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HANDBOOK OF  
OPTICAL  
MATERIALS

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**Laser and Optical Science and Technology Series**

Editor-in-Chief: Marvin J. Weber

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*Supplement I: Lasers*

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# HANDBOOK OF OPTICAL MATERIALS

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## Preface

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The *Handbook of Optical Materials* is a compilation of the physical properties of optical materials used in optical systems and lasers. It contains extensive data tabulations but with a minimum of narration, in a style similar to that of the *CRC Handbook of Chemistry and Physics*. References to original or secondary sources of the data are included throughout. The objective of the handbook is to provide a convenient, reliable source of information on the properties of optical materials.

Data in a handbook of optical materials can be presented by material (e.g., SiO<sub>2</sub>, CaF<sub>2</sub>, Ge), by property (e.g., refractive index, thermal expansion, hardness), by wavelength region (e.g., infrared, visible, ultraviolet), or by application (e.g., transmitting optics, laser hosts, polarizers). In this handbook data are grouped by material properties. Thereby one can compare different materials with respect to their properties and suitability for a particular application.

The volume is divided into sections devoted to various forms of condensed matter (crystals, glasses, polymers, metals), liquids, and gases. Within each section physical properties, linear and nonlinear optical properties, and many special properties such as electrooptic, magneto-optic, and elasto-optic properties of the materials are tabulated. The optical solids included are mainly inorganic materials; optical liquids are mainly organic substances.

If by an optical material one means a material that exhibits some optical property such as transmission, absorption, reflection, refraction, scattering, etc., the number of materials to be considered becomes unmanageable. Thus the inclusion of materials in this volume is selective rather than exhaustive. In the case of commercial optical glasses, for example, properties of representative types of glasses are given but not properties for all compositional variations. Glasses with special properties or for special applications are included, however.

Bulk materials rather than thin films and multilayer structures are considered. Although optical glasses epitomizes an engineered material, other engineered optical materials such as nanomaterials, quantum wells, or photonic crystals are also not included (although one of the last is listed in Appendix II).

Although today optics can encompass x-ray and millimeterwave optics, coverage is limited to materials for the spectral range from the vacuum ultraviolet (~100 nm) to the infrared (up to 100 μm) portion of the electromagnetic spectrum.

Among optical materials and properties not treated explicitly are photorefractive materials, liquid crystals, optical fibers, phase-change optical recording materials, luminescent materials (phosphors, scintillators), optical damage, and materials preparation and fabrication.

Much of the numerical data in this handbook is from Volumes III, IV, V, and Supplement 2 of the *CRC Handbook of Laser Science and Technology*. These volumes should be consulted for more detailed descriptions of properties and their measurement (the contents of the volumes and the contributors are given in the following pages). In many instances the data in these volumes have been reformatted and combined with additions and recent developments. Several new sections have been added. For example, gases can play various roles as

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an optical material—as transmitting media, active media for Faraday rotation, frequency conversion, filter, and phase conjugation. Physical and optical properties of a selected number of gases are therefore included in a final section.

The discovery of new optical materials has been accompanied by a somewhat bewildering and befuddling proliferation of abbreviations and acronyms. An appendix has been added to decode several hundred of these terms. Common or mineralogical names for optical materials are also included. Methods of preparing optical materials and thin films have developed their own terminology; many of these abbreviations are given in another appendix.

This volume has benefited from the efforts of many contributors to the *CRC Handbook of Laser Science and Technology* series. I am indebted to them for what in many cases have been very extensive compilations. In the course of preparing this volume I have also benefited from other input provided by Mark Davis, Alexander Marker, Lisa Moore, John Myers, and Charlene Smith; these are gratefully acknowledged. Finally, I appreciate the excellent help provided by Project Editors Samar Haddad and Joette Lynch, Production Supervisor Helena Redshaw, and the staff of the CRC Press in the process of preparing this handbook.

Marvin J. Weber  
Danville, California

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## The Author

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**Marvin John Weber** received his education at the University of California, Berkeley, and was awarded the A.B., M.A., and Ph.D. degrees in physics. After graduation, Dr. Weber continued as a postdoctoral Research Associate and then joined the Research Division of the Raytheon Company where he was a Principal Scientist working in the areas of spectroscopy and quantum electronics. As Manager of Solid State Lasers, his group developed many new laser materials including rare-earth-doped yttrium orthoaluminate. While at Raytheon, he also discovered luminescence in bismuth germanate, a scintillator crystal widely used for the detection of high energy particles and radiation.

During 1966 to 1967, Dr. Weber was a Visiting Research Associate with Professor Arthur Schawlow's group in the Department of Physics, Stanford University.

In 1973, Dr. Weber joined the Laser Program at the Lawrence Livermore National Laboratory. As Head of Basic Materials Research and Assistant Program Leader, he was responsible for the physics and characterization of optical materials for high-power laser systems used in inertial confinement fusion research. From 1983 to 1985, he accepted a transfer assignment with the Office of Basic Energy Sciences of the U.S. Department of Energy in Washington, DC, where he was involved with planning for advanced synchrotron radiation facilities and for atomistic computer simulations of materials. Dr. Weber returned to the Chemistry and Materials Science Department at LLNL in 1986 and served as Associate Division Leader for condensed matter research and as spokesperson for the University of California/National Laboratories research facilities at the Stanford Synchrotron Radiation Laboratory. He retired from LLNL in 1993 and is at present a staff scientist in the Department of Nuclear Medicine and Functional Imaging of the Life Sciences Division at the Lawrence Berkeley National Laboratory.

