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**Magnetic and Other Properties
of Oxides and Related Compounds**

**Magnetische und andere Eigenschaften
von Oxiden und verwandten Verbindungen**

Part c/Teil c



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Supplement and Extension to Volume 4

Magnetic and Other Properties
of Oxides and Related Compounds

Part c

Hexagonal Ferrites · Special Lanthanide
and Actinide Compounds

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K.A. Hempel · U. Köbler · H. Lütgemeier

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Vorwort

Der vorliegende Teilband III/12c ist der letzte des Bandes III/12 „Magnetische und andere Eigenschaften von Oxiden und verwandten Verbindungen“, des Ergänzungsbandes zu Band III/4. In diesem Teilband werden die Hexagonalferrite und verschiedene Familien von Lanthanid- und Aktinidverbindungen von bestimmten Strukturtypen behandelt. Der Umfang der seit 1970 veröffentlichten Daten zeigt das wachsende, starke Interesse an diesen Verbindungen.

Die meisten der in diesem Teilband benutzten Symbole stimmen mit den in den vorigen Teilbänden benutzten überein. Der Gebrauch zweier Einheitensysteme zeigt die jetzige Situation der magnetischen Forschung, in der die häufige Umrechnung von CGS- zu SI-Einheiten und umgekehrt üblich ist. Eine Liste der Umrechnungsfaktoren im vorderen Innendeckel wird deshalb dem Leser nützlich sein.

Das Substanzenverzeichnis am Ende des Bandes enthält alle in den Bänden III/4a, b und III/12a, b, c behandelten Substanzen und wird das Auffinden der Daten einzelner Substanzen erleichtern.

Wir danken den Autoren für ihre wirksame Arbeit und die gute Zusammenarbeit, der Landolt-Börnstein-Redaktion, insbesondere Herrn Dr. W. Polzin und Frau Rita Schattschneider, für ihre kritische Sorgfalt bei der Überprüfung der Manuskripte, der Druckfahnen und des Umbruchs sowie dem Verlag für die besondere Geduld bei der Drucklegung. Dieser Teilband wurde ohne finanzielle Unterstützung von anderer Seite veröffentlicht.

Darmstadt, Oktober 1982

Die Herausgeber

Preface

The present subvolume III/12c is the last one of volume III/12, "Magnetic and other properties of oxides and related compounds", the supplement to volume III/4. In this subvolume, the hexagonal ferrites and various families of lanthanide and actinide compounds of special structure types are treated. The amount of information available since 1970 signals the growing strong interest in these compounds.

The symbols used in this subvolume are mostly the same as in the previous subvolumes. The use of two systems of units illustrates the situation in magnetic research today, where conversion from CGS units to SI units and vice versa has to be frequently performed. A list of conversion factors is reproduced in the front cover for the reader's convenience.

The index of substances at the end of this subvolume contains all substances treated in volumes III/4a, b and III/12a, b, c and will help the user to identify quickly the information on the individual substances he is looking for.

We wish to thank the authors for their painstaking work and the good cooperation, the Landolt-Börnstein office, especially Dr. W. Polzin and Frau Rita Schattschneider, for their critical care in checking manuscripts, galleys and layout, and Springer Verlag for their usual attention in the publication. This subvolume is published without any financial support from other sources.

Darmstadt, October 1982

The Editors

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- 4 Spinels

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Symbols and units in the common unit systems

