Ferromagnetism

It is a phenomenon of spontaneous magnetisation. These materials can be magnetised and retain magnetism even if the external applied field is removed.

e.g. Fe, Co, Ni, Cd, Dy and their alloys

Characteristic Features

#1) The magnetic dipole moment per unit volume $\vec{M}$ produced in such substances is very high even in weak magnetic fields.

#2) The value of M is not linearly proportional ~~to~~ to the applied magnetic field B_a ~~...~~

i.e. $\chi_m = \frac{\mu_0 M}{B_a}$ is not constant but varies with the applied field

#3) Above a certain critical temperature called as Curie Temperature T_c these behave as paramagnetic substances. These obey the Curie Weiss law

$$\chi_m = \frac{C}{T - T_c} \quad \text{for} (T > T_c)$$

The susceptibility has a singularity at $T = T_c$. At this temperature and below it there exists a spontaneous magnetisation as χ_m is infinite as we have a finite value of $\vec{M}$ even if applied field B_a is zero.

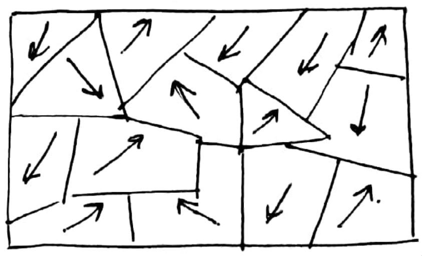
This is because the interaction b/w magnetic ions is strong enough to align their magnetic moments against the disorder produced by the "thermal effects" at temperature (T) above curie temperature (T_c) the spontaneous magnetisation vanishes

Thus the curie temperature (T_c) seperates the Disordered paramagnetic phase at ($T > T_c$) from ordered ferromagnetic phase at ($T < T_c$)

Weiss Field Theory of Ferromagnetism

Ferromagnetism involves the alignment of an appreciable fraction of the molecular magnetic moments in some favourable direction in the crystal. The fact that the phenomenon is restricted to transition and rare-earth elements indicates that it is related to the unfilled 3d and 4f shells of these substances.

As per Weiss Field theory a ferromagnetic material consists of DOMAINS. Within each domain the material is magnetically saturated in different directions



Although each domain is fully magnetized the material as a whole may have a net zero magnetisation. ① Each domain is a microscopic region of parallel alignment of atomic spins

② Avg. liner dimension of each domain is 10^{-4} mts and their volume is between 10^{-8} to 10^{-12} m^3

③ A domain may contain 10^{17} to 10^{21} atoms

④ The structure of a domain is determined by the conditions of minimum magnetic energy

⑤ Numer of domains and their structure are determined by the shape and size of the crystal

Now as per Weiss Field theory Spontaneous magnetisation is due to the co-operation b/w atomic dipoles within a single domain. Thus the dipoles in a domain have exchange symmetry between the spins and the extent of overlap

This exchange forces can be treated as being equivalent to an internal magnetic field $\vec{B_e}$ which is proportional to the magnetisation $\vec{M}$ within a domain. Thus in the **Mean Field** approximation each atom experiences a magnetic field proportional to magnetisation

$$B_e = \lambda M \quad \text{where } \lambda = \text{Weiss Const.} \quad \text{——(1)} \quad \text{independent of temp.}$$

If the external field is $\vec{B_a}$ then the effective field $\vec{B}$ acting on an ion or atom is given by

$$\vec{B} = \vec{B_a} + \vec{B_e} = \vec{B_a} + \lambda\vec{M} \quad \text{——(2)}$$

~~B = B~~ If N = atoms per unit volume
Then for paramagnetic material

$$M = N g_j J \mu_B B_j(x) \quad \text{——(3)}$$

where $B_j(x) = \left(\frac{2J+1}{2J}\right) \coth\left(\frac{2J+1}{2J}x\right) - \frac{1}{2J}\coth\left(\frac{x}{2J}\right)$

called as Brillouin function.
For Ferromagnetic substances

$$x = \frac{\mu B}{kT} = \frac{g_j J \mu_B B}{kT}$$

$$x = \frac{g_j J \mu_B (B_a + \lambda M)}{kT}$$

For spontaneous magnetisation in absence of applied field ($B_a = 0$) then $B = \lambda M$

$$\therefore x = \frac{g_j J \mu_B \lambda M}{kT} \quad \text{——(4)}$$

Suppose that all the domains are aligned along the magnetic field and magnetic moment per unit volume called as "<u>Saturation magnetic moment</u>" is given by

$$M_s = N g_j J \mu_B \quad \text{——(5)}$$

Comparing eq^n's (3) & (5) we get

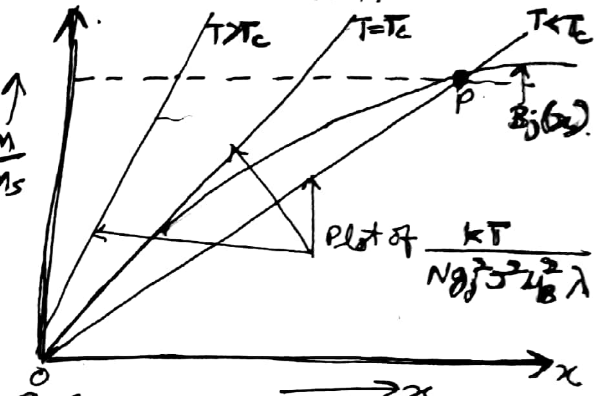
$$\frac{M}{M_s} = B_j(x) \quad \text{——(6)}$$