Dr. Weber is Editor-in-Chief of the multi-volume *CRC Handbook Series of Laser Science and Technology*. He has also served as Regional Editor for the *Journal of Non-Crystalline Solids*, as Associate Editor for the *Journal of Luminescence* and the *Journal of Optical Materials*, and as a member of the International Editorial Advisory Boards of the Russian journals *Fizika i Khimiya Stekla* (Glass Physics and Chemistry) and *Kvantovaya Elektronika* (Quantum Electronics).

Among several honors he has received are an Industrial Research IR-100 Award for research and development of fluorophosphate laser glass, the George W. Morey Award of the American Ceramics Society for his basic studies of fluorescence, stimulated emission, and the atomic structure of glass, and the International Conference on Luminescence Prize for his research on the dynamic processes affecting luminescence efficiency and the application of this knowledge to laser and scintillator materials.

Dr. Weber is a Fellow of the American Physical Society, the Optical Society of America, and the American Ceramics Society and a member of the Materials Research Society.

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## Section 1

### CRYSTALLINE MATERIALS

#### 1.1 Introduction\*

Crystalline materials included in this section are insulators and semiconductors that have a transparent region within the range from the vacuum ultraviolet (from ~100 nm) to the infrared (up to 100  $\mu\text{m}$ ) portion of the electromagnetic spectrum. Crystals with wide band gaps are transparent from the ultraviolet through the visible region; crystals with a narrower band gap may appear opaque but are transparent in the infrared region. Using this broad transparency definition of optical crystals, virtually all known crystals can be included. Coverage, however, is limited to those crystals which either occur in nature or are produced in the laboratory for optical use or with potential for such use. For this reason hydrate or hydroxide crystals are generally excluded because they are thermally less stable and have limited transmission range due to OH absorption. Highly hygroscopic materials are also excluded because of the obvious difficulty of handling, unless they have already been used, such as urea, KDP, CD\*A, etc. Only pure compounds are considered. Compounds containing elements having intrinsic absorptions due to incompletely filled d or f shell electrons are also avoided.

Other critical issues for the use of optical crystals are solid-state phase transitions that occur as a function of both temperature and pressure and polymorphism. Compounds that have a very small stability field or serious phase transition problems have limited use as optical materials. Phase change and decomposition temperatures of crystals are noted in Section 1.5 on thermal properties. Generally only the thermodynamically stable structure at room temperature and pressure are listed in this section. Compounds that have naturally occurring polymorphic forms are included, however, e.g.,  $\text{CaCO}_3$ ,  $\text{TiO}_2$ , and aluminum silicate  $\text{Al}_2\text{SiO}_5$ . In other cases, only the stable phase is listed, e.g., quartz ( $\alpha\text{-SiO}_2$ ).

Many compounds were considered appropriate as entries of optical crystals in Sections 1.1–1.3 regardless of the amount of information available. As Chai\* has noted, merely showing the existence of a compound with its chemical constituents can help to estimate the stability of its isomorphs and the structural tolerance of doping or other modifications. Most of the basic material properties such as optical transparency and refractive indices of an unstudied compound can be estimated with reasonable accuracy based on its better studied isomorphs that have measured properties listed in the tables.

Optical crystals in Sections 1.1–1.3 are classified into three categories:

*Isotropic crystals* include materials through which monochromatic light travels with the same speed, regardless of the direction of vibration, and the vibration direction of a light ray is always perpendicular to the ray path. Whereas amorphous materials such as glasses and plastics are isotropic, only those crystals with cubic symmetry are isotropic.

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\* This section was adapted from "Optical crystals" by B. H. T. Chai, *Handbook of Laser Science and Technology, Suppl. 2, Optical Materials* (CRC Press, Boca Raton, FL, 1995), p. 3 ff (with additions).

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*Anisotropic crystals* include materials through which a light ray may travel with different speeds for different directions of vibration and in which the angle between the vibration directions and ray path may not always be  $90^\circ$ . The index of refraction of such crystals varies according to the vibration direction of the light; the optical indicatrix is no longer a sphere but an ellipsoid. Depending on the geometry of the ellipsoid, it is necessary to divide the class of the anisotropic materials further into two subgroups. Crystals with tetragonal, hexagonal, and trigonal (or rhombohedral) symmetry exhibit a unique index of refraction (symbolized as  $e$  or  $\epsilon$ ) when light vibrates parallel to the  $c$ -axis (the extraordinary ray). For light vibrating at  $90^\circ$  to the  $c$ -axis (the ordinary ray), the refractive indices are the same (symbolized as  $o$  or  $\omega$ ) in all  $360^\circ$  directions. Crystals with these types of optical properties are called *uniaxial crystals*. Crystals with orthorhombic, monoclinic, and triclinic symmetry possess three significant indices of refraction, commonly symbolized as  $x$ ,  $y$ , and  $z$  or  $\alpha$ ,  $\beta$ , and  $\gamma$  in the order from smallest to largest. The shape of the indicatrix is a three-dimensional ellipsoid with all central sections being ellipses, except for two. These two are circular sections with a radius of  $\beta$ . The normal of the two circular sections are called the optical axes. Crystals with these types of optical properties are called *biaxial crystals*. In Sections 1.2 and 1.3 crystals are grouped as isotropic, uniaxial, and biaxial.

