 1823 Mitscherlich ordered the Pistor company in Berlin to construct a special vertical-circle goniometer with an 8-inch diameter circle whose circumference was divided into 6″ increments. As with Studer's goniometer, the reading could be taken from four different verniers and the axis moved with great precision by means of micrometer screws. The orientation and centering apparatus was also that suggested by Studer. The viewing telescope was mounted on a support such that its axis could only be moved vertically. The telescope ocular was equipped with a cross-hair reticle, and the optics provided a 20X magnification. The resulting light was so reduced that the measurement was restricted to highly reflective crystals such as quartz and calcite. Mitscherlich used the goniometer almost exclusively for the research he published in *About the expansion of crystallized bodies through warmth* (1837). The accuracy of these readings (3 to 4′) indicates that he read all four verniers and repeated the investigations ten times.

In 1864 Rose wrote:

> *The large goniometer that Mitscherlich used in his experiments was too awkward and costly to be recommended to mineralogists for precise crystal measurement. He therefore thought to construct a simpler instrument for general use. The divided circle was reduced in size and the divisions only made to 1/3rd of a degree, so that the vernier was only readable to a half minute. The images reflected from the crystal faces were observed through a telescope with only slight magnification, up to 3X.*

Mitscherlich first published his treatise *About a Goniometer* in 1843, but indicated that he had already worked on it for 16 years, that is, since 1827. The instrument was made by Pistor and some parts by Oertling. It is to be assumed that it was similar to the older instrument in most components. The 6-inch circle was only furnished with two verniers and the accuracy indicated to be less than 6′. The telescope support was movable parallel to the circle axis. A magnifying lens that could be rotated out of the way served for focusing the reflection and for exactly controlling the adjustment of the crystal edge. Mitscherlich describes a signal using an object at least 100 feet distant; however, he further states:

> *The object which image one sees must be sharply defined and well illuminated, a cross hair reticle in a telescope is suitable, which one turns towards the crystal. As Babinet and Rudberg suggested, one places a light in front of the ocular, whereby the cross hair is illuminated, and, if placed in the focal point of the objective, acts as an infinitely distant object during observation.*

The signal telescope, also known as a *collimator*, is located opposite to the observation telescope. The axes of both telescopes form a plane parallel to that of the circle. The objective of the collimator is directed to the crystal edge. A cross-hair reticle serves as a signal and the exiting light rendered parallel by a suitable lens system. With the use of two telescopes the focal point of both systems must be adjusted to infinity so that the reticle cross-hair is thereby observed as an infinitely distant signal. It is easily understandable that the congruence of two hairlines makes extremely precise measurements possible. Since the lens system significantly reduces the reflection on the crystal, the cross-hair reticle in the signal telescope can be replaced by a slit that is illuminated by a lamp placed behind it, and the signal light made parallel by a collector lens before exiting the collimator tube. To reduce reflections from the artificial light source falling directly on the crystal face a suitable shade is used.

Forty years later, **Aristide Brezina** (1848–1909), director of the Natural History Museum in Vienna, described *The new goniometer of the Imperial and Royal Geological Survey* (1884). This was in large part the same as that of Mitscherlich and was equipped with two telescopes. A supplementary holder made possible the measurement of crystals unstable in air. Brezina appeared to be

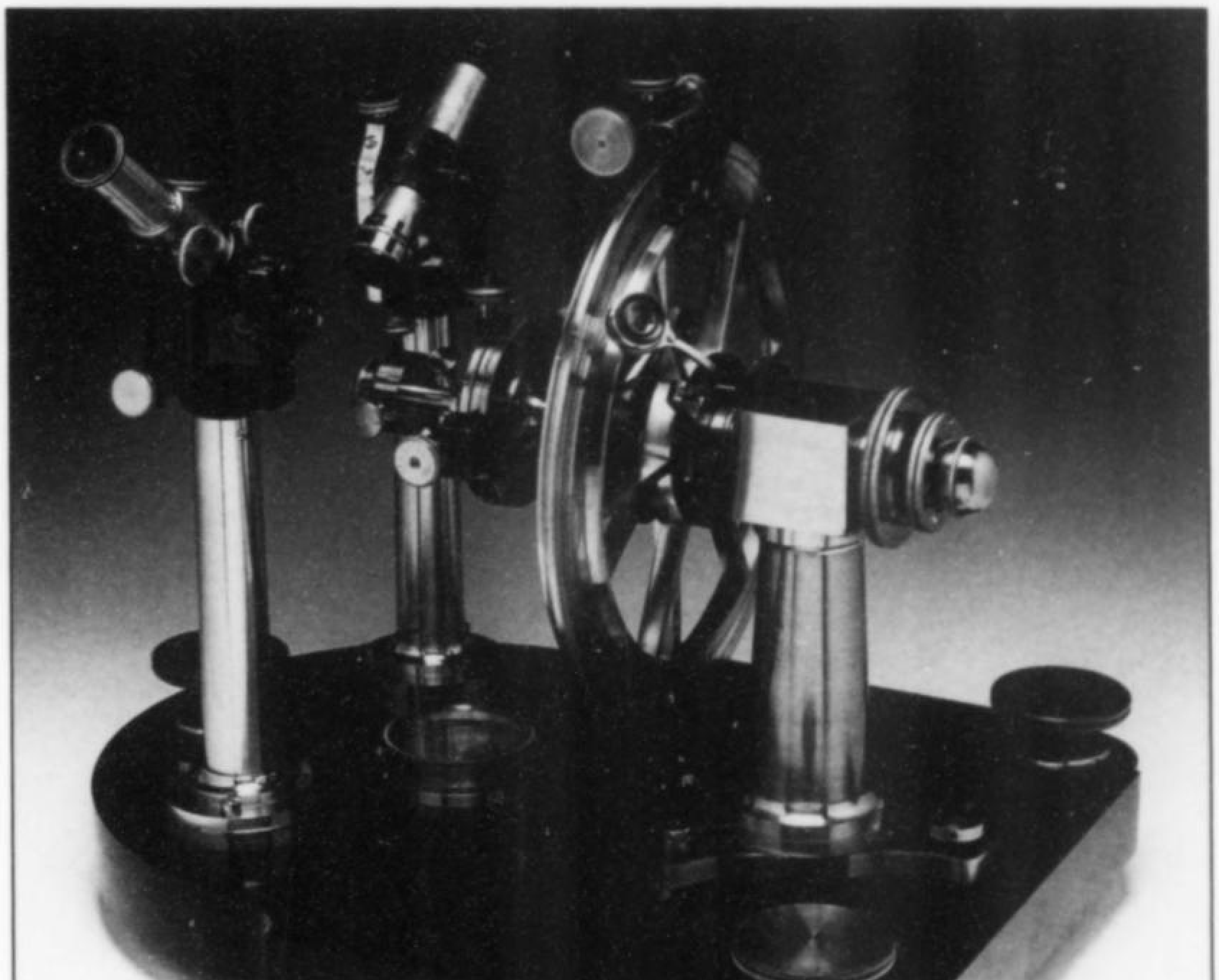
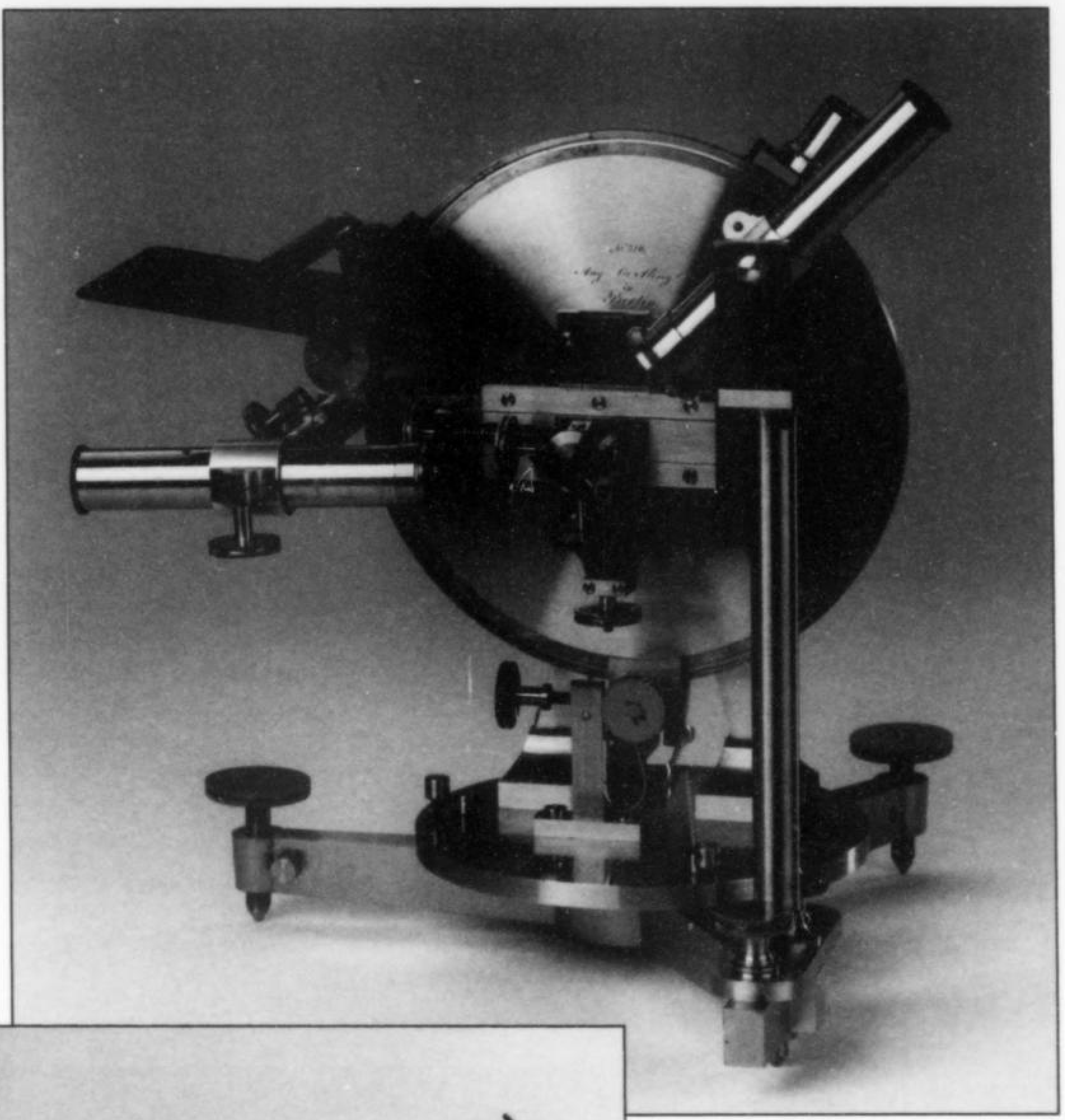


Figure 55. **Goniometer for precision measurements with telescope and collimator tubes. Signed: "F. W. Breithaupt, Cassel," ca. 1860. H. Obodda collection.**

Figure 56. **Mitscherlich-type goniometer with signal slit and/or collimator to be attached to vernier circle. Signed: "Aug. Oertling, Berlin," ca. 1860.**



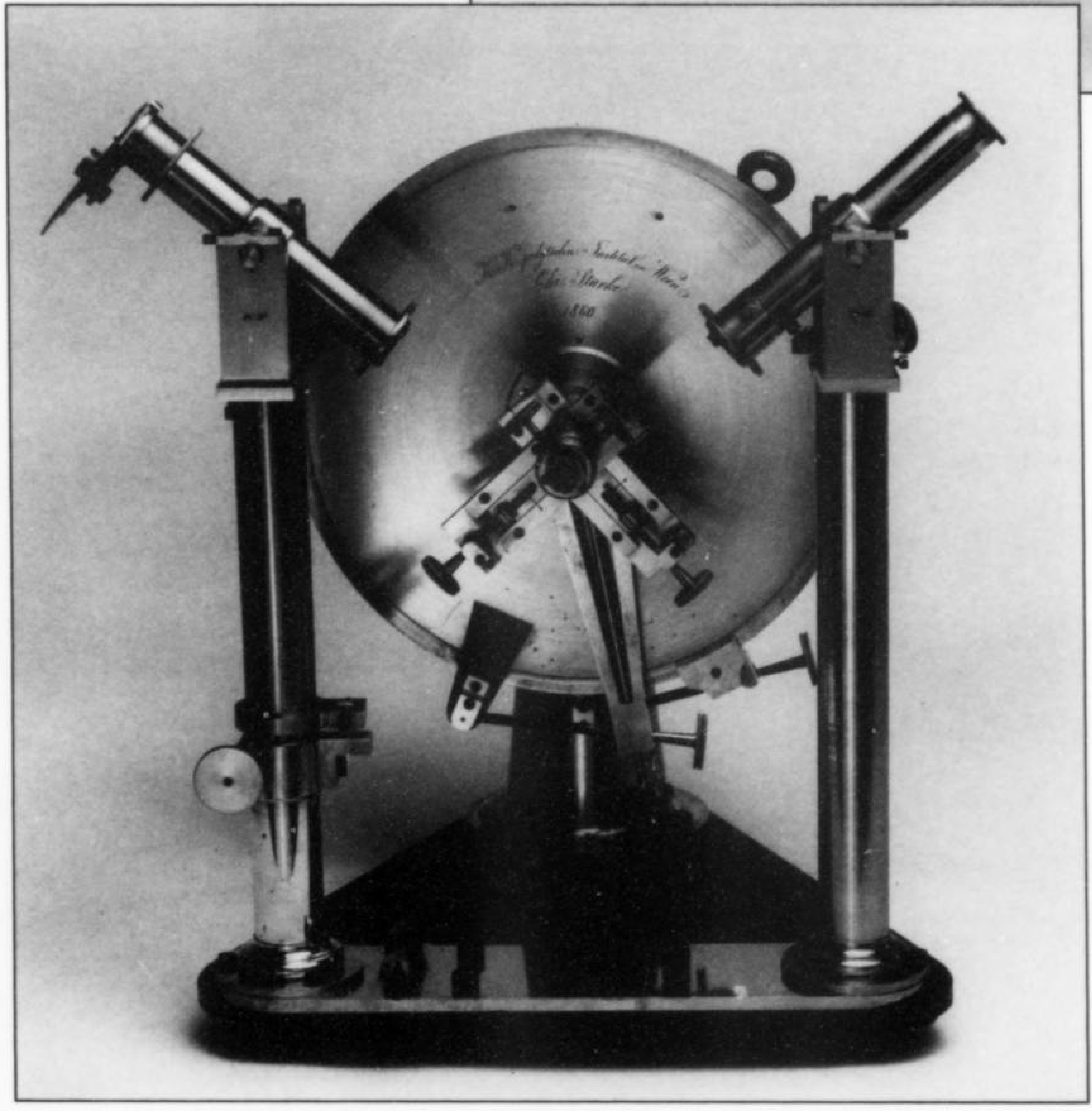


Figure 57. **Large Mitscherlich-type goniometer. Signed: "K. k. polytechn. Institut in Wien, (Vienna), Chr. Starke," dated 1860.**

interested in the history of the development of the goniometer, and we can thank him for a comprehensive bibliography on the subject. Brezina's original goniometer is still preserved at the Geological Survey in Vienna.

As already mentioned, Mitscherlich's original goniometer, now in the Deutsches Museum in Munich, had two screw holes for the support of a signal scope which was placed opposite to the observation scope. About Pistor's workshop, Rose (1864) wrote "it is the 'nursery' of all remaining mechanical workshops, such as those of Schiek, Oertling, Kleiner, Martins, and Halske, which were established, one after the other, in Berlin. In fact it appears that German and Austrian makers were predominantly, if not exclusively, responsible for the manufacture of this costly goniometer. As early as 1829, Pistor & Schiek offered a reflection goniometer made to Professor Mitscherlich's specifications with an 8-inch silver circle divided to 10″ indications, with microscope and telescope mounted on a marble base, for 250 Gulden. An identical instrument was offered by Breithaupt in Cassel in 1829, the price being 230 Reichsthaler (Fig. 55). The "microscopes" mentioned in the catalog text were accessory telescopes mounted in the extension of the vertical axis, which served to verify the exact centering and adjustment of the crystal edge; this accessory was used later on Hirschwald's microscope goniometer.

Oertling of Berlin offered a black plate with a thin slit that could be mounted on the graduated circle, as well as a black mirror that could be alternatively attached to the base plate (Fig. 56).

In 1860, Meyerstein in Göttingen offered a goniometer with a diameter of 6 inches with one telescope for 125 Thaler and with two telescopes for 140 Thaler. The construction displays a unique feature: aligned with the circle axis there is a fold-out knife edge that could be put in contact with the crystal edge for orientation.

Krantz's catalog of 1853 listed a large Mitscherlich goniometer for 40 pounds. Bartels (1891) and Carl Dietrich (1899) of Göttingen listed a goniometer with a 17-cm diameter and one telescope on a marble base for 375 Marks, and with two telescopes for 415 Marks, in their catalogs.

Further makers of Mitscherlich goniometers who have become known to the author are Max Wolz in Bonn, C. Gerhardt in Cologne and Georg Starke in Vienna (Fig. 57). One can only speculate on the reason why the Germans had a virtual monopoly on the construction of Mitscherlich goniometers.

The construction details of the precision models described above were later used for smaller, simplified versions. Klein (1876) indicated a market value of 150 Marks. Boehm & Wiedemann offered a goniometer of this type for 250 Marks (Fig. 59). Linhof in Munich asked a price of 150 Marks, and a similar model by Fuess in Berlin sold for 280 Marks. Among the others, instruments by Oertling and Boehm & Wiedemann are to be found in museums, and, rarely, are offered for sale in specialized shops.

RIESE'S AND BABINET'S GONIOMETERS

In the literature the French physicist **Jacques Babinet** (1794–1872) is given the honor of being the first to introduce the collimator tube with retention of the observation telescope (Haidinger, 1845; Dufrénoy, 1856; Klockmann, 1922). Babinet (1839) constructed his goniometer mainly to be used as a refractometer to determine indices of refraction. It was meant to be hand-held or set up horizontally (Fig. 58). The observation telescope is fastened firmly to the circle while the signal telescope is movable about the circle axis, with a tangent screw facilitating the rotation. A small, also rotatable table in the center of the circle serves as a crystal holder; no orientation and centering mechanism was added. Both telescopes are equipped with cross-hair reticles. The collimator tube is turned until the reflected image of the signal is successively brought into congruence with the cross-hair reticle in the observation telescope. The supplemental angle can be read off directly. This construction and measuring technique became the model for all modern (one-circle) reflecting goniometers.

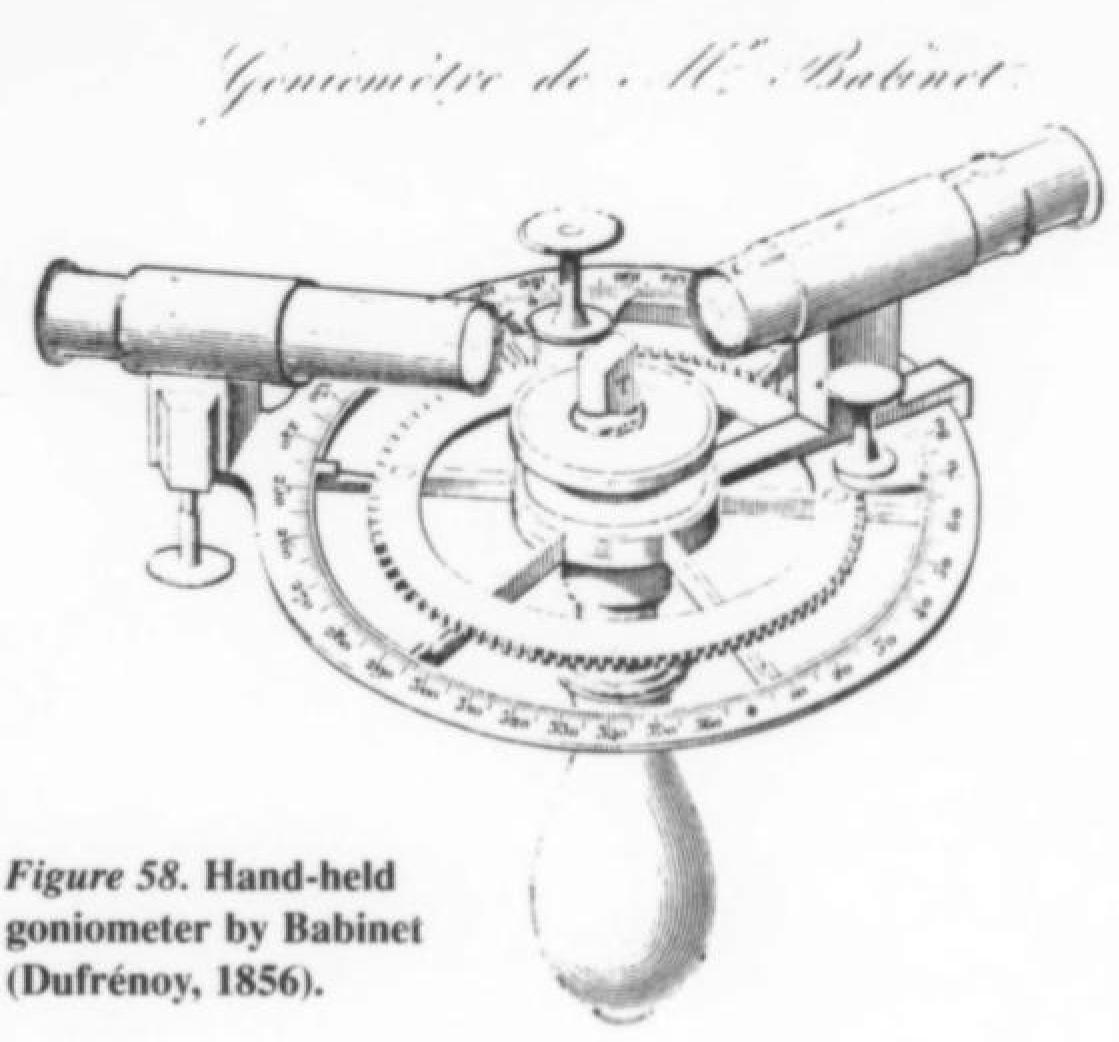


***Figure 58.* Hand-held goniometer by Babinet (Dufrénoy, 1856).**

The author is not familiar with the maker or location of any original Babinet goniometers. Krantz's catalog of 1853 lists a Babinet goniometer for 8 pounds 8 shillings.

Friedrich Christian von Riese (1790–1868) published his very precise and comprehensive (86-page) *Suggestions for a new goniometer* (1829), with exact construction plans, as early as 10 years before Babinet. In his foreword, Riese said that he had given his teacher, the Göttingen mineralogist Johann Friedrich Hausmann (1782–1859), a small treatise about his theories "quite a few years" before; it had dealt, he continues, with a still incomplete design for an instrument. It may therefore be inferred that, at least at the time of publication, the instrument had still not been built. Because of the extreme complexity of construction it would not be surprising if it were never built. In principle this goniometer employs an 8-inch vertical circle with four verniers. Two telescopes with cross-hair reticles can be turned singly or in tandem about the circle axis, as could the innermost axis, which was furnished with a very complicated crystal holder (Fig. 60). Riese described measuring techniques using either a mirror or one or two telescopes. The circle could also be positioned horizontally with the help of an accessory apparatus. Although this construction was probably never realized, the date of its suggestion, clearly earlier than for that of Babinet, gives priority of invention to Riese.

The Swedish physics professor **Fredrik Rudberg**'s (1800–1839) *Foerslag till en foerbaettred reflexions-goniometer* (1827) predates Babinet's publication as well. In his theoretical considerations Rudberg refers primarily to the sources of error in, and limits of the usefulness of, the Wollaston and Malus goniometers. He proposed placing two broad objective glasses (concave lenses) in the focal point of the cross-hairs. In Rudberg's sketches the optical systems are still not included in the telescope tubes. Edward Hoppe summed up in his 1926 *History of Optics*: "in contrast, in Rudberg's goniometer the crystal is mounted firmly so that the object is reflected from both faces simultaneously while the observation scope is movable and the angle between the two reflected rays can be read directly."

Figure 59. **Simple goniometer signed: "Böhm & Wiedemann, München," ca. 1880.**

From 1862 to 1864 **Viktor von Lang** (1838–1921), physics professor in Vienna, was an assistant to professor **Nevil Story Maskelyne** (1823–1911), Keeper of Minerals in the mineralogical department of the Natural History Museum in London. During this time he designed a goniometer which was constructed by the Powell & Lealand company. His work, *Construction of the Reflecting Goniometer,* first appeared in 1876. The instrument was also suitable for determining refractive indices and optic axis angles. The construction plans were for the most part similar to those for a Mitscherlich goniometer with two telescopes. For the first time the adjusting device did not consist of two hollow nested hemispheres, but of two perpendicular attached geared segmented arcs that could be adjusted through screw mechanisms. Also new is that the instrument could be altered and the angled observation scope support screwed directly to the circle and rotated with it. An identical instrument was built by the Copenhagen company of E. Jüngers. A few Lang goniometers survive, mostly in Scandinavian universities (Fig. 61).

A version of the already mentioned Wollaston goniometer designed by Miers was manufactured by the Troughton & Simms company and was similar to that of Lang. The two telescopes, however, are not directly connected to the circle, but are on separate movable arc supports arranged parallel to the circle plane.

FUESS AND HIS GONIOMETERS

Horizontal-circle goniometers predominated by the middle of the 19th century. One noteworthy example is the "spectral apparatus and reflective goniometer" (1866) of **Carl Cäsar Börsch** (1817–1890), a mathematician and geodesist from Kassel. This instrument was sold by the Breithaupt company in Kassel for the price of 120 Thalers.

In 1859 **Robert Wilhelm Bunsen** (1811–1899) developed spectral analysis. The construction of a spectrometer is in many ways similar to that of a goniometer, the most important difference being that the central crystal holder is replaced by a small table holding a glass prism, so that an interchange can easily be made. The instrument of Börsch & Breithaupt can be regarded as the precursor of the exceedingly successful model series made by the Fuess company in Berlin.

Figure 61. **Mitscherlich-type goniometer, signed: "E. Jünger's Mekaniske Etablissement i Kiöbenhavn," purchased in 1878. University of Innsbruck collection.**

From the time of the establishment of the German Reich in 1871 to the start of World War I, German precision mechanics and optics experienced an unexpected upswing. The close connection between science and technology resulted in enormous mutual intellectual ferment. The petrographic microscopes and measuring apparatuses for mineralogy and crystallography built by the precision mechanic **Rudolf Fuess** (1838–1917) achieved world-wide fame. The complete spectrum of apparatuses for these sciences is covered in his 158-page special catalog *Mineralogical and Crystallographic Instruments and Accessories* issued in 1913–1914. Because of their usefulness and accuracy Fuess's goniometers dominated the market and were almost without competition for nearly 50 years. The Model II, especially, seems to have been mass-

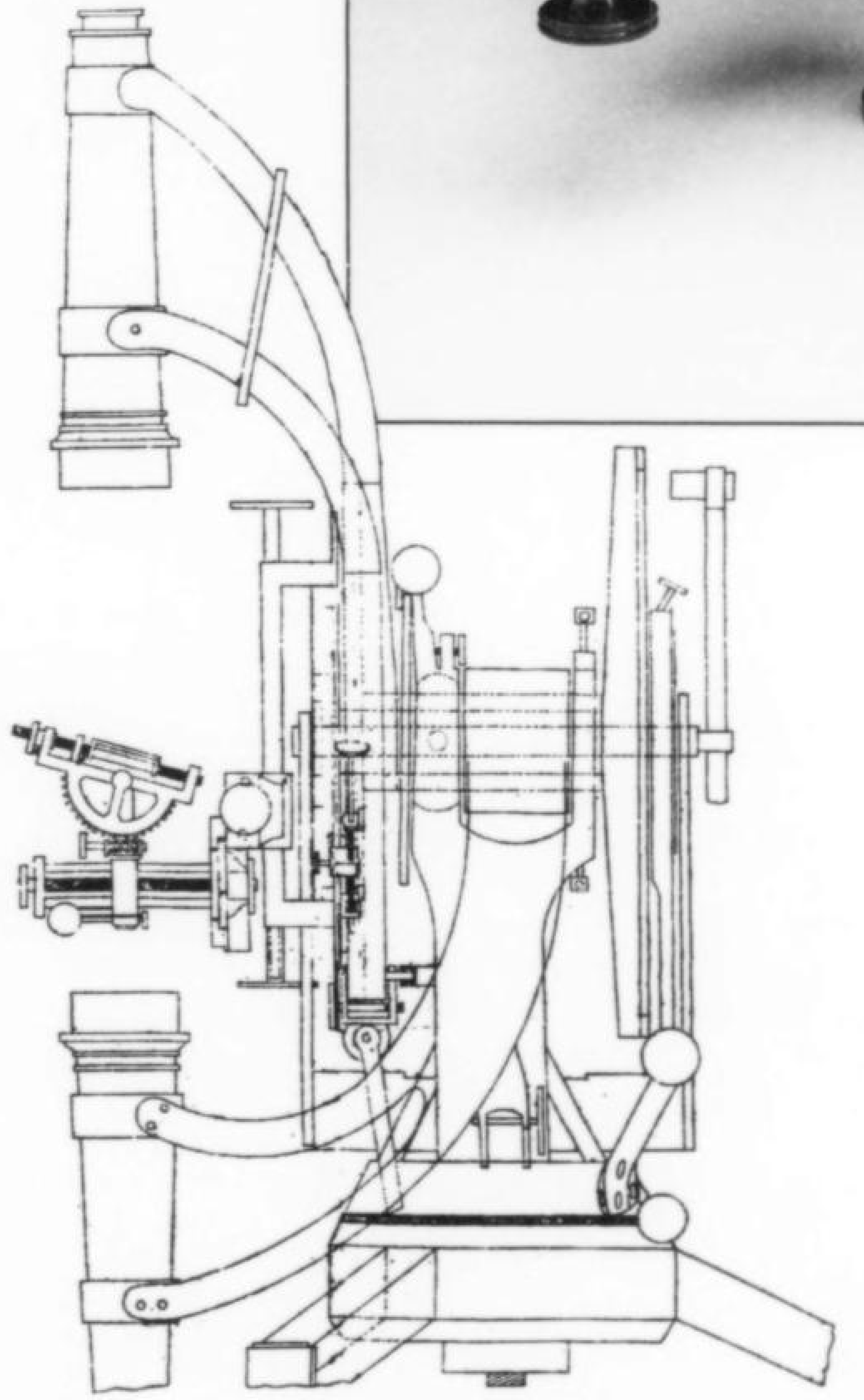


Figure 60. **Construction details of the Riese (1829) goniometer, probably never built.**

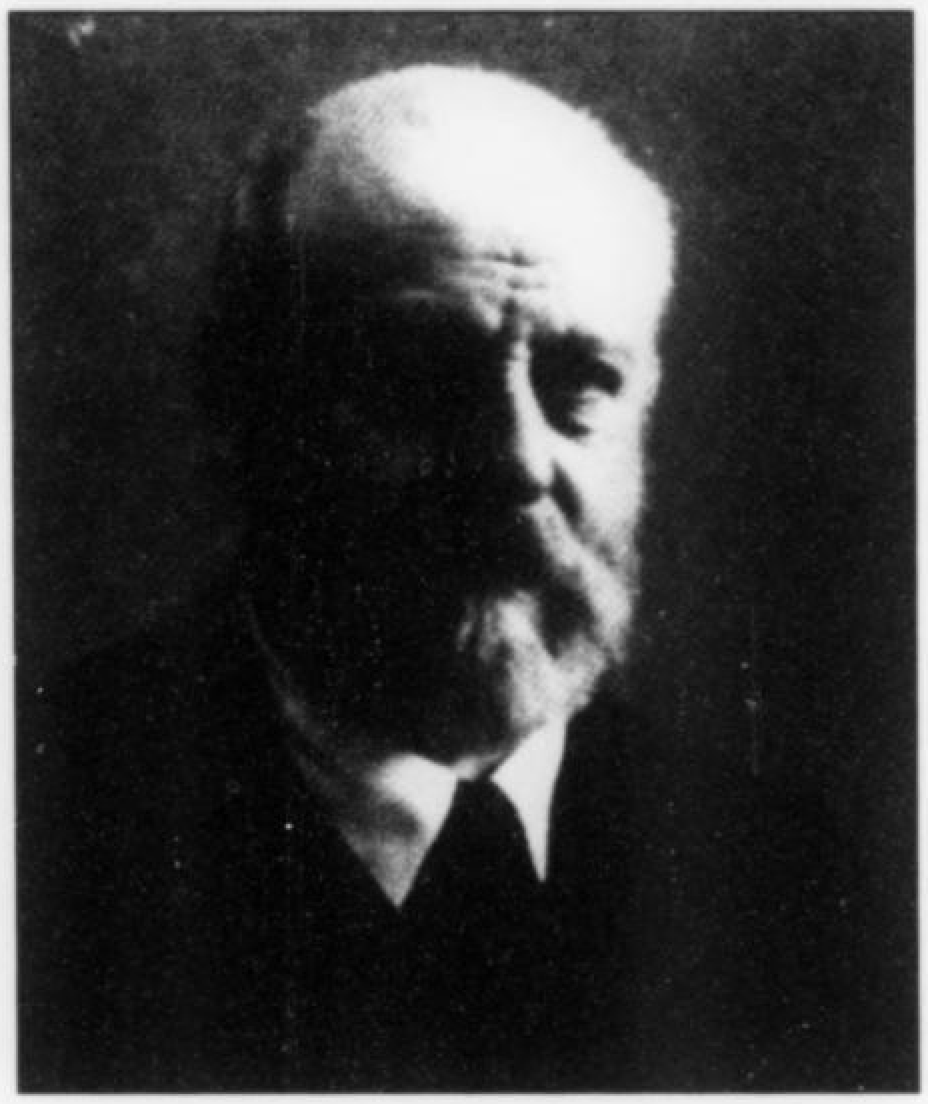


Figure 62. **Rudolf Fuess (1838–1917). His workshop dominated the market for mineralogical and crystallographical instruments between 1880 to 1930. The company catalog lists several hundred instruments and attachments for every conceivable purpose.**

Figure 63. **Paul Groth (1843–1927), mentor of R. Fuess and one of the fathers of modern crystallography and chemical mineralogy.**

produced. If one judges by the numbers of existing reflective goniometers, it would seem that the Fuess company manufactured more instruments than all of the other makers combined. It is therefore worthwhile to elaborate on the outstanding personality of Rudolf Fuess, and on his company, with its unique, highly specialized instruments, since almost no information has formerly been published on this subject.

Rudolf Fuess (Fig. 62) was born on September 28, 1838 in Moringen. After finishing school he began his mechanics apprenticeship with Hermann Pfaff in nearby Göttingen and with Hugo Schröder in Hamburg. Beginning in 1859 Fuess did special order work in Berlin, and in 1865 he opened an independent workshop at Mauerstraße 84. Economic success followed, and in 1870 the workshop moved to Wassertorstraße 46. During this time **Paul Heinrich Groth** (1843–1927) (Fig. 63), "the father of modern crystallography," must have become aware of the young mechanic. Groth was an instructor of mineralogy at the University of Berlin before he took over a professorship in Strassburg. This contact with Groth was of great importance to Fuess, especially in determining the direction his new company would take.

In 1871 Groth commissioned the construction of a "crystal-optic universal apparatus" and wrote "in Mr. Fuess I was fortunate to find an artist who was not only able to build the apparatus but also simplify and improve individual components thereof."

The company achieved particular success in the making of petrographic thin sections, of which the most comprehensive collections contained a thousand rock types. Fuess also recognized the market potential for stone saws and cutting machines with which the institutes could make their own thin sections.

The manufacture of mineralogical instruments and related equipment put the company on a solid economic basis, so that it could move to larger quarters at Jakobstrasse 108. Here there were already five mechanics' helpers, two opticians and two apprentices employed. In cooperation with Professor **Harry Rosenbusch** (1836–1914), the first completely equipped polarizing microscope was built in 1875–1876. It distinguishes itself in that the tube could be centered and the stage rotated, and the position of both Nicol prisms could be fixed by means of a clamping apparatus. The manufacture of polarizing microscopes remained a main occupation of Rudolf Fuess, culminating in 1929 with the fabrication of a theodolite microscope after Evgraf Fedorov (1853–1919); this was a marvel of microscope construction.

Fuess developed his most important goniometers between 1873 and 1879. At the Berlin Industrial Exhibition of 1879, his Models I and II, as well as his microscope- and lever-arm goniometers, demonstrated the quality of his workshop. These instruments were described in detail by Theodor Liebisch (1879); however, they were not contained in the 1873 catalog.

Schoof and Scheel (1919) observed "thereby it must be especially considered that during this period of development [Fuess] was manager, designer, draftsman and works director, all in one person." After the purchase of Greiner & Geissler, glassblowers, in 1877, the company increasingly manufactured meteorological, geodetic and hydrographic instruments, as well as spectrometers and heliostats.

In August of 1892 the company was moved to Düntherstrasse 8, and in 1912 to Florastrasse 3 in Steglitz near Berlin. Today this district is a southern suburb of Berlin. After 1892 the instruments were signed "R. Fuess Steglitz."

Instruments for new fields of work were increasingly made, especially for the developing field of aviation; binoculars and range finders were also produced in large quantities. Rudolf Fuess transferred his life's work to his son Paul in 1913, and died in Steglitz on November 21, 1917. Paul Fuess continued the business, and in 1936 opened a branch in Potsdam, where predominantly aviation instruments were made. At its apex, with production swelled by armament production, the R. Fuess company had 3,000 employees. After destruction and dismantling, the business came to

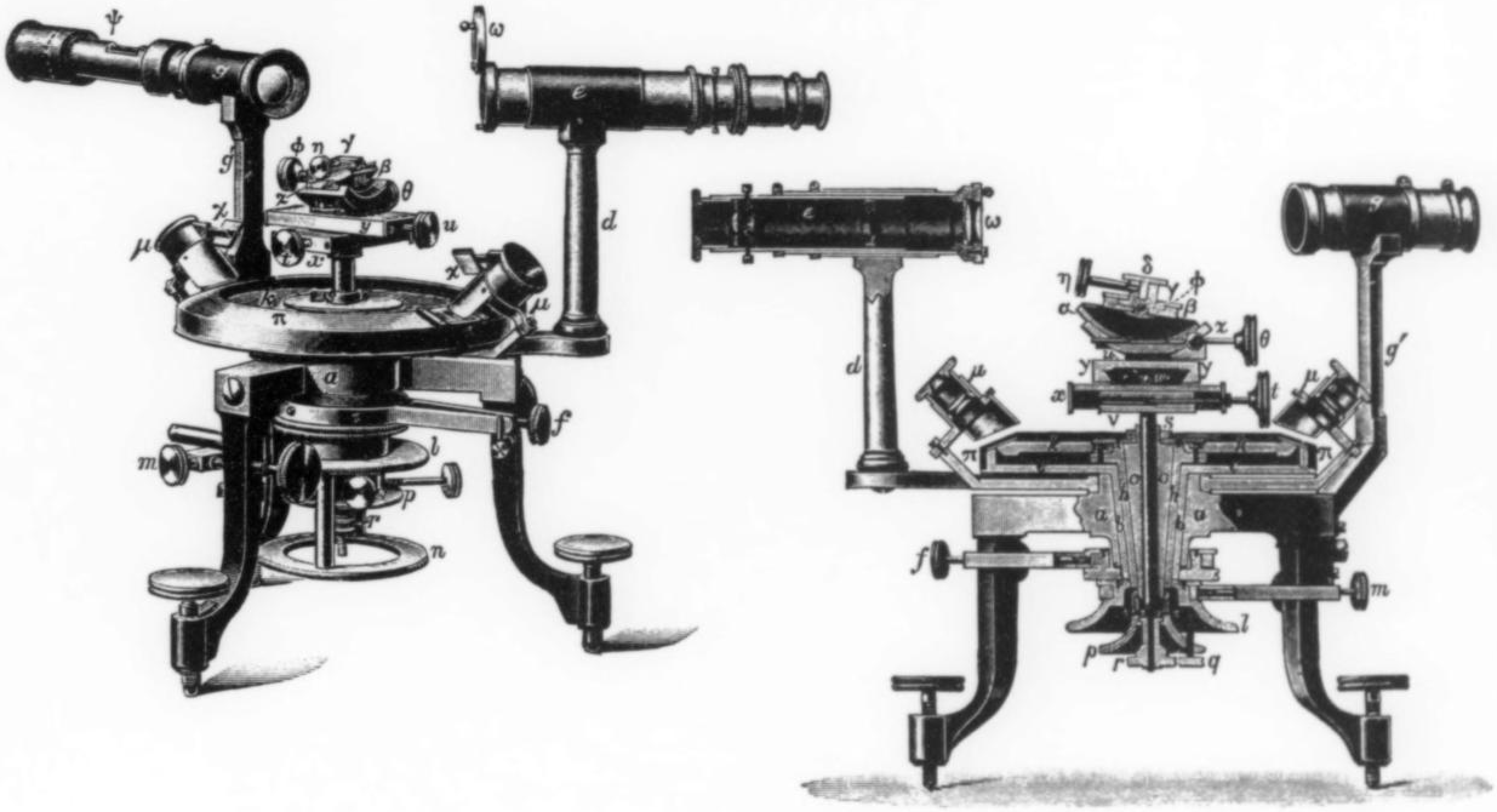


Figure 64. **Outline and section of the Fuess model II goniometer (Tutton, 1922).**

a standstill, but instrument construction began again in 1948–1949. The company now concentrated on ultraviolet spectrographs and instruments for spectral analysis. On April 1, 1965, Mrs. Gisela Fuess, the granddaughter of the founder, along with 200 employees, celebrated the 100th anniversary of the company. But the displacement of expensive mechanical-optical instruments by electronic-optical ones finally resulted in the tradition-steeped R. Fuess company being dissolved and removed from the register of companies in 1976; the factory was demolished that same year.

