Part IV Magnetic Properties of Materials

Chap. 14 Foundations of Magnetism

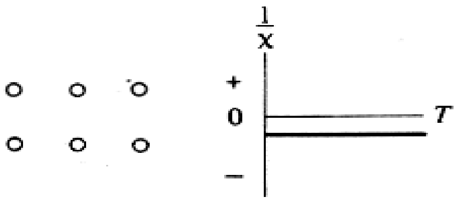
Chap. 15 Magnetic Phenomena and Their Interpretation- Classical Approach

Chap. 16 Quantum Mechanical Considerations

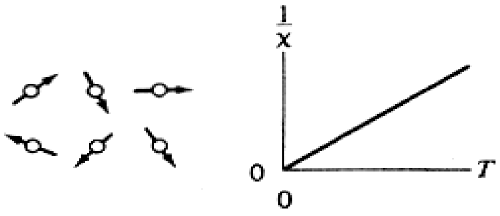
Chap. 17 Applications

15.1 Overview

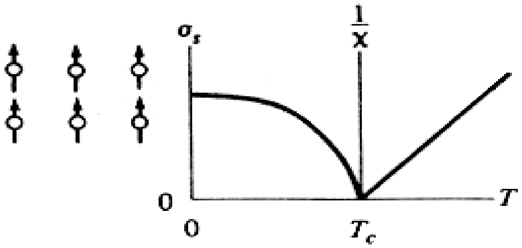
Different types of magnetism are characterized by the magnitude and the sign of the susceptibility



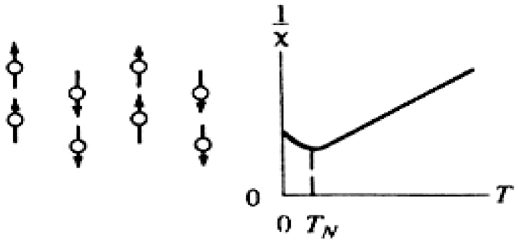
Diamagnetism



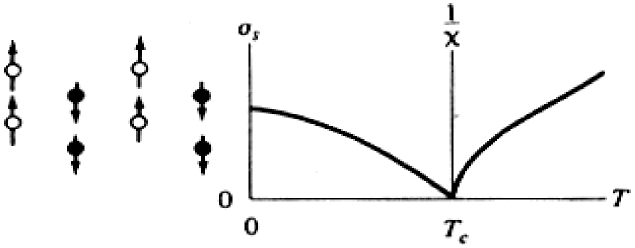
Paramagnetism



Ferromagnetism



Antiferromagnetism



Ferrimagnetism

KINDS OF MAGNETISM

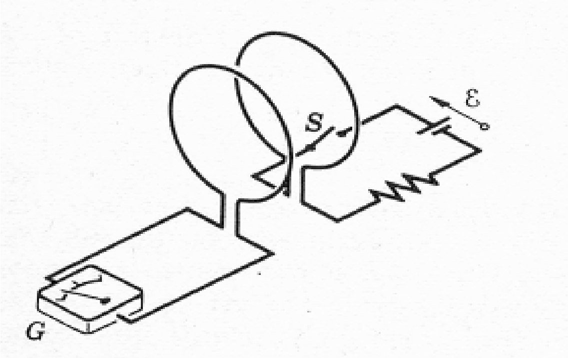
15.1 Overview

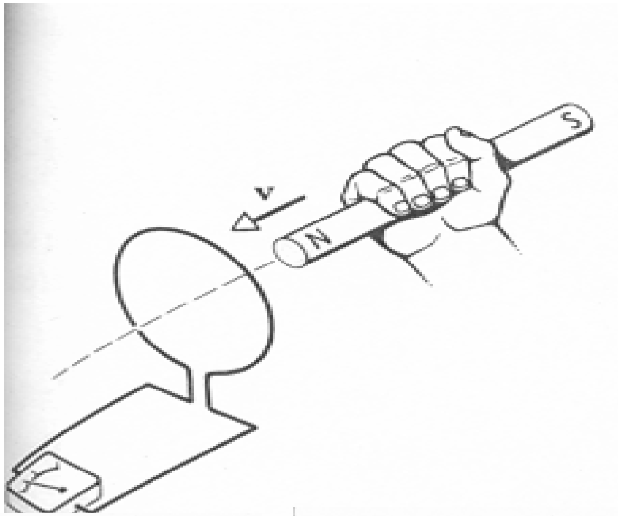
15.1.1 Diamagnetism

What is diamagnetism?

Diamagnetism may then be explained by postulating that the external magnetic field induces a change in the magnitude of inner-atomic currents in order that their magnetic moment is in then opposite direction from the external magnetic field.

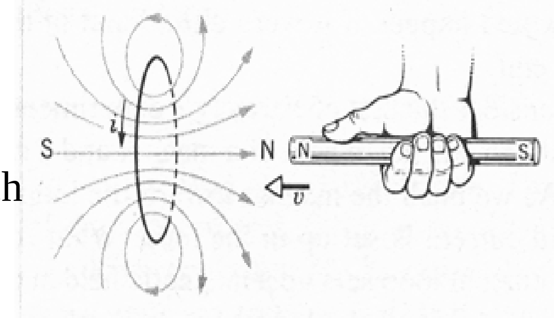
A more accurate and quantitative explanation of diamagnetism replaces the induced currents by precessions the electron orbits about the magnetic field direction. (Larmor precession)

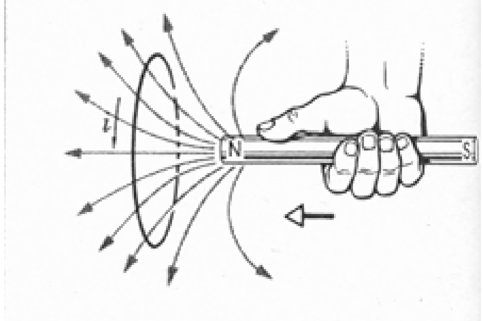




Lenz’s law :

The induced current will appear in such a direction that it opposes change that produce it.

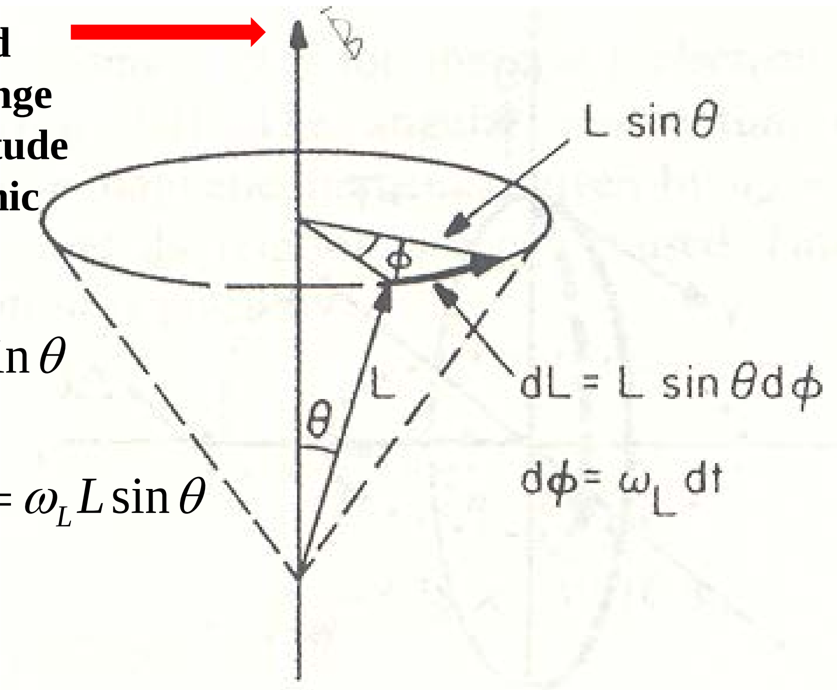




15.1 Overview

Larmor frequency

External field induce a change in the magnitude of inner-atomic currents



$$dL = L\sin\theta d\phi \quad \text{and } d\phi = \omega_L dt \quad \therefore \frac{dL}{dt} = \omega_L L\sin\theta$$

$$T = \frac{dL}{dt} \text{ by torque definition} \qquad \therefore -\mu_m B\sin\theta = \omega_L L\sin\theta$$

$$\therefore \omega_L = \frac{-\mu_m B}{L} = -\gamma B = -\frac{e}{2m}B$$

It has been observed that superconducting materials expel the magnetic flux lines when in the superconducting state (Meissner effect).

$$H = -M$$

$$\chi = \frac{M}{H} = -1$$

15.1 Overview

15.1.2 Paramagnetism

What is paramagnetism?

Paramagnetism in solids is attributed, to a large extent, to a magnetic moment that results from electrons which spin around their own axes.

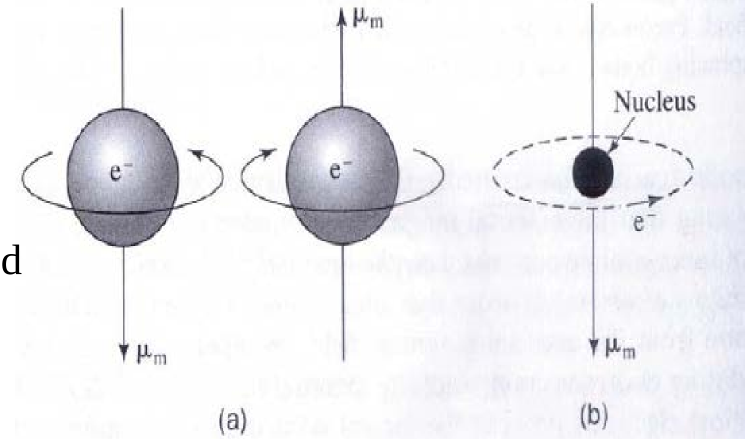


Figure 15.2. (a) Schematic representation of electrons which spin around their own axes. A (para)magnetic moment μ_m results; its direction depends on the mode of rotation. Only two spin directions are shown (called "spin up" and "spin down"). (b) An orbiting electron is the source of *electron-orbit paramagnetism*.

In Curie Law, Susceptibility is inversely proportional to the absolute temperature T

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

In Curie-Weiss Law,

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

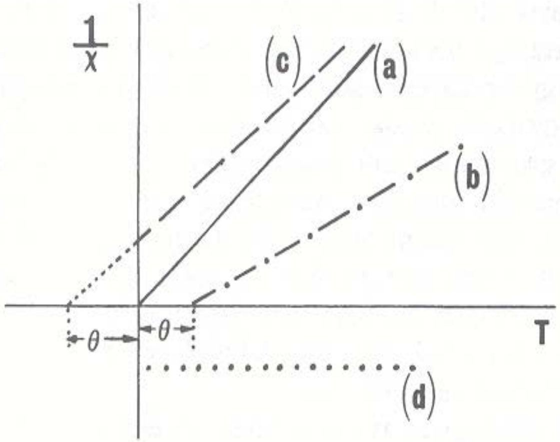
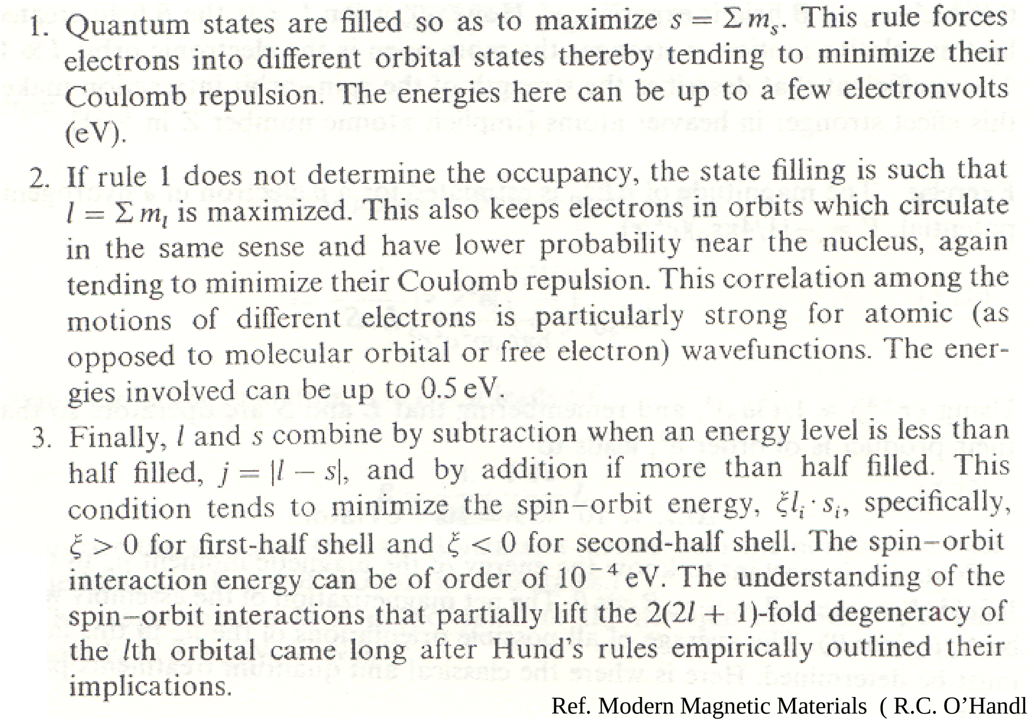


Figure 15.3. Schematic representation of (a) the Curie law and (b) and (c) the Curie-Weiss law. (d) The diamagnetic behavior is also shown for comparison.

