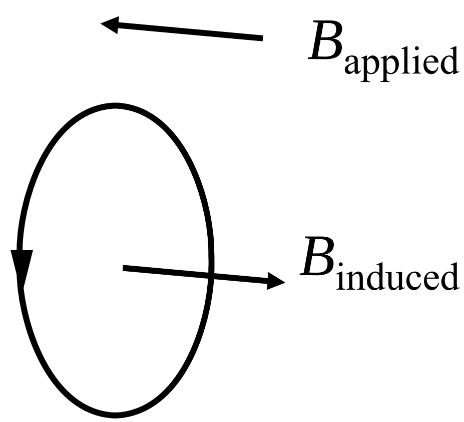
14. Magnetism

Nov 18, 2019

Diamagnetism

A free electron in a magnetic field will travel in a circle



The magnetic created by the current loop is opposite the applied field.

Diamagnetism

Dissipationless currents are induced in a diamagnet that generate a field that opposes an applied magnetic field.

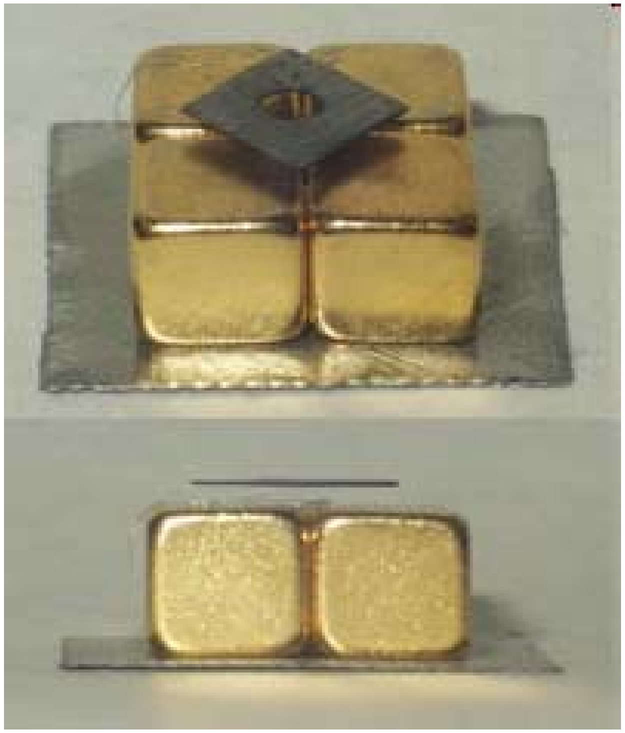
Current flow without dissipation is a quantum effect. There are no lower lying states to scatter into. This creates a current that generates a field that opposes the applied field.

$\chi = -1$ superconductor (perfect diamagnet)

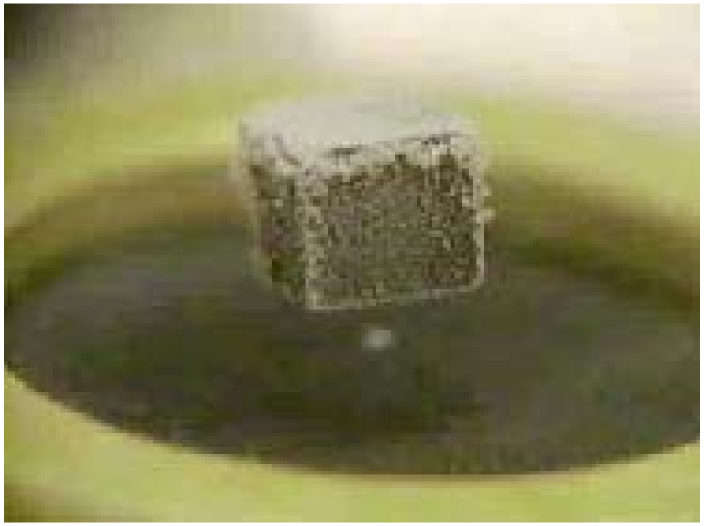
$\chi \sim -10^{-6} - 10^{-5}$ normal materials

Diamagnetism is always present but is often overshadowed by some other magnetic effect.

Levitating diamagnets



Levitating pyrolytic carbon



NOT: Lenz's law

$$V = -\frac{d\Phi}{dt}$$

Levitating frogs

χ for water is -9.05×10^{-6}

16 Tesla magnet at the Nijmegen High Field Magnet Laboratory

http://www.hfml.ru.nl/froglev.html

Andre Geim

2000 Ig Nobel Prize for levitating a frog with a magnet

The Nobel Prize in Physics 2010
Andre Geim, Konstantin Novoselov

- The Nobel Prize in Physics 2010
- Nobel Prize Award Ceremony
- **Andre Geim**

- **Biographical**
- Nobel Lecture
- Banquet Speech
- Interview
- Nobel Diploma
- Photo Gallery
- Other Resources

- Konstantin Novoselov

Andre Geim

Born: 1958, Sochi, Russia

Affiliation at the time of the award: University of Manchester, Manchester, United Kingdom

Prize motivation: "for groundbreaking experiments regarding the two-dimensional material graphene"

Diamagnetism

A dissipationless current is induced by a magnetic field that opposes the applied field.

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

Diamagnetic susceptibility	
Copper	-9.8×10^{-6}
Diamond	-2.2×10^{-5}
Gold	-3.6×10^{-5}
Lead	-1.7×10^{-5}
Nitrogen	-5.0×10^{-9}
Silicon	-4.2×10^{-6}
water	-9.0×10^{-6}
bismuth	-1.6×10^{-4}

Most stable molecules have a closed shell configuration and are diamagnetic.

Paramagnetism

Materials that have a magnetic moment are paramagnetic.

An applied field aligns the magnetic moments in the material making the field in the material larger than the applied field.

The internal field is zero at zero applied field (random magnetic moments).

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

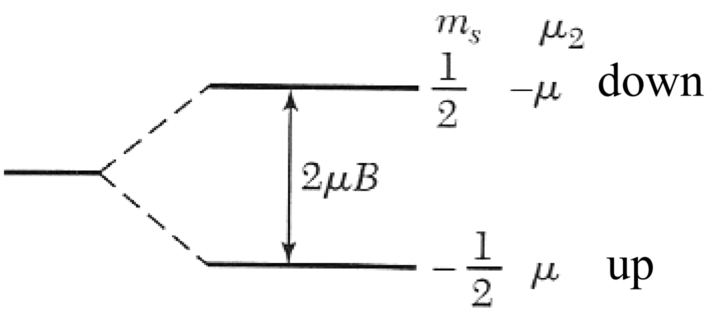
Paramagnetic susceptibility	
Aluminum	2.3×10^{-5}
Calcium	1.9×10^{-5}
Magnesium	1.2×10^{-5}
Oxygen	2.1×10^{-6}
Platinum	2.9×10^{-4}
Tungsten	6.8×10^{-5}

Boltzmann factors

To take the average value of quantity *A*

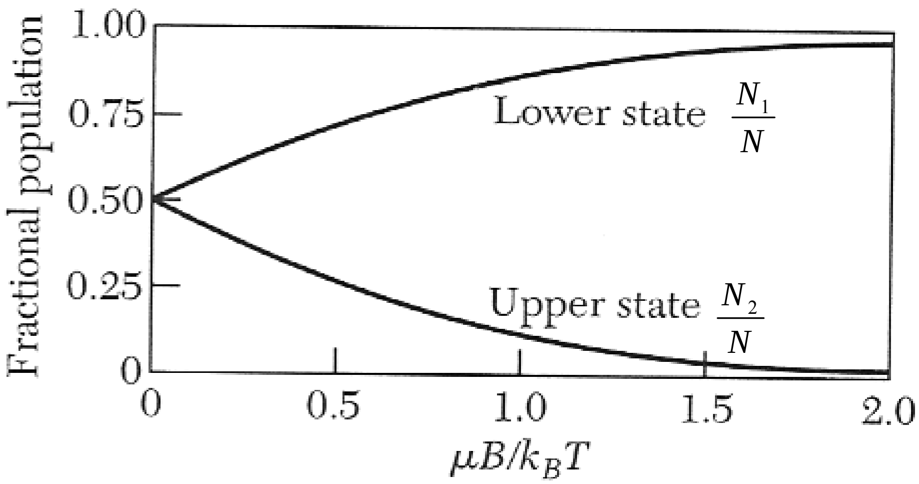
$$\langle A \rangle = \frac{\sum_i A_i e^{-E_i / k_B T}}{\sum_i e^{-E_i / k_B T}}$$