The description of the history of the Rudolf Fuess company would not be complete without the mention of **Karl August Leiss.** Leiss was born in Adelsheim on January 28, 1868. Little is known of his apprenticeship. In 1890 he began as a helper at Rudolf Fuess, and in 1893 he was made head of the optical department. In 1899 the book *The Optical Instruments of the R. Fuess Company* was published, and in it Leiss described the company's large variety of spectrometers, refractometers and crystallographic-mineralogical apparatuses with great technical knowledge. In March 1921 Leiss became self-employed but remained near the old workshop in Steglitz. The reasons for his leaving Fuess are not known. Very apparent, however, is the close similarity between the instruments he offered and those of Fuess; some of those relevant to mineralogy and crystallography were almost identical to Fuess's. Presumably there was an agreement between Paul Fuess and Karl Leiss. Since the Fuess catalog of 1943 still offered goniometers, some unchanged for 50 years, Paul Fuess appears not to have stopped making instruments of this type. The heyday of goniometer development was over by 1921, when Max von Laue (1879–1957) discovered the refraction of X-rays by crystal lattices.

The list of goniometers delivered by Leiss between 1921 and 1939 numbered only 28 instruments! The Leiss monochromators dominated the market, but tree-height measuring devices were also a continual sales success. After Karl Leiss's death in Heilbronn on April 25, 1940, his son-in-law, Karl Koletzko, took charge of the company. The monochromators and spectral apparatuses were again marketed after the end of World War II, but the company could not shift quickly enough to the new electronic measuring techniques. In 1985, the Leiss firm dissolved and was removed from the register of companies, bringing the 100-year tradition of the precision mechanical workshop of Fuess/Leiss to a final end.

Getting back to the Fuess goniometers themselves, around 1871, Rudolf Fuess developed a horizontal-circle goniometer that was to become the most widespread standard instrument, sufficient for most crystallographic investigations. According to **Alfred Howard Tutton** (1864–1938) it was "the goniometer par excellence for crystal angle work at ordinary temperature" (1911).

The Model II and IIa goniometers (Figs. 64, 66 and 67) were steadily improved with the help of numerous suggestions, especially from Paul von Groth and **Christian Friedrich Martin Websky** (1824–1886). In this way a whole series of models developed in time to meet the emerging demands. Model II could be refitted especially easily with accessory apparatus. It provided the mechanical base for two-circle and three-circle measurement techniques. The number of single and internally nested conical axes in particular required the highest accuracy during manufacture.

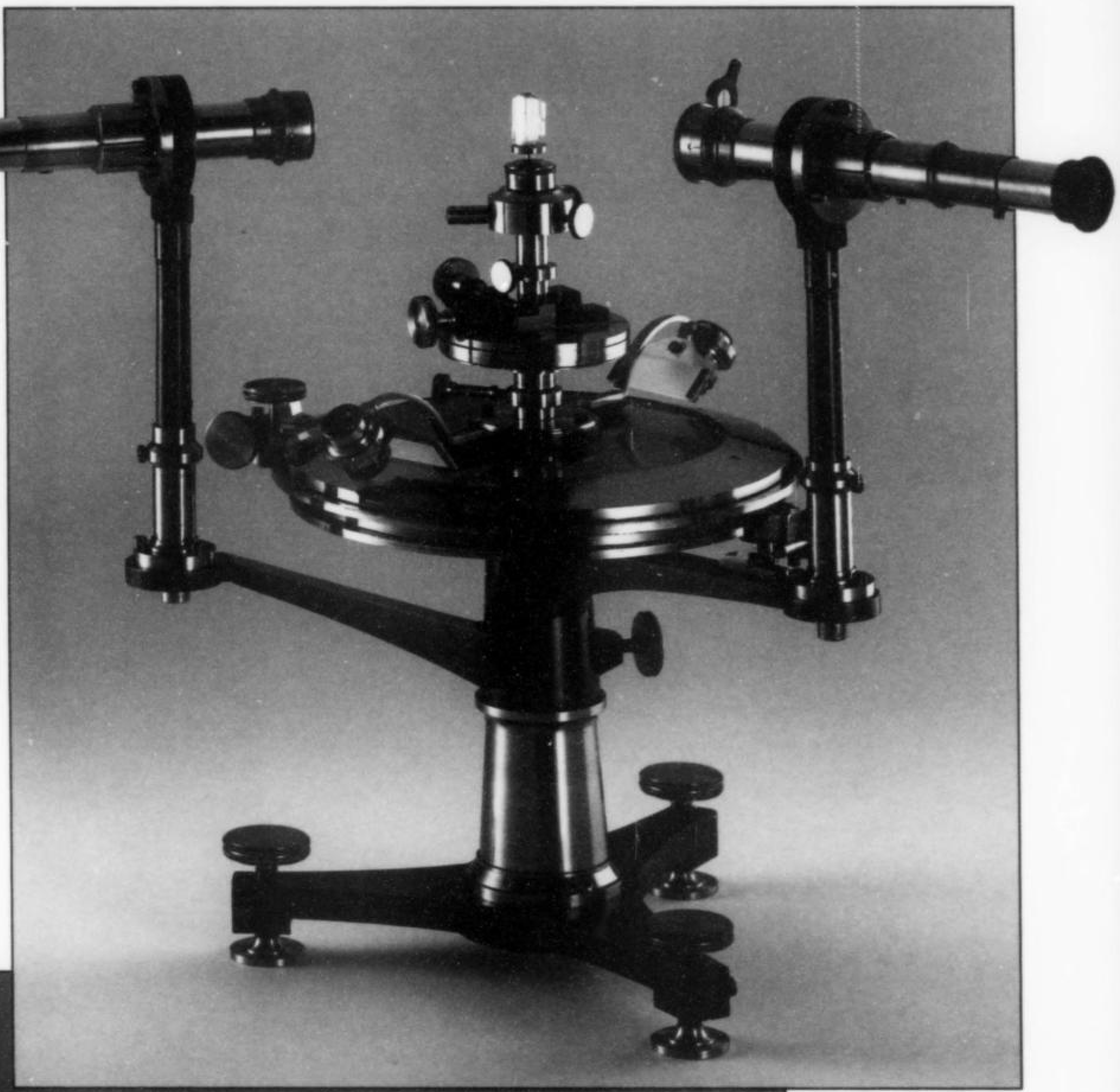


Figure 65. The Börsch goniometer; precursor of the standard Fuess goniometer. Signed: "F. W. Breithaupt & Sohn, Cassel," dated 1872.

Figure 66. Model IIa Fuess goniometer; undoubtedly the most widely used goniometer of all time. It includes a revolving signal disc and matching gas illuminator. Signed: "R. Fuess, Steglitz bei Berlin," ca. 1900.

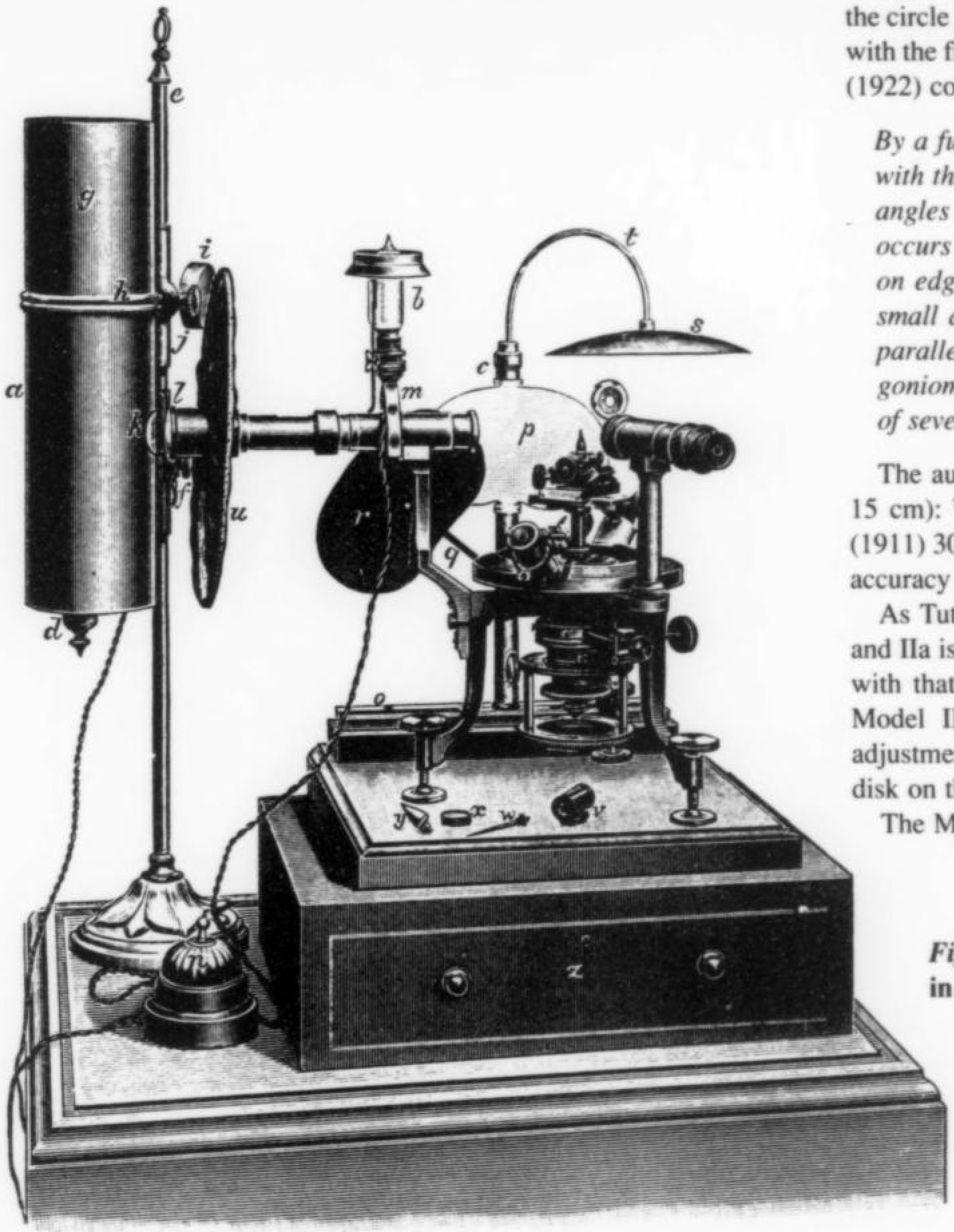


Figure 67. **Fuess model IIa goniometer in actual use (Tutton, 1922).**

A work even more extensive than Tutton's comprehensive description (see following two pages) was compiled by Websky (1880): *"About the installation and use of the Babinet system reflecting goniometer (model II) by R. Fuess in Berlin."* The four draw-tubes with different signals mentioned by Tutton, as well as the four telescope combinations along with further orientation accessories, were offered by Fuess in a special case (Fig. 68). In later constructions the four signals were combined in a single rotating disk (Fig. 69). The cross slit signal was introduced in 1879 by the Viennese mineralogist **Albrecht Schrauf** (b. 1837) to eliminate interference by striated faces and their reflected signals. Websky also described the testing and adjustment of the instrument in 1880. For this it is important to focus the telescope lens on a distant object in order to ensure the incidence of parallel light. The optic axis of the collimator and the observation telescope can be adjusted by means of a round parallel plane mirror mounted on the crystal holder. A vertical needle mounted in the crystal holder serves to adjust the vertical reticle so that it always remains in coincidence as the circle is turned.

Depending on the form and reflectivity of the crystal, the measurement is made in a light or totally darkened room. The signal slit is illuminated directly by means of a lamp, and incident light is kept from the crystal by a cardboard shade. A special darkening apparatus can be placed over the crystal. After centering and adjustment of the crystal edge, the axis of the crystal mount is made fast with that of the circle axis so that a turn of the crystal is only possible when the circle is turned as well. Through rotation of the circle and crystal through 360° the light reflections are adjusted with the fine adjustment screw and read off the vernier. Klockmann (1922) concludes that:

> *By a full rotation of 360° all faces whose edges are parallel with the centered edge must reflect, and one can measure all angles of a zone by centering and adjustment. The error that occurs with only one centered edge and reflections measured on edges of the remaining faces of a zone which are only a small distance from the center may be neglected due to the parallelism of light of the collimator. The observation at the goniometer is thus also an excellent means to test the zonality of several planes.*

The authors give different degrees of accuracy (circle diameter 15 cm): Websky (1880) 10″, Klockmann (1922) 15″ and Tutton (1911) 30″. However, for most investigations on natural crystals an accuracy of one minute is totally sufficient.

As Tutton mentions, the only difference between the Model II and IIa is that on the former the axis of the crystal holder is joined with that of the circle axis by a simple screw clamp, while the Model IIa accomplishes this through the use of a third fine adjustment mechanism that is mounted with a separate rotating disk on the underside of the goniometer.

The Models III and IV have the same dimensions as the Model

Figure 68. **Revolving disc showing the four collimator signals. Clockwise from right: rectilinear slit, "Schrauf" signal, round pinhole, "Websky" slit.**

Since the Fuess Model II instrument is still to be found, and is sometimes still used in many universities and museums, it seems appropriate to cite the very minute and detailed description of Tutton (1911):

One of the best forms of reflecting goniometer is that constructed by the firm of R. Fuess of Berlin, No. 2 model. It possesses a circle which reads with the aid of a vernier accurately to half-minutes. Its construction will be rendered in Figs. 64 a and b, the former representing the general appearance of the instrument, and the latter a vertical section on the scale of one quarter the actual size. It consists of three essential parts, (1) the rotating horizontal divided circle for the measurement of the angles, (2) a telescope and collimator, the latter provided with signal-slit, for the observation of the reflections of this signal from the crystal faces; and (3) a delicate but easily and rapidly manipulated apparatus for adjusting the crystal. The whole is carried by a stout circular table of brass *a*, supported by three feet provided with leveling screws, and having a hollow cone bored at its center, where it is thickened. Within this boring rests, and is rotatable, the conical axis *b* which carries a circular plate *c* provided at two diametrically opposite positions an inlaid silver arcs with vernier divisions, each of 30″. To this vernier-circle there is rigidly attached, below, a horizontal arm, which carries at its outer end a vertical column *d* on which is supported the observing telescope. Hence the latter moves with the vernier-circle, and both may be fixed at any position by the clamping screw *f*, which presses a ring against the lower flange of the rotating cone *b*. The collimator *g* is carried by the column *g*′, which is definitely fixed to the table *a*, so that when the clamping screw *f* is tightened the collimator and telescope are fixed relatively to each other, and this may be achieved at the angular position with respect to each other which is found most convenient for the observation of the reflection from crystal faces, which is usually somewhat over 90. In the hollow rotatable axis *b* a second similar one *h* is capable of rotation, which carries at its head the divided circle *k*, the silver scale of which is divided directly to 15′, and at its lower extremity a hollow milled disc *l* for the purpose of rotating the divided circle by hand, together with all its hollow cone bears within it, including the crystal on its holder, when the telescope and vernier have been fixed by *f*. A fixing screw *m*, working against a clamping ring as in the case of *f*, is provided for fixing the circle and all that it carries, quite independently of the fixation of the vernier-circle and telescope, so that either the divided circle with the crystal, or the verniers with the telescope, can be separately either moved or fixed. Moreover, the fixing by *f* and *m* does not occur directly to the fixed base or feet of the instrument, but to the ring in each case, and this ring is continued horizontally into a narrow V-shaped arm in order to provide a fine adjustment, by a screw working through the basal foot at right angles to the direction of *f* or *m*. The arm carries a strong spring alongside it, free at the outer end but screwed to the ring at the inner end, and when the adjusting screw pushes the arm, the free end of the spring is pressed against a little bracket carried by the foot, and thus fine adjustment is afforded until the spring and arm are forced into contact, and on releasing the screw the arm retrogresses along with it owing to the pressure of the spring. Hence, the divided circle and the crystal carried in rigid attachment with it may be fixed by *m*, and the telescope and the pair of verniers which move with it rotated about them, they may then be fixed by *f* at any desired point, and the fine adjustment carried out by use of the adjusting screw. Equally well, the telescope and verniers may be fixed by *f*, and the divided circle and the crystal which it carries may be rotated instead, by means of the disc *l*, or more readily still by a ring *n* attached below *l* by two vertical rods, and eventually fixed in the desired position by *m*, and finally adjusted by the adjusting screw. Within the conical axis *h*. there rotates still a third one *o*, manipulated by the milled disc *p* attached to its lower end. This axis is primarily intended for the support of the crystal, which is thus carried separately and not directly by, in order that the rotation of the delicately divided circle may be avoided during all the preliminary adjustment of the crystal, and unnecessary wear and tear of the all-important axis saved. Moreover, the further advantage is secured of rendering the crystal axis very free of movement, not having the weight of the circle to carry except during measurements, and thus enabling the preliminary adjustments to be very rapidly performed. The crystal axis *a* and the circle axis *h* can be locked together for the measurements either by a simple screw *q* as shown in Figure 64a (No. 2 model), or by a fixing screw and a fine adjustment screw similar to *f* and *m*, as shown in Figure 64, the latter being the arrangement on the latest form of this admirable Fuess instrument, model No. 2 *a*, which has been employed by the author throughout his researches. The crystal is still not carried directly by the conical axis *o*, but at the head of an innermost cylindrical axis, which is keyed to prevent rotation, and the lower end portion of which is narrowed, and provided with a screw thread which gears with a flanged vertically immovable nut terminating below for the purpose of manipulation in a small milled disc *r*, the rotation of which consequently causes vertical motion of the crystal axis. The object of this inner axis is thus to provide the crystal with an adjustment for height, so as to bring it to the level of the plane of the optic axis of the telescope and collimator. It may be fixed at this height, if required, by tightening the collar *s* by means of a key provided. The innermost axis just referred to bears the adjusting apparatus at the head of which the crystal is carried. This adjusting apparatus consists of two mutually rectangular horizontal movements for centering the crystal, and above them two circular movements in vertical planes also at right angles to each other, for adjusting the tilt of the crystal so as to bring the intersecting edge of any two faces, or the axis of any zone of faces, truly vertical and parallel to the goniometer axis. The two combined pairs of movements enable the edge or zone axis to be brought exactly into the axis of the divided circle of the goniometer. The lower centering movement is manipulated by the traversing screw *t*, and the upper one at right angles to the lower by a similar screw *u*. Each of these two screws is surrounded by a spiral spring confined between the fixed piece *v* or *w* (the nut of the screw) and the traversing box *x* or *y* to prevent "backlash." The fixed piece of the upper movement is only fixed as far as regards movement by *u*, being rigidly attached on the top and at right angles to the traversing box *x* of the lower movement, with which it therefore moves. On the traversing box *y* of this upper centering movement is fixed the cylindrical bed *z* of the lower adjusting segment, and on the latter the similar but smaller bed of the upper segment the circular movement of the two sliding cylinder-segments being effected by the two tangent screws and, provided with spring arrangements seen under the segments in Fig. 59, for ensuring perfect contact and free play. The two segments have a common centre of movement at a height somewhat above the small tabular crystal-holder, which fits by a little peg in a central vertical boring in the upper segment, in which position it may be fixed by the screw. This enables the crystal to be supported at approximately the centre of movement by and at the apex of a little cone of goniometer wax built up on the tabular holder-top, and thus the amount of centering required by the centering screws *t* and *u* is minimized. The angle of movement of each segment is about 40° on each side of the centre, which is ample to allow of several adjacent zones of faces being measured without resetting the crystal on the wax. The divisions of the divided circle *k* and of the vernier-circle *c* are protected by a brass cover-cap, attached below to *c*, and the scales themselves, which are engraved on silver surfaces inclined (the circle plate being beveled) towards the observer for convenience of reading, are read through two diametrically opposite glass-covered windows, at the places where the vernier divisions of *c* are engraved, by means of a pair of microscopes carried on suitable arms form the ring fitting loosely round the boss of the fixed table *a*. This method of support enables the microscope in either case to follow the vernier divisions; the latter are evenly illuminated by light reflected from a little adjustable mirror, and diffused through a thin screen of horn, and each microscope is furnished with an adjustment to the proper focal position for clear reading of the scale and vernier divisions. The collimator *g*, carried by the column *g′* in rigid connection with the fixed table of the instrument, is provided with an achromatic lens at the end nearest the crystal, and at the outer end, at the focus of the lens, with one of the four following interchangeable signals, each of which is fitted in a separate draw-tube sliding in the outer collimator tube (Fig. 67): (1) an ordinary rectilinear slit, provided with an adjustment for one of the jaws, in order to be able to vary the width of the opening by means of a little traversing screw. (2) A "Websky" slit, formed by two circular discs arranged in front of a round aperture, and the separation of which can be varied by the movement of one of them by the means of a traversing screw. This is the form of signal which is practically always employed in the measurement of crystal angles, for it combines the advantages of a narrow central part, the image of which may be readily adjusted exactly to the vertical spider line of the telescope eyepiece, with broad ends which transmit much more light than a parallel straight-edged slit narrow enough to allow accurate adjustment, and consequently affords bright images even from poor or minute faces which would scarcely show the image of a rectangular slit at all. (3) A round pinhole, which is sometimes useful to determine a small deviation of a face out of a zone, or for the study of groups of vicinal faces (adjacent faces only very slightly inclined, that is, nearly parallel, and affording signal images very close together). (4) A "Schrauf" signal which is sometimes used in preference to (3) in the case of very brilliant faces, and which consists of two broad rectangular slits arranged crosswise like the diagonals of a square, and with a horizontal and a vertical crosswire at their intersection in the centre of the field. The observing telescope *e* is provided with four interchangeable eyepieces, three of which are positive achromatic combinations magnifying respectively about seven, five and three times, the last of which is almost always used as being the best combination for affording good lighting of the signal reflections from the crystal faces, while still yielding adequate definition and delicacy of measurement. The fourth is used in connection with a lens supported, when required, by a suitable adapter about an inch in front of the objective; this combination furnishes an image which is actually less than the real size of the signal-slit, and is designed for use in those cases where the image afforded by the ordinary eyepiece is very feeble, owing either to the very minute size of the particular face, or to the dullness of the face, the concentration of light in such a small image rendering it visible and adjustable to the intersection of the crossed spider-lines when it would be almost invisible and certainly not accurately adjustable if the ordinary third eyepiece were used, which far more than counterbalances the loss of delicacy in the measurement. Each eye-piece carries at the focus of the lens combination, which is adjustable in a draw-tube, a pair of rectangularly crossed spider-lines, mounted in an inner ring adjustable for its position in the tube by four screws; the outer eyepiece tube in its turn slides in the main objective tube so that the telescope can be accurately adjusted for parallel rays, and when this is achieved the position can be made recoverable at any time by means of a collar, which can be fixed by a tightening screw and which has a V-shaped projection fitting in a corresponding notch in the fixed objective tube, and which is so adjusted that when the eyepiece is pushed home not only is adjustment for parallel rays effected but also the crossed spider-lines are accurately horizontal and vertical. In front of the objective, which is a similar achromatic lens to that carried by the collimator, there is attached, by a marginal pin so that it can be rotated out of the way when the telescope is to be used as such for parallel rays, an additional lens which converts the telescope into a low-power microscope the focus of which is in the axis of the goniometer, and which, therefore, affords the observer a magnified view of the crystal and thereby greatly facilitates the adjustment of the latter, and also enables the reflecting face to be identified by actual observation, the face appearing brilliantly illuminated while the rest of the crystal is relatively dark. A convenient mode of mounting the instrument, on a mahogany base forming the plinth for a glass case to protect the whole when not in use, is shown in Fig. 67, which exhibits also three essential accessories. These are: (1) the goniometer lamp *a*, (2) an intermittent light *b* for reading the verniers, and (3) a simple apparatus *c* for furnishing a white or black background.

II but are missing the fine adjustment mechanism for the vernier and telescope. Only one signal (Websky) and telescope combination is supplied, and the reading loupe is dispensed with. These models could be furnished with or without a cover for the graduated circle, and the graduations are made either on a silver or silver-plated brass surface.

The Model IVa is smaller (10-cm-diameter circle) and in all more simply constructed (Fig. 70). In contrast, the Model I meets the highest demands for precision, especially in the investigation of crystal angles which vary with raised temperatures. For this purpose it was equipped with a heating apparatus that supplied temperatures to 300°C, or with a cooling apparatus. The "large

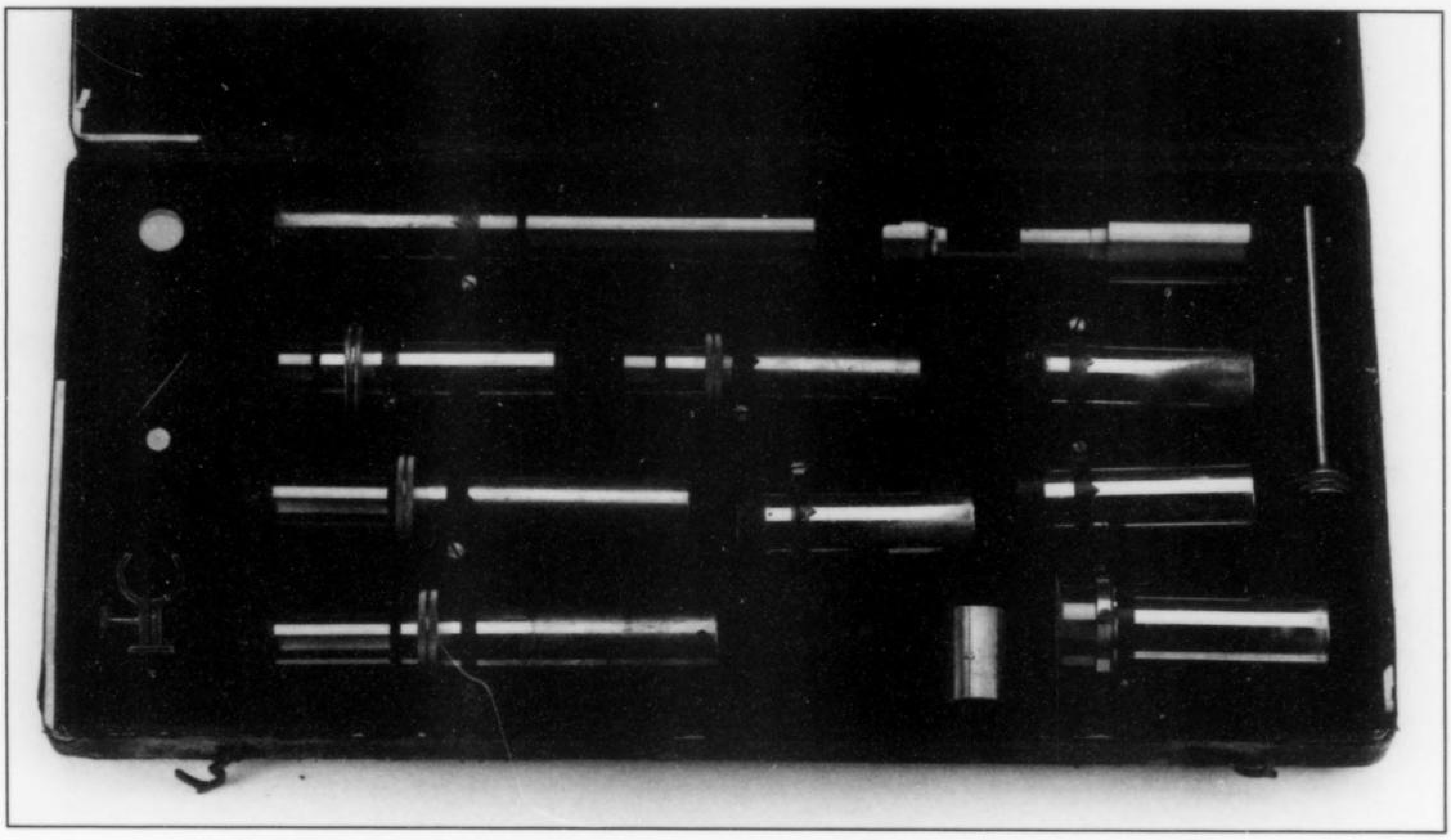


Figure 69. **Case with goniometer draw tubes for telescope combination and individual signals together with other attachments. R. Fuess, Berlin, ca. 1900.**

Figure 70. **Downsized model IVa goniometer by Fuess, Berlin, ca. 1910.**

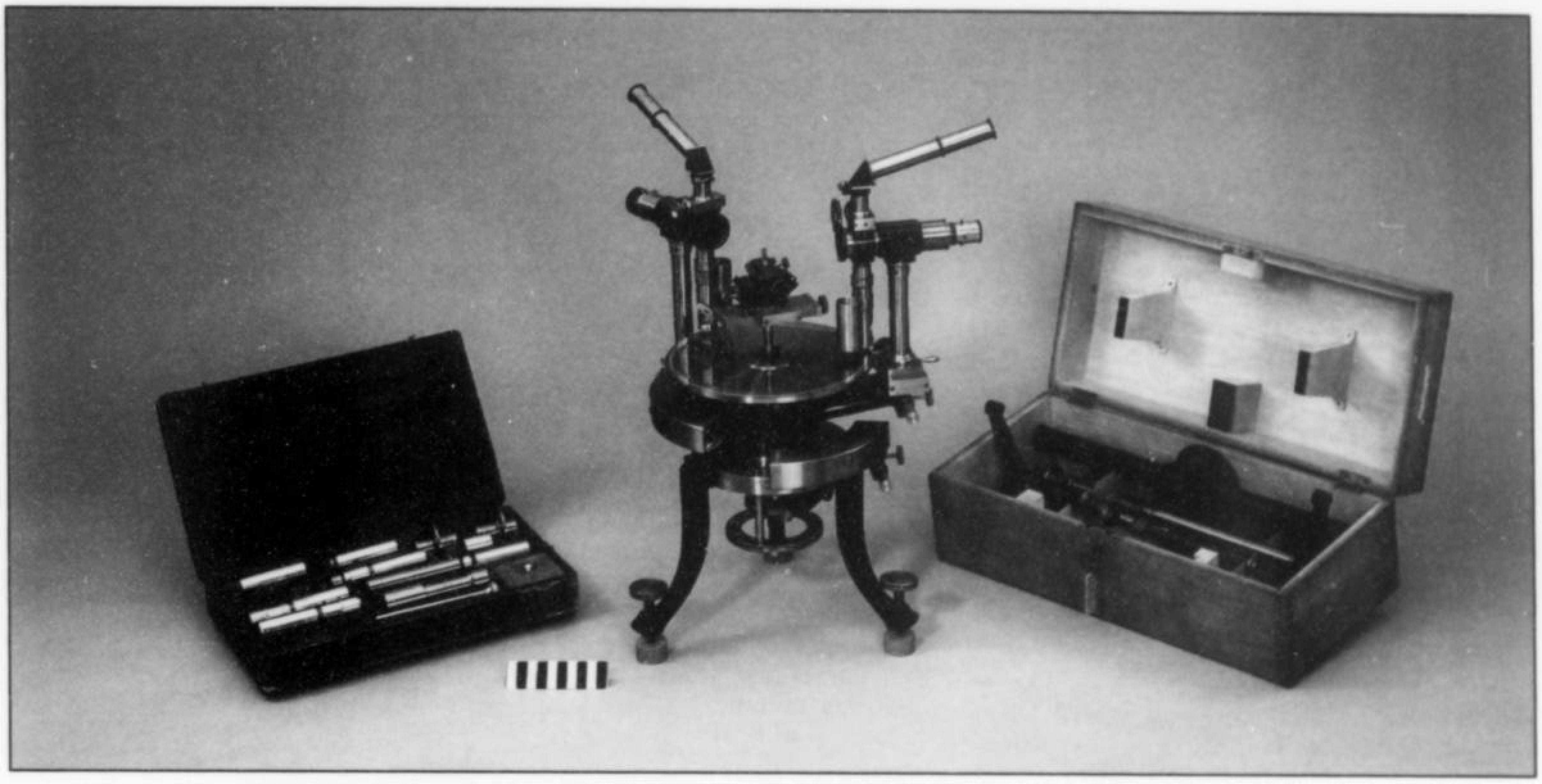


Figure 71. **Old type Fuess model I with read-out microscopes and cases for attachments, ca. 1890. Courtesy of the Trustees of the Natural History Museum, London.**

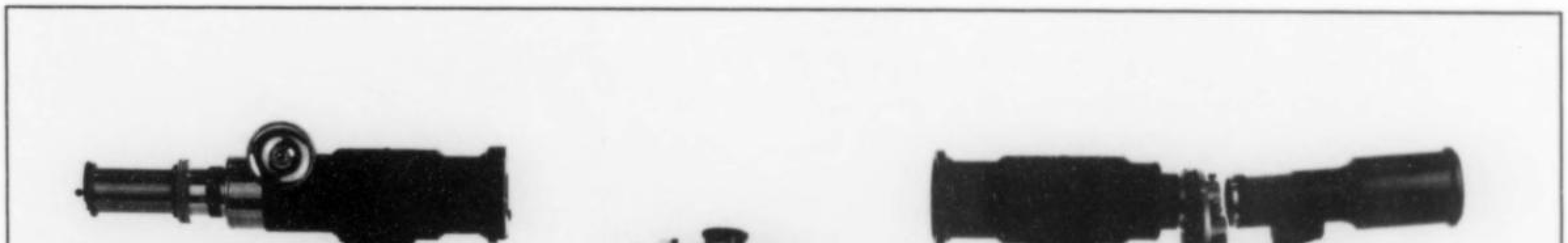


Figure 72. **Modernized version of Fuess model I goniometer with read-out screw micrometers, ca. 1920.**

Table 1. **The development of prices in Fuess catalogs.**

Model	*1871*	*1876*	*1883*	*1891*	*1894*	*1905*	*1909*	*1919*
I	350 (T)	1350	1350	1350		1350		
II	80 (T)	405	650	660		675	675	680
IIa				710	740	710	710	
III		300	450	460	460	460	525	
IV			350	340	340	350	370	
IVa					260	275	275	275

1871: Thaler; 1876–1919: Mark
Annual salary of a master craftsman at Fuess was less than 750 Marks.

goniometer" is similar in construction to the Model II. It differs by its larger dimensions (circle diameter 17 to 20 cm) and by its screw micrometer microscopes with a reading accuracy of 2″. In the original model the collimator holder as well as the observation telescope was positioned to rotate individually with a fine adjustment mechanism, and it was furnished with a diametrically positioned counterweight; this was dispensed with in later type I models (Figs. 71 and 72).

All Model I and II Fuess goniometers could be converted to spectrometers or total *reflectometers*, but their description, special conversions and measuring techniques in these functions will not be dealt with here. Also, the one-circle universal apparatus of Groth (1876), made by Fuess and Leiss (1899), and similar instruments designed by Miers (1904) and Hutchinson (1913) are noted only briefly. With these optical crystallographic universal apparatuses, goniometric measurements, as well as determination of the optical axes and the position of the main axis of double-refracting crystal plates, could be made. The combination and position of the lenses and Nicols prisms are the same as in a horizontal polarizing microscope, and are not further treated here.

The development of prices in Fuess catalogs is shown in Table 1.

The approximate years of the onset and development of inflation can be deduced from the above table. All models, some with later developments, can still be found in the 1943 catalog, although without prices. It has already been mentioned that the Fuess Models II and IVa were manufactured in large quantities. A remark in the 1919 catalog is informative: "This small and inexpensive, universally acknowledged instrument, the Goniometer IVa, has found a very large circulation, with many institutes owning 6 to 12 of them."

Finally it should be pointed out that despite the almost monopolistic position of Fuess, similar horizontal goniometers were manufactured by other instrument makers, including Breithaupt, Kassel (catalogs 1861, 1879), Linhof, Munich (compare Groth, 1905), SIP Societé Genevois d'Instrument de Physique, Geneva (catalogs 1871–1900), and Troughton & Simms, London (Fig. 73) (Miers, 1902; Tutton, 1911).

The London instrument is outfitted with a special signal, a modification of the Websky slit. It was designed by **Henry Alexander Miers** (1858–1942) and consists of four disks in front of a round opening. The description of a perforated diaphragm of aluminum foil which is placed in front of the crystal face originates with Bowman (1910). Using this method it is possible to use the smallest areas and prevent the blurry reflection of heavily striated crystal faces.

The Freiberger Praezisionsmechanik company in Freiberg, Saxony, has built similar instruments in recent times.