15.1 Overview

Hund’s rule



1. Quantum states are filled so as to maximize $s = \Sigma m_s$. This rule forces electrons into different orbital states thereby tending to minimize their Coulomb repulsion. The energies here can be up to a few electronvolts (eV).
2. If rule 1 does not determine the occupancy, the state filling is such that $l = \Sigma m_l$ is maximized. This also keeps electrons in orbits which circulate in the same sense and have lower probability near the nucleus, again tending to minimize their Coulomb repulsion. This correlation among the motions of different electrons is particularly strong for atomic (as opposed to molecular orbital or free electron) wavefunctions. The energies involved can be up to 0.5 eV.
3. Finally, l and s combine by subtraction when an energy level is less than half filled, $j = |l - s|$, and by addition if more than half filled. This condition tends to minimize the spin–orbit energy, $\xi l_i \cdot s_i$, specifically, $\xi > 0$ for first-half shell and $\xi < 0$ for second-half shell. The spin–orbit interaction energy can be of order of 10^{-4} eV. The understanding of the spin–orbit interactions that partially lift the $2(2l+1)$-fold degeneracy of the lth orbital came long after Hund’s rules empirically outlined their implications.

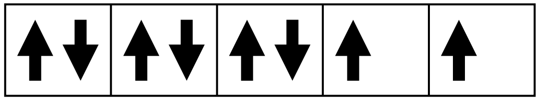


Figure 15.4. Schematic representation of the spin alignment in a *d*-band which is partially filled with eight electrons (Hund’s rule).

Ref. Modern Magnetic Materials (R.C. O’Handley)

Hund’s rules

(1) are based primarily on Coulomb repulsion and secondarily on spin-orbit interactions and

(2) account for the existence of atomic magnetic moments, even in some atoms with an even number of valance electrons

15.1 Overview

15.1.3 Ferromagnetism

-Spontaneous magnetization

-transition metals : Fe, Co, Ni, rare-earth : Gd, Dy

-alignment of an appreciable fraction of molecular magnetic moment in some favorable direction in crystal

-related o the unfilled 3d and 4f shells

-ferromagnetic transition temperature (Curie)

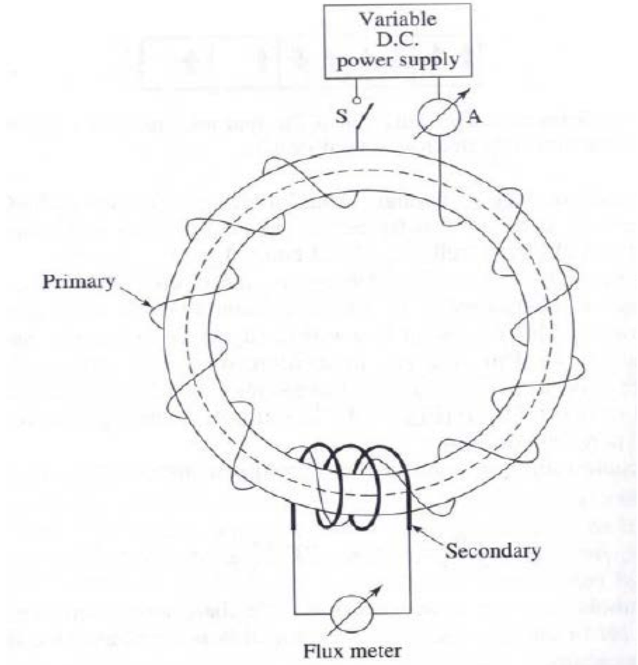


Figure 15.5. A ring-shaped solenoid with primary and secondary windings. The magnetic flux lines are indicated by a dashed circle. Note, that a current can flow in the secondary circuit only if the current (and therefore the magnetic flux) in the primary winding changes with time. An on–off switch in the primary circuit may serve for this purpose.

Hysteresis Loop

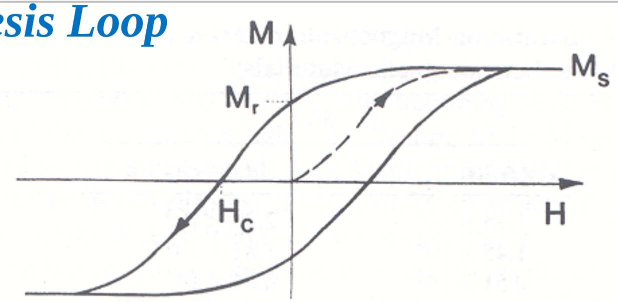


Figure 15.6. Schematic representation of a hysteresis loop of a ferromagnetic material. The dashed curve is for virgin material.

M_r = remanent magnetization

M_s = saturation magnetization

H_c = coercive field

15.1 Overview

TEMPERATURE-DEPENDENCE OF SATURATION MAGNETIZATION

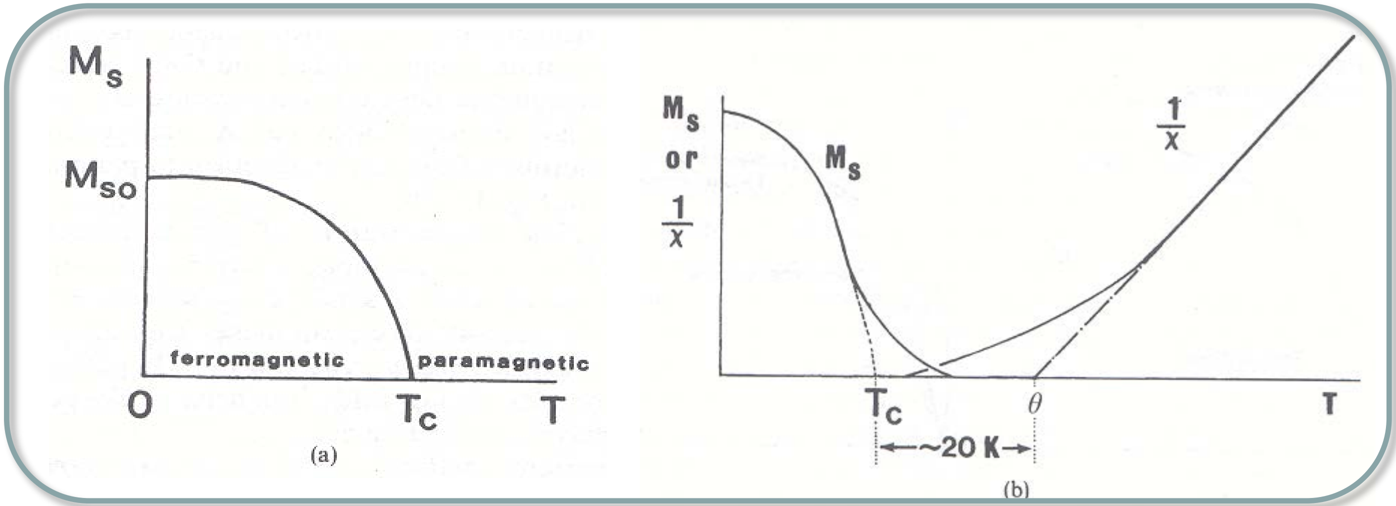


Figure 15.7 (a) Temperature dependence of the saturation magnetization of ferromagnetic materials. (b) Enlarged area near the Curie temperature showing the paramagnetic Curie point (see Fig. 15.3) and the ferromagnetic Curie temperature .

Above **Curie Temperature** T_c, ferromagnetics become paramagnetic.

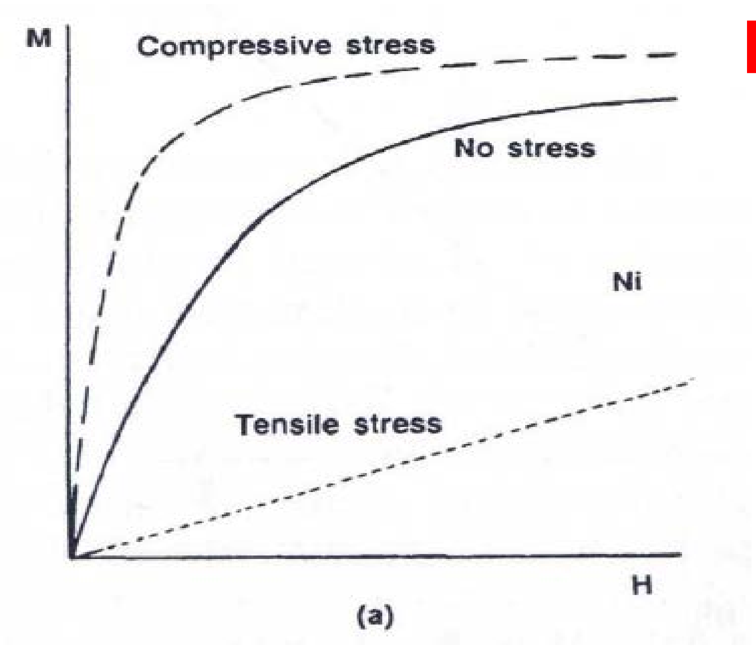
For ferromagnetics, the **Curie temperature** T_c and the constant θ in the Curie-Weiss law are nearly identical.

However a small difference exists because the transition from ferromagnetism to paramagnetism is gradual.

15.1 Overview

Piezomagnetism

The magnetization of ferromagnetics is stress dependent



A compressive stress increases M for Ni, while tensile stress reduces M.

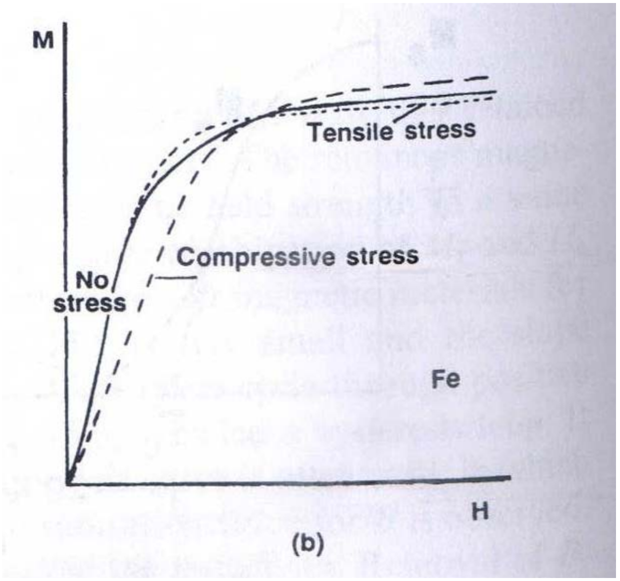
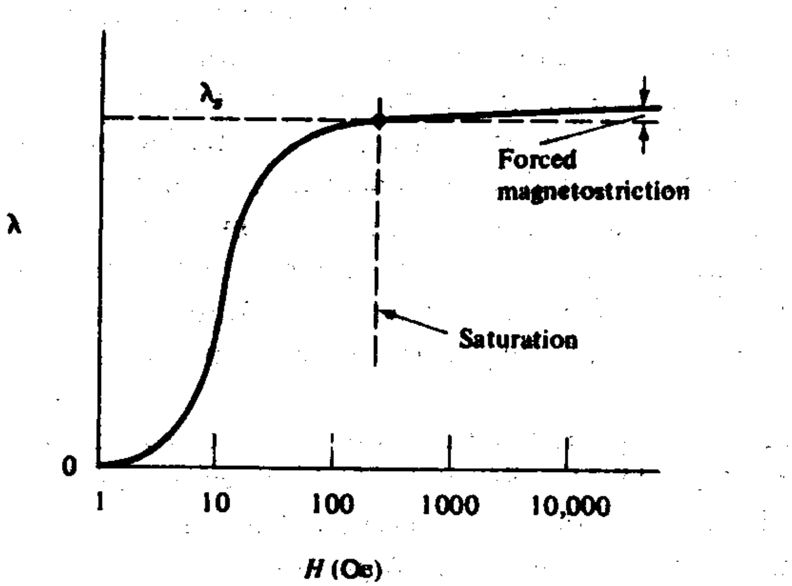


Figure 15.8. Schematic representation of the effect of tensile and compressive stresses on the magnetization behavior of (a) nickel and (b) iron. (Piezomagnetism.)

