Some relationships between the reflectivities of sulphide ore-minerals.

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[Read November 9, 1933.]

SINCE the early work of Drude and others on the reflection of light by opaque crystalline media, little progress has been made in the direct determination of the indices of refraction and absorption for such substances. Interest in the optical properties of the opaque minerals, however, has been greatly stimulated by the rapid development in the last few years of the methods of ore-microscopy first brought into prominence by Campbell in 1906. Full theoretical discussions have been given recently by Berek,[1] Koenigsberger,[2] and others, but the only quantitative measure feasible in routine microscopy at present is that of the reflectivity. Such measurements are readily carried out by means of a photometer-ocular (Schneiderhöhn,[3] Berek [4]) or a photoelectric ocular (Orcel [5]), and are of very considerable diagnostic value. They do not, however, lead to a determination of the actual values of the indices of refraction (n) and absorption (k); Cissarz [6] has shown, for example, that the theoretically feasible method of determining n and k by measurements of reflectivity (R) in media of different refractive indices fails in practice owing to the large error introduced in the results by a small error in the determination of the reflectivities. An important factor in limiting the application of mathematical theory to practical microscopy lies in the departure from normal incidence involved in the use of an objective below the illuminator, and the resulting variability of the

[1] M. Berek, Zeits. Krist., 1931, vol. 76, pp. 396–430; ibid., vol. 77, pp. 1–22; ibid., vol. 80, pp. 18–36; Neues Jahrb. Min., Abt. A, 1931, Beil.-Bd. 64, pp. 123–136. [Min. Abstr., vol. 5, pp. 122–123.]

[2] J. Koenigsberger, Neues Jahrb. Min., Abt. A, 1931, Beil.-Bd. 64, pp. 107–121.

[3] H. Schneiderhöhn, Centr. Min., Abt. A, 1928, pp. 394–396.

[4] M. Berek, Zeits. Krist., 1931, vol. 77, pp. 6–21.

[5] J. Orcel, Bull. Soc. franç. Min., 1930, vol. 53, pp. 301–349. [M.A. 4–444.]

[6] A. Cissarz, Neues Jahrb. Min., Abt. A, 1931, Beil.-Bd. 64, p. 158. [M.A. 5–125.]

cone of incidence with the aperture of the objective used. It is fortunate that the relative reflectivities are little affected by these factors (Berek,[1] and the author's own measurements), so that comparison of an unknown mineral with one of known reflectivity whilst employing the same set-up remains a useful method of diagnosis. The absolute reflectivities of a few standards are determined from their known physical constants.[2]

The R value therefore remains at present the only constant likely to be determined quantitatively, and largely through the work of Schneiderhöhn and Ramdohr[3] values for a number of sulphide ore-minerals are now available. It seems of interest to examine the results for any evidence of regular relationships.

Amongst the simple sulphides, selenides, and tellurides an increase of reflectivity with increasing atomic number can be traced, the figures in table I being self-explanatory. The more complex minerals, such as the series of sulphantimonites of lead xPbS.ySb$_2$S$_3$, show less obvious relationships, but the author has recently suggested a method of computation which appears to give interesting results.[4] The absorption index of these sulphides is of secondary importance

TABLE I. Showing increase in reflectivity with increasing atomic number.

Chalcosine	Cu_2S	20	Blende	ZnS	14·5	Orpiment	As_2S_3	26
Argentite	Ag_2S	33	Greenockite	CdS	17	Stibnite	Sb_2S_3	34·2
			Cinnabar	HgS	25·5	Bismuthinite	Bi_2S_3	43
Galena	PbS	37·5	Argentite	Ag_2S	33	Ginnabar	HgS	25·5
Clausthalite	PbSe	43	Naumannite	Ag_2Se	34·5	Tiemannite	HgSe	27
Altaite	PbTe	55	Hessite	Ag_2Te	40	Coloradoite	HgTe	31
Chalcosine	Cu_2S	20	Stromeyerite	CuAgS	26	Enargite	Cu_3AsS_4	21·5
Berzelianite	Cu_2Se	25	Eukairite	CuAgSe	27	Famatinite	Cu_3SbS_4	23·5
Sartorite	$PbAs_2S_4$	28	Proustite	Ag_3AsS_3	21			
Zinckenite	$PbSb_2S_4$	33	Pyrargyrite	Ag_3SbS_3	27			
Alaskaite	$PbBi_2S_4$	40						

[1] M. Berek, loc. cit., p. 4.

[2] A. Cissarz, Zeits. Krist., 1932, vol. 82, pp. 438–450. [M.A. 5–205.]

[3] H. Schneiderhöhn and P. Ramdohr, Lehrbuch der Erzmikroskopie, vol. 2, Berlin, 1931. [M.A. 4–434.]