Crystal symmetry plays a critical role in the selection of material for optical applications. Optically isotropic crystals are used most frequently for windows and lenses although a uniaxial single crystal (such as sapphire) precisely oriented along the optical axis can be used as a window material. Faraday rotator crystals for optical isolators based must be cubic or uniaxial, not biaxial. Anisotropic single crystals are widely used for other specific optical applications such as the polarizers, optical wave plates, and wedges. In nonlinear frequency conversion, all the optical materials used at present must not only be crystalline but also highly anisotropic and noncentrosymmetric.

For simplicity of crystal orientation and fabrication, materials with highest symmetry are preferred. It is easy to orient crystals with cubic (isometric), tetragonal, and hexagonal (uniaxial) symmetries. For the biaxial crystals, orthorhombic symmetry is still relatively easy to orient because all the crystallographic axes are still orthogonal and in alignment with the optical indicatrix axes. In monoclinic crystals, the crystallographic  $a$ - and  $c$ -axes are no longer orthogonal. With the exception of the  $b$ -axis, two of the optical indicatrix axes are no longer aligned with the crystallographic ones. With a few exceptions, crystals with triclinic symmetry are not listed because they are difficult to orient and have too many parameters to define (no degeneracy at all).

The preceding symmetry properties of a crystal structure refer to space group operations. For measured macroscopic properties the point group (the group of operations under which the property remains unchanged) is of interest. Eleven of the 32 point groups are centrosymmetric. Except for cubic 432, the remaining groups exhibit polarization when the crystal is subject to an applied stress (piezoelectric). Ten of these latter groups possess a unique polar axis and are pyroelectric, i.e., spontaneous polarize in the absence of stress. Crystallographic point groups and related properties are listed in the following table.

### Crystallographic Point Groups and Properties

Crystal system	International symbol	Schoenflies symbol	Centro-symmetric	Piezo-electric	Pyro-electric
Cubic	m3m	O <sub>h</sub>			
	-43m	T <sub>d</sub>			
	432	O			
	m3	T <sub>h</sub>			
	23	T			
Hexagonal	6/mmm	D <sub>6h</sub>			
	-6m2	D <sub>3h</sub>			
	6mm	C <sub>6v</sub>			
	622	D <sub>6</sub>			
	6/m	C <sub>6h</sub>			
	-6	C <sub>3h</sub>			
	6	C <sub>6</sub>			
Tetragonal	4/mmm	D <sub>4h</sub>			
	-42m	D <sub>2d</sub>			
	4mm	C <sub>4v</sub>			
	422	D <sub>4</sub>			
	4/m	C <sub>4h</sub>			
	-4	S <sub>4</sub>			
	4	C <sub>4</sub>			
Trigonal	-3m	D <sub>3d</sub>			
	3m	C <sub>3v</sub>			
	32	D <sub>3</sub>			
	-3	S <sub>6</sub>			
	3	C <sub>3</sub>			
Orthorhombic	mmm	D <sub>2h</sub>			
	mm2	C <sub>2v</sub>			
	222	D <sub>2</sub>			
Monoclinic	2/m	C <sub>2h</sub>			
	m	C <sub>s</sub>			
	2	C <sub>2</sub>			
Triclinic	-1	C <sub>i</sub>			
	1	C <sub>1</sub>			

Crystals in the following table are listed alphabetically by chemical name (with mineral name\* and acronym in parentheses) and include the chemical formula, crystal system, and space group. In the space group notation, a negative number indicates inversion symmetry.

\* A mineralogy database containing names, physical properties, and an audio pronunciation guide for a very large number of materials is available at [www.webmineral.com](http://www.webmineral.com).

