5f. Magnetic Properties of Materials

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5f-1. Types of Magnetism and Some Formulas.[2] *Diamagnetism.* Substances whose magnetic susceptibility

$$\chi = \frac{M}{H}$$

is negative are called diamagnetic. The Langevin-Pauli formula for the diamagnetic susceptibility of an atom is [1]

$$\chi = -\frac{Ne^2}{6mc^2}\sum \bar{r}^2$$

where $\bar{r}^2$ is the mean-square distance of the electron from the nucleus, and the summation is over all the electrons in the atom.

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[1] Section on properties of paramagnetic salts.

[2] Contributed by D. F. Bleil, U.S. Naval Ordnance Laboratory.

Paramagnetism. Substances whose magnetic susceptibility is positive are called paramagnetic. Langevin made a classical statistical analysis of an ensemble of dipole moments in thermal equilibrium in a magnetic field. The magnetization is given by

$$M = N\mu L\left(\frac{\mu H}{kT}\right)$$

where N is the number of atoms per unit volume and μ is their dipole moment. The Langevin function for $\chi = \mu H/kT$ is

$$L(x) = \operatorname{ctnh} x - \frac{1}{x}$$

If $\mu H \ll kT$, the Langevin formula reduces to the Curie law

$$\chi = \frac{N\mu^2}{3kT} = \frac{C}{T}$$

Introduction of the quantum theory into the statistics for atoms with total angular momentum quantum number J gives

$$M = NgJ\beta B_J\left(\frac{gJ\beta H}{kT}\right)$$

where g is the Landé factor, β (also μ_B) is the Bohr magneton, $eh/4\pi mc = 0.927 \times 10^{-20}$ erg/oersted, and the Brillouin function is

$$B_J(x) = \frac{2J+1}{2J}\operatorname{ctnh}\frac{2J+1}{2J}x - \frac{1}{2J}\operatorname{ctnh}\frac{x}{2J}$$

When the argument of the ctnh is much less than one, the susceptibility becomes

$$\chi = NJ(J+1)\frac{g^2\beta^2}{3kT}$$

Note. The above equations were derived on the assumption that the atoms are free and therefore they apply, in general, only to solids which are magnetically "dilute." For details, see Van Vleck [1].

Ferromagnetism. Ferromagnetic substances are characterized by the onset of a spontaneous magnetization (in a zero applied field) at temperatures for which $T < T_C$ where T_C is called the Curie temperature.

MOLECULAR FIELD (Modified Weiss). Consider the magnetic field applied to the dipoles in the Brillouin function to consist of the applied field H_a plus an internal field which is proportional to the magnetization. The effective field is

$$H_e = H_a + \gamma M$$

where γ is the molecular field coefficient. The magnetization is $M = NgJ\beta B_J(x) = M_0 B_J(x)$ where M_0 is the moment at 0 K, and when

$$x = \frac{gJ\beta H_e}{kT} \ll 1$$

$$M = \frac{Ng^2J(J+1)\beta^2 H_e}{3kT}$$

A nonvanishing solution for M exists for $H_a = 0$ when $T \leq T_C$, where

$$T_C = \frac{Ng^2\beta^2\gamma J(J+1)}{3k}$$

Combining the above equations to get a temperature function for the argument of $B_J(x)$ for $H_a = 0$, we have

$$x = \frac{3J}{J+1}\,\frac{M/M_0}{T/T_C}$$

For $T > T_C$ the susceptibility is

$$\chi = \frac{M}{H_a} = \frac{g\beta M_0(J+1)}{3k(T-T_C)} = \frac{C}{T-T_C}$$

This equation is called the *Curie-Weiss law.* It is usually written

$$\chi = \frac{C}{T-\theta}$$

where θ, called the *paramagnetic intercept* (Curie point), is found by experiment to be slightly larger than T_C when $T \gg T_C$ (see Sec. 5f-14). Many solids obey a Curie-Weiss law.

HEISENBERG EXCHANGE COUPLING. Heisenberg replaces[1] the molecular field assumption with the idea that the interaction between a pair of atoms i and j has the form

$$V_{ij} = -2\mathcal{J}\mathbf{S}_i \cdot \mathbf{S}_j$$

where $\mathbf{S}_i$ and $\mathbf{S}_j$ are quantum-mechanical spin operators, and $\mathcal{J}$ is the exchange energy. This problem has not been solved exactly; the most usual approximations are to consider interactions only between nearest neighbors and to assume that all states of the crystal with the same total spin have the same energy. For these approximations, the Heisenberg results can be taken over directly into the molecular field form from the preceding paragraph, with the following substitutions:

$$\mu \rightarrow g\beta S \qquad \mu^2 \rightarrow g^2\beta^2 S(S+1)$$
$$\gamma \rightarrow \frac{2z|\mathcal{J}|}{Ng^2\beta^2}$$

where z is the number of nearest neighbors of a given atom. For those atoms for which $L \neq 0$, $S(S+1)$ is replaced by $J(J+1)$. These procedures and results usually go by the name of the "first Heisenberg approximation." The literature (see Van Vleck [1] and Smart [3]) should be consulted for information about other approximate solutions of the spin-operator problem.

Antiferromagnetism (Molecular Field). Antiferromagnetic substances are those in which the magnetic ions can be divided into equivalent sublattices which become spontaneously magnetized in an antiparallel arrangement below some temperature T_N. The antiparallel alignment occurs because of a large negative exchange integral. Van Vleck[2] considered two simple interpenetrating cubic lattices and nearest-neighbor interactions. Call one sublattice A and the other B. The effective field on an ion of lattice A is due to the ions of B; thus

$$H_{eA} = H_a - 2\gamma M_B$$
$$H_{eB} = H_a - 2\gamma M_A$$

where γ is the same as in the ferromagnetic case except that each sublattice has $N/2$ (see Smart [3]) and $\mathcal{J}$ is now negative. The susceptibility for $T > T_N$ is

$$\chi = \frac{Ng^2\beta^2 J(J+1)}{3k(T+\theta)} = \frac{C}{T+\theta}$$

where $\theta = cT_N$, and $c = 1$ for the simple model.[3] The susceptibility below the Néel temperature for this simple model consists of two parts, the susceptibility parallel ($\chi_\parallel$) and perpendiculare ($\chi_\perp$) to the antiferromagnetic axis. $\chi_\parallel$ decreases and becomes

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[1] W. Heisenberg, *Z. Physik* **49**, 619 (1928).

[2] J. H. Van Vleck, *J. Chem. Phys.* **9**, 85 (1941).

[3] For other models see J. Samuel Smart, *Phys. Rev.* **86**, 968 (1952); see also ref. 3.

zero as $T \rightarrow 0$; thus the susceptibility at absolute zero for a polycrystalline solid is

$$\chi_{T=0} = \tfrac{2}{3}\chi_{T=T_N}$$

Ferrimagnetism (Molecular Field). Ferrimagnetic substances are those in which the magnetic ions can be divided into nonequivalent sublattices which become spontaneously magnetized in an antiparallel arrangement below some temperature T_C. A ferrite, i.e., $NiFe_2O_4$, is used as an example. It is a spinel structure having a close-packed cubic oxygen lattice in which there are 8 tetrahedral and 16 octahedral sites occupied by magnetic ions. The sites are labeled A and B, respectively. Néel,[1] using the molecular field theory, gave the effective fields at the A and B sites as

$$H_A = H_a + \gamma_{AA}M_A - \gamma_{AB}M_B$$
$$H_B = H_a - \gamma_{AB}M_A + \gamma_{BB}M_B$$

where

$$\gamma_{ij} = \frac{2z_{ij}\mathcal{J}_{ij}}{N_j g^2\beta^2}$$

z_{ij} is the number of nearest neighbors on the j sublattice to an atom on the i sublattice, $\mathcal{J}_{ij}$ is the exchange coupling between the electrons of those atoms, and N_j is the total number of magnetic ions on the j sublattice.

For $T > T_C$,

$$\chi = \frac{C}{T - T_C}\,\frac{T - \theta'}{T - T_{C'}}$$

where

$$C = \frac{Ng^2\beta^2J(J+1)}{3k} \qquad \lambda = \frac{N_A}{N} \qquad \mu = \frac{N_B}{N}$$
$$T_C = \tfrac{1}{2}C[\lambda\gamma_{AA} + \mu\gamma_{BB} + \sqrt{(\lambda\gamma_{AA} - \mu\gamma_{BB})^2 + 4\lambda\mu_{AB}{}^2]}$$
$$T_C' = \tfrac{1}{2}C[\lambda\gamma_{AA} + \mu\gamma_{BB} - \sqrt{(\lambda\gamma_{AA} - \mu\gamma_{BB})^2 + 4\lambda\mu_{AB}{}^2]}$$
$$\theta' = \lambda\mu C(\gamma_{AA} + \gamma_{BB} + 2\gamma_{AB})$$

For $T < T_C$,

$$M_A = N_A g\beta J y_A \qquad M_B = N_B g\beta J y_B$$

where

$$y_A = B_J\left[\frac{Ng^2\beta^2J^2}{3kT}(\lambda\gamma_{AA}y_A - \mu\gamma_{AB}y_B)\right]$$
$$y_B = B_J\left[\frac{Ng^2\beta^2J^2}{3kT}(-\lambda\gamma_{AB}y_A + \mu\gamma_{BB}y_B)\right]$$

where $B_J(x)$ is the Brillouin function.

Gyromagnetic Ratio. The magnetic moment of an amperian current loop is proportional to its angular momentum,

$$\mathbf{u} = \frac{g'e}{2mc}\mathbf{j} = \gamma'\mathbf{j}$$

or summed over an entire body,

$$\mathbf{M} = \gamma'\mathbf{J}$$

where $\mathbf{J}$ is the total angular momentum corresponding to the magnetic moment $\mathbf{M}$. Both γ' and $g' = \dfrac{2mc}{e}\gamma'$ are called the "gyromagnetic ratio." They are more properly called the "magnetomechanical ratio." A change in either $\mathbf{J}$ or $\mathbf{M}$ produces a corresponding change in the other.

BARNETT[2] EFFECT. Change of magnetization by rotation.

EINSTEIN–DE HAAS[3] EFFECT. Change of rotation by magnetization.

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[1] L. Néel, *Ann. Phys.* **3**, 137 (1948).

[2] S. J. Barnett, *Revs. Modern Phys.* **7**, 129 (1935).

[3] A. Einstein and W. J. de Haas, *Verhandl. deut. physik. Ges.* **17**, 152 (1915).

Measurements of many ferromagnetic materials by these methods yield values of $g' \leq 2$, indicating that for them the electron spin is the predominant source of magnetism. For a free ion $g' = g$ (spectroscopic splitting factor), but in a crystalline field both g' and g may depart considerably from 2. When the orbital admixtures are not necessarily small, the relation[1]

$$g' = \frac{g}{g - \rho}$$

departs from the Kittel-Van Vleck relation for which $\rho = 1$. For substances where $\rho \neq 1$ see Smart [3] and Smit [5].

Spin Resonance. A substance with a magnetic moment in a static magnetic field H will absorb energy from an oscillating magnetic field of small intensity at right angles to the static field. The peak of the absorption curve occurs at the angular frequency

$$\omega = \frac{2\pi g \mu H}{h} = \gamma_r H$$

where

$$\gamma_r = \frac{ge}{2mc}$$

where μ is the appropriate unit for the magnetic moment, and g is the spectroscopic splitting factor.

PROTONS. μ is the nuclear magneton $\mu_P = eh/4\pi M_P c$, and $g = 5.58$.

$$\frac{\omega}{2\pi} = \nu(\text{kHz}) = 4.26H \text{ (oersteds)}$$

FREE ELECTRONS

$$\mu = \beta \qquad \text{and} \qquad g = 2$$
$$\nu\ (\text{MHz}) = 2.80H \text{ (oersteds)}$$

PARAMAGNETIC SALTS.[2] The equation of motion, treating the body as a whole, may be obtained[3] by the use of $\mathbf{M} = \gamma_r \mathbf{J}$, and the torque $d\mathbf{J}/dt = \mathbf{M} \times \mathbf{H}$,

$$\frac{d\mathbf{M}}{dt} = \gamma_r(\mathbf{M} \times \mathbf{H})$$

where the components of $\mathbf{H}$ are

$$H_x = 2H_1 \cos \omega t \qquad H_y = 0 \qquad H_z = \text{static field}$$

The amplitude of the oscillatory field is small compared with that of the static field, and the resonance frequency is

$$\omega_0 = \gamma_r H_z$$

FERROMAGNETIC RESONANCE. Kittel[4] has shown that the above equations hold for ferromagnetic resonance if all demagnetizing effects are included. For example, the resonance frequency becomes

$$\omega = \gamma (BH)^{\frac{1}{2}}$$

for a specimen in the form of a thin disk with the static field parallel to the disk.

ANTIFERROMAGNETIC RESONANCE. Above the Curie temperature, paramagnetic resonance is found. Below the Curie temperature, the effective field[5] becomes

$$H_{\text{eff}} = [H_A(2H_E + H_A)]^{\frac{1}{2}}$$

where H_A is the effective anistropy field of one sublattice, and H_E is the exchange field.

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[1] M. Blume, S. Geschwind, and Y. Yafet, Generalized Kittel–Van Vleck Relation between g and g'; Validity for Negative g-Factors, *Phys. Rev.* **181,** 478 (1969).

[2] For metals, see F. J. Dyson, *Phys. Rev.* **98,** 349 (1955).

[3] F. Bloch, *Phys. Rev.* **70,** 460 (1946).

[4] C. Kittel, *Phys. Rev.* **71,** 270 (1947); **73,** 155 (1948).

[5] C. Kittel, *Phys. Rev.* **82,** 565 (1951).

FERRIMAGNETIC RESONANCE. The individual sublattices must be considered in the resonance equation. An effective splitting factor[1] for the combined sublattices is given by

$$g_{\text{eff}}\frac{e}{2mc} = \frac{|\mathbf{M}|}{|\mathbf{S}|} = \frac{|\Sigma \mathbf{M}_i|}{|\Sigma(\mathbf{M}_i/\gamma_i)|}$$

where $\mathbf{M}_i$ is the magnetization of the individual sublattice, and $\gamma_i = g_i(e/2mc)$ describes its magnetomechanical ratio.

References

1. Van Vleck, J. H.: "The Theory of Electric and Magnetic Susceptibilities," Oxford University Press, New York, 1932.
2. Kittel, C.: "Introduction to Solid State Physics," 3d ed., John Wiley & Sons, Inc., New York, 1967.
3. Smart, J. S.: "Effective Field Theories of Magnetism," W. B. Saunders Company, Philadelphia, 1966.
4. Bozorth, Richard M.: "Ferromagnetism," D. Van Nostrand Company, Inc., Princeton, N.J., 1951.
5. Smit, J., and H. P. J. Wijn: "Ferrites," John Wiley & Sons, Inc., New York, 1959.

5f-2. Magnetic Properties of Elements

TABLE 5f-1. SATURATION MAGNETIZATION AND CURIE POINTS OF FERROMAGNETIC ELEMENTS*

Element	σ_s(20°C)	M_s(20°C)	σ_0(0 K)	n_B	$T_{C'}$ K	θ, K	T_N, K	μ_{eff}	Ref.
Fe	218.0	1,714	221.7	2.216	1043	1100	...	3.20	1,3
Co	161.8	1,422	162.5	1.72	1404	1415	...	3.15	2
Ni	54.39	484	58.57	0.616	631	650	...	1.61	3
Gd	.....	†	250	7	293	302	...	‡	
Tb	.....	.....	330	9	222	238	229		
Dy	.....	.....	350	10	85	159	179		
Ho	.....	.....	345	10	20	87	131		
Er	.....	.....	300	9	20	40	84		
Tm	......	.....	230	7	25	....	56		
Cr	......	.....	....	.....	.....	.....	475		
Mn	......	.....	....	.....	.....	.....	100		

* σ_s and σ_0 = saturation moments per gram
M_s = saturation moment per cm^3
n_B = number of Bohr magnetons per atom
Tc and θ = ferromagnetic and paramagnetic Curie points
T_N = Néel temperature
μ_{eff} = effective Bohr magneton number in the paramagnetic state

† Values of M_0 (M_s at 0 K) are 2,000 (Gd) to 3,000 (Ho) for the ferromagnetic rare earths, zero at 20°C; n_B is nearly the theoretical value of gJ (Table 5f-3) with an uncertain additional value of a few tenths of a unit.

‡ Values of μ_{eff} of the trivalent rare earths are nearly the theoretical ones given in Table 5f-3, except for Sm and Eu [4] and Yb.

References for Table 5f-1

1. Vogt, E.: "Landolt-Bornstein Tabellen," vol. II, part 9, p. 16, Springer-Verlag OHG, Berlin, 1962.
2. Myers, H. P., and W. Sucksmith: *Proc. Roy. Soc. (London)*, ser. A, **207**, 427 (1951).
3. Danan, H., A. Herr, and A. J. P. Meyer: *J. Appl. Phys.* **39**, 669 (1968); Crangle, J., and G. M. Goodman, *Bull. Am. Phys. Soc.* II, **15**, 269 (1970).
4. Van Vleck, J. H.: "Theory of Electric and Magnetic Susceptibilities," Clarendon Press, Oxford, 1932.

5f-3. Properties of Ferromagnetic Compounds. Tables 5f-4 and 5f-5 show respectively properties of binary compounds of iron group elements and of rare earth elements; Tables 5f-6 to 5f-8 list properties of pure spinel ferrites, of spinel ferrites containing $ZnFe_2O_4$, and of other ferrites; Table 5f-9 applies to garnet ferrites and Table 5f-10 to known weak ferromagnets of various compositions and structures.

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[1] R. K. Wangsness, *Phys. Rev.* **93**, 68 (1954).