For more detailed lists, see p. 5, 52

Quantity		CGS-emu	SIU
P (P^*) [*]	magnetic moment	Gauss $\text{cm}^3 = \text{emu}$	A m^2 (V s m)
M (J) [*]	magnetic moment per unit volume = magnetization (magnetic polarization)	Gauss	A/m (V s/m^2)
σ	magnetic moment per unit mass	Gauss cm^3/g	$\text{A m}^2/\text{kg}$ (V s m/kg)
σ_m	magnetic moment per mole	Gauss cm^3/mole	$\text{A m}^2/\text{mole}$ (V s m/mole)
p_m	magnetic moment per molecule	Bohr magneton $\mu_B = \frac{e\hbar}{2mc}$	Bohr magneton $\mu_B = \frac{e\hbar}{2m}$ $(\mu_B = \frac{\mu_0 e\hbar}{2m})$
p_A	magnetic moment per atom	μ_B	μ_B
p_{eff}	effective magnetic moment ($= 2.83^{**})\sqrt{C_m}$ (CGS)) ($= 797.6^{**})\sqrt{C_m}$ (SIU))	μ_B	μ_B
χ	susceptibility	$\text{cm}^3 = \text{emu}$	m^3
χ_v	volume susceptibility	$\text{cm}^3/\text{cm}^3 = 1$	$\text{m}^3/\text{m}^3 = 1$
χ_g	specific (or mass) susceptibility	cm^3/g	m^3/kg
χ_m	molar susceptibility	cm^3/mole	m^3/mole
χ_A	susceptibility per gram-atom	$\text{cm}^3/\text{g-atom}$	$\text{m}^3/\text{g-atom}$
C_m	Curie constant per mole	$\text{K cm}^3/\text{mole}$	$\text{K m}^3/\text{mole}$
C_A	Curie constant per gram-atom	$\text{K cm}^3/\text{g-atom}$	$\text{K m}^3/\text{g-atom}$

^{*} In SI units there are two ways to define the magnetic counterpart of the dielectric polarization: $\mathcal{P} = D - \epsilon_0 E$; the magnetization $M = B/\mu_0 - H$, or the magnetic polarization $J = B - \mu_0 H$ with $J = \mu_0 M$. The magnetic moments are related correspondingly: $P^* = JV = \mu_0 MV = \mu_0 P$.

^{**} The numerical factors are of the dimension $(\text{K emu/mole})^{-1/2} = (\text{K cm}^3/\text{mole})^{-1/2}$ for CGS-emu, and $(\text{K m}^3/\text{mole})^{-1/2}$ for SI units.

T	temperature	$^{\circ}\text{C}, \text{K}$	Θ_D	Debye temperature
T_C	Curie temperature, ferri-, ferromagnetic		Θ_P	paramagnetic Curie temperature
T_N	Néel temperature, antiferromagnetic		ρ	density $\text{g cm}^{-3} = 10^3 \text{ kg m}^{-3}$
			(M)	molecular weight $\text{g mole}^{-1} = 10^{-3} \text{ kg mole}^{-1}$

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5 Hexagonal ferrites

5.0 Introduction*)

Since the discovery in 1951 of the, technically, very important magnetic properties of the ferrite $\text{BaFe}_{12}\text{O}_{19}$ with hexagonal crystal structure, many related compounds have been synthesized, and the properties of these mostly completely new structures have been investigated. At room temperature the magnetic moments of most of these compounds can be ordered in groups in such a way that the magnetic moments of the ions of one group are mutually parallel oriented, whereas the magnetic moments of the ions of different groups are oriented antiparallel to each other. Such an incompletely compensated antiferromagnetism was called ferrimagnetism by Néel, who was the first to describe this type of magnetism in order to explain the magnetization of ferrites with spinel structure [48N]. The technical interest in the oxides with hexagonal crystal structure is shown by the fact that some of these materials show a very high uniaxial magnetic anisotropy, so that they can be used as a ceramic permanent magnetic material which for some applications can compete technically, and economically, with the metallic permanent magnets of the AlNiCo-type. Other hexagonal ferrites have interesting properties as magnetic cores at frequencies above about 100 MHz. In electronic equipments for microwaves, single crystals and polycrystalline samples of hexagonal ferrites with still other chemical compositions are used successfully, because of their exceptionally high internal magnetic field, or because of the non-linear effects which appear at already relatively low amplitude of the high frequency field. For the h.f. applications it is essential that these semi-conducting ferrites can be prepared in such a way that their conductivity at room temperature is very low.

The chemical compositions and the crystal structures of the hexagonal ferrites show many similarities, and they are reviewed in sections 7.3 and 7.4 of volume III/4b. Section 5.5 (7.5 in vol. III/4b) includes the paramagnetic properties of the hexagonal ferrites while sections 5.6...5.10 (7.6...7.10 in vol. III/4b) deal with the properties of the compounds of each crystal structure separately. Because of the various uncertainties regarding the crystal structures of the calcium ferrites and the substituted calcium ferrites, the properties of these ferrites are given separately in section 5.11 (7.11 in vol. III/4b).