### Name, Formula, Crystal System, and Space Group for Optical Crystals

Name	Formula	Crystal system (Space group)
Aluminum antimonide	AlSb	Cubic (F-43m)
Aluminum arsenate	AlAsO <sub>4</sub>	Trigonal (P3 <sub>1</sub> 2)
Aluminum arsenide	AlAs	Cubic (F-43m)
Aluminum borate	AlBO <sub>3</sub>	Trigonal (R-3c)
Aluminum borate	Al <sub>4</sub> B <sub>2</sub> O <sub>9</sub>	Orthorhombic (Pbam)
Aluminum fluoride	AlF <sub>3</sub>	Rhombohedral (R32)
Aluminum fluorosilicate (topaz)	Al <sub>2</sub> SiO <sub>4</sub> F <sub>2</sub>	Orthorhombic (Pbnm)
Aluminum gallate	AlGaO <sub>3</sub>	Hexagonal (P6 <sub>3</sub> mmc)
Aluminum germanate	Al <sub>2</sub> Ge <sub>2</sub> O <sub>7</sub>	Monoclinic (C2/c)
Aluminum germanate	Al <sub>6</sub> Ge <sub>2</sub> O <sub>13</sub>	Orthorhombic (Pbnm)
Aluminum germanate	Al <sub>6</sub> Ge <sub>2</sub> O <sub>13</sub>	Orthorhombic (Pbnm)
Aluminum hafnium tantalate	AlHfTaO <sub>6</sub>	Orthorhombic (Pbcn)
Aluminum molybdate	Al <sub>2</sub> (MoO <sub>4</sub> ) <sub>3</sub>	Monoclinic (P2 <sub>1</sub> /a)
Aluminum niobate	AlNbO <sub>4</sub>	Monoclinic (C2/m)
Aluminum nitride	AlN	Hexagonal (6 <sub>3</sub> mc)
Aluminum oxide (corundum, sapphire, alumina)	Al <sub>2</sub> O <sub>3</sub>	Trigonal (R-3c)
Aluminum oxynitrate (ALON)	Al <sub>23</sub> O <sub>27</sub> N <sub>5</sub>	Cubic (Fd3m)
Aluminum phosphate (berlinite)	AlPO <sub>4</sub>	Trigonal (P3 <sub>1</sub> 2)
Aluminum phosphide	AlP	Hexagonal (6 <sub>3</sub> mc)
Aluminum silicate (andalusite)	Al <sub>2</sub> SiO <sub>5</sub>	Orthorhombic (Pmam)
Aluminum silicate (kyanite)	Al <sub>2</sub> SiO <sub>5</sub>	Triclinic (P-1)
Aluminum silicate (mullite)	Al <sub>6</sub> Si <sub>2</sub> O <sub>13</sub>	Orthorhombic (Pbnm)
Aluminum silicate (sillimanite)	Al <sub>2</sub> SiO <sub>5</sub>	Orthorhombic (Pbnm)
Aluminum tantalate (alumotantite)	AlTaO <sub>4</sub>	Orthorhombic (Pc2 <sub>1</sub> n)
Aluminum titanium tantalate	AlTiTaO <sub>6</sub>	Tetragonal (P4 <sub>2</sub> /mmm)
Aluminum tungstate	Al <sub>2</sub> (WO <sub>4</sub> ) <sub>3</sub>	Orthorhombic (Pcna)
Amino carbonyl (urea)	(NH <sub>2</sub> ) <sub>2</sub> CO	Tetragonal (I-42m)
Ammonium aluminum selenate	NH <sub>4</sub> Al(SeO <sub>4</sub> ) <sub>2</sub>	Trigonal (P321)
Ammonium aluminum sulfate	NH <sub>4</sub> Al(SO <sub>4</sub> ) <sub>2</sub>	Trigonal (P321)
Ammonium dihydrogen phosphate (ADP)	NH <sub>4</sub> H <sub>2</sub> PO <sub>4</sub>	Tetragonal (I-42m)
Ammonium gallium selenate	NH <sub>4</sub> Ga(SeO <sub>4</sub> ) <sub>2</sub>	Trigonal (P321)
Ammonium gallium sulfate	NH <sub>4</sub> Ga(SO <sub>4</sub> ) <sub>2</sub>	Trigonal (P321)
Ammonium pentaborate	NH <sub>4</sub> B <sub>5</sub> O <sub>8</sub> •4H <sub>2</sub> O	Orthorhombic (Aba2)
Antimony niobate (stibiocolumbite)	SbNbO <sub>4</sub>	Orthorhombic (Pna2 <sub>1</sub> )
Antimony oxide (senarmontite)	Sb <sub>2</sub> O <sub>3</sub>	Cubic (Fd3m)

