13. Magnetism

Nov. 15, 2018

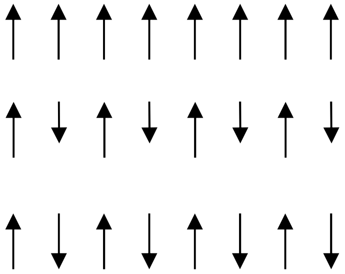
Magnetic ordering

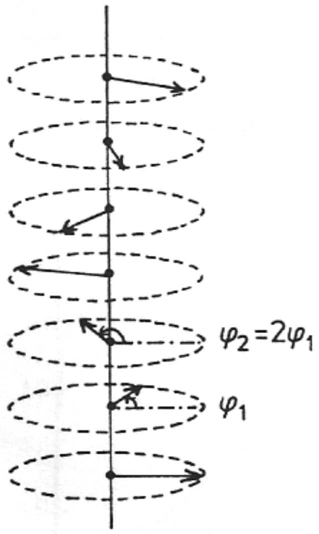
Ferromagnetism

Ferrimagnetism

Antiferromagnetism

Helimagnetism





All ordered magnetic states have excitations called magnons

Ferrimagnets

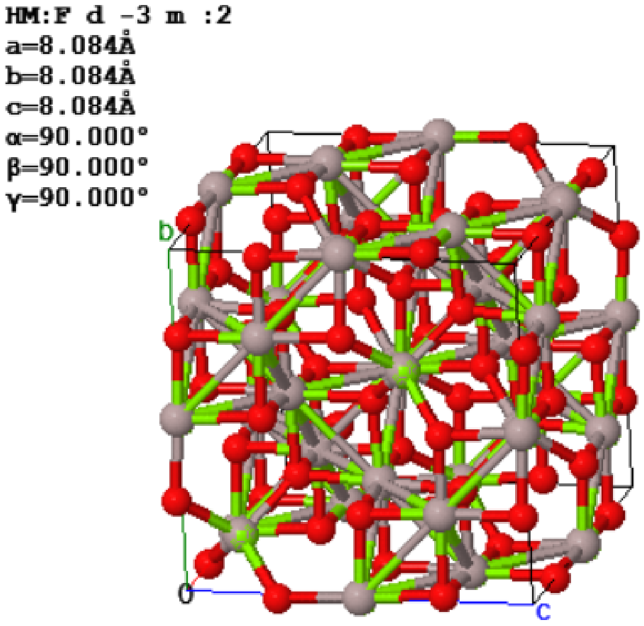
Magnetite Fe_3O_4
(Magneteisen)

Ferrites $MO{\cdot}Fe_2O_3$

M = Fe, Zn, Cd, Ni, Cu,
Co, Mg

↑ ↓ ↑ ↓ ↑ ↓ ↑ ↓

Two sublattices A and B.



$MgAl_2O_4$

Spinel crystal structure XY_2O_4

8 tetrahedral sites A (surrounded by 4 O) $5\mu_B \uparrow$

16 octahedral sites B (surrounded by 6 O) $9\mu_B \downarrow$

per unit cell

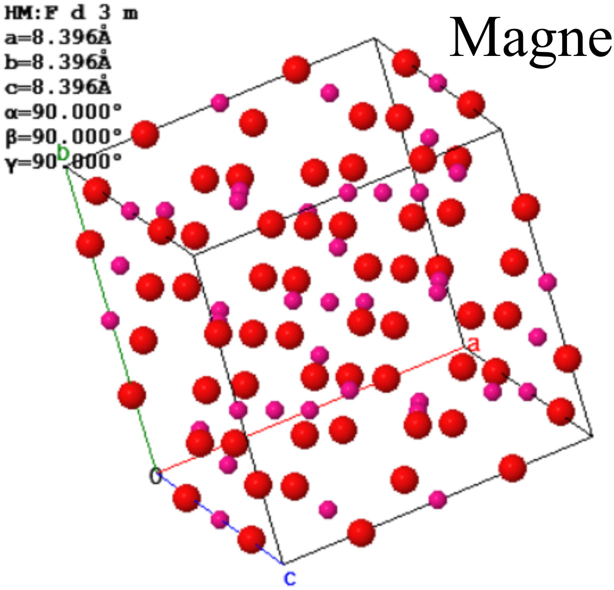
Ferrimagnets

Magnetite Fe_3O_4

Ferrites $MO \cdot Fe_2O_3$

M = Fe, Zn, Cd, Ni, Cu, Co, Mg

↑ ↓ ↑ ↓ ↑ ↓ ↑ ↓



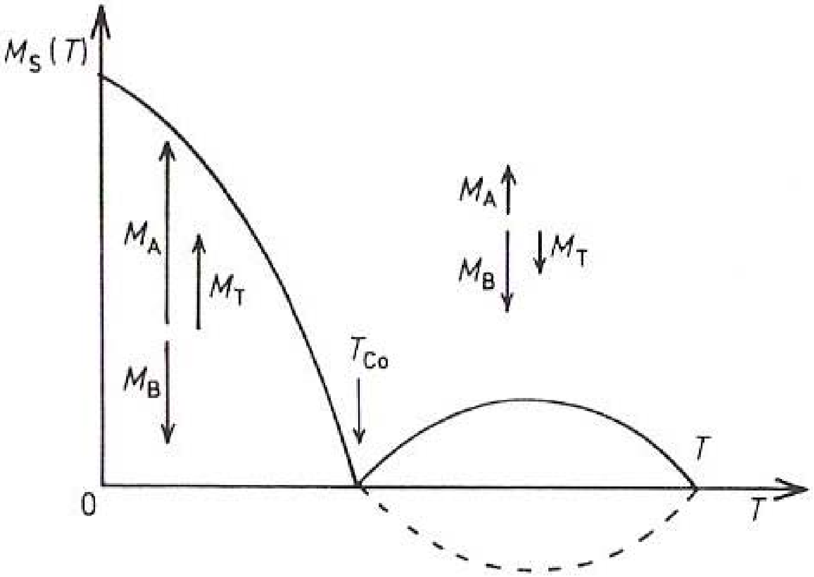
Magnetite

Exchange integrals J_{AA}, J_{AB}, and J_{BB} are all negative (antiparallel preferred)