Spin populations



$$\frac{N_1}{N} = \frac{\exp(\mu B / k_B T)}{\exp(\mu B / k_B T) + \exp(-\mu B / k_B T)}$$

$$\frac{N_2}{N} = \frac{\exp(-\mu B / k_B T)}{\exp(\mu B / k_B T) + \exp(-\mu B / k_B T)}$$

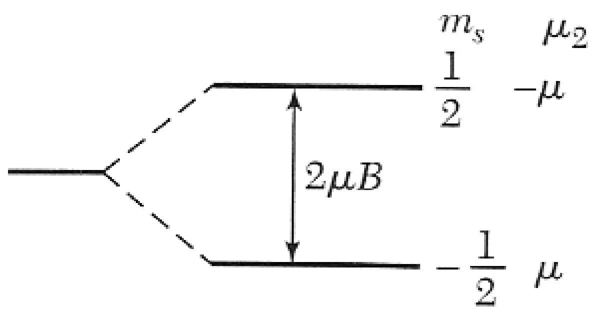


$$M = (N_1 - N_2)\mu / V$$

$$= n\mu \frac{\exp(\mu B / k_B T) - \exp(-\mu B / k_B T)}{\exp(\mu B / k_B T) + \exp(-\mu B / k_B T)}$$

$$= n\mu \tanh\left(\frac{\mu B}{k_B T}\right)$$

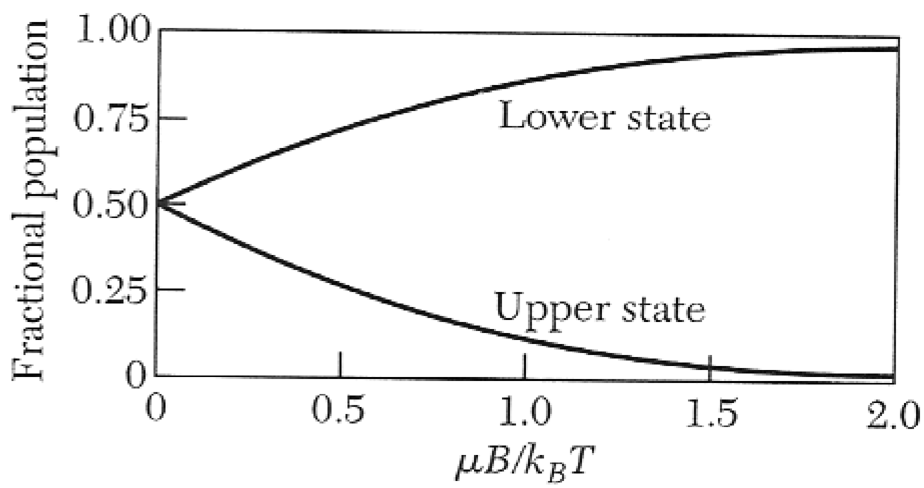
Paramagnetism, spin 1/2

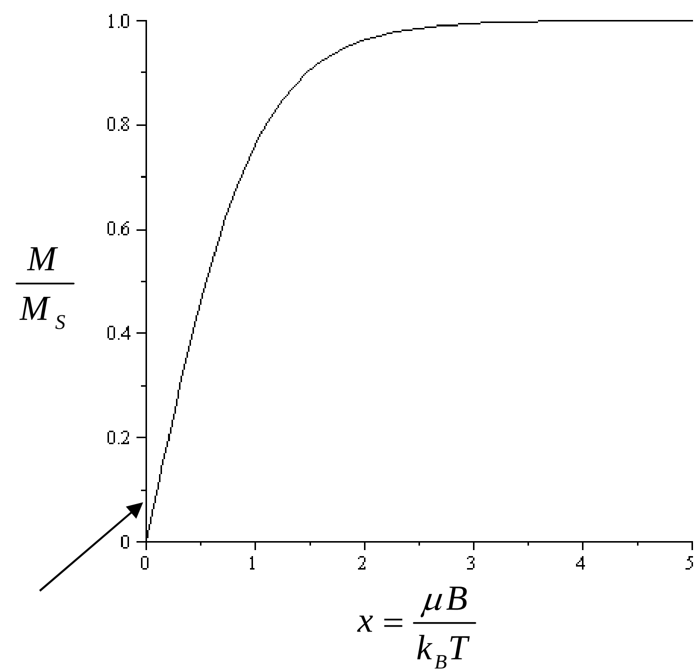


$$M = n\mu \tanh\left(\frac{\mu B}{k_B T}\right) \approx \frac{n\mu^2 B}{k_B T} = \frac{CB}{T}$$

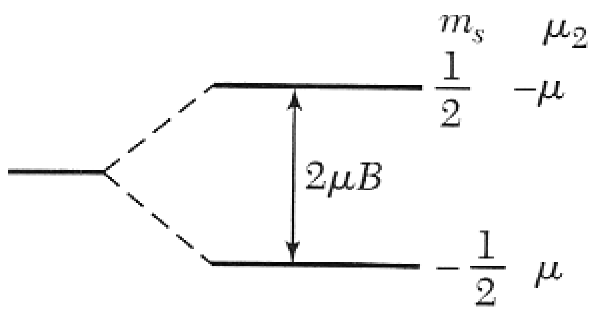
for $\mu B << k_B T$

Curie law





Paramagnetism, spin 1/2



$$M = n\mu \tanh\left(\frac{\mu B}{k_B T}\right) \approx \frac{n\mu^2 B}{k_B T} = \frac{CB}{T}$$

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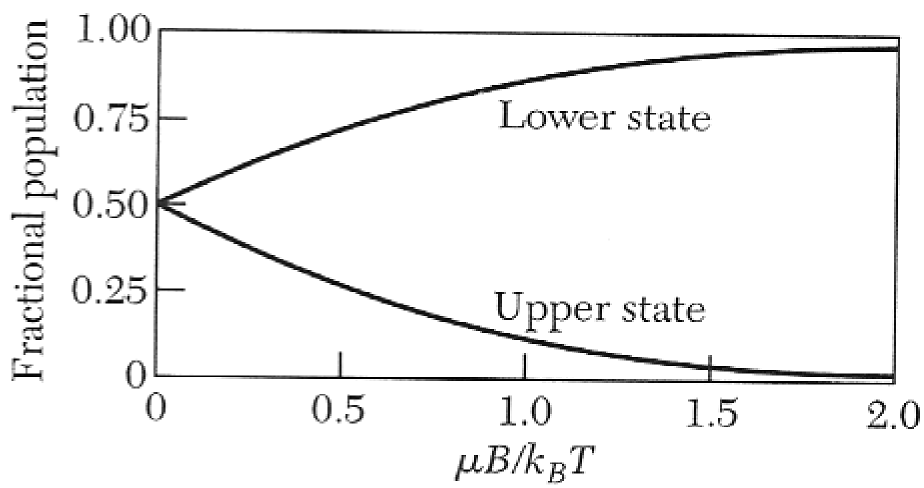
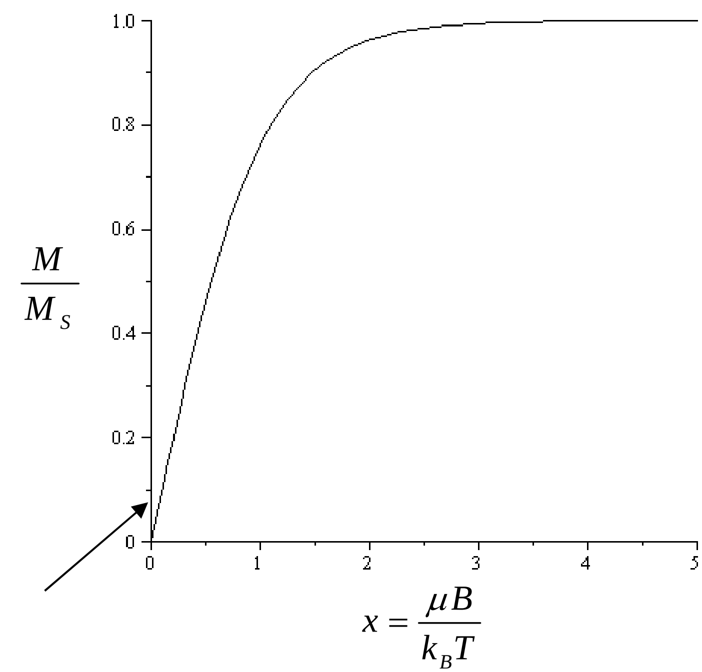
Curie law