**Name, Formula, Crystal System, and Space Group for Optical Crystals—continued**

<b>Name</b>	<b>Formula</b>	<b>Crystal system (Space group)</b>
Antimony oxide (valentinite)	Sb <sub>2</sub> O <sub>3</sub>	Orthorhombic (Pccn)
Antimony tantalate (stibiotantalite)	SbTaO <sub>4</sub>	Orthorhombic (Pc2 <sub>1</sub> n)
Arsenic antimony sulfide (getchellite)	AsSbS <sub>3</sub>	Monoclinic (P2 <sub>1</sub> /a)
Arsenic oxide (arsenolite)	As <sub>2</sub> O <sub>3</sub>	Cubic (Fd3m)
Arsenic sulfide (orpiment)	As <sub>2</sub> S <sub>3</sub>	Monoclinic (P2 <sub>1</sub> n)
Arsenic sulfide (realgar)	AsS	Monoclinic (P2 <sub>1</sub> n)
Barium aluminate	BaAl <sub>2</sub> O <sub>4</sub>	Hexagonal (P6 <sub>3</sub> 22)
Barium aluminate	Ba <sub>3</sub> Al <sub>2</sub> O <sub>6</sub>	Cubic (Pa3)
Barium aluminum borate	BaAl <sub>2</sub> B <sub>2</sub> O <sub>7</sub>	Monoclinic (P2/c)
Barium aluminum fluoride	Ba <sub>3</sub> Al <sub>2</sub> F <sub>12</sub>	Orthorhombic (Pnmm)
Barium aluminum germanate	BaAl <sub>2</sub> Ge <sub>2</sub> O <sub>8</sub>	Monoclinic (P2 <sub>1</sub> /a)
Barium aluminum silicate (celsian)	BaAl <sub>2</sub> Si <sub>2</sub> O <sub>8</sub>	Monoclinic (I2/a)
Barium antimonate	BaSb <sub>2</sub> O <sub>6</sub>	Triclinic (P-3 1 m)
Barium beryllium fluorophosphate (babefphite)	BaBe(PO <sub>4</sub> )F	Hexagonal(P-6c2)
Barium beryllium silicate (barylite)	BaBe <sub>2</sub> Si <sub>2</sub> O <sub>7</sub>	Orthorhombic (Pnma)
Barium tetraborate	BaB <sub>4</sub> O <sub>7</sub>	Monoclinic (P2 <sub>1</sub> /c)
Barium borate	β-BaB <sub>2</sub> O <sub>4</sub>	Trigonal (R3c)
Barium cadmium aluminum fluoride	BaCdAlF <sub>7</sub>	Monoclinic (C2/c)
Barium cadmium gallium fluoride	BaCdGaF <sub>7</sub>	Monoclinic (C2/c)
Barium cadmium magnesium aluminum fluoride	Ba <sub>2</sub> CdMgAl <sub>2</sub> F <sub>14</sub>	Monoclinic (C2/c)
Barium calcium magnesium aluminum fluoride	Ba <sub>2</sub> CaMgAl <sub>2</sub> F <sub>14</sub>	Monoclinic (C2/c)
Barium calcium magnesium silicate	BaCa <sub>2</sub> Mg(SiO <sub>4</sub> ) <sub>2</sub>	Orthorhombic
Barium calcium silicate (walstromite)	BaCa <sub>2</sub> Si <sub>3</sub> O <sub>9</sub>	Triclinic(P-1)
Barium carbonate (witherite)	BaCO <sub>3</sub>	Orthorhombic (Pnam)
Barium chloroarsenate (movelandite)	Ba <sub>5</sub> (AsO <sub>4</sub> ) <sub>3</sub> Cl	Hexagonal(P6 <sub>3</sub> /m)
Barium chloroborate	Ba <sub>2</sub> B <sub>5</sub> O <sub>9</sub> Cl	Tetragonal (P4 <sub>2</sub> 2 <sub>1</sub> -2)
Barium chlorophosphate (alforsite)	Ba <sub>5</sub> (PO <sub>4</sub> ) <sub>3</sub> Cl	Hexagonal(P6 <sub>3</sub> /m)
Barium chlorovanadate	Ba <sub>5</sub> (VO <sub>4</sub> ) <sub>3</sub> Cl	Hexagonal(P6 <sub>3</sub> /m)
Barium fluoride-calcium fluoride (T-12)	BaF <sub>2</sub> -CaF <sub>2</sub>	Cubic (Fm3m)
Barium fluoride (frankdicksonite)	BaF <sub>2</sub>	Cubic (Fm3m)
Barium fluoroarsenate	Ba <sub>5</sub> (AsO <sub>4</sub> ) <sub>3</sub> F	Hexagonal(P6 <sub>3</sub> /m)
Barium fluorophosphate	Ba <sub>5</sub> (PO <sub>4</sub> ) <sub>3</sub> F	Hexagonal(P6 <sub>3</sub> /m)
Barium fluorovanadate	Ba <sub>5</sub> (VO <sub>4</sub> ) <sub>3</sub> F	Hexagonal(P6 <sub>3</sub> /m)
Barium gallium fluoride	BaGaF <sub>5</sub>	Orthorhombic (P2 <sub>1</sub> 2 <sub>1</sub> 2 <sub>1</sub> )
Barium germanate	BaGeO <sub>3</sub>	Orthorhombic
Barium germanate	BaGe <sub>2</sub> O <sub>5</sub>	Monoclinic (P2 <sub>1</sub> /a)
Barium germanate	BaGe <sub>4</sub> O <sub>9</sub>	Hexagonal(P-6c2)
Barium germanium aluminate	BaGeAl <sub>6</sub> O <sub>12</sub>	Orthorhombic (Pnmm)
Barium germanium gallate	BaGeGa <sub>6</sub> O <sub>12</sub>	Orthorhombic (Pnmm)
Barium hexa-aluminate	BaAl <sub>12</sub> O <sub>19</sub>	Hexagonal (P6 <sub>3</sub> /mmc)
Barium lithium niobate	Ba <sub>2</sub> LiNb <sub>5</sub> O <sub>15</sub>	Orthorhombic (Im2a)
Barium lutetium borate	Ba <sub>3</sub> Lu(BO <sub>3</sub> ) <sub>3</sub>	Hexagonal(P6 <sub>3</sub> cm)
Barium magnesium aluminum fluoride	Ba <sub>2</sub> MgAlF <sub>9</sub>	Tetragonal (P4)