In sections 5.12...5.14, properties of some hexagonal ferrites of increasing significance are to be found which have been taken out of the above mentioned sections and arranged into groups. Apart from this, further hexagonal ferrites which do not belong to the above mentioned sections are listed in section 5.15.

5.1 Quantities and units

In today's literature the magnetic properties are discussed in the SIU (Système International d'Unités) or in units of the cgs-emu $\equiv$ electromagnetic cgs system. Therefore, and contrary to vol. III/4b, in tables and figures of this volume, the various quantities are given in cgs-emu or in SI units, i.e. in the units as used in the original papers. In this section 5.1., however, equations are given in both, cgs-emu and SIU system, in the second case indicated by a light shade, though in the original papers from which some equations have been taken, only the electromagnetic cgs system has been used. The relation between the magnetic induction, B , the magnetic field strength, H , and the magnetization, M , is given by

$$B = H + 4\pi M; \quad B = \mu_0(H + M). \quad (1)$$

a) Conductivity

The temperature-dependence of the conductivity σ of hexagonal ferrites can usually be described by the equation:

$$\sigma = \sigma_{\infty} e^{-q/kT} \quad (2)$$

where the activation energy q is probably a measure for the increase of the mobility of the negative charge carriers with increasing temperature.

b) Magnetic moment

Ferrites have mostly been obtained by a sintering process, so that the samples show a certain porosity. The overall density of the sample is then lower than the X-ray density of the compound. The saturation magnetization therefore is often not expressed as a magnetic moment per unit volume M_s , or $4\pi M_s$ (SIU: M_s), but rather as a specific saturation magnetization per gram of the substance, σ_s . The relation between both quantities is given by:

$$M_s = \sigma_s \rho; \quad M_s = \sigma_s \rho \quad (3)$$

*) With kind permission of H. P. J. Wijn sections 5.0 and 5.1 have been essentially taken from Volume III/4b.

where ρ denotes the density of the porous sample. The specific saturation magnetization at 0 K, σ_s^0 , is a measure of the magnetic moment p_m per molecule of the substance. The quantity p_m is usually expressed in number of Bohr magnetons according to the equation:

$$\frac{p_m}{\mu_B} = \frac{(M_A)}{N_A \mu_B} \cdot \sigma_s^0; \quad \frac{p_m}{\mu_B} = \frac{(M_A)}{N_A \mu_B} \cdot \sigma_s^0 \quad (4)$$

where (M_A) is the molar mass of the substance A, N_A the number of molecules per mole (Avogadro number) and μ_B the Bohr magneton:

$$N_A = 6.02 \cdot 10^{23} \text{ mole}^{-1},$$

$$\mu_B = \frac{e\hbar}{2mc} = 9.27 \cdot 10^{-21} \text{ erg Gauss}^{-1};$$

$$\mu_B = \frac{e\hbar}{2m} = 9.27 \cdot 10^{-24} \text{ A m}^2$$

and

$$N_A \mu_B = 5580.5 \text{ erg Gauss}^{-1};$$

$$N_A \mu_B = 5.580 \text{ A m}^2 \text{ mole}^{-1}.$$

c) Magneto-crystalline anisotropy of hexagonal crystals

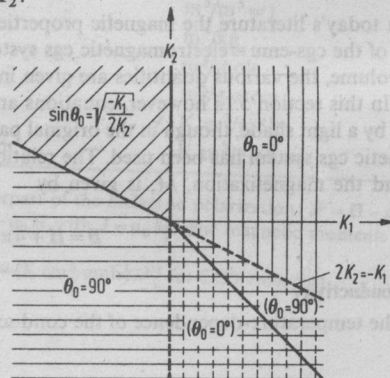
Because of the symmetry of the hexagonal crystal lattice, the magneto-crystalline anisotropy energy density is given by the equation:

$$w_k = K_1 \sin^2 \theta + K_2 \sin^4 \theta + K_3 \sin^6 \theta + K_3 \sin^6 \theta \cos 6(\phi + \psi). \quad (5)$$