15.1 Overview

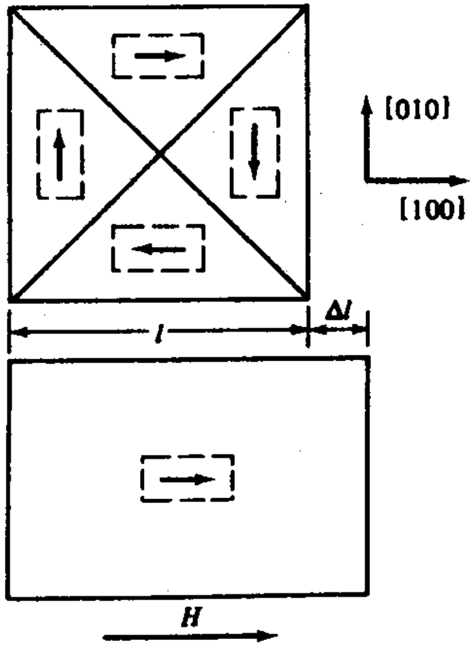
Magnetostriction

When a substance is exposed to a magnetic field, its dimensions change. This effect Called *magnetostriction.* (inverse of piezomagnetism)



$$\lambda = \frac{\Delta l}{l}$$

$$|\lambda| = 10^{-5} \sim 10^{-6}$$

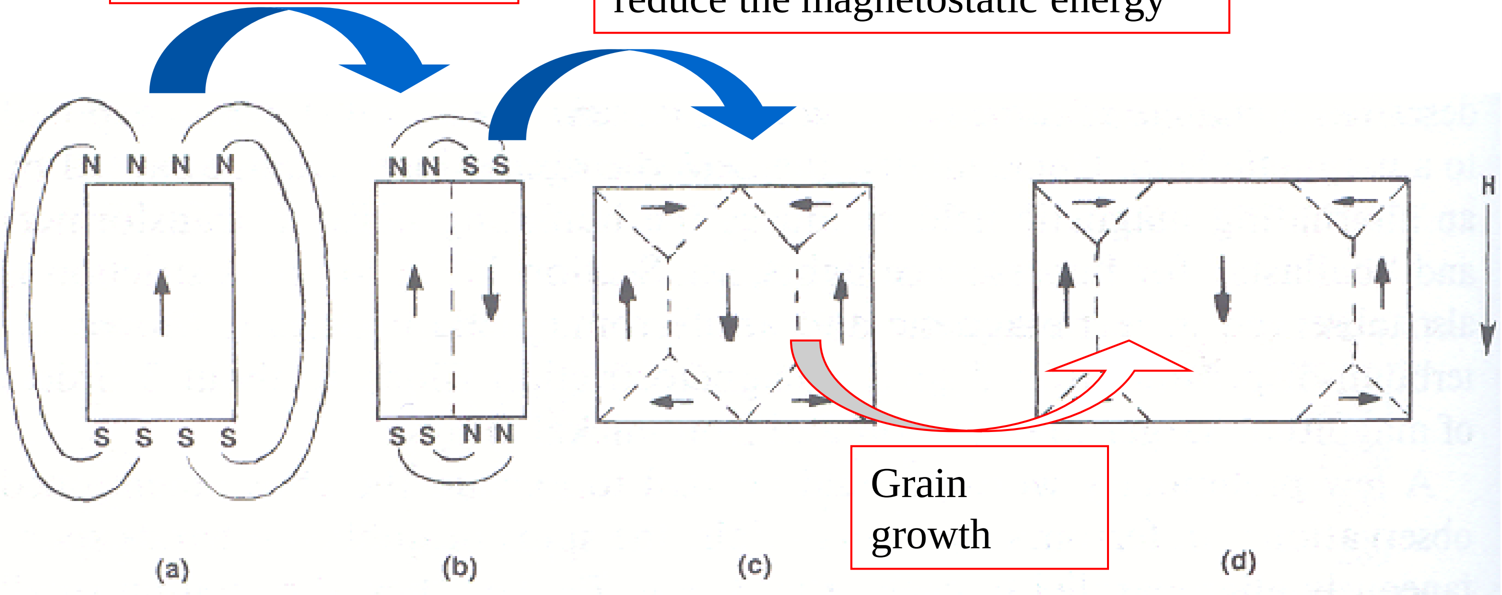


M orientation => change in dimension

15.1 Overview

DOMAIN

Minimization of magnetostatic energy with changing domain shape



Approximately half magnetostatic energy

Closed path within crystal to reduce the magnetostatic energy

Grain growth

Figure 15.9. (a) Spontaneous alignment of all spins in a single direction. (b) Division into two magnetic domains having opposite spin directions. (c) Closure domains in a cubic crystal. (d) Growth of a domain whose spins are parallel to an external magnetic field. (The domain walls are *not* identical with the grain boundaries.)

15.1 Overview

15.1.4 Antiferromagnetism

What is antiferromagnetism?

Antiferromagnetic materials exhibit just as ferromagnetics, a spontaneous alignment of moments below a critical temperature. However, the responsible neighboring atoms are aligned in an antiparallel fashion.

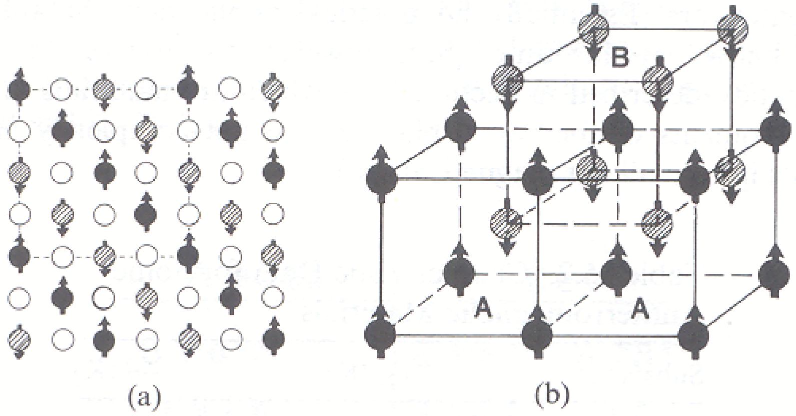
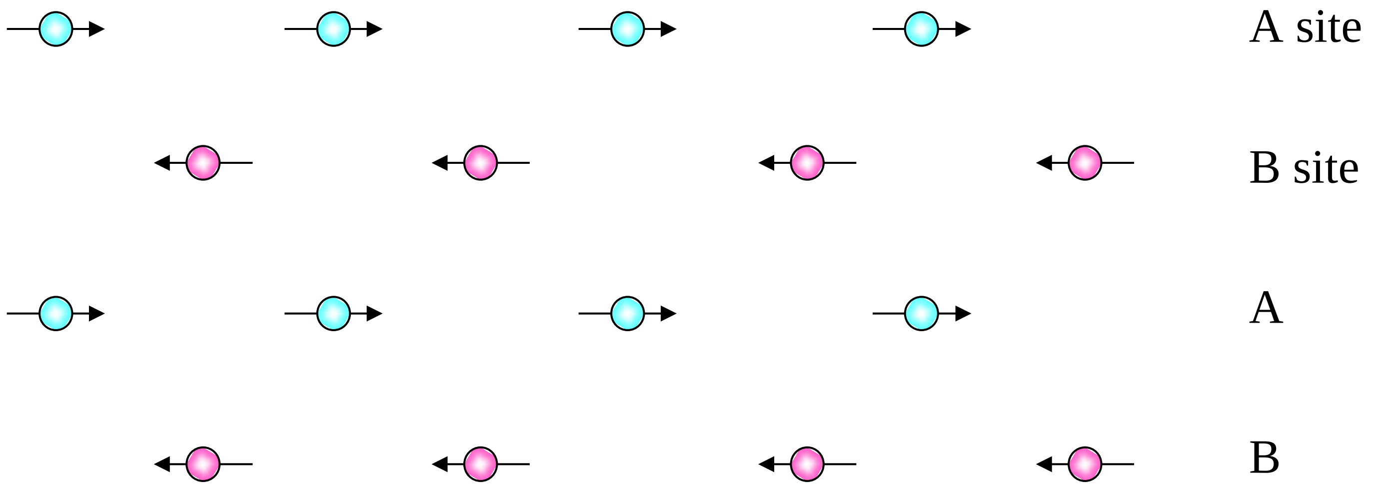


Figure 15.10. Schematic representation of spin alignments for antiferromagnetics at 0 K. (a) Display of a (100) plane of MnO. The gray (spin down) and black (spin up) circles represent the Mn ions. The oxygen ions (open circles) do not contribute to the antiferromagnetic behavior. MnO has a NaCl structure. (b) Three-dimensional representation of the spin alignment of manganese ions in MnF_2. (The fluorine ions are not shown.) This figure demonstrates the interpenetration of two manganese sublattices, A and B, having antiparallel aligned moments.

15.1 Overview

Antiferromagnetic ordering



15.1 Overview

TEMPERATURE-DEPENDENCE OF ANTIFERROMAGNETIC MATERIAL

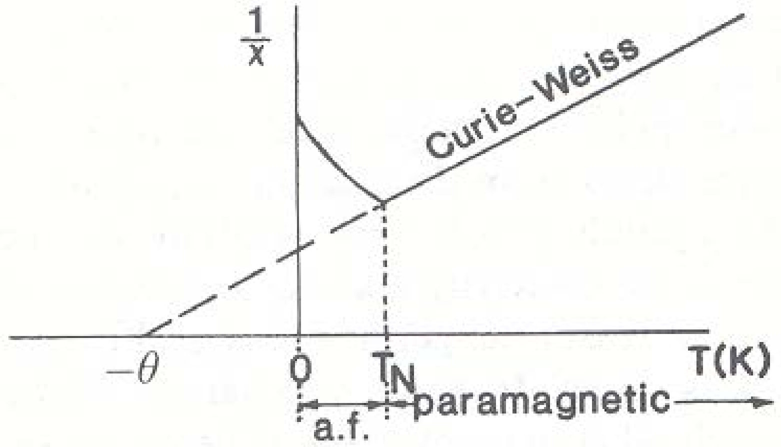
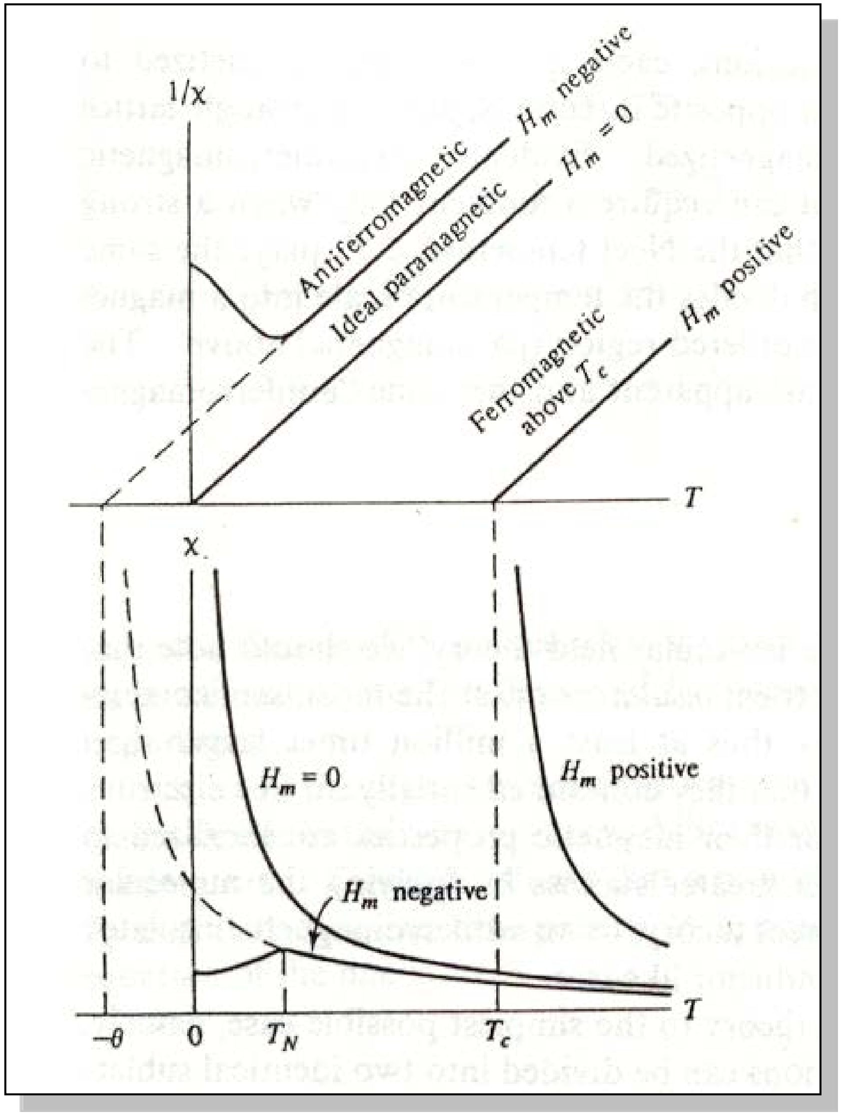


Figure 15.11. Schematic representation of the temperature dependence of a polycrystalline antiferromagnetic (a.f.) material.