**Name, Formula, Crystal System, and Space Group for Optical Crystals—continued**

Name	Formula	Crystal system (Space group)
Barium magnesium fluoride	BaMgF <sub>4</sub>	Orthorhombic (A2 <sub>1</sub> am)
Barium magnesium fluoride	Ba <sub>2</sub> MgF <sub>6</sub>	Tetragonal (I422)
Barium magnesium germanate	Ba <sub>2</sub> MgGe <sub>2</sub> O <sub>7</sub>	Tetragonal (P42 <sub>1</sub> m)
Barium magnesium silicate	Ba <sub>2</sub> MgSi <sub>2</sub> O <sub>7</sub>	Tetragonal (P42 <sub>1</sub> m)
Barium magnesium tantalate	Ba <sub>3</sub> MgTa <sub>2</sub> O <sub>9</sub>	Cubic (Fm3m)
Barium magnesium vanadate	BaMg <sub>2</sub> (VO <sub>4</sub> ) <sub>2</sub>	Tetragonal (I4 <sub>1</sub> /acd)
Barium molybdate	BaMoO <sub>4</sub>	Tetragonal (I4 <sub>1</sub> /a)
Barium niobate	BaNb <sub>2</sub> O <sub>6</sub>	Orthorhombic (Pcan)
Barium nitrate (nitrobarite)	Ba(NO <sub>3</sub> ) <sub>2</sub>	Cubic (P2 <sub>1</sub> 3)
Barium scandate	Ba <sub>2</sub> Sc <sub>4</sub> O <sub>9</sub>	Trigonal(R-3)
Barium scandate	BaSc <sub>2</sub> O <sub>4</sub>	Monoclinic (C2/c)
Barium scandate	Ba <sub>6</sub> Sc <sub>6</sub> O <sub>15</sub>	Tetragonal
Barium silicate (sabbornite)	β-BaSi <sub>2</sub> O <sub>5</sub>	Orthorhombic (Pmnb)
Barium sodium niobate	Ba <sub>2</sub> NaNb <sub>5</sub> O <sub>15</sub>	Orthorhombic (Im2a)
Barium sodium phosphate	Ba <sub>2</sub> Na(PO <sub>5</sub> ) <sub>5</sub>	Orthorhombic (P212121)
Barium strontium niobate	Ba <sub>3</sub> SrNb <sub>2</sub> O <sub>9</sub>	Hexagonal (P63/mmc)
Barium strontium tantalate	Ba <sub>3</sub> SrTa <sub>2</sub> O <sub>9</sub>	Hexagonal (P63/mmc)
Barium sulfate (barite)	BaSO <sub>4</sub>	Orthorhombic (Pbnm)
Barium tantalate	BaTa <sub>2</sub> O <sub>6</sub>	Orthorhombic (Pcan)
Barium tantalate	BaTa <sub>2</sub> O <sub>6</sub>	Orthorhombic (Pcan)
Barium tin borate	BaSnB <sub>2</sub> O <sub>6</sub>	Trigonal(R-3)
Barium tin silicate (pabstite)	BaSnSi <sub>3</sub> O <sub>9</sub>	Hexagonal (P-6c2)
Barium titanate	BaTiO <sub>3</sub>	Cubic (Fm3m)
Barium titanate	BaTiO <sub>3</sub>	Tetragonal (Pm3m)
Barium titanium aluminate	BaTiAl <sub>6</sub> O <sub>12</sub>	Orthorhombic (Pnnm)
Barium titanium aluminate	Ba <sub>3</sub> TiAl <sub>10</sub> O <sub>20</sub>	Monoclinic (C2/m)
Barium titanium borate	BaTiB <sub>2</sub> O <sub>6</sub>	Trigonal(R-3)
Barium titanium gallate	BaTiGa <sub>6</sub> O <sub>12</sub>	Orthorhombic (Pnnm)
Barium titanium oxide	BaTi <sub>4</sub> O <sub>9</sub>	Orthorhombic (Pnmm)
Barium titanium silicate (benitoite)	BaTiSi <sub>3</sub> O <sub>9</sub>	Hexagonal (P-6c2)
Barium titanium silicate (fresnoite)	Ba <sub>2</sub> TiSi <sub>2</sub> O <sub>8</sub>	Tetragonal (P4bm)
Barium tungstate	BaWO <sub>4</sub>	Tetragonal (I4 <sub>1</sub> /a)
Barium vanadate	Ba <sub>3</sub> (VO <sub>4</sub> ) <sub>2</sub>	Rhombohedral (R-3m)
Barium yttrium borate	Ba <sub>3</sub> Lu(BO <sub>3</sub> ) <sub>3</sub>	Hexagonal(P6 <sub>3</sub> cm)
Barium yttrium fluoride	BaY <sub>2</sub> F <sub>8</sub>	Monoclinic (C2/m)
Barium yttrium oxide	BaY <sub>2</sub> O <sub>4</sub>	Orthorhombic (Pnab)
Barium zinc aluminum fluoride	Ba <sub>2</sub> ZnAlF <sub>9</sub>	Orthorhombic (Pnma)
Barium zinc fluoride	BaZnF <sub>4</sub>	Orthorhombic (C222)
Barium zinc fluoride	Ba <sub>2</sub> Zn <sub>3</sub> F <sub>10</sub>	Monoclinic (C2/m)
Barium zinc fluoride	Ba <sub>2</sub> ZnF <sub>6</sub>	Tetragonal (I422)
Barium zinc gallium fluoride	Ba <sub>2</sub> ZnGaF <sub>9</sub>	Monoclinic (P2 <sub>1/n</sub> )
Barium zinc germanate	BaZnGeO <sub>4</sub>	Hexagonal (P6 <sub>3</sub> )
Barium zinc germanate	Ba <sub>2</sub> ZnGe <sub>2</sub> O <sub>7</sub>	Tetragonal (P42 <sub>1</sub> m)

