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BY
EDGAR T. WHERRY
Assistant Curator, Division of Mineralogy and Petrology, U. S. National Museum

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THE MICROSPECTROSCOPE IN MINERALOGY

By EDGAR T. WHERRY

ASSISTANT CURATOR, DIVISION OF MINERALOGY AND PETROLOGY, U. S. NATIONAL MUSEUM

The possibilities of the microspectroscope in the identification of minerals and the study of their composition have apparently not been generally appreciated by mineralogists. Occasional articles in the journals devoted to physics and microscopy have contained references to a few minerals; three contributions to the subject from a mineralogical point of view have appeared in recent years—brief discussions of absorption spectra in Miers' "Mineralogy"[1] and in Smith's "Gem-Stones"[2] and F. J. Keeley's "Microspectroscopic Observations"[3]; but in none of these is it treated as fully as might be desired. The present paper comprises descriptions of the spectra of a much larger number of minerals than has heretofore been examined.[4]

The apparatus which has proved most satisfactory in the studies here described consists of a Crouch binocular microscope stand, fitted with a 37 millimeter objective, an Abbe-Zeiss "Spectral-Ocular"[5] in the right hand tube, and in the other an ordinary low-power eyepiece, marked on the lower lens at the point where the image of a mineral grain falls when it is visible through the spectroscope slit; the prism which diverts part of the light into the left

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[1] Macmillan and Co., New York and London, 1902; pp. 275-276.

[2] Methuen and Co., London, 1912; pp. 59-62.

[3] Proc. Acad. Nat. Sci. Phila., 1911, pp. 106-116; Mr. Keeley has made a number of valuable suggestions in connection with the preparation of the present paper, which are herewith gratefully acknowledged.

[4] Col. Washington A. Roebling, of Trenton, N. J., kindly furnished the writer with samples of a number of rare minerals from his very complete collection to supplement those available at the Museum.

[5] Mr. Keeley states that he finds a Browning or Beck microspectroscope ocular useful for preliminary examinations; a Wallace grating-microspectroscope, obtained through the kindness of Mr. Thomas I. Miller, of Brooklyn, N. Y., was also tried, but the spectra it yields are too faint for mineral work in general.

hand tube is withdrawn after the mineral grain has been centered, so as to permit as much light as possible to pass through the spectroscope. A binocular microscope is not absolutely necessary, but frequent readjustments of the scale and slit have to be made if the mineral is observed by swinging out the upper part of the spectroscope and the slit holder.

Light may be obtained from any source yielding a brilliant white light, such as a Welsbach burner or a Nernst lamp, although sunlight or daylight are objectionable because of showing the Fraunhofer lines. For the study of minerals in thin sections, and in a few special cases mentioned below, this is reflected up through the specimen by means of the sub-stage mirror. In the majority of cases, however, better results are obtained by concentrating the light laterally on the specimen by a lens or by a parabolic mirror attached to the objective, and observing the brightest portion of its path. Not only does the latter plan yield the better spectra (apparently because they are connected with fluorescence phenomena), but it permits the examination of crystals on the matrix, gems in their settings, and other similar objects, and, further, does not require any polishing or special preparation of surfaces. The more intense the light the smaller the grains which can be studied in this way.

To set the wave-length scale of the instrument accurately a sodium flame is used, scale division 058.9[1] being brought into coincidence with the yellow (D) line. In addition, a small slip of "didymium" glass,[2] which can be readily inserted at the opening where light for the comparison spectrum enters, is very convenient, the interval between the strong absorption bands of neodymium and praseodymium in the yellow being set at about 058 (580 $\mu\mu$). See figure 1.

The scale of the instrument is graduated in hundredths of microns, but, except at the extreme red end, tenths of divisions can be readily estimated, and it is most convenient to state measurements in three-figure wave lengths. Since the edges of many of the absorption bands are so hazy that they cannot be located exactly, and since the positions of bands vary somewhat in different directions in anisotropic substances, as well as from one crystal to another in minerals of variable composition, readings are liable to an uncertainty of about 5 units. However, as the object of the present paper is not to establish wave lengths, but to record the general characteristics

[1] This corresponds to wave length 589 $\mu\mu$; all measurements are stated in the latter form.

[2] Obtainable from the Corning Glass Co., Corning, N. Y.

of the absorption spectra of the different minerals for determinative purposes, this degree of accuracy is quite sufficient.