$$T_N = \text{Nėel temperature}$$

$$\chi = \frac{C}{T-(-\theta)} = \frac{C}{T+\theta}$$

15.1 Overview



Antiferromagnetic

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

ferromagnetic

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

15.1 Overview

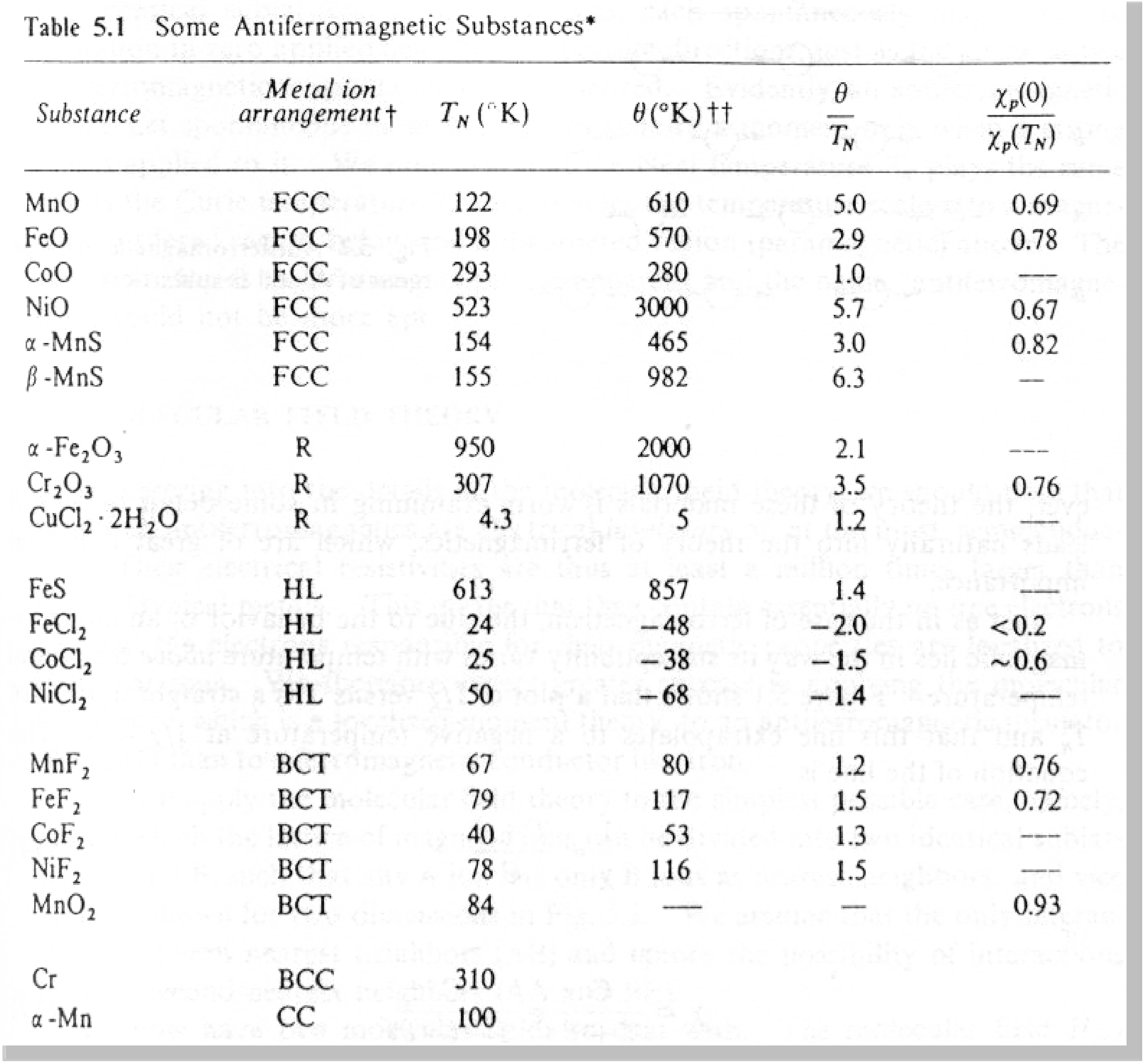
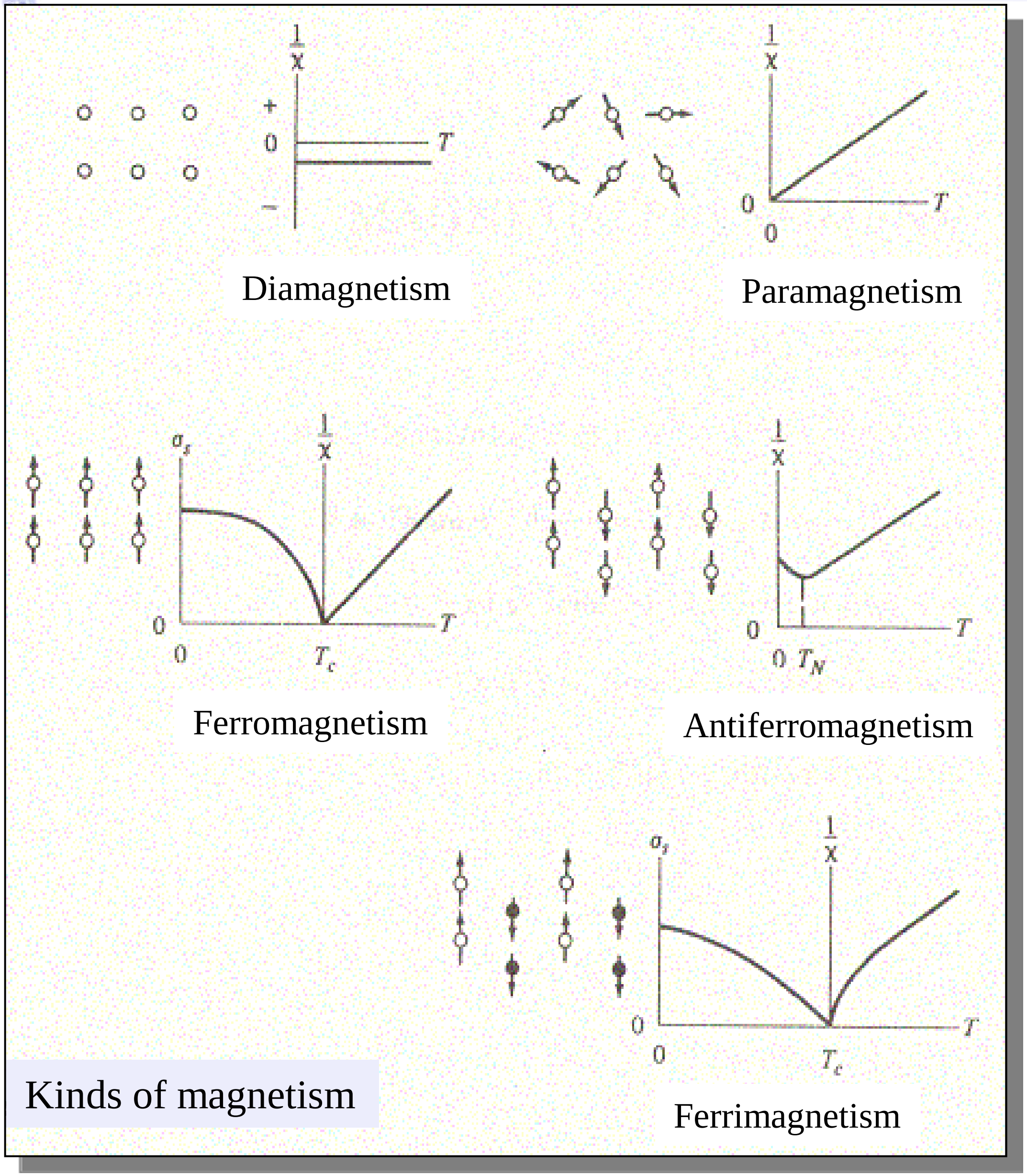


Table 5.1 Some Antiferromagnetic Substances*

Substance	Metal ion arrangement†	T_N (°K)	θ (°K)††	$\frac{\theta}{T_N}$	$\frac{\chi_p(0)}{\chi_p(T_N)}$
MnO	FCC	122	610	5.0	0.69
FeO	FCC	198	570	2.9	0.78
CoO	FCC	293	280	1.0	—
NiO	FCC	523	3000	5.7	0.67
α-MnS	FCC	154	465	3.0	0.82
β-MnS	FCC	155	982	6.3	—
α-Fe_2O_3	R	950	2000	2.1	—
Cr_2O_3	R	307	1070	3.5	0.76
$CuCl_2 \cdot 2H_2O$	R	4.3	5	1.2	—
FeS	HL	613	857	1.4	—
$FeCl_2$	HL	24	−48	−2.0	<0.2
$CoCl_2$	HL	25	−38	−1.5	~0.6
$NiCl_2$	HL	50	−68	−1.4	—
MnF_2	BCT	67	80	1.2	0.76
FeF_2	BCT	79	117	1.5	0.72
CoF_2	BCT	40	53	1.3	—
NiF_2	BCT	78	116	1.5	—
MnO_2	BCT	84	—	—	0.93
Cr	BCC	310			
α-Mn	CC	100			

15.1 Overview



Diamagnetism

Paramagnetism

Ferromagnetism

Antiferromagnetism

Ferrimagnetism

Kinds of magnetism

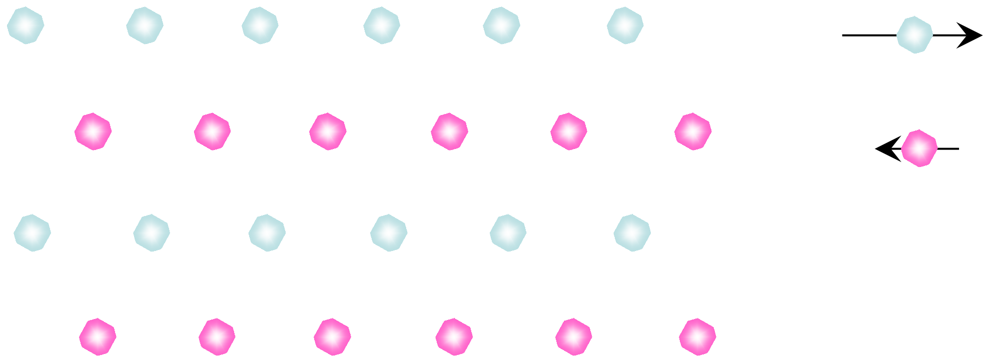
Non-cooperative (statistical) behavior

Cooperative behavior

15.1 Overview

15.1.5 Ferrimagnetism

Different elements, different moments

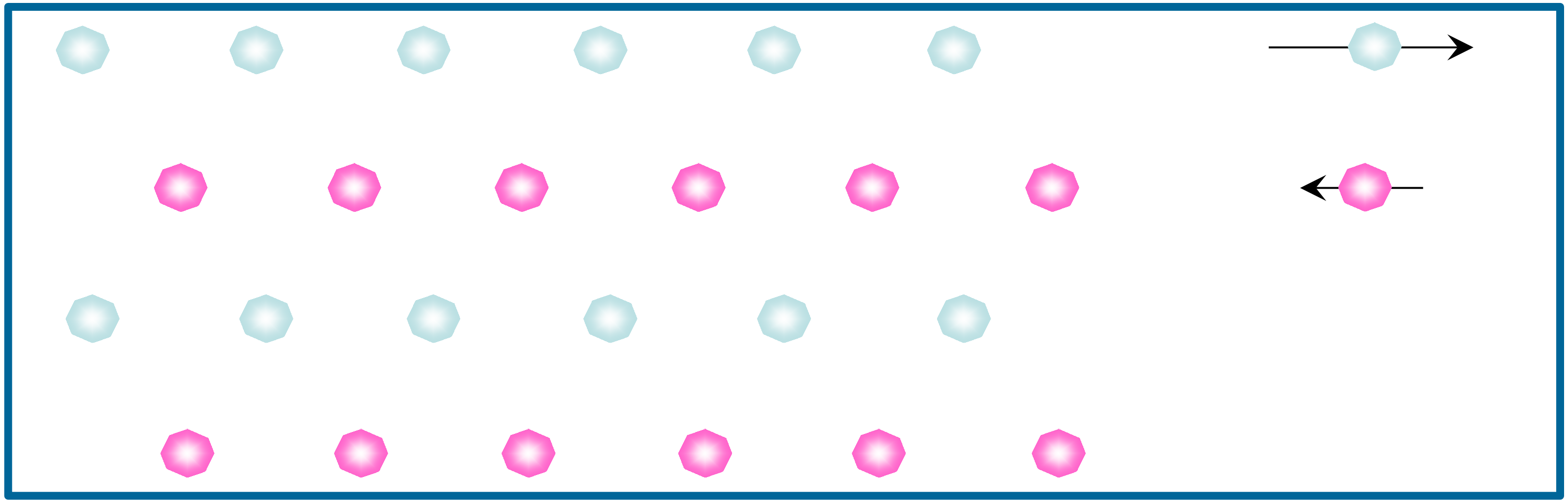


Ionic bonding, localized field theory

- Cubic: $MO \cdot Fe_2O_3$ M = Mn^{2+}, Ni^{2+}, Fe^{2+}, Co^{2+}, Mg^{2+}, Zn^{2+}, Cd^{2+} etc.
  (ferrite)
  soft magnet except $Co \cdot Fe_2O_3$
- Hexagonal: $BaO \cdot 6Fe_2O_3$
  hard magnet

15.1 Overview

Ferrimagnetic substances consist of self-saturated domains, and they exhibit the phenomena of magnetic saturation and hysteresis. Their spontaneous magnetization disappears above a certain critical temperature, T_c also called Curie temperature and they become paramagnetic