[4] F. C. Phillips, Nature, London, 1932, vol. 130, p. 998. [M.A. 5–206.]

only in determining the reflectivity, which is not in this sense true metallic reflection (Wright,[1] Tyndall [2]), and is due mainly to a very high refractive index. It is therefore a reasonable approximation to consider such minerals as transparent in small thicknesses still relatively great compared with the wave-length of the light employed (Orcel [3]). For a transparent substance the refractive index could be calculated from the reflectivity from Fresnel's relationship $n = (1 + \sqrt{R})/(1 - \sqrt{R})$. If such n values are calculated for these sulphides, they may then be used to derive from the Lorenz-Lorentz equation for the molecular refractivity, $MR = M\,(n^2 - 1)/d\,(n^2 + 2)$, values corresponding to the molecular refractivity as calculated for transparent substances. If this is done for the simple sulphides, &c., and for members of the corresponding complex series, an additive relationship is found to hold for these MR values over a wide range of molecular weight and of reflectivities within the degree of approximation already made. A series of such results is given in table II.

A number of uses can be made of such calculations. In the first place they indicate a method by which the reflectivity of an ore-mineral can be computed. Secondly, the figures afford a useful check on the values of the density quoted in the literature. Two instances of this may be briefly noted. In the preliminary calculations, a density of 6·53 was assumed for naumannite (Shannon [1]), giving an MR value for naumannite higher than that for hessite, and a computed value for eukairite much higher than the calculated value. Shannon's determination of the density, admittedly made on contaminated material, is certainly too low. For klaprothite a value of 4·6 is universally quoted in the literature, based on an early determination by Petersen; this gives widely discordant results and should probably read 6·4, the value obtained by calculating backwards from the computed MR value. It has proved impossible to obtain from the only authentic locality sufficient material in a pure state for a specific gravity determination, but a sample prepared artificially gave a value of 6·3. For the related sulphide wittichenite, the values quoted range from 4·3 to 6·7, and the value obtained by calculation is 6·2. A review of the densities of the sulphides, based on these and other considerations, is in progress.

[1] F. E. Wright, Proc. Amer. Phil. Soc., 1919, vol. 58, p. 426. [M.A. 1–198.]
[2] E. P. T. Tyndall, Physical Rev., 1923, vol. 21, p. 180.
[3] J. Orcel, loc. cit., p. 302.
[4] E. V. Shannon, Amer. Journ. Sci., 1920, ser. 4, vol. 50, p. 391. [M.A. 1–144.]

TABLE II. Comparison of the *MR* values of complex sulphides, calculated from the reflectivities, with those computed from the *MR* values of the simple sulphides.

Mineral.	Density.	Reflectivity.	*MR* values. Calculated.	*MR* values. Computed.
Aikinite	6·8	37·5	141	141
Alaskaite	6·2	40	104	95
Andorite	5·3	27·5	246	257
Aramayoite	5·6	31	83	86
Beegerite	7·2	36	224	232
Boulangerite... ...	6·3	34·5	137	140
Bournonite	5·8	30	242	253
Chalcostibite ...	5·0	35	82	77
Dufrenoysite ...	5·5	28	100	106
Emplectite	6·5	35	108	86
Eukairite	7·6	27	49	53
Freieslebenite ...	6·0	30·5	250	253
Geocronite	6·4	30·5	188	195
Jordanite	6·4	32·5	175	160
Klaprothite	6·4 ?	34	190	191
Lillianite	7·0	45	140	150
Livingstonite ...	4·8	32·5	150	138
Meneghinite... ...	6·4	35	166	167
Miargyrite	5·3	29	86	86
Pearceite	6·1	25·5	296	298
Plagionite	5·5	29	358	370
Plumosite	5·6	32	116	113
Polybasite	6·2	25·5	302	305
Proustite	5·5	21	121	132
Pyrargyrite	5·8	27	140	141
Rathite	5·3	33	183	186
Semseyite	5·9	35	488	480
Stephanite	6·2	27·5	190	195
Stromeyerite ...	6·2	26	48	46
Stylotypite	5·1	24·5	114	114
Tennantite	4·7	24	134	124
Tetrahedrite... ...	4·8	24	145	133
Wittichenite... ...	5·9	29·5	129	124
Zinckenite	5·3	33	88	86

A final and more speculative extension of these calculations may be briefly indicated. The refractivities calculated from the Lorenz-Lorentz equation should be strictly additive in any system in which the electron-shells of the constituents remain unaffected, and any departure from strict additivity is to be interpreted as a deformation of at least one of the constituents (Fajans and Joos [1]). Present interest in the molecular refractivities of transparent ionic substances

[1] K. Fajans and G. Joos, Zeits. Physik, 1924, vol. 23, p. 5.

lies in tracing such departures. The approximations introduced above will obscure any similar variations, but it seems worth while to note that, pursuing the conception of strict additivity, the *MR* values derived above are comparable with those obtained for anion and kation in the study of transparent ionic substances. Thus, taking values of *MR* Pb 9·93, Zn 1·70, Cd 4·46 (Wasastjerna [1]), values for *S* are obtained from 17·7 to 12·1, for Se 20·1, and for Te 28·3. Haase [2] derives from a study of the compounds of S, Se, and Te with the alkaline earths values for S 17·20 to 11·96, for Se 20·71 to 14·89, and for Te 27·90 to 23·39.

[1] J. A. Wasastjerna, Soc. Sci. Fennica Comm. Phys.-Math., 1923, vol. 1, no. 37.
[2] M. Haase, Zeits. Krist., 1927, vol. 65, p. 581. [M.A. 3–421.]