TABLE 5f-2. RELATIVE SATURATION MAGNETIZATION σ_s/σ_0, AS DEPENDENT ON TEMPERATURE RELATIVE TO THE CURIE POINT T/T_C

$\frac{T}{T_c}$	σ_s/σ_0 observed		Molecular field theory												
	Fe	Co, Ni	$J = \frac{1}{2}$	1	$\frac{3}{2}$	2	$\frac{5}{2}$	3	$\frac{7}{2}$	4	$\frac{9}{2}$	6	$\frac{15}{2}$	8	∞
0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
0.1	0.996	0.996	1.000	1.000	1.000	1.000	1.000	1.000	1.000	0.999	0.999	0.998	0.996	0.995	0.965
0.2	0.99	0.99	1.000	0.999	0.998	0.997	0.994	0.992	0.989	0.986	0.984	0.977	0.971	0.969	0.928
0.3	0.975	0.98	0.997	0.993	0.987	0.980	0.974	0.967	0.962	0.957	0.952	0.941	0.933	0.931	0.887
0.4	0.95	0.96	0.986	0.973	0.960	0.949	0.938	0.929	0.922	0.915	0.910	0.897	0.888	0.885	0.841
0.45			0.974	0.957	0.941	0.927	0.915	0.905	0.897	0.890	0.884	0.871	0.862	0.860	0.816
0.5	0.93	0.94	0.958	0.937	0.918	0.901	0.889	0.878	0.870	0.862	0.856	0.843	0.834	0.831	0.789
0.55			0.936	0.911	0.889	0.872	0.858	0.848	0.839	0.831	0.825	0.812	0.803	0.800	0.759
0.6	0.90	0.90	0.907	0.879	0.856	0.838	0.824	0.813	0.804	0.796	0.790	0.777	0.768	0.766	0.726
0.65			0.872	0.841	0.817	0.798	0.784	0.773	0.764	0.757	0.751	0.738	0.729	0.727	0.689
0.7	0.85	0.83	0.829	0.796	0.771	0.753	0.739	0.728	0.719	0.712	0.706	0.694	0.686	0.684	0.647
0.75			0.776	0.742	0.717	0.699	0.686	0.675	0.667	0.660	0.655	0.643	0.635	0.633	0.600
0.8	0.77	0.73	0.710	0.678	0.654	0.636	0.624	0.614	0.606	0.600	0.595	0.584	0.577	0.575	0.545
0.85	0.70	0.66	0.630	0.599	0.576	0.561	0.549	0.540	0.533	0.528	0.523	0.514	0.507	0.506	0.479
0.9	0.61	0.56	0.525	0.498	0.479	0.465	0.454	0.448	0.442	0.438	0.434	0.426	0.420	0.419	0.397
0.95	0.40	0.40	0.379	0.359	0.344	0.334	0.327	0.322	0.317	0.314	0.311	0.305	0.302	0.301	0.285
1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Theoretical values as calculated by S. Smart, "Effective Field Theories of Magnetism," pp. 139–154, W. B. Saunders Company, Philadelphia, 1966; M. I. Darby, *Brit. J. Appl. Phys.* **18**, 1415 (1967); and private communication for $J > \frac{7}{2}$.

TABLE 5f-3. SOME ATOMIC CONSTANTS, AND PROPERTIES, OF RARE-EARTH ELEMENTS*

Elements	S	L	J	g	gJ	μ_{eff}	G	C_m	d, g/cm³	m.p., °C	b.p., °C
(Y)......	0	0	0	....	0	0	0	0	4.48	1509	
La.......	0	0	0	....	0	0	0	0	6.19	920	4200
Ce.......	0.5	3	2.5	6/7	15/7	2.535	5/28	0.804	6.77	795	2900
Pr.......	1	5	4	4/5	16/5	3.578	4/5	1.600	6.78	935	3020
Nd.......	1.5	6	4.5	8/11	36/11	3.618	81/44	1.636	7.00	1024	3180
Pm.......	2	6	4	3/5	12/5	2.683	16/5	0.900†	....	..	2700
Sm.......	2.5	5	2.5	2/7	5/7	0.845	125/28	0.089†	7.54	1072	1600
Eu.......	3	3	0	....	0	0	0	0†	5.26	826	1430
Gd.......	3.5	0	3.5	2	7	7.937	63/4	7.879	7.89	1312	2700
Tb.......	3	3	6	3/2	9	9.721	21/2	11.818	8.27	1356	2500
Dy.......	2.5	5	7.5	4/3	10	10.646	85/12	14.171	8.54	1407	2300
Ho.......	2	6	8	5/4	10	10.607	9/2	14.069	8.80	1461	2300
Er.......	1.5	6	7.5	6/5	9	9.581	51/20	11.481	9.05	1497	2600
Tm.......	1	5	6	7/6	7	7.561	7/6	9.149	9.33	1545	2100
Yb.......	0.5	3	3.5	8/7	4	4.536	9/28	2.573	6.98	824	1500
Lu.......	0	0	0	0	....	0	0	0	9.84	1652	1900

* S, L, and J = quantum numbers of trivalent rare-earth ions and usually apply to the elements
g = Landé factor
gJ = theoretical saturation in Bohr magnetons per atom
μ_{eff} = effective paramagnetic moment per atom
G = $(g-1)^2J(J+1)$, DeGennes factor
C_m = Curie constant per mole (see Sec. 5f-1)
d = density

† C_m, the theoretical Curie constant for trivalent atoms, is usually observed in the metals and compounds except for Sm and Eu and Yb.

Table 5f-4. Magnetic Moment and Curie Temperature of Some Binary Compounds

Compound	Structure (type)	T_C, K	n_B per magnetic atom	Refs.
Au_4Mn	bc tetr. (Ni_4Mo)	363	4.15	1
Au_4V	bc tetr. (Ni_4Mo)	55	0.92	2, 3
CoB	orthorhombic (FeB)	477	0.28	4
Co_2B	tetragonal ($CuAl_2$)	429	0.76	5
Co_3B	orthorhombic (Fe_3C)	747	1.11	5
CoPt	tetragonal (AuCu)	813	0.17	6
CoS_2	fcc pyrite (FeS_2)	122 130	0.84 0.96	7–9
$CrBe_{12}$	tetragonal ($MoBe_{12}$)	50	~0.2	10
$CrBr_3$	hexagonal (BiI_3)	37	3.0	11, 12
$CrGe_2$	....	98	~0.1	13, 14
CrI_3	hexagonal (BiI_3)	68	3.1	15
CrO_2	tetragonal (TiO_2)	378 386	2.07	16
$Cr_{1.2}Pt_{2.8}$	fcc (Cu_3Au)	>77	Cr = 2.56 Pt = −0.47	17
$CrS_{1.19}$	hexagonal (NiAs)	$T_N = 160$ $T_C = 305$	0.11	18
CrTe	hexagonal (NiAs)	239–334	2.45	19–21
Cr_3Te_4	monoclinic	$T_N = 80$ $T_C = 329$	2.3	22
FeAl	cubic (CsCl)	623	~1.0	23
Fe_3Al	bcc (CsCl superlattice)	773	FeI = 1.46 FeII = 2.14	23, 24
FeB	orthorhombic (FeB)	598	1.12	25
Fe_2B	tetragonal $CuAl_2$	1043	1.91	26
$FeBe_5$	fcc ($MgCu_2$)	75	~0.1	27
Fe_3C	orthorhombic (Fe_3C)	3	2.01	26, 28
Fe_3Cr	cubic (Cu_3Au)	993	~1.3	29
Fe_3Ge	hexagonal (Ni_3Sn)	365	1.90	48
FeP	orthorhombic (MnP)	215	0.36	30
Fe_2P	hexagonal (Fe_2P)	266 278	0.77 1.32	30, 31
Fe_3P	tetragonal (Ni_3P)	716	1.84	30, 32
$FePd_3$	fcc (Cu_3Au)	540	Fe = 2.7 Pd = 0.5	17, 33
FePt	tetragonal (AuCu)	743	~0.2	34
FeRh	cubic (CsCl)	$T_N = 330$ $T_C = 675$	Fe = 3.0 Rh = 0.9	35, 36
Fe_3Si	cubic (Cu_2MnAl)	808	FeI = 1.15 FeII = 2.15	37, 38
Fe_3Sn	hexagonal (Ni_3Sn)	743	1.9	39
MnAs	hexagonal (NiAs)	up 318 down 306	3.4	40, 41
MnB	orthorhombic (FeB)	578	1.92	42
MnB_2	hexagonal (AlB_2)	143 157	0.19 0.25	43, 44
MnBi	hexagonal (NiAs)	633	3.52	45, 46
Mn_3Ga	hexagonal	470	~0.02	47
Mn_3Ge	hexagonal (Ni_3Sn)	28	0.38	48
Mn_5Ge_3	hexagonal (Mn_5Si_3)	320	2.5	49
Mn_3In	cubic (Cu_5Zn_8)γ brass	583	~0.1	50
$MnPt_3$	fcc (Cu_3Au)	<300	Mn = 3.60 Pt = 0.17	51
MnSb	hexagonal (NiAs)	583	3.53	52, 53
MnSi	cubic (FeSi)..............	34	0.4	54
Mn_5Sn_3	hexagonal (NiIn)	263	1.23	55
Mn_5Y	orthorhombic ($GdMn_5$)	490	2.2	56, 57
$MnZn_3$	hexagonal (Ni_3Sn)	>400	~1.0	58, 59
Ni_3Al	orthorhombic	75	~0.1	60
NiPt	tetragonal (AuCu)	136	0.06	61
Ni_3Y	rhombic ($CeNi_3$)	33	0.16	62
Sc_3In	hexagonal	7.5	0.06/Sc	63, 64
$ZrZn_2$	cubic (Cu_2Mg)	18	~0.2	65–68

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TABLE 5f-5. T_C, CURIE POINTS OF FERROMAGNETIC BINARY COMPOUNDS OF RARE-EARTH ELEMENTS R IN KELVIN*

Part 1

R =	Ce	Pr	Nd	Sm	Gd	Tb	Dy	Ho	Er	Tm	Lu	Y	Refs.
R_6Mn_{23}	...	...	...	439	469	...	443	434	415	...	...	486	1, 2
RFe_2	221	...	...	675	793	695	640	603	587	613	610	...	3
RFe_3	...	...	...	651	728	648	600	567	550	539	529	...	3
R_6Fe_{23}	...	429?	...	...	659	574	524	651	491	475	485	471	3
R_2Fe_{17}	91	287	327	395	460	409	362	319	293	248	235	245	3
RCo_2	...	48	106	209	413	238	154	90	38	33	...	...	4
RCo_3	78	349	395	...	612	506	450	418	401	370	...	301	5
R_2Co_7	151	574	609	713	762	693	647	644	644	...	...	459	3, 23
RCo_5	737	912	910	1020	1008	980	966	1000	986	1020	...	977	6, 23
R_2Co_{17}	1083	1171	1150	1190	1209	1180	1152	1173	1186	1182	...	1167	7, 23
RNi	...	20	35	45	73	50	48	31	10	4	...	...	8
RNi_2	...	8	20	22	77	46	32	23	14	14	...	...	8
RNi_3	...	20	27	85	116	98	69	66	62	43	...	...	9
R_2Ni_7	48	85	87	...	118	101	81	70	67	...	...	58	10
RNi_5	...	...	9	25	36	27	15	10	13	7	...	...	11, 8
R_2Ni_{17}	...	...	...	641	623	615	604	611	602	603	...	621	24
RAl_2	8	33	63	122	176	119	51	27	20	5	...	...	12
R_5Si_4	...	...	...	...	336	225	140	76	25	...	...	...	13
RRu_2	...	39	29	...	85	...	...	...	8	...	...	...	14
RRh_2	...	8	7	2	73	39	28	17	7	...	...	...	15
ROs_2	...	28	22	36	67	34	15	9	3	...	...	...	14
RIr_2	...	15	12	37	89	44	23	12	4	1	...	...	14
RPt_2	...	6	4	6	37	16	14	9	3	...	...	...	15

Part 2

Compound	T_C	Ref.	Compound	T_C	Ref.	Compound	T_C	Ref.
RMn_2	...	11, 16	$TbGa$	155	20	DyN	17	29, 31
$PrFe_7$	283	17	Gd_5Pd_2	335	22	HoN	13	29
$NdFe_7$	327	17	Tb_5Pd_2	30	22	ErN	16	29
Tm_3Ni	12	17a	Dy_5Pd_2	25	22	DyP	5	32
EuB	8	18	Ho_5Pd_2	10	22	HoP	5	31, 32
$PrSi_2$	11	19	Gd_2AgIn	122	21	$DyAs$	2	33
$CeGe_2$	5	19	NdH_2	10	27	EuO	69	34
$PrGe_2$	19	19	EuH_2	25	25	EuS	17	34
$NdGe_2$	4	19	NdN	35	28, 29	$EuSe$	7	34, 35, 36
$TbZn$	160	20	GdN	69	30	EuI_2	5	26
$GdCd$	262	21	TbN	42	29, 31	Dy_3Al_2	76	37
$TbHg$	80	20						

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* Data for compounds with nonmetallic elements compiled by F. Holtzberg and S. Methfessel, IBM Watson Research Center.

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TABLE 5f-6. SATURATION MAGNETIZATION AND CURIE POINTS OF SOME SIMPLE FERRITE SPINELS[a]

Ferrite	X-ray density[b]	$4\pi M_s$ at room temperature	t_C, °C
$MnFe_2O_4$	5.00	4,900[c]	295–330[c,d]
Fe_3O_4	5.24	6,000[b]	585[b]
$CoFe_2O_4$	5.29	5,300[b]	520[b]
$NiFe_2O_4$	5.38	3,230[c]	580–600[c,d]
$CuFe_2O_4$	5.35	1,700[b,e]	455[b]
$MgFe_2O_4$	4.55	1,450[c,e]	320, 440[c,d,e]
$CdFe_2O_4$	....	0	
$ZnFe_2O_4$[f]	5.33	0	60
$Li_{0.5}Fe_{2.5}O_4$	4.75	3,240–3,900[c,d]	590–680[c,d]

[a] Prepared by F. G. Brockman, Philips Laboratories, Briarcliff Manor, N.Y.

[b] J. Smit and H. P. J. Wiin, "Ferrites," John Wiley & Sons, Inc., New York, 1959.

[c] Wilhelm H. von Aulock, ed., "Handbook of Microwave Ferrite Materials," Academic Press, Inc., New York, 1965.

[d] Range of values indicates extremes of reported values from various workers.

[e] Depends on heat treatment.

[f] $ZnFe_2O_4$ magnetic when quenched, otherwise nonmagnetic; t_C for rapid quench.

TABLE 5f-7. BOHR MAGNETON NUMBERS OF SOME FERRITE SPINELS AND OF CORRESPONDING SOLID SOLUTIONS WITH $ZnFe_2O_4$[a]

Mol % $ZnFe_2O_4$	0	20	40	50	70
$MnFe_2O_4$[b]	4.5	5.6	6.7	7.0	6.3
$FeFe_2O_4$[c]	4.2	5.2	5.7	5.8	5.4
$CoFe_2O_4$[b]	3.7	5.0	6.1	6.3	5.2
$NiFe_2O_4$[b]	2.4	3.8	5.1	5.3	5.1
$MgFe_2O_4$[b]	1.8[d]	3.3[d]	4.2[d]	4.4[d]	4.2[d]
$(Li_{0.5}Fe_{0.5})Fe_2O_4$[c]	2.6	2.8	4.4	4.0	1.8
$CuFe_2O_4$[c]	1.3[d]	...	...	4.7[d]	

[a] Prepared by F. G. Brockman, Philips Laboratories, Briarcliff Manor, N.Y. Some values obtained by interpolation of data in references.

[b] C. Guillaud et al., from summary of E. W. Gorter.

[c] E. W. Gorter, *Philips Research Repts.* **9**, 295, 321, 403 (1954).

[d] Depends on heat treatment.

TABLE 5f-8. CURIE POINTS AND BOHR MAGNETON NUMBERS OF OTHER COMPOUNDS WITH THE SPINEL STRUCTURE*

Composition	T_C, K	n_B per molecule	Ref.	Composition	T_C, K	n_B per molecule	Ref.
$CoCr_2O_4$	98	0.18	1	$LiCo_{0.5}Mn_{1.5}O_4$	50	0.33†	14
$CuCr_2O_4$	133	0.72	1	$LiMg_{0.5}Mn_{1.5}O_4$	38	2.97†	14
$FeCr_2O_4$	88	0.84	2	$LiNi_{0.5}Mn_{1.5}O_4$	130	3.28	14
$MnCr_2O_4$	43	1.20	3	$Mg_{0.5}Mn_{2.5}O_4$	20	0.71	15
$MnFe_{0.5}Cr_{1.5}O_4$	224	0.77	4	$NiMn_2O_4$	113-160	1.75	16
$NiCr_2O_4$	78	0.33	1	$LiZn_{0.5}Mn_{1.5}O_4$	22	4.24	14
CoV_2O_4	145	1.20	3	$ZnNiMnO_4$	90	0.87	14
Co_2VO_4	160	1.33	5	$Zn_{0.5}Mn_{2.5}O_4$	20	0.61	15
FeV_2O_4	109	1.06	5	Mn_2SnO_4	58	0.35	17
Fe_2VO_4	440	0.72	5	$CdCr_2S_4$	86	5.15	18
MnV_2O_4	56	2.05	6	$CoCr_2S_4$	238	2.55	2
$NiFeAlO_4$	444	0.57	7	$CuCr_2S_4$	420	4.58	19
$NiFeGaO_4$	444	2.8-3.0	7	$CuCr_2S_3Cl$	218	5.14	20
$NiFeInO_4$	313	2.5	8	$FeCr_2S_4$	193	1.5	2
$NiFeVO_4$	610	0.70	9	$HgCr_2S_4$	36	5.35	18
$Li_{0.5}Fe_{0.5}Rh_2O_4$	130	0.1	9	$MnCr_2S_4$	66	2.0	21
$LiFe_2O_3F$	903	2.1	10	$CdCr_2Se_4$	129.5	5.62	22
Fe_2TiO_4	142	0.36	11	$CuCr_2Se_4$	460	4.94	19
$MnCo_2O_4$	203	0.04	2	$CuCr_2Se_3Br$	274	2.74	23
Mn_3O_4	43	1.85	12	$HgCr_2Se_4$	106	5.64	24
$Co_{1.8}Mn_{1.2}O_4$	191	1.1	13	$CuCr_2Te_4$	365	1.93	19
$CuCrMnO_4$	45	1.47†	14	$CuCr_2Te_3I$	294	4.10	23
$Cu_{1.5}Mn_{1.5}O_4$	80	3.35	14				
$CuNi_{0.5}Mn_{1.5}O_4$	150	3.15	14				
$CuRhMnO_4$	35	2.35	14				

* Compiled by M. W. Shafer, IBM Research Center, Yorktown Heights, N.Y.