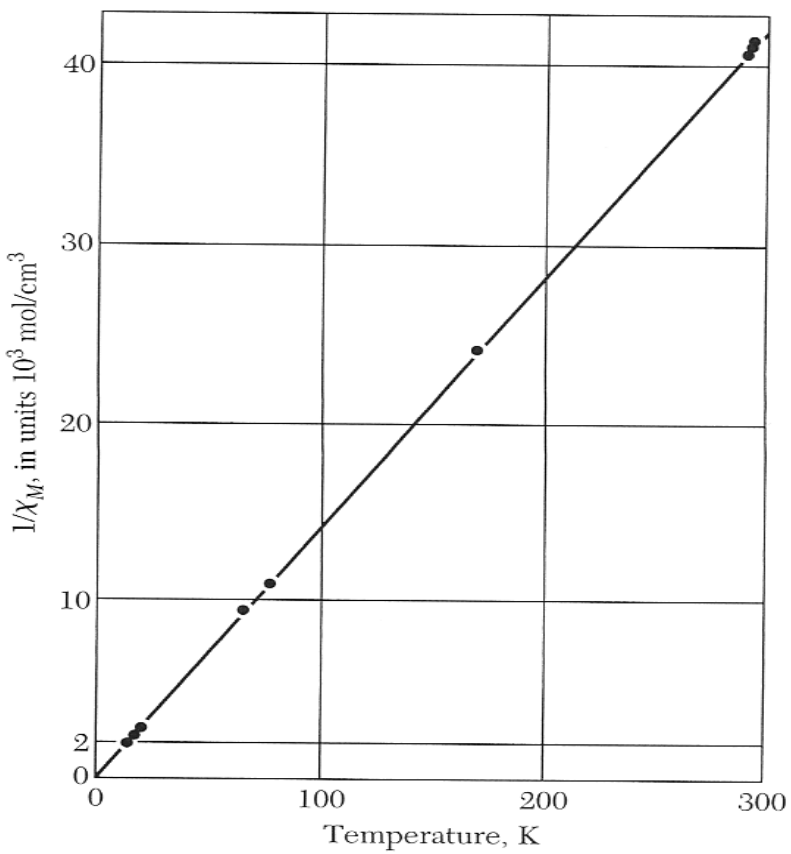
Curie law

for $\mu B << k_B T \quad M = CB/T$

$$\chi \propto \left.\frac{dM}{dB}\right|_{B=0} = \frac{C}{T}$$

C is the Curie constant

$Gd(C_2H_3SO_4)_3 9H_2O$



Atomic physics

In atomic physics, the possible values of the magnetic moment of an atom in the direction of the applied field can only take on certain values.

Total angular momentum

$J = L + S$ Orbital L + spin S angular momentum

Magnetic quantum number

$m_J = -J, -J+1, \cdots J-1, J$

Allowed values of the magnetic moment in the z direction

$$\mu_Z = m_j g_J \mu_B$$

Lande g factor → g_J

Bohr magneton → μ_B

$$g_J \approx \frac{3}{2} + \frac{S(S+1) - L(L+1)}{2J(J+1)}$$

$$\frac{\left\langle \psi_{Cu3d^{10}4s^{1}} \middle| H \middle| \psi_{Cu3d^{10}4s^{1}} \right\rangle}{\left\langle \psi_{Cu3d^{10}4s^{1}} \middle| \psi_{Cu3d^{10}4s^{1}} \right\rangle} < \frac{\left\langle \psi_{Cu3d^{9}4s^{2}} \middle| H \middle| \psi_{Cu3d^{9}4s^{2}} \right\rangle}{\left\langle \psi_{Cu3d^{9}4s^{2}} \middle| \psi_{Cu3d^{9}4s^{2}} \right\rangle}$$

Period																			
1	Hydrogen 1 H 1.008																		Helium 2 He 4.0026
2	Lithium 3 Li 6.94	Beryllium 4 Be 9.0122												Boron 5 B 10.81	Carbon 6 C 12.011	Nitrogen 7 N 14.007	Oxygen 8 O 15.999	Fluorine 9 F 18.998	Neon 10 Ne 20.180
3	Sodium 11 Na 22.990	Magnesium 12 Mg 24.305												Aluminium 13 Al 26.982	Silicon 14 Si 28.085	Phosphorus 15 P 30.974	Sulfur 16 S 32.06	Chlorine 17 Cl 35.45	Argon 18 Ar 39.95
4	Potassium 19 K 39.098	Calcium 20 Ca 40.078	Scandium 21 Sc 44.956		Titanium 22 Ti 47.867	Vanadium 23 V 50.942	Chromium 24 Cr 51.996	Manganese 25 Mn 54.938	Iron 26 Fe 55.845	Cobalt 27 Co 58.933	Nickel 28 Ni 58.693	Copper 29 Cu 63.546	Zinc 30 Zn 65.38	Gallium 31 Ga 69.723	Germanium 32 Ge 72.630	Arsenic 33 As 74.922	Selenium 34 Se 78.971	Bromine 35 Br 79.904	Krypton 36 Kr 83.798
5	Rubidium 37 Rb 85.468	Strontium 38 Sr 87.62	Yttrium 39 Y 88.906		Zirconium 40 Zr 91.224	Niobium 41 Nb 92.906	Molybdenum 42 Mo 95.95	Technetium 43 Tc [97]	Ruthenium 44 Ru 101.07	Rhodium 45 Rh 102.91	Palladium 46 Pd 106.42	Silver 47 Ag 107.87	Cadmium 48 Cd 112.41	Indium 49 In 114.82	Tin 50 Sn 118.71	Antimony 51 Sb 121.76	Tellurium 52 Te 127.60	Iodine 53 I 126.90	Xenon 54 Xe 131.29
6	Caesium 55 Cs 132.91	Barium 56 Ba 137.33	Lanthanum 57 La 138.91	*	Hafnium 72 Hf 178.49	Tantalum 73 Ta 180.95	Tungsten 74 W 183.84	Rhenium 75 Re 186.21	Osmium 76 Os 190.23	Iridium 77 Ir 192.22	Platinum 78 Pt 195.08	Gold 79 Au 196.97	Mercury 80 Hg 200.59	Thallium 81 Tl 204.38	Lead 82 Pb 207.2	Bismuth 83 Bi 208.98	Polonium 84 Po [209]	Astatine 85 At [210]	Radon 86 Rn [222]
7	Francium 87 Fr [223]	Radium 88 Ra [226]	Actinium 89 Ac [227]	**	Rutherfordium 104 Rf [267]	Dubnium 105 Db [268]	Seaborgium 106 Sg [269]	Bohrium 107 Bh [270]	Hassium 108 Hs [269]	Meitnerium 109 Mt [278]	Darmstadtium 110 Ds [281]	Roentgenium 111 Rg [282]	Copernicium 112 Cn [285]	Nihonium 113 Nh [286]	Flerovium 114 Fl [289]	Moscovium 115 Mc [290]	Livermorium 116 Lv [293]	Tennessine 117 Ts [294]	Oganesson 118 Og [294]
				*	Cerium 58 Ce 140.12	Praseodymium 59 Pr 140.91	Neodymium 60 Nd 144.24	Promethium 61 Pm [145]	Samarium 62 Sm 150.36	Europium 63 Eu 151.96	Gadolinium 64 Gd 157.25	Terbium 65 Tb 158.93	Dysprosium 66 Dy 162.50	Holmium 67 Ho 164.93	Erbium 68 Er 167.26	Thulium 69 Tm 168.93	Ytterbium 70 Yb 173.05	Lutetium 71 Lu 174.97	
				**	Thorium 90 Th 232.04	Protactinium 91 Pa 231.04	Uranium 92 U 238.03	Neptunium 93 Np [237]	Plutonium 94 Pu [244]	Americium 95 Am [243]	Curium 96 Cm [247]	Berkelium 97 Bk [247]	Californium 98 Cf [251]	Einsteinium 99 Es [252]	Fermium 100 Fm [257]	Mendelevium 101 Md [258]	Nobelium 102 No [259]	Lawrencium 103 Lr [266]	