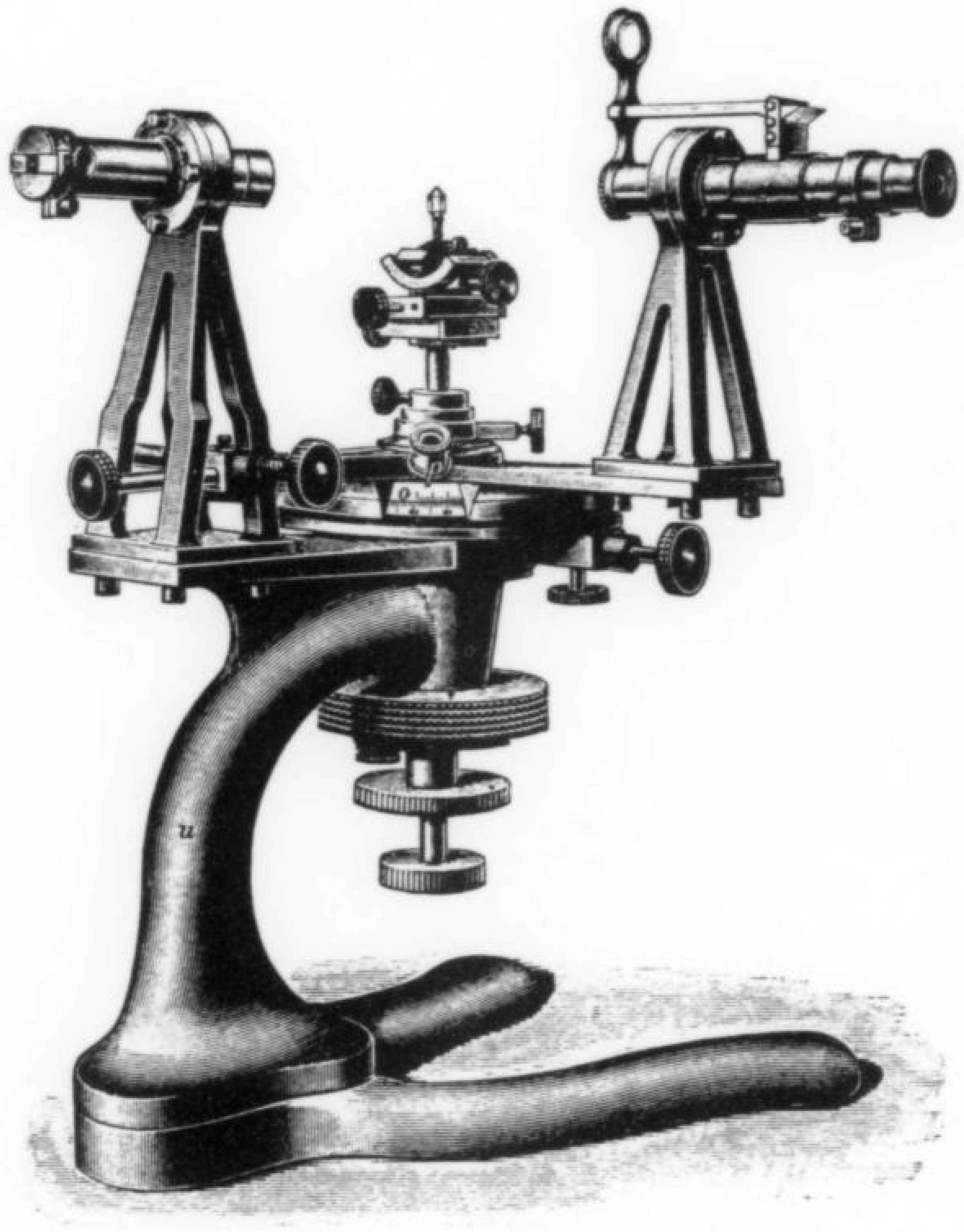


Figure 73. **Goniometer by Troughton & Simms, London (Tutton, 1922).**

Two-Circle Contact Goniometers

PRINCIPLE OF MEASUREMENT

With all single-circle measurement methods the facial angle, or complementary angle, is determined directly by optical or mechanical means. In the **two-circle method**, however, two angle coordinates, the so-called position angles, the facial norms, are determined, and the relative position of the face computed. As with the one-circle method, the measurement is made either by contact or reflection. Klockmann (1922) writes:

> *The method requires that one inserts for the planes those points in which the facial norms penetrate an imaginary sphere around the crystal, and that these two points, defined with reference to two firm circles (equator and zero meridian), are measured by width and height, and a transfer of the location made, as for a translation of the position of the earth onto a sky globe. For each point one gets two angles according to the geographical width and length, and from these one can calculate, through the computation of a spherical triangle, the angle between two crystal faces.*

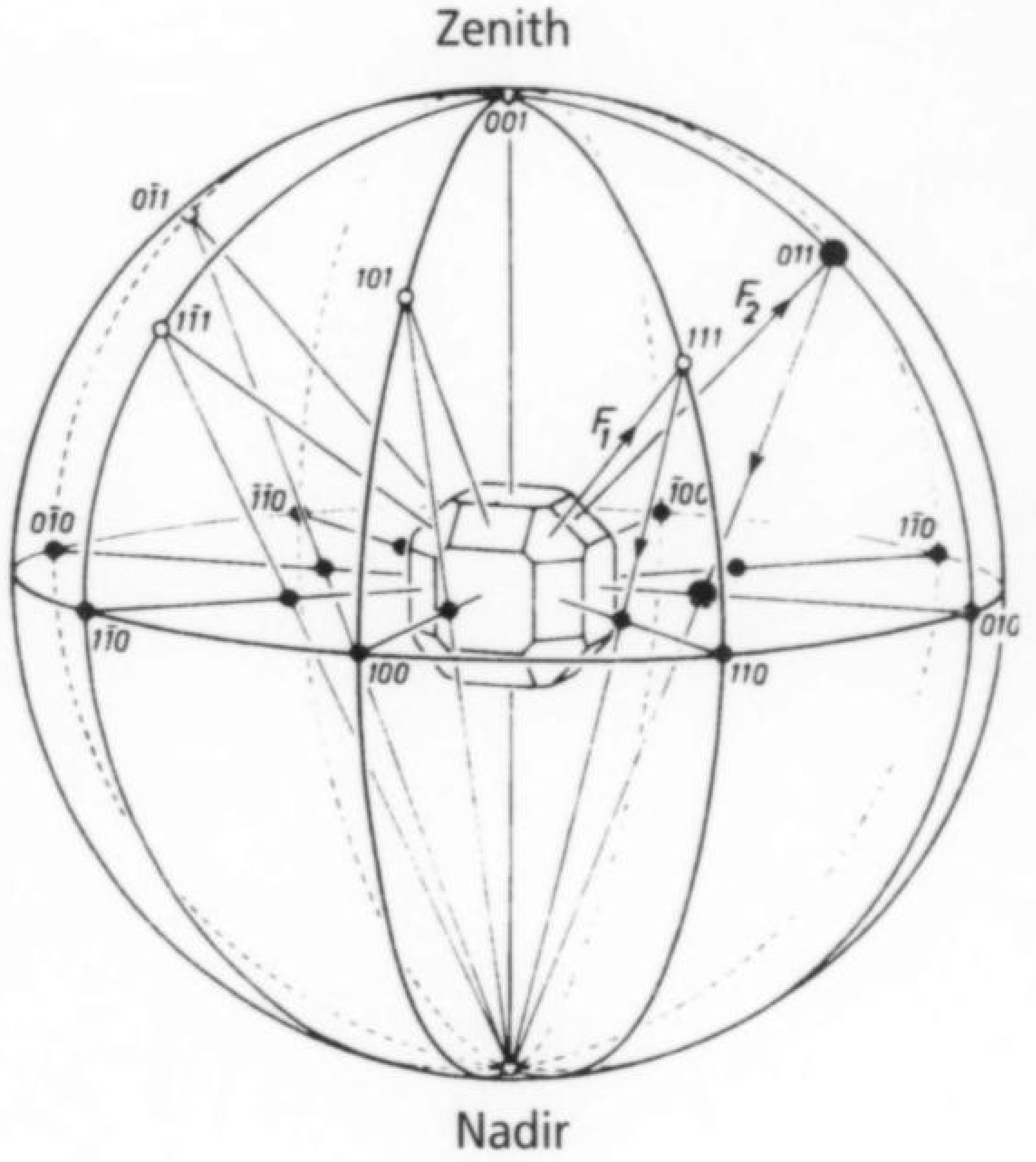


Figure 74. **Illustration of stereographic projection and of a face pole penetrating an imaginary sphere (Klockmann, 1922, edition of 1978).**

Because of the analogy between the two-circle goniometer, as used to project positions onto a sphere, and instruments used in geodetics, the two and three-circle goniometers are also known as *theodolite goniometers*. Figure 74 illustrates the principle of the measurement technique used to determine the angles of the facial norms. A line that originates from the center of the sphere intersects the face perpendicularly and penetrates an imaginary hemisphere. The point of intersection is defined by two angles. The azimuth-horizontal angle *phi* (ϕ) indicates the angle with reference an initial face *o* (zero meridian), and the vertical angle *rho* (ρ) describes the position relative to the pole (zenith)

The measured position angles are entered on a stereographic net, and the angles between all facial norms, and therefore all faces, can be computed using spherical trigonometry. Some of the numerical computations can be avoided by using different projection techniques.

GOLDSCHMIDT'S CONTACT GONIOMETER

The two-circle contact goniometer (Fig. 76, 77) was described by **Victor Mordecai Goldschmidt** (1853–1933) (Fig. 75) in 1896, a few years after his invention of the optical two-circle goniometer. Because of its sturdiness and low price it was useful in refining the techniques of two-circle measurements and in determining the angles on larger non-reflecting crystals and crystal models (Fig. 76). Goldschmidt was a professor at the University of Heidelberg from 1893. He, along with P. Groth in Munich and E. S. Federov in St. Petersburg, can be considered the founders of modern crystallography. In his three important works—*Index der Krystallformen* (1886–1891), *Krystallographische Winkeltabellen* (1897) and *Atlas der Krystallformen* (1913–1923)—Goldschmidt collected crystallographic knowledge in an encyclopedic fashion. Today these are still unrivaled reference books.

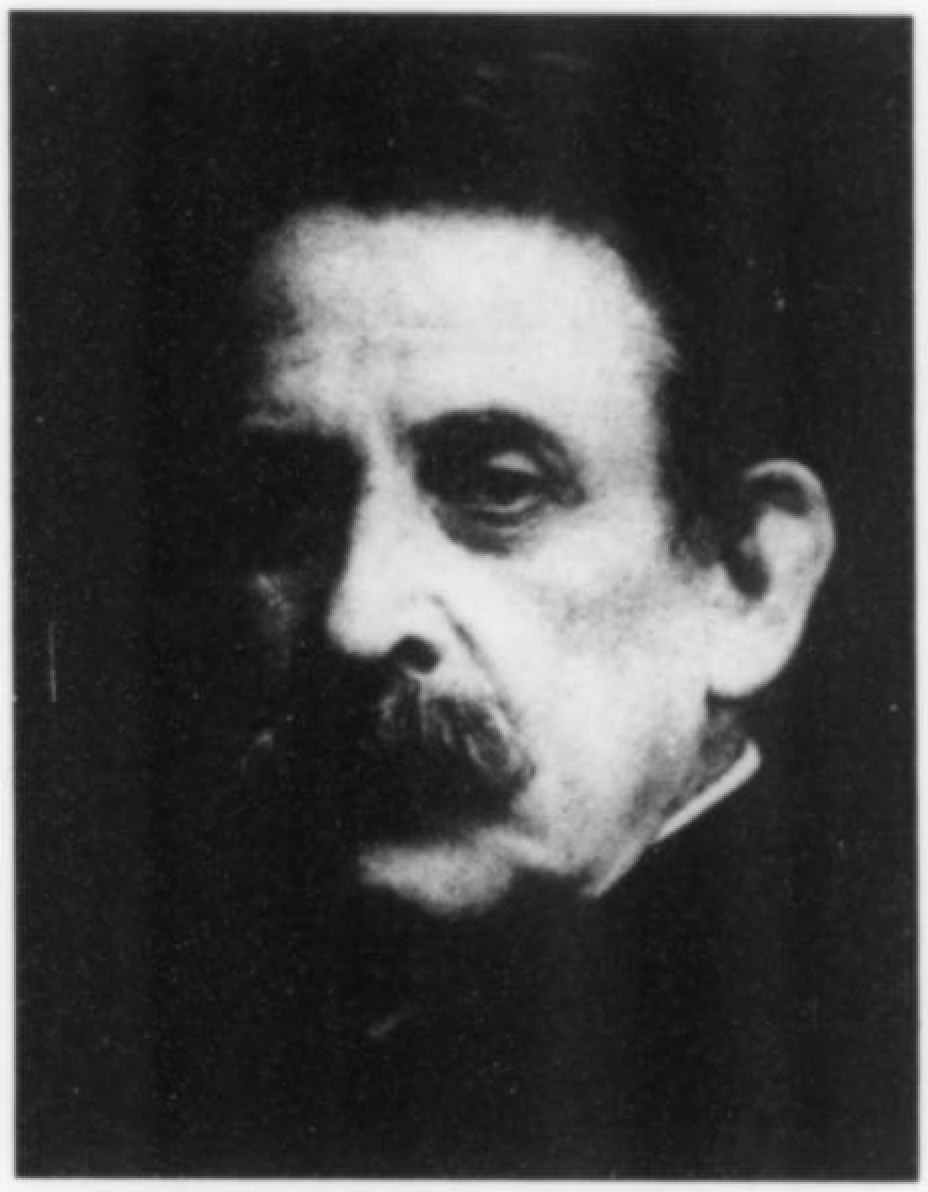


Figure 75. **Victor Mordecai Goldschmidt (1853–1933), crystallographic genius and co-inventor of the two-circle goniometer.**

In Heidelberg, Goldschmidt worked closely with the mechanic **Peter Stoe**, and later with Stoe's nephew Fritz Rheinheimer. This workshop, whose successors still exist, was, together with that of Fuess in Berlin, a leading manufacturer of two-circle goniometers. Victor Mordecai Goldschmidt should not be confused with the geochemist Victor Moritz Goldschmidt (1888–1947).

Tutton thoroughly described the instruments in 1911 (Fig. 77):

> *The horizontal circle* H *is divided into single degrees, and may be read to half a degree with the aid of an indicator* a. *The circle* H *rotates with the crystal* b, *which is attached by wax on the crystal-holder* c. *A universal ball and socket joint, sunk in the upper part of the main supporting column* k, *facilitates proper polar adjustment of the crystal. The vertical circle* V *is of hoop form, and is graduated 100° right and left of zero at the top of the vertical diameter. An indicator* l *is maintained in close contact with the limb by a spring, and it carries a radial rod* m *terminating in the perpendicular contact plane* n. *The rod can be pushed further in towards the centre, or withdrawn therefrom, in order to approach or recede from the crystal face parallel to which it is desired to*

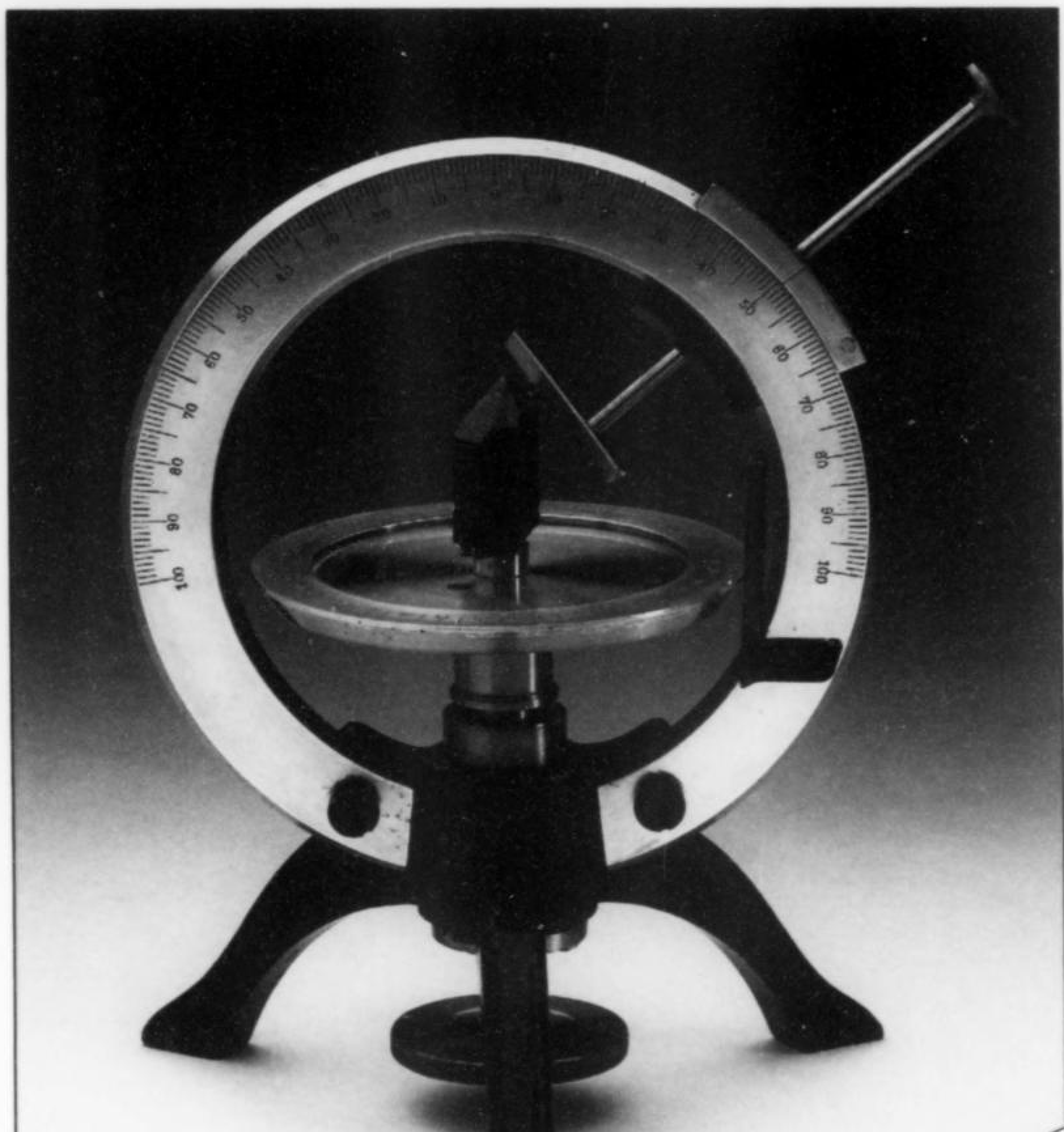


Figure 76. Two-circle contact goniometer, signed: "Fa. Stoe & Cie, Heidelberg," purchased 1896. University of Innsbruck, Austria collection.

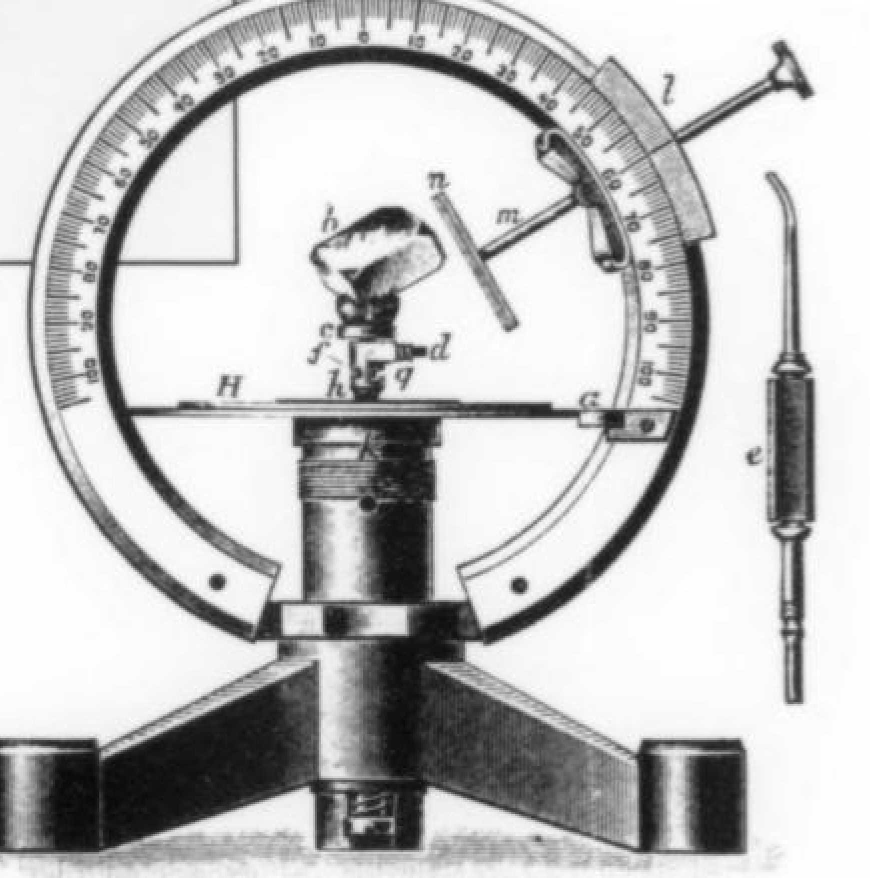


Figure 77. Illustration of Goldschmidt's two-circle contact goniometer (Tutton, 1922).

adjust the contact-plane; the rod is kept strictly radial throughout the operation by means of springs. The apparatus is mounted on a stout tripod o. *In using the instrument the crystal is usually set up on the holder* c *with the prism zone, if one is prominently developed, vertical, perpendicular to the horizontal circle* H. *The contact-plane* n *is then arranged with the rod horizontal with the rod at 90° and the prism face is adjusted truly parallel to the contact-plane* n *by "sighting"; that is, by approaching the surface of* n *to the crystal face until it is nearly in contact with the latter, and then adjusting the crystal, by manipulation of the ball and socket joint, until when regarded from all sides against a suitable background an equally thick or thin line of light is seen between the two surfaces. After polar alignment of the prism face the crystal faces can be aligned by rotating* H *and placing the contact plane parallel to them. The two angles combined are the coordinates of the facial pole.*

Goldschmidt's contact goniometer is ideal for demonstrating the analogy between determining geographical and crystallographic locations. The horizontal circle *H* corresponds to the equator on a globe, the vertical circle a meridian and its *0* point the north pole. The indicator represents the facial norm.

Goldschmidt (1896) refers to three variations in the construction of the instrument:

Model 1, as illustrated in Figure 76 and described above.

Model 2, outfitted with a mechanism that allows the horizontal circle to be raised or lowered together with the crystal holder. Otherwise the construction remains unchanged.

Model 3, in which the vertical circle is not constructed with a stationary arc but is connected to an independent axis. The rod and contact plane are connected by a rectangular holder to the vertical circle. A counterbalance assures the precise rotation of the vertical circle around the horizontal axis.

With the Model 3 Goldschmidt (1898) experimented with a variation of the measurement technique which he demonstrated in Heidelberg on November 7, 1896. His shadow goniometer is constructed on the principle of a sundial. Goldschmidt suggested that metal plates with attached perpendicular needles be fastened to the crystal faces. Opposite a two-circle contact goniometer Model 3 (without contact plane) a lamp *L* is placed that, along with the lens *C*, produces parallel light. Through rotation of the crystal faces in both axes of the instrument every face can be placed horizontal to the light rays. This position can be ascertained when the shadow of the needle disappears. The coordinates to the angles can be read off both the circles.

According to Goldschmidt, his Model 1 was first made by the mechanic Josef Kettner in Prague in 1895 and later improved by Stoe in Heidelberg. In particular the construction of the spherical joint for adjustment of the crystal holder was simplified. Fuess of Berlin also manufactured Model 1 as well as Model 3, but apparently was not successful in patenting it. In 1896 the price of a Model 1 asked by Stoe (as well as Fuess) was 32 Marks (1934 RM 40), and the Model 3 was 40 Marks.

Otto Mellis (1948) writes: "In the 20's the C. Leiss Company in Berlin manufactured a two-circle contact goniometer to the specifications of Prof. B. Popoff. Ten of these goniometers, somewhat improved by the designer, were used with success in teaching elementary crystallography in the Mineralogical-Petrographic Institute of Latvia in Riga." It is similar in construction to the Model 3.

Two-circle goniometers from Stoe are widely distributed, being found more frequently than simple contact goniometers. By contrast, there are almost no instruments of this type from Fuess. The close contact between Stoe and Goldschmidt probably gave Stoe a sales advantage over Fuess.

The logo of the *Mineralogical Record* pictures a Goldschmidt Model 1 goniometer, acquired from the collection of the Smithsonian Institution.

Two-circle Reflecting Goniometers

PRINCIPAL OF MEASUREMENT

With all two-circle reflecting goniometers the crystal can be rotated around two axes that are perpendicular to one another. This makes it possible to bring any desired face, not only those lying in one zone, into reflection without any troublesome adjustments or resetting of the crystal. Under favorable conditions all faces of a crystal may be measured with a single mounting. It is a requirement that the instrument be precisely adjusted so that the extension of both circles and the telescopes coincide in one point: the geometric center.

Tutton (1922) explains:

> *The crystal is adjusted on such a two-circle goniometer so that a face of importance with respect to the symmetry is parallel to the circle carrying the crystal on its axis of rotation. This face is termed the pole-face. The position of any other face is accurately given by its two coordinates, one of which, the azimuth* phi, *is read on the same circle carrying the crystal, and the other of which, the polar distance* rho, *is afforded by the second circle.*

As with a single-circle reflecting goniometer, the crystal faces are brought, one after the other, into the normal position, that is the position bisecting the angle between the collimator and the observing telescope. The angle between the telescopes cannot be altered throughout the measurement.

MILLER'S GONIOMETER

Although almost all authors cite 1893 as the year of the introduction of the two-circle reflecting goniometer, the best evidence suggests that priority belongs to **W. H. Miller** (1801–1880), the then-leading figure in British crystallography. In his classic work *A Treatise on Crystallography*, Miller introduced the currently used reciprocal indices. In a small article (1882) posthumously published by Miller's successor to the mineralogical chair at the University of Cambridge, **W. J. Lewis**, the following statement by Miller is contained:

> *In 1874, I received from Major Ross what appeared to be a bead of platinum, of approximate diameter 0.733 mm, which he had fused with the aid of a blowpipe, and which on cooling exhibited a large number of crystal-faces. . . . The bead was attached to the axis of a small Wollaston goniometer in a convenient position but without any special orientation. The small goniometer was then secured in an upright position on the graduated horizontal plate of the large goniometer so that the crystal lay in the intersection of their axes. . . . In this way 147 faces occupying somewhat more than a hemisphere were determined, and a stereographic projection of their poles made.*

If Miller had wished to measure the individual faces with his Wollaston goniometer, the repeated adjustment and determination of the mutual positions of the 147 faces would have been extraordinarily difficult. Miller's statement contains no detail about which two goniometers he combined in his "marriage"; Lewis adds that "The work was left in an incomplete state."

Miller's original instrument remains at the Museum of the History of Science, Cambridge. (It proved impossible to obtain a photograph from this institution.) It appears that the prototype of the two-circle reflecting goniometer was made simply by bolting a Wollaston goniometer to a horizontal-circle Troughton & Simms. Miller's description as passed on by Lewis seems to have gone unnoticed for 15 years until, in 1889, Federov, and shortly thereafter V. Goldschmidt and S. Czapski, independently rediscovered the method.

FEDOROV'S GONIOMETER

Science has **Evgraf Stepanovich Federov** (1853–1919) to thank for, among other things, the first derivation of the 230 space groups of crystals (1890), as well as the invention of the universal apparatus for microscopic-petrographic investigations. Fedorov's first description of his goniometer appeared in Russian in 1889, and, in more detail, in German in 1893. The instrument was built at the beginning of 1892, tested, and used for measurements. Both P. Groth and S. Czapski acknowledged the priority of Fedorov as the inventor of a fully functional two-circle goniometer. Doing so was probably easier for Czapski than for Goldschmidt, because Czapski's instrument was fundamentally different from those of Fedorov and Goldschmidt.

The original model of 1892/93 consisted essentially of a massive

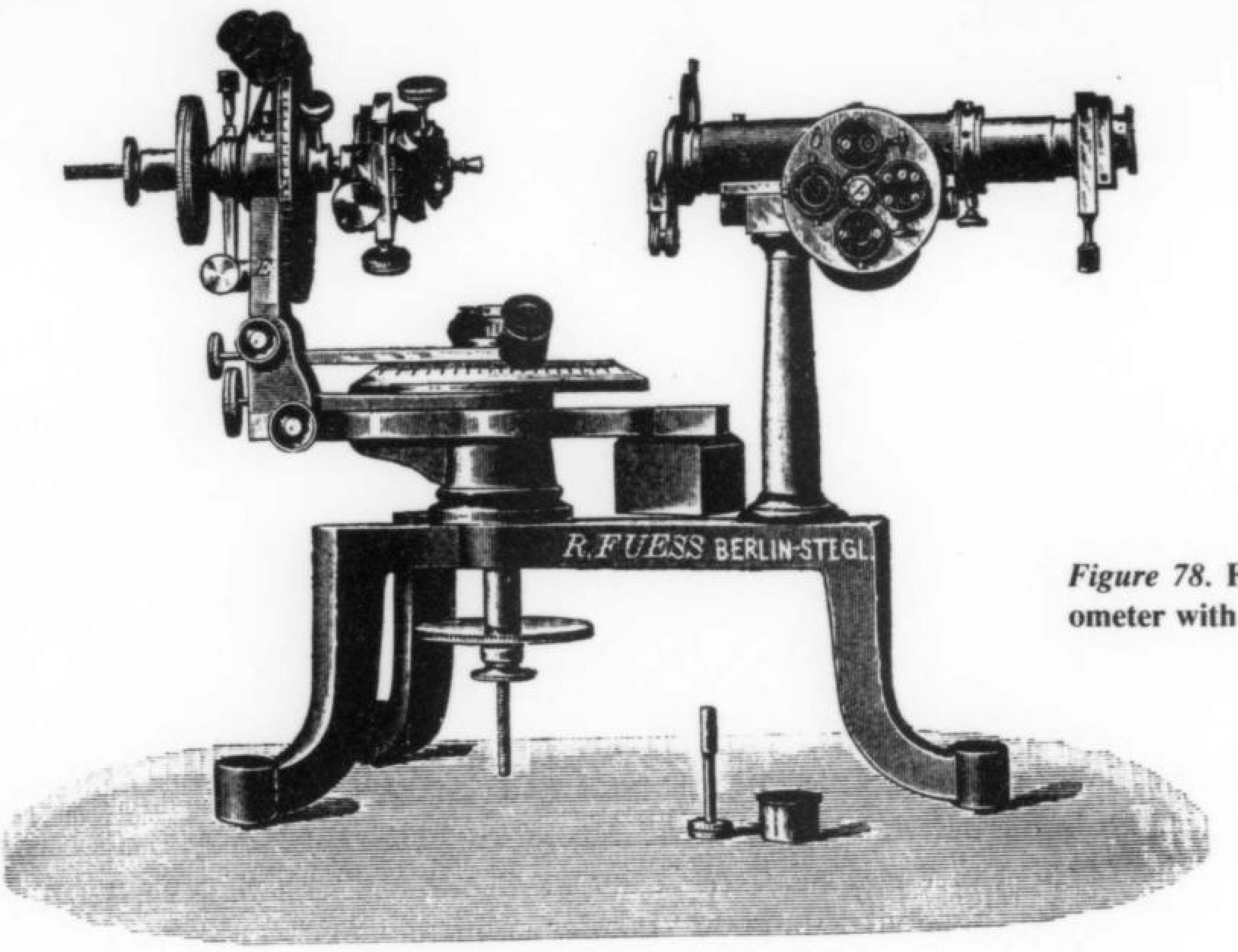


***Figure 78*. Fedorov two-circle reflecting goniometer with auto-collimation (Groth, 1905).**

three-legged base with one telescope firmly mounted on an angular pillar. The axial bearing for the horizontal circle, as well as the angle piece for the vertical circle and its corresponding counterweight, are also contained in the base (Fig. 78). The crystal holder is identical with Fuess's construction. It is mounted on the central axis of the vertical circle; an adjustment screw facilitates horizontal shift towards the geometric center of the instrument.

The azimuth angle *phi* is measured on the vertical circle and the polar angle *rho* on the horizontal one. The construction principle of the auto-collimator is novel: the telescope serves for both signal emission *and* observation of the reflected light, and this has the decided advantage that the dead angle of about 50–70 degrees lying between the axis of the collimator and observation telescope, around which the vertical circle cannot be rotated, is greatly reduced. The decided disadvantage of the auto-collimator is the weak light output, which prevents the measurement of small and poorly reflecting crystals. The auto collimation is achieved through an illuminated signal on the side of the telescope. The light rays produced are reflected on a thin glass which is mounted at a 45° angle in the axis of the tube. The signal exits through an objective lens and is reflected back from the crystal face when it is exactly perpendicular to the axis of the tube. A part of the reflection can be brought into coincidence with a reticle in the focal point of the objective.

In a second Fedorov model (1900), the goniometer head is replaced by a complicated system of two perpendicular arcs which provide (in a limited way) two extra circles. Additionally a separate collimator and observation telescope are recognizable in the illustration. Both are mounted on right angle arms, and the principle of auto collimation is no longer maintained.

On a third Fedorov model (1914), all collimation is dispensed with, as in the early phase of the reflecting goniometer, and a remote signal is chosen. Additionally, the vertical circle is mounted on a slide so that it can be moved in and out of the geometric center. The accuracy of the instrument is 30″ to 1′.

The original prototypes of Fedorov's goniometers were built by the instrument maker Petermann in St. Petersburg. These appear to have been preserved in the Geological Museum in Moscow, but, according to a notification by M. A. Nazarev (1994), they may possibly have been stolen in 1994. As early as 1895 Fuess offered a goniometer with Fedorov's auto-collimator for 750 Marks, and with a normal signal for 755 Marks. The third model, with no signal mechanism, was offered for 675 Marks in 1919. The author knows of no Fedorov apparatus by Fuess; these were surely built in very limited numbers.

GOLDSCHMIDT'S REFLECTING GONIOMETER

Like the development of the one-circle reflecting goniometer, that of the two-circle goniometer proceeded from a simple (no telescope) instrument (Wollaston-Miller), through the addition of an observation telescope (Malus-Fedorov), to an instrument with collimator and telescope, first made by Victor Goldschmidt. The 1893 model was similar in principle to that of 1896, but the latter was improved. An abbreviated form of Tutton's description, which illustrates the construction principle shown in Figure 79, is as follows:

> *Both circles are divided directly into quarter-degrees, and read by means of their verniers. A fine adjustment is provided for each circle. The axis of the vertical circle also has a central boring in which a triangular prismatic rod is capable of sliding, being driven in the direction of its length (horizontally) by the mother-nut* e. *It carries the centering and adjusting devices and the crystal holder. The telescope* (p) *and collimator* (x) *are arranged horizontally and do not travel with either circle. The column of the telescope may be moved and clamped relative to the collimator and the angle between them measured. . . . Very full directions for the adjustment of the instrument are given in the 1898 Memoir (by V. Goldschmidt).*

In 1910 Goldschmidt introduced his Model 1905 goniometer for measurement of large crystals and specimens up to 14 cm long and 10 cm wide. It was inspired by a visit to G. F. Kunz, New York, who supplied several large spodumene crystals from San Diego County for crystallographic measurement. Because of the large size of the crystals it was impossible to measure them on the

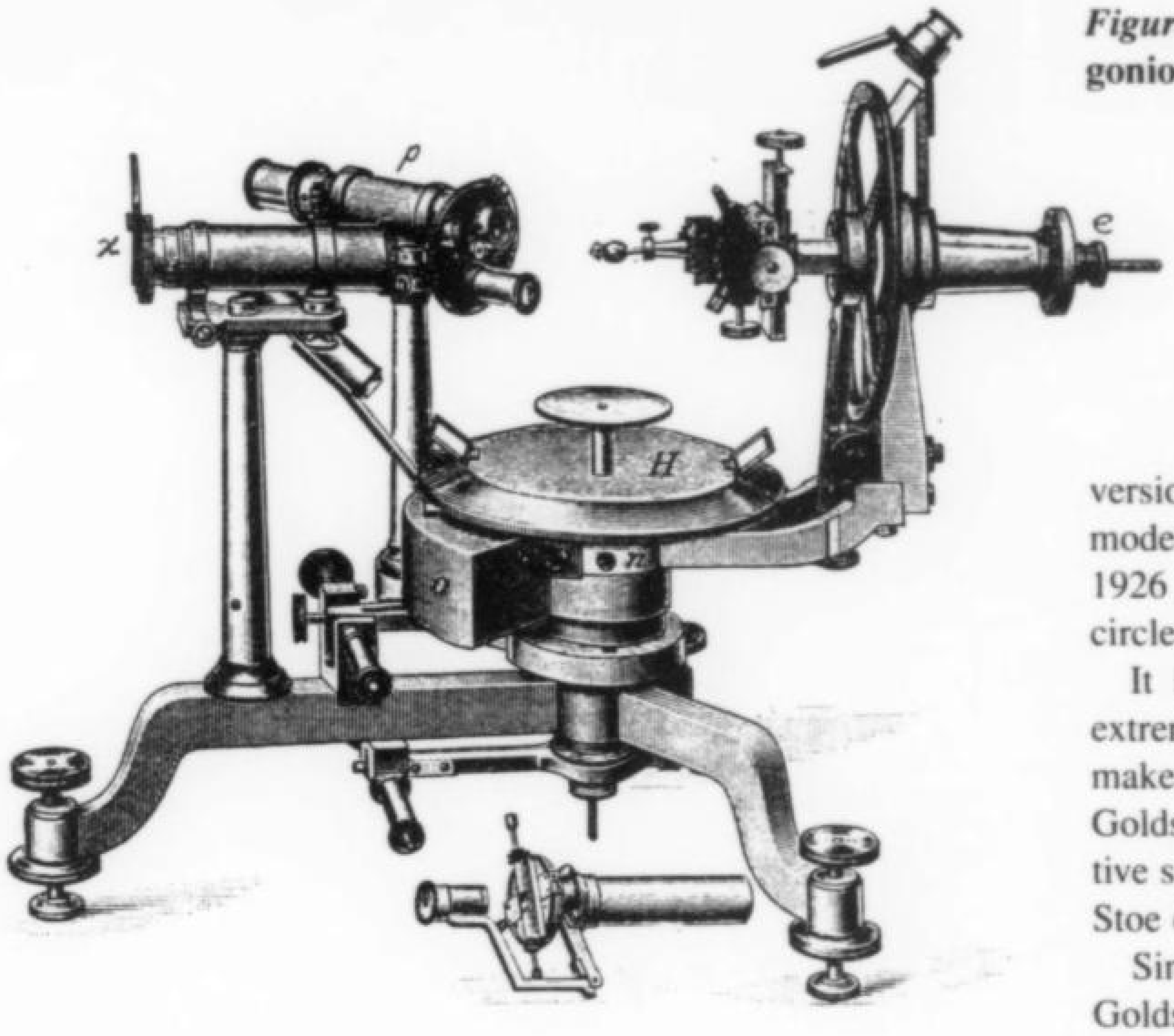


Figure 79. **Goldschmidt's two-circle reflecting goniometer (Tutton, 1922).**

models of 1893 or 1896. A two-circle so-called "large goniometer" (1897) seems also not to have been sufficient. As a result, a goniometer with even larger dimensions and increased load capacity was constructed in 1905.

Tutton (1922) continues:

> *The new 1920 model of the V. Goldschmidt two-circle goniometer, to which allusion was made as being probably the best two-circle goniometer yet constructed, . . . [has] improvements as follows: The mode of construction of the axes and their vertical and horizontal bearings and supports enables the horizontal circle to be rotated to any extent with respect to the vertical circle carrier, so that any pole-position can be employed, and the observer is not limited to particular and possibly very inconvenient pole-positions. Also, by mounting the vertical circle support on a slider, provided with rapid and fine motions along a horizontal arm carrying a scale, much greater latitude is afforded as regards the size of crystal investigated, and a greater extent and freedom of movement and possibility of fine adjustment to a desirable position is afforded to the vertical circle. The optical arrangements are also improved by the provision of a telescope affording a considerably larger field, by the addition of a condensor to the collimator and of an iris diaphragm to the telescope for hand adjustment. The accuracy of both circles is 30″.*

Of all two-circle reflecting goniometers the models designed by Goldschmidt and Stoe in Heidelberg were the most widely disseminated (Fig. 81). The original model (1893) and the model of 1896 were built by the mechanic Peter Stoe in Heidelberg; for the 1896 model, numerous optical improvements were suggested by **Karl Pulfrich** (1858–1927), the leader of the optical instrument division of Carl Zeiss in Jena. After 1909 the business was taken over by Stoe's nephew, Fritz Rheinheimer. After many ownership changes, the company, which still exists, moved from Heidelberg to Darmstadt.

The Stoe (Rheinheimer) company built a series of models of Goldschmidt goniometers. Model A is the large standard instrument of 1920. Models B, C, and D were variations of A. Model E was designated as a school goniometer and is a smaller, simplified version. The author knows nothing about Models F and G; the modern Models H and J will be discussed later. Stoe Company's 1926 letterhead contains references to five different sizes of two-circle reflecting goniometers.

It is very interesting to note that Groth's (1905) otherwise extremely accurate description of instruments and manufacturers makes no reference to Stoe and contains no illustration of Goldschmidt's instrument. This is possibly the result of a competitive situation, with Groth-Fuess on the one side and Goldschmidt-Stoe on the other.

Since no price lists exist, Stoe's prices can only be derived from Goldschmidt's (1910) footnotes. Model 1905, for the measurement of large crystals, was, at the time, priced at 2,000 Marks, and the Model 1896 cost about half that. Until 1900 about five, between 1900 and 1920 about seven, and after 1920 about ten Model A or similar types of instruments were manufactured per year. The Stoe-Rheinheimer goniometer developed into the most widely sold two-circle reflecting goniometer, and examples are still to be found in many institutions and museums.

According to statements by Karl Pulfrich (1920), the Carl Zeiss Company in Jena also manufactured a two-circle Goldschmidt reflecting goniometer beginning in 1898 (Fig. 82). Through some simple manipulation the vertical circle and its counterweight may be removed and a goniometer head may be mounted on the horizontal circle. In this way the theodolite goniometer can be converted into a one-circle goniometer. It appears that Zeiss goniometers were built in very small numbers, as they are extraordinarily rare. Goldschmidt's construction plans were also used by some modern goniometer makers such as Freiberger Praezisionsmechanik (Kleber, 1964), Laboratory Associates Boston (Wolfe, 1948), and others.

CZAPSKI'S AND NEDINSCO GONIOMETERS

Siegfried Czapski (1861–1907), assistant to Prof. Ernst Abbé at the time and later trustee of the Carl Zeiss Foundation, likewise introduced a design for a goniometer in 1893; he used a crystal refractometer, which has an analogous principle, as his inspiration. Czapski was aware of Goldschmidt's and Fedorov's independently developed instruments, and judged that "which of the three has the most advantages for practical use can only be decided through longer experience."