The angles θ and ϕ are polar coordinates and the constants K_i are the coefficients of the magneto-crystalline anisotropy. The phase angle ψ is zero for a particular choice of the axis of the coordinate system. The term with the coefficient K_3 can usually be neglected. In cases where the term with K_1 is predominant, the spontaneous magnetization is oriented parallel to the c -axis for $K_1 > 0$, the crystal has a so-called preferential direction of magnetization. For $K < 0$, the spontaneous magnetization is oriented perpendicular to the c -axis, the crystal has a so-called preferential plane of magnetization. In general the angle θ_0 between the direction of the spontaneous magnetization and the c -axis is a function of K_1 and K_2 , as illustrated in Fig. A. In cases where $0 < \theta_0 < 90^\circ$ the crystal shows a preferential cone for the spontaneous magnetization with a vertex $2\theta_0$, which is given by the equation:

$$\sin \theta_0 = \sqrt{-K_1/2K_2}. \quad (6)$$

Fig. A. The relation between the preferential direction of the magnetization vector in a hexagonal crystal and the corresponding values of the magneto-crystalline anisotropy coefficients K_1 and K_2 . For $\theta_0 = 0$ the c -axis is the preferential direction, for $\theta_0 = 90^\circ$ the basal plane is the preferential plane for the magnetization. In the sector of the diagram for which $\sin \theta_0 = \sqrt{-K_1/2K_2}$ all directions of the magnetization which make an angle of θ_0 with the c -axis of the crystal have the lowest energy (preferential cone for the magnetization). In the region $-2K_2 > K_1 > 0$ the spontaneous magnetization has metastable orientations [59CSEF].



The magneto-crystalline anisotropy field strength H^A is defined as the effective field strength that causes the same stiffness for a rotation of the magnetization over a small angle out of its preferential direction as the magneto-crystalline anisotropy does. In the case of a rotation with constant angle ϕ we get:

$$H_\theta^A = (1/M_s) (\partial^2 w_k / \partial \theta^2)_{\phi = \text{const}}; \quad H_\theta^A = (1/\mu_0 M_s) (\partial^2 w_k / \partial \theta^2)_{\phi = \text{const}} \quad (7)$$

so that for

$$\theta_0 = 0: \quad H_\theta^A = H^A = 2K_1/M_s; \quad H^A = 2K_1/\mu_0 M_s, \quad (7a)$$

$$\theta_0 = 90^\circ: \quad H_\theta^A = -(K_1 + K_2)/M_s; \quad H_\theta^A = -(K_1 + K_2)/\mu_0 M_s, \quad (7b)$$

$$\sin \theta_0 = \sqrt{-K_1/2K_2}: \quad H_\theta^A = 2(K_1/K_2)(K_1 + 2K_2)/M_s; \quad H_\theta^A = 2(K_1/K_2)(K_1 + 2K_2)/\mu_0 M_s. \quad (7c)$$

The effective anisotropy field strength for a rotation of the magnetization out of its equilibrium orientation along the surface of the preferential cone is given by:

$$H_{\phi}^A = (1/M_s \sin^2 \theta_0) (\partial^2 w_k / \partial \phi^2)_{\phi=0} = 36 |K_3| \sin^4 \theta_0 / M_s; \quad (8)$$

$$H_{\phi}^A = (1/\mu_0 M_s \sin^2 \theta_0) (\partial^2 w_k / \partial \phi^2)_{\phi=0} = 36 |K_3| \sin^4 \theta_0 / \mu_0 M_s.$$

d) Linear magnetostriction of a hexagonal crystal

According to [61G] the linear magnetostriction of a hexagonal crystal is given by the equation:

$$\lambda = \Delta l/l = k_0 + k_0^*(\beta_3^2 - \frac{1}{3}) + k_1(\alpha_3^2 - \frac{1}{3}) + k_2(\alpha_3^2 - \frac{1}{3})(\beta_3^2 - \frac{1}{3}) + k_3\{(\alpha_1\beta_1 + \alpha_2\beta_2)^2 - \frac{1}{2}(\alpha_1^2 + \alpha_2^2)(\beta_1^2 + \beta_2^2)\} + 2k_4\alpha_3\beta_3(\alpha_1\beta_1 + \alpha_2\beta_2) + \dots + k_0'H + k_0''H(\beta_3^2 - \frac{1}{3}) + \dots \quad (9)$$

where β_i indicate the direction in which the magnetostriction $\Delta l/l$ is measured and α_i are the direction cosines of the magnetization; α_3 and β_3 are the direction cosines with respect to the c -axis of the hexagonal crystal.