Brillouin functions

Average value of the magnetic quantum number

$$\langle m_J \rangle = \frac{\sum_{-J}^{J} m_J e^{-E(m_J)/k_B T}}{\sum_{-J}^{J} e^{-E(m_J)/k_B T}} = \frac{\sum_{-J}^{J} m_J e^{m_J g_J \mu_B B/k_B T}}{\sum_{-J}^{J} e^{m_J g_J \mu_B B/k_B T}} = \frac{1}{Z}\frac{dZ}{dx}$$

Lande g factor → g_J

Bohr magneton → μ_B

$$x = g_J \mu_B B / k_B T$$

$$Z = \sum_{-J}^{J} e^{m_J x} = \frac{\sinh\left((2J+1)\frac{x}{2}\right)}{\sinh\left(\frac{x}{2}\right)}$$

Brillouin functions

Average value of the magnetic quantum number

$$\langle m_J \rangle = \frac{\sum_{-J}^{J} m_J e^{-E(m_J)/k_B T}}{\sum_{-J}^{J} e^{-E(m_J)/k_B T}} = \frac{\sum_{-J}^{J} m_J e^{m_J g_J \mu_B B/k_B T}}{\sum_{-J}^{J} e^{m_J g_J \mu_B B/k_B T}} = \frac{1}{Z}\frac{dZ}{dx}$$

Lande g factor → g_J

$$x = g_J \mu_B B / k_B T$$

Bohr magneton → μ_B

$$Z = \sum_{-J}^{J} e^{m_J x} = e^{Jx}\left(1 + e^{-x} + e^{-2x} + \cdots\right) - e^{-(J+1)x}\left(1 + e^{-x} + e^{-2x} + \cdots\right)$$

$$= \frac{e^{Jx} - e^{-(J+1)x}}{1 - e^{-x}} = \frac{e^{-\frac{x}{2}}}{e^{-\frac{x}{2}}} \frac{e^{(J+\frac{1}{2})x} - e^{-(J+\frac{1}{2})x}}{e^{\frac{x}{2}} - e^{-\frac{x}{2}}} = \frac{\sinh\left(\left(2J+1\right)\frac{x}{2}\right)}{\sinh\left(\frac{x}{2}\right)}$$

Brillouin functions

$$Z = \sum_{-J}^{J} e^{-m_J x} = \frac{\sinh\left(\left(2J+1\right)\frac{x}{2}\right)}{\sinh\left(\frac{x}{2}\right)}$$

$$M = ng_J \mu_B \langle m_J \rangle = ng_J \mu_B \frac{1}{Z}\frac{dZ}{dx}$$

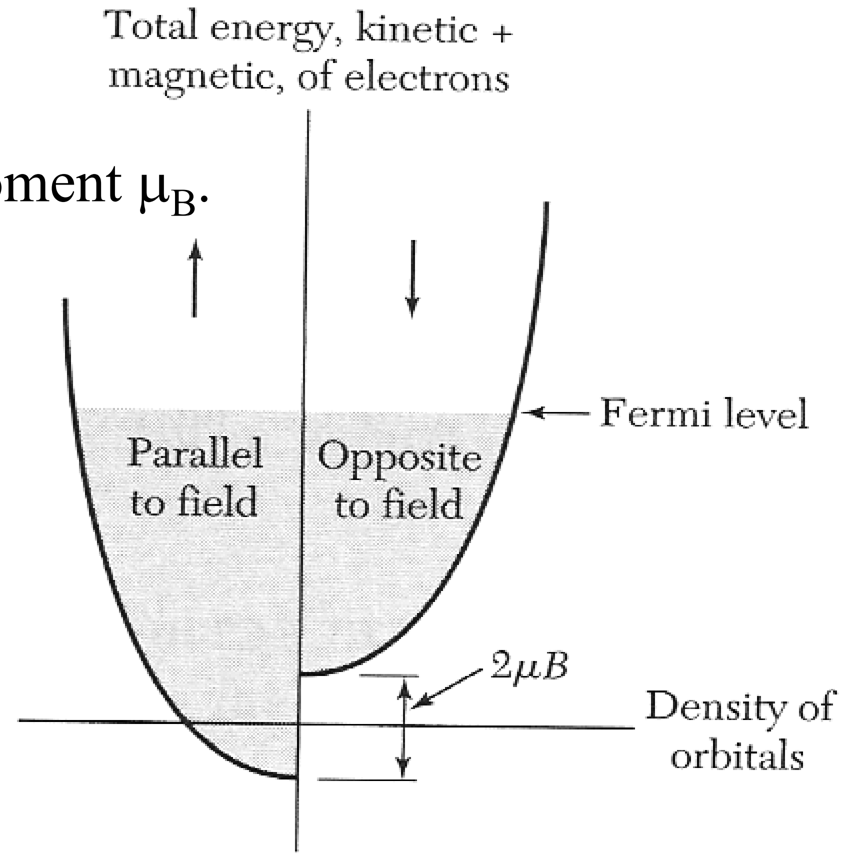
Brillouin function

$$M = ng\mu_B J\left(\frac{2J+1}{2J}\coth\left(\frac{2J+1}{2J}\frac{g\mu_B JB}{k_B T}\right) - \frac{1}{2J}\coth\left(\frac{1}{2J}\frac{g\mu_B JB}{k_B T}\right)\right)$$

Pauli paramagnetism

Paramagnetic contribution due to free electrons.

Electrons have an intrinsic magnetic moment μ_B.



$$n_+ \approx \frac{1}{2}n + \frac{1}{2}\mu_B B D(E_F)$$

$$n_- \approx \frac{1}{2}n - \frac{1}{2}\mu_B B D(E_F)$$

$$M = \mu_B(n_+ - n_-)$$

$$M = \mu_B^2 D(E_F) B = \mu_0 \mu_B^2 D(E_F) H$$

$$\chi = \frac{dM}{dH} = \mu_0 \mu_B^2 D(E_F)$$

If E_F is 1 eV, a field of B = 17000 T is needed to align all of the spins.