**Name, Formula, Crystal System, and Space Group for Optical Crystals—continued**

Name	Formula	Crystal system (Space group)
Barium zinc silicate	Ba <sub>2</sub> ZnSi <sub>2</sub> O <sub>7</sub>	Tetragonal (P4 <sub>2</sub> m)
Barium zinc silicate	BaZnSiO <sub>4</sub>	Hexagonal (P6 <sub>3</sub> )
Barium zirconium silicate	Ba <sub>2</sub> ZrSi <sub>2</sub> O <sub>8</sub>	Tetragonal (P4bm)
Barium zirconium silicate	Ba <sub>2</sub> Zr <sub>2</sub> Si <sub>3</sub> O <sub>12</sub>	Cubic (P2 <sub>1</sub> 3)
Barium zirconium silicate (bazirite)	BaZrSi <sub>3</sub> O <sub>9</sub>	Hexagonal (P6 <sub>3</sub> 22)
Beryllium aluminate	BeAl <sub>6</sub> O <sub>10</sub>	Orthorhombic (Pca2)
Beryllium aluminate (chrysoberyl)	BeAl <sub>2</sub> O <sub>4</sub>	Orthorhombic (Pnma)
Beryllium aluminum silicate (beryl)	Be <sub>3</sub> Al <sub>2</sub> Si <sub>6</sub> O <sub>18</sub>	Hexagonal (P6/mcc)
Beryllium fluoroborate (hambergite)	Be <sub>2</sub> BO <sub>3</sub> F	Monoclinic (C21)
Beryllium germanate	Be <sub>2</sub> GeO <sub>4</sub>	Trigonal(R-3)
Beryllium magnesium aluminate (taaffeite)	BeMg <sub>3</sub> Al <sub>8</sub> O <sub>16</sub>	Hexagonal
Beryllium oxide (bormellite)	BeO	Hexagonal (P6 <sub>3</sub> /mc)
Beryllium scandium silicate (bazzite)	Be <sub>3</sub> Sc <sub>2</sub> Si <sub>6</sub> O <sub>18</sub>	Hexagonal (P6/mcc)
Beryllium silicate (phenakite)	Be <sub>2</sub> SiO <sub>4</sub>	Trigonal(R-3)
Bismuth aluminate	Bi <sub>2</sub> Al <sub>4</sub> O <sub>9</sub>	Orthorhombic (Pbam)
Bismuth antimonate	BiSbO <sub>4</sub>	Monoclinic (P2 <sub>1</sub> /c)
Bismuth borate	Bi <sub>4</sub> B <sub>2</sub> O <sub>9</sub>	Monoclinic (P2 <sub>1</sub> /c)
Bismuth germanate	Bi <sub>2</sub> Ge <sub>3</sub> O <sub>9</sub>	Hexagonal (P6 <sub>3</sub> /m)
Bismuth germanate	Bi <sub>2</sub> GeO <sub>5</sub>	Orthorhombic (Cmc2 <sub>1</sub> )
Bismuth germanate	Bi <sub>12</sub> GeO <sub>20</sub>	Cubic (I23)
Bismuth germanate (BGO)	Bi <sub>4</sub> Ge <sub>3</sub> O <sub>12</sub>	Cubic (I43d)
Bismuth metaborate	BiB <sub>3</sub> O <sub>6</sub>	Monoclinic (2/m)
Bismuth molybdate	Bi <sub>2</sub> Mo <sub>2</sub> O <sub>9</sub>	Monoclinic (P2 <sub>1</sub> /m)
Bismuth molybdate	Bi <sub>2</sub> Mo <sub>3</sub> O <sub>12</sub>	Monoclinic (P2 <sub>1</sub> /m)
Bismuth niobate	BiNbO <sub>4</sub>	Orthorhombic (Pann)
Bismuth oxide (bismite)	Bi <sub>2</sub> O <sub>3</sub>	Monoclinic (P2 <sub>1</sub> /c)
Bismuth oxymolybdate (koechlinite)	γ-Bi <sub>2</sub> MoO <sub>6</sub>	Orthorhombic (Pba2)
Bismuth oxytungstate (rusellite)	Bi <sub>2</sub> WO <sub>6</sub>	Orthorhombic (Pba2)
Bismuth silicate	Bi <sub>2</sub> SiO <sub>5</sub>	Orthorhombic (Cmc2 <sub>1</sub> )
Bismuth silicate (eulytite)	Bi <sub>4</sub> Si <sub>3</sub> O <sub>12</sub>	Cubic (I43d)
Bismuth silicate (sillenite, BSO)	Bi <sub>12</sub> SiO <sub>20</sub>	Cubic (I23)
Bismuth tantalate	BiTaO <sub>4</sub>	Orthorhombic (Pnna)
Bismuth tin oxide	Bi <sub>2</sub> Sn <sub>2</sub> O <sub>7</sub>	Hexagonal (P6 <sub>3</sub> /m)
Bismuth titanate	Bi <sub>4</sub> Ti <sub>3</sub> O <sub>12</sub>	Orthorhombic (B2cb)
Bismuth titanium niobate	Bi <sub>3</sub> TiNbO <sub>9</sub>	Orthorhombic (A2 <sub>1</sub> am)
Bismuth titanium oxide	Bi <sub>12</sub> TiO <sub>20</sub>	Cubic (I23)
Bismuth vanadate (clinobisvanite)	BiVO <sub>4</sub>	Monoclinic (I2/a)
Bismuth vanadate (dreyerite)	BiVO <sub>4</sub>	Tetragonal (I4 <sub>1</sub> /amd)
Bismuth vanadate (pucherite)	BiVO <sub>4</sub>	Orthorhombic (Pnca)
Boron nitride	BN	Cubic (F-43m)
Boron phosphide	BP	Cubic (F-43m)
Cadmium antimonate	Cd <sub>2</sub> Sb <sub>2</sub> O <sub>7</sub>	Cubic (Fd3m)
Cadmium borate	CdB <sub>4</sub> O <sub>7</sub>	Orthorhombic (Pbca)