The main difference between Czapski's and all other two-circle reflecting goniometers is that in the Czapski model the crystal is fastened to the vertical axis of the horizontal circle. In his prototype Czapski dispensed with the centering and adjustment mechanism and fastened the crystal with wax directly to the central axis. A further important difference is that the circles are positioned independently of one another and are not fastened together by a single angle bracket. Thereby the stability of the instrument is considerably improved (Fig. 83), and inaccuracies that occur through the rotation of the heavy vertical circle and its counterweight can be avoided. As did Fedorov, Czapski used the auto-

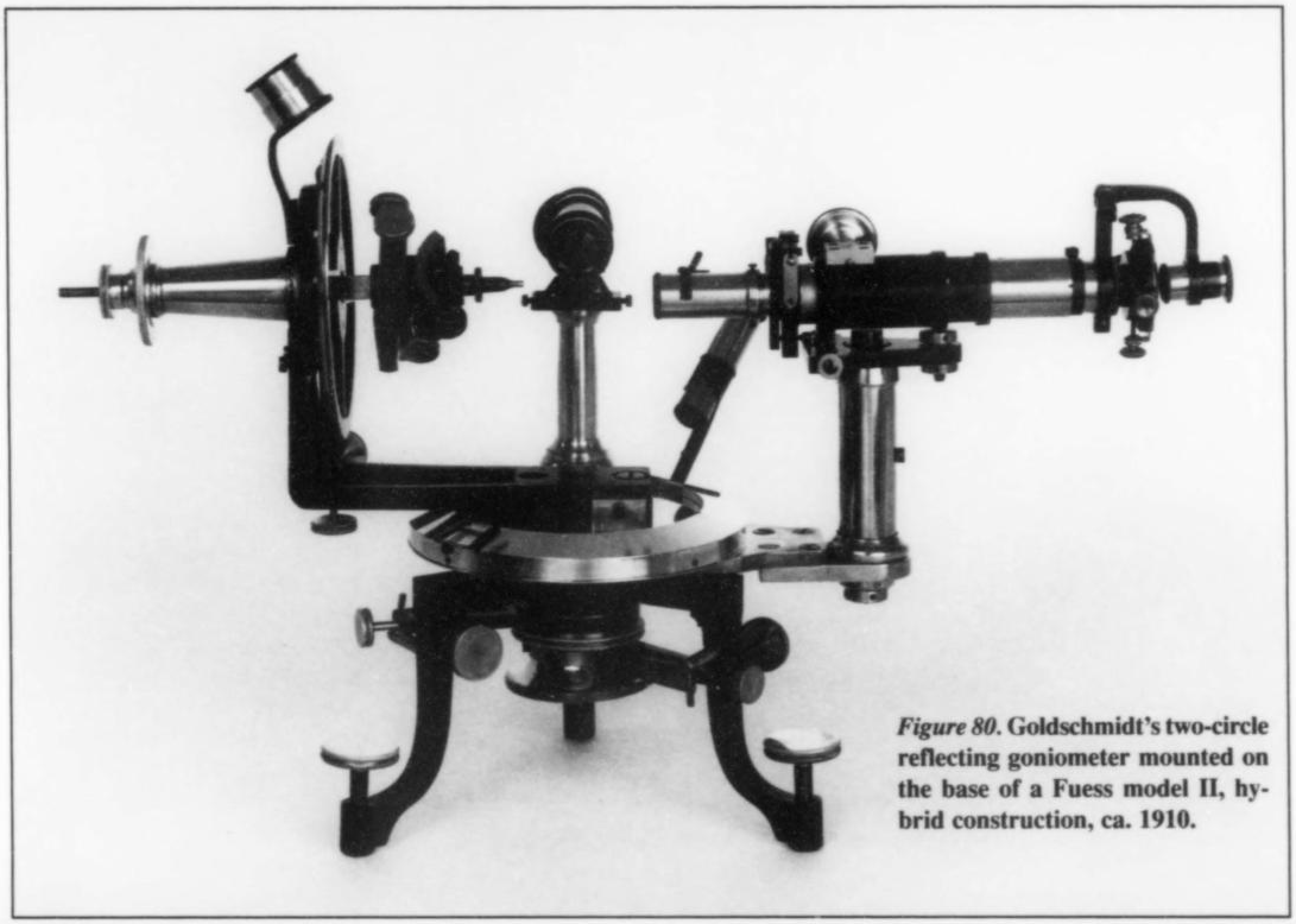


Figure 80. **Goldschmidt's two-circle reflecting goniometer mounted on the base of a Fuess model II, hybrid construction, ca. 1910.**

Figure 81. Large Goldschmidt two-circle reflecting goniometer, signed: "Fa. Stoe & Cie, Inh. Fritz Rheinheimer, Heidelberg," ca. 1905. O. Medenbach collection and photograph.

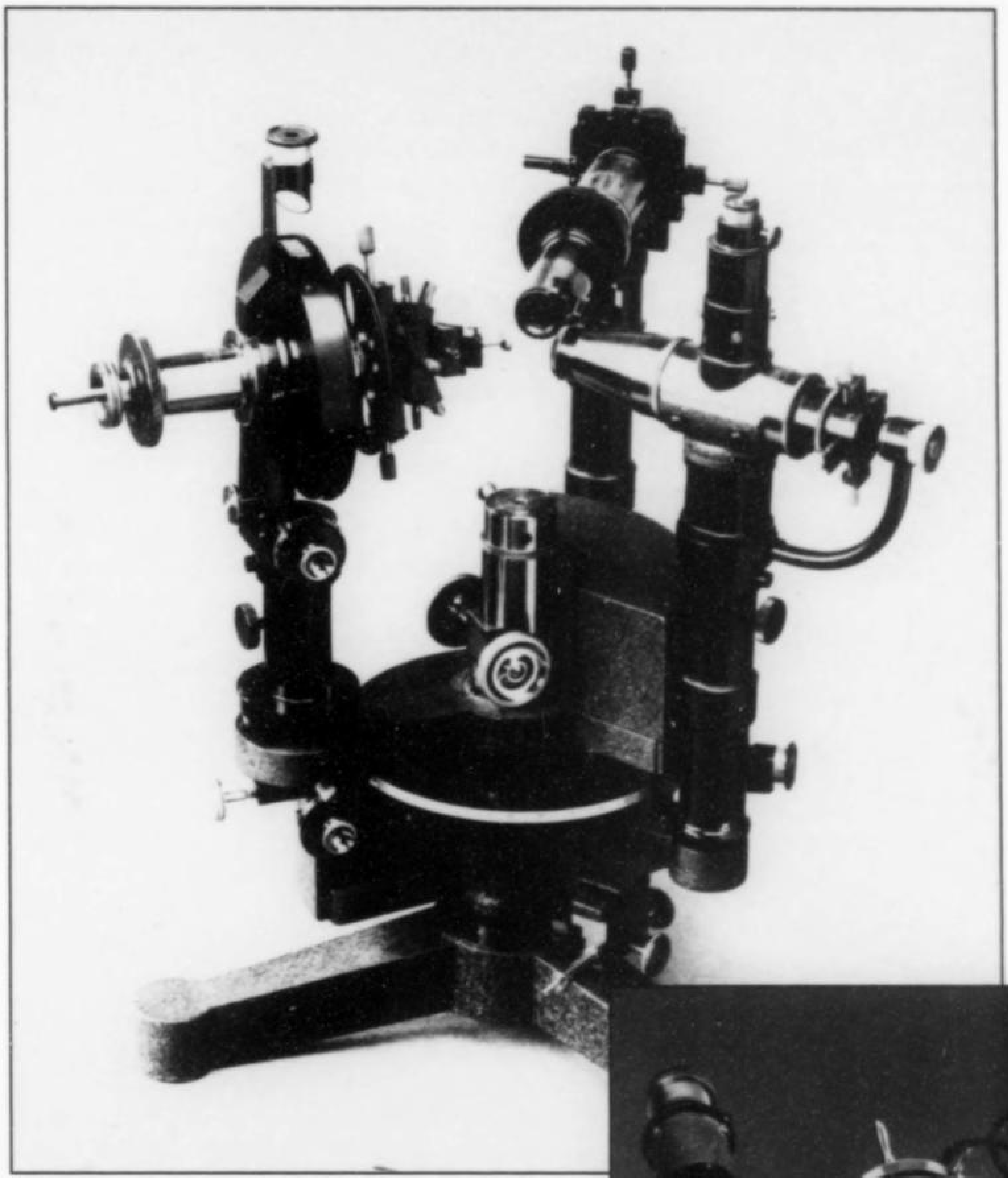
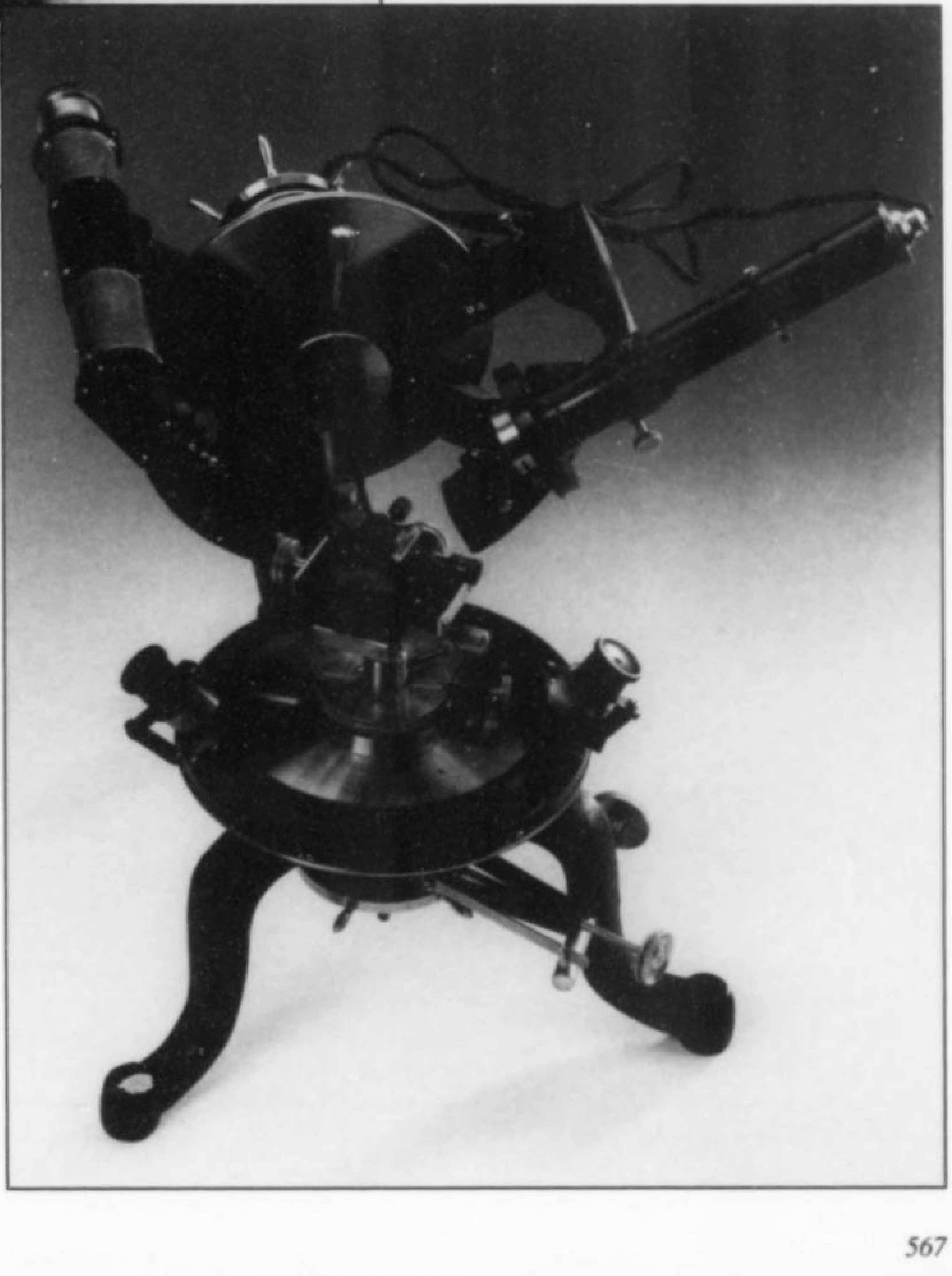


Figure 82. **Two-circle reflecting goniometer by Carl Zeiss, Jena, photographed in 1919.**

Figure 83. **Czapski two-circle reflecting goniometer with electrical illumination, signed: "R. Fuess, Berlin Steglitz," ca. 1920. Note that the crystal holder is mounted on the vertical axis of the horizontal circle.**



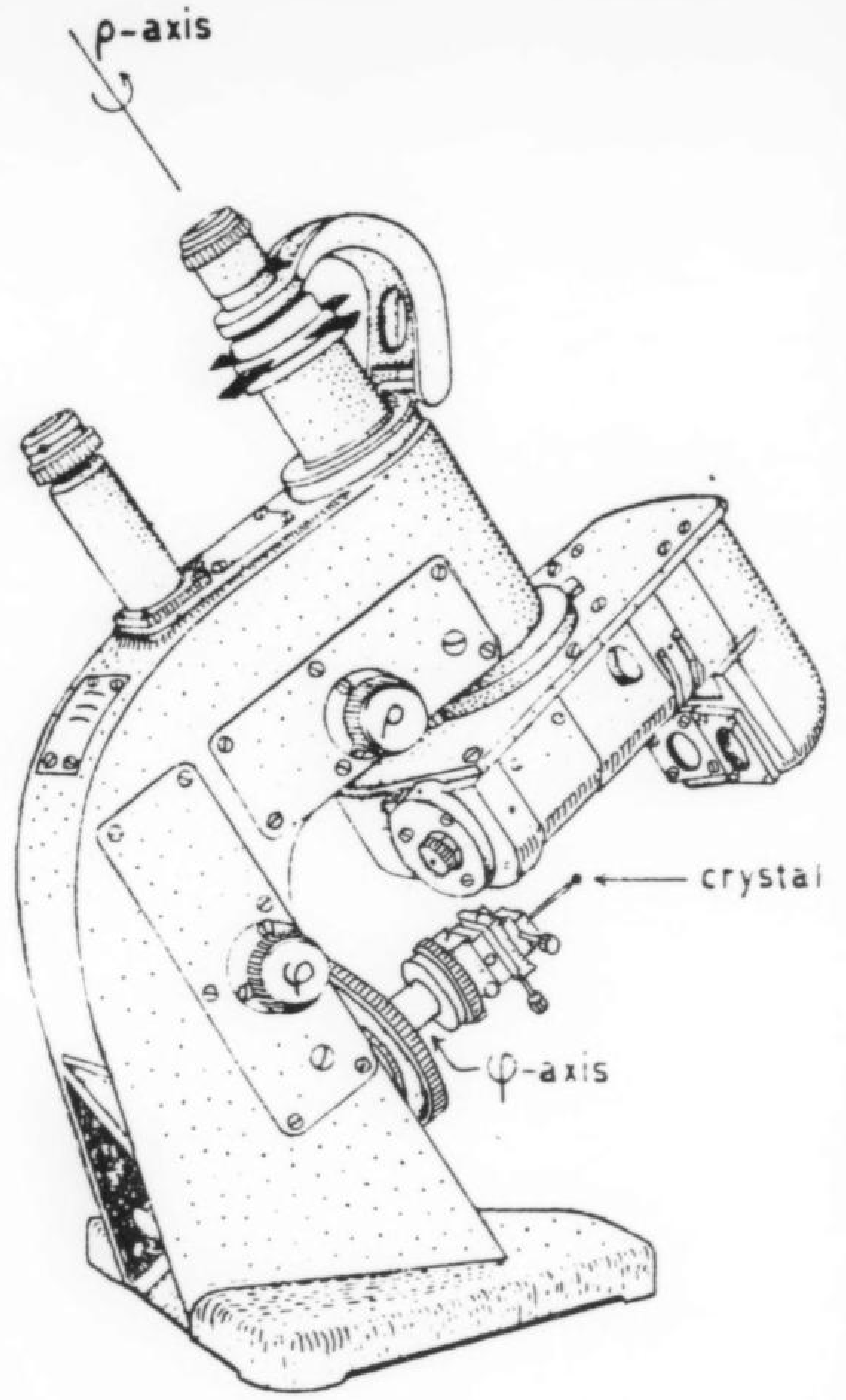


***Figure 84.* The Nedinsco two-circle reflecting goniometer. Technological advances reduced the dimensions to the size of a compact microscope (Terpstra and Codd, 1961).**

collimation method. After suggestions for improvement by Groth and **Carol Maria Viola** (1855–1925), director of the Iglesias, Sardinia Mining Academy, Leiss introduced a similar signal with collimator. The two telescope carriers are independently revolvable and fixable about the horizontal axis of the vertical circle. The collimator is illuminated by a 4-volt incandescent lamp or with an adjustable mirror. Viola (1897) also made the suggestion (probably not realized) for the construction of a universal instrument that will not be treated in detail here. Its novel feature was the possibility of adjusting the crystal by observing it through a loupe which is enclosed in the hollow axis of the vertical circle. The fine adjustment mechanism and various other parts are the same as in Fuess's Model II.

By contrast with other one-circle and two-circle technology, the reflecting position is attained with the Czapski goniometer not by turning the crystal face into view of the telescope, but by turning the entire telescope and collimator system as a unit around the crystal faces to search for reflections. With this goniometer all faces above and up to 30° under the horizontal (equatorial) plane can be measured. The azimuth angle *phi* is read from the horizontal circle and the polar angle *rho* from the vertical one. The accuracy, as with most Fuess instruments, is 30″.

The Czapski goniometer lends itself best to measuring boundary angles by the total reflection method. To convert the goniometer into a refractometer, the goniometer head is replaced by a hemisphere of high-refractive-index glass. In response to a suggestion in 1905 by **Johann Friedrich Karl Klein** (1842–1907), a combination of a normal one-circle reflecting goniometer and a Czapski theodolite goniometer was constructed. This instrument allowed, for example, the determination of the prism angle with the one-circle method, and used the theodolite method only for faces that did not lie in one zone.

In 1912, in Groth's laboratory in Munich, **Max von Laue** (1875–1957) proved the diffraction of X-rays by crystal lattices. With this discovery he opened the field of structure analysis and of investigation of the relation between morphology and chemistry. **Georg Wulff** (1863–1925) was one of the first to study the Laue diagrams using a Czapski goniometer.

Although Czapski worked for Carl Zeiss in Jena, it is not clear whether his goniometer was constructed there or whether the Zeiss workers only converted a refractometer. In 1896 Fuess offered his Czapski Model with auto-collimation, and after 1899 with normal signal. After 1905 the model by Klein, with accessory (one-circle) collimator and telescope, was on the market.

Following a suggestion from Fedorov and **Karl Stoeckl** (1873–1959), the adjustment mechanism of the Czapski goniometer gained a further circular arc system with reading verniers, in the center of which an "artificial crystal" could be placed. This addition enabled computations to be made on the instrument. In principle the two circular arcs of the adjusting mechanism made it a four-circle goniometer.

Fuess's prices (1903–1909) for the model with auto-collimation and for the one with normal signal were 600 and 675 Marks respectively; similar but simpler model variations were priced at 300 and 375 Marks. Klein's model cost 975 Marks and Stoeckel's goniometer 1,045 Marks.

In comparison to the Goldschmidt-Stoe instruments the Czapski-Fuess goniometers are relatively rare, but are still found in numerous important institutions.

About 60 years after Czapski's publication, his construction principle was newly adopted by **Pieter Terpstra** (1886–1973) in Groningen and the *Ned*erlandsche *Ins*trumenten *Co*mpagnie. By virtue of the progress in mechanized machining technology, the size of the *Nedinsco* instrument could be drastically reduced: it is comparable in size to a compact microscope. Through the use of glass circles, for example, the diameter of the circle could be reduced and the corresponding adjustment mechanism dispensed with. The locking screws and fine adjustment mechanism were eliminated through the use of a constant-slip coupling system (Fig. 84).

The analogies to the Czapski model are not immediately apparent but are notable. The tilted "horizontal circle" *phi* holds the goniometer head and the collimator, and the telescope system rotates about the "vertical circle" *rho*. The angle between the telescope and collimator axis is kept very small. The lighting system, which works by the Köhler principle, is very complicated, with various prisms directing the light. Using a very accurate unscattered lighting system it is possible to examine very small crystal faces in an only slightly dimmed room in daylight. Both angles may be read from one reading microscope simultaneously. The author is not familiar with prices of the Nedinsco instruments. They may still be found in some institutes.

ATTACHABLE VERTICAL CIRCLES BY STÖBER AND V. M. GOLDSCHMIDT

Franz Friedrich Stöber (b. 1862) from Gent, Belgium, and **Victor Moritz Goldschmidt** (1888–1947) from Oslo designed an attachable vertical circle for converting a normal Fuess Model II for use by the theodolite method. An important basic motivation was surely the less expensive price. A few simple manipulations were sufficient to mount either of the supplemental circles on the vertical axis of the horizontal circle. Leiss (1925) remarked: "these vertical circles have not been widely introduced because they have some disadvantages and guarantee by their whole mechanical construction not to give precise measurements."

The double ring named for Stöber (1898) is simply mounted on the axis of a Fuess Model II after the goniometer head has been completely removed (Fig. 86). The ring consists of an internal graduated circle that rides in an external vernier ring (11.5-cm diameter). Both are reciprocally adjustable by means of a fine movement mechanism. The simple crystal holder is mounted on the internal edge of the graduated circle and is movable radially in the empty space of the center of the ring. The total ring assembly can be pivoted fully between the collimator and telescope. Measurement is not possible only where the narrow lateral external surface crosses the collimator or telescope. No statements were made about the accuracy of the Stöber ring.

In a later, essentially more stable and costlier assembly the Stöber principle was retained. The justification and centering apparatus was placed in a movable third graduated circle that was mounted perpendicular to the vertical circle. Here we are dealing with a three-circle goniometer. The Euler cradles used in modern X-ray fluorescence techniques closely resemble Stöber rings.

An accessory similar to Stöber's was designed in 1912 by Victor Moritz Goldschmidt from Oslo (not to be confused with Victor Mordecai Goldschmidt from Heidelberg) (Fig. 87). Tutton (1922) described it as follows:

> *It consists of an ordinary Fuess No 2a goniometer, to which a new attachment is fitted, instead of the ordinary adjusting apparatus. The usual inner vertical axis supports first the centering apparatus of the usual kind, but more rigidly constructed and somewhat larger. On the upper slider is screwed the basal elongated ground plate of the vertical circle-fitting, the circle* v *itself being carried on its bearing at one end of the arm, and a counterpoise* c *placed on the other end on the opposite side of the centre. The bearing-fitting of the circle* v *is secured to the ground-plate by two screws which permit of the adjustment of the axis of rotation of this circle truly perpendicular to the axis of the ordinary horizontal circle. The circle* v *is divided into half-degrees and with the inner vernier reads to one minute. The circle may be fixed by a screw* a, *and fine adjusted by the screw* f. *The axis of this new vertical circle* v *carries two mutually perpendicular circular segmental guiding arcs and sliders* b1 *and* b2, *divided and reading by verniers to 5′, which replace the ordinary adjusting segments.*

Both goniometer accessories were constructed exclusively by Fuess in Berlin. The Stöber ring cost 105 Marks in 1903–1909 and was apparently no longer manufactured by 1919. In any case only Goldschmidt's theodolite accessory was available in that year's catalog, priced at 230 Marks.

These Stöber and Goldschmidt attachments are found relatively rarely. Most are still in their original fitted cases and are not recognized as the goniometer accessories they are.

WÜLFING'S AND LEISS'S GONIOMETERS

Leiss (1925) criticized all of the theodolite goniometers described above because of their one-sided positioning of the vertical circle. Wülfing (1924) also came to the conclusion that:

> *With such instruments one can make measurements accurate to more than 2 arc-seconds only with great difficulty. One must handle the movement of the circles carefully and subject their mutual position to very frequent monitoring. These instruments, therefore, stand in contention to the good tradition that a tool should be produced so that it saves more work than it makes.*

The constructions of **Ernst Anton Wülfing** (1860–1930), professor of mineralogy at the University of Heidelberg, and of C. Leiss both tackled the problem by positioning the axis of the vertical circle in two strong bearing supports. Wülfing's instrument also used a Fuess Model II as its basis (Fig. 85). The collimator *(K)* and telescope *(F)* are aligned in a straight line and simultaneously form the horizontal axis. Because of this alignment it is necessary to conduct the illuminating and reflected light rays through a complicated system of trapezoidally and prismatically formed glass bodies. The optical system is contained in a bridge-like construction that is rotatable around the horizontal axis of the vertical circle. This design shows parallels to that of a so-called "projection goniometer" that Victor Mordecai Goldschmidt had constructed in 1896.

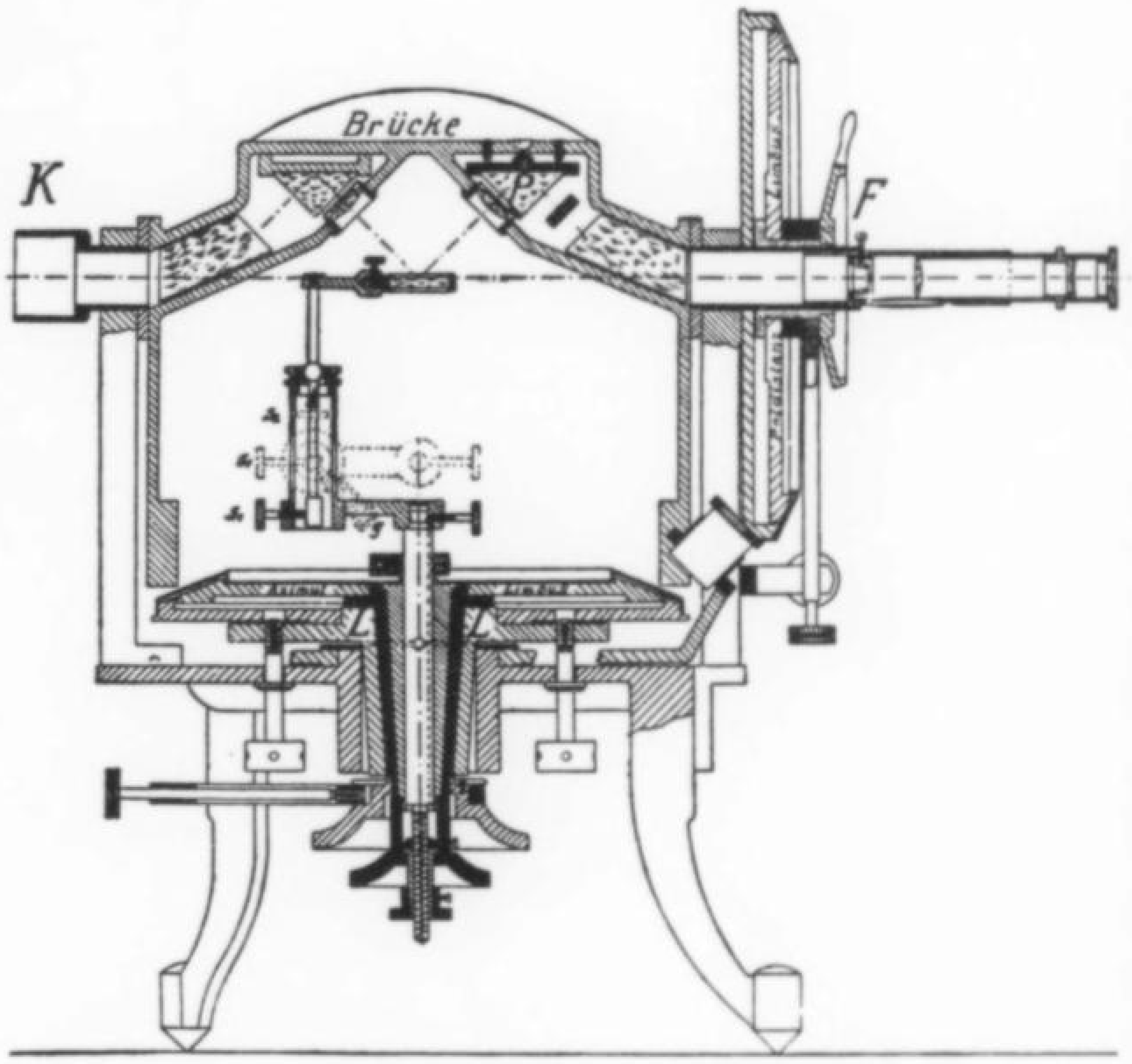


Figure 85. **Cross-section of a Wülfing bridge-goniometer (Wülfing, 1924).**

C. Leiss's new design of 1925 (Fig. 88) distinguishes itself above all because the observation telescope *(FO)* as well as the vernier microscopes for both circles are coplanar. This simplifies the readings, especially for crystals with many faces. The horizontal circle of this instrument is again supported by two bearings, and the goniometer head is partly under the plane of the hollow horizontal circle.

Both instruments were built by the Leiss Company, Berlin-

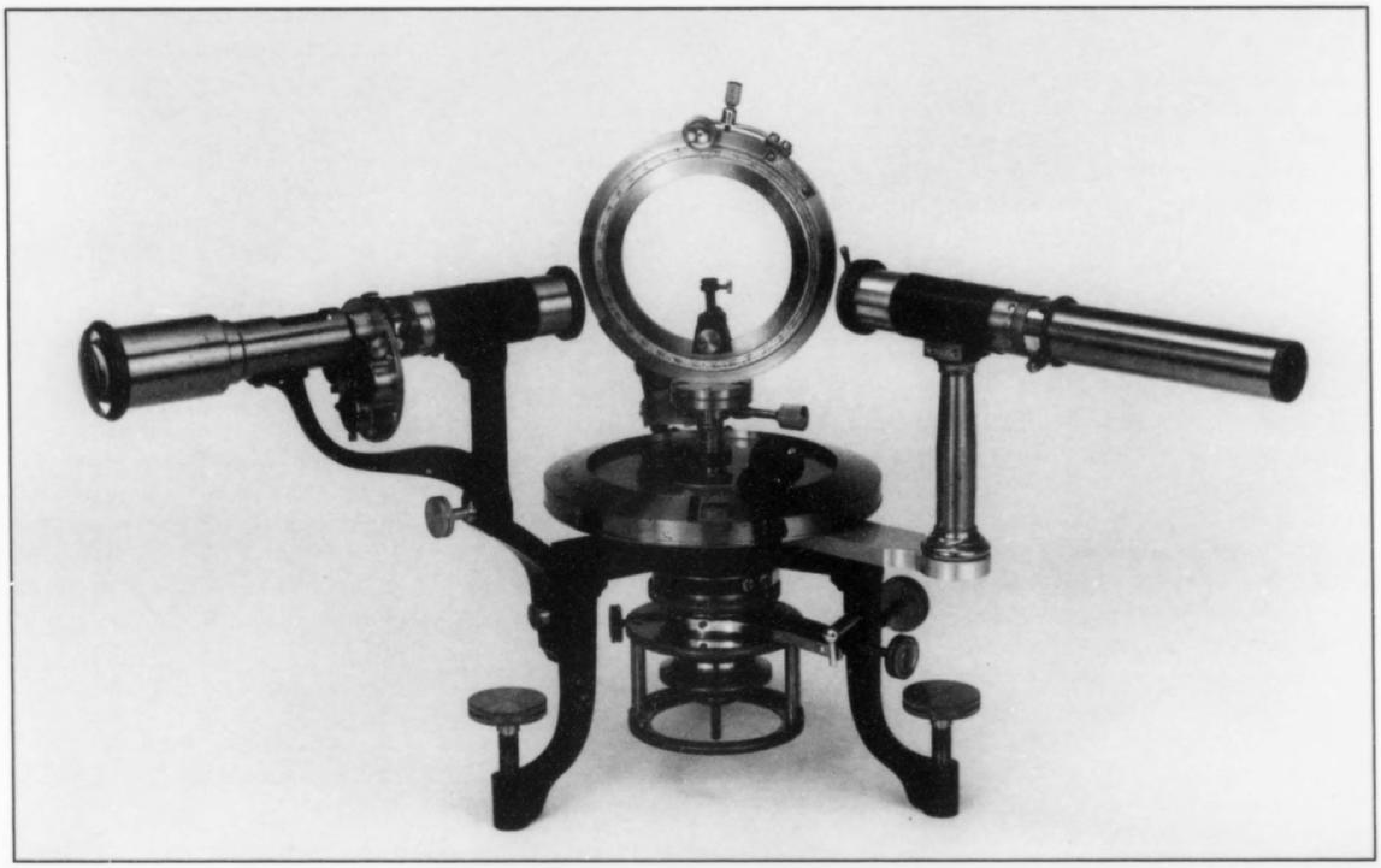


Figure 86. The "Stöber" ring attached to a model IIa goniometer, both signed: "R. Fuess, Berlin Steglitz," ca. 1910.

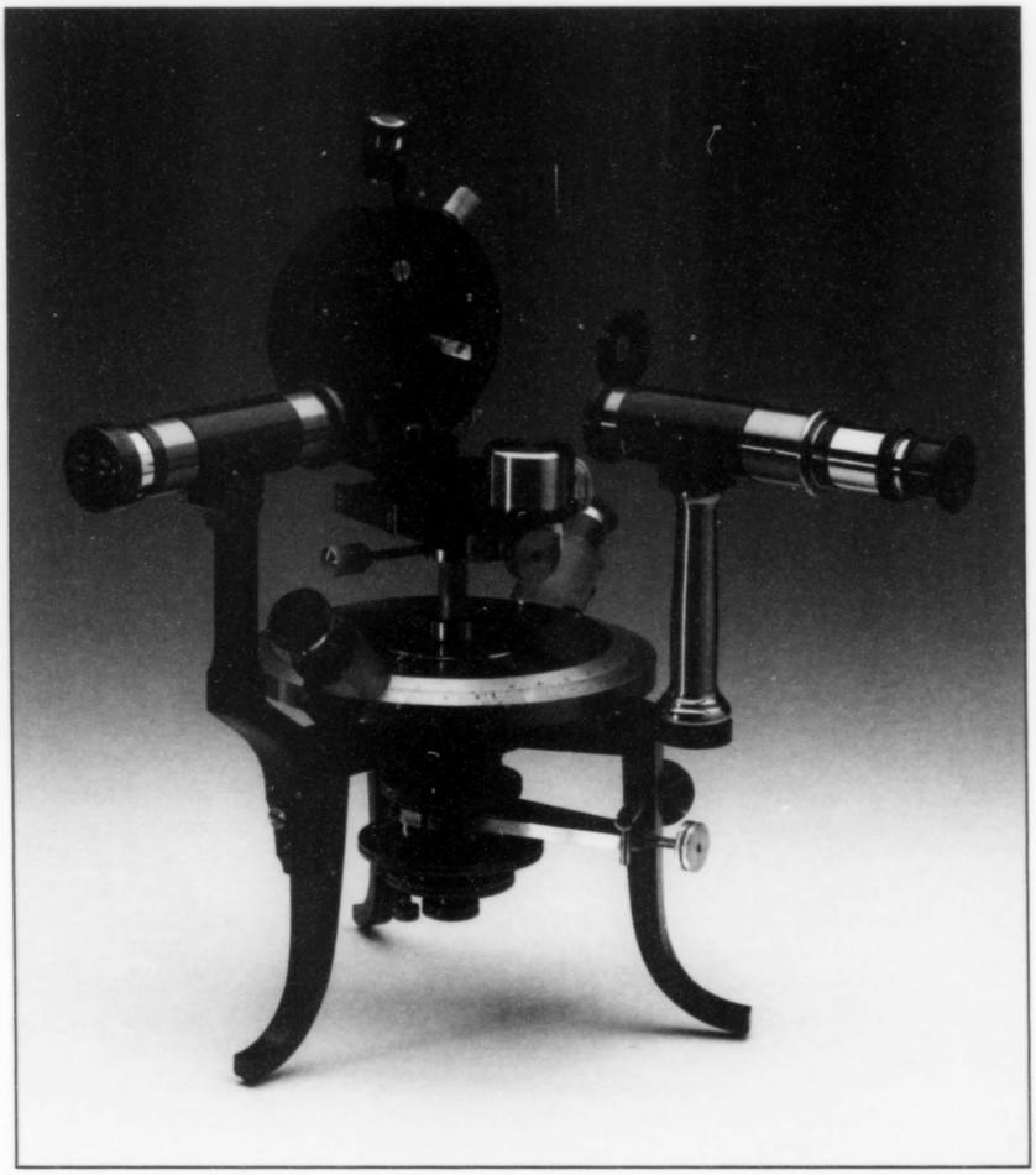


Figure 87. V. M. Goldschmidt attachment mounted on a model II goniometer, signed: "R. Fuess, Berlin–Steglitz," purchased in 1909. University of Innsbruck collection.