e) Ferromagnetic resonance in hexagonal crystals

The general equation for the ferromagnetic resonance frequency f_{res} for a magnetization M related to a preferential direction in the polar coordinates (θ and ϕ) is given by:

$$2\pi f_{\text{res}} = (\gamma/M \sin \theta) (w_{\theta\theta} w_{\phi\phi} - w_{\theta\phi}^2)^{1/2};$$

$$2\pi f_{\text{res}} = (\gamma/M \sin \theta) (w_{\theta\theta} w_{\phi\phi} - w_{\theta\phi}^2)^{1/2} \quad (10)$$

where $w(\theta, \phi)$ is the direction-dependent energy density of the magnetization [55SB]. The gyromagnetic ratio γ is given by

$$\gamma = g_{\text{eff}} \frac{\mu_B}{\hbar} = g_{\text{eff}} \frac{e}{2mc}; \quad \gamma = g_{\text{eff}} \frac{\mu_B}{\hbar} = g_{\text{eff}} \frac{e}{2m} \quad (11)$$

where g_{eff} is the effective Landé spectroscopic splitting factor for two or more sublattices and m is the electron mass. For the application of the general equation (10) two cases have to be considered:

I. Hexagonal crystal with preferential direction of magnetization parallel to the c -axis.

a) When a d.c.-magnetic field strength H is applied parallel to the preferential direction eq. (10) yields to the resonance equation first given by Kittel [48K]:

$$2\pi f_{\text{res}} = \gamma [(H + H^A) + (N_x - N_z) M]^{1/2} \cdot [(H + H^A) + (N_y - N_z) M]^{1/2};$$

$$2\pi f_{\text{res}} = \gamma \mu_0 [(H + H^A) + (N_x - N_z) M]^{1/2} \cdot [(H + H^A) + (N_y - N_z) M]^{1/2} \quad (12)$$

Here N_z is the demagnetization factor in the direction of the c -axis and N_x and N_y are the demagnetization factors in the other two directions of the orthogonal coordinate system.

b) For an a.c. magnetic field oriented perpendicular to the c -axis, i.e. in the case where $H \perp H^A$ the eq. (10) gives according to [55SB]:

$$2\pi f_{\text{res}} = \gamma \left[1 - \frac{(N_y - N_x) M}{H^A - (N_z - N_y) M} \right]^{1/2} \cdot [H^A - (N_z - N_y) M]^2 - H^2]^{1/2};$$

$$2\pi f_{\text{res}} = \gamma \mu_0 \left[1 - \frac{(N_y - N_x) M}{H^A - (N_z - N_y) M} \right]^{1/2} \cdot [H^A - (N_z - N_y) M]^2 - H^2]^{1/2} \quad (13a)$$

for

$$H \leq H^A - (N_z - N_y) M, \quad H \leq H^A - (N_z - N_y) M,$$

$$H^A > 4\pi M; \quad H^A > M$$

and

$$2\pi f_{\text{res}} = \gamma [H - (N_y - N_x) M]^{1/2} \cdot [H - \{H^A - (N_z - N_y) M\}]^{1/2};$$

$$2\pi f_{\text{res}} = \gamma \mu_0 [H - (N_y - N_x) M]^{1/2} \cdot [H - \{H^A - (N_z - N_y) M\}]^{1/2} \quad (13b)$$

for

$$H \geq H^A - (N_z - N_y) M,$$

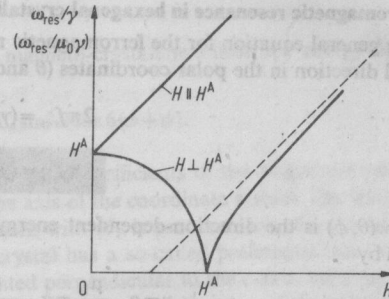
$$H \geq H^A - (N_z - N_y) M,$$

$$H^A > 4\pi M;$$

$$H^A > M.$$

Fig. B shows the graphs for the eqs. (12), (13a) and (13b) for the cases where demagnetizing fields do not appear.

