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THE USE OF THE TWO-CIRCLE CONTACT GONIOMETER IN TEACHING CRYSTALLOGRAPHY

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The two-circle contact goniometer was devised to supplement the two-circle reflecting goniometer, by furnishing a means for the measurement of medium-sized crystals not provided with sufficiently good reflecting faces for the successful use of the latter instrument. The contact goniometer has however proved itself adapted, in a greater degree even than the reflecting goniometer, to the demonstration of the principles of two-circle measurements, and their relation to geographic and astronomical measurements, and of the relations of normals to crystal faces and to projections, both stereographic and gnomonic. This simple and inexpensive instrument, a description of which is given on the following page, is thus fitted to serve a very important purpose in instructional work in crystallography.

With such laboratory directions as are given below, the student may be put to work on a natural crystal; and the definitions, axial characters, symmetry, forms, and symbols of the six systems are *discovered* by the student with little additional aid from the instructor. The making of a projection, determination of crystal constants, drawing of the crystal from the projection, and finally the cutting, from a gypsum cylinder, of an exact model of the crystal by the use of the Goldschmidt crystal modelling apparatus[1] give the student an intimate, complete, and ineffaceable knowledge of the crystal. This knowledge is won directly from the natural form; the time which might otherwise be spent in the study of wooden models is saved; there is no perplexing transition from perfect models

[1] V. Goldschmidt: Ueber einen Krystallmodellirapparat. *Z. Kryst. Min.*, **45**, 573, 2 text figs., 1908.

to distorted and imperfectly developed natural crystals; and finally when one or two crystals from each of the six systems have been studied in this way, the student has received the preliminary training of an investigator in crystallography.

The crystal, when mounted on the holder *t* of the contact goniometer (fig. 4), may be conceived of as occupying the center of a sphere of which *H*, the graduated horizontal circle, is the equator; *V*, the vertical circle, is any meridian; and zero (0) on the vertical circle is the north pole. *S*, the steel rod, is a normal successively to any crystal face to which *p*, the plate borne on the rod, is made parallel.

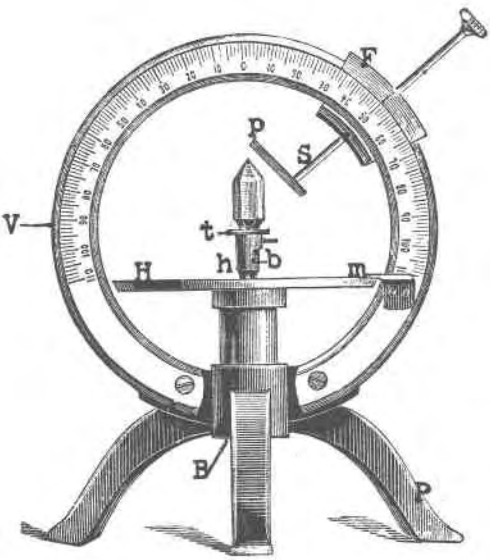

FIG. 4.

The position of this normal is fixed (1) by its longitude, *i.e.*, its distance measured on the equator from the zero meridian; (2) by its latitude, *i.e.*, the distance from the equator measured on a meridian. A like method is used to locate positions on the surface of the earth and to establish the positions of the heavenly bodies. In crystallographic determinations the first angular distance (longitude) is designated φ (*phi*); the complement of the second angular distance (latitude), *i.e.*, the distance from the pole (or zero) on the meridian is designated ρ (*rho*).

The position of the steel rod gives the position of a normal to each crystal face in a sphere from which spherical and stereographic projections are made. If a sheet of paper or cardboard be placed tangent to the vertical circle at zero, the prolongation of the normals until they pierce this paper will give the points representing the faces on the gnomonic projection.

The symmetry of a crystal is revealed in the operation of measurement. For all crystals possessing more than one plane of symmetry, the horizontal circle is a plane of symmetry; and the vertical circle, on rotation of the crystal, becomes a plane of symmetry in two, three, or four positions. The symmetrical relations of prismatic, of pinacoidal, of domal, and of pyramidal faces are also successively disclosed on rotation of the horizontal circle.