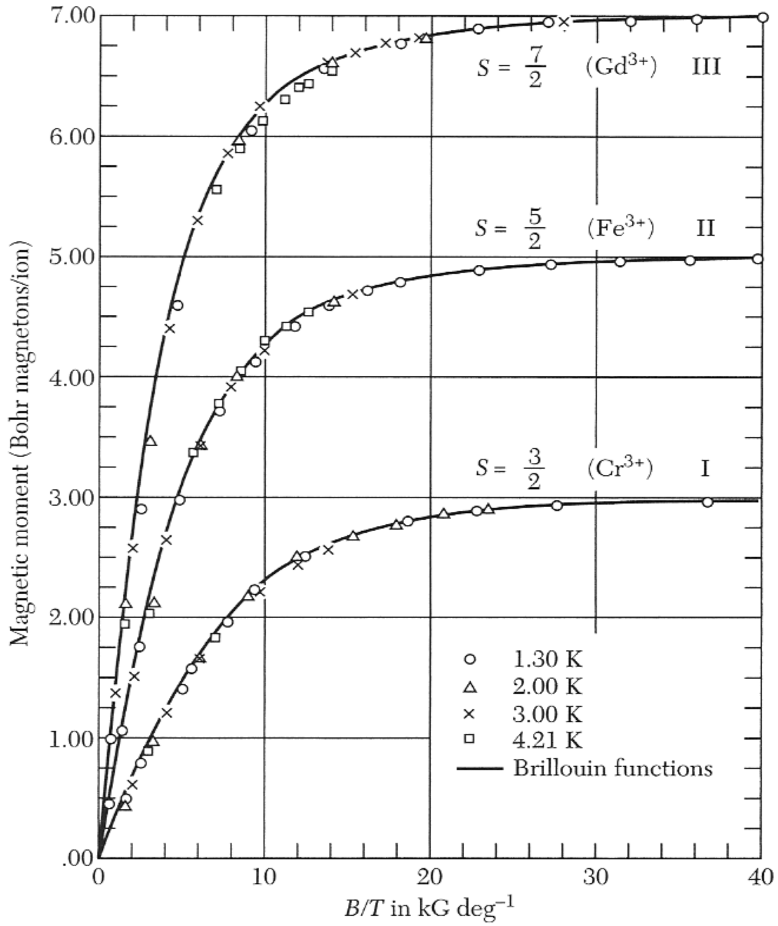
Pauli paramagnetism is much smaller than the paramagnetism due to atomic moments and almost temperature independent because $D(E_F)$ doesn't change very much with temperature.

Hund's rules (f - shell)

n	$l_z = 3,$	$2,$	$1,$	$0,$	$-1,$	$-2,$	-3	S	$L = \lvert\Sigma l_z\rvert$	J	
1	↓							1/2	3	5/2	
2	↓	↓						1	5	4	
3	↓	↓	↓					3/2	6	9/2	
4	↓	↓	↓	↓				2	6	4	$J = \lvert L - S\rvert$
5	↓	↓	↓	↓	↓			5/2	5	5/2	
6	↓	↓	↓	↓	↓	↓		3	3	0	
7	↓	↓	↓	↓	↓	↓	↓	7/2	0	7/2	
8	⇅	↑	↑	↑	↑	↑	↑	3	3	6	
9	⇅	⇅	↑	↑	↑	↑	↑	5/2	5	15/2	
10	⇅	⇅	⇅	↑	↑	↑	↑	2	6	8	
11	⇅	⇅	⇅	⇅	↑	↑	↑	3/2	6	15/2	$J = L + S$
12	⇅	⇅	⇅	⇅	⇅	↑	↑	1	5	6	
13	⇅	⇅	⇅	⇅	⇅	⇅	↑	1/2	3	7/2	
14	⇅	⇅	⇅	⇅	⇅	⇅	⇅	0	0	0	

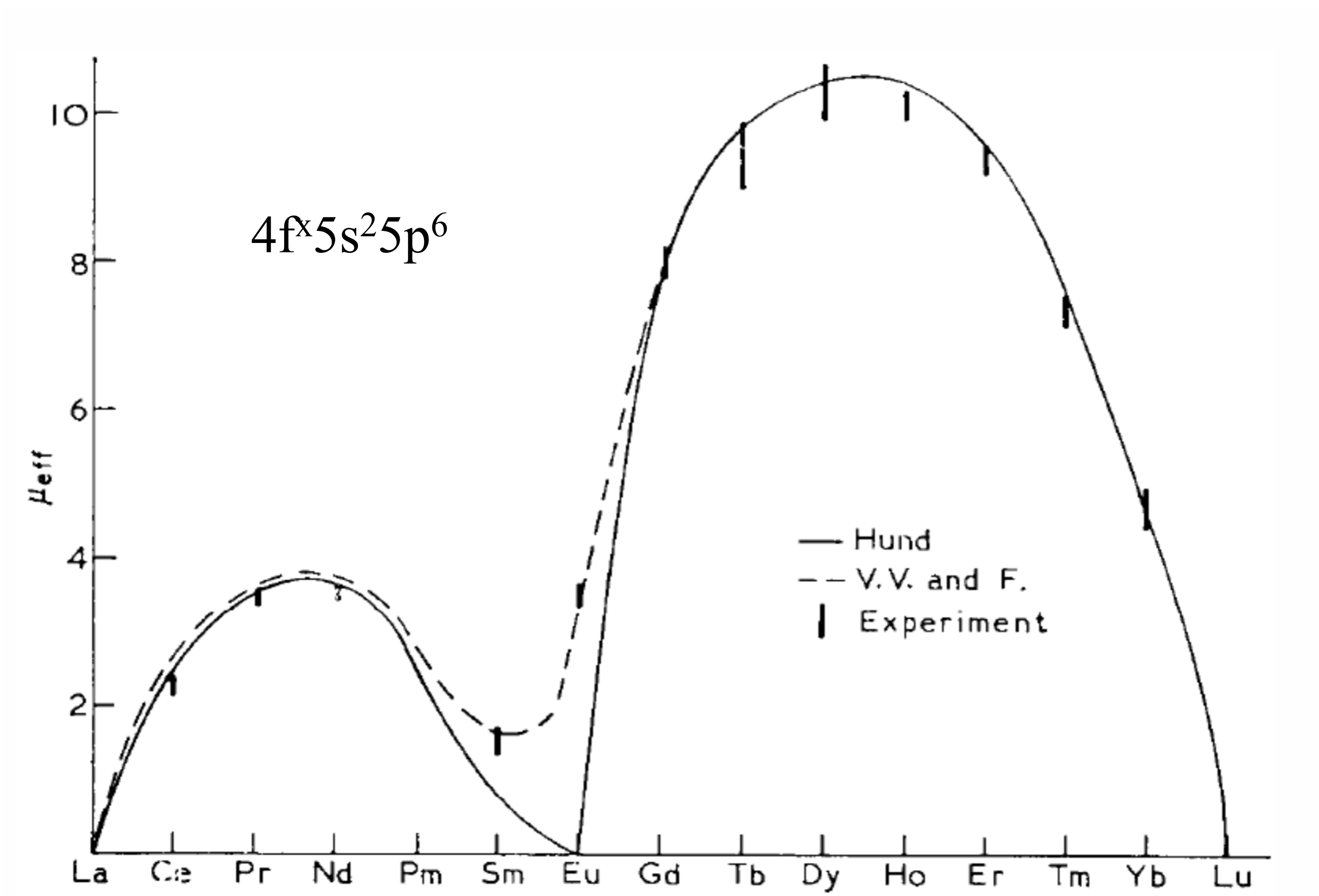
The half filled shell and completely filled shell have zero total angular mo

Paramagnetism



$$M = Ng\mu_B J\left(\frac{2J+1}{2J}\coth\left(\frac{2J+1}{2J}\frac{g\mu_B JB}{k_B T}\right) - \frac{1}{2J}\coth\left(\frac{1}{2J}\frac{g\mu_B JB}{k_B T}\right)\right)$$

Quantum Mechanics:
The Key to Understanding Magnetism
John H. van Vleck



http://nobelprize.org/nobel_prizes/physics/laureates/1977/vleck-lecture.pdf

Ferromagnetism

Below a critical temperature (called the Curie temperature) a magnetization spontaneously appears in a ferromagnet even in the absence of a magnetic field.