† Not completely saturated at 30 kOe.

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TABLE 5f-9. SPONTANEOUS MAGNETIZATION AND COMPENSATION POINTS OF SOME FERRITE GARNETS OF COMPOSITION $R_2Fe_5O_{12}$

R	n_B per $R_3Fe_5O_{12}$ (at 0 K)	Curie temperature,† K	Compensation temperature,‡ K
Y.	5.00	560	
Sm.	5.43	578	
Eu.	2.78	566	
Gd.	16.0	564	286
Tb.	18.2	568	246
Dy.	16.9	563	226
Ho.	15.2	567	137
Er.	10.2	550	83
Tm.	1.2	549	$4 < T < 20$† None‡
Yb.	0§	548	None†‡ 7.6¶
Lu.	5.07	549	

* Compiled by B. A. Calhoun, IBM Research Center, Yorktown Heights, N.Y.

† R. Pauthenet, *Ann. phys.* [13] **3**, 424 (1958).

‡ S. Geller, J. P. Remeika, R. C. Sherwood, H. J. Williams, and G. P. Spinoza, *Phys. Rev.* **137A**, 1034 (1965).

§ Spontaneous moment exists at higher temperatures.

¶ J. W. Henderson and R. L. White, *Phys. Rev.* **123**, 1627 (1961).

WEAK FERROMAGNETISM[1] (Table 5f-10). Under certain magnetocrystallographic symmetry conditions, the magnetic sublattice vectors of an antiferromagnet can depart from strict collinearity and lower, rather than raise, the value of the thermodynamic energy or potential. The noncollinearity is induced by intrinsic anisotropic forces, and the canting of the sublattice moments causes a small spontaneous magnetic moment to exist in a nominally antiferromagnetic material. The presence of this weak ferromagnetism is characterized by an energy expression, which is antisymmetric with respect to an interchange of the sublattice moments, of the form

$$l_i m_j \pm l_j m_i \qquad i \neq j = x, y, z$$

where

$$\mathbf{l} \equiv \mathbf{m}_1 - \mathbf{m}_2, \qquad \mathbf{m} \equiv \mathbf{m}_1 + \mathbf{m}_2$$

and $\mathbf{m}_1$, $\mathbf{m}_2$ are the antiferromagnetic sublattice vectors. (Note that $\mathbf{l}$ and $\mathbf{m}$ are perpendicular because $|\mathbf{m}_1| = |\mathbf{m}_2|$.) The minus sign in the energy equation corresponds to a two-ion exchange energy (type E in Table 5f-10) first recognized by Dzialoshinski [21][2] and later explained by Moriya [22] in the case of $Fe_2O_3(\alpha)$; the plus sign in the energy equation characterizes a single-ion anisotropy energy (type A) initially described by Dzialoshinski [13] and by Moriya [14] as the source of canting in NiF_2.

5f-4. Saturation and Curie Points of Magnetic Alloys. These and some related properties of a number of alloy systems are presented in the form of curves (Figs. 5f-1 to 5f-10), and in Tables 5f-11 and 5f-12.

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[1] Prepared by R. J. Joenk, IBM Corporation, Armonk, N.Y.

[2] The references in this paragraph are those for Table 5f-10. See also E. A. Turov, "Physical Properties of Magnetically Ordered Crystals," chaps. 5–8, Academic Press, Inc., New York, 1965; and T. Moriya, "Weak Ferromagnetism," in "Magnetism," G. T. Rado and H. Suhl, eds., Academic Press, Inc., New York, 1963, vol. 1, p. 85.

TABLE 5f-10. MAGNETIC PROPERTIES OF NOMINALLY ANTIFERROMAGNETIC MATERIALS WITH A WEAK FERROMAGNETIC MOMENT DUE TO SMALL-ANGLE CANTING

Compound	Non-magnetic space group*	Type	T_N, K	$\hat{\mathbf{l}}$	$\hat{\mathbf{m}}$	$\lvert\mathbf{m}\rvert$, μ_B per atom	References
$BiCrO_3$	....	....	123	....	.....	0.017	1
CuF_2	C_{2h}^{5}†	E	69	Near c	b	$\approx 2 \times 10^{-4}$	2
$Ni(IO_3)_2 \cdot 2HO(\beta)$	D_{2h}^{15}	....	3	....	.....	≈ 0.1	3, 4
$NaMnF_3$	D_{2h}^{16}‡	E	60	[100]	[001]	....	5, 6
$NaNiF_3$	D_{2h}^{16}	E	156	[100]	[001]	0.058	7–9
$KMnF_3$	D_{2h}^{16}	A	88§	....	.....	0.0034	10
$RFeO_3$¶	D_{2h}^{16}	E	620–750	[100]	[001]	0.05	11, 12
NiF_2	D_{4h}^{14}	A	73	⟨100⟩	⟨010⟩	0.029	13–15
PdF_2	D_{4h}^{14}	A	217	⟨100⟩	⟨010⟩	0.0031	16
CrF_3	D_{3d}^{6}**	E	80	(111)	(111)	0.056	17–19
FeF_3	D_{3d}^{6}	E	≈365	(111)	(111)	....	17, 20
$Fe_2O_3(\alpha)$	D_{3d}^{6}	E	960††	(100) near (111)	[100]	0.006	21–24
$MnCO_3$	D_{3d}^{6}	E	32	[010]	[100]	0.034	21, 25, 26
$CoCO_3$	D_{3d}^{6}	E	18	$\theta = 46°$	.....	0.26	21, 25, 27, 28
$NiCO_3$	D_{3d}^{6}	E	25	$\theta = 63°$	.....	0.33	29, 30
UO_2‡‡	O_h^{5}	....	31	{001}	.....	0.011	31, 32

* The space group is usually identified in the paramagnetic temperature range of the crystal; in the ordered state the symmetry is generally lower, but often indistinguishably so for most purposes.

† The crystallographic axes are labeled such that $a > b > c$ is the symmetry axis.

‡ The crystallographic axes are labeled such that $a < b < c$

§ Weak ferromagnetism is observed below 81.5 K.

¶ Here R = Y, La, and the rare earths. The data refer to the ordering of the Fe sublattices; the moment is temperature dependent because of spin reorientation and rare-earth ordering at various lower temperatures.

** The z axis is the threefold symmetry axis, and x is a twofold axis; θ is the polar angle.

†† There is a transition to an uncanted state at 260 K.

‡‡ More than two sublattices are probably required for a descriptive model.

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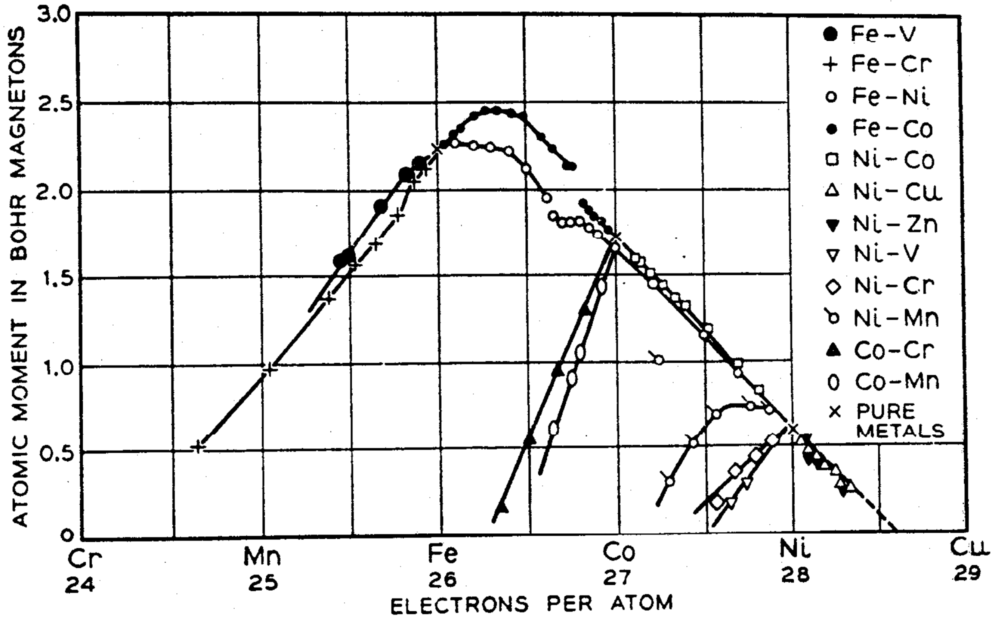

FIG. 5f-1. Saturation magnetization of intra-iron-group alloys as dependent on electron concentration. Data by Peschard (1925), Weiss, Forrer and Birch (1929), Forrer (1930), Sadron (1932), Fallot (1936, 1938), Farcas (1937), Marian (1937), and Guillaud (1944). [*R. M. Bozorth, Phys. Rev.*, **79,** 887 (1950).]

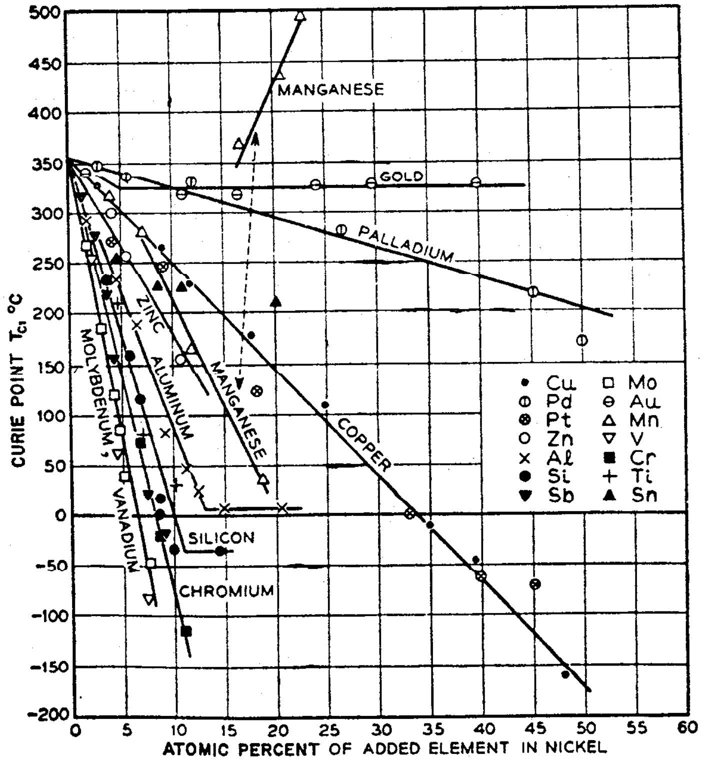

FIG. 5f-2. Change of Curie point with the composition of nickel alloys (atomic percent). Data by V. Marian, *Ann. physique* [11]**7,** 459 (1937). (*Bozorth, "Ferromagnetism," D. Van Nostrand Company, Inc., Princeton, N.J., p.* 721, 1951.)

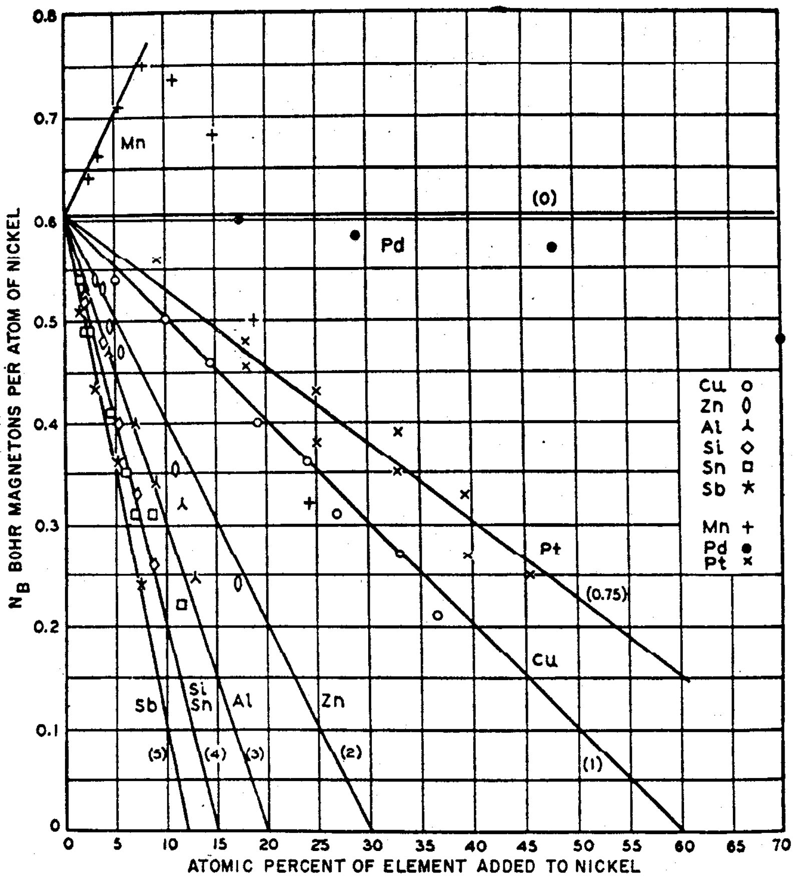

FIG. 5f-3. The saturation magnetization of nickel as affected by the addition of other elements having 1, 2, 3, . . . , electrons in the outermost shell. Data by Sadron, *Ann. physique* [10]**17**, 371 (1932). (*Bozworth, "Ferromagnetism," D. Van Nostrand Company, Inc., Princeton, N.J., p.* 440, 1951.)

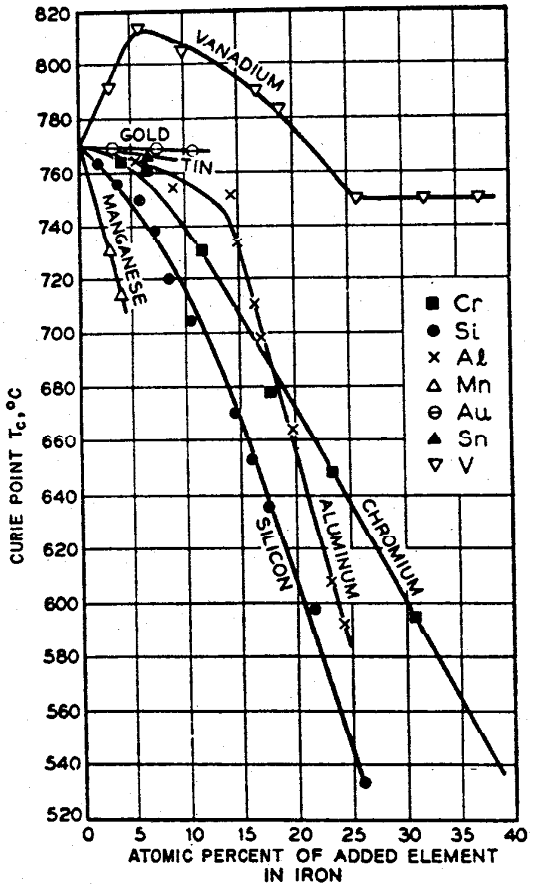

FIG. 5f-4. Change of Curie point of iron alloys with composition (atomic percent). Data by M. Fallot, *Ann. physique* [11]6, 305 (1936). (*Bozworth, "Ferromagnetism," D. Van Nostrand Company, Inc., Princeton, N.J., p. 722, 1951.*)

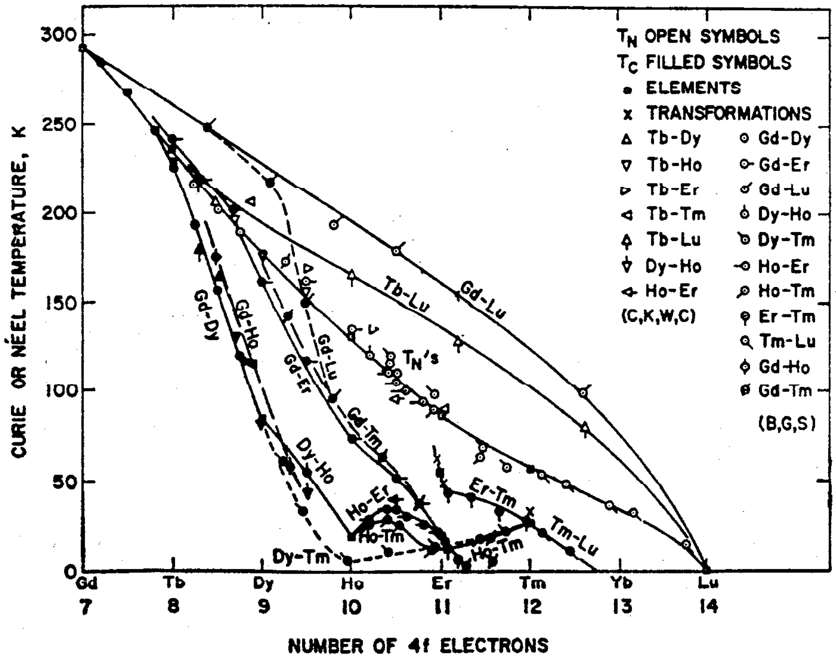

FIG. 5f-5. T_C, T_N, and T_x (change in magnetic structure) for heavy rare-earth alloys with one another. [1,2,3]

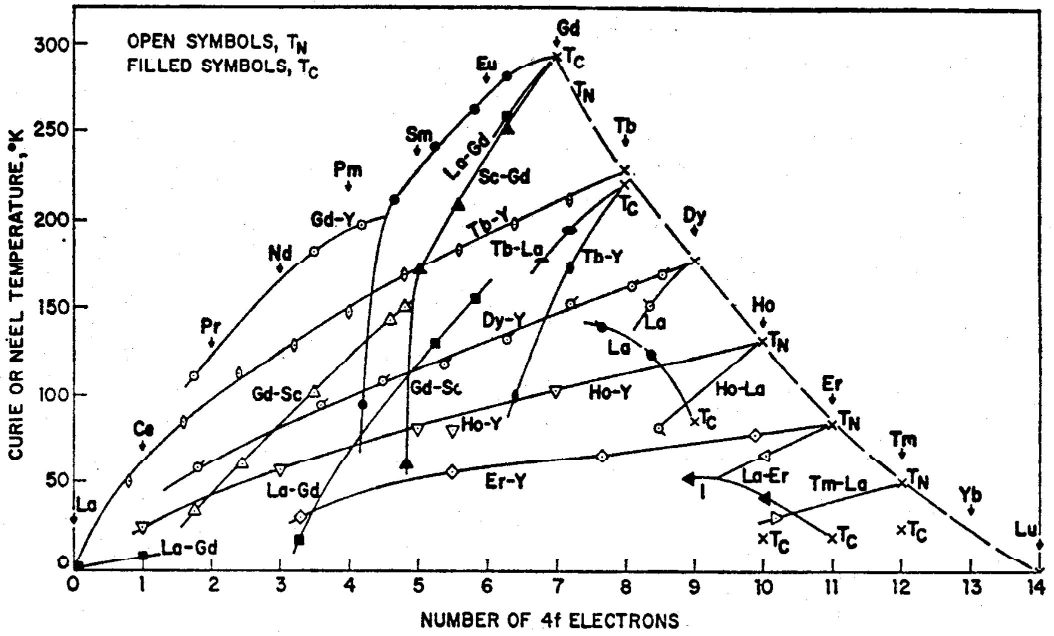

Fig. 5f-6. Dependence of Néel and Curie points of rare-earth metals on additions of nonmagnetic La, Y, and Sc. Note that La often stabilizes the ferromagnetic phase, Y and Sc the antiferromagnetic phase. Data for La alloys [4,5]; for Y alloys [1,4,6,7]; and for Sc alloys [8,9].

