

CHAPTER I

INTRODUCTION



1.1 Fundamentals

In general, magnetism originates from the magnetic moment due to the rotational motion of charged particles, both orbital motion and spin. The origin of this concept can be traced to the molecular current theory of Ampere (1775-1836). The magnetic moment due to the spin is given by

$$\mu_s = g\mu_B \langle S \rangle \quad (1.1)$$

where g is Landé g -factor, μ_B is the Bohr magneton and $\langle S \rangle$ is the average spins of the system. This equation was derived by Dirac's relativistic quantum mechanics.

The magnetic properties of a material is characterized by the magnetic susceptibility, χ , which is the response to an applied magnetic field, H , and the relation can be expressed by

$$M = \chi H \quad (1.2)$$

where M is called magnetization, which is the magnetic moment per unit volume. The relative susceptibility is $\bar{\chi}$, defined as

$$\bar{\chi} = \frac{\chi}{\mu_0} \quad (1.3)$$

Where μ_0 is the permeability of vacuum.

1.2 Classification⁽¹⁾

The observed value of relative susceptibility ranges from very weak magnetism to very strong magnetism. The behavior of the susceptibility can be interpreted in terms of the magnetic structure of material. Most materials can be classified as follow.

a) Diamagnetism is very weak magnetism and is characterized by a negative susceptibility. This means that the induced magnetic moment is opposite to the direction of the applied field. This magnetism originates from the orbital motion of electrons about nuclei induced by an external field. While all substances consist of diamagnetic atoms or ions, this type of magnetism is so weak that it can be covered completely by the other types of magnetism.

b) Paramagnetism is the most common phenomenon. The paramagnetic substances contain magnetic atoms or ions whose spins are isolated from their magnetic environment and can freely change their directions. The individual atoms or molecules have permanent magnetic moments. The susceptibility is positive and temperature dependent since the spins can be thermally agitated so that they take at random orientation. The magnetic behavior or susceptibility characteristic of this type of magnetism is inversely proportional to the absolute temperature, i.e., χ obeys the Curie law,⁽²⁾

$$\chi = \frac{C}{T} \quad (1.4)$$

where C is Curie constant.

c) Ferromagnetism, the spins of this material are aligned in parallel to one another as a result of the strongly coupled dipole moments and is a case of strong magnetism. At absolute zero, this alignment is complete and has its maximum spontaneous magnetization. As the temperature is increased, the spontaneous magnetization is reduced by the thermal agitation until it becomes zero at a characteristic temperature known as the Curie temperature. Above the Curie point, the susceptibility is given approximately by the Curie-Weiss law,⁽³⁾

$$\chi = \frac{C}{T-\theta} \quad (1.5)$$

where θ is characteristic temperature of the material or Curie temperature

d) Ferrimagnetism: For this case of magnetism, the lattice of the material is characterized by having two kinds of magnetic ions occupying two sublattices called A and B. The spin on A sites point in plus direction, while the other B sites align in the minus direction. The magnetization of different sublattice does not have to cancel each other. Thus there may exist appreciable net spontaneous magnetization at absolute zero. As is in the other cases, the spontaneous magnetization can be reduced by thermal agitation of the spins on each sublattice. At a certain temperature, Néel or Curie point, the arrangement of the spins becomes completely random and the spontaneous magnetization vanishes. Above the Néel point, the substance behaves like paramagnetism. However the Curie-Weiss law is not to representative of the temperature dependence of magnetism.

Instead, the temperature dependence of χ is given by

$$\frac{1}{\chi} = C(T - \theta) - \frac{a}{T-b} \quad (1.6)$$

where a , b , c are positive constants and θ is a negative Weiss constant.

e) Antiferromagnetism: This case may be treated as special case of ferrimagnetism. In materials exhibiting this type of behavior, the lattice can be considered to composed of two equivalent interpenetrating nearest neighbouring sublattices having the same spin values but in antiparallel directions. The net magnetic moment of the spontaneous magnetization is zero at all temperature, and has the maximum saturation magnetization at absolute zero and decrease by thermal agitation, until the spontaneous magnetization disappears at a temperature called the Néel point⁽³⁾. Above the Néel temperature, the variation of susceptibility is given by

$$\chi = \frac{C}{T-\theta} \quad (1.7)$$

where θ is negative value.

f) Metamagnetism: This phenomenon can be considered as a transition from ferromagnetism to antiferromagnetism and vice versa, which caused by the application of a strong field or change in temperature.

g) Parasitic ferromagnetism: This behavior is a weak ferromagnetism accompanying antiferromagnetism. At the Néel point, the spontaneous magnetization is disappeared.