Iron, nickel, and cobalt are ferromagnetic.

Ferromagnetism overcomes the magnetic dipole-dipole interactions. It arises from the Coulomb interactions of the electrons. The energy that is gained when the spins align is called the exchange energy.

Schrödinger equation for two particles

$$-\frac{\hbar^2}{2m}\left(\nabla_1^2+\nabla_2^2\right)\psi+V_1(\vec{r}_1)\psi+V_2(\vec{r}_2)\psi+V_{1,2}(\vec{r}_1,\vec{r}_2)\psi=E\psi$$

$\psi(\vec{r}_1,\vec{r}_2)=\psi_1(\vec{r}_1)\psi_2(\vec{r}_2)$ is a solution to the noninteracting Hamiltonian, $V_{1,2}=0$

$$\psi_A\left(\vec{r}_1,\vec{r}_2\right)=\frac{1}{\sqrt{2}}\left(\psi_1(\vec{r}_1)\psi_2(\vec{r}_2)-\psi_1(\vec{r}_2)\psi_2(\vec{r}_1)\right)\begin{pmatrix}\uparrow\uparrow\\ \frac{1}{\sqrt{2}}\left(\uparrow\downarrow+\downarrow\uparrow\right)\\ \downarrow\downarrow\end{pmatrix}$$

$$\psi_S\left(\vec{r}_1,\vec{r}_2\right)=\frac{1}{\sqrt{2}}\left(\psi_1(\vec{r}_1)\psi_2(\vec{r}_2)+\psi_1(\vec{r}_2)\psi_2(\vec{r}_1)\right)\frac{1}{\sqrt{2}}\left(\uparrow(\vec{r}_1)\downarrow(\vec{r}_2)-\downarrow(\vec{r}_1)\uparrow(\vec{r}_2)\right)$$

Exchange (Austauschwechselwirking)

$$\psi_A(\vec{r}_1,\vec{r}_2)=\frac{1}{\sqrt{2}}\left(\psi_1(\vec{r}_1)\psi_2(\vec{r}_2)-\psi_1(\vec{r}_2)\psi_2(\vec{r}_1)\right)$$

$$\langle\psi_A|H|\psi_A\rangle=\frac{1}{2}[\langle\psi_1(\vec{r}_1)\psi_2(\vec{r}_2)|H|\psi_1(\vec{r}_1)\psi_2(\vec{r}_2)\rangle-\langle\psi_1(\vec{r}_1)\psi_2(\vec{r}_2)|H|\psi_1(\vec{r}_2)\psi_2(\vec{r}_1)\rangle$$
$$-\langle\psi_1(\vec{r}_2)\psi_2(\vec{r}_1)|H|\psi_1(\vec{r}_1)\psi_2(\vec{r}_2)\rangle+\langle\psi_1(\vec{r}_2)\psi_2(\vec{r}_1)|H|\psi_1(\vec{r}_2)\psi_2(\vec{r}_1)\rangle]$$

$$\psi_S(\vec{r}_1,\vec{r}_2)=\frac{1}{\sqrt{2}}\left(\psi_1(\vec{r}_1)\psi_2(\vec{r}_2)+\psi_1(\vec{r}_2)\psi_2(\vec{r}_1)\right)$$

$$\langle\psi_S|H|\psi_S\rangle=\frac{1}{2}[\langle\psi_1(\vec{r}_1)\psi_2(\vec{r}_2)|H|\psi_1(\vec{r}_1)\psi_2(\vec{r}_2)\rangle+\langle\psi_1(\vec{r}_1)\psi_2(\vec{r}_2)|H|\psi_1(\vec{r}_2)\psi_2(\vec{r}_1)\rangle$$
$$+\langle\psi_1(\vec{r}_2)\psi_2(\vec{r}_1)|H|\psi_1(\vec{r}_1)\psi_2(\vec{r}_2)\rangle+\langle\psi_1(\vec{r}_2)\psi_2(\vec{r}_1)|H|\psi_1(\vec{r}_2)\psi_2(\vec{r}_1)\rangle]$$

The difference in energy between the ψ_A and ψ_S is twice the **exchange energy**.

Exchange

The exchange energy can only be defined when you speak of multi-electron wavefunctions. It is the difference in energy between the symmetric solution and the antisymmetric solution. There is only a difference when the electron-electron term is included. Coulomb repulsion determines the exchange energy.

In ferromagnets, the antisymmetric state has a lower energy. Thus the state with parallel spins has lower energy.

In antiferromagnets, the symmetric state has a lower energy. Neighboring spins are antiparallel.

Ordered states have a lower entropy than free electrons.

Mean field theory (Molekularfeldtheorie)

Heisenberg Hamiltonian $H = -\sum_{i,j} J_{i,j} \vec{S}_i \cdot \vec{S}_j - g\mu_B \vec{B} \cdot \sum_i \vec{S}_i$

Exchange energy

Mean field approximation

$$H_{MF} = \sum_i \vec{S}_i \cdot \left(\sum_\delta J_{i,\delta} \left\langle \vec{S} \right\rangle + g\mu_B \vec{B} \right)$$

Looks like a magnetic field B_{MF}

δ sums over the neighbors of spin *i*

$$\vec{B}_{MF} = \frac{1}{g\mu_B} \sum_\delta J_{i,\delta} \left\langle \vec{S} \right\rangle$$

magnetization → $\vec{M} = g\mu_B \frac{N}{V} \left\langle \vec{S} \right\rangle$

eliminate $\langle S \rangle$

Mean field theory

$$\vec{B}_{MF} = \frac{V}{Ng^2\mu_B^2} zJ\vec{M}$$

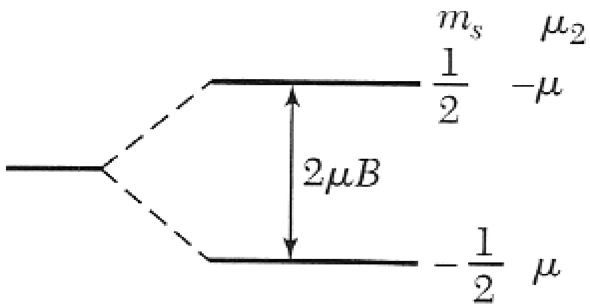
z is the number of nearest neighbors

In mean field, the energy of the spins is

$$E = \pm\frac{1}{2} g\mu_B (B_{MF} + B_a)$$

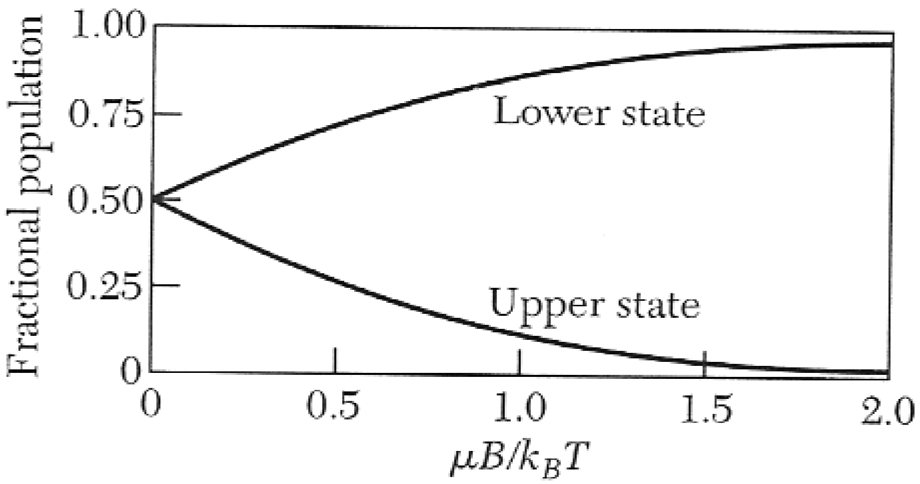
We calculated the populations of the spins in the paramagnetism section

