Magnetism

Matter in magnetic field is described by the following expressions:

$$B = \mu_0 H + M = \mu_0 H(1-\chi_m) = \mu_0 \mu H$$

with M- magnetization, $\chi_m = \frac{\mu_0 M}{B}$ is magnetic suszeptibility, Magnetism is alignment of magnetic dipols in external magnetic field, induced Dipoles result in **diamagnetism**: $\chi_m < 0 \approx -10^{-6}$ appears for atoms with paired spins =closed shells, described by $\chi_m = -\frac{\mu_0 Z e^2 N}{6m} < r^2 >$ Langevin equation;

Paramagnetism appears at atoms with unpaired spin, S<>0, $\mu = \frac{N\_atoms\_with\_spin}{Volume}$,

magnetization is $M = N\mu L(\frac{\mu\ B}{k_B T})$, where L is Langevin-Function, For μB<<kT , $L \approx \frac{\mu H}{3kT}$ and

$M \approx \frac{N\mu^2 H}{3k_B T}$ resulting in $\chi_m = \frac{M}{B} = \frac{N\mu^2\mu_0}{6k_B T} = \frac{C}{T}$ *Curie –Law*, C- Curie constant. Relation

$\frac{1}{\chi_m} \approx T$ good fulfilled for high temperatures, deviations at low T, quantum mechanics allows for finite number of energy levels of an atom in magnetic field. $E = m_J g\mu_B B = \mu B$ with μ_B as Bohr magneton, g is Lande factor and magnetic QN m_J=J,J-1,…-J, never complete alignment parallel B, but always perpendicular component, Summarizing over all allowed spin orientations we get

$$M = N\frac{\sum_{-J}^{J} g\mu_B m_J \exp(\frac{g\mu_B m_J B}{k_B T})}{\sum_{-J}^{J} \exp(\frac{g\mu_B m_J B}{k_B T})} = Ng\mu_B J B_J(y)$$, where Bj(y) is the Brillouin function

$B_J(y) = \left\{\frac{2J+1}{2J}\coth[\frac{2j+1}{2J}y] - \frac{1}{2J}\coth[\frac{y}{2J}]\right\}$ with $y = \frac{g\mu_B m_J B}{k_B T}$, Forlarge J; $B_J(y) \rightarrow$ L (Langevin), For y<<1 expansion of coth(y)→ $B_J(y) = \left\{\frac{y(J+1)}{3J}\right\}$ yields

$\chi_m = \frac{M}{B} = \frac{\mu_0 N g^2 \mu_B{}^2 J(J+1)}{3k_B T} = \frac{\mu_0 N p^2 \mu_B{}^2}{3k_B T} = \frac{C}{T}$, $p\mu_B = \mu_{eff}$ is effective dipole moment, $B_J(y)$=0 for B=0; $B_J(y)$=1 for B→to infinite, or T→0, $M_{max} = Ng\mu_B J$, measured by $\chi_m(T)$, with $p = g\sqrt{J(J+1)}$, good egreement with experiment except Eu^{3+}, Sm^{3+}…due to low spin-orbit coupling

Cunducting electrons contribute only partially to solid state paramagnetism. This is due to the fact that electrons by fraction T/T_F close to Fermi level are able to change the spin under influence of an external field. Therefore their contribution changes to $\chi_m = \frac{N\mu_B{}^2}{k_B T}\frac{T}{T_F} = \frac{N\mu_B^2}{k_B T_F}$. This can be explained in terms of density of states, expressed for both spin states. For B=0 , D(E)↑=D(E)↓. After application of an external field both D(E) changes by $D(E\pm\mu_B B)$. Because the E_F has to be same for both spin densities of state there is a redistribution of electrons as