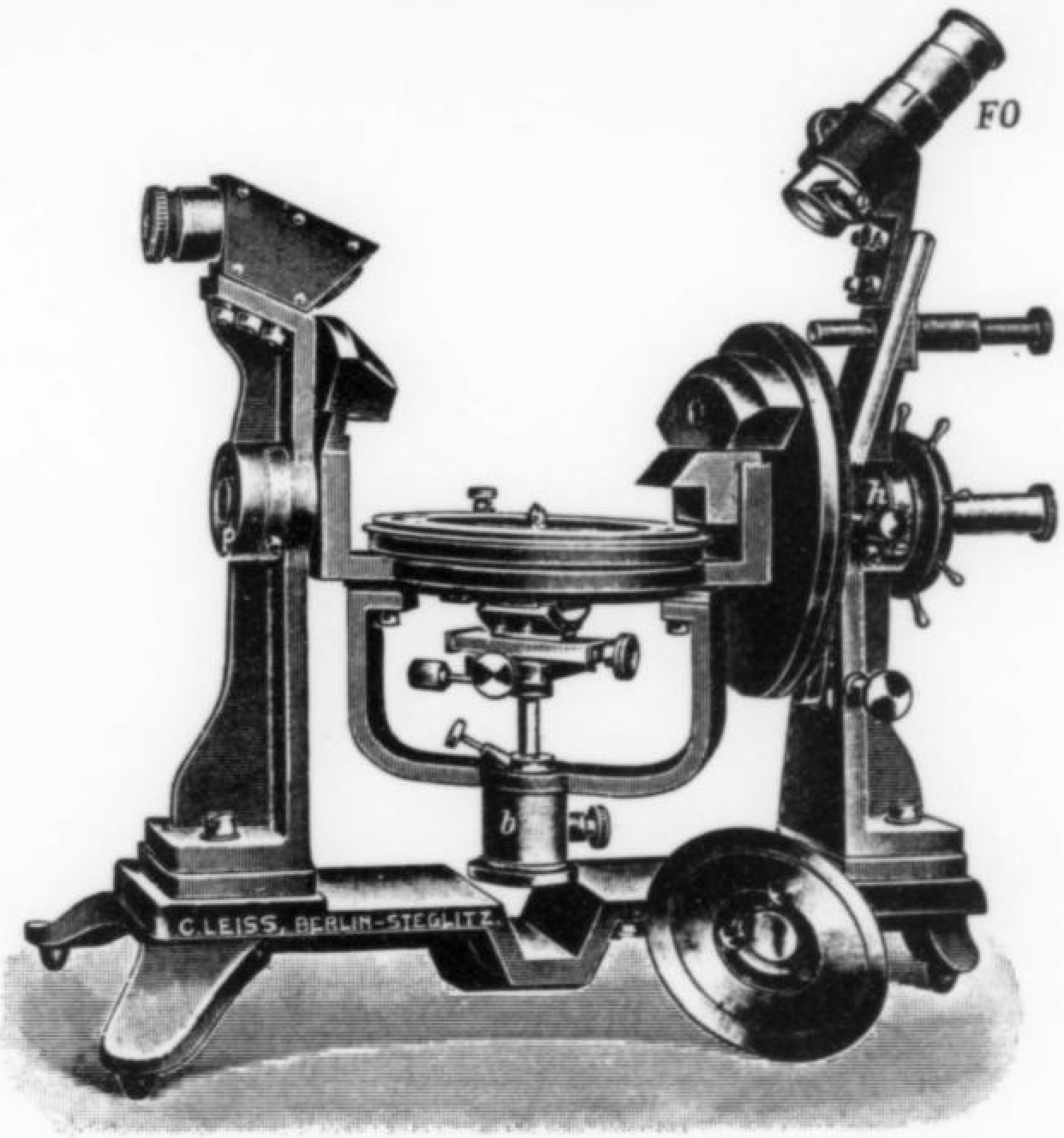
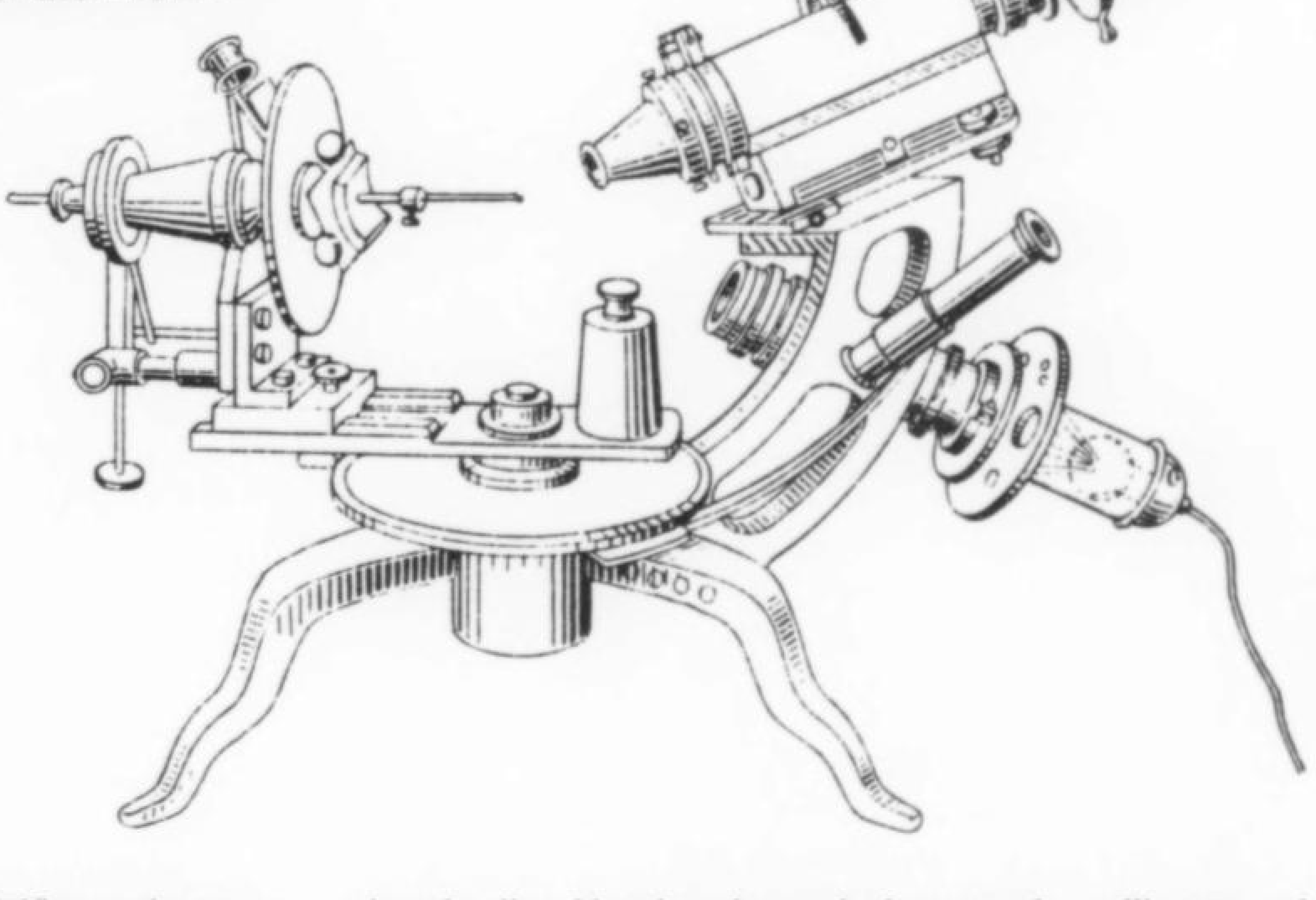


Figure 88. **The improved Leiss two-circle reflecting goniometer with bearing support (Leiss, 1925).**

Figure 89. **Modification of the classical instrument. Observation telescope and collimator are arranged in a vertical plane (Terpstra and Codd, 1961).**



Steglitz. This is remarkable in the case of the Wülfing goniometer, because one can assume that the Heidelberg Institute worked almost exclusively with Stoe-Rheinheimer. The Wülfing apparatus appears to be a one-only construction, and is not in Leiss's 1927 catalog. The author is not aware of prices or surviving instruments of either type.

MODERN GONIOMETERS BY TERPSTRA

After all possible combinations and variations of two-circle reflecting goniometers were tried through the course of time, only one problem was left to solve. In almost all models the measuring area was limited because the carrier of the vertical circle could only be revolved between the positions of the collimator, on one side, and the telescope mount, on the other. This classic arrangement was modified by, **P. Terpstra** (probably in the 1950's). In the modern goniometer the planes of the collimator and telescope no longer lie horizontally but are arranged vertically, one above the other. The deciding difference in this design principle (Fig. 89) is that the line bisecting the angle between the collimator and telescope is perpendicular to the vertical axis of the horizontal circle. This is achieved by placing the collimator axis upward 45° and the axis of the telescope 45° downward. Thereby the dead angle of the measurement area is greatly diminished.

The first instrument with this design was constructed by Rheinheimer (Stoe & Cie) (Terpstra and Codd, 1961, p. 323). Stoe's contemporary models J and JU also have this design. The goniometer built by the Techne Ltd. Company, designated the CM-goniometer after W. L. Codd and W. T. Moore, is notable for its improved mechanism. The adjustment mechanism is built to the old Petzvaal system as a hemisphere in its corresponding shell. The crystal itself is mounted on a magnetic holder which is freely movable on the flat disc of the adjustment mechanism.

These modern instruments are seldom used for the determination of crystal morphology in the classical sense, but as aids to the quick orientation of single crystals for X-ray structure analysis, or to measure the angles on faceted gem stones.

Three-circle Reflecting Goniometers

Although the crystal rarely has to be remounted and adjusted with the two-circle method, problems do occur when the desired face is not included in a crystal zone or its edge does not lie vertical to this zone. In this case, complex computations are necessary to determine the indices. These computations can be dispensed with in the *three-circle method*, because here every desired crystal edge is parallel to an arbitrary direction in space. The crystal is mounted only once; the measurement can be made in any desired zone and the orientation determined simultaneously. All movement is made with the crystal, the telescope and collimator remain in stationary positions.

The arrangement of the three circles must meet the following conditions:

(1) The horizontal circle does not alter its position.

(2) The vertical circle stands perpendicular to the horizontal circle and is revolvable about it.

(3) The third circle has an axis that can be placed in any space, and its circle plane is at right angles to the vertical circle.

(4) The extensions of all three axes meet at one point, the optic center.

The last condition especially requires a lengthy and complicated adjustment so that the disadvantages of this very expensive instrument outweigh the above-mentioned advantages. The three-circle reflecting goniometer has never been able to maintain viability.

The technology was developed by **George Frederick Herbert Smith** (b. 1872), of the British Museum of Natural History, and two three-circle goniometers were built for the Museum (Smith 1899, 1904) (Fig. 92). Tutton (1922) writes:

> *The first form was simply obtained by adding to an ordinary No 2a Fuess goniometer a second circle arranged vertically, which carried by means of a rectangular elbow bracket-bearing a third circle supporting the crystal at the end of its axis, with the usual adjusting and centering movements. With this adapted instrument, however, measurements can only be made through little more than a right angle in any particular zone other than the zone of reference, without readjustment of the vertical and third circles. In a second instrument, which was constructed by Messrs. Troughton and Simms, this difficulty is largely overcome by reflecting the line of reference—which is the line bisecting the angle between the telescope and collimator in the ordinary single-circle goniometer and the adapted one just referred to—at right angles to its normal position by means of mirrors, so that on rotation of the vertical circle round the axis of the horizontal circle the axis of the vertical circle may be brought into coincidence with the line of reference in two positions on diametrically opposite sides of the centre, and still be free for somewhat further movement beyond 180° of movement thus already afforded. . . .The later instrument of Herbert Smith, in which a much greater angular range is obtained by the reflection of line of reference, the telescope and collimator being very close together so as to be nearly parallel and pointing to one side of the centre. . . . The telescope and collimator are separate optical tubes (not auto-collimating) but are supported by the same pillar rigidly connected with the fixed tripod table. . . . A further accessory of considerable use is a camera lucida. It consists of a double Amici prism, for reflecting the object in the direction of the drawing-paper supported on the base-board of the instrument.*

The attachment for the prototype, as well as a complete second Smith goniometer, were constructed by the Troughton & Simms Co., London, the goniometer costing 97£ 15s. Both instruments are unique and can be found at the British Museum of Natural History.

As in the cases of one-circle and two-circle goniometers, there was simultaneous and independent development and construction of three-circle instruments. In 1900 the Göttingen mineralogist **Johann Friedrich Karl Klein** (1842–?) described a so-called "crystal polymeter" that employed the same design as Smith used. This polymeter served not only as a one-, two-, or three-circle goniometer but also as an axial angle apparatus, total reflectometer or polarizing microscope (Fig. 90).

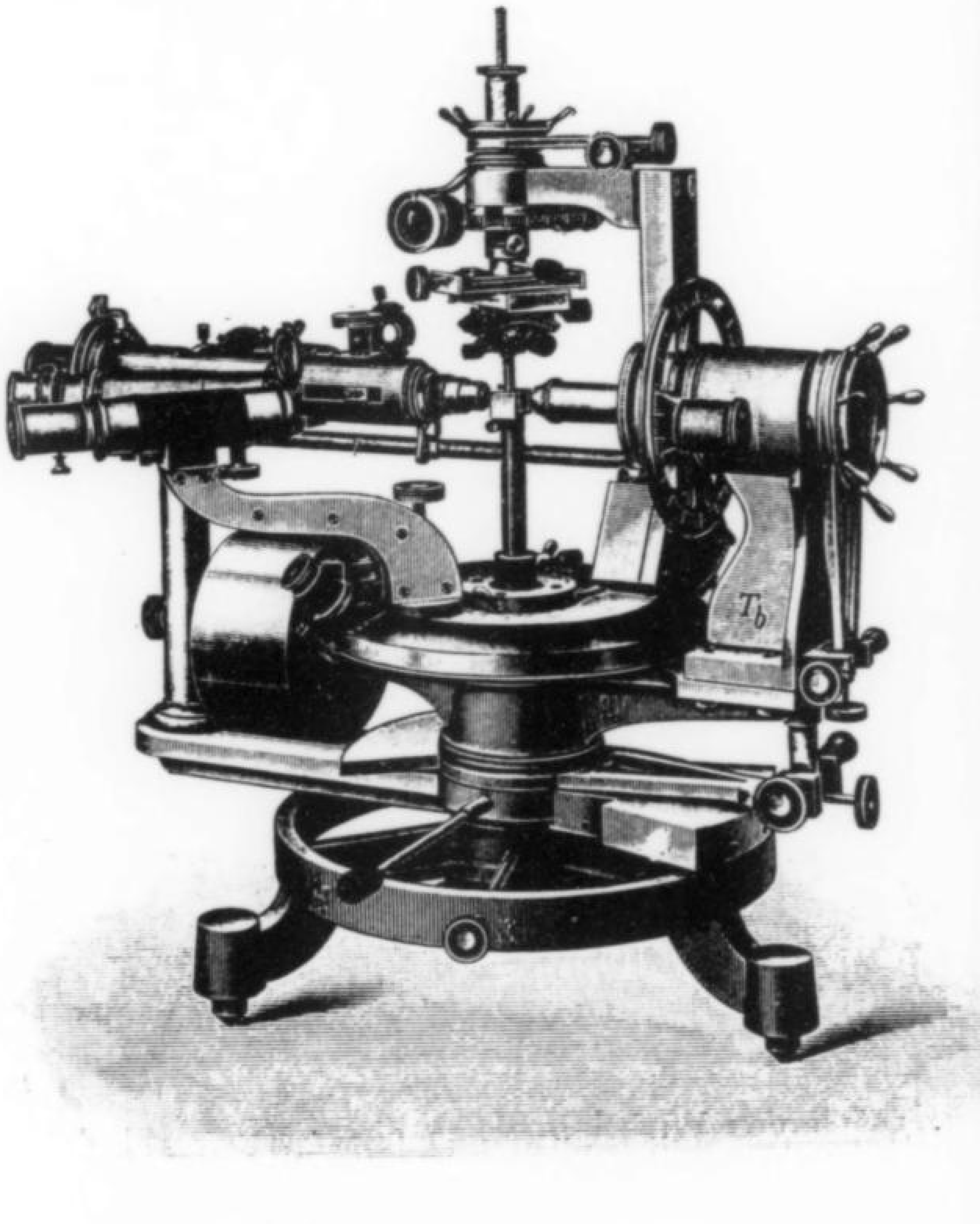


Figure 90. **Klein's three-circle goniometer. This so-called "polymeter" was the largest goniometer ever built (Groth, 1905).**

In 1900 the polymeter cost an enormous 2,250 Marks and the three-circle goniometer 1,750 Marks. The author is unaware of any existing instruments. This gigantic machine was, of course, manufactured by R. Fuess.

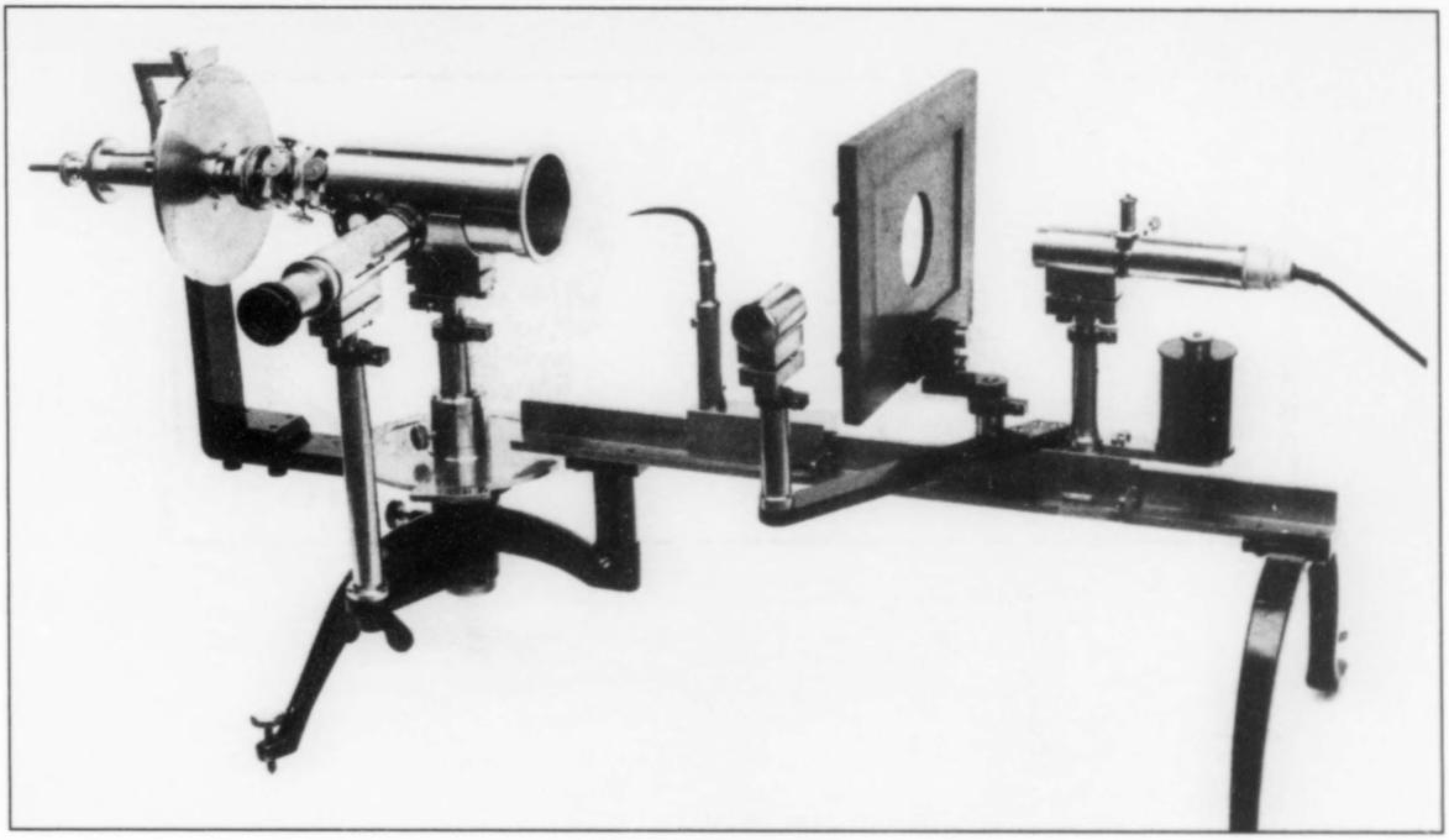


Figure 91. **Model E two-circle goniometer with modifications for photographic recording, by S. Rösch, signed: "Stoe. & Cie, Heidelberg," ca. 1930.**

The Decline of Classical Goniometry

With Klein's crystal polymeter and the three-circle instruments of Smith, the development path of the goniometer came to an end. After about 1900, larger and larger goniometers were built to measure smaller and smaller crystals; one cannot help thinking of the mass extinction of the dinosaurs.

In this regard Terpstra and Codd (1961) remark:

> *After 1900, however, development began to slow down. Crystallometry began to be neglected, in many laboratories, fine goniometers were relegated to the gallery of historic instruments. This process was even accelerated when Laue, Knipping and Friedrich published (in 1912) the results of experiments carried out under the inspiration of the diffraction theory of the physicist (and former pupil of Groth) Max von Laue. The age of crystal structure had begun.*

The measurement of X-ray diffraction uses a technology analogous to that of the reflecting goniometer. In place of visible light, X-rays are utilized, and a scintillator replaces the observation telescope. The X-rays do not reflect from the outer faces of the crystal but penetrate its interior, and are diffracted by ion lattices. A hundred years passed between the invention of the reflecting goniometer by Wollaston in 1809 and Laue's revolutionary discovery in 1912 which ended the era of classical crystal morphology.

Photographic goniometer

One of the last attempts to revive classical goniometric studies was made in 1926 by the Leipzig mineralogist **Siegfried Rösch** (b. 1899) who was later employed by the optical firm of Leitz, Wetzlar. There were earlier experiments by V. Goldschmidt in cooperation with C. Pulfrich and by M. Schwarzmann (1900) to photographically record the light signals reflected by crystal faces. However, it was Rösch who first introduced an operating instrument to replace the visual method. The most important advantage of photographic goniometry is the registration of light rays reflected by minute crystal faces which cannot be distinguished by an observer. This can be achieved by varying the exposure and/or the sensitivity of the photographic paper.

The apparatus devised for research with reflection-photography is based on a standard Modell E two-circle goniometer of Stoe in Heidelberg (see Fig. 91). The regular observation telescope is retained solely for crystal-adjustment purposes. The electric fitting of the light source and its collimating lens is placed on the outer end of a long horizontal bar with a metric scale. Its rider can be slid in or out, similar to the arrangement of an optical bench. In front of the light unit there is a pillar that carries a wooden frame to house a photographic plate with a format of 13 x 18 cm. This pillar may also be moved along the sliding bar to approach or withdraw from the crystal holder.

The light is emitted either from the rear of the photographic plate which has a central hole, or from the side of the plate redirected by a mirror mounted at a 45° angle. The photographic paper may

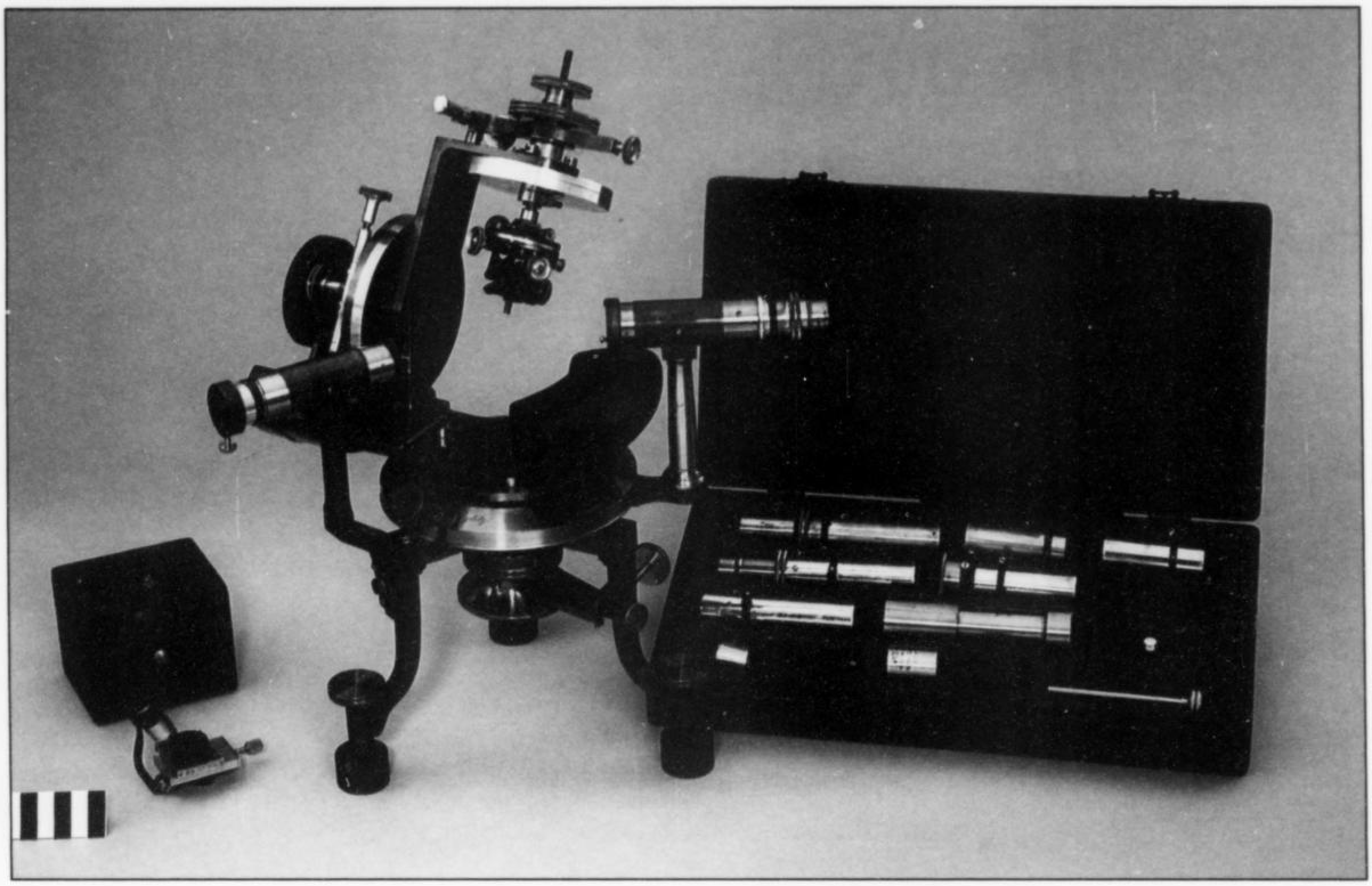


***Figure 92.* Smith three-circle goniometer mounted on a Fuess model II base. Attachments by Troughton & Simms, London, ca. 1900. Courtesy of the Natural History Museum, London.**

alternatively be inserted into a horizontal steel cylinder that is mounted on the vertical axis of the goniometer. This cylinder may be adjusted by two traversing boxes underneath. Normally the cylinder axis is aligned with the horizontal axis of the vertical circle of the goniometer and may be simultaneously rotated about the horizontal circle. However, there is a hole on either side of the cylinder, thus providing for illumination at right angles to the axis of the cylinder. A hook on a sliding pillar is used for adjustment purposes only.

It is interesting to note that Rösch suggested that his "reflectograph" be predominately employed in gemology. The author knows of only one photographic goniometer, but it appears very likely that many more exist in laboratories of the gemstone industry.

Conclusion

Most goniometers were produced in small series, or as one-of-a-kind models, as the result of close cooperation between important crystallographers and the leading instrument makers. They are irreplaceable witnesses to cultural history and the history of the sciences of mineralogy and crystallography. In these specialized instruments the perfection of the craft of the precision machinist and optician was combined with a large measure of esthetic sensibility.

One of the main purposes of the above treatise is to awake the interest of responsible persons in institutions where such goniometers and valuable crystallographic instruments are stored, unnoticed, in inaccessible rooms. The author urges that these treasures be prized, and, whenever possible, placed in public exhibitions for all to see. The current world supply of pre–World War II reflecting goniometers of all types probably does not exceed 800, and half of those are probably of Fuess company manufacture.

Acknowledgments

The author is grateful, above all, to Mr. Peter Embry for many valuable citations and much constructive criticism. Many museums provided information about the existence of instruments, and about their makers: The Natural History Museum (London), the Humboldt Museum (Berlin), the Deutsches Museum (Munich), the Bergakademie (Freiberg), the University of Innsbruck, and Herb Obodda (Short Hills, New Jersey) kindly furnished photographs of goniometers in their possession. Thanks are also due to the photographers Neuhofer (Deggendorf), Bungartz (Freising), Medenbach (Bochum), Knopfe (Freiberg), and Scovil (Phoenix).

My thanks also to Mr. Herb Obodda of Short Hills, New Jersey, who accepted the difficult task of translating the German text, and to Thomas Moore who refined the translation.

And finally, I would like to dedicate this work to my wife, Karin, who has patiently tolerated my craze for brass and glass.

The following compilation of goniometer makers and literature is as complete as possible. If interested readers can make further additions to it, the author thankfully invites their contributions.

Manufacturers of Goniometers

The information concerning 100 manufacturers of goniometers listed below came to the author's attention over a period of approximately 15 years. Though far from complete—especially concerning makers of contact goniometers—it probably includes almost all important goniometer makers from 1789 to ca. 1950. To assist instrument collectors some allusion is made to the relative rarity of the various types of goniometers in the collections of institutions.

Abbreviations Used

Type of goniometer		*Rarity*	
c :	contact	Lit. :	only known from literature
W :	Wollaston	1 :	single instrument known
M :	Mitscherlich	+ :	2 to 3 instruments known
H :	Horizontal	* :	4 to 10 instruments known
2c :	two-circle	# :	abundant
s :	special		

AUSTRIA

Ekling, Johann Michael: Vienna, Spiegelgasse 109, c, 1

Lenoir, G. A.: Vienna, c, 1

Huck, G. Vienna, c, 1

Prokesch, Wenzel: founded 1789, Vienna, Kothgasse 46, s, Lit. Haidinger 1865

Schneider, Ernest: Founded 1872, Währing near Vienna, Martinstr., later Vienna, Stadlgasse, M, 1

Starke, Georg Christoph: (1794–1865) and son Christoph (1832–1917), founded 1817 (1819?) K. + K. Polytechnisches Institut., Vienna, Karlsgasse 11, 1866 Starke and his brother-in-law Kammerer, Carl. Liquidation 1940, M, 1

Stadler, Josef: Linz, W, 1

BELGIUM

Boet, P: Bruxelles, 2c, 1

DENMARK

Jünger's, E.: Mechanisches Etablissement: Copenhagen, Dronningens Tvergade 277, owned by Jürgensen, Urban (1776–1830), son Louis (1806–1863), M, +, identical instrument made by Powell & Lealand, London

FRANCE

Bazaille: Paris, Place Dauphine 22, Rue de l'école de Médécin 113 W, +

Bénevole & Coquais: Paris, W, 1

Brunner, Johann: (1804–1862), sons Emile (1834–1895), Leon (1840–1902), founded 1828, Paris, W, +

Cauchoix, Robert Aglaé: (1776–1845), founded ca. 1800, sold to Rossin in 1836, Paris, rue de la Loi 505, quai Voltaire 27, s, 1

Chevalier, Louis Vincent: (1734–1804, sons Vincent Jacques Louis (1771–1841) and Jean Gabriel Auguste (1778–1848), grandson Charles (1804–1895), founded 1765, Paris, quai d'Horloge 31, 21, 67, 69, Palais royale 163, W, *

Deleuil, Joseph: (1805–1862), son Jean Adrien (1825–1894), founded ca. 1820, sold 1893 to Pillon-Velter, Paris, rue du pont Lodi 6, rue faiguière 42, rue Dauphine 24, W, 1

Deyrolle, Emile: founded 1836, Paris, rue de Bac 46, c, 1

Duboscq, Louis Jules: (1817–1862), founded 1849, merger with Pellin from 1883–1886, Paris, rue de l'odeon 21, W, *

Ducretet, Eugène: (1844–1915), founded 1864, Paris, rue Claude-Bernard 75, W?, Lit. Brieux 1980

Dumotiez, Louis Joseph. (1757–1815?), brother Pierre Francois founded ca. 1780, Paris, rue du Jardin 2, rue des Fossés Saint Victor, later taken over by Pixii, c, *

Férat, Jean Baptiste: Paris, assistant to Vincard, c, +

Fortin, Louise (?): (1750–1831), Paris, s, Lit. Malus

Gambey, Henry Prudence: (1787–1847), founded 1803, Paris, rue la loi, quai Voltaire 27, rue de Faubourg St. denis 52, rue Pierre-Levée, W, 1

Lutz, Edouard: founded in 1848, sold to Duplouich in 1896, Paris, rue du pont de Lodi, s, W, 1 Hofmann, 1878

Pellin, Phillippe: successor of Duboscq, Paris, rue de l'odeon 21, W, *

Pixii, Nicolas Constant: (1776–1861), son Antoine Hippolyte (1808–1835), took over Dumotiez in 1815, Paris, rue du Jardinet 27 c, +

Picart, A.: founded 1868, Paris, rue Mayet 20, W, *

Putois, Etienne Antoine: (1763–1798?), Paris, quai d'Horloge, cooperation with Rochette, W, 1

Rochette, Gaspard (1754–?), Paris, quai de l'Horloge 51, quai du Nord, c, W, *

Rousseau Paul & Cie: Paris, rue Soufflot 17, rue le Goff 2, W, 1

Richer, Emile: son Jean Francois, founded 1780, sold in 1870 to Guyard & Canary, Paris, rue de Harlai 6, rue de la Cerisaie 13, c, Lit. Hauy 1822

Secretan, Marc Francois Louis: (1804–1867), son Auguste (1833–1874), brothers in law George (1837–1906), George Emmanuel (1837–1906), successor of Lerebours N.P., Paris place du pont neuf 13, place Dauphine 28, W, +

Soleil, Jean Francois Baptiste: (1798–1878), son Henri, founded 1819, in 1849 separation of Soleil H.-Laurent L.-Jobin A. and Duboscq-Pellin, W, +

Vincard, Nicolas: (?–1788), Paris, quai de l'Horloge, c, Lit.

GERMANY

Apel, Friedrich: (?–1851), son Wilhelm (?–1898), founded 1808 Göttingen, Prinzenstr. 2, cooperation with Lüders 1826–1829, W, 1

Behm, Otto: Karlsruhe, 20th century, W, 1

Bénèche, L.: founded 1850, Berlin, Großbeerenstr. 19, 50, Lit.

Böhm, Josef (1804–1875) & **Wiedemann**, Franz (1832–1913): son Franz Jr. (1862–1944), Munich, Kaufingerstr. 20, Karlsplatz 20, moved to Eching, Bahnhofstr. 26 in 1944, still in existence, W, * (replicas)

Breithaupt, Friedrich Wilhelm: (1780–1855), son Georg (1806–1888), founded 1762, Kassel, Georgenstr. 1, Adolfstr. 13, still in existence, M, +

Desaga, C.: founded 1836, Heidelberg, Hauptstr. 60, c, +

Diederichs, Karl: founded 1875 with Bartels, Göttingen, Weenderstr. 52, Kornmarkt 5, Walkenmühlenweg 12, sold to Spindler & Hoyer in 1898, Lit.

Ertel, Traugott Leberecht: (1777–1858), son Georg (1813–1863), founded 1825, liquidated 1984, Munich, Luisen-Karlstr., Lit.

Fuess, Rudolf: (1838–1917), son Paul (1867–1944), founded 1865, liquidation 1976, Berlin Steglitz, 1865: Mauerstr. 84, 1870: Wassertorstr. 46, 1873: Alte Jakobstr. 108, 1892: Düntherstr. 8, all conceivable types of goniometers, most important maker, at least 100 instruments known

Gerhardt, C: Bonn, M, 1

Halle, Gustav Bernhard: (1842–1926), founded 1873, sold to Ritter, Erich and Frank, Anton in 1906, Berlin, Hermanstr. 59, Karlsgartenstr. 20, Lit.

Hensoldt, Moritz Karl: (1821–1903), founded 1852, Sonneberg near Wetzlar, W, 1

Huber Diffraktionstechnik: owner Nippus, Michael, Rimsting, contemporary company still extant, 2c

Einzelbach, Theodor: Stuttgart, ca 1850, Lit.

Kohl, Max: (1853–1908), founded 1876, Chemnitz, Beckerstr. 17 Dorfstr. 20, possibly only retailer

Körner, ?: Jena, H, Lit. Suckow 1837

Leiss, Carl August: (1868–1940), in charge of optical department at Fuess, R., separation 1921, Berlin, Stubenrauchplatz 1, liquidation 1985, H 2c, 1

Liebherr, Benedikt: Landshut, ca. 1820, W. 1

Lingke, Friedrich Wilhelm: (1784–1867), son August Friedrich (1811–1875), founded 1804, sold to Hildebrand, Max (1839–1910) and Schramm, Ernst. Eventually the company was renamed **Freiberger Präzisionsmechanik**, still extant, Freiberg, c, +; 2c modern, +

Linhof, Valentin: (1854–1929), founded ca. 1888, Munich, many addresses, H, +

Meyerstein, Moritz: (1808–1882), founded 1833, liquidated 1874 Göttingen, Weenderstr. 4, M, *

Oertling, Johann August Daniel: (1803–1866), son August Friedrich, founded 1827, Berlin, Oranienburgerstr. 57, M, *

Pistor, Carl Philipp Heinrich: (1778–1847), founded 1813, cooperation with **Schieck**, Friedrich Wilhelm (1790–1870) from 1829 to 1836 and with **Martins**, Carl Otto (1816–1871) from 1841 onwards. Liquidation in 1873, Berlin, Mauerstr. 34, M, 1

Steeg, Wilhelm & **Reuter**, Peter: founded 1855, Homburg, Kirdorfertr. 9–13, still existing in 1960, H , 1

Stoe, Peter & **Rheinheimer**, Fritz: founded 1887 in Heidelberg, Nephew Rheinheimer in charge from ca. 1905, sold to Wolfel, E. R. in 1961, Heidelberg, Landfriedenstr. 6, Jubiläumsplatz 70, Today in Darmstadt, Hilperstr. 10. 2c and modern 2c, most important maker of 2c goniometers, #

Studer, Johann Gotthelf: (1783–1832), Freiberg, son in law of Breithaupt, s, 1

Voigt, Gustav (1844?–1886) & **Hochgesang**?: founded in 1869, sold to Brunné in 1886, liquidated in 1957, Göttingen, In der Neustadt 25, Rotherstr. 13, Untere Maschstr. 26, W-c, Lit.

Wolz, Max: founded 1883, Bonn, Beethovenstr. 32, M, 1

Zeiss, Carl Friedrich: (1816–1888), founded 1846, Jena, still existing optical firm, 2c, 1

GREAT BRITAIN

Accum, Friedrich Christian: (1769–1838); London, Old Compton St., merged with Garden, W, 1

Adams, Dudley: (1760–1826), London, 53 Charing Cross, 60 Fleet St., 6 Jewry St., Lit. Bournon 1808

Adie, Alexander: (?–1858), successor to Miller & Adie since 1823 Edinburgh, 15 Nicholson St., 50 Princes St., Lit.

Akers Research Laboratories: Cambridge ?, modern 2c

Bancks, Robert: (1796–1834), London 411, 440 Strand, 119 New Bond St., W, 1

Cary, William: (1759–1834), brother John (1789–1852), London 272, 182, 181 Strand, W, *

Dollond, George: (1774–1852), London, 59 St. Pauls Churchyard, W, +

Elliot Brothers: London, 56, 449, 30 Strand, 101, 102 St. Martin's Lane c + W, +

Griffin, John Joseph: London, 53 Baker St., later J. J.Griffin & sons, 22 Garrick St., W, 1

Harris, William: (?–1848), London, 47, 50 High Holborn, c + s, 1

Jones, William: (1763–1831), brother Samuel (1784–1834), London, 30, 135 Holborn, 135 Lower Holborn, c + W, *

Negretti, Angelo Ludovico Enrico: (1819–1879) & **Zambra**, Joseph Warren (1822–?), London, 19 Leather Lane, 11 Hatton Gardens, 45 Cornhill, Holborn Viaduct, W, 1

Newman, John: London. 7–8 Leicter Square, 122 Regent St., W, 1

Troughton, Edward: (1753–1836) & **Simms**, Williams (1793–1860), London, 136, 138 Fleet St., 340 Woolich St. Carlton, W, *

Powell, Hugh: (1799–1883) & **Lealand**, Peter, London, 170 Euston Rd., c + s, +

Pye, William C.: London?, W, 1

Robinson, Thomas Charles: London, 38 Devonshire St., Portland Pl. W, 1

Sax, J.: London, 8 Hatton Garden, c, 1

Steward, James Henry: London, 406, 457 Strand, 7 Grace Church St., W, *

Unicam Instruments Ltd: Arbury Works, Cambridge, modern 2c,

Watson, William: (1837–1899), London, 313 High Holborn, Lit.

West, Francis: (?–1846), London, 17 Rupert Ct., 83 Fleet St., Lit.

Williams: London, c, 1

IRELAND

O'Reilly, Joseph Patrick: Dublin, Lit. Biedermann 1876
Spencer & Son: probably Dublin, W, 1
Yeates, George: Dublin, 2 Grafton St., W, 1

NETHERLANDS

Nedinsco: N.V. Nerderlansche Instrumenten Compagnie, Venlo, modern 2c, +

RUSSIA

Petermann: St. Petersburg, Lit. Fedorov

SWEDEN

Hellström, Peter: (1758–1826), son Peter, founded 1795 by Odelstierna, Carl, Liquidation 1860, ?, 1

SWITZERLAND

SIP: Societé genevoise pour la construction d'instruments de physique. Founded 1862, Geneva, Chemin Gourgas 5, 1952: rue des vieux grenadiers 8, H, +

CZECHIA

Kettner, Josef: Prague, Náprstekgasse 243, c, Lit. Goldschmidt

USA

Benjamin, E. B.: New York, c, 1
Duffey: Philadelphia, 91 South 8th St., W, 1
Laboratory Associates: Belmont Ma., 60 White St., modern 2c
Queen, J. W.: Philadelphia and New York, c, 1
Tuttle, Morehouse & Taylor Co: New Haven, Co. c, *

Chronological Bibliography

(77) PLINY THE ELDER, G. *Historia naturalis*. Book XXXVII, 56.

(1609) DE BOODT, A. B. *Gemmarum et lapidum historia*. Hanoviae (Hannover).

(1665) HOOKE, R. *Micrographia: Or some Physiological Descriptions of minute bodies made by magnifying glasses*. London.

(1669) BARTHOLINUS, E. *Experimenta Crystalli Islandici, Hafniae (Copenhagen)*. Translated by K. Mieleitner. Ostwald's Klassiker der exakten Wissenschaften, 1922, Leipzig.

(1669) STENO, N. De *Solido intra Solidum naturaliter contento Dissertationis Prodomus*. Florentiae, translated by K. Mieleitner. Ostwald's Klassiker der exakten Wissenschaften, 1923, Leipzig.

(1685) VAN LEEUWENHOEK, A. Concerning the figures of the salts of crystals. *Philosophical Transactions*, **24**, 1906–1912.

(1688) GUGLIELMINI, D. *Riflessioni filosofiche dedotte dalla Figuri de Sali . . .* Eredi d'Antonio Pisarri, Bologna, 38 p.

(1690) HUYGHENS, C. *Traité de la Lumière*. Leiden, translation by E. Lommel. Abhandlung vom Licht, 1964, Darmstadt.

(1710) LA HIRE, G. P. *Observations sur un espèce de Talc qu'on trouve communément proche de Paris au-dessus des bancs de pierre platre*. Histoire de l'Academie des Science, Paris, 341–352.

(1723) CAPPELLER, M. A. *Prodomus Crystallographiae*. Lucernae, translated by K. Mieleitner, 1922, Munich.

(1753) BAKER, H. *Employment of the Microscope*. 1st ed., London.