A 20 centimeter spherical glass flask, ground, inverted, and fitted on a wooden pedestal, as devised by Professor Goldschmidt for use in his own laboratory, is serviceable in explaining to a class the method of locating crystal faces by angular measurements, (φ and ρ), and in making clear the principles of projections.

Laboratory Directions for Crystal Measurements and Crystal Projection.

1. Make several free-hand sketches of the crystal, one top view and from two to four side views, each roughly 3 cm. in diameter; with small crystals a reading glass should be used, magnifying the natural size three to five times.

2. Number carefully every crystal face in your sketches, first with pencil and, after verification, with pen and ink.

3. Prepare the following table in your laboratory notebook:

No.	Symbol	Letter	Horizontal Reading	Vertical Reading	φ	ρ

4. Mount the crystal with heated wax,[1] in *vertical* position on the holder *t* (consisting of platform and rod).

5. Using key, fasten the holder in the center of the goniometer with dominant vertical faces of the crystal in alignment with the

[1] A mixture of beeswax and rosin, melted together in equal parts, is most satisfactory.

four holes, *b*, and by means of the ball and socket adjustment at *B* in figure (hidden by leg) using key in holes, carefully orient the crystal. The crystal is oriented when its prismatic faces read 90 degrees, or when the face normal to its polar axis reads zero, on the vertical circle.

6. Measure successively the *position angles* of the available crystal faces in (*a*) the prismatic zone, and (*b*) the pyramidal zone. These are the positions of normals to the crystal faces with reference to a horizontal (equatorial) plane and to a vertical (meridional) plane. White or black paper placed on the horizontal circle may add to the ease of reading. The plate carried on the steel rod should never be brought into actual contact with the crystal face, but the trace of the crystal face should be made parallel to the plate, which should be kept *exactly horizontal* for the readings on the horizontal circle, and *exactly parallel* to the plane of the vertical circle for the readings on that circle. The horizontal circle is graduated only to 5°, but can be read to 1° by means of the vernier at *m*. List your readings, horizontal and vertical, in table opposite the number of each face. Be very careful to identify the faces in your sketches, and to place the readings opposite the correctly identified faces.

7. Find the center of a sheet of drawing paper. From this center draw two circles with radii of 5 and 10 cm. respectively. Draw 0° (360°) and 90° meridional lines, and plot the *normal points*, that is, the positions of the normals established by the horizontal and vertical readings.[1]

8. When normal points are all plotted, draw *zonal lines*, making the necessary compensations to give equal distances (like units) in parallel directions.

9. Select two coördinates, one front and back, and the other right and left.

10. Determine the symbols (*p*, *q*) of the normal points, by means of their relations to these coördinates. The positions of the normal points of the most prominent pyramidal or domal planes are taken as the unit distances (p_0 and q_0) on the coördinates. Note the *rationality of indices*. Insert the symbols in their proper places in the table.

[1] An explanation of the conversion of angular readings to linear distances for plotting, which appears at this point in the laboratory directions, is omitted here because it will be given in the next article in this series, on gnomonic projection.

11. Define the system to which the crystal belongs; (*a*) in terms of axes, (*b*) in terms of symmetry.

12. Determine the elements[1] of the crystal, graphically and by calculation: that is the values of p_0, q_0, r_0; λ, μ, ν (polar elements); a, b; α, β, γ (linear elements); and list them in upper left-hand corner of drawing paper.

13. Correct to the 0° meridian, and insert in the table the corrected values of φ and ρ.

14. Compare these values with those given in Goldschmidt's *Winkeltabellen* for the crystal under study, and insert in the table the proper letters.

15. Complete the projection by drawing a border parallel to the new 0° and 90° meridians, and place in this border the symbols of all the faces in the prismatic zone.

16. Make from the projection two drawings of crystal: top view and side view.[2]

Notes

If it becomes necessary, in advanced work, to measure a crystal on which neither prismatic, basal, nor other pinacoidal planes are developed, the student must proceed in mounting the crystal as with the two-circle reflecting goniometer, bearing in mind that the roles of *V* and *H* are reversed.