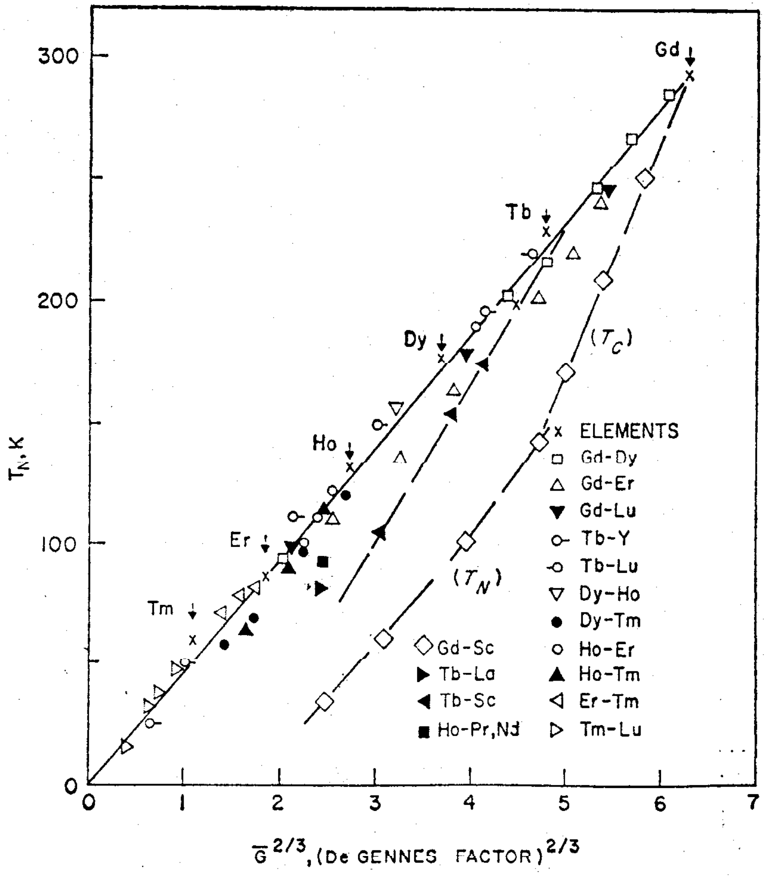

Fig. 5f-7. Néel points for rare-earth elements and various binary alloys, plotted against two-thirds power of average de Gennes factor, $G = (g - 1)^2J(J + 1)$. Data as follows: Gd-Dy [4,5]; Gd-Er [1,5]; Gd-Lu [5]; Gd-Sc [6]; Tb-Sc [6,9]; Tb-Y, Lu [7]; Tb-La [8]; Ho-Pr, Nd [8]; and R-R [10]. [(*de Gennes, P.: Compt. rendu, Sci.* (Paris) **247**, 1836 (1968)).]

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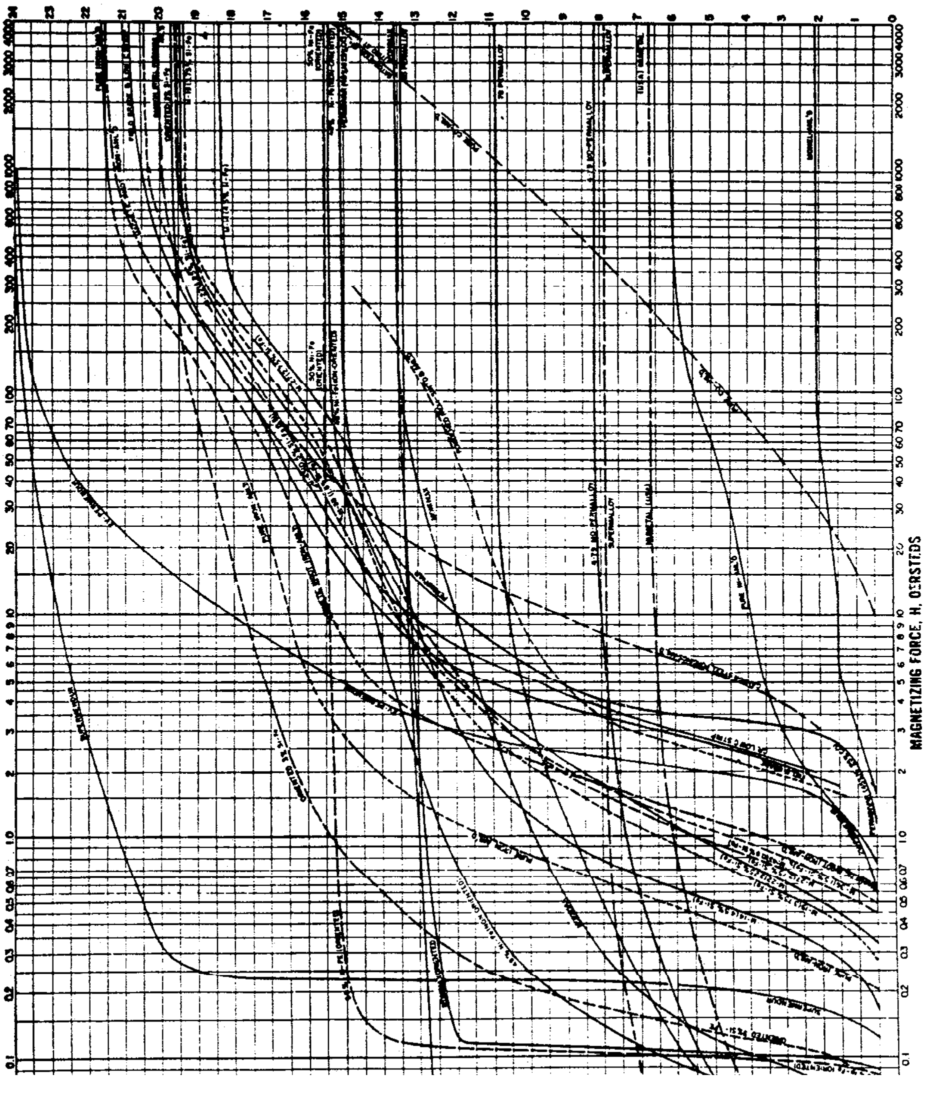

ent magnetization curves for various magnetically soft materials. (*Prepared by H. H. Helms, Laboratory.*)

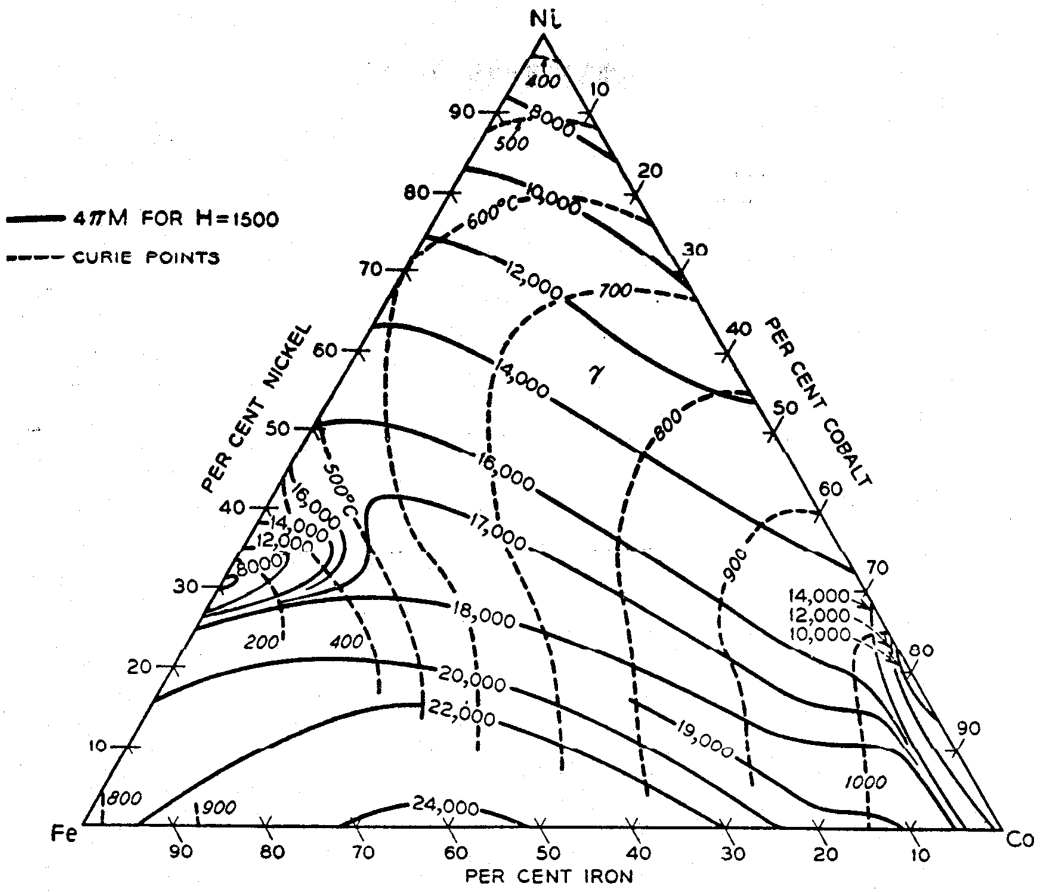

FIG. 5f-9. Approximate saturation ($4\pi M$ for $H = 1{,}500$) and Curie points of Fe-Co-Ni alloys. Temperature in °C. [*T. Kase, Sci. Repts. Tôhoku Imp. Univ.* **16**, 491 (1927).]

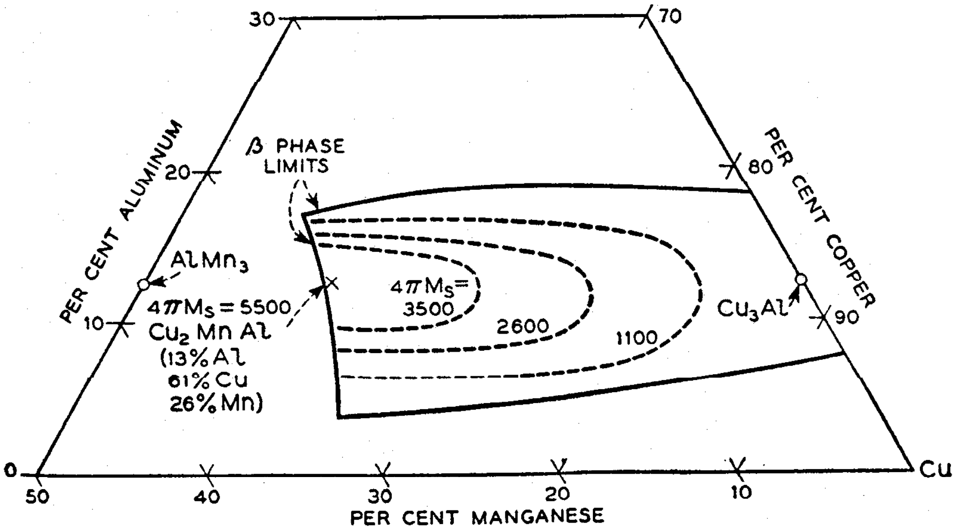

FIG. 5f-10. Saturation induction of Heusler Mn-Cu-Al alloys. Amounts in weight percent. [*Data by O. Heusler, Ann. Physik* [5]**19**, 155 (1934).]

TABLE 5f-12. MAGNETIC PROPERTIES OF HEUSLER-TYPE COMPOUNDS*

Compound	T_C	n_B	Compound	T_C	n_B
Cu_2MnAl	600	3.6	Ni_2MnGa	379	4.2
Cu_2MnIn	520	4.0	Ni_2MnIn	323	4.4
Cu_2MnSn	530	4.1	Ni_2MnSn	344	4.1
Co_2MnSi	985	5.1	Ni_2MnSb	360	3.3
Co_2MnGa	694	4.1	Pd_2MnGe	170	3.2
Co_2MnGe	905	5.1	Pd_2MnSn	189	4.2
Co_2MnSn	829	5.1	Pd_2MnSb	247	4.4
			Au_2MnAl	258	3.1

* As summarized by R. S. Tebble and D. J. Craik, "Magnetic Materials," Wiley Interscience, London 1969, p 152. Data by Endo, Ohoyama, Kimura, Oxley, Tebble, Williams, and Webster.

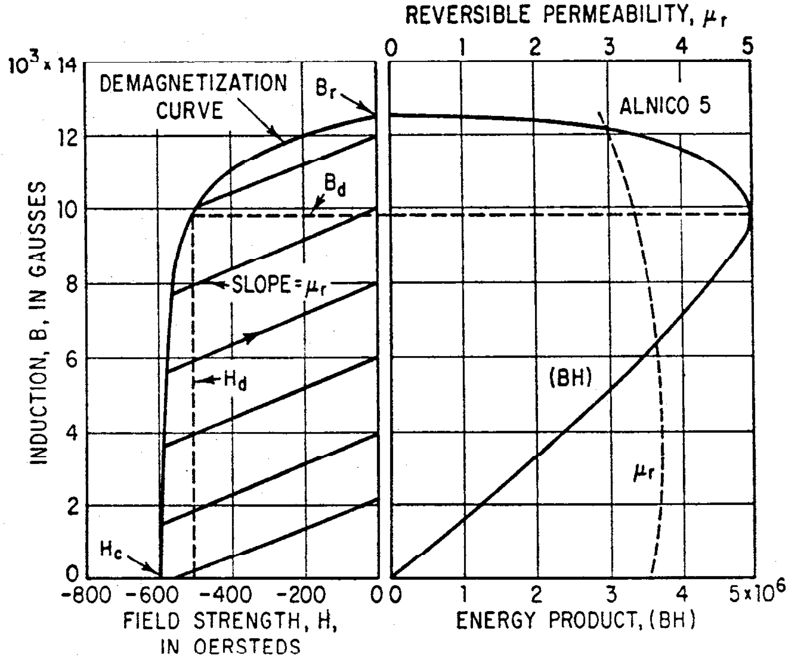

FIG. 5f-11. Demagnetization curve of Alnico 5, showing B_r, H_c, and optimum operating point (B_d, H_d). Also energy-product curve and reversible permeability μ_r as function of B.

5f-6. Losses. Losses in magnetic materials in alternating fields at low inductions (<100 gauss, approximately) are usually described by the following equation:[1]

$$\frac{R}{\mu L \nu} = aB + c + e\nu$$

R is in ohms (series) and L in henrys, as measured on an a-c bridge, μ the permeability, ν the frequency of alternating current in cps, B the maximum induction in gauss during the cycle, and a, c, and e the constants given in Table 5f-14. The constant a is generally ascribed to hysteresis, c to lag, and e to eddy currents.

The loss angle δ is related to these constants and Q as follows:

$$\tan \delta = \frac{1}{Q} = \frac{R}{\omega L} = \frac{R}{2\pi\nu L}$$

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[1] C. D. Owens, *Proc. IRE* **41**, 359 (1953).