Spin populations



$$\frac{N_1}{N} = \frac{\exp(\mu B / k_B T)}{\exp(\mu B / k_B T) + \exp(-\mu B / k_B T)}$$

$$\frac{N_2}{N} = \frac{\exp(-\mu B / k_B T)}{\exp(\mu B / k_B T) + \exp(-\mu B / k_B T)}$$



$$M = (N_1 - N_2)\mu$$

$$= N\mu \frac{\exp(\mu B / k_B T) - \exp(-\mu B / k_B T)}{\exp(\mu B / k_B T) + \exp(-\mu B / k_B T)}$$

$$= N\mu \tanh\left(\frac{\mu B}{k_B T}\right)$$

Mean field theory

$$M = \frac{1}{2} g \mu_B \frac{N}{V} \tanh\left(\frac{g \mu_B \left(B_{MF} + B_a \right)}{2 k_B T} \right)$$

For zero applied field

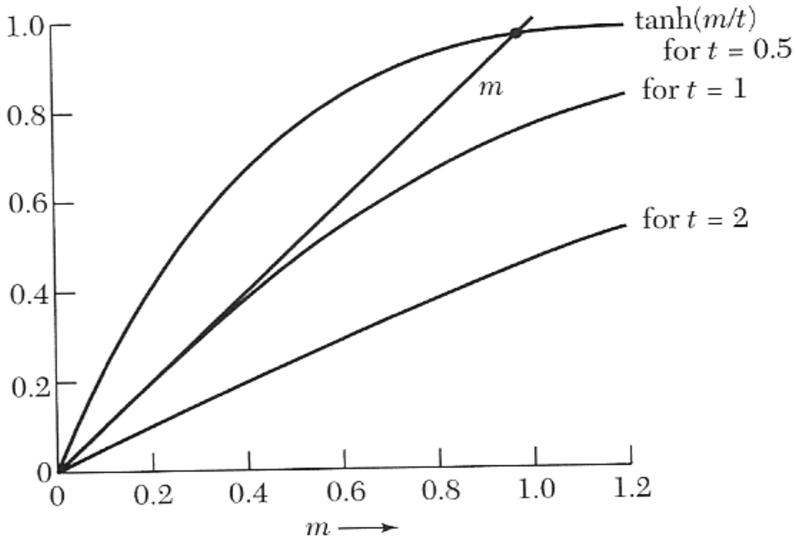
$$M = M_S \tanh\left(\frac{T_c}{T} \frac{M}{M_s} \right)$$

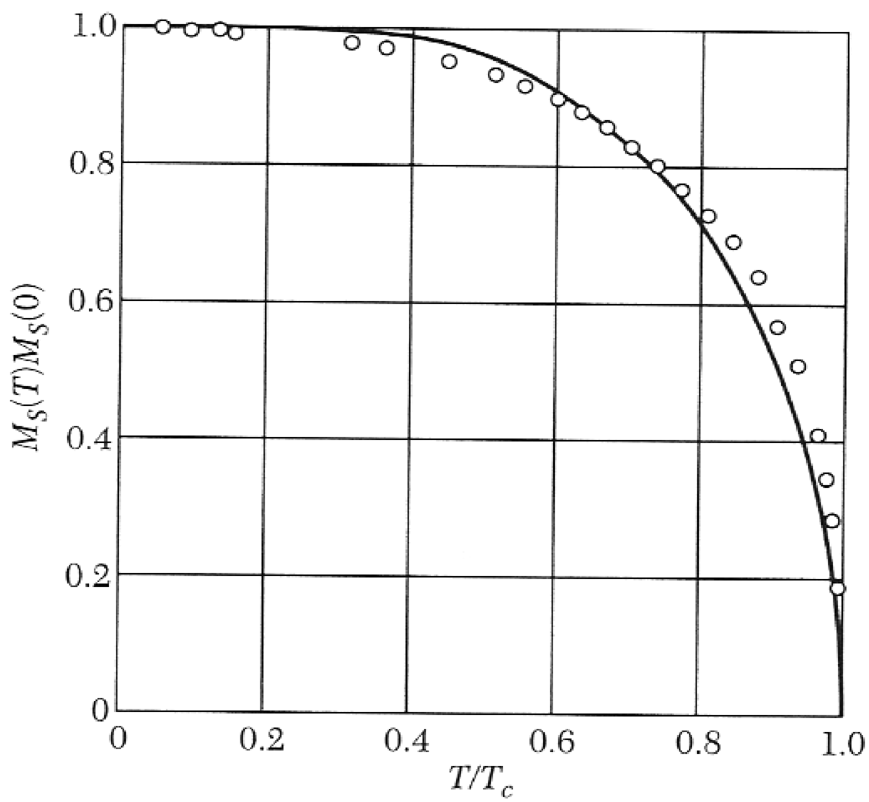
$$M_S = \frac{N}{2V} g \mu_B \quad \text{and} \quad T_c = \frac{z}{4 k_B} J$$

M_s = saturation magnetization $\qquad T_c$ = Curie temperature

Mean field theory

$$M = M_S \tanh\left(\frac{T_c}{T}\frac{M}{M_s}\right)$$





$$m = \tanh\left(\frac{m}{t}\right)$$

Experimental points for Ni.

$$M_S = \frac{N}{2V} g\mu_B \quad \text{and} \quad T_c = \frac{z}{4k_B} J$$

Source: Kittel

Ferromagnetism

Material	Curie temp. (K)	
Co	1388	
Fe	1043	
$FeOFe_2O_3$	858	
$NiOFe_2O_3$	858	
$CuOFe_2O_3$	728	
$MgOFe_2O_3$	713	
MnBi	630	
Ni	627	
MnSb	587	
$MnOFe_2O_3$	573	
$Y_3Fe_5O_{12}$	560	
CrO_2	386	
MnAs	318	
Gd	292	
Dy	88	
EuO	69	Electrical insulator
$Nd_2Fe_{14}B$	353	$M_s = 10\, M_s(\mathrm{Fe})$
Sm_2Co_{17}	700	rare earth magnets

$$M_S = \frac{N}{2V} g \mu_B$$

$$T_c = \frac{z}{4k_B} J$$

Curie - Weiss law

$$M = \frac{1}{2} g \mu_B \frac{N}{V} \tanh\left(\frac{g \mu_B \left(B_{MF} + B_a \right)}{2 k_B T} \right)$$

$$\vec{B}_{MF} = \frac{V}{N g^2 \mu_B^2} z J \vec{M}$$

Above T_c we can expand the hyperbolic tangent $\tanh(x) \approx x$ for $x << 1$

$$M \approx \frac{1}{4} g^2 \mu_B^2 \frac{N}{V k_B T} \left(\frac{V}{N g^2 \mu_B^2} z J M + B_a \right)$$