$N\downarrow - N\uparrow = (N/2 + \Delta N/2) - (N/2 - \Delta N/2) = \Delta N$ resulting in M=$\mu_B \Delta$N, By integration one gets $N\downarrow,\uparrow = \frac{V}{6\pi^2}(\frac{2m}{\hbar^2})^{3/2}(E_F \pm \mu_B B)^{3/2}$ resulting in $M = \frac{3}{2}N_e\frac{\mu_B B}{E_F} = N_e\mu_B\frac{3\mu_B B}{2k_B T_F} \rightarrow \chi_m = \frac{3N_e\mu_B^2}{2k_B T_F}$

Due to external magnetic field the electron levels of the filled states will split causing diamagnetic contribution. Following Landau it is $\chi_{dia} = -\frac{1}{3}\chi_{para}$, → in total $\chi_{tot} = \chi_{para} - \frac{1}{3}\chi_{para} = \frac{N_e{\mu_B}^2}{k_B T_F}$

There are various forms of Ferromagnetism = spontaneous magnetic polarization without external field: simple Ferromagnet (parallel spins), simple antiferromagnet (anti-parallel spins, Ferrimagnets(parallel or antiparallel spins of different amount), tilted Antiferromagnets, spiral magnetism, band ferromagnetism,

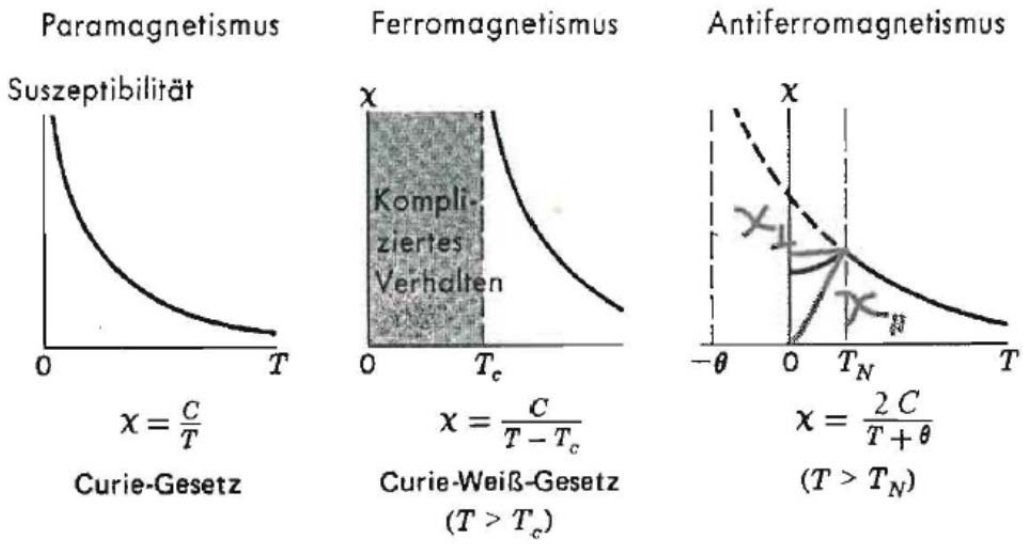
Ferromagnetism appears below a critical temperature, T_c – Curie-temperature, above T_c the material becomes paramagnetic , susceptibilty becomes $\chi_m = \frac{C}{T - T_c}$ *Curie-Weiß law*, Origin of ferromagnetism is the internal interaction caused by exchange fields between next neighbors or by "molecular fied". Weiß supposed the existence of internal magnetic field: $B_E = \lambda\mu_B M$, Magnetic moment of an atoms "feels" magnetization by neighbored atoms creating mean field, for T>Tc and small magnetization $\mu_0 M = \chi(B + B_E)$, with $\chi_m = \frac{C}{T}$ (Curie) → $\mu_0 M = \frac{C}{T}(B + \lambda\mu_0 M) = \frac{CB}{T - \lambda C}$