$|J_{AB}| > |J_{AA}|, |J_{BB}|$

↑ ↓ ↑ ↓ ↑ ↓ ↑ ↓ Ferrimagnetism

gauss = 10^{-4} T
oersted = $10^{-4}/4\pi\times10^{-7}$ A/m



D. Gignoux, magnetic properties of Metallic systems

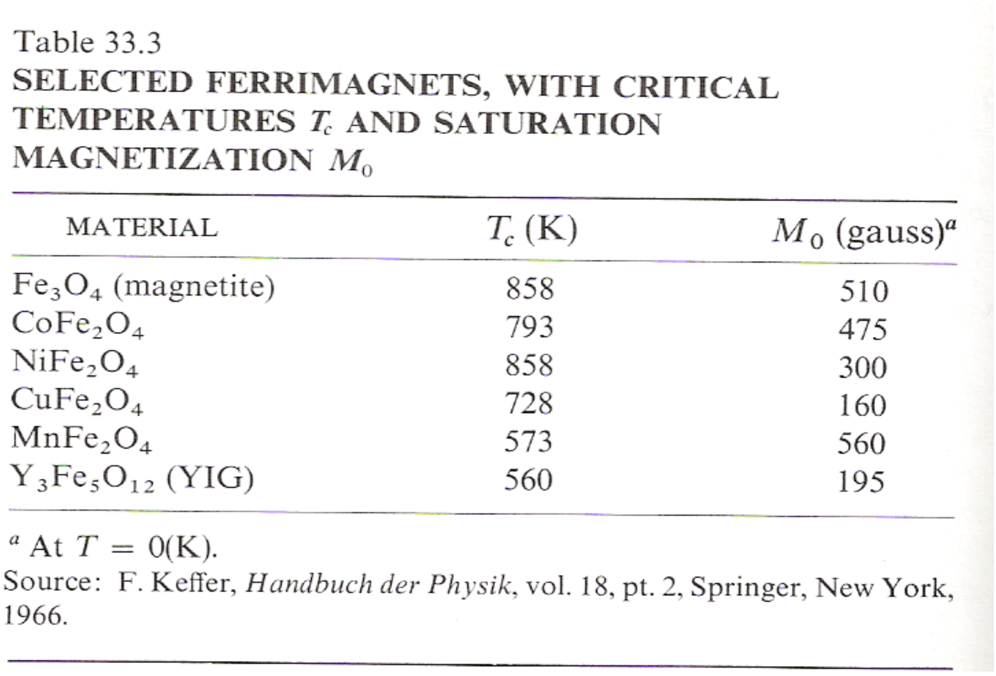


Table 33.3

SELECTED FERRIMAGNETS, WITH CRITICAL TEMPERATURES T_c AND SATURATION MAGNETIZATION M_0

MATERIAL	T_c (K)	M_0 (gauss)[a]
Fe_3O_4 (magnetite)	858	510
$CoFe_2O_4$	793	475
$NiFe_2O_4$	858	300
$CuFe_2O_4$	728	160
$MnFe_2O_4$	573	560
$Y_3Fe_5O_{12}$ (YIG)	560	195

[a] At $T = 0$(K).

Source: F. Keffer, *Handbuch der Physik*, vol. 18, pt. 2, Springer, New York, 1966.

Kittel

Antiferromagnetism

Negative exchange energy $J_{AB} < 0$.

↑↓↑↓↑↓↑↓

At low temperatures, below the Neel temperature T_N, the spins are aligned antiparallel and the macroscopic magnetization is zero.

Spin ordering can be observed by neutron scattering.

At high temperature antiferromagnets become paramagnetic. The macroscopic magnetization is zero and the spins are disordered in zero field.

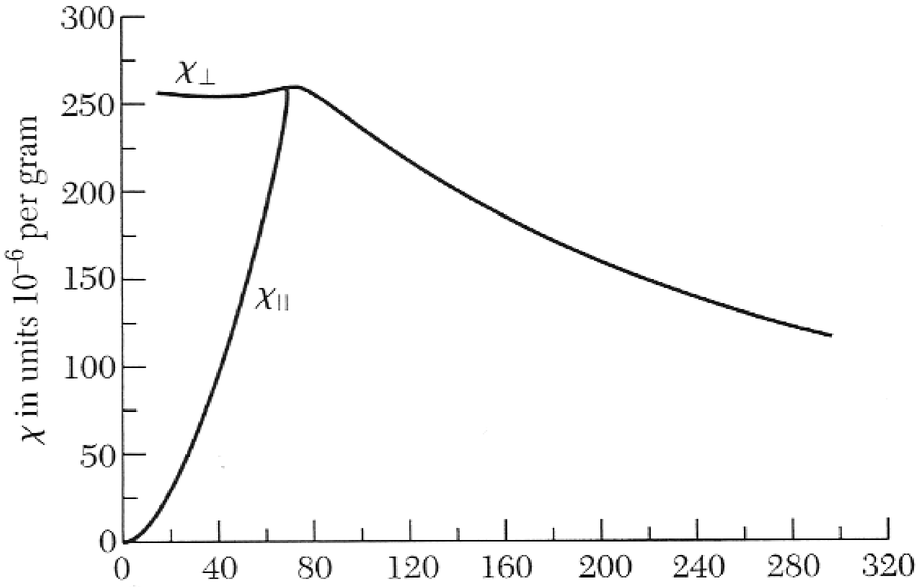
$$\chi = \mu_0 \frac{\vec{M}_A + \vec{M}_B}{\vec{B}_a} = \frac{C}{T + \Theta}$$

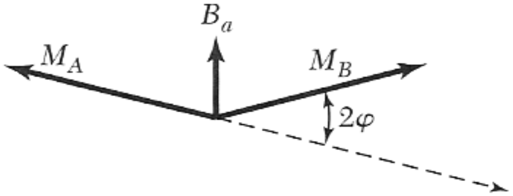
Curie-Weiss temperature

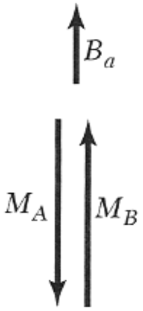
Antiferromagnetism ↑↓↑↓↑↓↑↓

Average spontaneous magnetization is zero at all temperatures.