TABLE 5f-13. CONSTANTS OF PERMANENT-MAGNET MATERIALS*

Name	Composition, % by weight, remainder iron	H_c, coercive force, oersteds	B_r, residual flux density, gauss	Optimum point		(B_dH_d)max, energy product, 10^6 G·Oe	μ_r, reversible permeability at H_d, B_d	Density, g/cm³	Mechanical properties	Preparation
				H_d	B_d					
1% carbon steel	1C, 0.5 Mn	51	9,000	34	5,900	0.20	.....	7.8	Hard, strong	Hot-roll, machine, punch, heat-treat.
5% tungsten steel	5W, 0.7 C	70	10,500	47	7,000	0.33	30	8.1	Hard, strong	Hot-roll, machine, punch, heat-treat.
3½% chromium steel	3.5 Cr, 1 C, 0.5 Mn	66	9,500	45	6,500	0.29	35	7.8	Hard, strong	Hot-roll, machine, punch, heat-treat.
36% cobalt steel	36 Co, 3.75 W, 5.75 Cr, 0.8 C	240	9,750	147	6,300	0.93	12	8.2	Hard, strong	Cast, hot-roll, heat-treat.
Remalloy 2	12 Co, 20 Mo	340	8,550	220	5,400	1.2	.....	8.4	Hard, malleable	Hot-roll, machine, punch.
Vicalloy 2	52 Co, 13 V	415	9,000	325	7,000	2.3	.....	8.2	Ductile	Cold-roll, draw.
Cunico 1	50 Cu, 21 Ni, 29 Co	680	3,400	400	2,000	0.8	3.2	8.3	Ductile	Cold-roll, machine.
Cunife 1	60 Cu, 20 Ni	500	5,400	320	4,000	1.3	1.7	8.6	Ductile	Draw, cold-roll, machine, punch.
Alnico 2	10 Al, 17 Ni, 12.5 Co, 6 Cu	550	7,250	350	4,600	1.60	6.4	7.1	Hard, brittle	Cast, ground.
Alnico 5	8 Al, 14 Ni, 24 Co, 3 Cu	620	12,500	525	10,200	5.30	4.3	7.3	Hard, brittle	Cast, ground.
Alnico 5-DG	8 Al, 14 Ni, 24 Co, 3 Cu	650	12,900	580	10,500	6.10	4.0	7.3	Hard, brittle	Chill-cast.
Alnico 5-7 (complete orientation)	8 Al, 14 Ni, 24 Co, 3 Cu	730	13,200	640	11,500	7.40	3.0	7.3	Hard, brittle	Chill-cast into hot mold, ground.
Alnico 6	8 Al, 16 Ni, 24 Co, 3 Cu, 2 Ti	750	10,500	525	7,100	3.70	4.8	7.4	Hard, brittle	Cast, ground.
Alnico 8	7 Al, 15 Ni, 35 Co, 4 Cu, 5 Ti	1,600	8,300	950	5,060	5.0	2.6	7.3	Hard, brittle	Cast, ground.
Alnico 9	7 Al, 15 Ni, 35 Co, 4 Cu, 5 Ti	1,450	10,500	1,100	7,700	8.5	1.3	7.3	Hard, brittle	Cast, ground.
Bismanol	79.2 Bi, 20.8 Mn	3,650	4,800	2,000	2,640	5.3	1.1	8.1	Hard, brittle	Press in field at 280°C.
Platinum cobalt	76.7 Pt, 23.3 Co	4,300	6,450	2,800	3,400	9.5	1.2	15.7	Ductile	Cold-work, draw, machine.
ESD Fe-Co (Lodex)	64 Fe-36 Co in Pb-Sb matrix	940	7,300	650	5,400	3.4	2.6	8.6	Malleable	Press in field.
Silmanal	86.75 Ag, 8.8 Mn, 4.45 Al	6,300 (H_{ci})	590	284	292	0.083	1.1	9.0	Ductile	Cold-roll, draw.
Barium ferrite	$BaO \cdot 6\ Fe_2O_3$	1,850	2,200	900	1,100	1.0	1.15	4.7	Hard, brittle	Press, sinter.
Oriented	$BaO \cdot 6\ Fe_2O_3$	2,200	4,000	1,750	2,000	3.5	1.05	5.0	Hard, brittle	Press in field.
Rubber bonded	BaO–$6\ Fe_2O_3$	1,480	2,200	1,000	1,100	1.1	1.1	3.7	Flexible	Rolled sheet.
Samarium-cobalt†	$SmCo_5$	8,400	8,700	.....	......	18.5	.....	95% theoretical	Hard, brittle	Press in field, uniaxial deformation.
Cast rare earth alloy‡	$Co_{3.5}Fe_{0.4}Cu_{1.35}Sm$	4,000	6,400	.....	......	8.8	.....	....	Hard, brittle	Cast, age.

* Revised by H. H. Helms, Jr. and E. Adams, U.S. Naval Ordnance Laboratory.

† K. H. J. Buschow, W. Luiten, P. A. Naastepad, and F. F. Westendorp, *Philips Tech. Rev.* **29** (1968).

‡ E. A. Nesbitt, *J. Appl. Phys.* **40**, 1259 (1969).

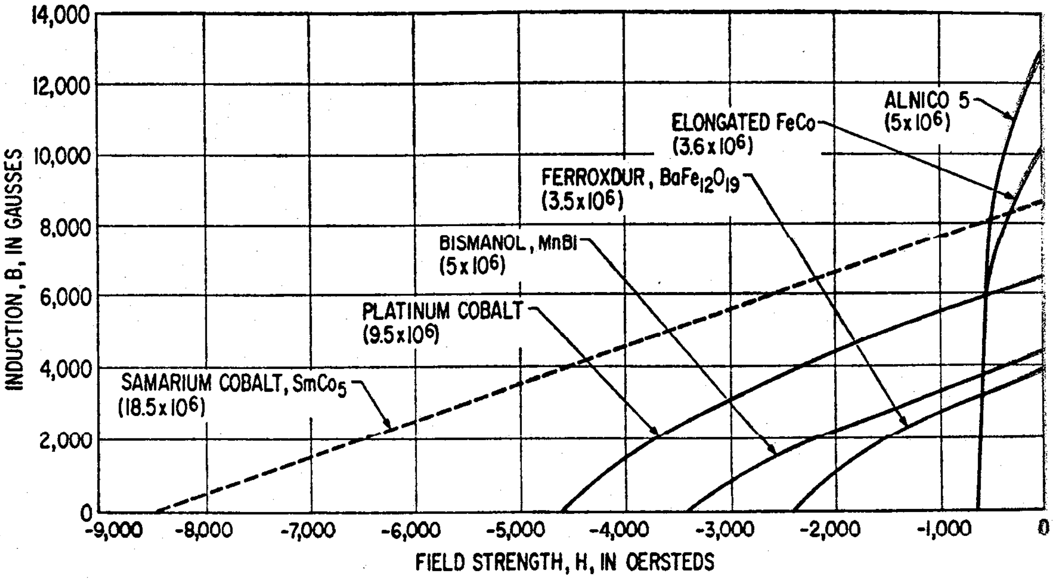

FIG. 5f-12. Demagnetization curves and maximum energy products, $(BH)_m$, of several types of permanent-magnet materials. (*Prepared by H. H. Helms and E. Adams, U.S. Naval Ordnance Laboratory.*)

This is valid only at low frequencies, when eddy-current shielding is negligible. Hysteresis losses at low inductions are described by the Raleigh relation

$$W_h = \frac{4\pi}{3} \frac{d\mu}{dH} H^3$$

per cycle, H being the maximum field strength during the cycle and $d\mu/dH$ the slope of the μ vs. H curve (near μ_0).

At high inductions, e.g., $B = 100$ to saturation, the relation often used to calculate hysteresis loss per cycle at maximum induction B is

$$W_h = \eta B^{1.6}$$

η being an empirical constant varying from 1 to 10^6.

TABLE 5f-14. MATERIAL CONSTANTS FOR LOSSES AT LOW INDUCTIONS
(a is hysteresis constant, c the "lag" constant, and e the eddy-current constant)

Material	Size	μ_0	$a \times 10^6$	$c \times 10^6$	$e \times 10^9$
Carbonyl iron	5 μ	13	5	60	1
Mo Permalloy	0.001-in. sheet	13,000	2	0.	10
Mo Permalloy	120 mesh	125	1.6	30	19
Mo Permalloy	400 mesh	14	11	140	7
Mn Zn ferrite	....	1,500	1.6	4.8*	0.3
Ni Zn ferrite	....	200	7	....	0.2

* $\nu < 1$ Mc/sec, higher values at higher frequencies.

5f-7. Antiferromagnetic Materials Studied by Neutron Diffraction.[1] *Introduction.* Since Table 5g-22 in the second edition of the Handbook was compiled, any magnetic structural distinction between ferro- (and ferri-) magnetic and antiferromagnetic materials has become increasingly arbitrary in view of the existence of many complex noncollinear or modulated structures with ferromagnetic components, which in some

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[1] Compiled by D. E. Cox, Brookhaven National Laboratory, Upton, N.Y.

cases transform at some intermediate temperature to yet another structure. In general, such materials have been included in the table, and the only ones which have been systematically excluded are collinear ferromagnetic and ferrimagnetic materials. Even a few of the latter have been listed, however, if it is felt that the structural features are closely related to a basic antiferromagnetic arrangement.

Although the table was initially compiled in considerable detail with a format very similar to that of its predecessor, space limitations competing with an almost tenfold increase in the literature have necessitated the present highly abbreviated and concise form (Table 5f-15). A more detailed compilation is available on request from the author (Brookhaven National Laboratory Report No. 13822). For similar reasons, it has also not been possible to provide any structural details of a number of very interesting complex arrangements, in either the table or the accompanying figures. This is also true for solid solutions, where it is clearly impracticable to attempt to list all the relevant data. Reference to the original article is strongly urged in these cases.

Format and Abbreviations for Table 5f-15. COLUMN 1: MATERIAL. Materials have as far as possible been listed within structurally similar groups with the magnetic atoms in alphabetical order. There are, however, a number of departures from the latter scheme, for example, where compounds contain more than one such atom.

COLUMN 2: CRYSTAL CLASS AND NÉEL TEMPERATURE. The crystal classes have been abbreviated as follows: **C**(cubic), **T**(tetragonal), **H**(hexagonal), **R**(rhombohedral), **O**(orthorhombic), and **M**(monoclinic). The magnetic structures of all rhombohedral systems have been described in terms of the hexagonal unit cell. The crystal class is usually that cited in the neutron diffraction determination above the initial ordering temperature. The actual structure is sometimes known to be distorted from that assumed, and where there is a distortion associated with the (or one of the) magnetic transition(s), this has been denoted by *. A distortion apparently unconnected with any magnetic transition has been denoted by **. The Néel temperatures where listed are those cited in the neutron diffraction references, and are not necessarily determined by diffraction techniques. A second (or third) figure in parentheses indicates the temperature of a second (or third) transition, and † implies that the temperature in question corresponds to a Curie point (i.e., the appearance of a spontaneous moment).

A typical entry might be C: 64, which means a cubic lattice with a Néel point of 64 K.

COLUMN 3: MAGNETIC STRUCTURE. Most of the abbreviations used here can be found by reference to the figures and captions at the end. The description f. (or a.f.) sheets implies a structure with ferromagnetic (or antiferromagnetic) sheets which are coupled antiparallel to adjacent sheets. The symbol †† denotes that the structure described occurs over part of the composition range in solid solutions, and the symbol # (also used in column 4) denotes the presence of two magnetic phases. The use of braces indicates that the magnetic structure in question involves components from more than one type of mode and is therefore noncollinear. Changes in magnetic structure or additional magnetic ordering are entered opposite the appropriate transition temperature listed in parentheses in column 2.

It is to be noted that the magnetic unit cell is in many cases some multiple of the chemical cell; in order to save space this is not explicitly stated in the table but is very often obvious by reference to the appropriate figure.

COLUMN 4: MOMENT AND DIRECTION. A typical entry in this column lists first the magnetic moment in boldface type, followed by its direction. For example, the entry **1.7**: ⊥[100]; 36°, [010] means a moment of $1.7\mu_B$ directed perpendicular to [100] and 36° from [010]. Where there are multiple entries of this sort, each moment and direction is that appropriate to the entry listed in column 3 on the same horizontal line. The moments which have been tabulated are for the most part those determined at the lowest temperature studied, which is 4.2 K in the majority of cases.

TABLE 5f-15. ANTIFERROMAGNETIC MATERIALS STUDIED BY NEUTRON DIFFRACTION

Material	Crystal class and Néel temperature, K	Magnetic* structure	Moment (in μ_B) and direction	References
NaCl and related structures, (see also Fig. 5f-13)				
CoO	**C***: 291	f2 (Fig. 5f-13) f2 or complex	**3.8**: 11.5°, [001] **3.5**: 27.4°, [001]	290, 343, 363 247, 248
CrN	**C***: 273	f4A	**2.4**: $[1\bar{1}0]$	125
FeO	**C***: 198	f2	**3.3**: [111]	343, 345, 363
$LiFeO_2$	**C**	f2	**2.5-4.5**: $\perp$[111]	138
MnO	**C***: 120	f2	**5**: $\perp$[111]	343, 362, 363
(Mn,Co) O	**C**	f2	....	42
α-MnS	**C**	f2	**5**: $\perp$[111]	123, 363
$Mn_{0.33}Cr_{0.67}S$	**C**: 240	f1	**4.1**: $\perp$[001]	96
(Mn,Cr) S	**C**	....	....	96
MnSe	**C**	f2	$\perp$[111]	363
$Mn_{0.9}Li_{0.1}Se$	**C***: 71	f3	**4.6**: 45°, [001]	318
(Mn,Li) Se	**C**	....	....	318
NiO	**C***: 530	f2	**1.8**: $\perp$[111]	15, 16, 344, 346, 363
CeAs	**C**: 8	f1	**0.7**: [001]	341
CeSb	**C**: 16	complex	....	341
ErP	**C**: 3.1	f2	**5.7**: $\perp$[111]	112
ErSb	**C**: 3.7	f2	**7.0**: $\perp$[111]	112
EuSe	**C**: 5.8	{f2 {sinusoidal	$\perp$[111]? $\perp$[111]	323
EuTe	**C**: 7.8	f2	$\perp$[111]	410
GdBi	**C**	f2	....	266
GdS	**C**	f2	....	266
GdSb	**C**	f2	....	266
GdSe	**C**	f2	....	266
HoP	**C**: 5.5†	complex	**8.8**: $\perp$[001]	112
HoSb	**C**: 9	f2	**9.3**: [100]	112
TbAs	**C**: 12	f2	**7.7**: [111]	112
TbP	**C**: 9	f2	**6.2**: [111]	112
TbSb	**C**: 14	f2	**8.2**: [111]	112

UAs	**C**: 123, 128	f1	**1.9, 2.1**: [001]	**260, 388, 412**
	(>4.2)	f1A	**2.2**: [001]	
UN	**C**: 53	f1	**0.8**: [001]	148
UP	**C**: 125	f1	**1.7, 1.9**: [001]	149, 367
$UP_{0.95}S_{0.05}$	**C**: 122	f1	**1.7**: [001]	255
	(27)	f1 and f1A#	**1.9**: [001]	
U(P,S)	**C**			246
USb	**C**: 243	f1	>**2.6, 2.2**	260, 312
Perovskite and related structures (see also Fig. 5f-14)				
$DyAlO_3$	**O**: 3.48	{G A	**4.7**: [100] **7.2**: [010]	81, 195
$TbAlO_3$	**O**: 4.0	{G A	**6.9**: [100] **4.6**: [010]	82, 267
Ba_2CoWO_6	**C**: 17	f2 (Fig. 5f-13b)	**2.0**: 23°, [111]	143
$KCoF_3$	**C**: 135	G	**4.4**	353
$TbCoO_3$	**O**: 3.31	{A G}(Tb)	**6.4**: [100] **4.6**: [010]	267
$DyCrO_3$	**O**: 146	G(Cr)	**2.8**: [001]	70, 77
	(2.16)	complex(Dy)	**9.6**: ⊥[001]	
$ErCrO_3$	**O**: 133	G(Cr)	**2.9**: varies	70, 74
	(16.8)	C(Er)	**5.2**: [001]	
$HoCrO_3$	**O**: 140	G(Cr)	**2.9**: varies	62, 70
	(~12)	{F C}(Ho)	**3.4**: [100] **7.0**: [010]	
$KCrF_3$	**T**	A	**4.3**: ⊥[001]	353
$LaCrO_3$	**O**: 282	G	**2.5, 2.8**: ⊥[001]	70, 216, 296
$LuCrO_3$	**O**: 112	G	**2.5**: ⊥[010]; 63°, [100]	70
$NdCrO_3$	**O**: 224	G(Cr)	**2.6**: varies	70, 74
	(~10)	C(Nd)	**1.3**: [001	
$PbCrO_3$	**C**: 240	G	**1.9**	349
$PrCrO_3$	**O**: 239	G(Cr)	**2.5**: varies	70
	(>4.2)	F(Pr)	**0.5**: [001]	
$TbCrO_3$	**O**: 158	G(Cr)	**2.9**: [001]	70, 76, 267
	(4)	{F C}(Tb)		
	(3.05)	complex(Tb)	**8.5**: ⊥[001]	
$TmCrO_3$	**O**: 124	G(Cr)	**2.6**: varies	70
	(>4)	F(Tm)	**0.8**: [001]	

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* The use of f1 and f2 are explained in Fig. 5f-13; G, A, F, and C in Fig. 5f-14.

TABLE 5f-15. ANTIFERROMAGNETIC MATERIALS STUDIED BY NEUTRON DIFFRACTION (*Continued*)

Material	Crystal class and Néel temperature, K	Magnetic* structure	Moment (in μ_B) and direction	References
$YCrO_3$	**O**: 141	G	**3.0**: [100]	70
$YbCrO_3$	**O**: 118	G(Cr)	**2.8**: ⊥ [010]; 68°, [100]	70
$KCuF_3$	**T**	A	**05**: ⊥[001]	198
$LaErO_3$	**O**: 2.4	A G C	**1.1**: [100] **4.3**: [010] **4.5**: [001]	283
$BiFeO_3$	**C****: 673	G	**4.0**	211, 324
$ErFeO_3$	**O**: 620 (4.3)	G(Fe) C(Er)	**4.6**: varies **5.8**: [001]	218
$HoFeO_3$	**O**: 700 (6.5)	G(Fe) F C(Ho)	**4.6**: varies **3.4**: [100] **6.7**: [010]	218
$KFeF_3$	**C**: 115	G	**4.4**	353
$LaFeO_3$	**O**: 750	G	**4.4**, **4.6**	216, 296
$NdFeO_3$	**O**: 760	G(Fe)	**4.6**	218
Pb_2FeNbO_6	**C**	G	**0.8**	155
$Pb_3Fe_2WO_9$	**C**: 363	G	**3.3**	324
$RbFeF_3$	**C**: 105	G	**4.3**	396
Sr_2FeMoO_6	**T**: 450†	G	....	293
$TbFeO_3$	**O**:681 (8.4) (3.1)	G(Fe) F C(Tb) A G(Tb)	**4.8**: varies **2.4**: [100] **1.9**: [010] **6.6**: [100] **5.6**: [010]	75, 267
$TmFeO_3$	**O**	G(Fe)	varies	257
$CaMnO_3$	**C**: 110	G	**2.6**	414
$Ca_{0.85}Bi_{0.15}MnO_3$	**O**: 110	C G	....	389
$KMnF_3$	**C****: 88–95	G	**5.1**	353
$LaMnO_3$	**O**: 100	A	**3.9**: ⊥[001]	216, 414
$(La,Ca)MnO_3$	....	C and F††	....	414
$La(Mn,Cr)O_3$	....	....	....	57