(1772) WALLERIUS, J. G. *Systema Mineralogicum*. Holmiae 1772, Vindobonae 1778.

(1782) LA BLANCHERIE, P. (ed.) Un goniomètre ou mesure angle, par M. Carangeot. *Nouvelles de la République des Lettres et des Arts*, No. **14**, 111.

(1783) CARANGEOT, A. Goniomètre ou mesure angle. *Observations sur la Physique*, **22**, 193–196.

(1783) L'ISLE, R. de. *Cristallographie*. Paris, 2nd ed. Vol. 4, 26–29, 93, pl. VIII.

(1786) CARANGEOT, A. Lettre de M. Carangeot . . . M. de la Metherie, sur le goniomètre. *Observations sur la Physique*, **29**, 226–227.

(1787) CARANGEOT, A. Lettre de M. Carangeot . . . M. Kaestner, sur de prétendues erreurs dans la description du goniomètre. *Observations sur la Physique*, **31**, 204–206.

(1801) HAUY, R. J. *Traité de Minéralogie*. Paris, 5 Vols. Vol. I, 248–253, pl. VIII.

(1802) WOLLASTON, W. H. On the oblique refraction of Iceland crystal. *Philosophical Transactions*, **92**(2), 381–387.

(1805) BANCKS, R. Account of a graphometer for measuring the angles of crystals. *Nicholson's Journal of Natural Philosophy*, **12**, 374–375, pl. XV.

(1806) LUCAS, J. A. H. *Tableau Méthodique des Espèces Minerales*. Paris.

(1807) TILLOCH, A. (ed.) Lectures—List of patents for new inventions. *Philosophical Magazine*, **28**, 373.

(1808) BOURNON, J. L. de. *Traité complet de la chaux carbonatée et de l'arragonite*. London, 3 Vols.

(1809) BURROW, E. J. An account of a goniometer invented by the Rev. E. J. Burrow. *Nicholson's Journal of Natural Philosophy*, **22**, 1–2, pl. I.

(1809) TILLOCH, A. (ed.) Intelligence and miscellaneous articles. *Philosophical Magazine*, **34**, 77.

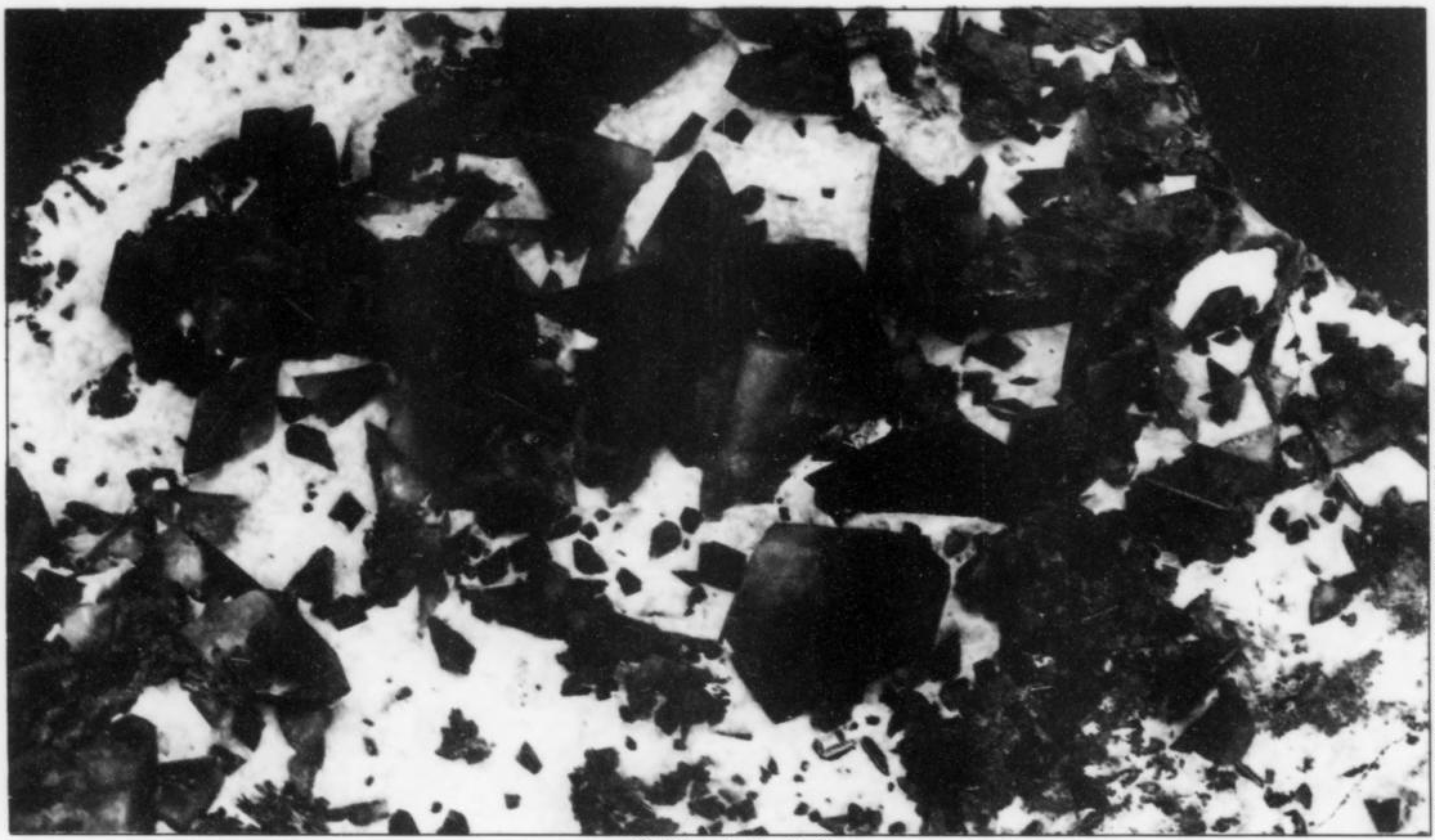
(1809) WOLLASTON, W. H. Description of a reflective goniometer. *Philosophical Transactions*, **99**, 253–258, pl. XI. Also in *Annalen der Physik*, **37**(4), 357–364.

(1810) MALUS, E. L. *Théorie de la double réfraction de la lumière dans les substances cristalisées*, 98–102.

(1811) BIOT, J. B. Bericht über das Flintglas des Hrn. d'Artigues und die achromatische Fernröhre des Hrn. Cauchoix in Paris. *Annalen der Physik und Chemie*, **37**, 365–400.

(1811) BIOT, J. B. *Rapport sur la fabrication en grand de flint glass*. Le Moniteur Universel, Paris, No. 38, 147–148; No. 39, 150–152. Also in *Annalen der Physik und Chemie*, **39**, 150–152.

(continued on page 580)



California Benitoite

Jeffrey Wheeler Photo—Collector's Edge specimen

CALIFORNIA DEALERS

Coogan Gold Company
Ed and Kay Coogan
P.O. Box 1631
Turlock, CA 95381
Tel: (209) 634-5222
Micromounts, TN's, Min., Cab.

Si and Ann Frazier
Si and Ann Frazier
Suite 306, 6331 Fairmont Ave.
El Cerrito, California 94530

Gemini Minerals
Joe & Susan Kielbaso
P.O. Box 70062
San Diego, CA 92167
Tel: (619) 223-0620
FAX: (619) 223-0385
By Appointment Only
Fine Minerals, Wholesale and Retail

Cal Graeber Minerals
Cal and Kerith Graeber
P.O. Box 2347
Fallbrook, California 92088
Tel: (619) 723-9292
By Appointment Only

Jewel Tunnel Imports
Rock H. Currier
13100 Spring Street
Baldwin Park, CA 91706-2283
Tel: (818) 814-2257
FAX: (818) 338-4617
Wholesale Only

Kristalle
875 North Pacific Coast Hwy.
Laguna Beach, California 92651
Tel: (714) 494-7695
E-mail: leicht@kristalle.com
WEB: http://www.kristalle.com

Debbie Meng's Minerals
Debbie Y. Meng
P.O. Box 117
Marina, California 93933
Tel/Fax: (408) 883-9348
E-mail: debbie.meng@usa.net
Specialty: Fine Chinese Minerals

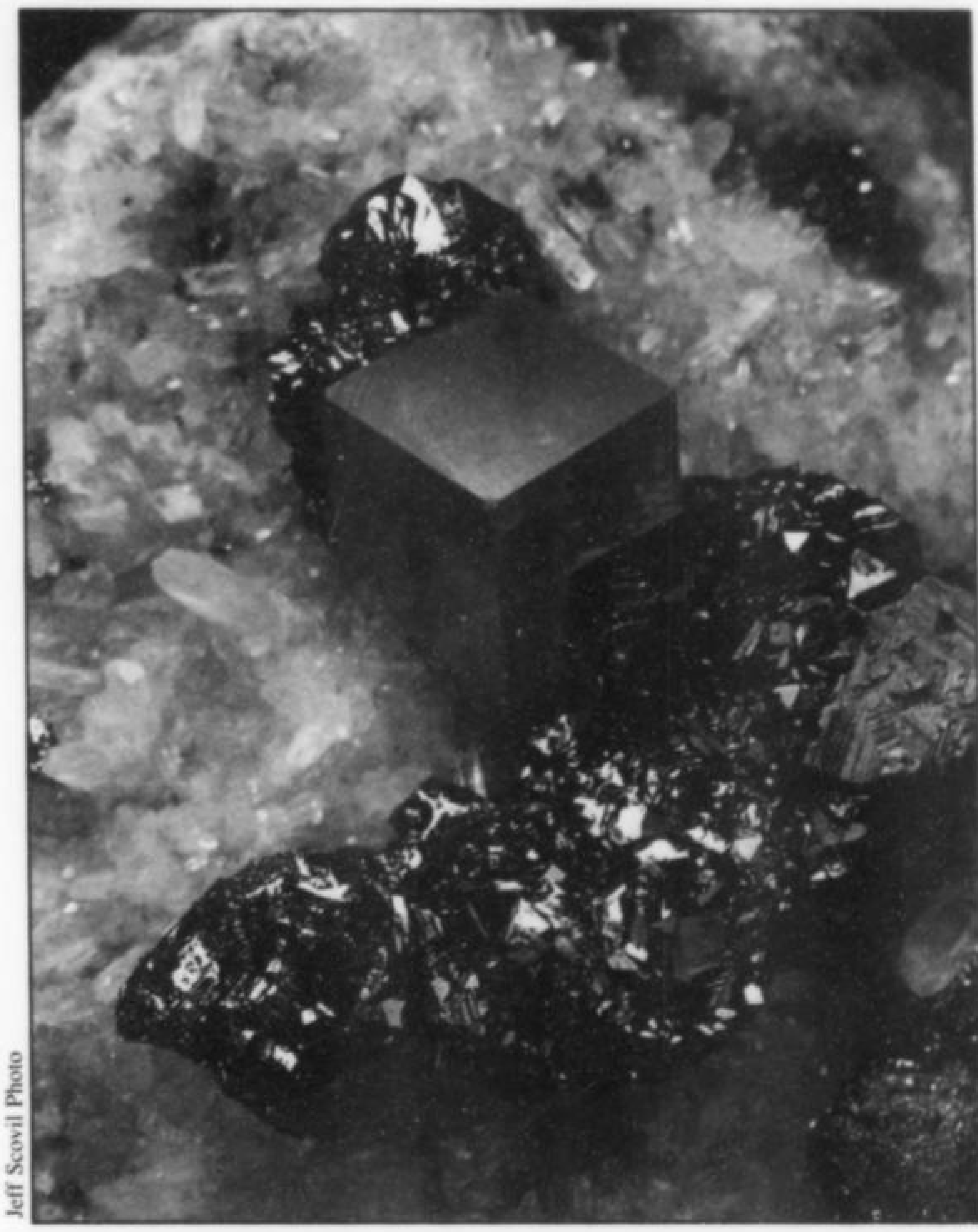
Pala International & The Collector
912 So. Live Oak Park Road
Fallbrook, California 92028
Tel: (619) 728-9121
US Wats 1-(800)-854-1598

Roberts Minerals
Ken and Rosemary Roberts
P.O. Box 1267
Twain Harte, California 95383
Tel: (209) 586-2110

Bruce & Jo Runner Minerals
13526 South Avenue
Delhi, California 95315
Tel: (209) 634-6470
Micromount List $2
Showroom by Appt. only

Silverhorn
Mike Ridding
1155 Coast Village Road
Montecito, California 93108
Tel: (805) 969-0442

Colorado Dealers!



RHODOCHROSITE, 1.6 CM, WITH TETRAHEDRITE, SWEET HOME MINE, MARTY ZINN COLLECTION

Jeff Scovil Photo

David Bunk Minerals

David Bunk
1441 W. 46th Street, #8
Denver, CO 80211
303-477-6897 (by appointment)
Colorado & Worldwide Specimens

Columbine Mineral Shop

Benjy & Liz Kuehling
P.O. Box 541
633 Main Street
Ouray, CO 81427
970-325-4345, 9 a.m. to 9 p.m.
Open 7 days, May 1-Oct. 31
Off-season by Appointment
Fine Minerals for Collectors

The Crystal Group

George Fisher & Doug Collyer
511 Foothills Road
Colorado Springs, CO 80906
719-634-0635 (By Appt. Only)
Amazonite & Smoky Quartz
Fine Colorado Minerals

Genesis Epoch

Mel & Pam Bersch
248 Little Park Rd.
Grand Junction, CO 81503
970-242-3134 (call for appt.)
Tsumeb Minerals, Western Colo.
Fluorite/Amethyst & Fossils
E-mail: MPBERSCH@aol.com

Glacier Peak Art, Gems & Minerals

Joseph & Susan Dorris
1686 So. 21st Street
Colorado Springs, CO 80904
719-442-6630
Producing Colorado Amazonite &
Smoky Quartz. Beginner to
Advanced, Worldwide Minerals
http://www.frii.com/~glacier

Green Mountain Minerals

Stanley Korzeb
13993 E. Arizona Ave.
Aurora, CO 80012
303-368-1209 (Call for Appt.)
Species, Fine Minerals, write for List

Bill Hayward Minerals

Bill & Christopher Hayward
3286 Quitman Street
Denver, CO 80212
303-455-1977 (Call for Appt.)
Colorado & Pikes Peak Minerals

L & T Creations

Lee A. McKinney
1800 Winfield Drive
Lakewood, CO 80215
By Appt. Only 303-232-6451
Colorado Amazonite

LJP—Colorado

Larry & Carmen Piekenbrock
1180 York Avenue
Cañon City, CO 81212-8612
719-275-7530 (Call for Appt.)
Fine Minerals, Micros, etc.
WWWeb:http://www.collectors-mall.com/

COLORADO MINERAL AND FOSSIL SHOW

Holiday Inn Denver North

SEPT. 16-20, 1998

10 a.m. to 7 p.m. Daily
INFO: P.O. Box 999 • Evergreen, CO 80437

George Witters Minerals

George & Cindy Witters
2210 Park Lake Dr.
Boulder, CO 80301
303-664-5864
FAX: 303-926-1933
Fine Minerals, Worldwide
By Appointment Only

Mountain Minerals International

Dudley Blauwet
P.O. Box 302
Louisville, CO 80027-0302
303-665-0672
FAX: 303-664-1009
Buy/Sell/Trade
Minerals, Gems, Gem Rough

The Sunnywood Collection

Bill & Elsie Stone
12068 E. Amherst Place
Aurora, CO 80014
303-368-7497 (by Appt. only)
Premium Minerals, Fossils &
Carvings Artistically Mounted
www.sunnywood.com

XTAL—Dennis Beals

Dennis & Diane Beals
6006 S. Holly St., Suite 256
Englewood, CO 80111
303-771-9225 (by Appt. only)
FAX: 303-771-9308
Fine Mexican minerals & more

(1813) ACCUM, F. C. *Elements of Crystallography after the Method of Hauy.* London, 86–95, pl. IV.

(1813) BREWSTER, D. *A Treatise on New Philosophical Instruments.* Edinburgh, 89–105, pl. IV.

(1814) PHILLIPS, W. *On the Oxyd of Tin.* Transactions of the Geological Society, London, **2**, 336–376.

(1814) WEISS, C. S. *Übersichtliche Darstellung der verschiedenen natürlichen Abteilungen der Krystallisations-Systeme.* Abhandlungen der königlichen Akademie der Wissenschaften, Berlin, 289–344.

(1815) FRAUNHOFER, J. *Bestimmung des Brechungs- und Farbzerstreuungs- Vermögens verschiedener Glassorten.* Denkschrift Akademie der Wissenschaften, München, 193–226, pl. I–III.

(1815) GILBERT, L. W. (ed.) Physikalische Instrumente. *Annalen der Physik*, **49**, 190–192.

(1816) BIOT, J. B. *Traité de physique expérimentale et mathématique.* Paris, Vol. III, 157–165, pl. II.

(1816) BOHNENBERGER, J. G. F. *Beschreibung eines neuen Instruments zur Messung der Winkel der Krystalle.* Tübinger Blätter für Naturwissenschaften und Arzneykunde, 2-1, 64.

(1816) WEISS, C. S. *Über eine verbesserte Methode für die Bezeichnung der verschiedenen Flächen eines Krystallisations-Systems.* Abhdl. der königl. Akademie der Wissenschaften, Berlin, 286–314.

(1817) EMMETT, J. B. Description of the reflecting goniometer. *Philosophical Magazine*, **49**, 347–349, pl. IV.

(1817) MALUS, E. L. *Description et usage d'un Goniomètre répétiteur.* Memoirs de Physique et de Chimie de la Societé d'Arcueil, **3**, 122–129, published posthumously.

(1818) HAUY, R. J. Observations sur la mesure des angles des cristeaux. *Annales des Mines*, **3**, 411–442.

(1818) MUNCKE, G. W. Beschreibung eines Repetitions-Goniometers. *Leonhard's Taschenbuch für die gesamte Mineralogie*, **13**, 438–459.

(1818) WEISS, C. S. *Übersichtliche Darstellung der verscheidenen natürlichen Abteilungen der Kristallisationssysteme.* Konigl. Akad. der Wissenschaften, Berlin, 289–344.

(1819) BAKEWELL, R. *An Introduction to Mineralogy.* London, 127–128, pl. II.

(1820) BROCHANT DE VILLIERS, A. J. M. *Die Krystallisation in geometrischer und physikalischer Hinsicht.* Translated by H. Kersten. Heidelberg, 32–40, pl. I, II.

(1820) PISTOR, C. P. H. Bemerkungen über das Wollaston'sche, Breithaupt'sche und das Studer'sche Goniometer. *Annalen der Physik*, **66**, 325–326.

(1820) STUDER, J. G. Beschreibung zweier verbesserter Repetitions-Goniometer. *Annalen der Physik*, **66**, 1–14, pl. I.

(1821) BIOT, J. B. *Précis élémentaire de physique expérimentale.* Paris, 2nd ed. (first edition 1816). Vol. II, 138–145, pl. IV.

(1821) NORDENSKIÖLD, N. Über die Messung der Krystallwinkel. *Schweigger's Journal für Chemie und Physik*, new series, **1–4**, 395–404, pl. II.

(1822) BAUMGARTNER, A. Ein neues Reflexions-Goniometer. *Annalen der Physik*, **71**, 1– 6, pl. I.

(1822) HAUY, R. J. *Traité de Cristallographie.* 2nd ed. Paris, Vol. 1, 22–24, 114.

(1822) MOHS, F. *Grundriss der Mineralogie.* Dresden, 2 Vols. 1822–1824.

(1823) BROOKE, H. J. *A familiar Introduction to Crystallography Including an Explanation of the Principle and Use of the Goniometer.* London, 25–32.

(1823) NEUMANN, F. E. *Beiträge zur Krystallonomie.* Berlin.

(1824) BOURNON, J. L. *Description du Goniomètre perfectionné de M. Adelmann.* Paris, 16 p., 1 pl.

(1825) KUPFFER, A. T. *Preisschrift über genaue Messung der Winkel an Krystallen.* Berlin.

(1825) MARX, E. M. *Geschichte der Crystallkunde.* Karlsruhe, Baden.

(1826) FRANKENHEIM, M. Crystallonomische Aufsätze. *Isis*, **19**, 497–512, 542–562.

(1827) RUDBERG, F. Vorschlag zu einem verbesserten Reflexionsgoniometer. *Kastner's Archiv für die Gesamte Naturlehre*, **10**, 461–469, pl. III.

(1829) RIESE, F. C. *Vorschläge zu einem neuen Goniometer mit welchem man sowohl spiegelnde als matte Krystalle so genau, als es die Natur ihrer Oberflächen nur gestattet, messen kann.* Bonn.

(1830) BEUDANT, F. S. *Traité de Mineralogie.* Paris, Vol. I, 19–28, pl. I.

(1830) HERSCHEL, J. F. W. *Preliminary Discourse on the Study of Natural Philosophy.* London, 354.

(1830) NAUMANN, C. F. *Lehrbuch der reinen und angewandten Krystallographie.* Leipzig, 354–390.

(1831) EATON, A. Improvement in the reflecting goniometer. *American Journal of Science and Arts*, **20**, 158–159.

(1831) KUPFFER, A. T. *Handbuch der rechnenden Krystallonomie.* St. Petersburg.

(1831) NAUMANN, C. F. Notiz über den Fehler der Excentrität der Kante bei Messungen mit Wollaston's Goniometer. *Annalen der Physik und Chemie*, **22**, 395–397.

(1833) DEGEN, A. F. E. Verbesserungen am Reflexionsgoniometer. *Annalen der Physik und Chemie*, **27**(3), 687–688, pl. IV.

(1833) GRAVES, R. A simplification of Dr. Wollaston's reflective goniometer. *American Journal of Science and Arts*, **23**, 75–78.

(1836) FRANKENHEIM, M. L. Chemische und krystallonomische Beobachtungen: 1. Eine Vorrichtung um unter dem Mikroskope Winkel zu messen. *Annalen der Physik und Chemie*, **37**, 637.

(1837) MITSCHERLICH, E. Über die Ausdehnung der krystallisierten Körper durch die Wärme. *Annalen der Physik und Chemie*, **41**, 137–152.

(1837) SANG, E. Account of an improvement in the construction of Wollaston's goniometer. *Edinburgh New Philosophical Journal*, **22**, 213–219.

(1837) SUCKOW, G. Vorschlag zu einem neuen Goniometer. *Erdmann's Journal für Praktische Chemie*, **2**, 158–160, pl. I.

(1839) ARAGO, D. F. J. *Comptes rendues Hebdomadaires des séances de l'Academie des Sciences.* Paris, Vol. 8, 710.

(1839) RADICKE, G. *Handbuch der Optik.* Berlin, 343–345, 456–458.

(1841) NAUMANN, C. F. *Anfangsgründe der Krystallographie.* Dresden und Leipzig, 30–36, pl. III–IV.

(1842) BECQUEREL, A.C. *Traité de Physique.* Paris, Vol. I, 116.

(1843) MITSCHERLICH, E. *Über ein Goniometer.* Abhandlungen der preus. Akademie der Wissenschaften, Berlin, Physik.-math. Klasse, 189–197.

(1845) BECQUEREL, A. C. *Populäre Naturlehre.* Translated by G. Kissling. Vol. II, 8–17, pl. I.

(1845) HAIDINGER, W. *Handbuch der bestimmenden Mineralogie.* Wien, 66–71.

(1846) SCHMIDT, C. *Entwurf einer allgemeinen Untersuchungsmethode der Säfte und Secrete des thierischen Organismus, part II.* Krystallonomische Untersuchungen, 18–28, Mitau & Leipzig.

(1847) BROOKE, C. Abstract of a lecture on the use of the goniometer. *Transactions of the Pharmaceutical Society*, **6**, 559–561.

(1848) LEESON, H. B. *Description of a Double Refracting Goniometer.* Memoirs and Proceedings of the Chemical Society, London, Part II, 550–552, pl. XIII.

(1849) BRAVAIS, A. Mémoire sur les polyèdres de forme symétrique. *Journal de Math*, M. Liouville, **14**, 137–180.

(1850) DUTIROU, ?. Détermination des indices de réfraction des sept raies de Fraunhofer dans une série nombreuse de verres. *Annales de Chimie et de Physique*, 3e série, **28**, 176–197.

(1850) SILLIMAN, B., and DANA, J. D. Optical examination of several American micas. *American Journal of Science and Arts*, 2nd. series, **10**, 372–373.

(1852) BROOKE, H. J., and MILLER, W. H. *An Elementary Introduction to Mineralogy by the Late William Phillips.* 6th ed., 50–53.

(1852) SHEPARD, C. U. *A Treatise on Mineralogy.* New Haven, 22–25.

(1853) ARAGO, D. F. J. *Oevres.* Paris. Vol. III, *Malus, Invention du Goniomètre Répétiteur,* 147.

(1853) KRANTZ, A. *Catalogue of Mineralogical, Geological and Palaeontological Specimens, Collections, Models, etc.*

(1854) HAIDINGER, W. *Graphische Methode annähernder Winkelmessungen, besonders an kleineren Krystallen.* Sitzungsberichte, Akademie der Wissenschaften, Wien, **14**, 3–8.

(1855) HAIDINGER, W. *Vereinfachte Methode der graphischen Winkelmessung kleiner Krystalle.* Sitzungsberichte, Akademie der Wissenschaften, Wien, **17**, 187–189.

(1855) QUENSTEDT, F. A. *Handbuch der Mineralogie.* Tübingen, 11–13.

(1856) DUFRÉNOY, A. *Traité de Minéralogie.* Paris, Vol. I, 187–204.

(1856) HAIDINGER, W. Ein optisch-mineralogisches Aufschraube-Goniometer. *Annalen der Physik und Chemie*, **97**, 590–599, pl. V.

(1856) MILLER, W. H. *Lehrbuch der Krystallographie.* Translated by J. Grailich. Wien, 167–251, pl. XI–XIII.

(1856) NAUMANN, K. F. *Elemente der theoretischen Krystallographie.* Leipzig.

(1857) CASAMAJOR, P. A method of measuring the angles of crystals by reflection without the use of a goniometer. *American Journal of Science*, 2nd series, **24**, 251–253.

(1857) KOBELL, F. Über eine neue Methode, Krystallwinkel zu messen. *Erdmanns Journal der Praktischen Chemie*, **71**, 144–146.

(1857) PFAFF, F. Über die Messung der ebenen Krystallwinkel und deren Verwerthung für die Ableitung der Flächen. *Annalen der Physik und Chemie*, **102**, 457–464, pl. III.

(1858) DAUBER, H. Untersuchungen an Mineralien der Sammlung des Hrn. Dr. Krantz in Bonn. *Annalen der Physik und Chemie*, **103**, 107–133.

(1860) MILLER, W. H. On the measure of the dihedral angles of crystals. *Philosophical Magazine*, 3rd ser., **19**, 328–329.

(1864) KOBELL, F. *Geschichte der Mineralogie.* München.

(1864) ROSE. G. Zur Erinnerung an E. Mitscherlich. *Zeitschrift der Deutschen geologischen Gesellschaft*, **16**, 21–72.

(1866) BÖRSCH, C. C. L. Spectral-Apparat und Reflexions-Goniometer, construiert von Dr. Börsch. *Annalen der Physik und Chemie*, **129**, 384–393, pl. V.

(1866) SCHRAUF, A. *Lehrbuch der Krystallographie.* Wien, 205–215.

(1867) WEBSKY, M. Über einen Beobachtungs-Apparat zur Ausführung goniometrischer Messungen an unvollkommenen Krystallen oder sehr kleinen Flächen. *Annalen der Physik und Chemie*, **132**, 623–628.

(1871) GROTH, P. Über Apparate und Beobachtungsmethoden für krystallogaphisch optische Untersuchungen. *Annalen der Physik und Chemie*, **144**, 34–55, pl. I.

(1872) O'REILLY, J. P. *On a New Form of Goniometer.* Proceedings of the Royal Irish Academy, 2nd series, **1**, 294–296, pl. XX.

(1872) PFAFF, F. *Das Mikrogoniometer.* Erlangen.

(1876) GROTH, P. *Physikalische Krystallographie.* Leipzig. (First edition)

(1876) KLEIN, C. *Einleitung in die Krystallberechnung.* Stuttgart.

(1876) LANG, V. *Construction des Reflexionsgoniometers.* Denkschrift der Akademie der Wissenschaften, Wien, 41–44, pl. I–III.

(1876) MASKELYNE, N. S. Handbook of the special loan collection of scientific apparatus, South Kensington Museum. *Crystallography-Mineralogy*, 304–320.

(1876) MILLER, W. H. On a new form of the reflective goniometer. *Philosophical Magazine*, 5th series, **8**, 281–288. Also Proceedings of the Crystallological Association, **1**, 1–6.

(1877) BERTRAND. E. De la mesure des angles dièdres des cristeaux microscopiques. *Comptes rendus herbdomadaires des séances de L'Academie des Sciences*, **85**, 1175–1178.

(1877) HANNAY, J. B. On an easily constructed form of reflecting goniometer. *Mineralogical Magazine*, **1**, 110–111, pl. IV.

(1878) DANA, E. S. *A Text-Book of Mineralogy.* 2nd ed., New York, 83–87.

(1878) LASAULX, ?. *Bericht über die wissenschaftlichen Apparate auf der Londoner Internationalen Ausstellung im Jahre 1876.* Edited by A. W. Hofmann, Braunschweig.

(1879) HIRSCHWALD, J. Das Mikroskop-Goniometer, ein neues Instrument zum Messen von Krystallen mit spiegellosen Flächen. *Neues Jahrbuch für Mineralogie, Geologie, Paläontologie*, 301–308, pl. V.

(1879) LANG, Y. On a horizontal goniometer. *Philosophical Magazine*, 5th ser., **7**, 136–138, pl. VII.

(1879) LIEBISCH, T. Die krystalloptische Apparate. *In* Löwenherz, *Bericht über die wissenschaftlichen Instrumente auf der Berliner Gewerbe Ausstellung*, Berlin, 320–340.

(1879) MALLARD, E. *Traité de Cristallographie.* Paris, 216–233.

(1879) SCHRAUF, A. Über die Form des Signals für Krystallmessungen. *Zeitschrift für Kristallographie*, **3**, 356–358, pl. X.

(1879) WEBSKY, M. Über die Lichtreflexe schmaler Kristallflächen. *Zeitschrift für Kristallographie*, **3**, 241–258.

(1880) CALDERON, L. Besprechung des Mikroskop-Goniometers von J. Hirschwald. *Zeitschrift für Kristallographie*, **4**, 219–221.

(1880) HIRSCHWALD, J. Über das Mikroskop-Goniometer. *Neues Jahrbuch für Mineralogie*, **1**, 156–157.

(1880) LIEBISCH, T. Die krystalloptischen Apparate. *In:* Lowenherz, L. (ed.), *Bericht über die wissenschaftlichen Instrumente auf der Berliner Gewerbeausstellung*, 1879, Berlin, 321–356.

(1880) WEBSKY, M. Über Einrichtung und Gebrauch der von R. Fuess in Berlin nach dem System Babinet gebauten Reflexionsgoniometer. *Zeitschrift für Kristallographie*, **4**, 545–568.

(1882) LEWIS, W. J. *On the measurements of a bead of platinum, by the late Prof. W. H. Miller.* Proceedings of the Cambridge Philosophical Society, **IV-1**, 236–239.

(1884) BREZINA, A. *Das neue Goniometer der k.k. geologischen Reichsanstalt Jahrbuch d. k.k. geol. Reichsanstalt.* Wien, 34-2, 321–334.

(1884) SCHMIDT, A. Über das Fuess'sche Fühlhebelgoniometer. *Zeitschrift für Kristallographie*, **8**, 1–24.

(1884) SCHNEIDER, E. Über eine neue Justiervorrichtung an einem Krystallgoniometer. *Zeitschrift für Instrumentenkunde*, **4**, 242–243.

(1885) ZIRKEL, F. *Elemente der Mineralogie begründet von Naumann, C. F.* Leipzig, 12th ed., 96–99.

(1886) GOLDSCHMIDT, V. *Index der Krystallformen der Mineralien*. Berlin, 3 Vols., 1886–1891.

(1887) MALLARD, E. Sur une disposition particulière du goniomètre Wollaston. *Bulletin de la Société francaise de Minéralogie*, **10**, 231–236.

(1888) CARPENTIER, P. G. Goniomètre de Wollaston pour les petits cristeaux. *Bulletin de la Société francaise de Minéralogie*, **11**, 261–263.

(1888) TSCHERMAK, G. *Lehrbuch der Mineralogie*. Wien, 3rd ed., 5th. ed. 1897.

(1889) BAUMHAUER, H. *Das Reich der Krystalle*. Leipzig, 348–351.

(1890) FEDOROV, E. S. *Simmetria pravilnykh sistem figur.* St. Petersburg.

(1890) FUESS, R. Ein neuer Erhitzungsapparat für das Reflexionsgoniometer. *Neues Jahrbuch für Mineralogie*, **1**, 161–164.

(1892) MIERS, H. A. A student's goniometer. *Mineralogical Magazine*, **9**, 214–216, pl. III–V.

(1893) CZAPSKI, S. Ein neues Krystallgoniometer. *Zeitschrift für Instrumentenkunde*, **13**(1), 1–5, 242–244.

(1893) FEDOROV, E. Universal-(Theodolit-) Methode in der Mineralogie und Petrographie. *Zeitschrift für Kristallographie*, **21**, 574–714.

(1893) GOLDSCHMIDT, V. Goniometer mit zwei Kreisen (Krystallmessung durch Ortsbestimmung). *Zeitschrift für Kristallographie*, **21**, 210–232.

(1893) SORET, C. *Eléments de Cristallographie Physique*. Genève, Paris, 144–151.

(1895) GROTH, P. *Physikalische Kristallographie*. Leipzig. (Third edition)

(1895) MASKELYNE, N. S. *Crystallography*. Oxford, 388–405.

(1896) GOLDSCHMIDT, V. Ein Projektionsgoniometer. *Zeitschrift für Kristallographie*, **25**, 538–583?, pl. VII.

(1896) GOLDSCHMIDT, V. Anlegegoniometer mit zwei Kreisen. *Zeitschrift für Kristallographie*, **25**, 321–327, pl. VI.

(1896) LIEBISCH, T. *Grundriss der physikalischen Krystallographie*. Leipzig.

(1896) MITSCHERLICH, A. (ed.) *Gesammelte Schriften von Eilhard Mitscherlich*. Berlin.

(1897) GOLDSCHMIDT, V. *Kristallographische Winkeltabellen*. Berlin.

(1897) HESSEL, J. F. C. *Krystallometrie oder Krystallonomie und Krystallographie*. Leipzig, Vol. I, 10–19.

(1897) LEISS, C. Über Universalgoniometer und Krystallrefraktometer. *Neues Jahrbuch für Mineralogie, Geologie, Paläontologie*, **1**, 78–81.

(1897) VIOLA, C. M. Über ein Universalinstrument für Krystallographie. *Zeitschrift für Kristallographie*, **28**, 165–168, pl. III.

(1898) GOLDSCHMIDT, V. Über Grobgoniometer. *Zeitschrift für Kristallographie*, **29**, 589–594, pl. VIII.

(1898) GOLDSCHMIDT, V. Das zweikreisige Goniometer (Modell 1896) und seine Justierung. *Zeitschrift für Kristallographie*, **29**, 333–345, pl. VII.

(1898) STÖBER, F. Über ein einfaches Theodolitgoniometer und seine Verwendung zu stauroskopischen Bestimmungen. *Zeitschrift für Kristallographie*, **29**, 25–32.

(1899) LEISS, C. *Die optischen Instrumente der Firma R. Fuess*. Deren Beschreibung, Justierung und Anwendung, Leipzig.

(1899) LEISS, C. Theodolitgoniometer nach Czapski mit gewöhnlicher Signalgebung. *Zeitschrift für Kristallographie*, **31**, 49–51.

(1899) SMITH, G. F. H. A three-circle goniometer. *Mineralogical Magazine*, **12**, 175–182. Also in *Zeitschrift für Kristallographie*, **32**, 209–216.

(1900) KLEIN, C. *Das Krystallpolymeter, ein Instrument für krystallographisch optische Untersuchungen*. Sitzungsberichte der k. pr. Akademie der Wissenschaften, Berlin, 248–257.

(1900) PENFIELD, S. L. Contactgoniometer und Transporteur einfacher Construction. *Zeitschrift für Kristallographie*, **33**, 548–554.

(1900) SCHWARZMANN, M. Kristallphotogrammetrie. *N. Jb. Miner.*, **2**, 1–38.

(1901) FEDOROV, E. Universalgoniometer mit mehr als zwei Drehachsen und genaue graphische Rechnung. *Zeitschrift für Instrumentenkunde*, **21**, 26–27.

(1902) LEISS, C. Krystallpolymeter nach C. Klein. *Zeitschrift für Instrumentenkunde*, **22**(7), 201–209.

(1902) MIERS, H. A. *Mineralogy*. London, 99–106.

(1903) MIERS, H. A. *An enquiry into the variation of angles observed in crystals*. Philosophical Transactions of the Royal Society. Series A, **202**, 459–523.

(1904) SMITH, G. F. H. An improved form of three-circle goniometer. *Mineralogical Magazine*, **14**, 1–15. Also in *Zeitschrift für Kristallographie*, **42**, 214–227.

(1904) STÖCKL, K. Das Fedorow'sche Universalgoniometer in der Construction von Fuess. *Zeitschrift für Kristallographie*, **39**, 23–?.

(1904) VIOLA, C. M. *Grundzüge der Krystallographie*. Leipzig, 45–48.

(1905) GROTH. P. *Physikalische Krystallographie*. 4th ed., Leipzig. See also 1st ed., 1876; 2nd ed., 1885; 3rd ed., 1895.

(1905) KLEIN, C. *Über Theodolit-Goniometer.* Sitzungberichte der kgl. Akademie der Wissenschaften, Berlin, 94–101.

(1910) BOWMAN, M. A. An attachment to the goniometer for use in the measurement of crystals with complex faces. *Mineralogical Magazine*, **15**, 177–179.

(1910) GOLDSCHMIDT, V. Über Messen großer Krystalle. *Zeitschrift für Kristallographie*, **47**, 49–?.

(1910) SMITH, G. F. H. A camera lucida attachment for the goniometer. *Mineralogical Magazine*, **15**, 388–389.

(1911) HUTCHISON, M. A. A universal goniometer. *Mineralogical Magazine*, 100–108.

(1911) TUTTON, A. E. H. *Crystallography and practical crystal measurement*. London, 1st ed. 1911; 2nd ed. 1922 (2 Vols.).

(1912) GOLDSCHMIDT, V. Über ein mehrkreisiges Goniometer und seine Anwendung. *Zeitschrift für Kristallographie*, **51**, 28–39.

(1912) LAUE, M., KNIPPING, P., and FRIEDRICH, P. *Interferenzerscheinungen bei Röntgenstrahlen*. Sitzungsberichte der Bayerischen Akademie der Wissenschaften, München, 363–373.

(1913) GOLDSCHMIDT, V. *Atlas der Kristallformen*. Heidelberg, 9 Vols., 1913–1923.

(1915) STÖBER, F. Ein neues Zweikreisgoniometer, seine Anwendung und Hilfsapparate. *Zeitschrift für Kristallographie*, **54**, 442–453, pl. XI.

(1919) GORDON, S. G. The evolution of the goniometer. Report on a meeting of the Philadelphia Mineralogical Society held on May 8, 1919. *American Mineralogist*, **4**, 89.

(1919) SCHEEL, K., and SCHOFF, E. Rudolf Fuess. *Zeitschrift der Deutschen Gesellschaft für Mechanik und Optik*, **5**(6), 25–30.

(1919) SMITH, G. F. H. A student's goniometer. *Mineralogical Magazine*, **18**(87), 366–367.

(1920) PALACHE, C. The two-circle goniometer. *American Mineralogist*, **5**(2).

(1920) PULFRICH, C. Ein- und zweikreisiges Kristall-Goniometer. *Zeitschrift für Instrumentenkunde*, **40**, 212–215.

(1921) LEISS, C. Neues Reflexionsgoniometer und Spektrometer. *Zeitschrift für Kristallographie*, **56**, 616–625.

(1922) BURMESTER, L. Die geschichtliche Entwicklung des kristallographischen Zeichnens und dessen Ausführung in schräger Projektion. *Zeitschrift für Kristallographie*, **51**, 19–21.

(1922) KLOCKMANN, F. *Lehrbuch der Mineralogie*. Stuttgart, 18–26. (Ramdohr, P. and Strunz, H., 16th ed., 1978.)