Different elements, different moments

15.1 Overview

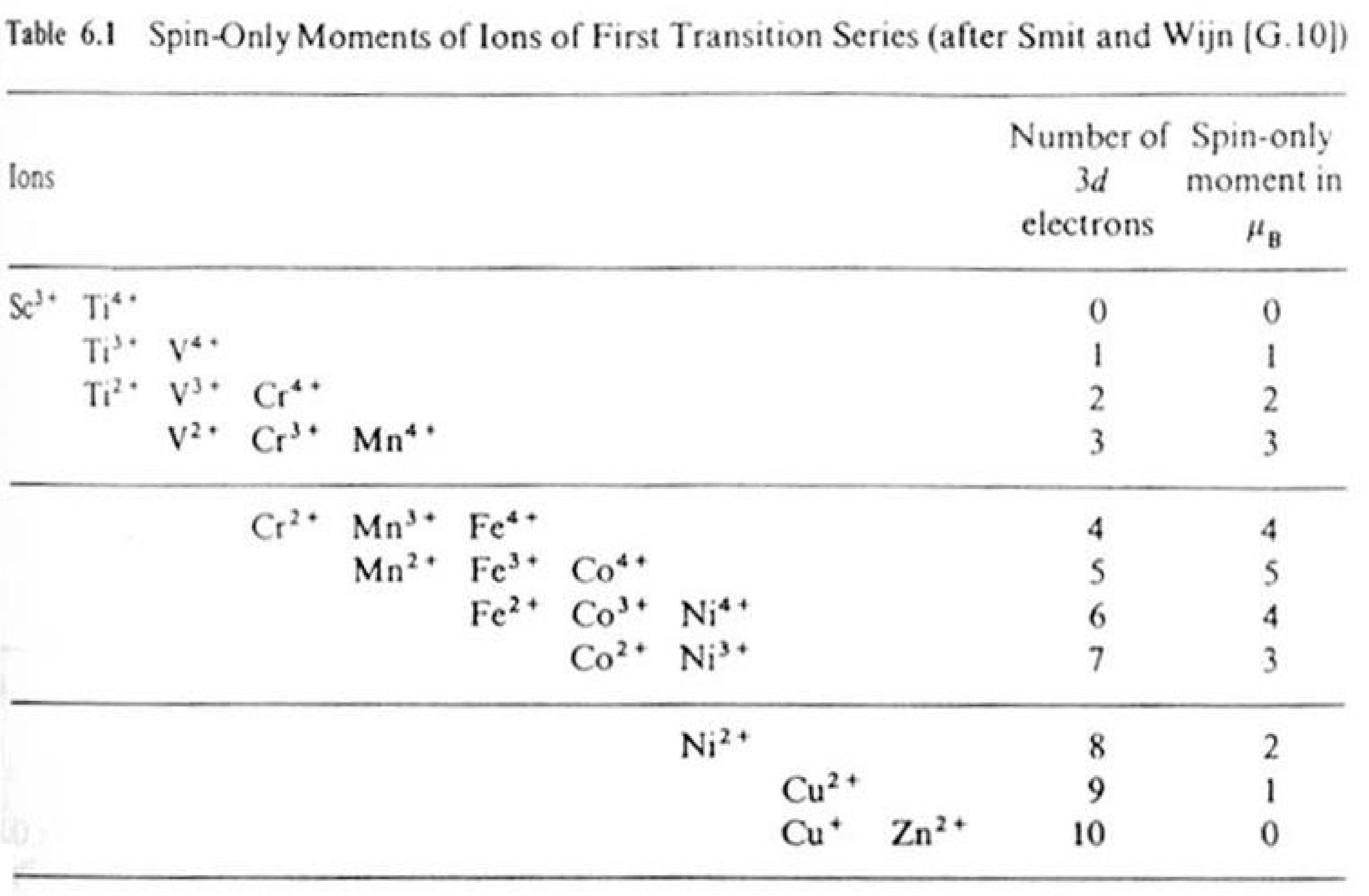
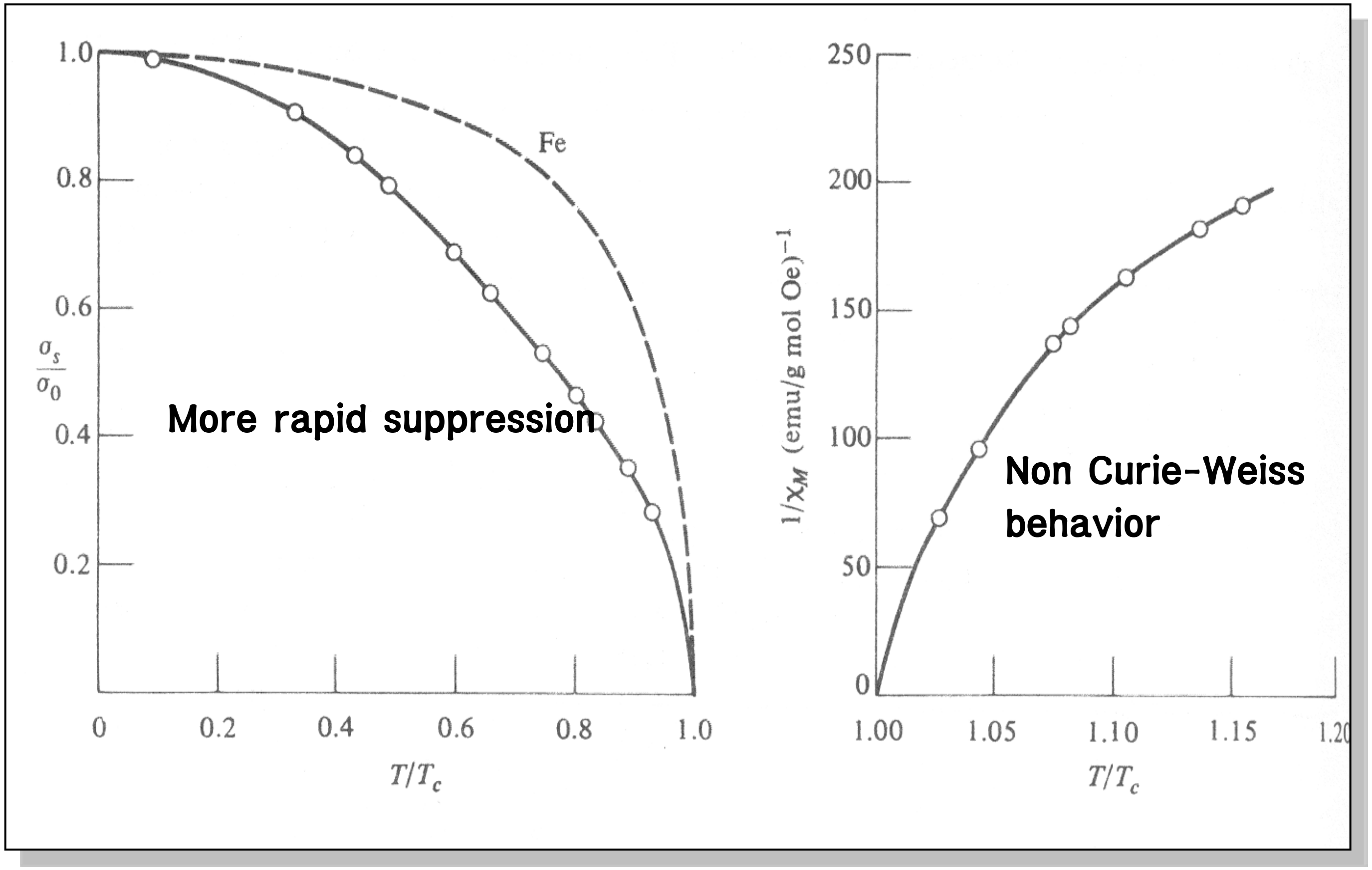


Table 6.1 Spin-Only Moments of Ions of First Transition Series (after Smit and Wijn [G.10])

Ions										Number of 3*d* electrons	Spin-only moment in μ_B
Sc^{3+}	Ti^{4+}									0	0
	Ti^{3+}	V^{4+}								1	1
	Ti^{2+}	V^{3+}	Cr^{4+}							2	2
		V^{2+}	Cr^{3+}	Mn^{4+}						3	3
			Cr^{2+}	Mn^{3+}	Fe^{4+}					4	4
				Mn^{2+}	Fe^{3+}	Co^{4+}				5	5
					Fe^{2+}	Co^{3+}	Ni^{4+}			6	4
						Co^{2+}	Ni^{3+}			7	3
							Ni^{2+}			8	2
								Cu^{2+}		9	1
								Cu^{+}	Zn^{2+}	10	0

15.1 Overview



More rapid suppression

Non Curie-Weiss behavior

Example : NiO •Fe_2O_3

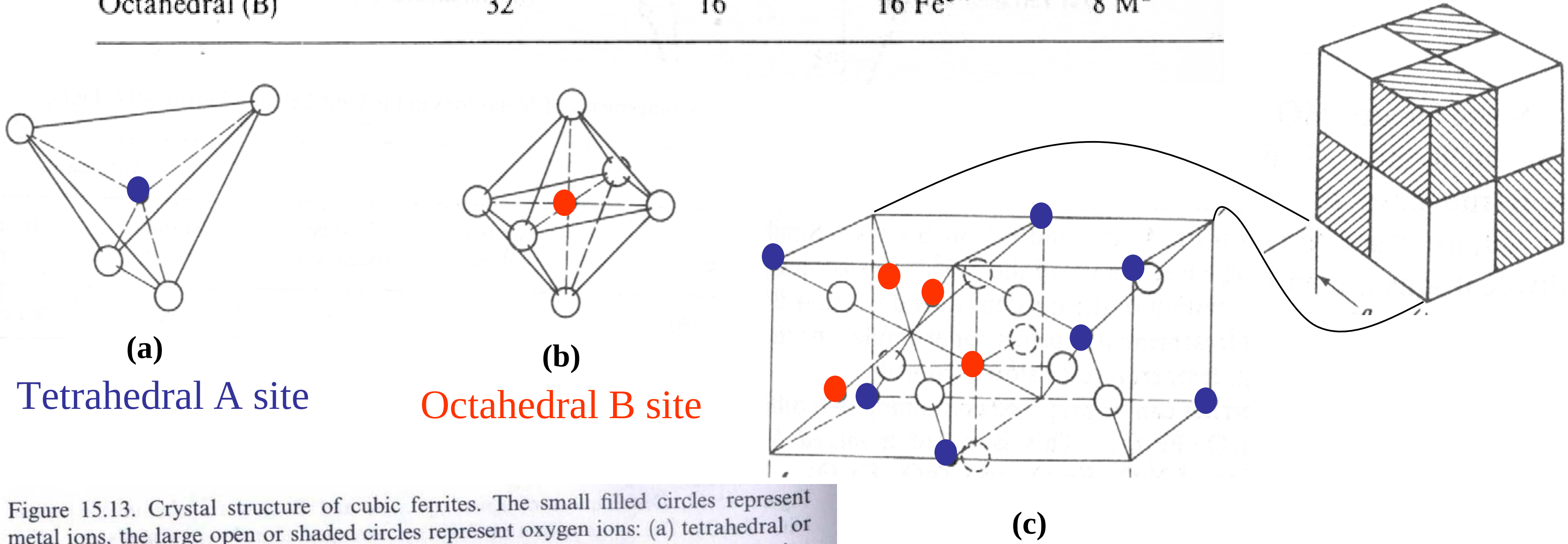
12 μ_B if ferromagnetic ordering (5 Bohr magnetrons for Fe^{+3} and 2 for Ni^{+2})

but experimental value is 2.3 μ_B (56 emu/g) at 0 K

15.1 Overview

Table 6.2 Arrangements of Metal Ions in the Unit Cell of a Ferrite $MO \cdot Fe_2O_3$

			Occupants	
Kind of site	Number available	Number occupied	Normal spinel	Inverse spinel
Tetrahedral (A)	64	8	8 M^{2+}	8 Fe^{3+}
Octahedral (B)	32	16	16 Fe^{3+}	8 Fe^{3+} 8 M^{2+}

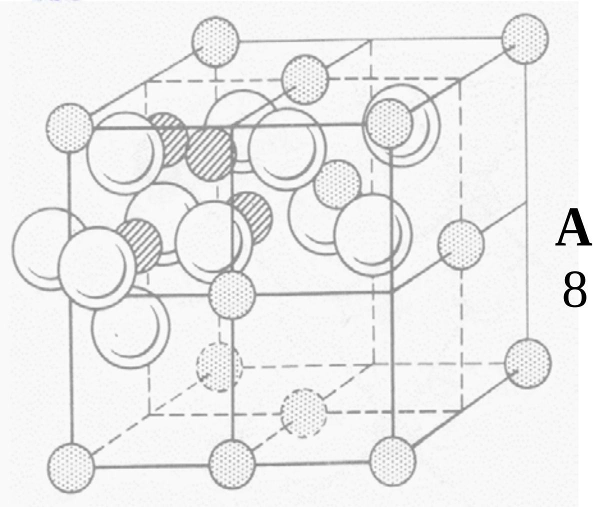


Tetrahedral A site

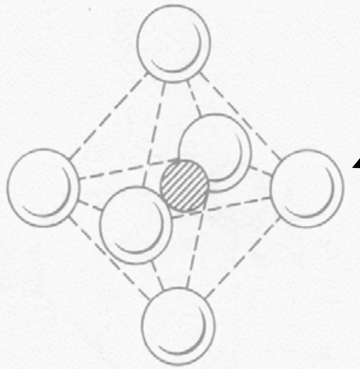
Octahedral B site

Figure 15.13. Crystal structure of cubic ferrites. The small filled circles represent metal ions, the large open or shaded circles represent oxygen ions: (a) tetrahedral or A sites; (b) octahedral or B sites; and (c) one-fourth of the unit cell of a cubic ferrite. A tetrahedron and an octahedron are marked. Adapted from J. Smit, and H.P.J. Wijn, *Ferrites*, Wiley, New York (1959).

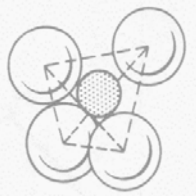
15.1 Overview



AB_2O_4
8 molecules



Octahedral interstice (32 per unit cell)

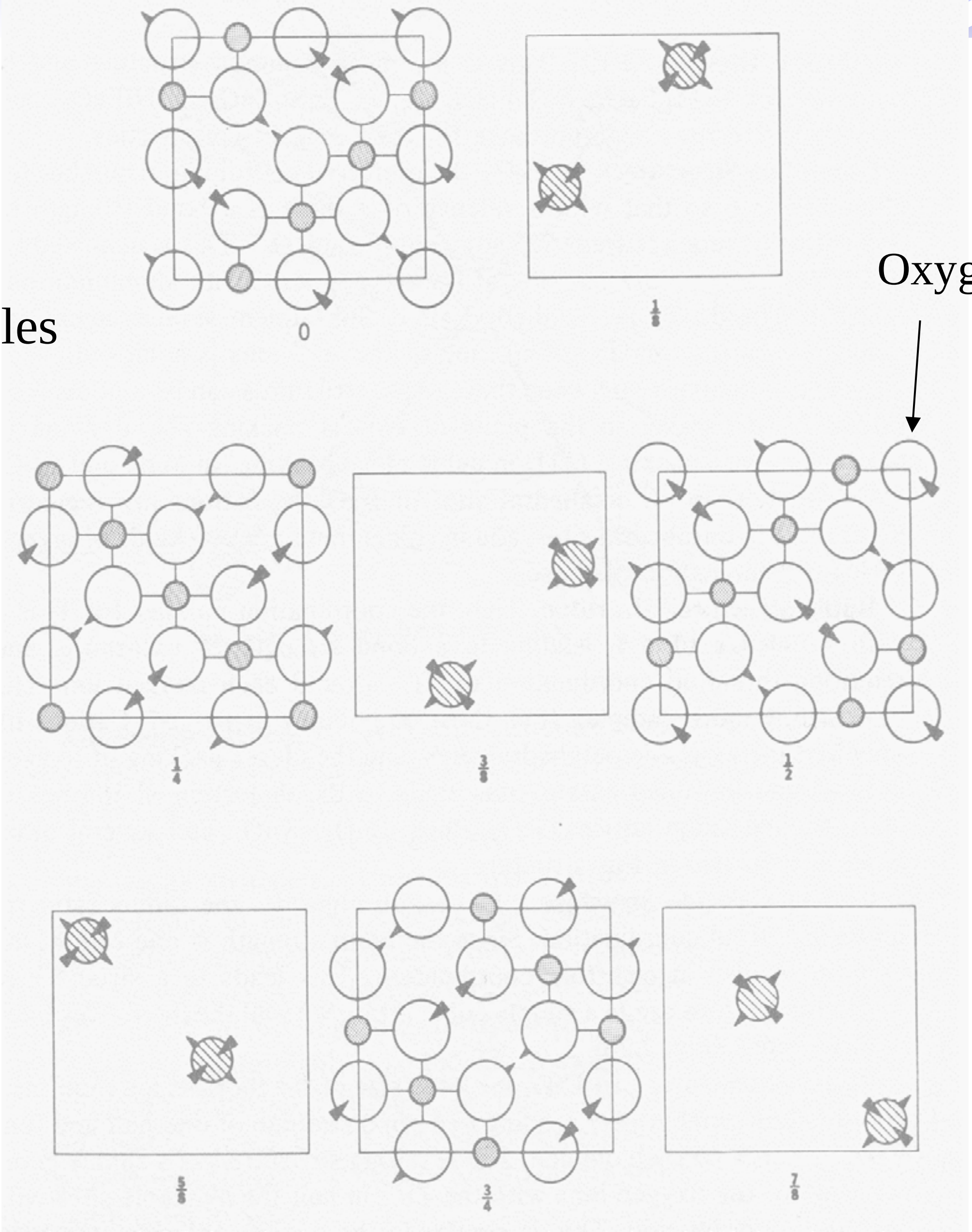


Tetrahedral interstice (64 per unit cell)