Fig. B. The angular frequency for ferromagnetic resonance, ω_{res} , as a function of the external magnetic field strength H parallel or perpendicular to the preferential direction for the magnetization (c -axis) of a crystal with hexagonal symmetry [59SW].



II. Hexagonal crystals with planar anisotropy.

a) When the magnetic field strength H is oriented parallel to the y -direction in the preferential plane, which will also be the xy -plane, of the orthogonal system the resonance frequency given by (10) is as follows:

$$2\pi f_{\text{res}} = \gamma [H - (N_y - N_x) M]^{1/2} \cdot [H + H_\theta^A + (N_z - N_y) M]^{1/2};$$

$$2\pi f_{\text{res}} = \gamma \mu_0 [H - (N_y - N_x) M]^{1/2} \cdot [H + H_\theta^A + (N_z - N_y) M]^{1/2} \quad (14)$$

If only magneto-crystalline energy is considered, according to [59BK] this equation reduces to:

$$2\pi f_{\text{res}} = \gamma \left[H + \frac{2K_1}{M} - \frac{6K_4}{M} \right]^{1/2} \left[H \pm 36 \frac{K_4}{M} \right]^{1/2}; \quad (14a)$$

$$2\pi f_{\text{res}} = \gamma \mu_0 \left[H + \frac{2K_1}{\mu_0 M} - \frac{6K_4}{\mu_0 M} \right]^{1/2} \left[H \pm 36 \frac{K_4}{\mu_0 M} \right]^{1/2}$$

where the minus and the plus signs in the second factor correspond to an unstable and a stable equilibrium orientation of the magnetization in the plane, respectively, and K_4 is another constant in the serial development of the anisotropy energy.

b) For a magnetic field parallel to the direction for difficult magnetization (c -axis) the resonance frequency is given by:

$$2\pi f_{\text{res}} = \gamma [(H - H_\theta^A) - (N_z - N_x) M]^{1/2} [(H - H_\theta^A) - (N_z - N_y) M]^{1/2}; \quad (15)$$

$$2\pi f_{\text{res}} = \gamma \mu_0 [(H - H_\theta^A) - (N_z - N_x) M]^{1/2} [(H - H_\theta^A) - (N_z - N_y) M]^{1/2}$$

for

$$H > H^A + N_z M,$$

$$H > H^A + N_z M.$$

In the derivation of eqs. (14) and (15) the anisotropy field strength H_0^A is neglected with respect to H and H_0^A since it is usually lower by several orders of magnitude. In the special case where only magneto-crystalline energy has to be considered, [59BK], the eq. (15) reduces to:

$$2\pi f_{\text{res}} = \gamma H^{1/2} \left(H - \frac{2K_1}{M} - \frac{4K_2}{M} - \frac{6K_3}{M} \right)^{1/2};$$

$$2\pi f_{\text{res}} = \gamma \mu_0 H^{1/2} \left(H - \frac{2K_1}{\mu_0 M} - \frac{4K_2}{\mu_0 M} - \frac{6K_3}{\mu_0 M} \right)^{1/2}$$

(15a)

5.2 List of symbols and abbreviations

a) Symbols

a, c [Å]	lattice parameters
B [G]	magnetic induction
$(BH)_{\text{max}}$ [G · Oe]	maximum energy product of permanent magnetic materials
d [mm]	crystal thickness
f [Hz]	frequency
f_{res} [Hz]	resonance frequency
H [A m ⁻¹], [Oe]	magnetic field strength
H^A [Oe]	magnetocrystalline anisotropy field strength
H_c [Oe]	coercive field strength for magnetization
K_i [erg cm ⁻³]	magnetocrystalline anisotropy constant
M [A m ⁻¹], [Oe]	magnetization
μ_{ms} [μ_B]	saturation magnetic moment (per formula unit)
μ_0 [μ_B]	spontaneous magnetic moment (per formula unit)
q [eV]	activation energy
$\frac{\Delta R}{R}$	reluctance
S [VK ⁻¹]	Seebeck coefficient
T [°C], [K]	temperature
T_c [°C]	Curie temperature
T_N [K]	Néel temperature
$\tan \delta$	dielectric loss factor
$\epsilon = \epsilon' - i\epsilon''$	complex dielectric constant
Θ_p [K]	paramagnetic Curie temperature
λ	magnetostriction constant
$\mu = \mu' - i\mu''$	complex magnetic permeability
μ_i	initial magnetic permeability
ρ [Ω cm]	resistivity
ρ_x [g cm ⁻³]	X-ray density
σ [Ω^{-1} cm ⁻¹]	electrical conductivity
σ [G cm ³ g ⁻¹]	specific magnetization
σ_s [G cm ³ g ⁻¹]	specific saturation magnetization
$\chi = \chi' - i\chi''$	complex magnetic susceptibility
χ_g [cm ³ g ⁻¹]	susceptibility per gram
χ_m [cm ³ mole ⁻¹]	susceptibility per mole
ω [rad s ⁻¹]	angular frequency