→ $\chi_m = \frac{M}{B} = \frac{C}{T - \lambda C} = \frac{C}{T - T_C}$ singularity at T=Tc, Curie-Weiß law is well confirmed by experiment, behavior at T<Tc by evaluation of Brillouin function, determine crossing point between $M = \frac{kT}{\mu\mu_0\lambda}x$, and $M = N\mu\tanh\frac{\mu\mu_0\lambda M}{kT}$ with $x = \frac{\mu\mu_0\lambda M}{kT}$, yields M(T)/M(0)=1 at T=0 and zero at $T=T_c$. Origin of internal field is "molecular field: an atom with unpaired spin is surrounded by other atoms in certain geometrical arrangement, depending on next neighbor distances the energy separation between the bonding and antibonding orbital changes and results in paired or mainly unpaired arrangement, Phase transition between different magnetization can be induced by local distortions of the crystal field. Exchange interaction is expressed by Heisenberg exchange energy $U = -2J\hat{S}_i\hat{S}_j$ where J is exchange integral, ferromagnetic coupling :J>0, antiferromagnetic coupling:J<0, $J = \frac{\mu^2\mu_0 N}{Z}\lambda$ cannot be explained by dipole-dipole interaction but interplay between kinetic energy and Coulomb energy → Exchange interaction, For metals like Fe, Co, Ni…*Slater criterion* expresses J as function of r/2a, where a is next neighbor distance. It provides J>0 for r/2a > 1,5 and J<0 for r/2a < 1.5.

Antiferromagnetic takes place in MnF_2 ; for example, and has been discovered by magnetic neutron scattering. Here Mn atoms are arranged in bcc sublatticd where the center atom carries spin up, but the corner atoms spin down. Antiferromagnetism is described by Neel and vanishes above Neel Temperature T_N The susceptibility at $T>T_N$ is $\chi_m = \frac{2C}{T + \Theta}$ where Θ is Curie-Weiss temperature, where $T_N = \kappa M$ is the antiferromagnetic x-change interaction, the functional behavior can be

presented by $\chi_m \approx \frac{1}{T}$ curve shifted to "negative" Curie-Weiß temperature Θ. In range 0> T>T_N the total magnetization is zero and AF order increases up to the value $\chi_m(T_N)$ given by above function. AF order induces a twice as large magnetic unit cell compared to the crystallographic unit cell ofMnF_2 crystal.

Spin waves (**magnons**) are excited in spiral ferromagnets, it appears a lowest excitation state in a simple ferromagnet containing an antiferromagnetic perturbation. Analogous to phonons magnonsa sho dispersion relation as $\hbar\omega = 2JS[Z - \sum \cos(ka)$ over z next neighbors and J>0, For Z=2 it is $\hbar\omega = 4JS[1-\cos(ka)]$. Magnons are excited by temperature and follow Bose statistics: $< n_k >= \frac{1}{\exp(\frac{\hbar\omega_k}{kT}) - 1}$ and a density of states $D(\omega) = \frac{1}{4\pi^2}(\frac{\hbar}{2JSa^2})^{3/2}\omega^{1/2}$ providing total number of excited magnons: $\sum_k n_k = \int d\omega D(\omega) < n(\omega) >$. Normalized magnon number follows Bloch´s $T^{3/2}$ law $\frac{\sum n_k}{NS} = \frac{\Delta M}{M(0)} = \frac{0.057}{SQ}(\frac{kT}{2JS})^{3/2}$ and can be measuted by inelastic neutron scattering (see phonons)



Solid Ferromagnets:For T<<Tc all magnetic moments aligned but not all moments of whole crystal in same direction. Due to reasons of reduction of exchange energy, they split into domains of always different major spin direction separated by Bloch walls. Domains are optimized in energy if the inner field cycle is complete, i.e. magnetic field lines keep within the material. These Bloch walls have finite (about 300 d in Fe) thickness because spins do not completely switch between next neighbor but rotate by small amount from neighbor to neighbor. Strength of magnetization and energy for changing magnetization depends on crystal direction. In Fe [100] is "easy" axis but [111] is strong axis, Ni is opposite, Under application of an external magnetic field the size of domains with moment parallel to external field grow on cost of domains with oblique or opposite local spin direction. This results into a hysteresis curve M(B) which shows $W = \oint BdM$. – power loss.