The plotting of normal points may be accomplished rapidly and accurately by substituting for the tables of linear distances the Goldschmidt-Wright projection transporteur.[3] With large classes the tables (to be published in a subsequent article) are more practical.

[1] The numbers of variable elements (polar or linear), to be determined are:

	p_0	q_0	r_0				Planes of Symmetry.	Lines of Symmetry	Points of Symmetry	Total
Isometric (0).....	1	1	1	90°	90°	90°	9	3	1	9
Tetragonal (1)....	$p_0 =$	$q_0 \gtrless$	1	90°	90°	90°	5	4	1	5
Hexagonal (1)....	$p_0 =$	$q_0 \gtrless$	1	90°	90°	60°	7	6	1	7
Orthorhombic (2).	$p_0 >$	q_0	1	90°	90°	90°	3	2	1	3
Monoclinic (3) ...	$p_0 \gtrless$	q_0	1	90°	μ	90°	1	1	0	1
Triclinic (5)......	$p_0 >$	q_0	1	λ	μ	ν	0	0	0	0

The number of variable elements (polar or linear) to be determined ranges for the six systems as above listed as follows: 0.1.1.2.3.5. Their number is thus a further clue to the system. The student may be assisted to define point of symmetry and line of symmetry in projections. The numbers of symmetrical lines for the six systems are respectively as follows: 8.4.6.2.1.0.

[2] Directions for crystal drawing will be given in a subsequent paper in this series.

[3] *Z. Kryst. Min.*, **45,** 569–572, 190.

The projection figure restores the symmetry of the crystal, even tho it has apparently been completely lost in the natural crystal thru distortion in growth. It also indicates the position of the faces demanded by the symmetry, should some of them be missing on the natural crystal.

The relation of the Goldschmidt symbols, which are obtained very simply from the gnomonic projection, to Miller's symbols, to the Naumann and Weiss notation, and, in the hexagonal system, to the Bravais symbols, is readily understood; and the transformation of symbols is a desirable exercise.[1] By means of the gnomonic projection the reciprocals of the parameters—the indices—are directly obtained, and the student has no difficulty therefore in understanding why indices instead of parameters are used in the Goldschmidt and Miller symbols. The numerical values of *hkl* and of *m* and *n* are obtained from the projection.

The values of P_0 and Q_0 are obtained by measurement from the projection, and as $R_0 = 5$ cm. in the projection, in order to make $R_0 =$ unity, as required by the Goldschmidt symbols, P_0 and Q_0 are divided by 5. This is strictly true only in the isometric, tetragonal, hexagonal, and orthorhombic systems. In the monoclinic system one must first divide by 5, then multiply by sine μ. In the triclinic system, one must divide by 5 and then multiply by cosine ρ of the basal plane.

In the monoclinic system there are the following determinations to make: Projection elements (I). H = 5 cm. P_0', Q_0', R_0', and E′. Divide I by 5 to obtain II. (II). h′ = 1. p_0', q_0', r_0', e′, and h′. Multiply II by h (sine μ) to obtain III. (III). $r_0 = h = 1$. p_0, q_0, r_0, e, h, λ, μ, and ν. Given in *Winkeltabellen*. That p_0, q_0, and e are not the elements determined in the projection can be found by making a projection from the φ and ρ values in the *Winkeltabellen*, and then determining graphically the elements, which will be found to correspond to P_0', Q_0', and e′.

In the triclinic system there are the following determinations to make: Projection elements (I). X_0', Y_0', P_0', and Q_0'. Divide I by 5 to obtain II. (II). x_0', y_0', p_0', and q_0'. Divide II by cosine ρ of basal plane to obtain III. (III). x_0, y_0, p_0, and q_0. Given in *Winkeltabellen*.

The utility of the two-circle contact goniometer, in combination with the gnomonic projection, is obvious. Its simplicity, its time-saving character, the readiness with which indices are found, and the ease of calculation and of crystal drawing, are all advantages which the crystallographer cannot fail to appreciate.

[1] With the use of pins and cork models of ground forms of each system the significance of symbols can be demonstrated, and an illuminating exercise in their use be given the student; see Goldschmidt "Ueber krystallographische Demonstration mit Hilfe von Korkmodellen mit farbigen Nadelstiften."