b) Abbreviations

d.c.	direct current
FMR	ferromagnetic resonance
Me, M	metal
NMR	nuclear magnetic resonance

Note: In this contribution figure and table numbers which refer to Vol. III/4b are characterized by an asterisk.

5.3 Chemical compositions and phase diagrams of hexagonal ferrites

(See Vol. III/4b, p. 555).

5.4 Crystal structures

(See Vol. III/4b, p. 557).

5.5 Paramagnetic properties of ferrites with hexagonal crystal structure

Table 1. (See also Vol. III/4b, Table 3* and Figs. 16*...19*, p. 561).

Compound	Ref.	Remarks	Fig.
BaFe ₁₂ O ₁₉ BaZn _x Ti _x Fe _{12-2x} O ₁₉	73F 70DWA	theoretical χ of ferrimagnet with five sublattices χ''/χ'_0 vs. H for $x=2.25$ at 295 K	
PbFe ₁₂ O ₁₉	66ABB		1
SrFe ₁₂ O ₁₉ SrAl _x Fe _{12-x} O ₁₉ SrCr _{3.2} Fe _{8.8} O ₁₉	70BKMG 73FPG 69BKM 70BK, 70BKMG	anisotropy of χ $1/\chi$ vs. T for different x , Néel parameters anisotropy of χ anisotropy of χ	2

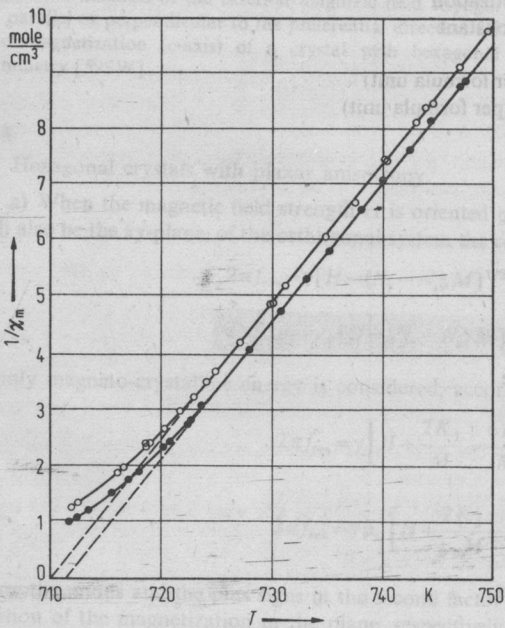


Fig. 1. PbFe₁₂O₁₉. The inverse of the molar susceptibility, $1/\chi_m$, vs. temperature, T . Open circles: measured $\parallel$ to the c -axis; full circles: measured $\perp$ to the c -axis [66ABB].

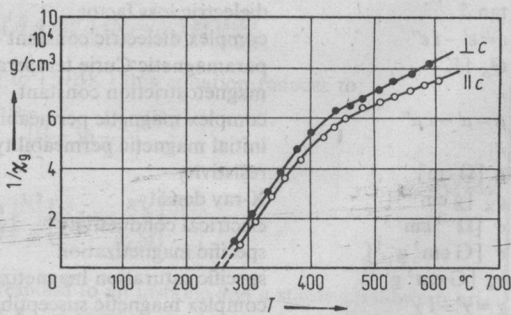


Fig. 2. SrCr_{3.2}Fe_{8.8}O₁₉. Temperature dependence of the paramagnetic inverse susceptibility per gram, $1/\chi_g$, vs. temperature, T , along the c -axis ($\parallel$) and in the basal plane ($\perp$) [69BKM].