Source: Kittel







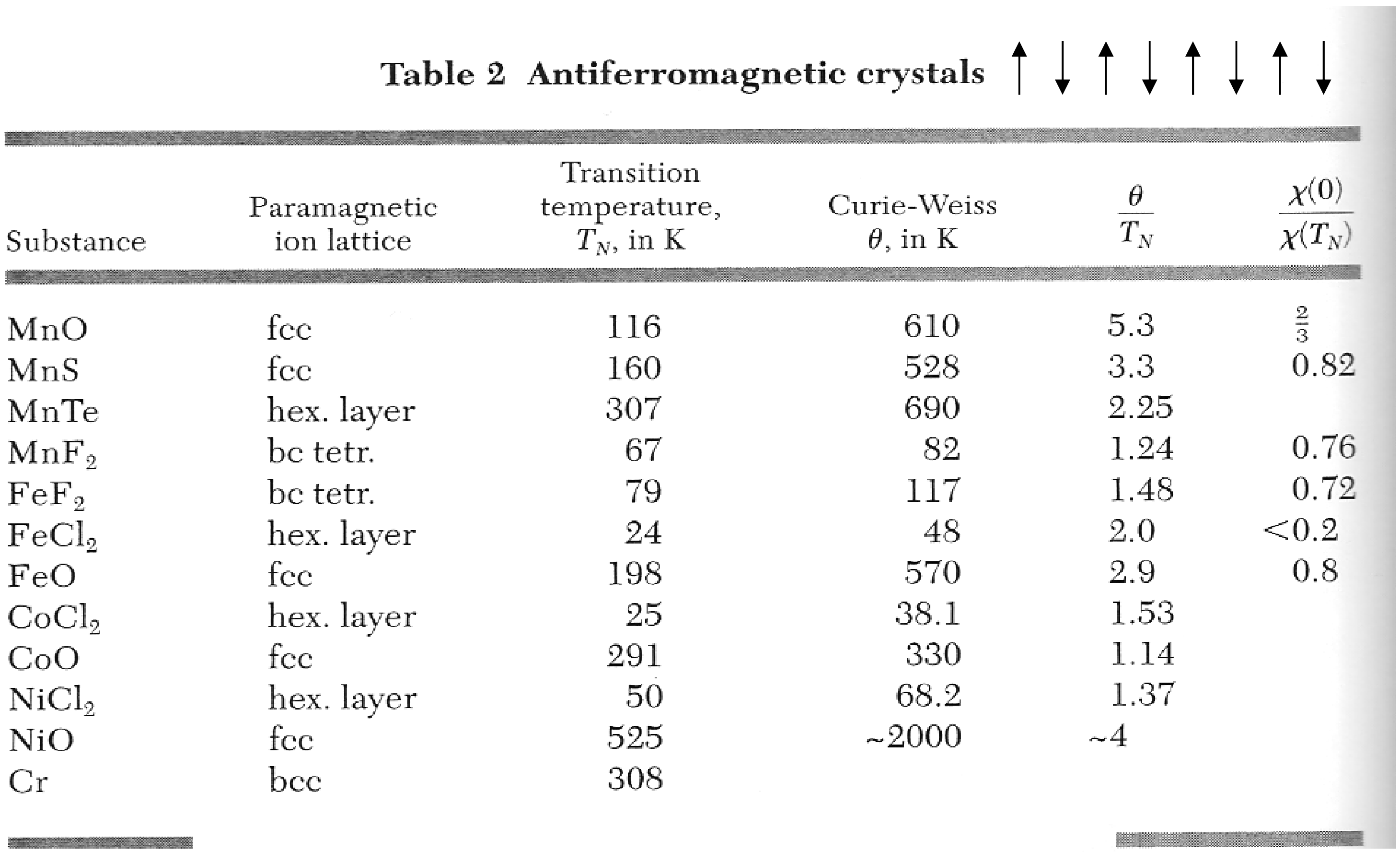
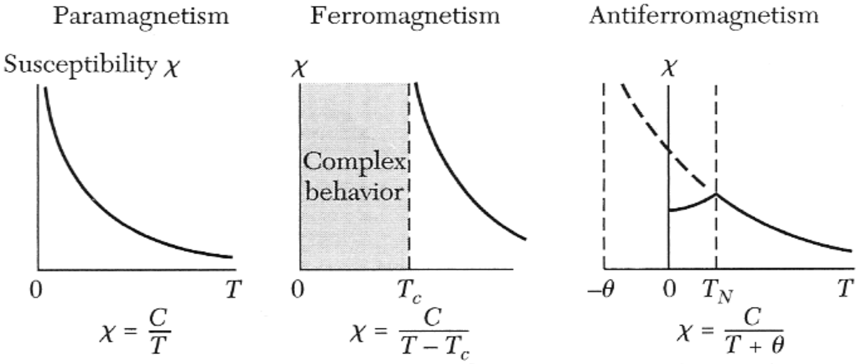


Table 2 Antiferromagnetic crystals ↑ ↓ ↑ ↓ ↑ ↓ ↑ ↓

Substance	Paramagnetic ion lattice	Transition temperature, T_N, in K	Curie-Weiss θ, in K	$\frac{\theta}{T_N}$	$\frac{\chi(0)}{\chi(T_N)}$
MnO	fcc	116	610	5.3	$\frac{2}{3}$
MnS	fcc	160	528	3.3	0.82
MnTe	hex. layer	307	690	2.25	
MnF_2	bc tetr.	67	82	1.24	0.76
FeF_2	bc tetr.	79	117	1.48	0.72
$FeCl_2$	hex. layer	24	48	2.0	<0.2
FeO	fcc	198	570	2.9	0.8
$CoCl_2$	hex. layer	25	38.1	1.53	
CoO	fcc	291	330	1.14	
$NiCl_2$	hex. layer	50	68.2	1.37	
NiO	fcc	525	~2000	~4	
Cr	bcc	308			



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

$\chi = \frac{C}{T - T_c}$ Curie-Weiss law ($T > T_c$)

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

from Kittel

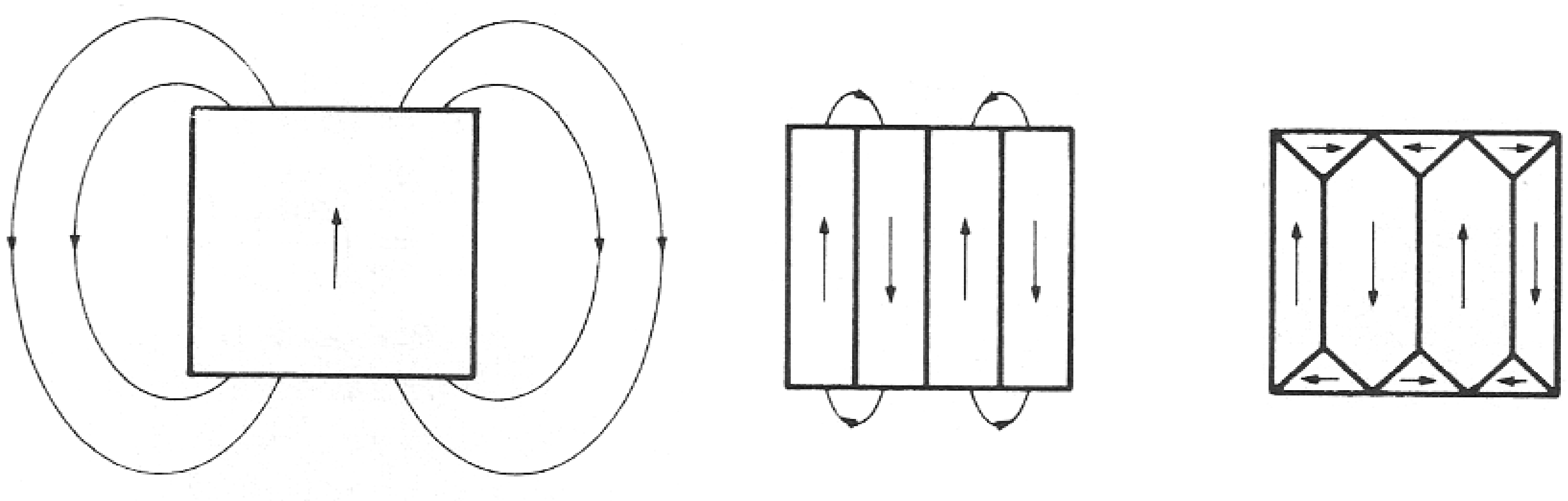
Applications of magnetism

Hard magnets: permanent magnets, motors, generators, microphones

Soft magnets: transformers

Magnetic recording

Magnetic domains (weisssche Bezirke)



Magnetic energy density

$$\frac{B^2}{2\mu_0}$$

Costs energy to introduce domain walls where spin up regions are adjacent to spin down regions.