NH_4MnF_3	**C**: 84	G	......	321
$NaMnF_3$	**C****: 60	G	......	321
$NdMnO_3$	**O**: 85	A(Mn)	**1.7**: ⊥[100]; 36°, [010]	340
$PrMnO_3$	**O**: 91	A(Mn)	**1.8**: [010]	340
$RbMnF_3$	**C**: 82	G	......	321
Mn_3GaN	**C**: 298	triangular	**2.3**: ⊥[111]	79
Ba_2NiWO_6	**C**	f2 (Fig. 5f-13b)	**1.9**: ⊥[111]	143
$KNiF_3$	**C**: 275	G	**2.2**	353
$NaNiF_3$	**O**: 149	G	[100]	159
$EuTiO_3$	**C**: 5.3	G	......	265
$TbVO_3$	**O**	C(V)	**1.3**: [100]	267, 272
		$\left\{\begin{matrix}C\\F\end{matrix}\right.$(Tb)	**5.9**: [100] **4.8**: [010]	
Spinel and related structures				
$CoAl_2O_4$	**C**: 4	(Fig. 5f-15a)?	......	347
$MnAl_2O_4$	**C**: 6.4	(Fig. 5f-15a)	**3.6**	347
Co_3O_4	**C**: 40	(Fig. 5f-15a)	**3.3**	348
$GeCo_2O_4$	**C**: 20	complex	**3.4**: ∼60°, [111]	62
		complex	**3.2**: [413] and [$\bar{1}$43]	333
$CoCr_2O_4$	**C**: 97† (31)	ferrimagnetic spiral	......	270
		complex	**2.5**(Co), **2.7** (Cr): ⊥[001]	334
$CuCr_2O_4$	**T**: 135†	(Fig. 5f-15b)	⊥[001]	294, 338
$FeCr_2O_4$	**C****: 80, 84† (35,42)	ferrimagnetic spiral	....	37, 358
$HgCr_2S_4$	**C**: 60	spiral	**2.7**: ⊥⟨100⟩	190
$MgCr_2O_4$	**C***: 15	complex	⊥[001]	336
$MnCr_2O_4$	**C**: 43† (18)	ferrimagnetic spiral	...... **4.3**(Mn), **2.0**(Cr_I), **3.1**(Cr_{II})	127, 157, 187
		complex	**3.1**(Mn), **3.0**(Cr): ⊥[001]	335
$NiCr_2O_4$	**T**: 65	unsolved	......	339
$ZnCr_2O_4$	**C**: 15	unsolved	......	184
$ZnCr_2Se_4$	**C**: 20	spiral	⊥[001]	330, 331
$GeFe_2O_4$	**C**: 10	complex	⊥[001]	332
$Mn(Fe,Cr)_2O_4$	......	......	......	264
$ZnFe_2O_4$	**C**: 9	complex	......	183
$MnGa_2O_4$	**C**: 33	(Fig. 5f-15a)	**3.6**: [111]	85
$CoMn_2O_4$ (various degrees of inversion)	**T**: 95–105† (70)	ferrimagnetic (Fig. 5f-15b)	...... **3.2**–**3.4**(tetr.): [110] **2.9**–**2.1**(oct.): ±58-39°, [110]	88

TABLE 5f-15. ANTIFERROMAGNETIC MATERIALS STUDIED BY NEUTRON DIFFRACTION *(Continued)*

Material	Crystal class and Néel temperature, K	Magnetic* structure	Moment (in μ_B) and direction	References
$CrMn_2O_4$	**T**: 65†	ferrimagnetic	....	89
	(>4.2)	(Fig. 5f-15b)	**4.1**(tetr.): [110]	
			1.7(oct.): ±23°, [110]	
$FeMn_2O_4$	**T**: 393†	ferrimagnetic	....	90
	(55)	complex	**4.3**(tetr.), **3.1**(oct.)	
$NiMn_2O_4$	**C**: 116–164†	ferrimagnetic	....	86, 87
(various degrees of inversion)	(70)	complex	**3.9**(tetr.), **1.3**(oct.)	
$GeNi_2O_4$	**C**: 15	complex	**2.2**: ⊥[111]	67
α-Mn_2TiO_4	**T**: 62	complex	**4.9**(Mn_I), **4.8** (Mn_{II} and	80
			Mn_{III}): ⊥[010]	
CoV_2O_4	**C**	complex?	....	156
MgV_2O_4	**C**: 45	complex	**1.1**: [001]	327
MnV_2O_4	**T**: 56†	ferrimagnetic	....	156, 326, 329, 337
	(52)	(Fig. 5f-15a)	**4.4–4.5**(Mn): [001]	
			1.2(V): ±ca.50°, [001]	
NiAs and related structures				
CrAs	**O**(Pnma): 300	spiral	....	400
Cr(Mn,As)	**O**	....	....	400
Cr_2FeSe_4	M	(Fig. 5f-16b)	**2.6**(Cr), **3.4**(Fe): 55°, [10$\bar{1}$]	111
Cr_2NiS_4	M	(Fig. 5f-16b)	**2.0**(Cr), **1.3**(Ni): 45°, [10$\bar{1}$]	24
Cr_2TiS_4	M	(Fig. 5f-16b)	....	253
CrS	**M**: 460	complex	**3.4**	380
Cr_2S_3	**H**: 125	spiral	**2.1**: ⊥[001]	250
Cr_2S_3	**R**: 122	complex	**2.4**: 61°, [001]	78
Cr_3S_4	**M**: 280	(Fig. 5f-16b)	**2.3**: 29°, [10$\bar{1}$]	25, 65
Cr_5S_6	**H**: 303†	ferrimagnetic	....	249
	(168)	spiral	**2.6–3.0**: ⊥[001]	
CrSb	**H**: 705, 723	(Fig. 5f-16a)	**2.7**, **2.8**: [001]	376, 384
Cr(Sb,Te)	**H**	canted††	....	139, 385
(Cr,Mn)Sb	**H**	canted††	....	139, 315, 384
CrSe	**H**: 300	triangular	**2.9**: mainly ⊥[001]	126
Cr_3Se_4	**M**: 80	(Fig. 5f-16b)	(10$\bar{1}$); 30°, [010]	65

CrTe	**H**: 330†	ferromagnetic	....	385
	(150)	ferromagnetic a.f. (101) sheets	~**1**	
Cr_3Te_4	**M**: 329†	ferromagnetic	....	65
	(80)	ferromagnetic Fig. 5f-16b)		
FeS	**H***: 600	(Fig. 5f-16a)	**4**: varies	18, 22
$Fe_{1-x}S$	....	(Fig. 5f-16a)	....	22, 365, 377, 378, 380
Fe_3Se_4	**M**	(Fig. 5f-16a)	**2.2**(Fe_I), **1.4**(Fe_{II}): [110]	23
Fe_7Se_8	**M**: 483, 460†	(Fig. 5f-16a)	**3.6**(Fe_I), **4.5**(Fe_{II}): varies	19, 208
MnP	**O**(Pnma): 291†	ferromagnetic	....	163,166
	(50)	spiral	1.3, **1.6**: ⊥[001]	
MnTe	**H**: 320, 323	(Fig. 5f-16a)	**4.6**: ⊥[001]	154, 244, 370
NiS	**H**: 263	(Fig. 5f-16a)	1.7: [001]	379, 380
Rutile and related structures				
CoF_2	**T**: 50	(Fig. 5f-17a)	**3.0**: [001]	161
$CrCl_2$	**O**: 20	complex	~**3**: along long Cr-Cl	98
CrF_2	**M**: 53	(Fig. 5f-17a)	~**3**: along long Cr-F	98
Cr_2TeO_6	**T**: 105	G (Fig. 5f-17b)	**2.5**: ⊥[001]	242, 280
Cr_2WO_6	**T**: 69	A (Fig. 5f-17b)	**2.1**: ⊥[001]	242, 278, 280
FeF_2	**T**: 90	(Fig. 5f-17a)	**4.6**: [001	161
FeOF	**T**: 315	(Fig. 5f-17a)	**4.8**: [001	109
Fe_2TeO_6	**T**: 219	G (Fig. 5f-17b)	**4.2**, **4.7**: [001]	242, 279
$Mn_{0.5}Cr_{0.5}O_2$	**T**: 390†	(Fig. 5f-17a) ferromagnetic	**0.5**: ⊥[001 **0.4**: ⊥[001]	395
MnF_2	**T**: 75	(Fig. 5f-17a)	**5.0**: [001]	161, 295
MnO_2	**T**: 84	spiral	⊥[001]	160, 422
NiF_2	**T**: 83	(Fig. 5f-17a)	**5.0**: 10°, [001]; ⊥[001	161
		(Fig. 5f-17a)	⊥[001]	8
VF_2	**T**: 7	spiral	⊥[001]	256
V_2WO_6	**T**	A(Fig. 5f-17b)	....	242
Olivine and related structures (see also Fig. 5f-18)				
$CaCoSiO_4$	**O**(Pbnm): 16	complex	....	305
Co_2SiO_4	**O**(Pbnm): 49	C(Co_I)	**3.3**: [001]	307
		C(Co_{II})	**3.3**: [001]	
$LiCoPO_4$	**O**(Pbnm): 23	A	[001]	351
Cr_2BeO_4	**O**(Pbnm): 28	spiral	**1.6**(Cr_I), **2.8**(Cr_{II}): ⊥[010]	146

TABLE 5f-15. ANTIFERROMAGNETIC MATERIALS STUDIED BY NEUTRON DIFFRACTION (*Continued*)

Material	Crystal class and Néel temperature, K	Magnetic* structure	Moment (in μ_B) and direction	References
Fe_2SiO_4	O(Pbnm): 65	C(Fe_I)	[001]	350
		C(Fe_{II})	[001]	
		C	[001]	
	(23)	G(Fe_I)	[100]	
		A	[010]	
		C	**3.2**: [001]	141
	65	A(Fe_I)	**2.1**: [100]	
		G	**1.1**: [010]	
		C(Fe_{II})	**3.9**: [001]	
$LiFePO_4$	O(Pbnm): 50	A	**3.8**: [001]	352
$CaMnSiO_4$	O(Pbnm): 9	G	[100]	108
$LiMnPO_4$	O(Pbnm): 35	A	**5.2**: [010]	303
Mn_2SiO_4	O(Pbnm): 50	C(Mn_I)	[010]	350
		C(Mn_{II})	[010]	
	(13)	C	[010]	
		G(Mn_I)	[100]	
		C	**3.6**: [010]	141
		G(Mn_I)	**3.6**: [001]	
		C(Mn_{II})	**4.7**: [010]	
$LiNiPO_4$	O(Pbnm): 23	A	[100]	351
Ni_2SiO_4	O(Pbnm): 34	complex	⊥[001]	302
PbFCl and related structures				
UAs_2	T: 283	(Fig. 5f-19b)	**1.6**: [001]	309
UBi_2	T: 183	(Fig. 5f-19a)	**1.6**: [001]	259
UOS	T: 55	(Fig. 5f-19c)	**1.9**: [001]	50
UOSe	T: 90	(Fig. 5f-19c)	**2.2**: [001]	287
UOTe	T: 160	(Fig. 5f-19a)	**2.7**: [001]	286
UP_2	T: 203	(Fig. 5f-19b)	**1.0**: [001]	387
USb_2	T: 206	(Fig. 5f-19b)	**0.9**: [001]	259
Corundum and related structures				
$CoTiO_3$	R: 38	(Fig. 5f-20c)	⊥[001]	300

$Nb_2Co_4O_9$	**H**: 30	f. [001] chains	$\sim$**3**: [001]	58
Cr_2O_3	**R**: 318	(Fig. 5f-20a)	**2.8**: [001]	91, 131
α-Fe_2O_3	**R**: 948	(Fig. 5f-20b)	$\sim$**5**: varies	122, 135, 147, 284, 297, 320, 342, 363
α-$(Fe,Cr)_2O_3$	**R**	spiral††	....	137
α-$(Fe,Rh)_2O_3$	....	....	....	235
α-$(Fe,V)_2O_3$	....	....	....	235
$FeTiO_3$	**R**: 68	(Fig. 5f-20c)	$\sim$**4.0**: [001]	355
α-Fe_2O_3–$FeTiO_3$	**R**	ferrimagnetic††	....	357
$MnTiO_3$	**R**: 41	a.f. (001) sheets	**4.6**: [001]	354
$Nb_2Mn_4O_9$	**H**: 125	f. [001] chains	$\sim$**5**: [001]	58
$NiTiO_3$	**R**	(Fig. 5f-20c)	**2.3**: $\perp$[001]	354
$CrVO_4$ type structures (see also Fig. 5f-21)				
α-$CoSO_4$	**O**: 15.5	C	**2.9**: [010]	144, 168
		G	**1.4**: [001]	
β-$CrPO_4$	**O**: 22	spiral	**2.5**: $\perp$[001]	145
$CrVO_4$	**O**: 50	A	**2.1**: 27°, [100]; 64°, [010]; 81°, [001]	168
$FeSO_4$	**O**: 21	C	**4.1**: [010]	168
$MnSO_4$	**O**	spiral	**4.8**	411
$NiSO_4$	**O**: 37	C	**2.1**: [010]	168
$NiSeO_4$	**O**	A	$\perp$[001]	171
$CuSO_4$ type structures (see also Fig. 5f-21)				
β-$CoSO_4$	**O**: 12	A	**2.3, 2.7**: [100]	61, 93
		G	**1.5, 1.9**: [010]	
		C	**1.7, 1.9**: [001]	
$CoSeO_4$	**O**	A	....	171
		G		
		C		
$CuSO_4$	**O**: 35	A	**0.8**: [100]	14, 271
$MnSeO_4$	**O**: 20	A	**5.0**: [100]	171
Calcite type structures				
$CoCO_3$	**R**: 20.4	(Fig. 5f-22)	46°, [001]	9
$FeCO_3$	**R**: 20	(Fig. 5f-22)	**5.0**: [001]	7, 317
$MnCO_3$	**R**: 32	(Fig. 5f-22)	$\perp$[001]	7, 95, 316
$NiCO_3$	**R**: 25	(Fig. 5f-22)	63°, [001]	10

TABLE 5f-15. ANTIFERROMAGNETIC MATERIALS STUDIED BY NEUTRON DIFFRACTION (*Continued*)

Material	Crystal class and Néel temperature, K	Magnetic* structure	Moment (in μ_B) and direction	References
Garnet type structures				
$Dy_3Al_5O_{12}$	**C**: 2.49, 2.54	a.f. [100] chains	**9.0, 9.5**: ⟨100⟩	188, 195
$Er_3Ga_5O_{12}$	**C**: 0.79	a.f. [100] chains	**5.9**: ⟨100⟩	180
$Ho_3Al_5O_{12}$	**C**: 0.95	a.f. [100] chains	**5.8**: ⟨100⟩	181
$Nd_3Ga_5O_{12}$	**C**: 0.52	f. [100] chains	**3.6**: ⟨100⟩	179
$Tb_3Al_5O_{12}$	**C**: 1.35	a.f. [100] chains	**5.7**: ⟨100⟩	181
$YMnO_3$ type structures (see also Fig. 5f-23)				
$ErMnO_3$	**H**: 79	triangular	**3.5**(Mn): ⊥[001]; 70° ⟨100⟩	221
$HoMnO_3$	**H**: 76	triangular	**3.5**(Mn): ⟨100⟩	221
$LuMnO_3$	**H**: 91	triangular	**3.7**(Mn): ⊥[001]; 55°, ⟨100⟩	221
$ScMnO_3$	**H**: ∼120	triangular	∼**4.0**: ⊥[001]; ≃24°, ⟨100⟩	221
$TmMnO_3$	**H**: ∼86	triangular	∼**3.8**(Mn): ⊥[001]; ∼45°, ⟨100⟩	221
$YMnO_3$	**H**: 80	triangular	**3.5**: ⟨100⟩	62, 64, 69, 221
VF_3 and related structures				
CoF_3	**R**: 460	(Fig. 5f-22)	**4.4**: [001]	416
CrF_3	**R**: 80	(Fig. 5f-22)	**3.0**: ⊥[001]	416
FeF_3	**R**: 394	(Fig. 5f-22)	∼**5.0**: ⊥[001]	416
MnF_3	**M**: 43	f. (101) sheets	**4.0**: (101)	416
MoF_3	**R**: 185	(Fig. 5f-22)	∼**3**: ⊥[001]	407
Miscellaneous anhydrous halides				
$CoBr_2$	**H**: 19	(Fig. 5f-24a)	**2.8**: ⊥[001]	405
$CoCl_2$	**R**: 25	(Fig. 5f-24b)	**3.0**: ⊥[001]	405
$CoCs_3Cl_5$	**T**: 0.52	f. (101) sheets	**3.2**: [001]	182
$CrCl_3$	**H**: 17	(Fig. 5f-24b, with vacancies)	**2.7**: ⊥[001]	99
$FeBr_2$	**H**: 11	(Fig. 5f-24a)	**4.4**: [001]	405
$FeCl_2$	**R**: 24	(Fig. 5f-24b)	**4.5**: [001]	192, 405
$FeCl_3$	**R**: 15	spiral	**4.3**: ⊥[140]	102
K_2IrCl_6	**C**: 3.05	f3A (Fig. 5f-13c)	[001]	197, 275
Cs_2MnCl_4	**T**	(Fig. 5f-24c)	[001]	202

$CsMnF_3$	**H**: 64	f. (001) sheets	⊥[001]	321
K_2MnF_4	**T**	(Fig. 5f-24c)	**4.5**: [001]	263
$MnBr_2$	**H**: 2.16	complex	[010]	217, 415
MnI_2	**H**: 3.4	spiral	**4.6**: ⊥[307]	101
K_2NiF_4	**T**: 97	(Fig. 5f-24c)	[001]	83, 325, 328
$RbNiF_3$	**H**	complex	....	322
K_2ReBr_6	**C****: 15.3	f1 (Fig. 5f-13a)	⊥[001]?	275
K_2ReCl_6	**C****: 11.9, 12.4	f1 (Fig. 5f-13a)	**2.6**, **2.7**: ⊥[001]	275, 374
α-$RuCl_3$	**H**: ~30	....	~**0.2**	164
Miscellaneous oxides				
$Co_3B_2O_6$	**O**: 30	complex	....	301, 304
$CoUO_4$	**O**: 12	f. (111) sheets	**4.2**(Co): ⊥[010]	59
β-$CaCr_2O_4$	**O**	complex	....	133
$CrUO_4$	**O**	A(Cr) (Fig. 5f-25) A(U)	**2.4**: [010] **0.3**: [010]	38
CuO	**M**: 230	f (10$\bar{1}$) sheets	....	92
Er_2O_3	**C**: 3.36	complex	**6.1**(Er_I): ⟨111⟩ **5.4**(Er_{II}): ⟨100⟩	71, 282
$Ba_{0.4}Sr_{1.6}Zn_2Fe_{12}O_{22}$	**H**: 400† (380)	ferrimagnetic spiral	.... ⊥[001]	314, 371, 372
$BaCoFe_{17}O_{27}$	**H**	spiral	....	419
$BaSc_{1.8}Fe_{10.2}O_{19}$	**H**	spiral	....	6
$CaFe_2O_4$	**O**: 200, 285 (120–170,140)	a.f. chains#	**4.1**–**4.4**: [001]	13, 72, 133, 399
$Ca(Fe,Cr)_2O_4$	**O**	....	....	133
$Ca_2Fe_2O_5$	**O**: 720, 730	complex	**4.5**, **4.9**: [001]	131, 170, 383
$FeSb_2O_4$	**T**	A C (Fig. 5f-21) G	**3.5**: ⊥[001]	175
$FeTi_2O_5$	**O**	a.f. [100] chains	....	273
$FeWO_4$	**M**: 66	f. (100) sheets	**4.4**: ⊥[010]; 29°, [100]	390
$LiFeO_2$	**T**: ~315	complex	**4.5**: [001]	138
β-$NaFeO_2$	**O**: 723	f. (101) sheets	**4.2**: [001]	63
$FeUO_4$	**O**: 55 (42†)	C(Fe) C F (Fe) (Fig. 5f-25) C(U)	[010] **2**: [100] **4**: [001] **0.4**: [100]	40, 41
Gd_2O_3	**C**: ~1.6	unsolved	....	115
$BiMn_2O_5$	**O**: 52	complex	⊥[001]	73