From (4) $\quad M = \frac{x kT}{g_j J \mu_B \lambda} \quad \text{——(7)}$

Comparing eq^n (7) and (5) we get

$$\frac{M}{M_s} = \frac{kT}{N g_j^2 J^2 \mu_B^2 \lambda} x \quad \text{——(8)}$$

The simultaneous solution of eq^n. (6) & (8) can be obtained by plotting a graph $\frac{M}{M_s}$ against x... It is as shown.



Discussion

At Critical Temperature (Curie pt T_c)
Clearly the plot of eq^n (8) is tangent to plot of eq^n (4)
The slope is given by

$$\frac{M}{M_s} = \frac{kT}{N g_j^2 J^2 \mu_B^2 \lambda} x$$

at $T = T_c$

$$\frac{M/M_s}{x} = \frac{kT_c}{N g_j^2 J^2 \mu_B^2 \lambda} \quad \text{——(9)}$$

for $x \ll 1$ $\quad B_j(x) \simeq \frac{(J+1)}{3J} x$

Thus tangent to the curve at the origin has a slope given by

$$\frac{B_j(x)}{x} = \frac{J+1}{3J} \quad \text{——(10)}$$

equating eq^n's (9) & (10) we get

$$\left.\begin{aligned} \frac{kT_c}{N g_j^2 J^2 \mu_B^2 \lambda} &= \frac{J+1}{3J} \\ T_c &= \frac{N g_j^2 \mu_B^2 \lambda}{3k} J(J+1) \end{aligned}\right\} \text{——(11)}$$

$T_c = \frac{N \mu_j^2 \lambda}{3k}$ here μ_j is the total magnetic moment per atom given as

$$\mu_j = g_j \mu_B \sqrt{J(J+1)}$$

Thus $T_c \propto \lambda$ (Weiss Field Constant)

Below Curie Temperature $T<T_c$

Blow T_c the curve of $B_j(x)$ and $\frac{M}{M_s}$ meet at two pts i.e origin O & pt P. The intersection at $x=0$ is classically unstable condition. While pt P corresponds to "spontaneous magnetisation". Thus at temperatures below T_c spontaneous magnetisation occurs even in the absence of magnetic field.

Subsituting

$$\frac{k}{N g_J^2 J^2 \mu_B^2 \lambda} = \frac{1}{T_c}\,\frac{J+1}{3J}$$

from eqn (11) in eqn (8)

$$\frac{M}{M_s} = \frac{T}{T_c}\left(\frac{J+1}{3J}\right)x \quad \text{—} (12)$$

in eqn (12) M_s is the maximum value of spontaneous magnetisation and eqn (12) gives its dependence on temperature

Generally a sample of ferromagnetic material at temp $T<T_c$ is not magnetised. It becomes magnet under the influence of external magnetic field. This is because the spontaneously magnetised domains within a ferromagnetic material are so arranged so as to form closed chains and these cancel the magnetic effect of one another and as such the material as a whole is unmagnetised or neutral.

Above Curie Temperature $(T>T_c)$

In this region there is no spontaneous magnetisation and is the paramagnetic region. In case of paramagnetics

$$M = \frac{NJ(J+1)g_J^2\mu_B^2 B}{3kT}$$

$$M = \frac{NJ(J+1)g_J^2\mu_B^2(B_a+\lambda M)}{3kT}$$

$$\text{or } M\left[1-\frac{NJ(J+1)g_J^2\mu_B^2\lambda}{3kT}\right] = \frac{NJ(J+1)g_J^2\mu_B^2 B_a}{3kT}$$

$$M\left(1-\frac{T_c}{T}\right) = \frac{C}{\mu_0 T}B_a$$

where $C = \frac{\mu_0 N J(J+1) g_J^2 \mu_B^2}{3k}$ = Curie Constant

$$\Rightarrow \frac{\mu_0 M}{B_a}\left(\frac{T-T_c}{T}\right) = \frac{C}{T}$$

$$\text{or } \chi_m = \frac{\mu_0 M}{B_a} = \frac{C}{T-T_c}$$

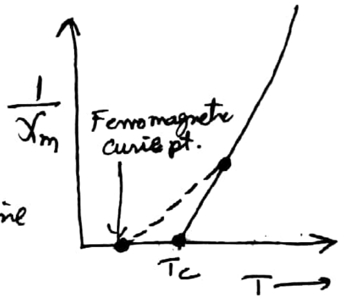
Called as Curie Weiss law

as per this law

$$\frac{1}{\chi_m} = \frac{T}{C} - \frac{T_c}{C}$$

Thus the graph b/w $\frac{1}{\chi_m}$ and T is a st line

For $\frac{1}{\chi_m} = 0$ $T = T_c$



The slight curve near the curie pt T_c leads to the distinction b/w ferromagnetic and paramagnetic curie pts.