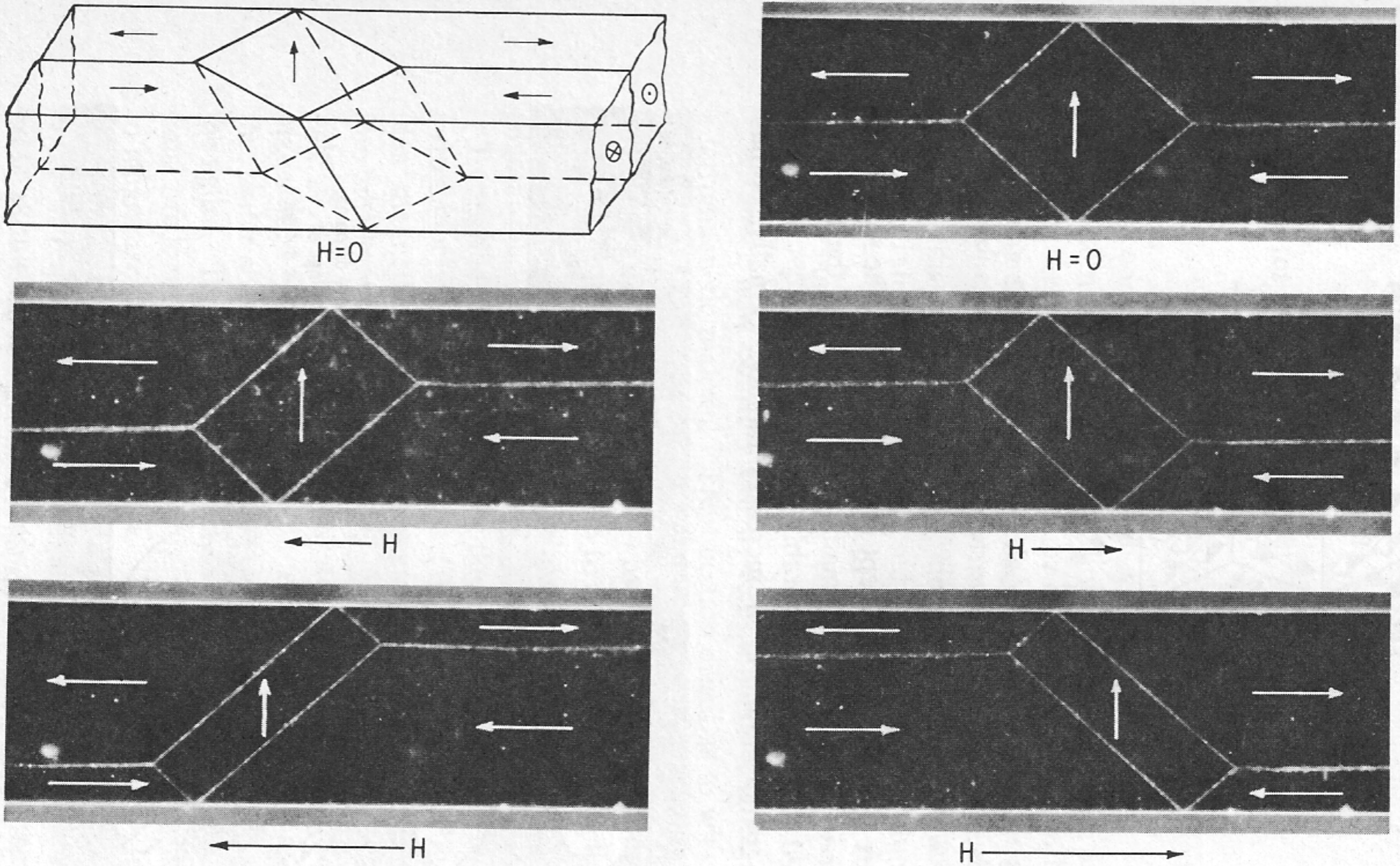


Figure 9.7

Ferromagnetic domains

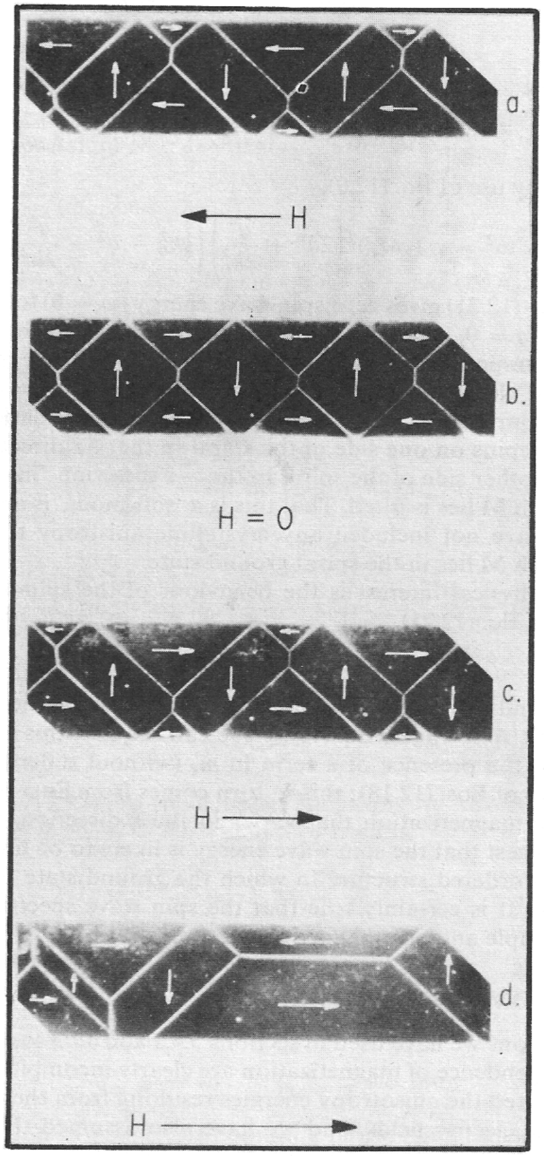
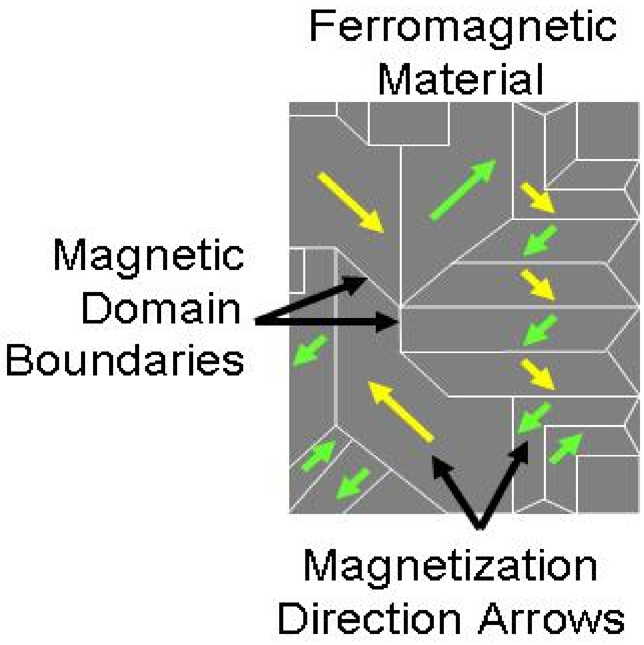