Oxygen

B site: 16b

A site: 8a



Oxygen

15.1 Overview

Normal spinel: $AO(B_2O_3)$

A^{2+} on tetrahedral sites, B^{3+} on octahedral sites

(e.g.) ZnFe2O4, CdFe2O4, MgAl2O4, CoAl2O4, MnAl2O4

$MO\cdot Fe_2O_3$ (M = Zn, Cd)
non-magnetic (paramagnetic)
$8M^{2+}$: A site, $16Fe^{3+}$: B site

Inverse spinel: $B(AB)O_4$

half of the B^{3+} on tetrahedral sites, A^{2+} and remaining B^{3+} on octahedral sites

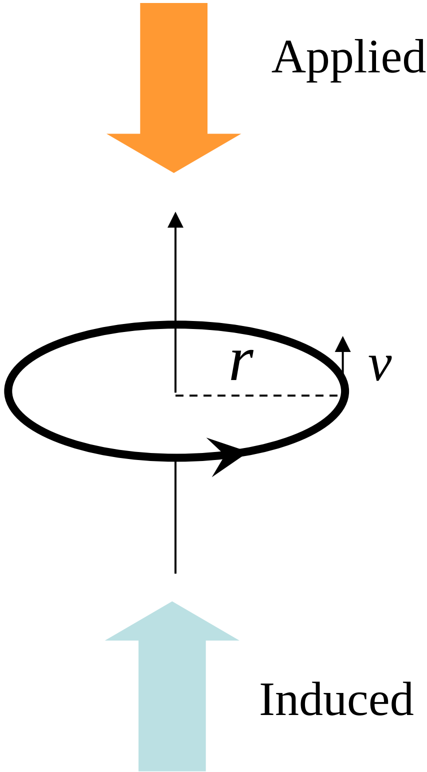
(e.g.) $FeMgFeO_4$, $FeTiFeO_4$, Fe_3O_4, $FeNiFeO_4$

$MO\cdot Fe_2O_3$ (M = Fe, Co, Ni)
Ferrimagnetic
$8M^{2+}$: B site, $16Fe^{3+}$: A,B sites
(disordered state)

Mixed ferrite: $NiO\cdot Fe_2O_3 + ZnO\cdot Fe_2O_3 \rightarrow \rightarrow (Ni,Zn)O\cdot Fe_2O_3$

15.2 Langevin Theory of Diamagnetism

Classical model



$$\mu_m = I \cdot A = \frac{evr}{2}$$

e : electron charge

r : radius of the orbit

s : length of the orbit $(= 2\pi r)$

v : velocity of the orbiting electron

t : revolution time

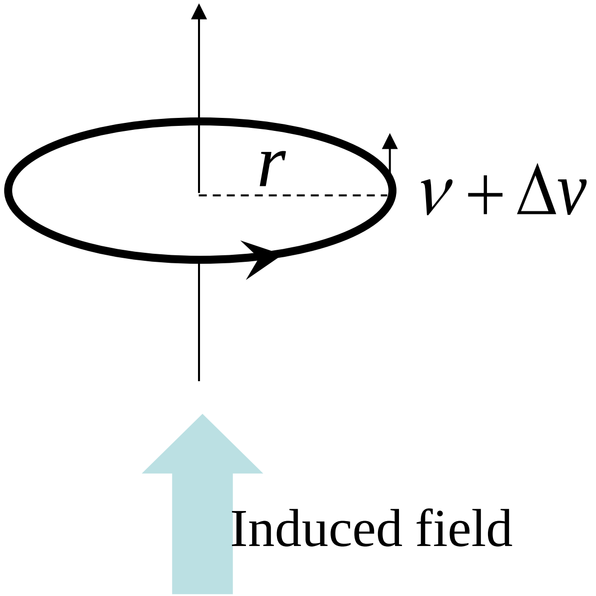
$$\mu_m = I \cdot A = \frac{e}{t} A = \frac{e}{s/v} A = \frac{ev\pi r^2}{2\pi r} = \frac{evr}{2}$$

15.2 Langevin Theory of Diamagnetism

$\mathscr{E}$: electric field strength

V_e : induced voltage

L : orbit Length



$$\mathscr{E} = \frac{V_e}{L}, \qquad V_e = -\frac{d\phi}{dt} = -\frac{d(\mu_0 HA)}{dt}$$

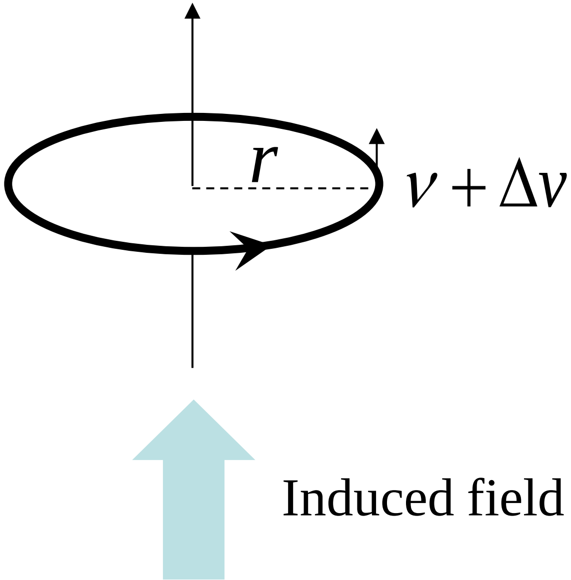
$$F = ma = \mathscr{E}e \qquad \therefore\ a = \frac{dv}{dt} = \frac{\mathscr{E}e}{m}$$

$$\mu_m = I \cdot A = \frac{evr}{2}$$

Thus,

$$\frac{dv}{dt} = \frac{\mathscr{E}e}{m} = \frac{V_e e}{Lm} = -\frac{eA\mu_0}{Lm}\frac{dH}{dt} = -\frac{e\pi r^2\mu_0}{2\pi rm}\frac{dH}{dt} = -\frac{er\mu_0}{2m}\boxed{\frac{dH}{dt}}$$

15.2 Langevin Theory of Diamagnetism



A change in the magnetic field strength from 0 to H yields a change in the velocity of the electrons :

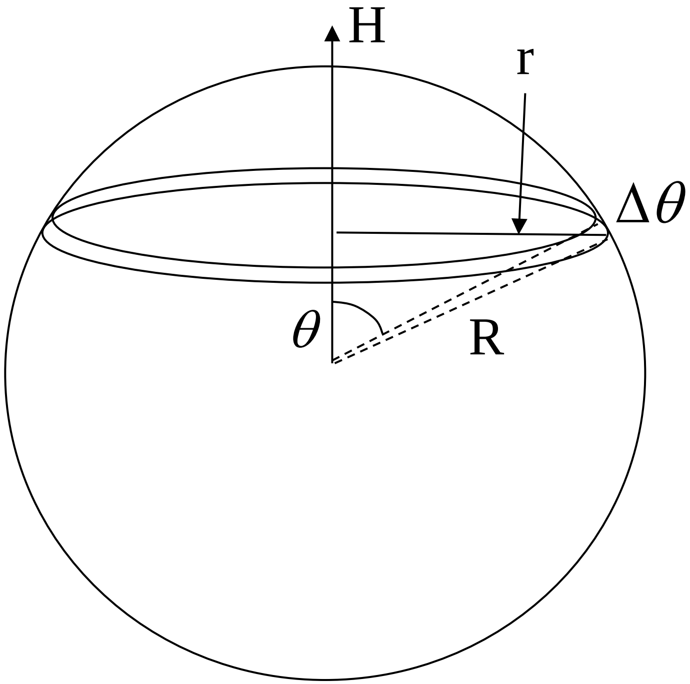
$$\int_{v_1}^{v_2} dv = -\frac{er\mu_0}{2m}\int_0^H dH \qquad \text{or} \qquad \Delta v = \int_{v_1}^{v_2} dv = -\frac{er\mu_0 H}{2m}$$

Magnetic moment per electron

$$\Delta\mu_m = \frac{e\Delta vr}{2} = -\frac{e^2r^2\mu_0 H}{4m}$$

15.2 Langevin Theory of Diamagnetism

Average value of magnetic moment per electron



$$r = R\sin\theta$$

$$<r^2>= R^2 <\sin^2\theta>$$

$$<\sin^2\theta>=\frac{\int_0^{\pi/2}\sin^2\theta d\theta}{\int_0^{\pi/2}d\theta}=2/3$$

$$\therefore \quad <r^2>= R^2 <\sin^2\theta>=\frac{2}{3}R^2$$

$$\overline{\Delta\mu_m} = - -\frac{\mu_0 e^2 r^2 H}{4m} = -\frac{2}{3}\frac{\mu_0 e^2 R^2 H}{4m} = -\frac{\mu_0 e^2 R^2 H}{6m}$$

15.2 Langevin Theory of Diamagnetism

Average value of magnetic moment per atom

$$\overline{\Delta\mu_m} = -\frac{e^2 Z \overline{r}^2 \mu_0 H}{6m}$$

Z : atomic number

$\overline{r}$: average radius of all electronic orbits

Magnetization caused by this change of magnetic moment

$$M = \frac{\mu_m}{V} \equiv -\frac{e^2 Z \overline{r}^2 \mu_0 H}{6mV}$$

Diamagnetic Susceptibility

$$\chi_{dia} = \frac{M}{H} = -\frac{e^2 Z \overline{r}^2 \mu_0}{6mV} = -\frac{e^2 Z \overline{r}^2 \mu_0}{6m}\frac{N_0\delta}{W}$$

N_0 : Avogadro constant

δ : density

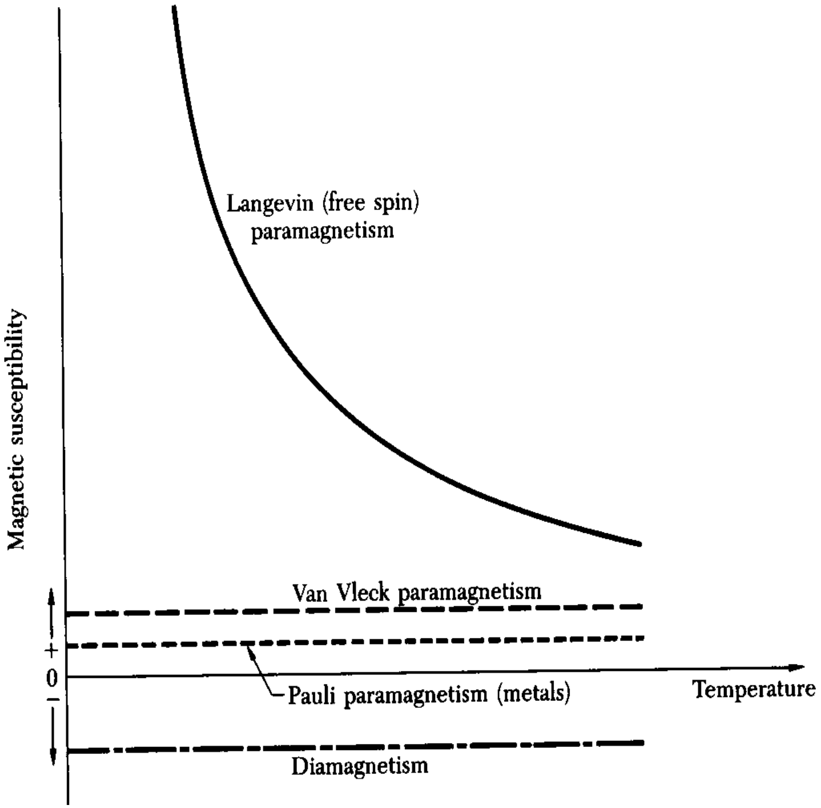
W : atomic mass

15.2 Langevin Theory of Diamagnetism

$$\boxed{\Delta m = -\frac{2}{3}\frac{\mu_0 e^2 r^2 H}{4m_e}}$$

$$\boxed{\Delta m_n = -\frac{\mu_0 e^2 H}{6m_e}\sum_i r_i^2}$$

$$\boxed{\Delta M = -\left(\frac{N_0 \rho}{A}\right)\frac{\mu_0 Z e^2 \bar{r}^2 H}{6m_e}}$$