Solve for M

$$M \approx \frac{g^2 \mu_B^2 N}{4 V k_B} \frac{B_a}{T - T_c}$$

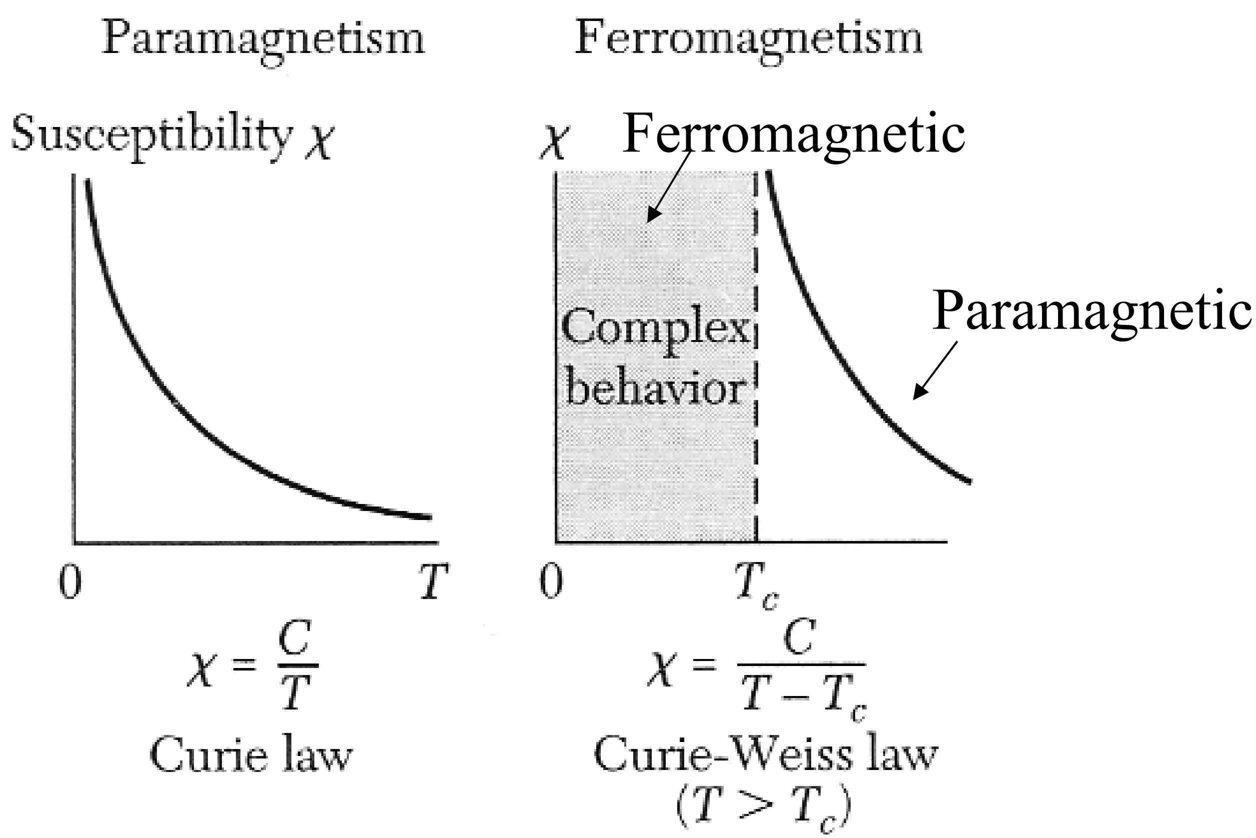
$$T_c = \frac{z}{4 k_B} J$$

Curie Weiss Law $\chi = \frac{dM}{dH} \approx \frac{C}{T - T_c}$

Critical fluctuations near T_c

Ferromagnets are paramagnetic above T_c

Source: Kittel



Critical fluctuations near T_c.

Magnetization of a Magnetite Single Crystal Near the Curie Point*

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(Received January 20, 1956)

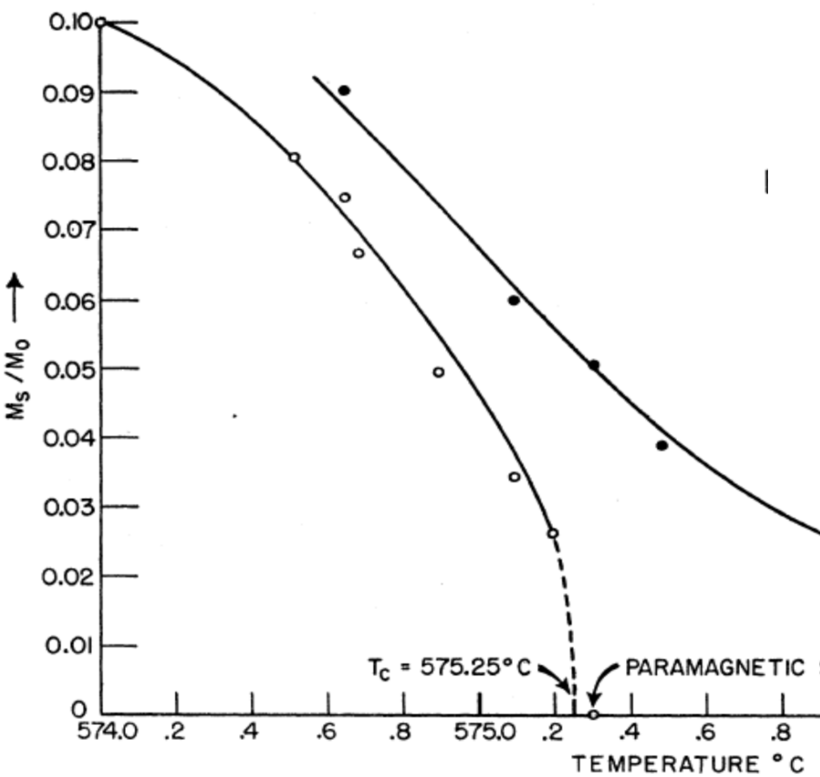


FIG. 9. M_s/M_0 *vs* T in the [111] direction near the Curie point for single-crystal magnetite.

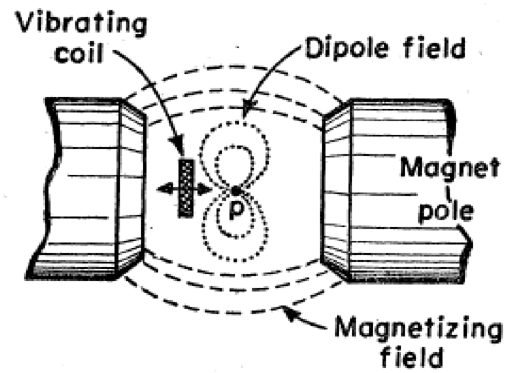


FIG. 2. Principle of the vibrating-coil magnetometer.

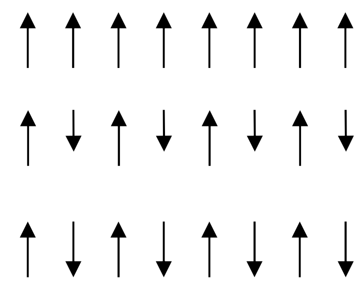
Magnetic ordering

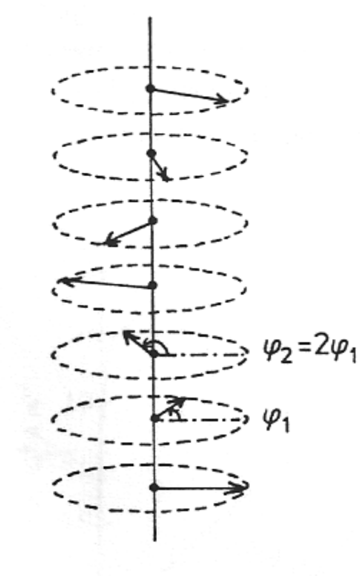
Ferromagnetism

Ferrimagnetism

Antiferromagnetism

Helimagnetism





All ordered magnetic states have excitations called magnons