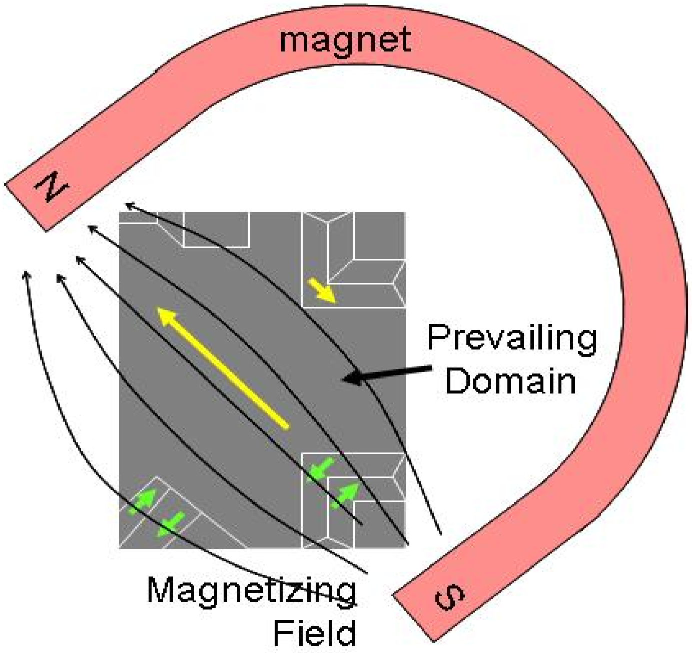
Fig. 12.5. Photographs showing reversible domain wall motion in a 50 μm whisker from (*a*) to (*b*) to (*c*), with an irreversible jump from (*c*) to (*d*).
{R. W. de Blois and C. D. Graham, *J. Appl. Phys.*, **29**, 931 (1958)}.

Weak fields: favorable domains expand
Strong fields: domains rotate to align with field

Irreproducible jump between c and d.