$$\boxed{\Delta M / \Delta H = \chi_V = -\left(\frac{N_0 \rho}{A}\right)\frac{\mu_0 Z e^2 \bar{r}^2}{6m_e}}$$

$$\chi_V = -18.85\times 10^{-6}$$

15.3 Langevin Theory of (Electron orbit) Paramagnetism

Assumptions: no interaction, only m , H interaction, and thermal agitation

In a state of thermal equilibrium at temperature T
The probability of an atom having an energy E follows the Boltzmann distribution

$$\propto \exp(-E_p / kT)$$

$$E_p = -\mu_m \mu_0 H \cos\alpha$$

$$dn = \mathrm{K}\, dA \exp(-E_p / k_B T)$$

$$dA = 2\pi R^2 \sin\alpha\, d\alpha$$

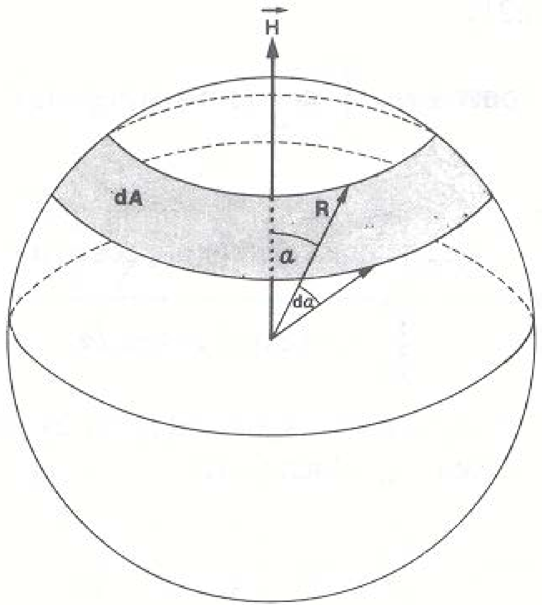


Figure 15.16. Schematic representation of a unit sphere in whose center the electrons are thought to be located.

If R=1 (unit sphere)

$$dn = \mathrm{K} \cdot 2\pi \sin\alpha\, d\alpha \exp(\frac{\mu_m \mu_0 H}{k_B T} \cos\alpha) \qquad \zeta = \frac{\mu_m \mu_0 H}{k_B T}$$

15.3 Langevin Theory of (Electron orbit) Paramagnetism

Intergrating “dn” to calculate the number of total atoms in a unit volume

$$n = 2\pi K \cdot \int_0^{\pi} \sin\alpha \exp(\zeta \cos\alpha) d\alpha$$

$$\therefore \; K = \frac{n}{2\pi \int_0^{\pi} \sin\alpha \exp(\zeta \cos\alpha) d\alpha}$$

The magnetization M is the magnetic moment per unit volume.

$$\therefore \; M = \int_0^{n} \mu_m \cos\alpha \, dn$$

$$= K \cdot 2\pi\mu_m \int_0^{\pi} \cos\alpha \sin\alpha \exp(\zeta \cos\alpha) d\alpha = \frac{n\mu_m \int_0^{\pi} \cos\alpha \sin\alpha \exp(\zeta \cos\alpha) d\alpha}{\int_0^{\pi} \sin\alpha \exp(\zeta \cos\alpha) d\alpha}$$

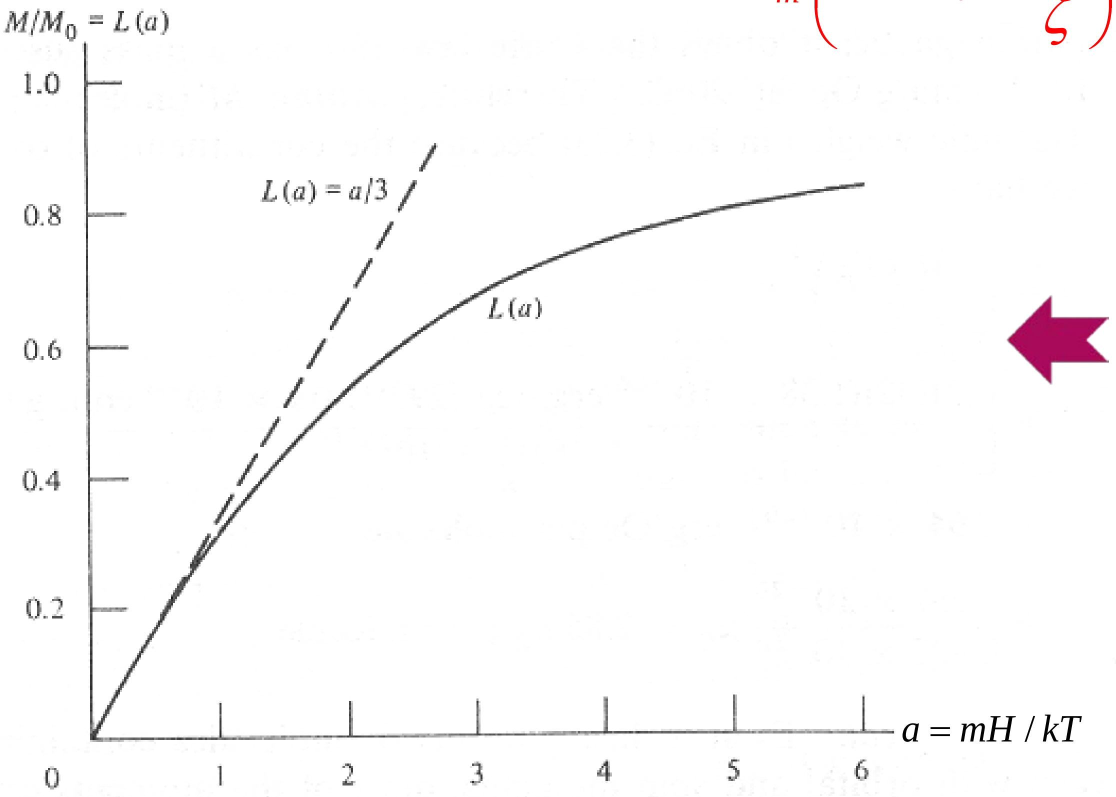
This function can be brought into a standard form by setting

$x = \cos\alpha$ and $dx = -\sin\alpha \, d\alpha$

$$M = n\mu_m \left(\coth\zeta - \frac{1}{\zeta} \right) = n\mu_m \left(\frac{\zeta}{3} - \frac{\zeta^3}{45} - \frac{\zeta^5}{945} - \cdots \right)$$

15.3 Langevin Theory of (Electron orbit) Paramagnetism

$$M = n\mu_m\left(\coth\zeta - \frac{1}{\zeta}\right) = n\mu_m\left(\frac{\zeta}{3} - \frac{\zeta^3}{45} - \frac{\zeta^5}{945} - \cdots\right)$$



Langevin function, L(a)

a means ζ

15.3 Langevin Theory of (Electron orbit) Paramagnetism

$M_0 = n\mu_m$: the maximum possible magnetization

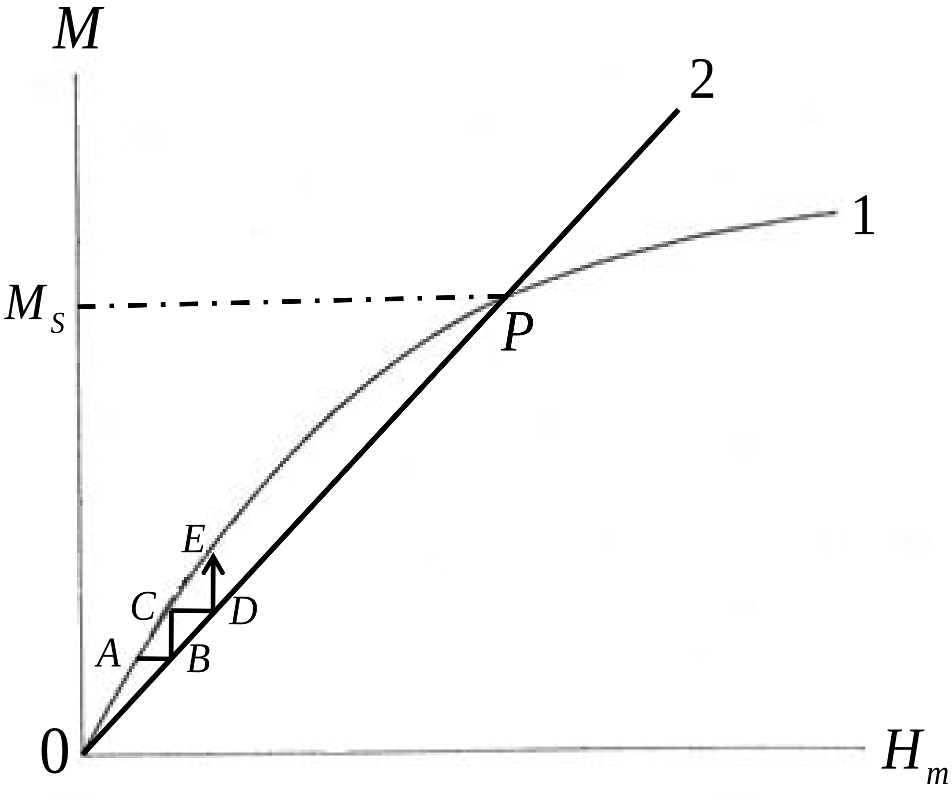
Because $\zeta = \dfrac{\mu_m \mu_0 H}{k_B T}$ is usually small,

$$\frac{M}{M_0} = \frac{\zeta}{3} \quad \Rightarrow \quad \therefore\ M = M_0 \frac{\zeta}{3} = \frac{n\mu_m^2 \mu_0 H}{3k_B T}$$

$$\chi_{para} = \frac{M}{H} = \frac{n\mu_m^2 \mu_0}{3k_B} \frac{1}{T} \equiv C \cdot \frac{1}{T}$$

$$C = \frac{n\mu_m^2 \mu_0}{3k_B}$$

15.4 Molecular Field Theory



Spontaneous magnetization by a molecular field

A magnetization greater than P will spontaneously revert to P, in the absence of an applied field. The substance has therefore become spontaneously magnetized level P, which is the value of M_S

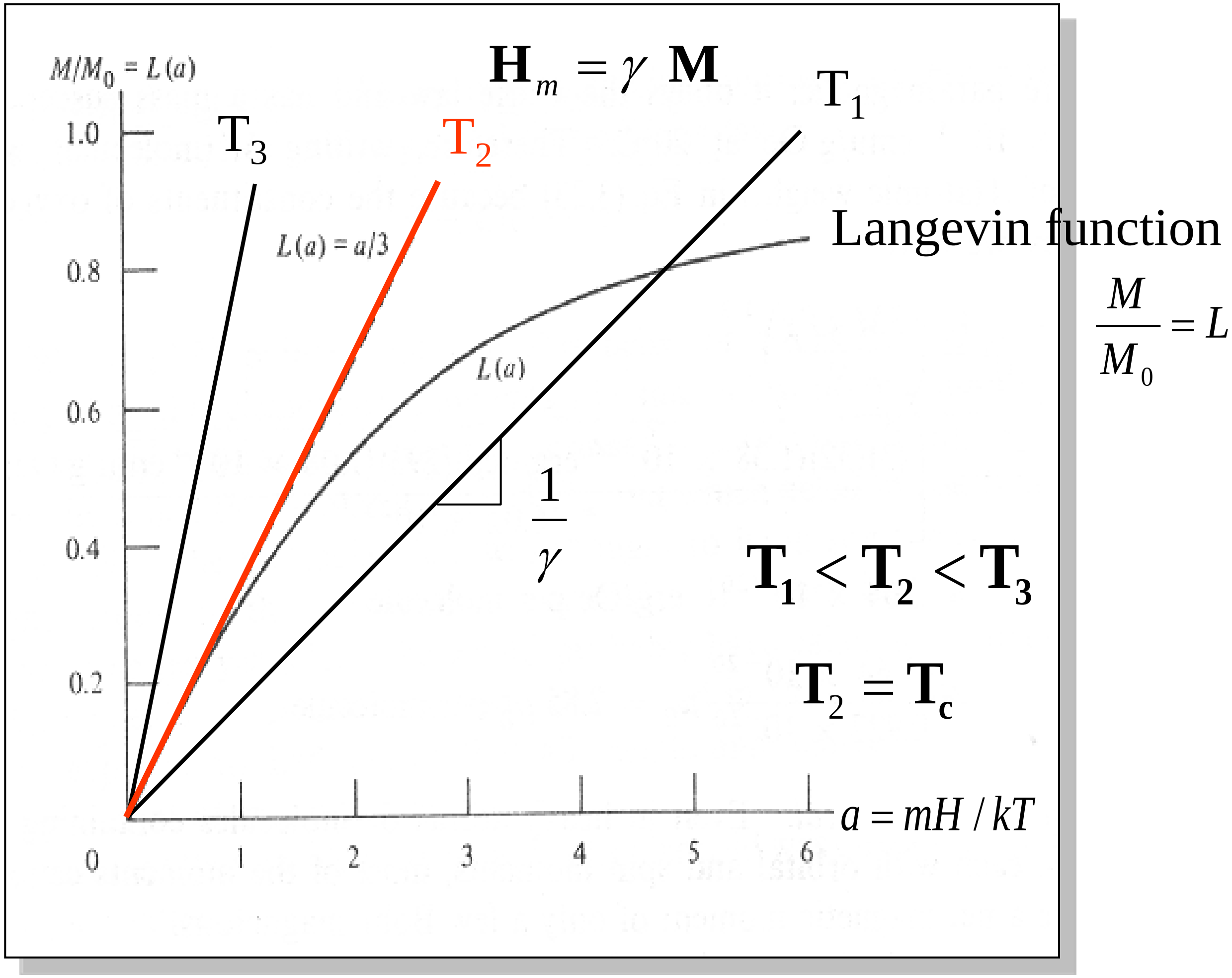
Ferromagnetic

↓

Paramagnetic subject to a very large molecular field

Molecular field ➔ $\mathbf{H}_m = \gamma \mathbf{M}$

15.4 Molecular Field Theory



$$\frac{M}{M_0} = L(a) = \coth a - \frac{1}{a}$$

Figure 15.18. Langevin function $L(\zeta)$, i.e., (15.28) and plot of (15.38) for three temperatures.