The light diffused by mineral grains shows in most cases more intense absorption bands than that transmitted directly through them, yet it must penetrate considerably to be affected at all, so that only transparent or fairly translucent minerals yield any effects; in addition they must be more or less distinctly colored. The number of minerals suitable for microspectroscopic study is therefore rather limited, but the fact that the specimens need not be scratched, broken,

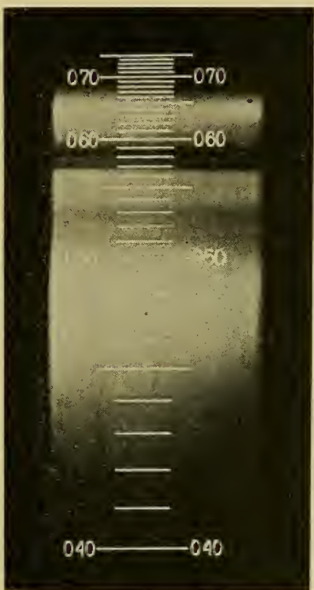

Fig. 1.—The wave length scale of the Abbe-Zeiss microspectroscope, with the absorption spectrum of "didymium" glass, the interval between the two strongest bands of which is set at 058. The several bands lie at 067.5, 062.5, 059.0, 058.2, 057.4, 053.1, 052.5, 051.2, 048.0, 044.8, and 043.3. Transmitted light; source, Welsbach burner; exposure 1 hour; Wratten and Wainwright Panchromatic plate.

or altered in any way renders the method of considerable use in the identification of crystals too valuable to be broken up for the usual tests, and in particular of cut gems, whether free or in their settings. Even where other methods are applicable the spectra may serve as confirmatory tests.

This method has proved especially useful in determining the genuineness of rubies, sapphires, and emeralds sent to the Museum for examination and report, in picking out corundum, zircon, and garnet from gem gravels in the collection, in distinguishing greenockite from other minerals occurring as yellow coatings, and in the identification of a number of other minerals. The microspectroscope may also be applied to the measurement of the thickness of iridescent films and the discovery of the origin of various color phenomena, but this phase of the subject has been fully discussed by Keeley in the paper cited and need not be further considered here.

THE RARE EARTH MINERALS

The strong absorption bands shown by salts of certain of the rare earth metals have long been recognized as a good means for their detection in solutions, and several writers have pointed out that minerals containing them also show the bands, and have called attention to the value of this property for identification of these minerals. In the preparation of this paper all available minerals known to contain appreciable amounts of the rare earths have been examined. Most of the light colored ones, as listed in the tables below, were found to exhibit two or more of these bands, all except the violet calcite yielding much more intense effects when viewed at an angle to the path of the light than when observed in the direction of the transmitted ray. Not only is the presence of these absorption bands useful as a means of distinguishing rare earth minerals from all others, but it may even serve to differentiate certain of the individual species; the positions and intensities of the bands vary from one to another in a fairly characteristic way, although identification on this basis alone is not always certain, since slight variations may occur between different grains of the same mineral.

The presence of the rare earth metals in calcite from Joplin, Missouri, was discovered by W. P. Headden[1] by analytical procedure, and has recently been reaffirmed by Pisani,[2] the amounts present being mostly less than 0.05 per cent. Headden found that the violet calcite from this locality gives " didymium " absorption bands. With the microspectroscope this material shows, by transmitted light, two distinct bands, matching approximately those of neodymium in the " didymium " glass comparison spectrum, and being probably due to that element, the salts of which have a violet tint. The most deeply colored specimens show these bands when as thin as 3 millimeters, although the paler tinted varieties show them only in greater thicknesses, while the colorless and yellow portions

[1] Amer. Journ. Sci., ser. 4, vol. 21, 1906, p. 301.

[2] Compt. rend., vol. 158, 1914, p. 1121.

of the same crystals fail to show the slightest trace of them. Violet calcite from another locality, Rossie, New York, also shows these bands faintly.

On heating the violet calcite in an air bath to about 400° for ten minutes the color is completely discharged (yellow light being emitted) and the absorption bands disappear. The simplest explanation of this behavior is that the rare earths are originally present as carbonates (in solid solution of the mix-crystal type), and in that form show the absorption bands, but that, on heating, these compounds are converted into oxides, which do not show them. Headden's observation that the yellow calcite from Joplin contains more rare earths than other varieties can be readily reconciled with the absence of bands in its spectrum by recognizing that the metals may be present in it only as oxides in the first place.

It is therefore concluded that violet calcite probably owes its color to the presence, in mix-crystal form, of traces of a carbonate of neodymium.

Yellow titanite labeled as from "Mont Blanc" and brown apatite from several places in Ontario, Canada, show the neodymium bands with about the same intensity as the violet calcite, although the violet color is hidden by stronger ones due to iron or other constituents. The remainder of the minerals listed in the rare earth tables are well known compounds of those elements.

URANIUM MINERALS

Transparent minerals containing uranium in the uranic form show an absorption spectrum consisting of several bands in the green, blue, and violet, viewing the grains at an angle to the path of the light giving the most brilliant effects. The variation in the positions and relative intensities of these bands from one species to another is particularly well marked and of some diagnostic value, although more than 30 per cent of uranium must be present, and many minerals with even this amount yield no spectra.