Magnetizing a magnet

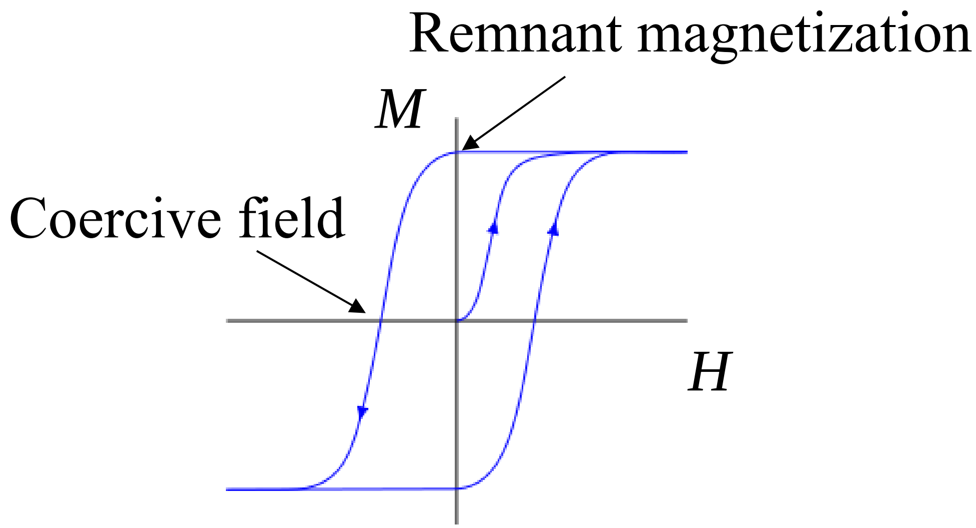




Weak fields: favorable domains expand

Strong fields: domains rotate to align with field

Hysteresis



$$B = \mu_0 \left(H + M \right)$$

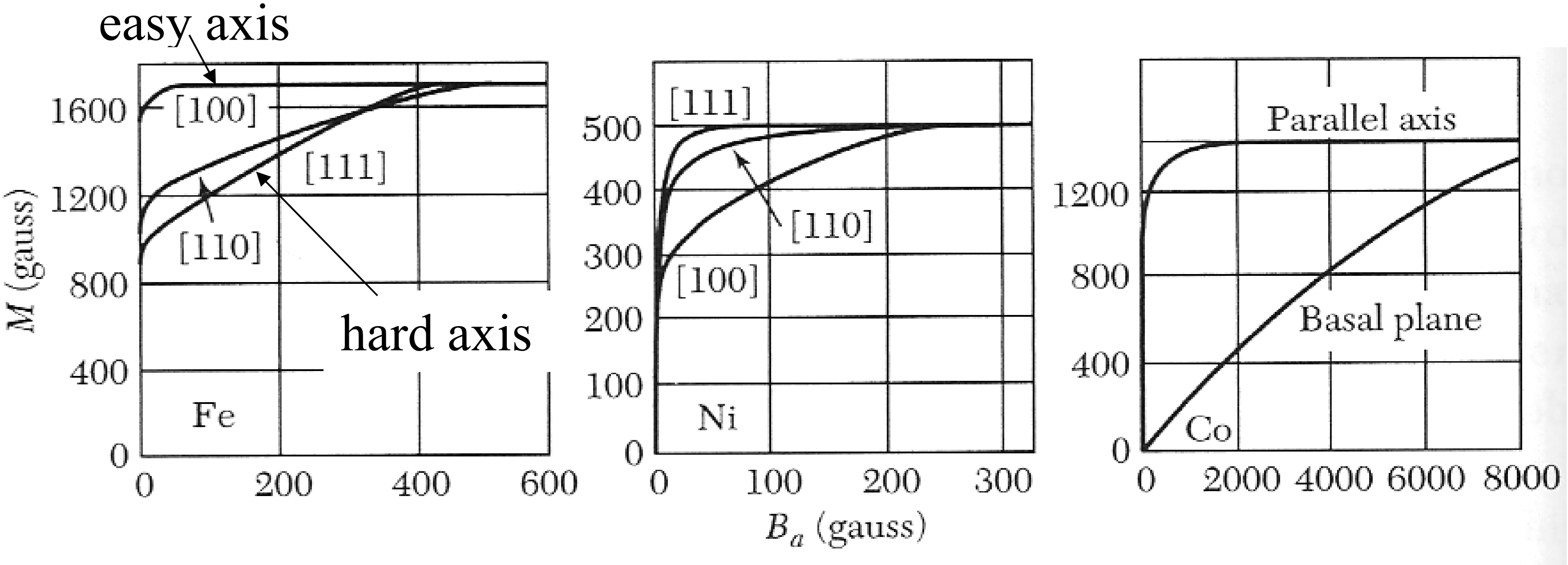
$$M = \chi H$$

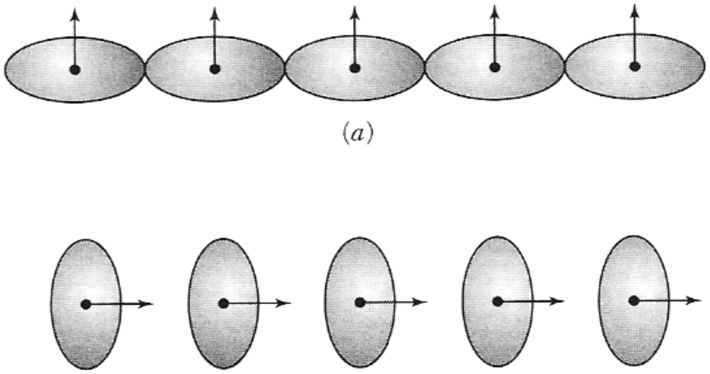
$$B = \mu_0 (1 + \chi) H = \mu_r \mu_0 H$$

$$\mu_r = \left(1 + \chi \right)$$

Area of the loop is proportional to energy dissipated in traversing the loop.

Anisotropy energy





Spin-orbit coupling couples the shape of the wavefunction to the spin. The exchange energy depends on the overlap of the wavefunctions and thus on spin direction.

Bloch wall

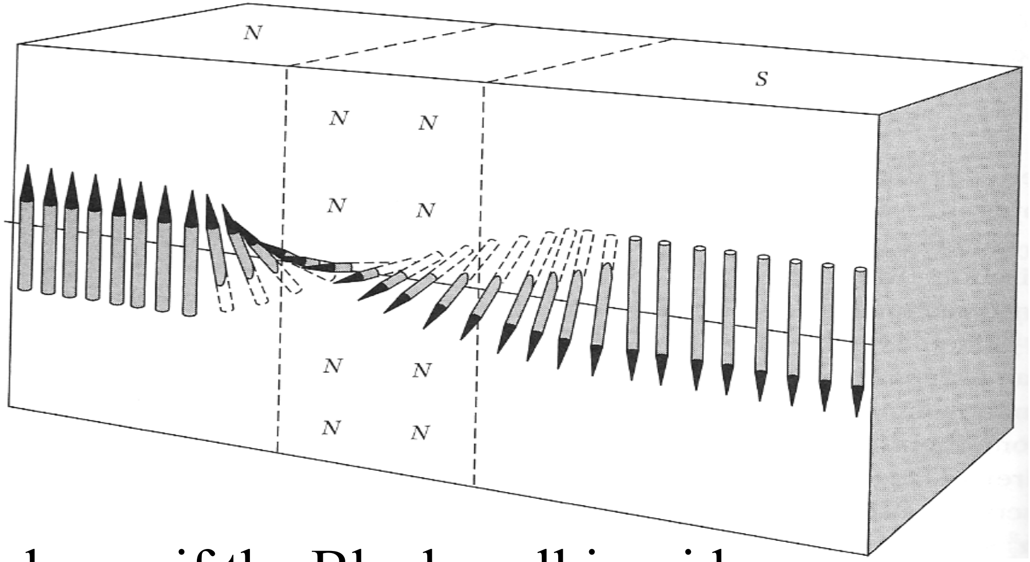
energy of two spins

$$w = -J\vec{S}_i \cdot \vec{S}_j = -JS^2 \cos\varphi \approx -JS^2\left(1-\frac{\varphi^2}{2}\right)$$

neglecting the constant part

$$w \approx JS^2 \frac{\varphi^2}{2}$$

$$\varphi = \frac{\pi}{N}$$



energy of a line of spins

$$Nw \approx \frac{JS^2\pi^2}{2N}$$

energy is lower if the Bloch wall is wide

energy per unit area $\approx \dfrac{JS^2\pi^2}{2Na^2}$

a is the lattice constant

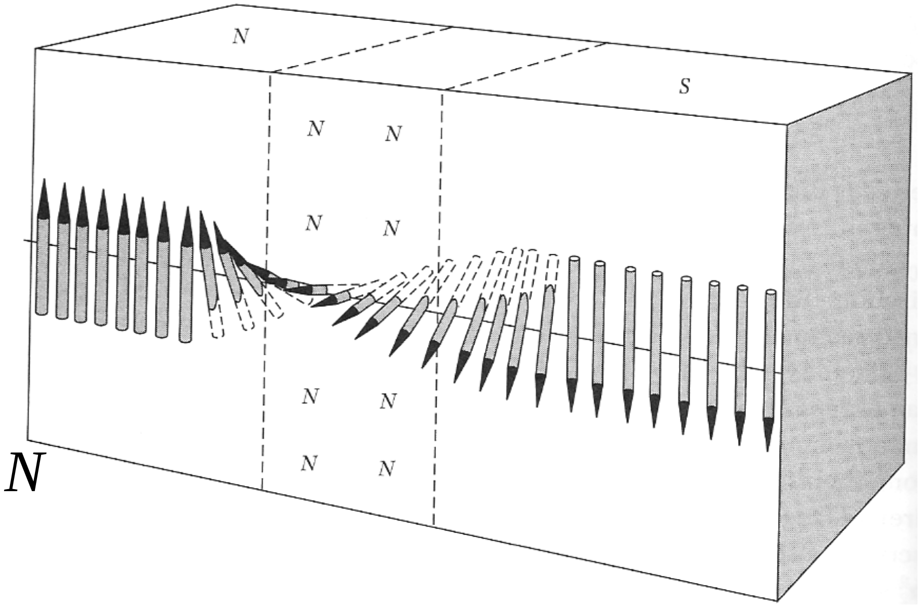
Bloch wall

Anisotropy energy depends on the number of spins pointing in the hard direction

$\approx KNa$

Na = thickness of wall

anisotropy constant J/m^3



Total energy per unit area:

$$E = \frac{JS^2\pi^2}{2Na^2} + KNa \qquad [\mathrm{J/m^2}]$$

smaller for large N smaller for small N

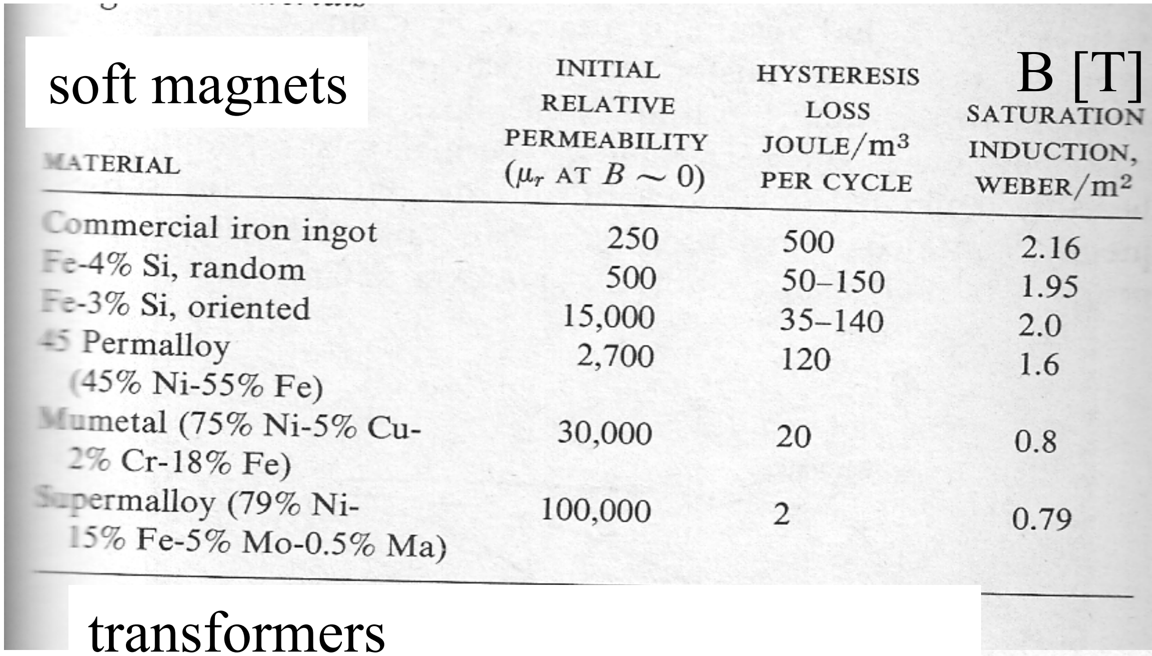
$$\frac{dE}{dN} = 0 \Rightarrow -\frac{JS^2\pi^2}{2N^2a^2} + Ka = 0$$

$$N = \sqrt{\frac{JS^2\pi^2}{2Ka^3}}$$

$N \sim 300$ for iron

Soft magnetic materials

soft magnets

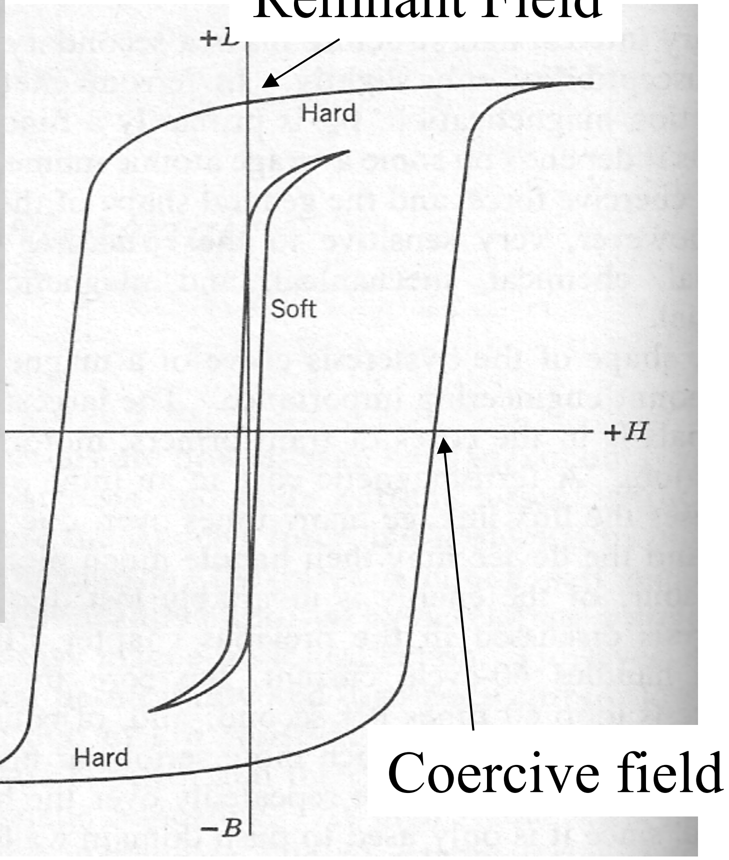


MATERIAL	INITIAL RELATIVE PERMEABILITY (μ_r AT $B \sim 0$)	HYSTERESIS LOSS JOULE/m³ PER CYCLE	B [T] SATURATION INDUCTION, WEBER/m²
Commercial iron ingot	250	500	2.16
Fe-4% Si, random	500	50–150	1.95
Fe-3% Si, oriented	15,000	35–140	2.0
45 Permalloy (45% Ni-55% Fe)	2,700	120	1.6
Mumetal (75% Ni-5% Cu-2% Cr-18% Fe)	30,000	20	0.8
Supermalloy (79% Ni-15% Fe-5% Mo-0.5% Ma)	100,000	2	0.79

transformers

magnetic shielding

ferrites have low eddy current losses



$$B = \mu_0 \left(H + M \right)$$

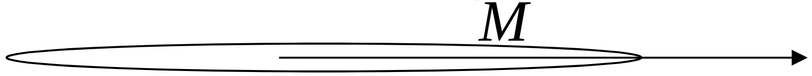
$$B = \mu_r \mu_0 H \qquad M = \chi H$$

$$\mu_r = 1 + \chi$$

Single domain particles

Small 10 - 100 nm particles have single domains.