TABLE 5f-15. ANTIFERROMAGNETIC MATERIALS STUDIED BY NEUTRON DIFFRACTION (*Continued*)

Material	Crystal class and Néel temperature, K	Magnetic* structure	Moment (in μ_B) and direction	References
$CaMn_2O_4$	**O**: 225	complex	**3.6**: [100]	12
$Mn_3B_2O_6$	**O**	spiral?	…	304
α-Mn_2O_3	**C**: 90	unsolved	…	110
$MnUO_4$	**O**: (~50)12	f. (100) sheets	**4.9**: [010]	39
$MnWO_4$	**M**: 16	complex	$[10\bar{1}]$	151
$Ni_3B_2O_6$	**O**: 49	complex	…	304
CaV_2O_4	**O**	complex	**1.1**: [010]	189
UO_2	**C**: 30.8, 30.6	f1 (Fig. 5f-13a)	**1.8**: ⊥[001]	169, 191, 413
Yb_2O_3	**C**: 2.25	complex	**1.1**(Yb_I): ⟨111⟩ **1.9**(Yb_{II}): ⟨110⟩	282
Miscellaneous chalcogenides				
$AgCrSe_2$	**R**: 50	(Fig. 5f-24b)	**2.7**: ⊥[111]	252
$NaCrSe_2$	**R**: 40	(Fig. 5f-24b)	**2.3**: ⊥[111]	252
$CuFeS_2$	**T**	f. (001) sheets	**3.9**: [001]	153
$FeNb_3S_6$	**H**	complex	**3.7**: [001]	251
FeS_2	**C**	f2 (Fig. 5f-13b)	…	84
β-MnS	**C**	f3A	**5**: ⊥[001]	123
β-MnS	**H**	complex	**5**: ⊥(011)	123
MnS_2	**C**	f3A (Fig. 5f-13c)	**5**: [001]	185
$MnSe_2$	**C**	complex	**5**: [001]	130, 185
$MnTe_2$	**C**	f1 (Fig. 5f-13a)	**5**: ⊥[001]	185
Miscellaneous hydrates				
$CoCl_2 \cdot 2D_2O$	**M**: 17.5	f. [001] chains	**2.8**: [010]	140, 142
$CoCl_2 \cdot 6H_2O$	**M**: 2.25	a.f. (001) planes	[001]	213
$CuCl_2 \cdot 2D_2O$	**O**: 4.3	$\left\{\begin{matrix}A\\G\end{matrix}\right.$(Fig. 5f-21)	**~1**: [100] **~0.1**: [001]	360, 373, 392
$CuF_2 \cdot 2H_2O$	**M**: 10.9	(Fig. 5f-17a)	**0.8**: ~[001]	1
$LiCuCl_3 \cdot 2H_2O$	**M**: 4.4	a.f. [100] chains	**~1**: ⊥[010]; 49°, [001]; 158°, [100]	3
$Fe_3(PO_4)_2 \cdot 4H_2O$	**M**: 15†	complex	**4.6**: ~⊥[100]; 10°, (101)	4
$Fe_2SO_4 \cdot H_2O$	**M**	f. (100) sheets	⊥[010]	261
$NiCl_2 \cdot 6H_2O$	**M**	f. (101) sheets	10°, [100]	214

CaC_2 and related xtructures				
$AlCr_2$	**T**: 598	f. (001) sheets in sequence(+ − − +)	**0.9**: 65°, [001]	29
$MnAu_2$	**T**: 363	spiral	**3.0**: ⊥[001]	193, 194
CeC_2	**T**: 33	(Fig. 5f-17a)	**1.7**: [001]	30
DyC_2	**T**: 59	sinusoidal	**11.8**: [001]	33
HoC_2	**T**: 26	spiral	**6.9**: ⊥[100]	30
NdC_2	**T**: 29	(Fig. 5f-17a)	**3.0**: [001]	30
PrC_2	**T**: 15	(Fig. 5f-17a)	**1.1**: [001]	30
$TbAu_2$	**T**: 55	sinusoidal	[001]	31
	(42.5)	f. (100) sheets	**9.0**: [001]	
$TbAg_2$	**T**: 35	f. (100) sheets	**9.0**: [001]	32
TbC_2	**T**: 66 (40)	spiral	**5.1**: ⊥[100]	30, 32
α-KO_2	**T****: 7.1	f. (001) sheets	~**1**(O_2^-); ⊥[001]	375
CsCl and related structures (see also Fig. 5f-14)				
DyAg	**C**: 51	C	**9.8**: [001]	26
FeRh	**C**: 678†	F	....	359
	(338)	G	**3.3**	
Fe-Rh	....	....	....	60, 233, 285, 359
AuMn	**C***: 515	A	⊥[001]	44, 46
	(403)	A	**4.1**: [100] and [001]∥	
Au-Mn	....	....	....	46
Au_2MnAl	**C**: 147†	F	....	49
(ordered)	(65)	spiral	**4.4**: ⊥[001]	
$Au_2(Mn,Al)_2$	....	....	....	49
MnHg	**C***: 460	G	**3.7**, **3.9**: varies	291, 310, 311
β-MnZn	**C**	{F {G	**1.7** **2.9**	196, 192
Pd_2MnAl (disordered)	**C**: 240	G	**4.4**	402
Pd_2MnIn (disordered)	**C**	G	**4.3**	401
Pd_2MnIn (ordered)	**C**: 142	f2 (Fig. 5f-13b)	**4.3**: ⊥[111]	401
TbAg	**C**: 100	C	~**9.0**: [001]	104
Tb(Ag,In)	**C**	....	⊥[001]	107
Tb(Ag,Pd)	**C**	....	....	107
TbCu	**C**: 115	C	~**8.9**: [001]	104

TABLE 5f-15. ANTIFERROMAGNETIC MATERIALS STUDIED BY NEUTRON DIFFRACTION (*Continued*)

Material	Crystal class and Néel temperature, K	Magnetic* structure	Moment (in μ_B) and direction	References
CuAu-I and related structures				
CrPt	**C**	(Fig. 5f-26)	**2.2**: ⊥[001]	319
MnNi	**T**: 1073	(Fig. 5f-26)	**3.8**, **4.0**: ⊥[001]	205, 313
Mn-Ni	**T**	...	...	313, 368, 369
MnPd	**T**: 813	(Fig. 5f-26)	**4.4**: ⊥[001]	212, 238, 313
Mn_2Pd_3	**T**: 643, 653	(Fig. 5f-26)	**4.1**, **4.3**: ⊥(001)	176, 215, 239
$Mn_{11}Pd_{21}$	**T**	(Fig. 5f-26)	**4.0**: ⊥[001]	212
Mn-Pd	**T**	...	...	212, 313
MnPt	**T**: 973, 970	(Fig. 5f-26)	**4.3**: varies	20, 313
Mn-Pt	**T**	...	...	20, 21, 313
Cu_3Au and related structures				
Pt_3Fe	**C**: 170	C(Fig. 5f-14)	**3.4**: [001]	47, 209, 236
Pt-Fe	...	...	⊥[001]	47
$Pt_{3-x}(Fe,Mn)_{1+x}$	...	...	...	48
$(Pt,Pd)_3Fe$	**C**	...	...	210, 232
Mn_3Pt	**C**: 475	complex	[001]	241, 416
	(365)	triangular	**3.0**: ⟨112⟩	
	523	...	...	366
	(388)			
Mn-Pt	**C**	...	...	241
$Mn_3(Pt,Rh)$	**C**	...	...	241
$(Mn,Fe)_3Pt$	**C**	...	...	240, 241
Mn_3Rh	**C**: 855	triangular	**3.5**: ⟨112⟩	229, 241
Pd_3Mn	**T**: 170	complex	**4.0**(Mn), **0.2**(Pd): ⊥[001]	103
α-Zn_3Mn	**C***: 150	A (Fig. 2)	**2.5**: ⊥[001]	292
Cu_2Sb and related structures				
Cr_2As	**T**: 393	complex	**1.1**(Cr_I), **1.2**(Cr_{II}): ⊥[001]	397
Fe_2As	**T**: 353	(Fig. 5f-27c)	**1.0**(Fe_I), **1.5**(Fe_{II}): ⊥[001]	207
FeMnAs	**T**	(Fig. 5f-27a)	**0.2**(Fe), **3.6**(Mn): ⊥[001]	421
Mn_2As	**T**: 573	(Fig. 5f-27a)	3.7(Mn_I), **3.5**(Mn_{II}): ⊥[001]	34
Mn_2Sb	**T**: 550†	(Fig. 5f-27b)	**2.1**(Mn_I), **3.9**(Mn_{II}): varies	17, 404
$Mn_2Sb_{0.7}As_{0.3}$	**T**	(Fig. 5f-27b)	[001]	34
	(308–388)	(Fig. 5f-27a)	2.3(Mn_I), **2.8**(Mn_{II}): ⊥[001]	

$Mn_{1.9}Cr_{0.1}Sb$	**T**	(Fig. 5f-27b)	[001]	120
		(Fig. 5f-27a)	**1.4**(Mn_I), **2.8**(Mn_{II}): [001]	
$Mn_{1.97}Cr_{0.03}Sb$	**T**	(Fig. 5f-27b)	varies	35
	(135)	complex	⊥[001]	
	(115)	(Fig. 5f-27a)	**1.8**(Mn_I), **3.7**(Mn_{II}): ⊥[001]	
$Mn_{1.9}Cr_{0.1}Sb_{1.95}In_{0.05}$	**T**	(Fig. 5f-27b)	[001]	119
		(Fig. 5f-27a)	⊥[001]	
$(Mn,Cr)_2Sb$	**T**	. . . .	. . . .	35
Rare-earth metals and alloys (see also Fig. 5f-28)				
Ce	**H**: 12.5	complex	**0.6**: [001]	408
Dy	**H**: 179	spiral	**9.5** ⊥[001]	409
	(90†)	ferromagnetic		
Er	**H**: 80	sinusoidal	**7.6**: [001]	100, 106
	(52)	complex	**9.0**	
	(20†)	spiral		
Eu	**C**: 91	spiral	**5.9**: ⊥[100]	298
Ho	**H**: 130	spiral	⊥[001]	222, 225, 393
	(~40)	distorted spiral	⊥[001]	
	(~20†)	distorted spiral	**9.5**	
Nd	**H**: 19	sinusoidal (Nd_1)	**2.3**: [10$\bar{1}$0]	281
	(7.5)	sinusoidal (Nd_2)	**1.8**: 30°, [10$\bar{1}$0]	
Pr	**H**: 25	sinusoidal	. . . .	105
Tb	**H**: 226, 229	spiral	⊥[001]	152, 220, 393
	(216,221†)	ferromagnetic		
Tm	**H**: 56	sinusoidal	[001]	219
	(40)	antiphase	**7.0**: [001]	
ErAl	**O**: 10	complex	**7**: ⊥[001]	55
HoAl	**O**: 26†	complex	**8.4**: ⊥[001]	54
TbAl	**O**: 72	complex	**8.8**: ⊥[001]	56
$TbMn_2$	**C**: 40	spiral	**5.0**-**8.0**(Tb), **1.1**-**2.5**(Mn): ⊥[001]	129
$TbNi_2$	**C**: 46†	{F {G	**7.2**(Tb): [111]? ⊥[111]?	162
Dy-X (X = Er,Y)	. . . .	. . . .	. . . .	113
Er-X (X = Ho,Sc,Th,Y)	. . . .	. . . .	. . . .	113, 116, 117, 224, 274, 361
Gd-X (X = Sc,Y)	. . . .	spiral††	. . . .	118

TABLE 5f-15. ANTIFERROMAGNETIC MATERIALS STUDIED BY NEUTRON DIFFRACTION (*Continued*)

Material	Crystal class and Néel temperature, K	Magnetic* structure	Moment (in μ_B) and direction	References
Ho-X (X = Sc,Tb,Th,Y)	...	...	...	113, 116, 117, 224, 258
Nd-Th	...	...	...	116
Pr-Th	...	...	...	116
Tb-X (X = La,Lu,Sc,Th,Y)	...	...	...	113, 114, 116, 117, 220, 226
Tm-Y	...	...	...	113
Transition metals and miscellaneous alloys and intermetallic compounds				
Cr	**C**: 311.5 (115)	sinusoidal sinusoidal	$\perp\langle 100\rangle$ **0.6**: $\langle 100\rangle$	27, 45, 53, 94, 97, 124, 172, 174, 186, 276, 356, 364, 394, 403, 406
Cr$_{1-x}$Co$_x$ ($x \leq 0.053$)	**C**	(Fig. 5f-17a)††	...	158
Cr$_{1-x}$Fe$_x$ ($x \leq 0.047$)	**C**	(Fig. 5f-17a)††	...	28, 199
Cr$_{1-x}$Mn$_x$ ($x \leq 0.48$)	**C**	(Fig. 5f-17a)††	...	52, 173, 177, 178, 204, 243, 277
Cr$_{0.995-x}$Mn$_x$V$_{0.005}$ ($x \leq 0.025$)	**C**	(Fig. 5f-17a)††	...	228
Cr$_{1-x}$Ni$_x$ ($x \leq 0.01$)	**C**	...	...	158
Cr$_{1-x}$Re$_x$ ($x \leq 0.008$)	**C**	(Fig. 5f-17a)††	...	277
Cr$_{1-x}$V$_x$ ($x \leq 0.02$)	**C**	...	...	178, 227, 277
Cr$_{1-x}$X (X = V,Mn,Nb,Mo,Tc,Ru,Rh, Ta,W,Re)	**C**	(Fig. 5f-17a) in a number of cases for $x >$ ca. 0.01	...	223
CrAu$_4$	**T**: ~400	...	...	386
γ-Cu$_x$Mn$_{1-x}$ ($0.05 \leq 0.31$)	**C***	fl (Fig. 5f-13a)	[001]	43, 269

γ-Fe	**C**: 8	fl (Fig. 5f-13a)	**0.7**: 19°, [001]	2
FeGe	**H**: 410	(Fig. 5f-29)	**1.7**: [001]	5, 398
$Fe_{1.77}Ge$	**H**: 500†	complex	**1.3**(Fe_{I}), **1.1**(Fe_{II}): ⊥[001]	206
$FeGe_2$	**T**: 270, 315	$\left\{\begin{matrix} C \\ G \end{matrix}\right.$ (Fig. 5f-21)	⊥[001] ⊥[001]	165
		C (Fig. 5f-21)	⊥[001]	68, 234, 289
$(Fe,Mn)_5Ge_3$	**H**	. . . .	. . . .	36, 381
Fe_3Mn	**C**: 425	pyramidal	**1.7**: ⟨111⟩	230
$Fe_{0.69}Mn_{0.31}$	**C**: 435	pyramidal	**1.5**: ⟨111⟩	391
γ-Fe-Mn	**C**	. . . .	. . . .	200, 201
$(Fe,Ni)_3Mn$	**C**	. . . .	. . . .	230
FeSn	**H**: 373	(Fig. 5f-29)	**1.5**: ⊥[001]	418
$FeSn_2$	**T**: 384	C (Fig. 5f-21)	**1.6**	202, 306
α-Mn	**C**: 95	complex	**0.1**–**1.8**	203, 245, 308, 364
Mn_3Ge	**H**: 360	triangular	**2**: varies	229
$Mn_3(Pt,Rh)$ (disordered)	**C***	fl (Fig. 5f-13a)	[001]	237
Mn_5Si_3	**H**: 68	sinusoidal	**0.4**(Mn_{I}), **1.2**(Mn_{II}): ⊥[001]	254
Mn_3Sn	**H**: 420	triangular	**2.5**: ⊥arbitrary [hkO]	229
	~(270)	spiral		
$(Mn,Fe)_3Sn$	**H**	. . . .	. . . .	231
$MnSn_2$	**T**: ~325	f. (110) sheets[a]	**2.3**: [110]	128, 134
	(~74)	f. (110) sheets in sequence + + − −	**2.3**: [110]	
Other compounds				
α-FeOOH	**O**(Pbnm): 362, 403	f. (001) sheets	**5**: [001]	167, 382
HoD_2	**C**: 8	unsolved	. . . .	136
Mn_2N	**O**: 301	complex	**1.6**: [001]; 15°, [100]	268
MnOOH	**O**: ~40	spiral	. . . .	150
Mn_2P	**H**: 103	sinusoidal	~0(Mn_{I}), **0.8**(Mn_{II}): ⊥⟨100⟩	420
α-O_2	**M**(C2/m): 24	f. (100) sheets	⊥(001)	51, 121
		f. (100) sheets	[010]	11
TbD_2	**C**: 40	sinusoidal	**7.9**: [001]	136

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[a] There is also a small sinusoidal component in the region $74 < T < 90$ K.