Some specimens of the mineral zircon yield, as has long been known, a number of absorption bands, which correspond to those shown by uranium salts after reduction with zinc, that is, when in the uranous condition. This uranium, which is present in minute amount, mostly less than 0.5 per cent, has the same valence as the zirconium and no doubt replaces a part of it, giving a blue color to the mineral, which may, however, be hidden by other tints, due to iron, manganese, etc. It therefore cannot be predicted whether a given crystal of zircon will show a spectrum or not, but, on the other hand, if an unknown mineral shows these bands, it is reasonably certain to be zircon, for no other mineral is as yet known to contain uranous uranium.

THE GARNET GROUP

The red colors of garnets of the varieties pyrope, almandite, spessartite, and essonite have been variously interpreted as due to gold,[1] tin,[1] iron,[2] chromium,[3] manganese,[4] and vanadium.[5] Two different sets of bands seem to be superposed in the spectra of the members of this group, (A) a narrow band at 620 and a broad one centering at about 590 (these often coalesce); and (B) two broad bands at about 530 and 500. In order to correlate, if possible, these spectra with the amounts of the last three of the above listed elements, specimens were analyzed by fusing with sodium carbonate and nitrate, extracting with water, comparing the color of the solution with that of potassium chromate of known strength, then acidifying with sulfuric acid, evaporating, adding hydrogen peroxide, and titrating the vanadium with standard permanganate[6]; manganese being determined colorimetrically in the residues (except in the case of spessartite, where the average of published analyses was used). The results were as follows:

Variety	Locality	Color	Spectra A	Spectra B	Cr Per ct.	V Per ct.	Mn Per ct.
Pyrope.....	Bohemia........	deep red..	strong.	none...	1.12	none	1.40
Almandite..	Wrangell, Alaska	deep red..	distinct	strong.	0.03	0.02	1.45
Almandite..	India...........	violet-red.	distinct	strong.	0.02	0.03	1.20
Spessartite..	Amelia C. H., Va.	brown....	distinct	distinct.	0.02	0.01	33.65
Essonite....	Ceylon..........	brown-red	distinct	none...	0.02	none	0.25
Essonite....	Ceylon..........	brown....	faint..	distinct.	0.01	0.01	0.35

In this table it is evident that spectrum A is connected with the presence of chromium, while B is, if anything, related to the vana-

[1] "In former ages . . . . it was believed that gold and tin were the coloring principle of garnet." Feuchtwanger, Treatise on Gems, New York, 1838, p. 18. I am indebted to Dr. William S. Disbrow, of Newark, N. J., for calling my attention to this reference.

[2] According to most writers; but inspection of analyses shows no relation between the color and the content of either ferrous or ferric iron.

[3] First detected by Klaproth, Beitr. Chem. Min., vol. 5, 1810, p. 171; mentioned as the cause of color of pyrope in many books on precious stones.

[4] Regarded as the cause of the color by various writers, and of the absorption spectrum by Brun, Arch. sci. phys. nat., ser. 3, vol. 28, 1892, p. 410, and by Keeley, loc. cit.

[5] Uhlig, Verh. nat. Ver. preuss. Rheinl. Westfal., vol. 67, 1910, p. 307; Zeits. Kryst. Min., vol. 53, 1913, p. 203.

[6] Cain and Hostetter, Journ. Amer. Chem. Soc., vol. 34, 1912, p. 274.

dium content. Many artificial salts of the former metal, as well as the chlorite minerals colored violet by it, show spectrum A, so it may be considered proved that one factor in the color of magnesium (and manganese) garnets is the element chromium. (Calcium garnets, which are colored green by this element, show an entirely different spectrum.) Spectrum B, it must be admitted, has never been observed in minerals or artificial compounds of vanadium, but no other silicates containing vanadium as a red compound have been available for study (the green roscoelite showing no bands) and as the mode of combination has great influence on the character of the spectra shown by a given element, it may be regarded as probable that vanadium is a second factor in the color of garnets. The total manganese shows no connection with the spectrum, and the presence of more or less ferrous iron in all garnets precludes the possibility of the existence of any manganic compound.

TABLES

The results of the examination of about 200 minerals with the microspectroscope are here presented in tabular form. Only a third of them exhibit distinctive spectra, but as the absence of bands may also have diagnostic value in some cases, it has seemed best to list all those tried. The wave lengths of bands which are especially characteristic of the various minerals are given in bold face type, and of those which are faint and difficult to see in parentheses. The limits of visibility (recorded as "To 700, 440 on," etc.) vary rather widely with the thickness of mineral through which the light passes, but are added for the sake of completeness.

To increase the practical usefulness of the tables a determinative table, or analytical key, is added after the lists of mineral spectra. It is based on general character of spectrum, number of bands and mineral colors, and covers all minerals showing bands of sufficient intensity for diagnostic purposes.