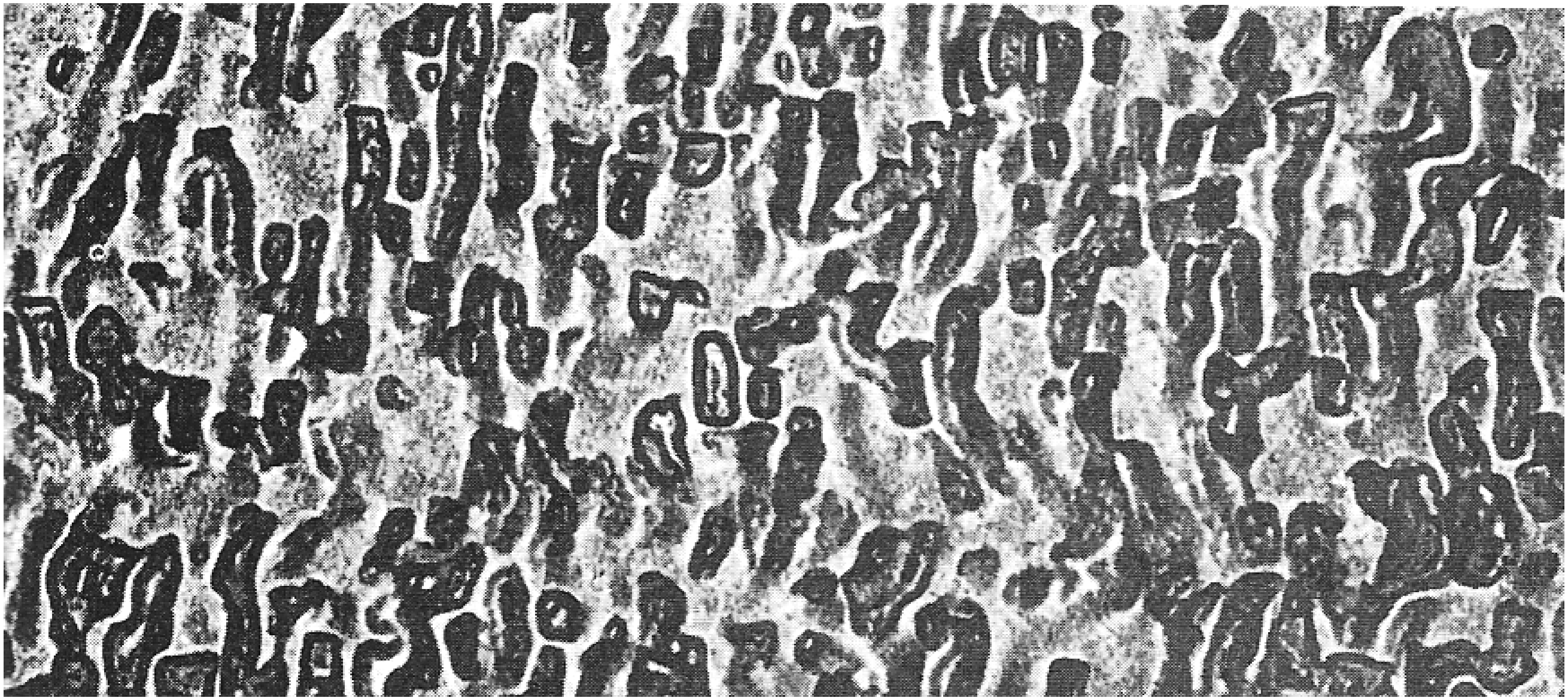
Elongated particles have the magnetization along the long axis.



Single domains are used for magnetic recording. Long crystals can be magnetized in either of the two directions along the long axis.

Shape anisotropy.

Hard magnets



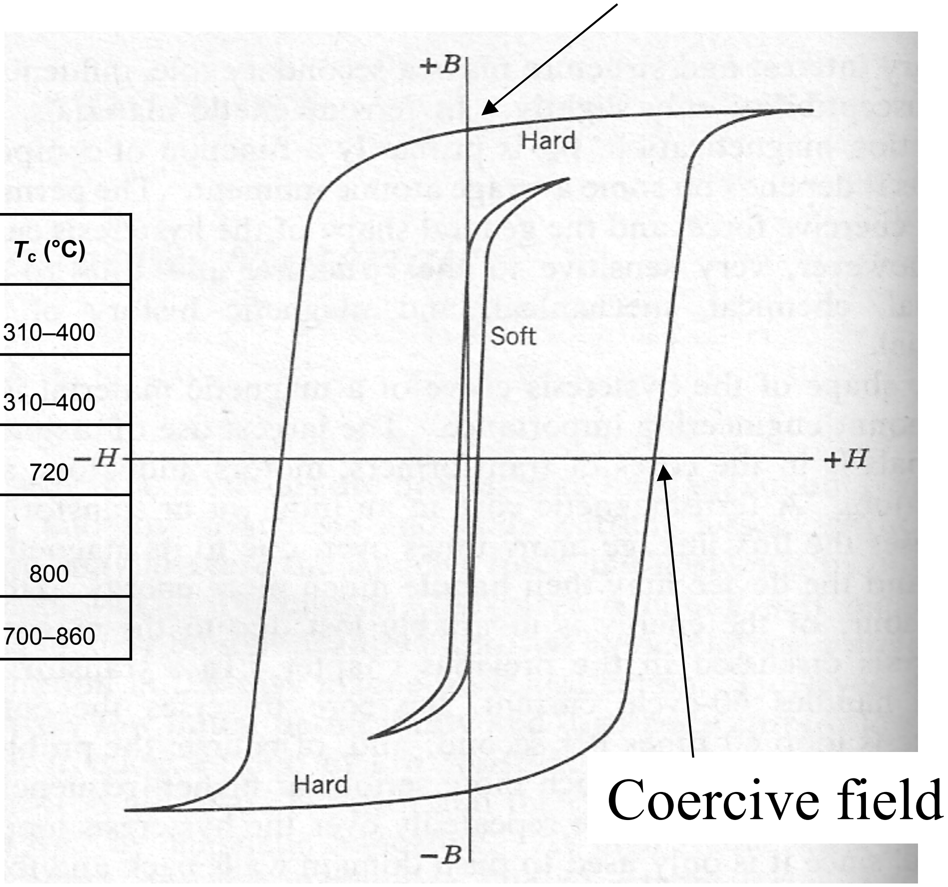
Grains too small to contain Bloch walls must be flipped entirely by the field.

Alnico: 8-12% Al, 15-26% Ni, 5-24% Co, up to 6% Cu, up to 1% Ti, rest is Fe

Hard magnetic materials

hard magnets

Magnet	B_r (T)	H_{ci} (kA/m)	$(BH)_{max}$ (kJ/m^3)	T_c (°C)
$Nd_2Fe_{14}B$ (sintered)	1.0–1.4	750–2000	200–440	310–400
$Nd_2Fe_{14}B$ (bonded)	0.6–0.7	600–1200	60–100	310–400
$SmCo_5$ (sintered)	0.8–1.1	600–2000	120–200	720
$Sm(Co,Fe,Cu,Zr)_7$ (sintered)	0.9–1.15	450–1300	150–240	800
Alnico (sintered)	0.6–1.4	275	10–88	700–860



Remnant Field

Coercive field

Permanent magnets, magnetron, motors, generators
ferrites can also be hard magnets

Defects are introduced to pin the Bloch walls in a hard magnet.