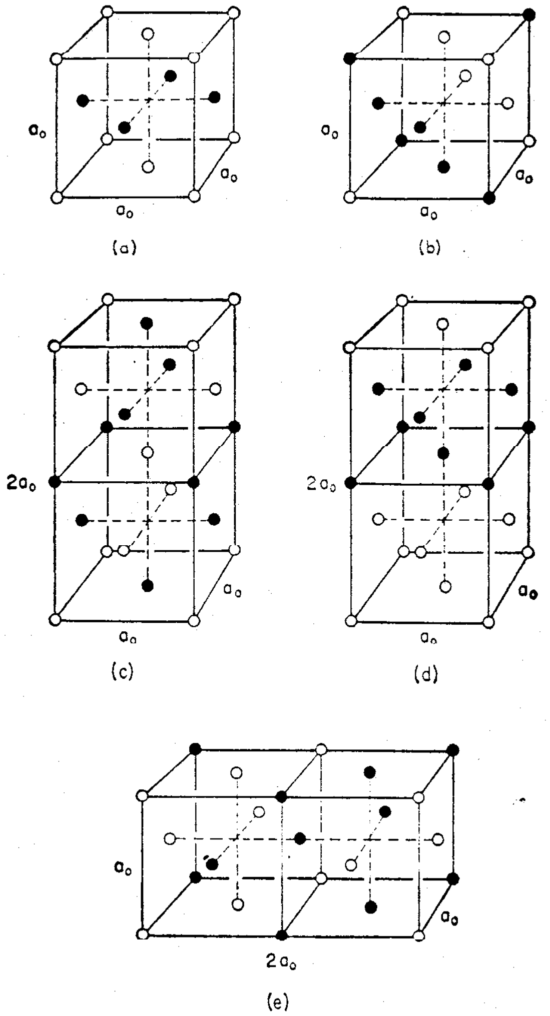
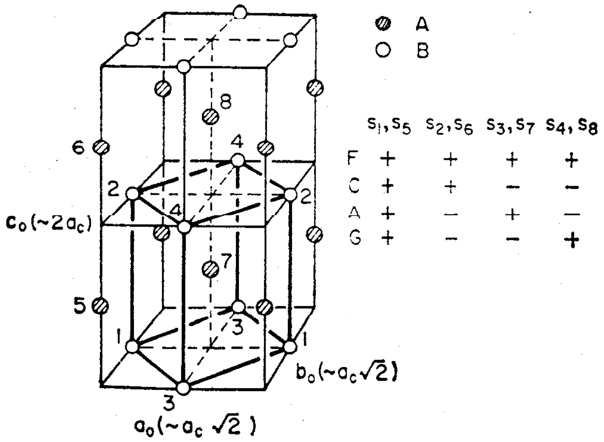


FIG. 5f-13. Ordering in f.c.c. structures: (*a*) type 1(f1), (*b*) type 2(f2), (*c*) type 3A (f3A), (*d*) type 1A(f1A), (*e*) type 4(f4).



	s_1,s_5	s_2,s_6	s_3,s_7	s_4,s_8
F	+	+	+	+
C	+	+	−	−
A	+	−	+	−
G	+	−	−	+

FIG. 5f-14. Ordering in orthorhombic perovskite (ABO_3) type structures. The ideal simple cubic cell (a_c) is shown in heavy outline.

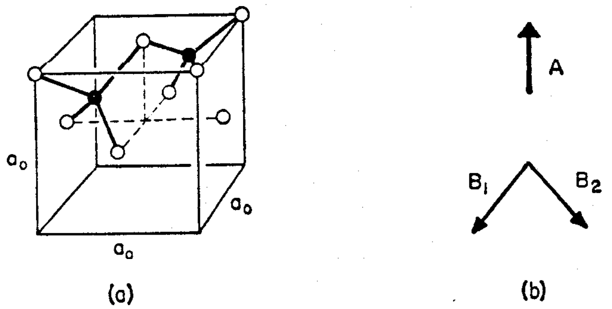


FIG. 5f-15. Ordering in spinel-type structures: (*a*) tetrahedral (*A*) nearest neighbors antiparallel, (*b*) schematic Yefet-Kittel canting of octahedral (*B*) moments.

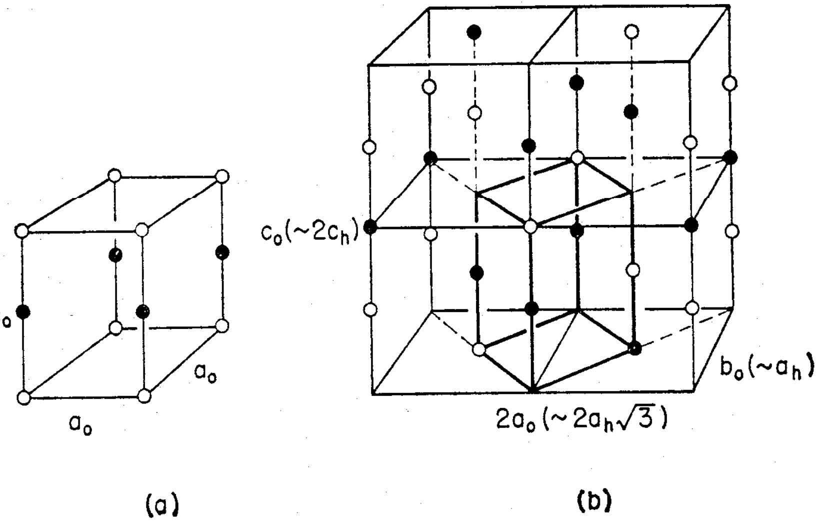


FIG. 5f-16. (*a*) CrSb and (*b*) Cr_3S_4 type magnetic structures. The ideal hexagonal cell (a_h, c_h) is shown in heavy outline in the latter case.

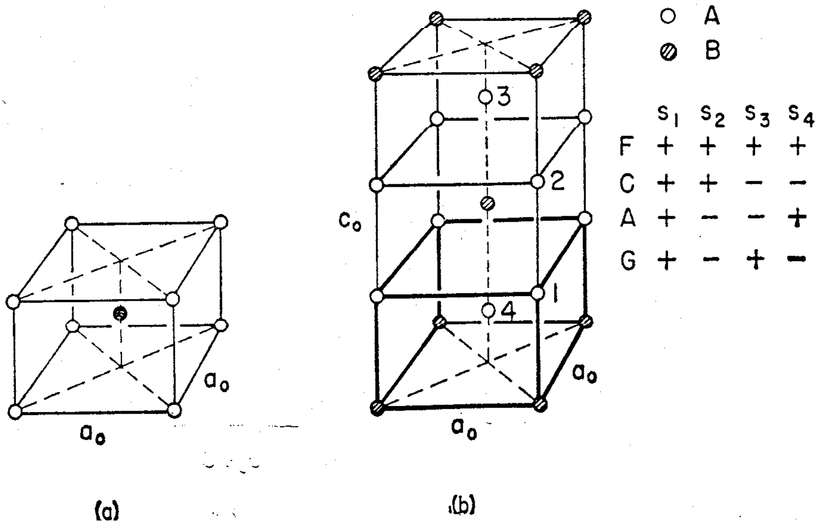
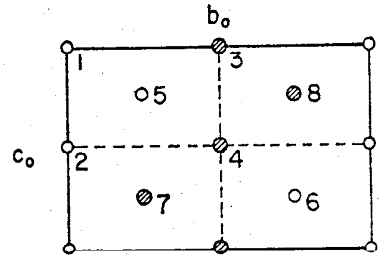


FIG. 5f-17. (*a*) b.c. tetragonal antiferromagnetic MnF_2 type structure; (b) ordering in trirutile (A_2BO_6) type structures. *B* is a nonmagnetic ion. The rutile cell is shown in heavy outline.



○ x = 0.0
⊘ x = 0.5

	s_1, s_5	s_2, s_6	s_3, s_8	s_4, s_7
F	+	+	+	+
C	+	+	−	−
A	+	−	+	−
G	+	−	−	+

FIG. 5f-18. Ordering in olivine (Mg_2SiO_4) type structures projected on (100)-*Pbnm* orientation. Atoms 5 to 8 have been placed in idealized positions.

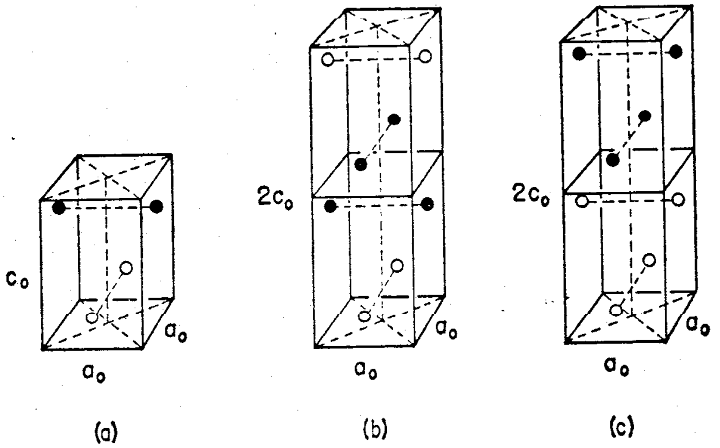


FIG. 5f-19. (*a*) UBi_2, (*b*) UAs_2, and (*c*) UOS type magnetic structures.

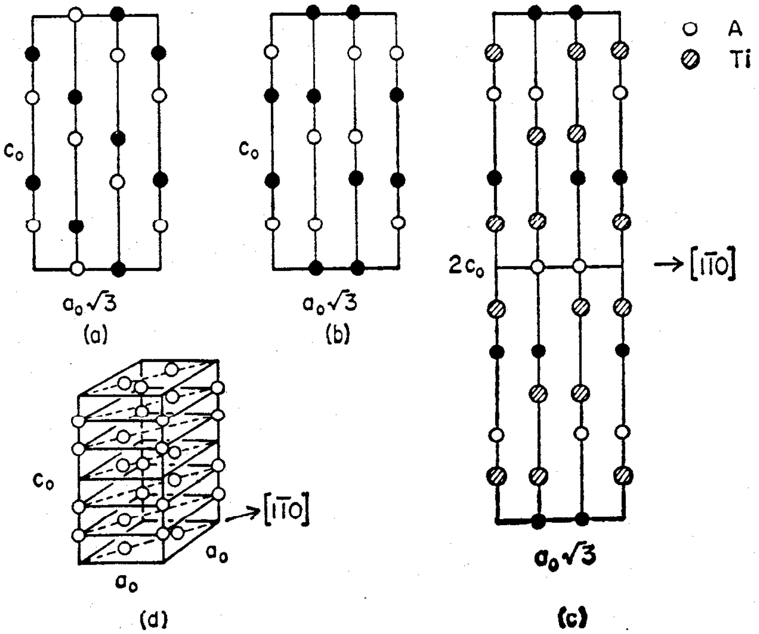
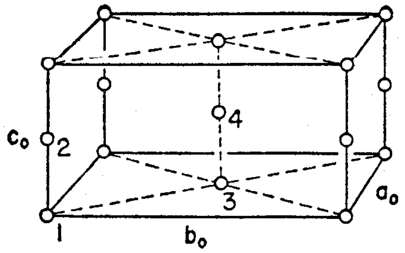


FIG. 5f-20. (*a*) Cr_2O_3, (*b*) Fe_2O_3, and (*c*) $FeTiO_3$ type magnetic structures projected on (110). (*d*) cation positions in corundum and related structures.



	s_1	s_2	s_3	s_4
F	+	+	+	+
C	+	+	−	−
A	+	−	+	−
G	+	−	−	+

FIG. 5f-21. Ordering in $CrVO_4$ and $CuSO_4$ type structures.

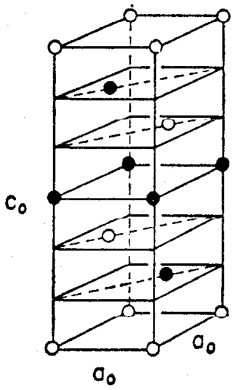


FIG. 5f-22. $MnCO_3$ (and CoF_3) type magnetic structure.

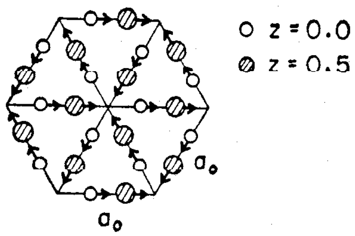
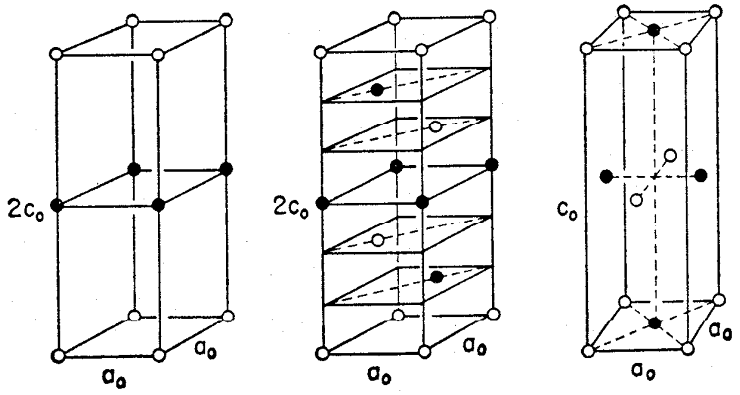
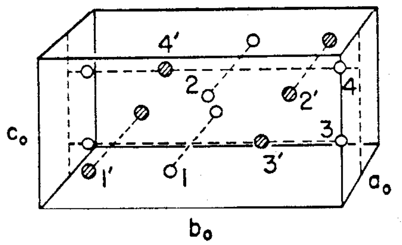


FIG. 5f-23. $YMnO_3$ type magnetic structure projected on (001).



(a) (b) (c)

FIG. 5f-24. (*a*) $CoBr_2$, (*b*) $CoCl_2$, and (*c*) K_2NiF_4 type magnetic structures.



○ Cr or Fe

⊘ u

	$s_{1,1'}$	$s_{2,2'}$	$s_{3,3'}$	$s_{4,4'}$
F	+	+	+	+
C	+	+	−	−
G	+	−	+	−
A	+	−	−	+

FIG. 5f-25. Ordering in $CrUO_4$ and $FeUO_4$.

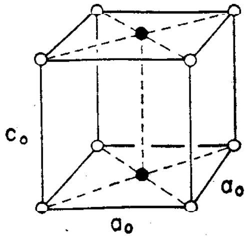


FIG. 5f-26. Ordering in CuAu-I type structures.

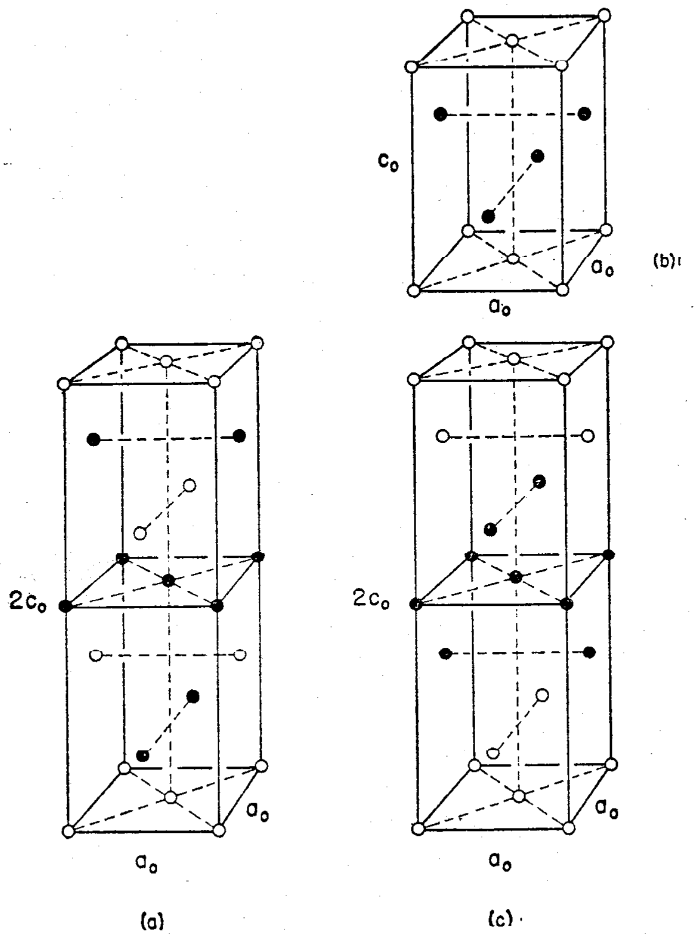


FIG. 5f-27. (*a*) Mn_2As, (*b*) Mn_2Sb, and (*c*) Fe_2As type magnetic structures.

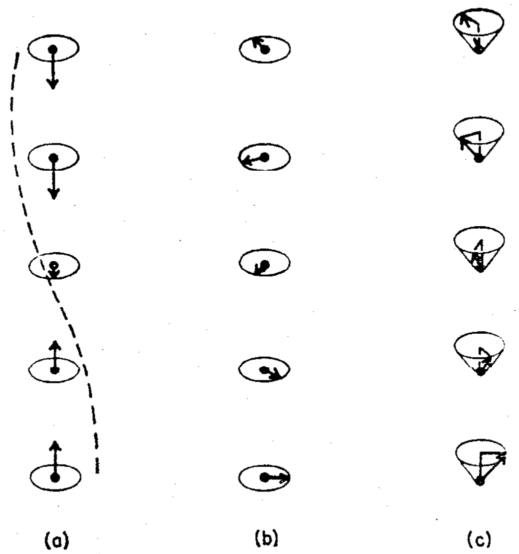


FIG. 5f-28. (*a*) Longitudinal sinusoidal, (*b*) screw spiral, and (*c*) ferromagnetic screw-cone spiral magnetic structures.

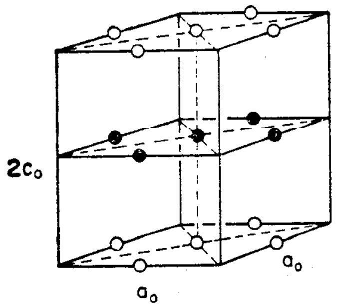


FIG. 5f-29 FeSn type magnetic structure.

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5f-8. Gyromagnetic Ratios and Spectroscopic Splitting Factors. The magnetomechanical ratio g' is defined by the relation

$$g' = \frac{M}{J}\frac{2mc}{e}$$

where m/e is the mass-to-charge ratio of the electron and c is the velocity of light. M/J is the ratio of the magnetic moment to the angular momentum of the electrons which contribute to the spontaneous magnetization as measured in an Einstein-de Haas or a Barnett-effect experiment (Sec. 5f-1).