Finally, as this method may also prove useful for demonstrating the presence or absence of certain chemical elements, a table of the elements showing spectra, with their forms, and the limits to the amounts present, is also given. It should be noted here that the elements causing the colors and absorption bands of some minerals are as yet unknown; thus, the band at or near wave length 605 in the rare earth minerals with the yttrium group in excess cannot be ascribed to any known element; and in the other tables interrogation points (?) in the "coloring elements" columns show the lack of information in many cases.

MINERALS SHOWING THE RARE EARTH ABSORPTION SPECTRA

Cerium Group in Excess

Elements causing bands	Red		Orange		Yellow		Green				Blue		Violet	
		Nd	Er	Nd	Pr	Nd	Sm	Nd	Nd, Er	Nd	Pr, Sm	Pr	Pr	
Tysonite	To 700	**675**	(650)	(623)	**595**	580–570	...	(532)	522	(513)	(485)	...	...	440 on
Bastnäsite	To 690	675	(650)	(623)	(590)	**579 569**	...	(532)	522	(511)	(485)	...	...	450 on
Parisite	To 690	675	...	**623**	**590**	to **570**	...	533	**522**	**512**	485	(470)	(445)	440 on
Cordylite	To 680	(675)	...	...	(590)	**581** (575)	...	(533)	521	512	(485)	470	...	440 on
Lanthanite	To 680	(675)	...	(620)	(590)	**579 570**	...	(532)	**520**	**510**	(485)	(470)	(445)	440 on
Calcite, violet	To 690	...	...	...	...	**582**	...	...	(525)	...	...	...	...	430 on
Cerite	To 680	(675)	...	(620)	**590**	to **570**	...	(533)	(525)	(512)	(485)	...	...	440 on
Titanite, yellow	To 670	...	...	...	...	(585)	...	...	(525)	...	...	...	...	460 on
Mosandrite	To 680	...	...	...	...	(585)	...	...	(525)	...	...	...	...	440 on
Tritomite	To 670	...	...	...	...	(585)	...	...	(525)	...	...	...	...	460 on
Freyalite	To 680	(675)	...	...	(590)	**585 575**	...	**530**	(525)	(512)	(485)	...	...	460 on
Britholite	To 680	(675)	...	...	(590)	**588–578**	...	530	(520)	(512)	(485)	...	..	460 on
Aeschynite	To 670	...	...	...	...	(585)	...	...	(525)	...	...	...	...	440 on
Pyrochlore	To 680	...	...	...	...	**588–578**	...	...	(525)	...	...	...	...	460 on
Microlite	To 670	...	...	...	...	(585)	...	...	(525)	...	...	...	...	450 on
Monazite	To 690	**675**	(645)	622	**590**	to **570**	(555)	(532)	**523**	512	485	...	...	450 on
Rhabdophanite	To 690	**675**	645	622	**595**	to **570**	(555)	533	**524**	512	485	(470)	(445)	430 on
Churchite	To 690	(675)	...	(620)	**590**	**578**	...	(535)	524	(510)	(485)	...	...	440 on
Apatite, brown	To 670	...	...	...	...	(585)	...	...	(525)	...	...	...	...	460 on
Gummite	To 660	...	...	...	...	585	...	...	**525**	...	...	...	...	460 on

Yttrium Group in Excess

Elements causing bands	Red		Orange		Yellow		Green				Blue		Violet	
		Nd	Er	Nd	Pr*	Nd	Sm	Nd	Nd, Er	Nd	Pr, Sm	Pr	Pr	
Rowlandite	To 660	...	(645)	...	(600)	**585–575**	(555)	...	**522**	...	(485)	...	...	450 on
Yttrialite	To 670	...	(645)	...	(600)	(585)	(555)	...	(522)	...	(485)	...	...	460 on
Fergusonite	To 670	...	...	...	...	(585)	(555)	...	(522)	...	...	...	...	450 on
Yttrotantalite	To 670	...	(650)	...	(600)	(585)	(555)	...	**522**	...	...	...	...	460 on
Xenotime	To 660	...	**645**	...	**605**	...	**555**	...	522	...	(485)	...	...	450 on

Tritomite includes caryocerite, melanocerite, and steenstrupine; fergusonite includes sipylite; yttrotantalite includes risörite; the following show no spectra, being for the most part too opaque: allanite, ankylite, blomstrandite, cenosite, euxenite, gadolinite, hatchettolite, loranskite, polycrase, rogersite, samarskite, tengerite, and thorite. Certain specimens of autunite and other secondary uranium minerals, when derived from rare earth bearing primary minerals, show the same spectrum as gummite.

* See last paragraph on page 7.