(1922) TUTTON, A. E. H. *Crystallography and practical crystal measurement*. London, 2nd ed. (2 vols.).

(1923) MIELEITNER, K. Zur Geschichte der Mineralogie. Die Anfänge der Theorien über die Struktur der Kristalle. *Fortschritte der Mineralogie, Kristallographie und Petrographie*, **8**, 199–219.

(1924) WÜLFING, E. A. Ein neues Theodolitgoniometer. *Zeitschrift für Kristallographie*, **60**, 70–76.

(1925) LEISS, C. *Die modernen optischen Meßinstrumente der Kristallographen und Petrographen*. Ihre Beschreibung und Justierung, Jena.

(1926) FRIEDEL, G. *Lecons de Cristallographie*. Nancy-Paris-Strasbourg, 1–8.

(1926) GROTH, P. *Entwicklungsgeschichte der mineralogischen Wissenschaften*. Berlin.

(1926) HOPPE, E. *Geschichte der Optik*. Leipzig, 76–83.

(1926) RÖSCH, S. *Goniometrie auf photograpischem Wege*. Ber. Sächs. Akad. Wiss., Leipzig, math.-phys. Kl., Vol. 77, 88–98.

(1926) RÖSCH, S. *Über Reflexphotographie*. Abh. Sächs. Akad. Wiss., Leipzig, Vol. 39, No. 6, 1–62.

(1933) BÄR, A. Neue Anlegegoniometer zur Messung, Berechnung und Zeichnung der Kristalle. *Zeitschrift für Kristallographie*, **85**, 275–311, 369–393.

(1934) GOLDSCHMIDT, V. *Kursus der Kristallometrie*. Edited by H. Himmel and K. Muller, Berlin.

(1938) TERPSTRA, P. *Simple Instructions for Crystal Measurement with a New Two-circle Goniometer, Especially Adapted to the Use in Chemical Laboratories*. Rec. Trav. Chem. Pays-Bas, 57.

(1948) MELLIS, O. Zwei Notizen über Theodolitgoniometer. *Geol. Fören. Förhandl.*, **70**(2), 271–278, Stockholm.

(1948) WOLFE, C. W. A new two-circle goniometer. *American Mineralogist*, **33**, 739–743.

(1957) DAUMAS, M. (ed.) *Encyclopaedie de la Pléiade*. Histoire de la Science, Paris, 1079–1089.

(1961) TERPSTRA, D., and CODD, L. W. *Crystallometry*. Groningen.

(1962) BELOV, N. V. *Chetyrnadtsat reshetok Brave i 230 prostranstvennykh grupp simmetrii* (the 14 Bravais Lattices and the 230 Three-Dimensional Group of Symmetries. Moscow-St. Petersburg.

(1964) HOLLEMAN, A. F., and WIBERG, E. *Lehrbuch der Anorganischen Chemie*. Berlin.

(1964) KLEBER, W. *Einführung in die Kristallographie*. Berlin, 37–39.

(1966) BURKE, J. G. *Origins of the Science of Crystals*. Berkeley and Los Angeles.

(1969) METZGER, H. *La Genèse de la Science des Cristeaux*. Paris, 66–67.

(1970) GILLISPIE, C. C. (ed.) *Dictionary of Scientific Bibliography*. New York, 16 Vols.

(1973) KRÄTZ, O. *Der Nachlaß Eilhard Mitscherlichs in der Abteilung Chemie des Deutschen Museums*. Deutsches Museum, Abhandlungen und Berichte, **41-3**, 29–48.

(1980) BRIEUX, A. (ed.) *L'industrie francaise des instruments de précision 1901–1902*. Facsimile reprint of the 1901–1902 catalog.

(1982) SCHMITZ, E. H. *Handbuch zur Geschichte der Optik*. Vol. 2, *Von Newton bis Fraunhofer*, 108–115.

(1984) BURCKHARDT, J. Die Entdeckung der 32 Kristallklassen durch M. L. Frankenheim im Jahre 1826. *Neues Jahrbuch für Mineralogie*, Monatshefte, **31**, 481ff.

(1985) DE CLERCQ, P. R. (ed.) *Nineteenth-century Scientific Instruments and Their Makers*. Leiden.

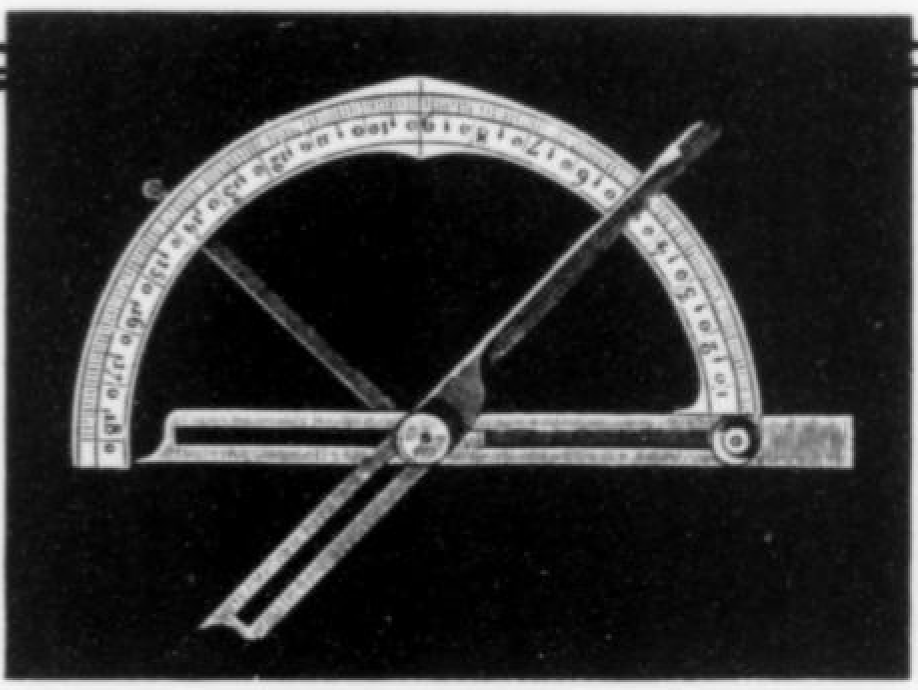
(1986) FABIAN, E. *Die Entdeckung der Kristalle*. Leipzig.

(1987) WEIL, H. *Die Berliner Mechaniker und Optiker Rudolf Fuess, Carl Leiss und Bernhard Halle*. Sammlerinformation, 5, by H. Baden, unpublished.

(1990) LIMA-DE-FARIA, J. (ed.) *Historical Atlas of Crystallography*. Dordrecht, Boston, London.

(1994) NAZAROV, M. A. Collection stolen. *In:* Letters to the editor. *Mineralogical Record*, **25**, 302.

(1995) MEDENBACH, O., and MIRWALD, P. W. Rho und Phi, Omega und Delta. Die Winkelmessung in der Mineralogie. *Mineralien-Welt*, **6**(5), 16–25.



EDITOR'S NOTE: The Houston Museum of Natural Science currently has on exhibit 15 rare goniometers from the Herbert Obodda Collection of Antique Mineralogical Instruments, and will soon add 12 more to the exhibit. This may well be the largest display of antique goniometers in the world. The instruments, all on long-term loan to the museum, are in a separate gallery room attached to the Cullen Hall of Gems and Minerals.

THE MUSEUM DIRECTORY

Geology and Meteorite Museums University of New Mexico
Curators: Gary Smith (Geology)
Adrian Brearley (Meteorites)
Tel: (505) 277-4204
Dept. of Earth & Planetary Sciences
Northrop Hall, Univ. of New Mexico
Albuquerque, NM 87131
Hours: 9–4 M–F (closed on school holidays)
Specialties: Worldwide minerals and meteorites, New Mexico fossils, Harding Pegmatite Mine Collection

Colburn Gem & Mineral Museum
Tel: (704) 254-7162
Fax: (704) 251-5652
Website: www.main.nc.us/colburn
Pack Place Education, Arts & Science Center
2 South Pack Square
Asheville, NC 28801
Hours: 10–5 Tues.–Sat. (all year);
1–5 Sun. (June-Oct.);
Closed Mondays and holidays
Specialties: North Carolina and worldwide minerals and gems
Accessible to persons with disabilities

Harvard Mineralogical Museum
Curators: Dr. Carl A. Francis
William Metropolis
Tel: (617) 495-4758
24 Oxford Street
Cambridge, Mass. 02138
Hours: 9–4:30 M–Sat.; 1–4:30 Sun.
Specialties: Systematic Mineral Collection

William Weinman Mineral Museum
Asst. Curator: Doug Gravely
Tel: (770) 386-0576
51 Mineral Museum Dr.
White, GA 30184
Hours: 10–4:30 Tues.–Sat., 2–4:30 Sun.
Specialty: Georgia & worldwide minerals & fossils

Western Museum of Mining & Industry
Curator: Terry A. Girouard
Tel: (719) 495-2182
Telnet pac.ppld.ord (Library Cat.)
Dir. of Educ.: Eric L. Clements
Tel: (719) 488-0880
Fax: (719) 488-9261
www.wmmi.org
1025 North Gate Road
Colorado Springs, CO 80921
Hours: 9–4 M–Sat., (12-4 Sun., June–Sept. only), closed holidays
Specialties: Colorado minerals & ores, Western mining equip. & memorabilia, 11,000-vol. research library

Denver Museum of Natural History
Curator of Geology: Jack A. Murphy
Tel: (303) 370-6445
Dept. of Earth Sciences
20001 Colorado Blvd.
Denver, CO 80205
Hours: 9–5 daily
Specialties: Colorado minerals

Geology Museum Colorado School of Mines
Curator: Virginia A. Mast
Tel: (303) 273-3823
Golden, Colorado 80401
Hours: 9–4 M–Sat., 1–4 Sun.
(closed on school holidays & Sundays in the summer)
Specialties: Worldwide minerals; Colorado mining & minerals

A. E. Seaman Mineralogical Museum
Curator (mineralogy):
George W. Robinson
Adjunct Curator: Dr. John A. Jaszczak
Tel: (906) 487-2572
Michigan Technological Univ.
Houghton, Michigan 49931
Hours: 9–4:30 M–F
Specialty: Michigan minerals, copper minerals & worldwide minerals

Houston Museum of Natural Science
Curator (mineralogy): Joel Bartsch
Tel: (713) 639-4673
Fax: (713) 523-4125
1 Herman Circle Drive
Houston, Texas 77030
Hours: 9–6 M–Sat., 12–6 Sun.
Specialty: Finest or near-finest known specimens

Museums listed alphabetically by city

THE MUSEUM DIRECTORY

Natural History Museum of Los Angeles County

Curator (Mineral Sciences):
Dr. Anthony R. Kampf
Tel: (213) 763-3328
Collections Manager:
Dorothy L. Ettensohn
Tel: (213) 763-3327
Fax: (213) 749-4107
900 Exposition Blvd.
Los Angeles, CA 90007
Hours: 10–4:45 Tues.–Sun.
Specialties: Calif. & worldwide minerals, gold, gem crystals, colored gemstones
Support organization:
The Gem and Mineral Council
Website: http://nhm.org/~gmc

Carnegie Museum of Natural History

Collection Manager: Marc L. Wilson
Tel: (412) 622-3391
4400 Forbes Avenue
Pittsburgh, PA 15213
Hours: 10–5 Tues.–Sat.,
10–9 F, 1–5 Sun.,
closed Mon. & holidays
Specialty: Worldwide minerals & gems

Museum of Geology

Director: Philip R. Bjork
Tel: (605) 394-2467
South Dakota School of
Mines & Technology
501 E. St. Joseph Street
Rapid City, SD 57701-3995
Hours: 8–5 M–F, 9–4 Sat., 1–4 Sun.
Specialty: Black Hills minerals, esp. pegmatites

New Mexico Bureau of Mines & Mineral Resources—Mineral Museum

Director: Dr. Virgil W. Lueth
Tel: (505) 835-5140
E-Mail: vwlueth@nmt.edu
Fax: (505) 835-6333
Assistant Curator: Lynn Heizler
Tel: (505) 835-5166
New Mexico Tech
801 Leroy Place
Socorro, NM 87801
Hours: 8–5 M–F, 10–3 Sat., Sun
Specialties: New Mexico minerals, mining artifacts, worldwide minerals

Penn State Earth & Mineral Sciences Museum

Curator: Andrew Sicree
Tel: (814) 865-6427
E-mail: sicree@geosc.psu.edu
Steidle Building
University Park
State College, PA 16802
Hours: 9–5 M–F & by Appt.
(closed holidays)
Specialties: Mineral properties exhibits; "velvet" malachite; old Penna. minerals, mining art

Arizona-Sonora Desert Museum

Collections Manager &
Mineralogist: Anna M. Domitrovic
Tel: (520) 883-1380 ext. 152
Fax: (520) 883-2500
2021 N. Kinney Road
Tucson, AZ 85743-8918
Hours: 8:30-5 Daily (Oct.-Feb.)
7:30-6 Daily (Mar.-Sept.)
Specialty: Arizona minerals

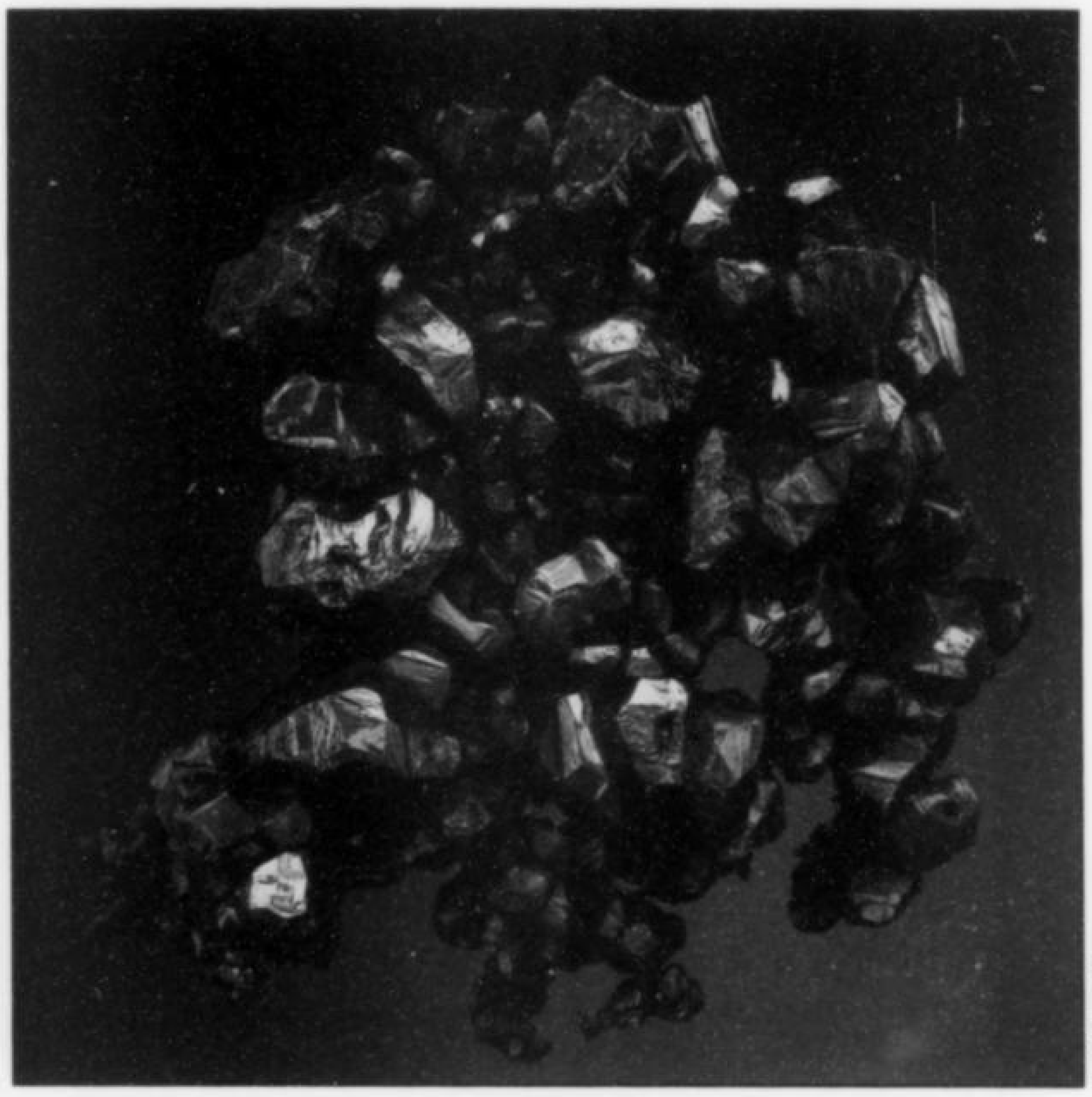
Europe

Giazotto Mineralogical Museum

Curator: Adalberto Giazotto
Tel: 39-50-501587
Lungarno Gambacorti 39
Pisa, Italy
Hours: by Appointment
Specialty: Italian and Worldwide minerals

Additional listings welcome!

Send vital information, as shown, to the editor. There is a modest annual fee (lower than our regular advertising rates).

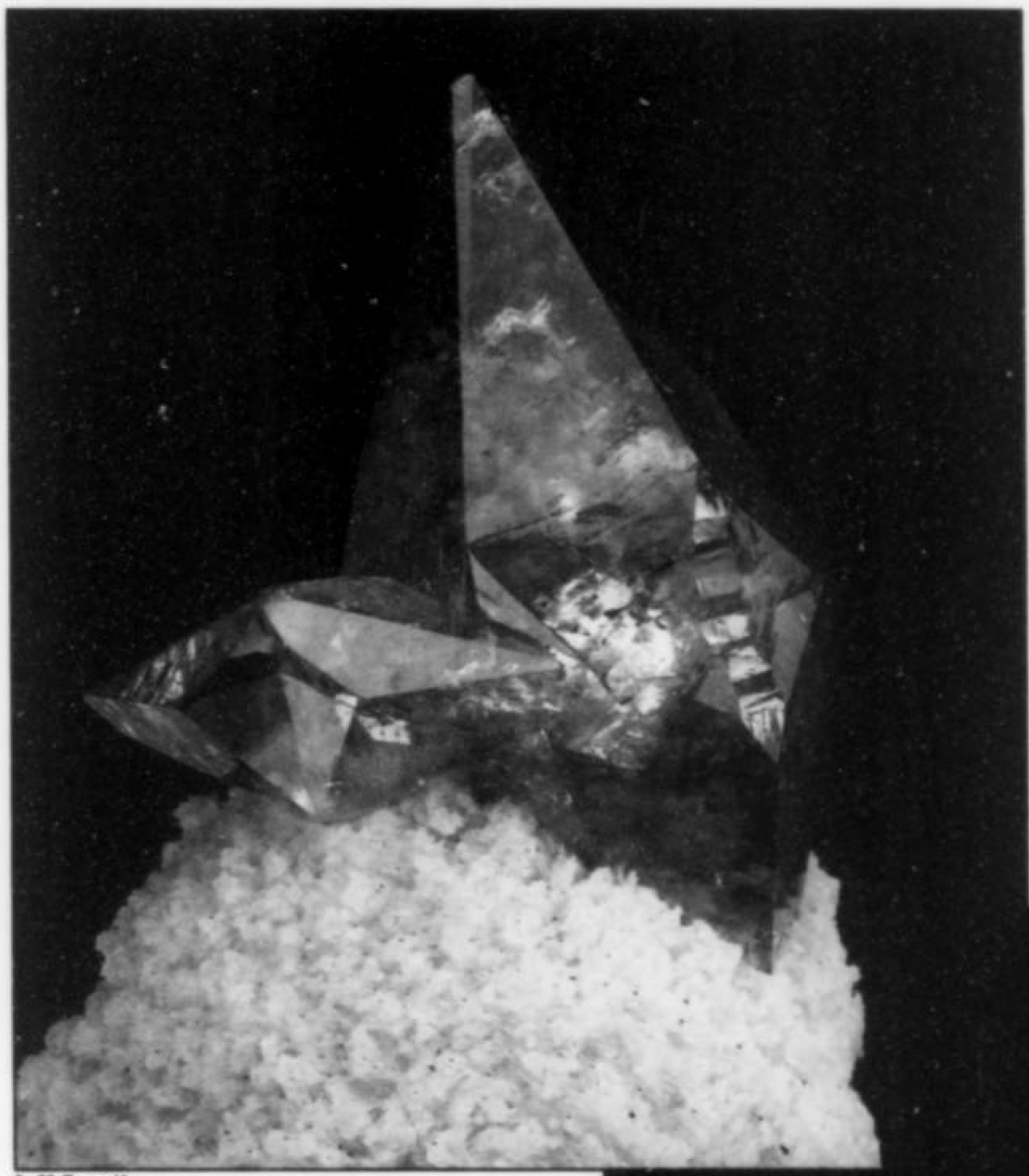


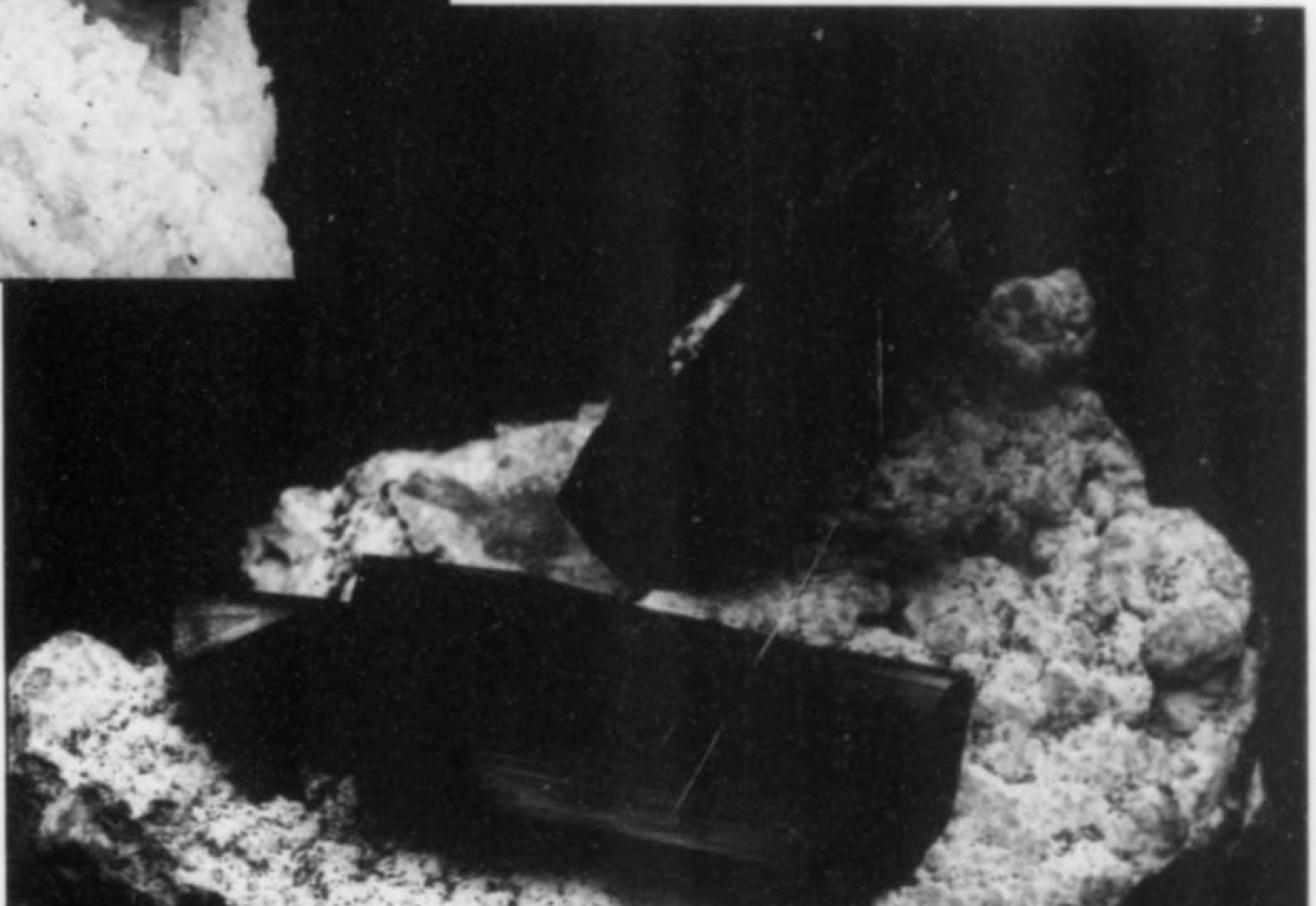
Jeff Scovil

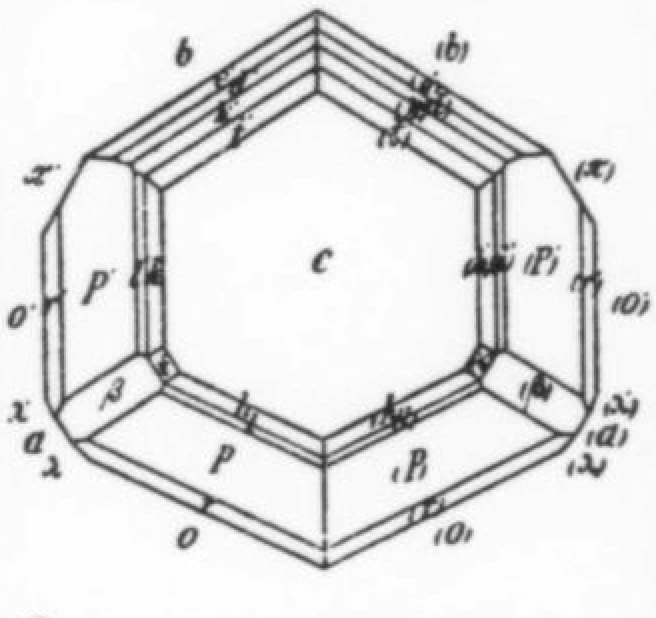
COPPER
Keweenaw, Michigan
12 cm high
Steve Neely Collection

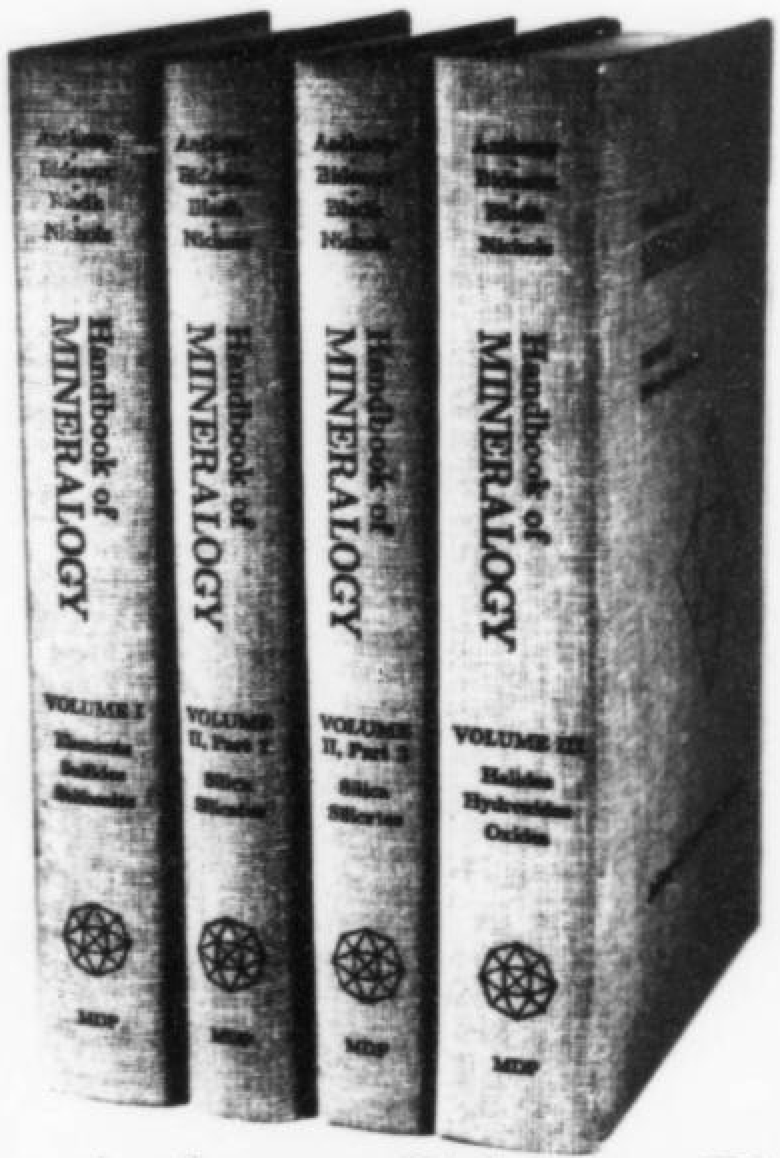
Jeff Scovil

NOVACEKITE
Brumado, Brazil
7 cm wide
Steve Neely Collection






b
(b)
x
(x)
c
P
(P)
o
(o)
x
a
(a)
p
(B)



Arizona Dealers

Copper City Rock Shop
John & Karen Mediz
566 Ash Street
Globe, AZ 85501
Tel: (520) 425-7885
FAX: (520) 425-4506
Southwestern minerals
since 1970. See us at shows
or visit our store (call first).

Crystal Pockets
George Godas
6304 S. Clark Drive
Tempe, Arizona 85283
(602) 820-3067
Arizona Lead Mineral

Kino Rocks & Minerals
6756 S. Nogales Highway
Tucson, Arizona 85706
(520) 294-0143
9–11:15/Noon–5:30
(Closed Sun.)
No Catalog—No List

David Shannon Minerals
David & Colleen
6649 E. Rustic Drive
Mesa, Arizona 85215
(602) 985-0557
Minerals, Boxes & Supplies.
Send 3 stamps for list.

Em's Gems Plus Three
Em & Ogle Love
8846 E. 35th Circle
Tucson, Arizona 85710
(520) 886-6942
Fine moderately
priced specimens for
collectors and museums. Shows
only.

Evan Jones Minerals
3520 N. Rose Circle Dr.
Scottsdale, AZ 85251
Tel/Fax: (602) 946-5826
By Appointment Only.
Fine Minerals for Collectors.
Specializing in Arizona,
Mexico & Worldwide Classics.
We Buy Collections.

Top-Gem Minerals
1201 B North Main Street
Tucson, Arizona 85705
Tel: (520) 622-6633
FAX: (520) 792-2928
Mon-Fri 8:30–4:30
and by Appt.
No Catalog or List
Wholesale Only
Mex. & Tenn. minerals, boxes

NATIONAL MINERALS
Your prime source for TOP QUALITY
aesthetic ZEOLITES and Bulk Material.
By the Piece, Flat or Kilo.
Competitive Prices, Excellent Service.
FAX/Mail requirements to:
NATIONAL MINERALS, G3/7 Sunder Nagar
Malad (W), Bombay-400064, INDIA.
Tel: 874-9984, 872-6874. Fax: 91-22-873-6161.

Arizona Minerals
TUCSON SHOW 1999
• EXECUTIVE INN Rm. 128 •
Dick Morris • Mark Hay

Simkev Minerals
fine microminerals for discriminating collectors
MICROS ONLY - FREE LIST
79 Pine St.S., Port Hope, Ontario, L1A 3G2, Canada
Ph:(905) 885-5483 Fax:(905) 885-1161
E-mail: simkev@nhb.com

EMERALD CROWN
COLLECTIBLES
Specializing in Esthetic Mineral
Specimens from Around the Globe
VISIT OUR WEBSITE:
www.emeraldcrown.com
CALL US AT: (941) 423-4103
E-MAIL US AT: emerald@acun.com
2980 Ridley Lane, North Port, FL 34286
ALL MAJOR CREDIT CARDS ACCEPTED

DIAMOND CRYSTAL SPECIMENS
Kelsey Lake mine, Colorado
Microcrystals to 2 carats plus
PRISMA ENTERPRISES
P.O. Box 218, Timnath, CO 80547
Tel./Fax: 970-221-0338

HAWTHORNEDEN

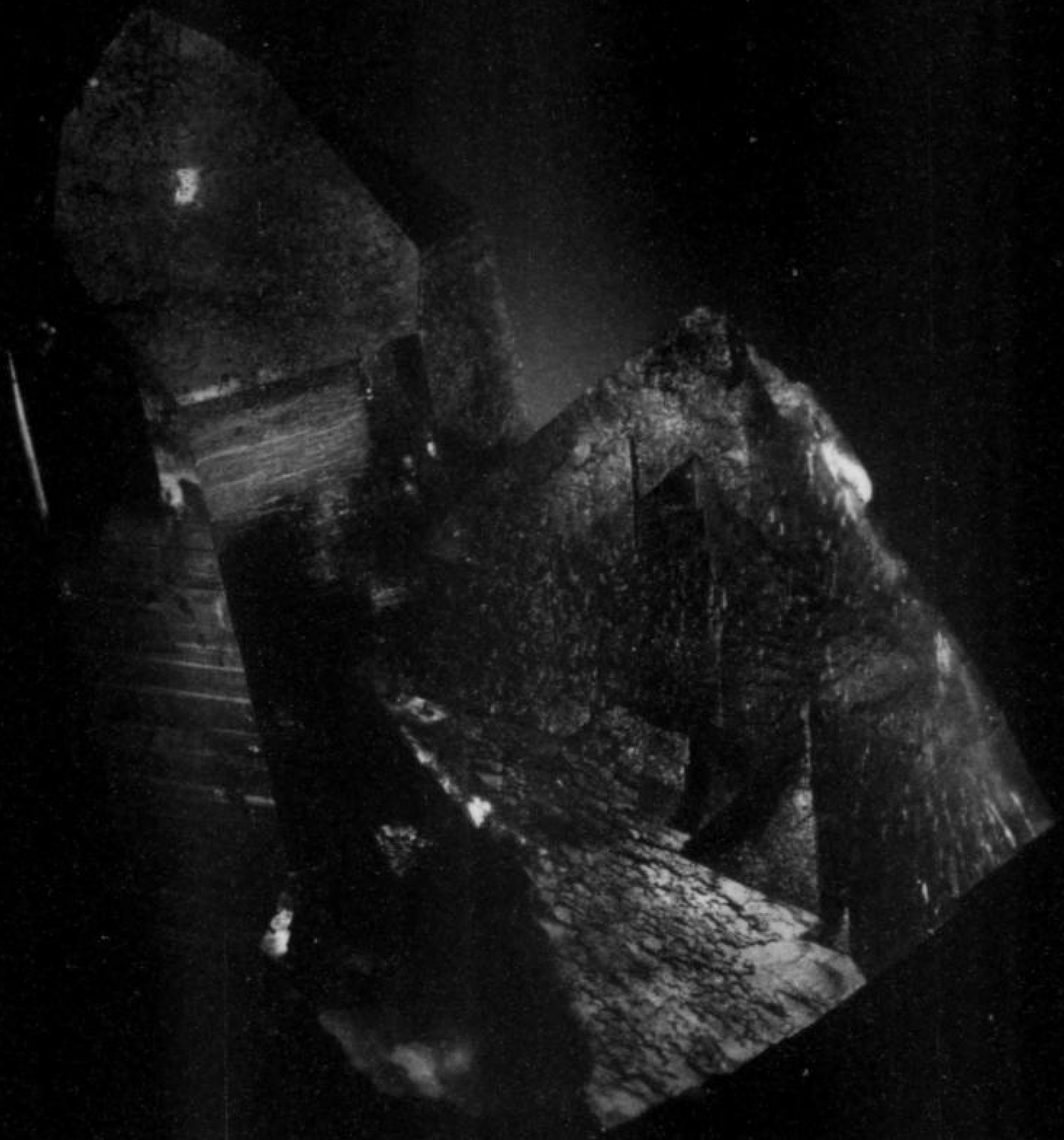
FINE MINERAL SPECIMENS
Thumbnail to Cabinet Size

WANTED TO PURCHASE—OLD COLLECTIONS

Open Mid-June to September
(Otherwise By Chance or By Appointment)

Three miles south of Bancroft, Ontario, on the West side of Hwy. 62

Wendy & Frank Melanson
L'Amable, Ontario K0L2L0
Tel: (613) 332-1032 • FAX: (613) 332-0585



Fluorite, Mont Blanc, Chamonix, France, 4 cm. Photo by Jeff Scovil.

Fine Mineral Specimens

Specializing in Great Classics Afghan & Pakistani Pegmatite Minerals.

lists issued.

See me at Booth M7, Tucson Convention Center. I'll have Pakistani Gem XLS and Old Classics from a collection recently purchased.

H. Obodda
Box 51
Short Hills, N.J. 07078
(973) 467-0212

Tucson Show-Executive Inn, Room 135—
Feb. 3-13, 1999
When in Detroit please call to visit
our new showroom
Just 35 minutes from Detroit Metropolitan Airport

NORTH STAR MINERALS

SPECIALIZING IN THE MISSISSIPPI VALLEY-TYPE DEPOSITS OF SOUTHERN ILLINOIS
NEW MINERALS FROM BULGARIA AND EASTERN EUROPE

Ross C. Lillie
7249 Woodlore Dr., W. Bloomfield, MI 48323
Tel./Fax: (248) 926-9929 • E-mail: Norstar@mich.com

Michigan Silver

PERU!

Mineral Specimens · Peruvian Pyrite by the Ton · Quartz Points · Rough Blue & Pink Andean Opal · Chrysocolla · Stonecarvings in Hard & Soft Stone · Fossils · Peruvian Handicraft Beads

► WHOLESALE ONLY ◄

Vicjon Enterprises Inc.
12025 W. Wisconsin Drive
Lakewood, CO 80228
Tel: (303) 987-1296 · FAX: (303) 988-7883

SEE US IN DENVER HOL. INN N. #290, SEPT.

Carousel

GEMS AND MINERALS

1202 Perion Drive
Belen, New Mexico 87002
505-864-2145
Please send $2 U.S. ($4 outside U.S.) for a 1-year subscription to our mineral list.

WRIGHT'S ROCK SHOP

Fine Mineral Specimens!
We Buy Collections!

SHOWS:

Aug. 28–30	Carnegie Museum Pittsburgh
Sept. 15–19	Denver, CO (Holiday Inn Rm. 115)
Oct. 9–11	Detroit, MI
Oct. 16–18	Houston, TX

3612 ALBERT PIKE, HOT SPRINGS, AR 71913 • Tel: (501) 767-4800

GOLD SPECIMENS!!

Buy legal high-grade from Sigma and Lamaque Mines
Val D'Or, Quebec, Canada

Bright, lustrous and very rich

Large and Small, Ore Grade to Highly Esthetic
Proceeds go to an Education Fund

Call **Dave Joyce** at
416-861-8318, ext. 245
Fax 416-367-5693

FREE CATALOG

Over 800 sizes of plastic boxes.
- Hinged
- Non-hinged
- Micromount
- Perky and magnifier boxes

ALTHOR

2 Turnage Lane, P.O. Box 640, Bethel, CT 06801
Tel: (800) 688-2693 · FAX (203) 830-6064

WILLIS' EARTH TREASURES

CLOSE-OUT SALES—SPECIALS
SEE US IN TUCSON
EXECUTIVE INN—ROOM 138

Franklin Fluorescent Minerals
Worldwide Mineral Specimens

Joyce & Dick Willis
309 Prospect Street
Stewartsville, NJ 08886
(908) 859-0643

P.O. Box 1384 • Somerset West 7129
South Africa
International Tel: 27 21 - 855 3267
International Fax: 27 21 - 855 4119
E-mail: owen@intekom.co.za

Colin & Helga Owen

SPECIALIZING IN MINERAL SPECIMENS FROM N'CHWANING AND WESSELS MINES, KALAHARI MANGANESE FIELD

By Appointment Only.
Just 30 Minutes Drive from Cape Town

Rare Minerals, Meteorites, Analytical Services & Microscopes–Monthly Lists

EXCALIBUR MINERAL COMPANY

1000 North Division Street • Peekskill, NY 10566-1830
Tel: (914) 739-1134 Fax: (914) 739-1257
www.bestweb.net/~excalmin

NEW!
SUPPLY CATALOG
$2.00


5000
FEDERAL RESERVE NOTE
THE UNITED STATES OF AMERICA
WILL PAY TO THE BEARER ON DEMAND
7-G
G1A
WASHINGTON, D.C.
MADISON
FIVE THOUSAND DOLLARS


Smithsonite - Tsumeb

Photo: Mark Schneider
Now in John Schneider collection

DAN & JILL WEINRICH

Dealers in Fine Mineral Specimens

NEW MINERAL VIDEO WITH 75 OF OUR BEST SPECIMENS!