**Name, Formula, Crystal System, and Space Group for Optical Crystals—continued**

<b>Name</b>	<b>Formula</b>	<b>Crystal system (Space group)</b>
Cadmium borate	$\text{Cd}_2\text{B}_2\text{O}_5$	Triclinic (P1)
Cadmium borate	$\text{Cd}_2\text{B}_6\text{O}_{11}$	Monoclinic (P2 <sub>1</sub> /b)
Cadmium borate	$\text{CdB}_2\text{O}_4$	Cubic (P-43m)
Cadmium carbonate (otavite)	$\text{CdCO}_3$	Rhombohedral (R-3c)
Cadmium chloride	$\text{CdCl}_2$	Rhombohedral (R-3m)
Cadmium chloroarsenate	$\text{Cd}_5(\text{AsO}_4)_3\text{Cl}$	Hexagonal (P6 <sub>3</sub> /m)
Cadmium chlorophosphate	$\text{Cd}_5(\text{PO}_4)_3\text{Cl}$	Hexagonal (P6 <sub>3</sub> /m)
Cadmium chlorovanadate	$\text{Cd}_5(\text{VO}_4)_3\text{Cl}$	Hexagonal (P6 <sub>3</sub> /m)
Cadmium fluoride	$\text{CdF}_2$	Cubic (Fm3m)
Cadmium fluorophosphate	$\text{Cd}_5(\text{PO}_4)_3\text{F}$	Hexagonal (P6 <sub>3</sub> /m)
Cadmium gallate	$\text{CdGa}_2\text{O}_4$	Cubic (Fd3m)
Cadmium germanate	$\text{Cd}_2\text{GeO}_4$	Orthorhombic (Pbnm)
Cadmium germanium arsenide	$\text{CdGeAs}_2$	Tetragonal (I-42d)
Cadmium germanium phosphide	$\text{CdGeP}_2$	Tetragonal (I-42d)
Cadmium indium oxide spinel	$\text{CdIn}_2\text{O}_4$	Cubic (Fd3m)
Cadmium iodide	$\text{CdI}_2$	Hexagonal (P6 <sub>3</sub> mc)
Cadmium niobate	$\text{Cd}_2\text{Nb}_2\text{O}_7$	Cubic (Fd3m)
Cadmium oxide (monteponite)	$\text{CdO}$	Cubic (Fm3m)
Cadmium scandium germanate	$\text{Cd}_3\text{Sc}_2\text{Ge}_3\text{O}_{12}$	Cubic (Ia3d)
Cadmium selenide (cadmoselite)	$\text{CdSe}$	Hexagonal (P6mm)
Cadmium silicon arsenide	$\text{CdSiAs}_2$	Tetragonal (I-42d)
Cadmium silicon phosphide	$\text{CdSiP}_2$	Tetragonal (I-42d)
Cadmium sulfide (greenockite)	$\text{CdS}$	Hexagonal (6mm)
Cadmium tellurite (Irtran 6)	$\text{CdTe}$	Cubic (Fm3m)
Cadmium tin arsenide	$\text{CdSnAs}_2$	Tetragonal (I-42d)
Cadmium tin borate	$\text{CdSnB}_2\text{O}_6$	Rhombohedral (R-3c)
Cadmium tin phosphide	$\text{CdSnP}_2$	Tetragonal (I-42d)
Cadmium titanate	$\text{CdTiO}_3$	Rhombohedral (R-3)
Cadmium tungstate	$\text{CdWO}_4$	Monoclinic (P2/c)
Cadmium vanadate	$\text{CdV}_2\text{O}_6$	Monoclinic (C2/m)
Cadmium vanadate	$\text{Cd}_2\text{V}_2\text{O}_7$	Monoclinic (C2/m)
Calcium aluminate	$\text{CaAl}_2\text{O}_4$	Monoclinic (P2 <sub>1</sub> /n)
Calcium aluminate	$\text{Ca}_3\text{Al}_2\text{O}_6$	Cubic (Pa-3)
Calcium aluminate	$\text{CaAl}_4\text{O}_7$	Monoclinic (C2/c)
Calcium aluminate	$\text{Ca}_5\text{Al}_6\text{O}_{14}$	Orthorhombic (C222)
Calcium aluminate (brownmillerite)	$\text{Ca}_2\text{Al}_2\text{O}_5$	Orthorhombic
Calcium aluminate (mayenite)	$\text{Ca}_{12}\text{Al}_{14}\text{O}_{33}$	Cubic (I43d)
Calcium aluminum borate	$\text{CaAlBO}_4$	Orthorhombic (Pnam)
Calcium aluminum borate	$\text{CaAl}_2\text{B}_2\text{O}_7$	Hexagonal (P6 <sub>3</sub> 22)
Calcium aluminum borate (johachidolite)	$\text{CaAlB}_3\text{O}_7$	Orthorhombic (Cmma)
Calcium aluminum fluoride	$\text{CaAlF}_5$	Monoclinic (C2/c)
Calcium aluminum fluoride	$\text{Ca}_2\text{AlF}_7$	Orthorhombic (Pnma)
Calcium aluminum fluoride (prosopite)	$\text{CaAl}_2\text{F}_8$	Monoclinic



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