MINERALS SHOWING THE URANIUM ABSORPTION SPECTRA

Uranic Uranium

	Red	Orange	Yellow	Green		Blue			Violet			
Liebigite	To 680	...	...	(535)	(515)	495	(480)	**463**	455	(440)	430	on
Voglite	To 670	...	...	...	...	504	**488**	472	458	**447**	440	on
Autunite	To 680	...	(550)	(532)	(**515**)	**499**	484	(468)	(455)	**445**	440	on
Uranocircite	To 680	...	(**552**)	(**535**)	515	495	(485)	(470)	(455)	448	440	on
Torbernite	To 670	...	...	...	...	**503**	**487**	470	458	**445**	430	on
Uranospinite	To 680	...	...	(530)	...	**495**	482	(467)	(455)	(440)	430	on
Zeunerite	To 670	...	...	...	...	505	**489**	472	459	**448**	430	on
Johannite	To 680	...	...	...	...	**497**	**479**	(466)	(450)	...	440	on
Uranium glass	To 630	595	570	545	525	**505**	**485**	465	...	...	460	on

Liebigite includes uranothallite; johannite includes uranochalcite and voglianite; the following do not show definite spectra: carnotite, rutherfordine, trögerite, uraconite, uraninite, uranophane, uranopilite, uranosphærite, walpurgite, and zippeite; it may further be noted that specimens labeled phosphuranylite have proved in almost every case to show the spectrum of autunite, and have yielded calcium on qualitative examination, but an authentic specimen of this mineral in the Brush collection, loaned for examination through the kindness of Prof. Ford, showed no spectrum beyond slight general absorption in the blue. See also note to rare earth table.

Uranous Uranium

	Red			Orange		Yellow		Green		Blue		Violet
Zircon, blue	To 690	685	(660)	**651**	618	**588**	560	537	**512**	483	(460)	440 on
Zircon, green	To 690	685	(660)	**651**	618	**588**	(560)	537	**512**	483	(460)	440 on
Zircon, yellow	To 690	(685)	...	**651**	(618)	588	...	(537)	(512)	(483)	...	450 on
Zircon, pink	To 690	(685)	...	**651**	(618)	588	...	(537)	512	(483)	...	440 on

Brown, white and colorless zircons do not show spectra.

Color Red, Pink or Orange

	Coloring elements	Red	Orange	Yellow	Green	Blue	Violet
Hematite	Fe'''	To 690	...	...	...	...	440 on
Botryogen	Fe'''	To 680	...	...	560	on	...
Spherocobaltite	Co''	To 680	...	(570 to	540)	...	430 on
Erythrite	Co''	To 680	...	...	**560–540**	(500–490)	430 on
Roselite	Co''	To 680	...	(570 to	540)	...	430 on
Zincite	Mn''	To 680	...	(600–570)	...	510	on ...
Rhodochrosite	Mn''	To 670	...	580 to	540	...	460 on
Rhodonite	Mn''	To 670	...	580 to	540	...	460 on
Zoisite var. thulite	Mn''	To 670	...	...	560–530	...	450 on
Piedmontite	Mn''	To 660	...	...	...	...	450 on
Tourmaline var. rubellite.	Mn''	To 670	...	...	(560 to	490)	430 on
Hübnerite	Mn''	To 680	...	...	...	...	460 on
Corundum, pink	Cr'''	To 700 **680**	...	600–570	...	...	460 on
Corundum var. ruby	Cr'''	To 700 **680**	...	600–570	...	...	450 on
Corundum var. ruby, synthetic.	Cr'''	To 700 **680**	...	600 to	510	...	460 on
Garnet var. pyrope (see text).	Cr'''	To 670	620 to	560	...	...	460 on
Garnet, grossularite, pink.	Cr'''	To 660	(610 to	580)	...	...	460 on
Crocoite	Cr^{vi}	To 670	...	570	on ...	...	...
Cuprite	Cu'	To 700	**630**	...	...	...	450 on
Imitation ruby (Cu-glass).	Cu'	To 680	...	600–560	...	...	460 on
Garnet var. almandite (see text).	$V'''+Cr'''$	To 680	620	**585–570**	530–520	**510–495**	450 on
Garnet var. spessartite.	$V'''+Cr'''$	To 680	(620)	580–565	(540–520)	470	on ...
Rutile	V^{v}	To 680	...	...	...	...	450 on
Vanadinite	V^{v}	To 670	...	580 to	550	490	on ...
Pascoite	V^{v}	To 670	...	...	550	on ...	...
Wulfenite	V^{v}	To 670	...	...	560	on ...	...
Cinnabar	Hg''	To 690	610 to	590	...	...	460 on
Realgar	As''	To 680	...	580 to	540	470	on ...
Proustite	As'''	To 670	...	600–570	...	...	460 on
Pyrargyrite	Sb'''	To 670	610 to	580	...	...	460 on
Halite	?	To 680	...	(580 to	540)	480	on ...
Fluorite	?	To 670	...	...	...	...	440 on
Quartz var. rose-quartz.	?	To 680	...	...	...	...	440 on
Spinel	?	To 680	...	(580 to	540)	...	460 on
Calcite	?	To 670	...	...	...	490	on ...
Beryl	?	To 670	...	...	...	...	440 on
Topaz	?	To 680	...	(570 to	530)	...	450 on

The diagnostic importance of the spectra of the red corundums (shown in reflected light only) was pointed out by Keeley (*op. cit.*, p. 109).