15.4 Molecular Field Theory

$$a = \frac{\mu H_m}{k_B T} = \frac{\mu\gamma\, M}{k_B T} = \frac{\mu\gamma\, M}{k_B T} \cdot \frac{M_0}{M_0}$$

$$\frac{M}{M_0} = \left(\frac{k_B T}{\mu\gamma M_0} \right) \cdot a$$

$$\frac{k_B T}{\mu\gamma M_0} = \frac{1}{3} \ \ at \ \ T = T_c$$

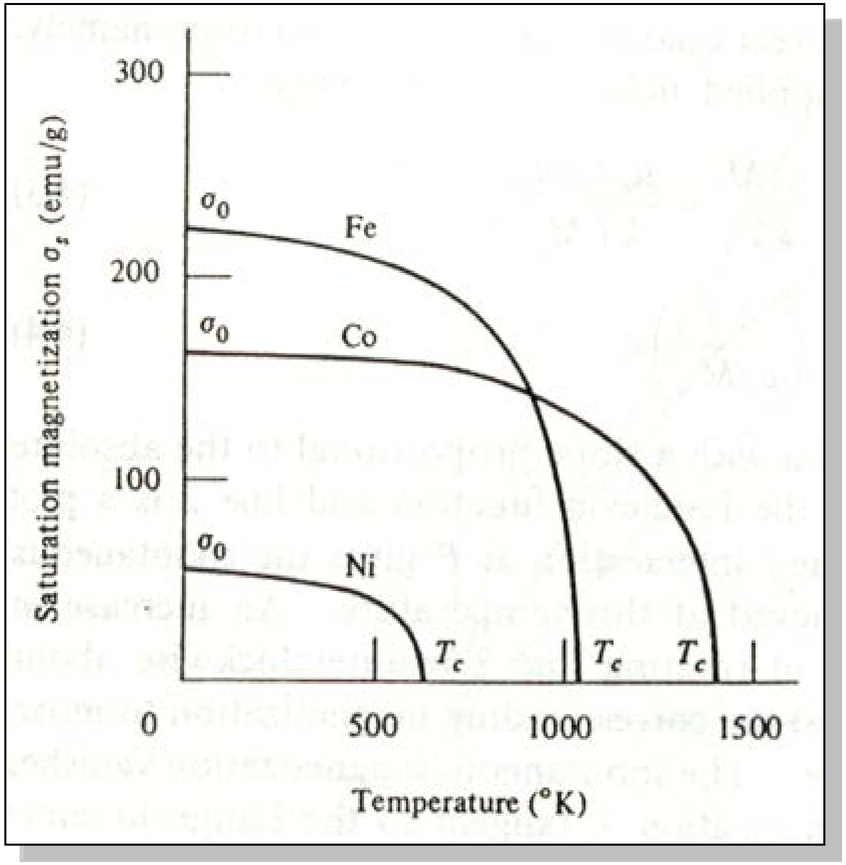
$$\frac{k_B T_c}{\mu\gamma M_0} \left(\frac{T}{T_c} \right) = \frac{1}{3} \left(\frac{T}{T_c} \right) = f\left(\frac{T}{T_c}\right)$$

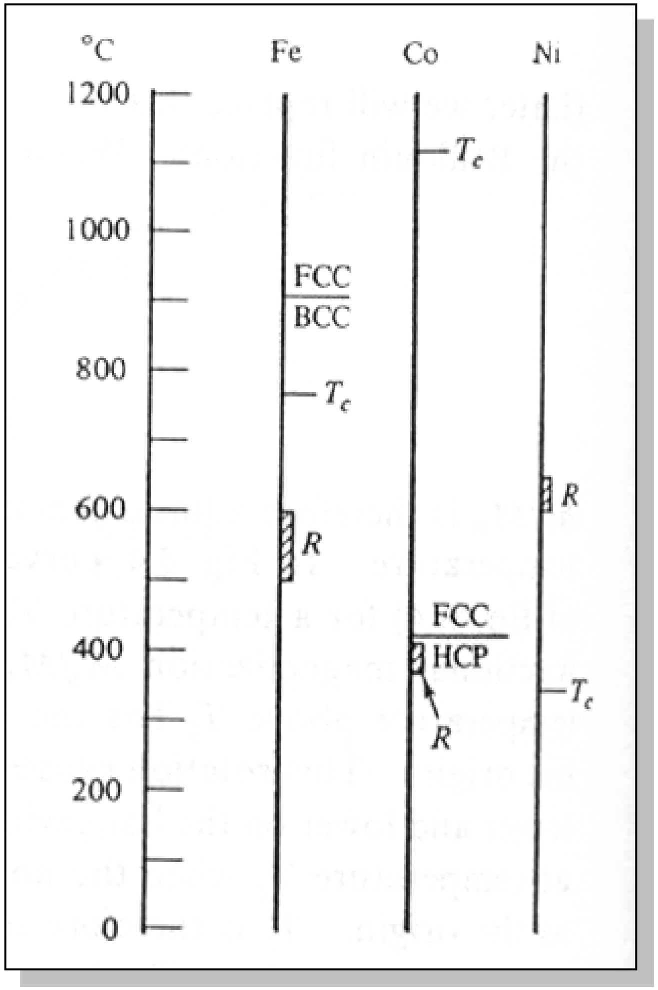
$$\frac{M_s}{M_0} \approx f\left(\frac{T}{T_c}\right)$$

Law of corresponding states

15.4 Molecular Field Theory

Saturation magnetization
& Curie temperature





15.4 Molecular Field Theory

$$\frac{M}{M_0} = \frac{2J+1}{2J}\coth\left(\frac{2J+1}{2J}\right)a' - \frac{1}{2J}\coth\frac{a'}{2J}$$

Brillouin function

$$\coth x \approx \tfrac{1}{x} + \tfrac{x}{3} \quad for \quad small \quad x$$

$$B(J,a') = \left(\frac{J+1}{3J}\right)a'$$

$$\frac{M}{M_0} = \left(\frac{k_B T}{\mu\gamma M_0}\right)\cdot a' \qquad a' = \frac{\mu H_m}{k_B T} = \frac{\mu\gamma M}{k_B T}$$

$$\frac{k_B T}{\mu\gamma M_0} = \frac{J+1}{3J}$$

at T=T$_c$

$$\frac{M}{M_0} = \left(\frac{J+1}{3J}\right)(T/T_c)a'$$

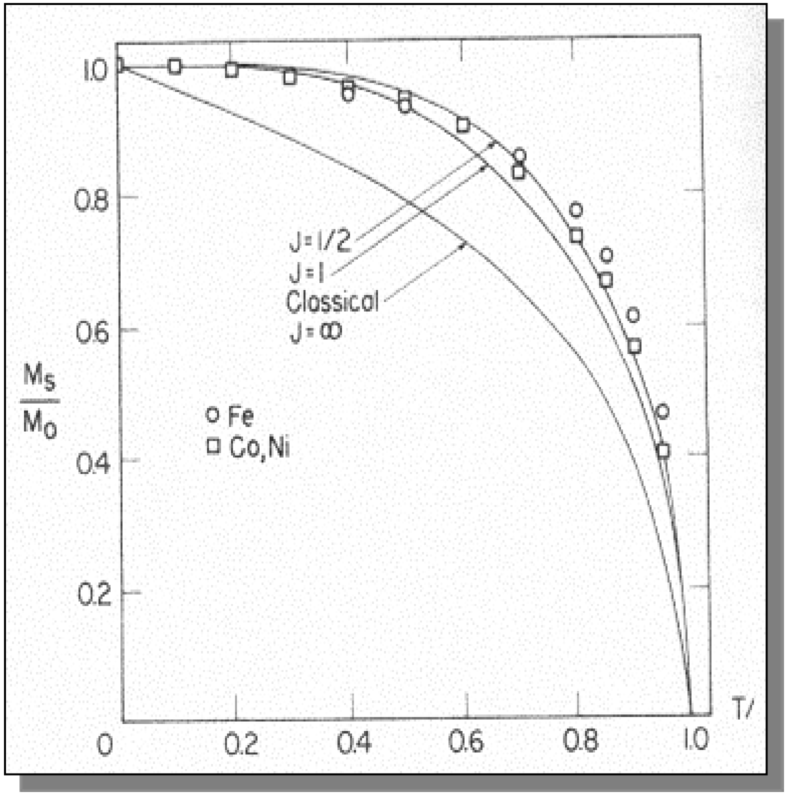
$$\frac{k_B T_c}{\mu\gamma M_0}\left(\frac{T}{T_c}\right) = \frac{J+1}{3J}\left(\frac{T}{T_c}\right)$$

15.4 Molecular Field Theory

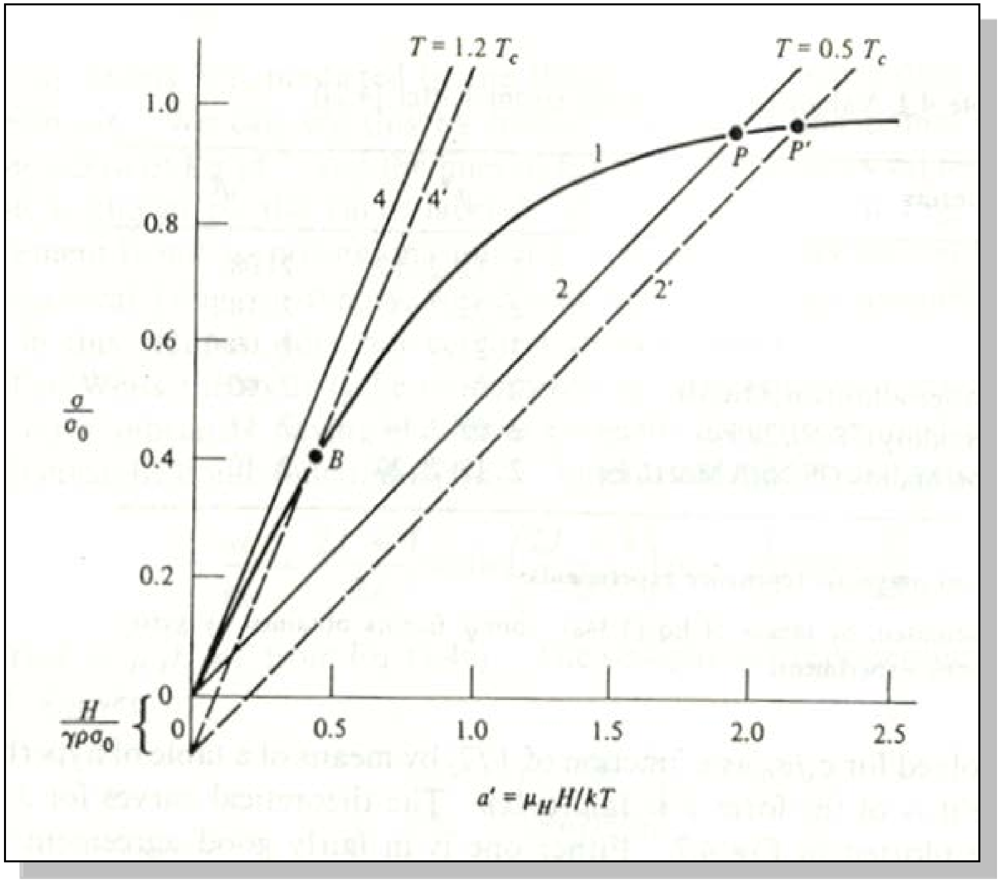
$$J \to \frac{1}{2}, \qquad \frac{M}{M_0} = \tanh a'$$

$$\frac{M}{M_0} = \left(\frac{J+1}{3J}\right)(T/T_c)a' \quad \Rightarrow \quad \frac{M}{M_0} = (T/T_c)a'$$

$$\frac{M}{M_0} = \tanh\left(\frac{M/M_0}{T/T_c}\right)$$



15.4 Molecular Field Theory



$$\frac{\sigma}{\sigma_0} = \left(\frac{kT}{\mu_H \gamma\rho\sigma_0}\right) a^{\backprime} - \frac{H}{\gamma\rho\sigma_0}$$

$$\frac{\sigma}{\sigma_0} = \left(\frac{J+1}{3J}\right) a^{\backprime}$$

$$\chi = \frac{\sigma}{H} = \frac{\mu_H \sigma_0 (J+1)/3kJ}{T - [\mu_H \gamma\rho\sigma_0 (J+1)/3kJ]}$$

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

When a magnetic field is applied

$$\mathbf{H} = \mathbf{H}_{appl} + \mathbf{H}_m = \mathbf{H}_{appl} + \gamma\mathbf{M}$$

$$C = \frac{\mu_H \sigma_0 (J+1)}{3kJ} \qquad \theta = \frac{\mu_H \gamma\rho\sigma_0 (J+1)}{3kJ}$$

15.4 Molecular Field Theory

Short range order

Spontaneous magnetization

Spin states

Spin fluctuation
due to thermal agitation