5.6 M(magnetoplumbite)-type ferrites

5.6.1 Survey of the chemical substitution in the M structure and room temperature lattice constants

Table 2. Survey of the chemical substitution in the M structure. (See also Vol. III/4b, Table 4*, p. 562 and Figs. 20*...23*, p. 564).

Compound	c Å	a Å	Ref.	Remarks	Properties	
					Tables	Fig.
BaFe ₁₂ O ₁₉			71GS	addition of rare-earth	1, 3, 4, 5, 6, 7, 8	3, 13, 20, 21, 22, 23
BaAl _x Fe _{12-x} O ₁₉			68BS-3 70VZ 71HK-2	see Fig. 20*, 21* see Fig. 20*, 21*	4, 5, 6, 7	5, 9, 15
BaAs _x Fe _{12-x} O ₁₉			73KG 74EK-1 75EK-1	<i>M</i> H _c , <i>σ</i> vs. <i>T</i>	4	
BaCr _x Fe _{12-x} O ₁₉ Ba _{1-x} D _x Fe _{12-x} P _x O ₁₉			71KH 74G	see Fig. 20*, 21* <i>σ</i> vs. <i>T</i> D = K ¹⁺ , Bi ³⁺ , P = Cu ²⁺ , Ni ²⁺ , Mn ⁴⁺ , Zn ²⁺ , Ti ⁴⁺	4, 5, 6 4	4, 10, 15
BaGa _x Fe _{12-x} O ₁₉ BaGa ₂ Sc _{1.2} Fe _{8.8} O ₁₉ BaIn _x Fe _{12-x} O ₁₉	23.63	5.95	73HK-1 73ACCY 70EM 71KH 71PVZS 71VZ		4, 5, 6 4 4, 5, 7	15 4, 5, 10, 11
BaIn _{3.4} Fe _{8.6} O ₁₉ Ba _{1-x} Pb _x Fe ₁₂ O ₁₉ Ba _x Pb _y Sr _{1-(x+y)} Fe ₁₂ O ₁₉ BaSb _x Fe _{12-x} O ₁₉	23.790	6.000	72ALNY 74AFS 76MMO-1 72EK 75EK-1 75EK-2 74L		4 4 4, 5 5	12
BaSb _{0.5} ⁵⁺ Fe _{1.0} ²⁺ Fe _{10.5} ³⁺ O ₁₉ BaSc _x Fe _{12-x} O ₁₉			69AY 69ASYL 71VZ		4, 5	5, 17
BaSc _{1.5} Fe _{10.5} O ₁₉ Ba _x Sr _{1-x} Fe ₁₂ O ₁₉ Ba _{0.75} Sr _{0.25} Fe ₁₂ O ₁₉			71PSSF 69JMF 70WK	admixture of B ₂ O ₃ , Al ₂ O ₃ , Ga ₂ O ₃	4 4, 5 4	
Ba _{1-y} Sr _y Al _x Fe _{12-x} O ₁₉ BaTi _{0.6} Fe _{0.6} ²⁺ Fe _{10.8} ³⁺ O ₁₉ BaTi _x Co _x Fe _{12-2x} O ₁₉ BaTi ₂ Co ₂ Fe ₈ O ₁₉ Ba(Ti, Ni) _x Mn _y Al _z Fe _{12-x-(y+z)} O ₁₉ BaZn _{1/2x} Ge _{1/2x} Fe _{12-x} O ₁₉ BaZn _{2/3x} Nb _{1/3x} Fe _{12-x} O ₁₉ BaZn _{2/3} Ta _{1/3} Fe ₁₁ O ₁₉ BaZn _x Ti _x Fe _{12-2x} O ₁₉ BaZnTiMnFe ₉ O ₁₉			68BS-3 74L 76KG 73BKSZ 69D 71KH 71KH 71KH 72MTS-2 73MASE	<i>a</i> vs. <i>x</i> , <i>y</i>	4 5 4, 5, 7 4 7 4 4 4 1, 7 4, 5	19 4, 10 4, 10, 13 13

continued