Color Yellow or Brown

	Coloring elements	Red	Orange	Yellow	Green	Blue	Violet
Sphalerite	Fe''	To 680	...	...	...	510	on ...
Goethite	Fe'''	To 650	...	...	550	on	...
Siderite	Fe'''	To 680	...	...	...	470	on ...
Garnet var. andradite	Fe'''	To 670	...	...	...	480	on ...
Garnet var. grossularite	Fe'''	To 670	...	...	...	470	on ...
Vesuvianite	Fe'''	To 660	...	...	...	480	on ...
Staurolite	Fe'''	To 670	...	...	(560–550)	470	on ...
Tourmaline	Fe'''	To 650	...	...	...	490	on ...
Copiapite	Fe'''	To 680	...	...	...	490	on ...
Imitation topaz (Fe-glass)	Fe'''	To 660	...	...	...	490	on ...
Corundum	Fe'''	To 670	...	...	...	...	**455** 440 on
Greenockite	Cd''	To 670	...	...	**525–515**	500	on ...
Iodyrite	Ag'	To 680	...	...	...	...	(445) 440 on
Orpiment	As'''	To 680	...	...	...	480	on ...
Wulfenite	Mo^{vi}	To 670	...	...	...	...	460 on
Sulfur	S^o	To 680	...	...	...	480	on ...
Selensulfur	Se^o	To 680	...	...	...	480	on ...
Fluorite	?	To 680	...	...	...	...	440 on
Quartz var. citrine	?	To 670	...	...	...	470	on ...
Cassiterite	?	To 670	...	...	...	...	450 on
Chrysoberyl	?	To 670	...	...	...	...	460 on
Calcite	?	To 660	...	...	...	480	on ...
Smithsonite	?	To 670	...	...	...	...	460 on
Beryl	?	To 670	...	...	...	...	450 on
Olivine	?	To 670	...	...	...	...	460 on
Willemite	?	To 670	...	...	...	...	440 on
Thorite	?	To 670	...	...	...	480	on ...
Topaz	?	To 670	...	...	...	...	460 on
Axinite	?	To 670	...	...	...	...	450 on
Titanite	?	To 660	...	...	...	470	on ...
Apatite	?	To 660	...	...	...	470	on ...
Barite	?	To 670	...	...	...	470	on ...

In addition, many rare earth and uranium minerals, listed in the preceding tables, are yellow or brown in color.

Color Green

	Coloring elements	Red	Orange	Yellow	Green	Blue	Violet
Corundum	Fe'''+Ti'''	To 670	...	...	...	...	**455** 440 on
Diopside	Fe''	To 670	...	...	...	...	450 on
Actinolite	Fe''	To 650	...	...	...	...	460 on
Olivine	Fe''	To 670	...	...	...	**500–490**	(460) 430 on
Epidote	Fe''+Fe'''	To 670	...	...	...	(478)	**458** 430 on
Tourmaline	Fe''	... To	630	...	...	...	450 on
Clinochlore	Fe''	To 650	...	...	...	...	460 on
Serpentine	Fe''	To 650	...	...	...	...	460 on
Melanterite	Fe''	To 650	...	...	...	...	450 on
Manganosite	Mn''	To 700	650 t	o 575	520	on	
Zaratite	Ni''	... To	640	...	...	500	on ...
Cabrerite	Ni''	... To	620	...	...	500	on ...
Spodumene var. hiddenite.	Cr'''	...	... To	580	...	500	on ...
Beryl var. emerald.	Cr'''	To 680	**(640) (620)**	...	...	470	on ...
Garnet var. demantoid.	Cr'''	To 680	(640) (620)	...	...	510	on ...
Garnet var. uvarovite.	Cr'''	...	... To	570	...	500	on ...
Vesuvianite	Cr'''	To 670	...	...	...	480	on ...
Muscovite var. fuchsite.	Cr'''	To 670	(650)	...	...	500	on ...
Atacamite	Cu''	... To	630	...	...	500	on ...
Malachite	Cu''	... To	630	...	...	500	on ...
Aurichalcite	Cu''	... To	640	...	...	500	on ...
Dioptase	Cu''	... To	640 (610 t	o 580)	...	490	on ...
Chrysocolla	Cu''	... To	640	...	...	500	on ...
Tyrolite	Cu''	... To	620	...	...	500	on ...
Brochantite	Cu''	... To	630	...	...	500	on ...
Natrochalcite	Cu''	... To	620	...	...	500	on ...
Imitation emerald (Cu-glass).	Cu''	... To	620	...	...	490	on ...
Roscoelite	V'''	... To	640	...	...	470	on ...
Calciovolborthite	V'''	To 650	...	...	...	510	on ...
Fluorite	?	To 660	630–610	...	...	500	on ...
Quartz var. chrysoprase.	?	... To	630	...	...	...	450 on
Spinel	?	To 660	...	...	...	(490)	460 on
Chrysoberyl var. alexandrite.	?	To 690	...	**600–570**	...	(490–470)	560 on
Microcline	?	To 660	...	...	...	500	on ...
Beryl	?	To 670	...	...	...	...	450 on
Willemite	?	To 660	...	...	...	...	460 on
Datolite	?	To 660	...	...	...	...	450 on
Andalusite (gem variety).	?	... To	640	...	**555** 525	510	on ...
Prehnite	?	To 670	...	...	...	...	450 on
Titanite	?	To 670	...	...	...	500	on ...
Apatite	?	To 660	...	...	...	...	450 on
Pyromorphite	?	To 660	...	...	...	510	on ...
Variscite	?	To 660	...	...	...	500	on ...
Wavellite	?	To 660	...	...	...	...	450 on