Send $8 (outside U.S. and Canada—$25)

FREE *Illustrated catalogs* issued!

LOOK for us on the internet—***FREE PHOTOS*** of any specimen in our stock sent upon request!

16216 Copperwood Lane • Grover, MO 63040
Tel: 314-230-8323 • FAX: 314-256-6540
www.DanWeinrich.com • e-mail: Weinrch@aol.com

*

Now
Dispersing
the Collection
of

Robert
Ferguson
(1767–1840)

OLD
EUROPEAN
CLASSICS!

See:
Rob Lavinsky
www.theark-
enstone.com
John Veevaert
www.trinity-
minerals.com

Oceanside

gem imports, inc.

Huge stock of fine minerals—many never shown. Wide range of Sizes/Prices. List avail. for *cut stones* only. NO SHOWS. Write or call for more information.

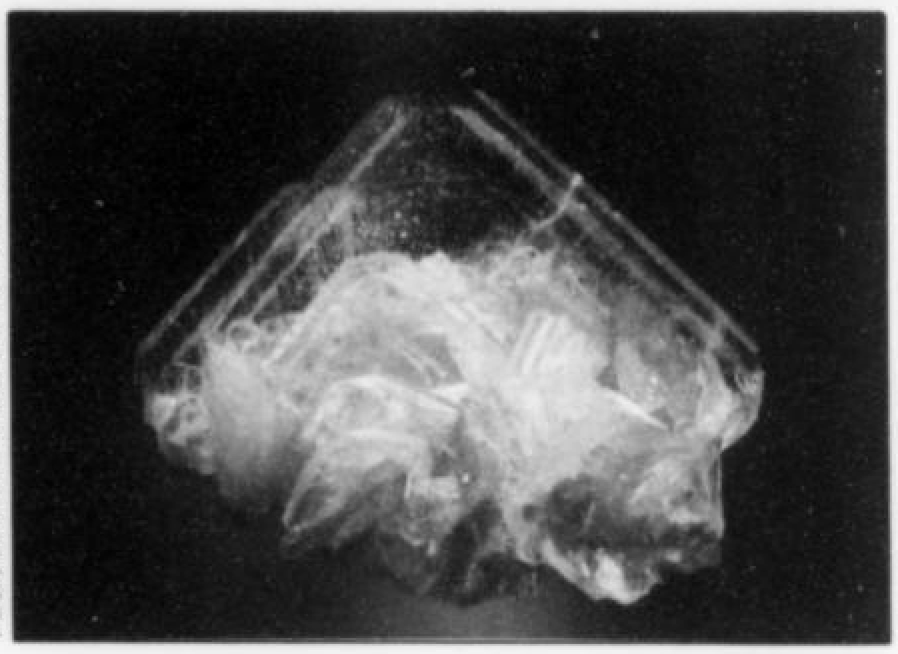
P.O. Box 222
Oceanside, NY 11572
Tel: (516) 678-3473 • Hrs. by Appt.

THE
ROCKSMITHS

Nov. 6–8	St. Louis, MO
Nov. 7–8	Concord, CA
Nov. 13–15	Austin, TX
Nov. 20–22	Marietta, GA (Atlanta area)
Nov. 21–22	W. Palm Beach, FL (New Loc.: Fairgrounds)
Jan. 15–17	Lakewood, CO (Denver area)
Feb. 11–14	Tucson, AZ (TGMS Main Show, Convention Center)

5th & Toughnut. Box 157. Tombstone, Arizona 85638

Classic Mineral Videos!


FLUORAPOPHYLLITE, 7.5 cm. CHINA

JEFF SCOVIL PHOTO

Aesthetic Minerals for sale on our 2-hour Video Catalog!
Fine specimens in all sizes! At least 4 Videos per year!
Satisfaction Guaranteed or your money Happily Refunded!
ORDER YOUR VIDEO—$12 in any format.
We buy specimens & collections—Competitive Prices Paid!
Trade-ups accepted on better specimens (same species).
Buy-backs on wanted specimens!

THE ARKENSTONE

Robert Lavinsky

P.O. Box 948672, La Jolla, CA 92037 USA • Tel: (619) 587-1141
FAX: (619) 534-8180 (ATTN: ROB) • E-mail: lavinsky@biomail.ucsd.edu

JOHN BETTS
FINE MINERALS

Minerals from old collections, new discoveries, and classic localities for the discriminating collector.

NEW ARRIVALS

Sharp, lustrous uraninite crystals from Topsham, Maine.

World-class crystallized native coppers from Broken Hill, Tsumeb and Michigan.

SHOW SCHEDULE

Nov. 7–8	Nassau County, Old Westbury, NY
Nov. 21–22	Sacred Heart Univ., Fairfield, CT
March 6–7	New York City, NY

215 West 98 Street, No. 2F, New York, NY 10025
Phone: 212-678-1942 Fax: 212-242-7020
Hours by Appointment
Cash Paid For Collections—Write For Free List
JHBNYC@AOL.COM

ONLINE MINERAL GALLERY
HTTP://MEMBERS.AOL.COM/JHBNYC/GALLERY.HTM

FREE
ALL-NEW VIDEO

Cuprite, Zaire, photo J. Scovil

Classic specimens at *rational* prices.
Call now for a free video catalog!

- Satisfaction guaranteed on all purchases.
- We pay top prices for fine specimens/collections.
- Passing through Texas? We'd enjoy meeting you.

FREE VIDEO: Call (972) 540-6999
International orders: $25 for PAL or SECAM video; credit cards only

LYMAN & SMITH
FINE MINERALS

P.O. Box 2256 • McKinney, TX 75070 • (Dallas area)
(972) 540-6999 • FAX (972) 540-1907

E-mail: info@fineminerals.com • Website: www.fineminerals.com

FINE & RARE MINERALS

FABRE
MINERALS
Jordi Fabre
C/Arc de Sant Martí 79 Local
08032-BARCELONA (SPAIN)

☎ (34) 93-450-4478
Fax (34) 93-450-4745

By Appt. only
No Catalog

Now on The Web
at the
FABRE MINERALS
Home Page!
fabre-minerals.com/index.html
E-mail:
enquiry@fabre-minerals.com

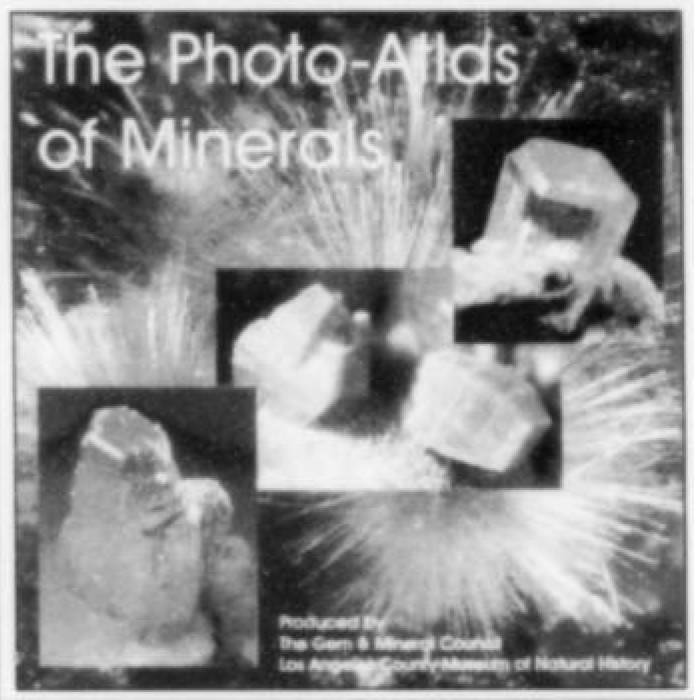
See you at

St-Marie-aux-Mines Show (Théâtre) •

Munich Show (stand 2505) •

Tucson Show, Executive Inn Lobby

IN THE FISHBOWL!



The Photo-Atlas of Minerals

- More than 6,500 high-resolution images
- Descriptive data for all known minerals
- Mineral name pronunciations (audio)
- Origins of mineral names
- Mineral synonyms and varieties
- Crystal forms, symmetry & twinning
- Mineral localities with index maps
- Modern Strunz mineral classification
- Glossary of mineral terminology
- Cross-indexes for easy searching
- Copy and print images and data
- Mineral identification game

Windows CD-ROM
Only $49.95

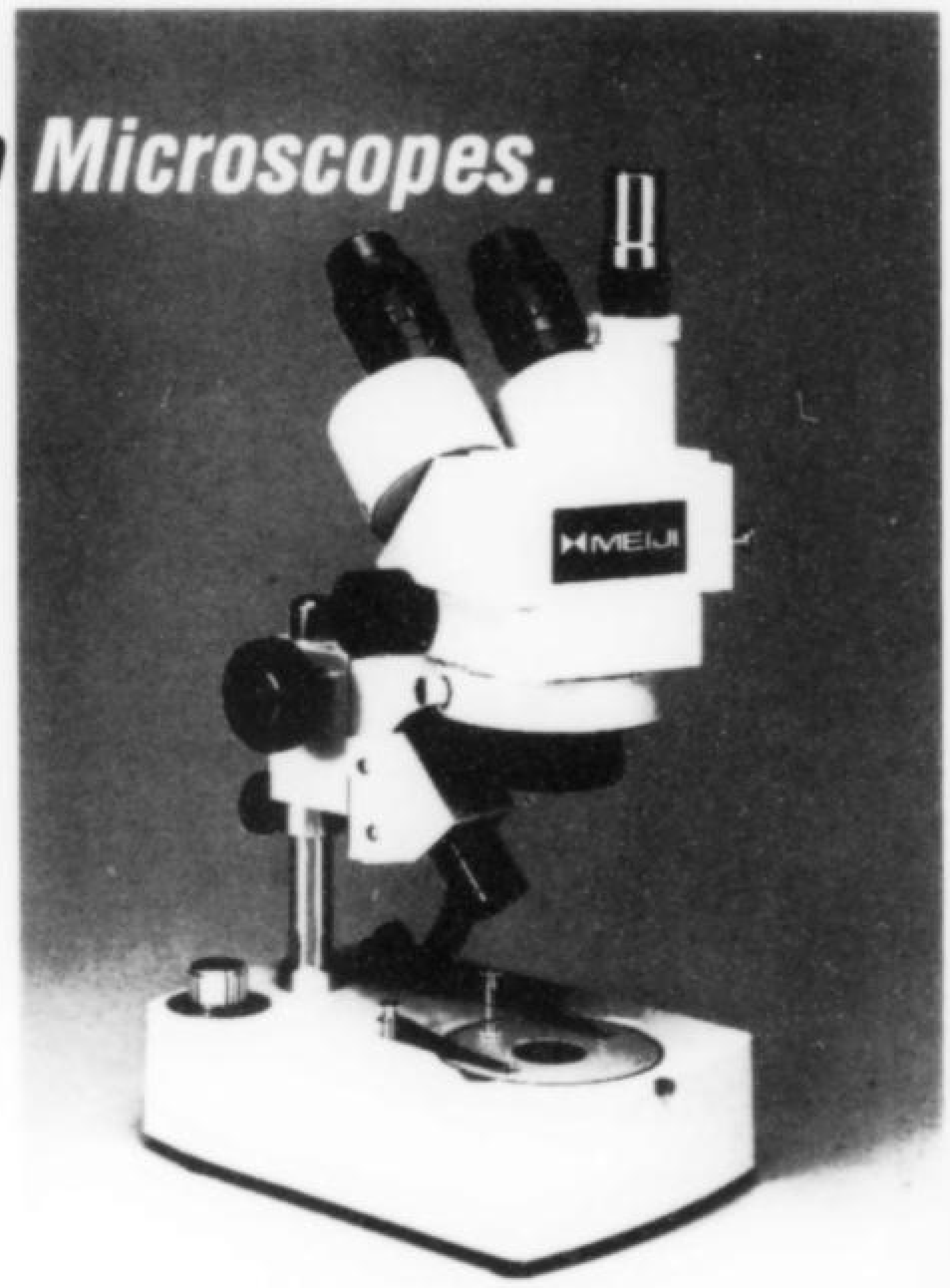
Plus $5.00 shipping and handling
California orders add 8¼% sales tax.

The Gem & Mineral Council
Los Angeles County Museum of Natural History
900 Exposition Blvd., Los Angeles, CA 90007

Phone: 213-763-3326
FAX: 213-749-4107
http://nhm.org/~gmc

Crystal Clear.

The Meiji EM Series of Modular Stereo Microscopes.



If you are looking for precision, durability, quality and value in a stereo microscope, we invite you to take a closer look at Meiji's EM Series of Stereo Microscopes.

The modular design (A wide variety of bodies, single magnification or zoom— rotatable 360°, auxiliary lenses, eyepieces, stands, holders, etc.) gives you the freedom to create the ideal instrument for your specific needs or application, and Meiji stands behind every instrument with its limited ***Lifetime Warranty.***

For more information on these economically priced stereo microscopes, please call, FAX or write us today.

MEIJI
TECHNO

MEIJI TECHNO AMERICA
2186 Bering Drive, San Jose, CA 95131, ***Toll Free Telephone: 800.832.0060***
FAX: 408.428.0472, Tel: 408.428.9654

**UNUSUAL CRYSTALS
FROM
AROUND THE WORLD**

*CORUNDUM IS
OUR SPECIALTY!*

GEM-FARE
P.O. Box 213
Pittstown, N.J. 08867
Phone/Fax (908) 806-3339
REQUEST CRYSTAL LIST

MINERAL COLLECTION
for Sale
1200+ specimens, TN to MIN.,
and some Cabinet pieces.
Includes Cabinets, Min. Records, Books
James L. Hicks
639 Sussex Blvd., Kingston, Ont.
Canada K7M 5A9. Eves: (613) 389-3378

Blue Sky Mining
DANIEL BELSHER
8890 N. Federal Blvd., #52-D
Denver, CO 80221 U.S.A.
Tel: 303-428-8771 • FAX: 303-428-8773

See me at the
Denver, Tucson &
St. Marie-aux-
Mines Shows
NO LISTS
by Appt. only

Collector, Commercial & Educational Mineral Specimens from Mexico. Wholesale/Retail

WASHINGTON, DC AREA
- BUYING & SELLING GREAT MINERALS AT SHOWS, BY APPOINTMENT IN VIRGINIA, AND BY MAIL (NO LISTS)
- PROMPT RESPONSE TO INQUIRIES.

C. CARTER RICH
—FINE MINERALS—

- SPECIALIZING IN FINE OLD CLASSICS FROM FINE OLD COLLECTIONS!
- SEE ME IN TUCSON AT THE INN SUITES, ROOM 121. EASY PARKING!!

PO BOX 69
ALDIE, VA 20105 (703) 327-6373

CLAUDETITE

Rich crystals throughout matrix, rare and poisonous; Germany

Over 1,000 Mineral Listings plus Boxes & Supplies
—Send three stamps for complete catalog—

DAVID SHANNON MINERALS
6649 E. RUSTIC DR. MESA, AZ 85215 (602) 985-0557 Phone/Fax

JENDON
MINERALS

P.O. Box 6214
Rome, Georgia 30162-6214
Tel: 706-291-4618
No List. Please write for specific requests.

Tysons' Minerals

fine mineral specimens

Rod & Helen Tyson
10549 133rd Street
Edmonton, Alberta Canada T5N 2A4
(403) 452-5357

Fine Australian & Worldwide Minerals, Fossils, Rare Australian Species, Meteorites & Tektites. Retail & Wholesale supplier since 1984. Now see us on the main floor at the Tucson Convention Center in February.

AUSROX

Robert Sielecki
exploration geologist
Janine Rea
mine geologist
42 Hex St., Tottenham
Melbourne, Victoria 3012
Australia (phone (61-3)9-314-9612)
FAX: (61-3)9-315-1819

See You In:
Tucson
Tokyo
Denver
Munich

Ed Rogers
Rare & Out of Print Books

Catalogs issued on mineralogy, gemology, mining, meteoritics, paleontology & exploration

(719) 539-4113
Fax 539-4542
Send or fax us your want lists.
e-mail:
erogers@lynx.sni.net

WEB CATALOG! http://www.geology-books.com/erogers

PO Box 455 · Poncha Springs, CO 81242 USA

Can't make it to the Denver Show ?!?!

Can't take vacation? Want to use your money for rocks instead of travel expenses?

SHOP FROM HOME,
LIVE VIA THE WORLD WIDE WEB

We will have a large website updated twice-daily with information on new finds appearing at the show (some offered exclusively over the internet) as well as a wide range of individual specimens priced from $10 to $5,000.

http://www.thevirtualshow.com

Website now open! Send us your want list and we will attempt to find specimens for you at the show!

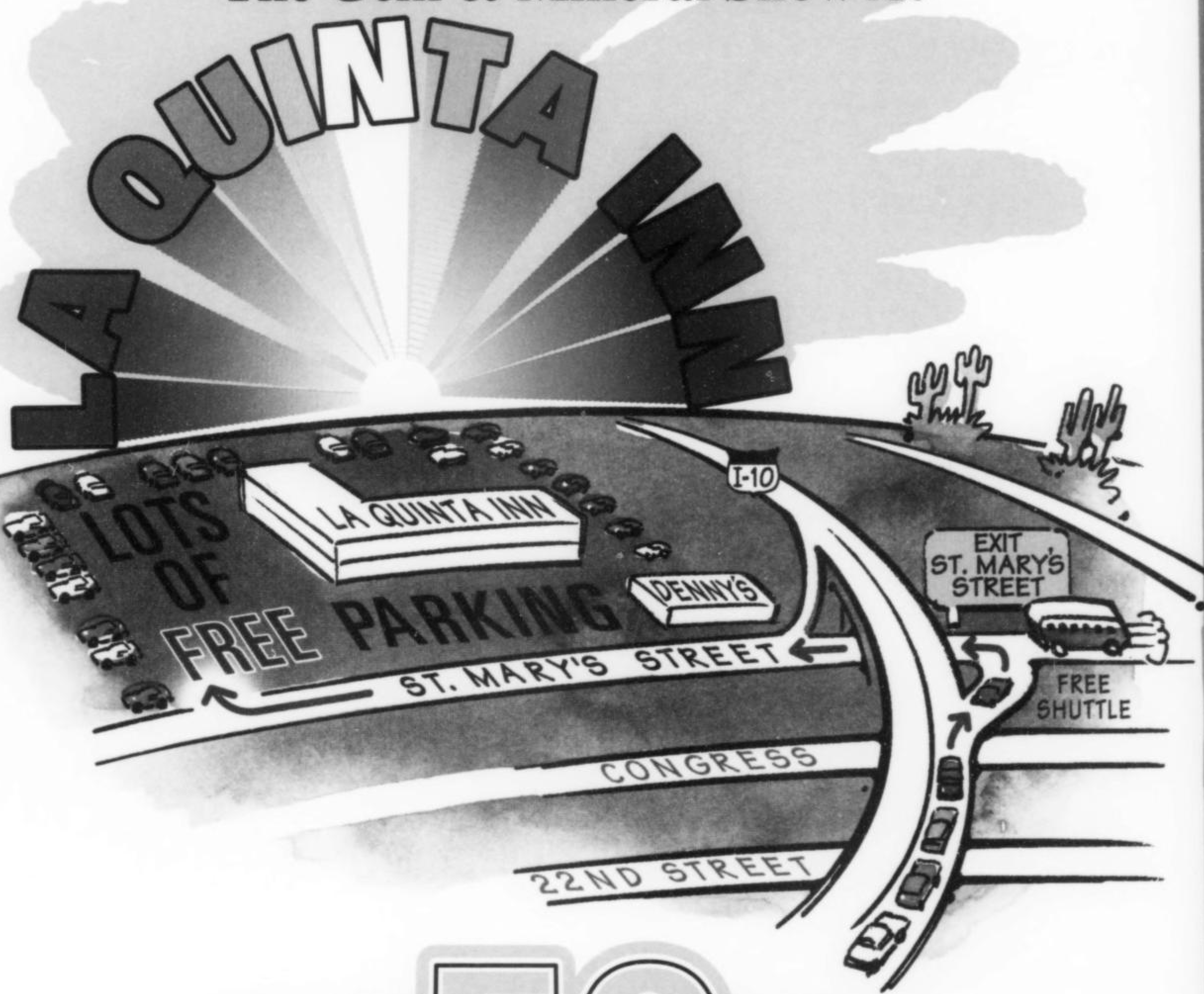
All want lists due by 9/5/98.

a joint project of The Arkenstone, Trinity Mineral Company, and PaleoArt
(Rob Lavinsky, John Veevaert, and Chris French)

In Tucson

Come Direct To Us First!

The Gem & Mineral Show At



OVER 50 DIRECT

IMPORTERS & MINERS

Discover La Quinta, a show with • Great atmosphere • Plenty of FREE Parking • No tents • Mineral specimens directly imported from around the world • Friendly dealers. This is the way shows used to be. Some dealers open as early as February 1. Come to La Quinta first - you'll be glad you did!

Cobaltoan Dolomite, Tsumeb, Namibia, 16.5 cm, Pamela Zilly Photo

VICTOR • YOUNT

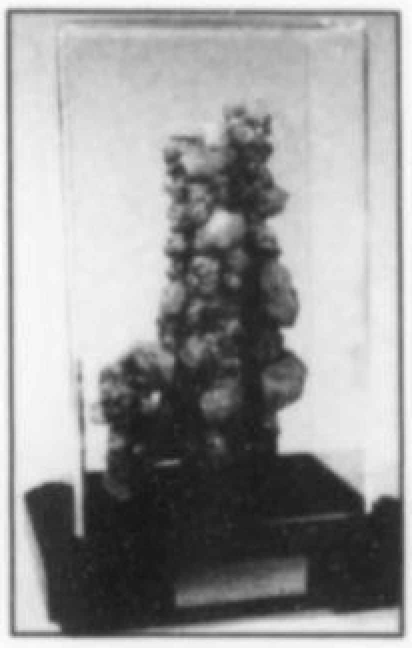
8388 Lunsford Road
Warrenton, Virginia 20187-8834
Tel: (540) 347-5599

Please Note our New Address!

The Sunnywood Collection

"We specialize in the presentation of natural art."

Premium **Minerals, Fossils & Carvings** artistically mounted!



VISIT OUR WEBSITE:
www.sunnywood.com

Order specimens directly from our website with secure order form.

VISA

MasterCard

DISCOVER

12068 E. Amherst Place
Aurora, Colorado 80014
tel/fax 303-368-7497
E-mail: minerals@sunnywood.com
We accept all major credit cards.

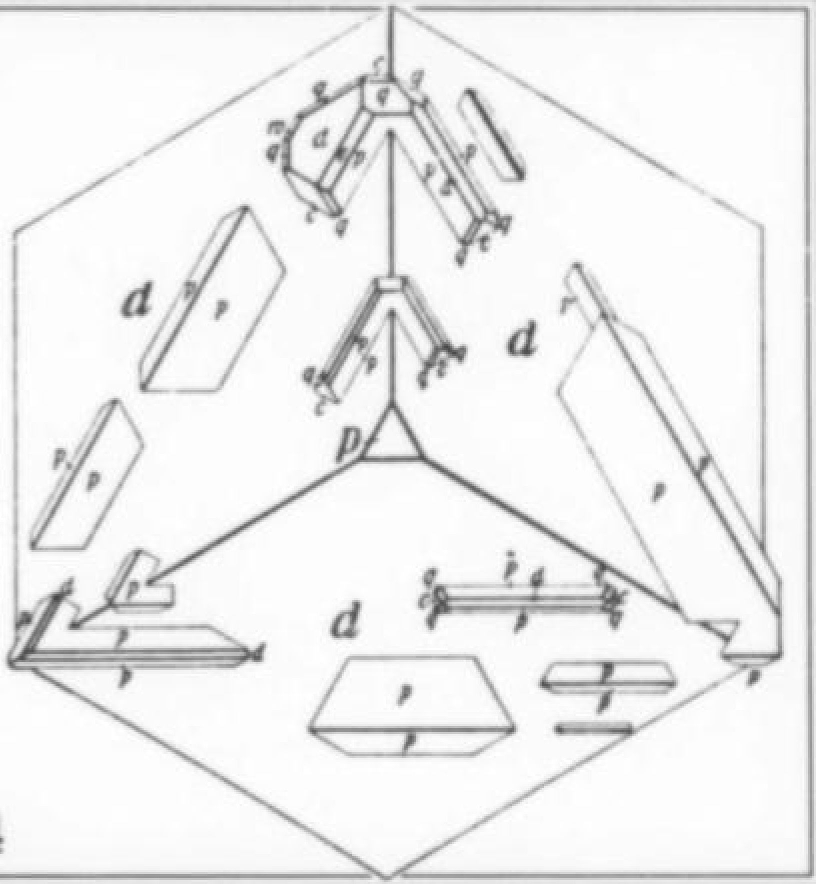
The Best of My Mineral Collection
can be seen on the Internet at
www.LHCONKLIN.com
The Rest can be seen at my Showroom.

LAWRENCE H. CONKLIN

Gallery-showroom hours 10 to 5
Mondays–Fridays
No appointment necessary.

Ask to receive my free lists which are now published regularly.

2 West 46th Street • New York, NY 10036 • 212-382-0304



Volume 11 is here!

IC Minerals on Video, now in our fourth year!

Featuring 100 fine mineral specimens on our full-length color video!

$10 postpaid in the U.S. PAL or SECAM call or write for info.
Subscriptions available. Credit Cards Accepted.

The only way to buy minerals through the mail!

"An excellent video of specimens for sale. . . . The photographic quality is among the best I've seen."
(Wendell Wilson)

IC Minerals
P.O. Box 1376, Goldenrod, FL 32733 • Tel & Fax: (407) 679-0905 E-mail: icm@.com

Searching the world . . .

. . . to bring you the finest in mineral specimens and meteorites at competitive prices.

- *Fine Display-Quality Mineral Specimens, Rare Species, and Fluorescent Minerals:* Send for our lists of thumbnail, miniature, and cabinet specimens. First quality mineral specimens for collection and display, plus rare species for systematic collection, reference, and research. Fluorescent minerals are available for display and systematic collections.
- *Micromount and Specimen Boxes of All Kinds:* Separate listings are available detailing prices and sizes of micromount, plastic magnifier boxes, white cotton-lined specimen boxes, display stands, gem display boxes, paleomagnetic sampling cubes, showcase boxes, white folding boxes, display bases, etc.
- *Meteorites, Tektites, Moldavites, Fulgurites, and Trinitite:* Specimens of all sizes for private collections and institutional display, from worldwide localities. New and used books also available.
- *Mineralogical Books:* Send for our separate price list with information covering new books on mineralogical subjects, as well as older, out of print mineralogical and geology books.
- *Back Issues of the Mineralogical Record:* Ask for our listing of out-of-print issues currently in stock. Send us your want list, if you need back issues to complete your set. Send us your offers, if you have back issues available for sale.
- *Worldwide Mail Order Service:* For more than 35 years, since 1959, we have been supplying Minerals, Meteorites, Books, Boxes, and back issues of the Mineralogical Record to collectors around the world. Orders can be placed by mail, phone, FAX, or e-mail—addresses are given below.
- *Price Lists:* Send a very large SASE for price lists on any of the above subjects. Non-USA, send two International Reply Coupons. OR . . . . . Check out our new web site on the internet to see price lists and color photographs: http://www.minresco.com

Mineralogical Research Co.

Eugene & Sharon Cisneros
15840 East Alta Vista Way, San Jose, California 95127-1737, USA
e-mail: xtls@minresco.com • PHONE: 408-923-6800 • FAX: 408-926-6015
Look for our booth at major Western U.S. Shows
A Division of the Nazca Corporation

http://www.minresco.com
WE'RE ON THE INTERNET!
CHECK OUT OUR
WEB SITE!

Advertisers Index

ONE OF THE WORLD'S PREMIER CRYSTAL COLLECTIONS
Featuring Gem Crystals, Gold Specimens and Hundreds of Worldwide Classics
Hundreds of Specimens Priced under $1,000. Write for List.
Order your 96-minute Video! (see below)

ONE OF THE WORLD'S DEFINITIVE GOLD COLLECTIONS

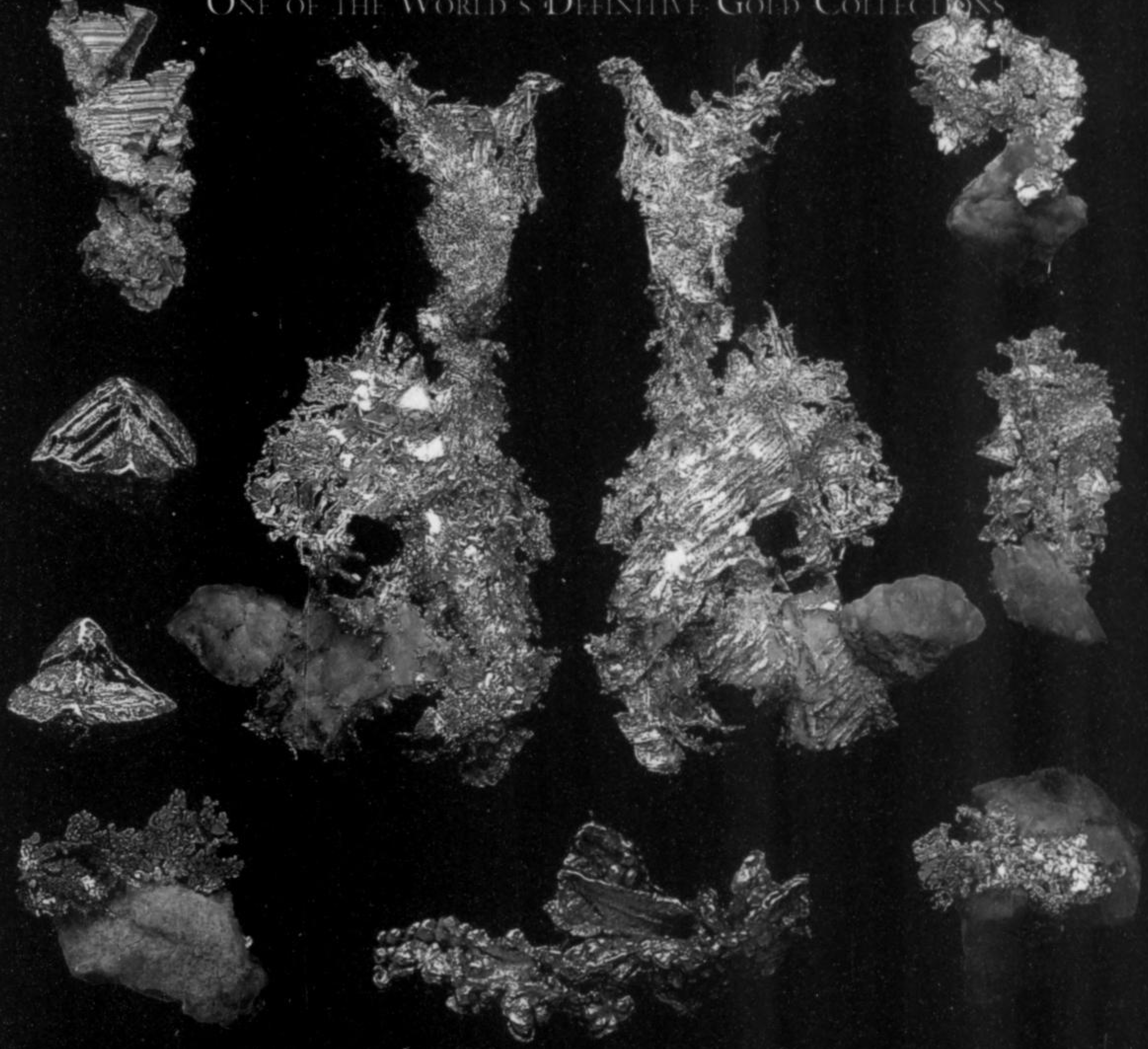


Photo by Jeffrey Scovil

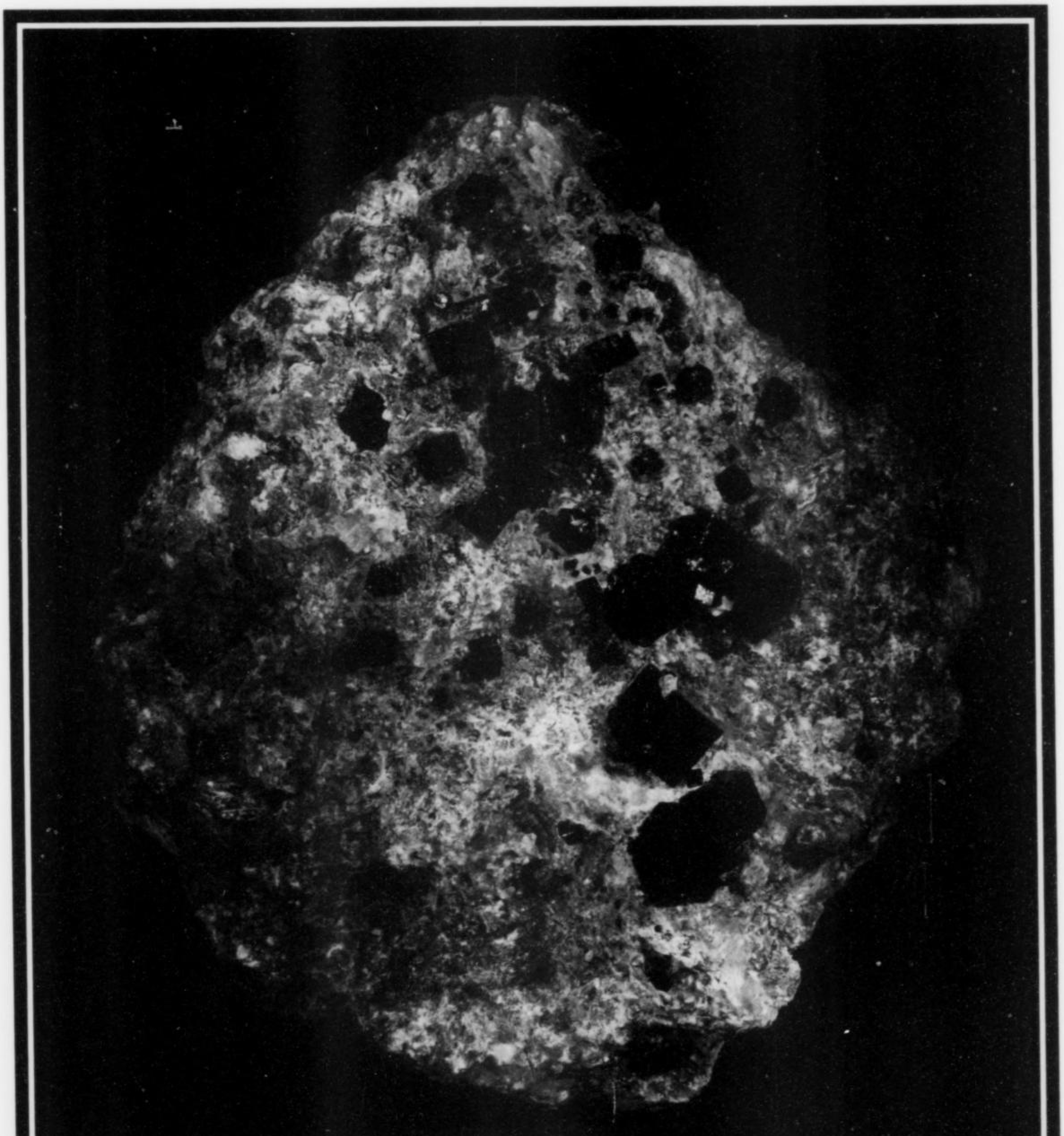
I WILL BE TRAVELING around the country giving private showings of the collection. Please contact me so that I may visit you when I am in your area.

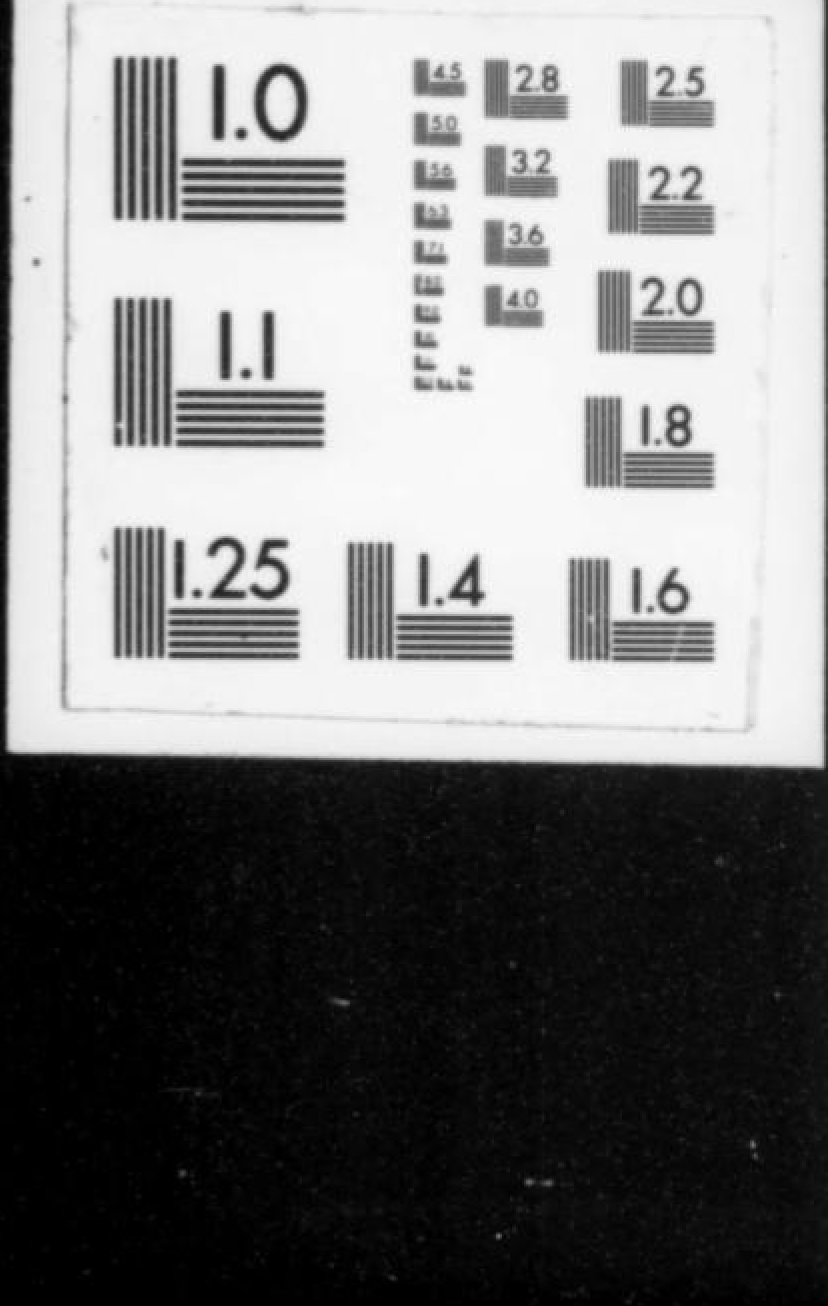
You can preview this collection with a 96-minute, professionally prepared video. This live-action presentation features 180 specimens, individually filmed, and 35 mine location photos to illustrate the history and workings of many great mines and their crystal treasures. This unique, educational video graphically illustrates the 12 criteria used to assemble this world-class collection. To order your video send $29.50 plus $2.50 postage.

Dr. Wendell Wilson in his video review in *M.R.*, Nov/Dec 1992, p. 504, says "The collector of aesthetic mineral specimens will find much to savor in Keith Proctor's video catalog of his collection. . . . It really delivers in terms of extraordinary mineral images and specimen information and will stand for many years to come as a historically valuable documentation of one of the great private collections of our time."

"The video offers an opportunity to see and study Proctor's exquisite specimens at leisure. Many are pictured on slowly revolving turntables, allowing all sides of the specimens to be seen, and their three-dimensional shapes to be fully realized, as reflections play across crystal faces and gemmy interiors . . . this really is one of the best private collections ever assembled." Video Review: Nov/Dec '92

KEITH PROCTOR
88 RAVEN HILLS COURT, COLORADO SPRINGS, COLORADO 80919-1316 • TEL: (719) 598-1233




1.0
4.5
5.0
5.6
6.3
7.1
8.0
2.8
3.2
3.6
4.0
2.5
2.2
2.0
1.1
1.8
1.25
1.4
1.6