A few green minerals are included in the rare earth and uranium tables. The absorption band shown by manganosite has recently been observed by Ford (Amer. Journ. Sci., vol. 38, 1914, p. 502).

Color Blue

	Coloring elements	Red	Orange	Yellow	Green	Blue	Violet
Glaucophane	$Fe''+Fe'''$	To 670	...	...	...	...	440 on
Tourmaline var. indicolite.	$Fe''+Fe'''$	To 650	...	...	...	...	450 on
Vivianite	$Fe''+Fe'''$	To 660	...	...	...	...	460 on
Imitation sapphire (Co-glass).	Co''	To 700 **670** to	**640**	**600–580**	550–530	...	430 on
Spinel	Co''	... To	640	(590)	**555–545**	(510) **465** to **455**	430 on
Covellite	Cu''	To 650	...	...	...	...	440 on
Boleite	Cu''	To 650	...	...	...	...	450 on
Smithsonite (stained)	Cu''	... To	640	...	...	...	450 on
Azurite	Cu''	To 650	...	...	...	**510–480**	430 on
Calamine (stained)	Cu''	To 660	...	...	...	...	440 on
Turquois	Cu''	To 650	...	...	...	...	440 on
Chalcanthite	Cu''	... To	620	(590 to 550)		...	440 on
Linarite	Cu''	To 650	...	(600–560)	...	...	440 on
Corundum var. sapphire.	Ti'''	To 660	...	...	...	...	425 on
Corundum var. sapphire, synthetic.	Ti'''	To 650	...	...	...	...	430 on
Octahedrite	Ti'''	To 650	...	...	...	...	440 on
Cyanite	Ti''' (?)	To 660	...	...	...	...	430 on
Dumortierite	Ti'''	To 650	...	...	...	...	450 on
Benitoite	Ti'''	To 650	...	...	...	...	425 on
Halite	Na^{o}	To 680	610 to 580		...	...	440 on
Calcite	?	To 660	...	...	...	...	440 on
Beryl var. aquamarine.	?	To 660	...	...	...	...	460 on
Iolite	?	To 680	...	...	...	**500–490**	425 on
Sodalite	?	To 660	...	...	...	...	430 on
Lazurite	?	To 660	...	...	...	...	440 on
Topaz	?	To 660	...	...	...	...	440 on
Euclase	?	To 660	...	...	...	...	450 on
Lazulite	?	To 660	...	...	...	...	460 on
Barite	?	To 660	...	...	...	...	440 on
Celestite	?	To 660	...	...	...	...	440 on

Color Violet or Purple

	Coloring elements	Red	Orange	Yellow	Green	Blue	Violet
Pyroxene var. violan.	Mn'''	To 680	...	...	...	...	440 on
Spodumene var. kunzite.	Mn'''	To 650	...	...	**560–520**	...	440 on
Tremolite var. hexagonite.	Mn'''	To 670	...	(580–570)	...	...	450 on
Hodgkinsonite.......	Mn'	To 660	...	(590–570)	...	...	450 on
Axinite	Mn''	To 670	...	...	...	...	460 on
Lepidolite	Mn''	To 670	...	(580–570)	...	...	460 on
Imitation amethyst (Mn-glass).	Mn'''	To 650	...	(590)	(545)	...	430 on
Spinel...............	Co''	To 670	...	(590)	**555–545**	...	(460) 440 on
Chlorite var. kotschubeite, kämmererite, etc.	Cr'''	To 670	(610 to 560)		...	...	450 on
Dumortierite	Ti'''	To 670	...	...	...	...	430 on
Corundum	Cr'''+Ti'''	To 700 (680)	...	(590–560)	...	...	450 on
Garnet var. almandite.	V'''	To 670	(620)	**590–570**	540–520	510–490	460 on
Fluorite	?	To 670	...	(600 to 550)		...	440 on
Quartz var. amethyst.	?	To 660	...	...	(520 to 490)		430 on
Diaspore	?	To 660	...	...	...	...	450 on
Apatite..............	?	To 660	...	...	...	...	440 on

Violet calcite and lanthanite are included in rare earth list.

ANALYTICAL KEY

Group I.—Spectrum Composed of Narrow Bands

Number of bands	Wave length of strongest	Elements	Minerals
10	650	Uranium (uranous)......	Zircon (certain varieties)
9	575	Neodymium + praseodymium	See tables
8	500	Uranium (uranic)......	See tables
6	555	Samarium+erbium....	See tables
2	585	Neodymium (0.005–0.5%)	See tables

Group II.—Spectrum Composed of Broad Bands

A.—Color Red

4	575	Chromium+vanadium.	Garnet (almandite and spessartite)
2	680	Chromium	Corundum (ruby and pink)
2	550	Cobalt................	Erythrite
1	630	Copper (cuprous).......	Cuprite
1	600	Chromium.............	Garnet (pyrope)

B.—Color Yellow

1	520	Cadmium (as sulfide)	Greenockite
1	455	Iron (ferric)...........	Corundum (oriental topaz)

C.—Color Green

2	640	Chromium.............	Beryl (emerald)
2	585	?	Chrysoberyl (alexandrite)
2	555	?	Andalusite (gem variety)
2	495	Iron (ferrous).........	Olivine (chrysolite, peridote)
2	460	Iron (ferric)	Epidote
1	455	Iron (ferric)...........	Corundum (oriental emerald)

D.—Color Blue

4	550	Cobalt	Spinel
[3	655	Cobalt.................	Cobalt glass (imitation sapphire)]
1	500	Copper.................	Azurite
1	495	?	Iolite

E.—Color Violet

4	575	Chromium + vanadium.	Garnet (almandite)
3	555	Cobalt.................	Spinel
2	680	Chromium	Corundum (oriental amethyst)
1	540	Manganese (?)........	Spodumene (kunzite)

THE ELEMENTS AND THEIR SPECTRA

Elements	Forms	Percentages	Compounds	Average positions of bands
Antimony	Sb'''	18–22	Ag_3SbS_3	610–580
Arsenic	As''	70	AsS	580–540
	As'''	13–15	Ag_3AsS_3	600–570
Cadmium	Cd''	78	CdS	525–515
Chromium	Cr''' (red)	0.1–2.5	$(Al, Cr)_2O_3$	680 600–570
	Cr''' (red)	0.01–3.0	$(Mg, Fe)_3(Al, Cr)_2(SiO_4)_3$	620 585–570
	Cr''' (violet)	3–10	$Mg(Al, Cr)(OH)SiO_4$	(610–560)
	Cr''' (green)	0.1–0.2	$Be_3(Al, Cr)_2(SiO_3)_6$	(640) (620)
Cobalt	Co''	28	$Co_3(AsO_4)_2 \cdot 8H_2O$	560–540 (500–490)
	Co''	0.1–0.5	$(Mg, Co)Al_2O_4$	(590) 555–545 (510) 465–455
Copper	Cu'	89	Cu_2O	630
	Cu''	55	$Cu_3(OH)_2(CO_3)_2$	510–480
	Cu''	26	$CuSO_4 \cdot 5H_2O$	(590–550)
Erbium	Er'''	1–20	$(Y, Er)PO_4$, etc.	645 520
Iron	Fe''	4–25	$(Mg, Fe)_2SiO_4$	500–490 (460)
	Fe'''	0.1–1.0	$(Al, Fe)_2O_3$	455
	Fe'''	4–15	$Ca_2(Al, Fe)_3(OH)(SiO_4)_3$	(480) 460
Manganese	Mn'' (green)	77	MnO	650–575
	Mn'' (red)	48	$MnCO_3$, etc.	(580–540)
	Mn'''	0.1	$Li(Al, Mn)(SiO_3)_2$	560–520
Mercury	Hg''	86	HgS	610 590
Neodymium	Nd'''	0.5–15.0	Various; see tables	675 620 580 570 530 520 510
	Nd'''	0.005–0.5	Various; see tables	585 (525)
Praseodymium	Pr'''	0.5–15.0	Various; see tables	590 485 470 445
Samarium	Sm'''	1	$(Y, Sm)PO_4$, etc.	555 485
Uranium	Uiv	0.1–1.5	$(Zr, U)SiO_4$	685 660 650 620 590 560 535 510 485 460
	Uvi	30–50	(UO_2)-Ca salts	(550) (535) 515 500 485 470 455 445
	Uvi	35–55	(UO_2)-Cu salts	500 485 470 455 445
Vanadium	V''' (red)	0.01–0.05	$(Mg, Fe)_3(Al, V)_2(SiO_4)_3$	(530–520) 510–495