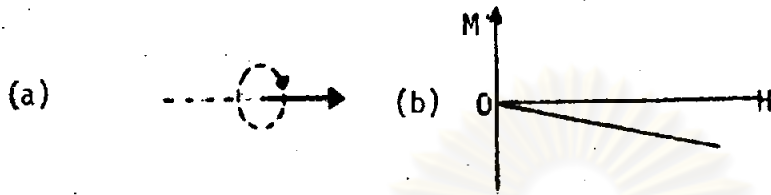


Figure 1 Diamagnetism

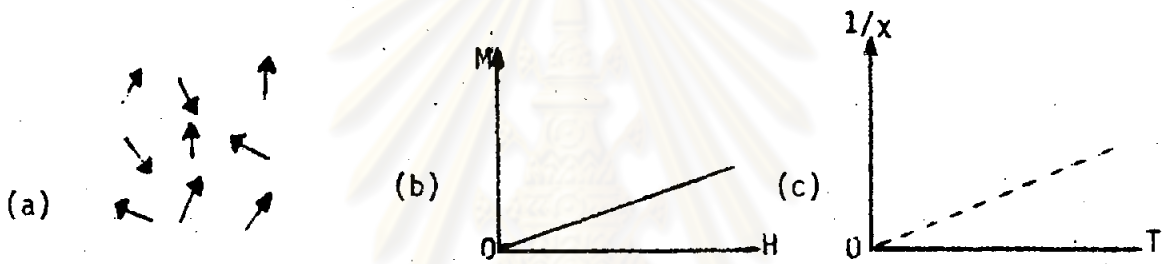


Figure 2 Paramagnetism

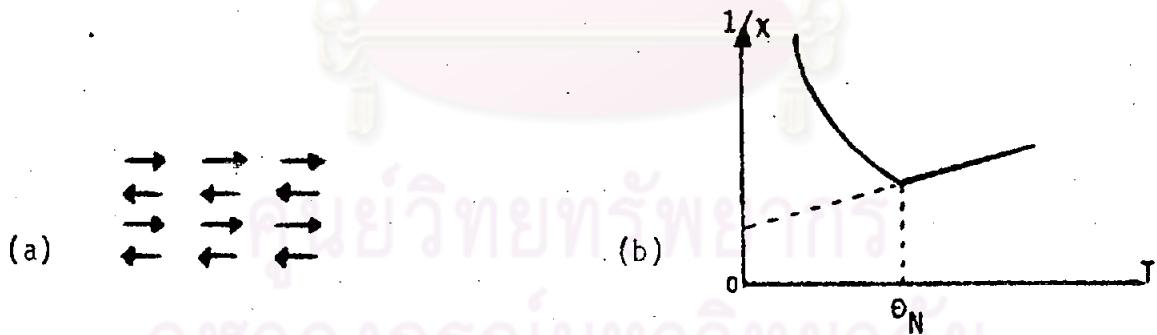


Figure 3 Antiferromagnetism

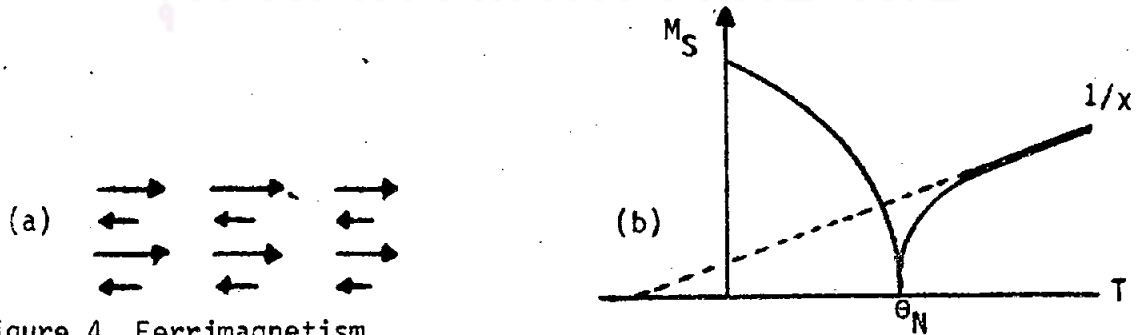
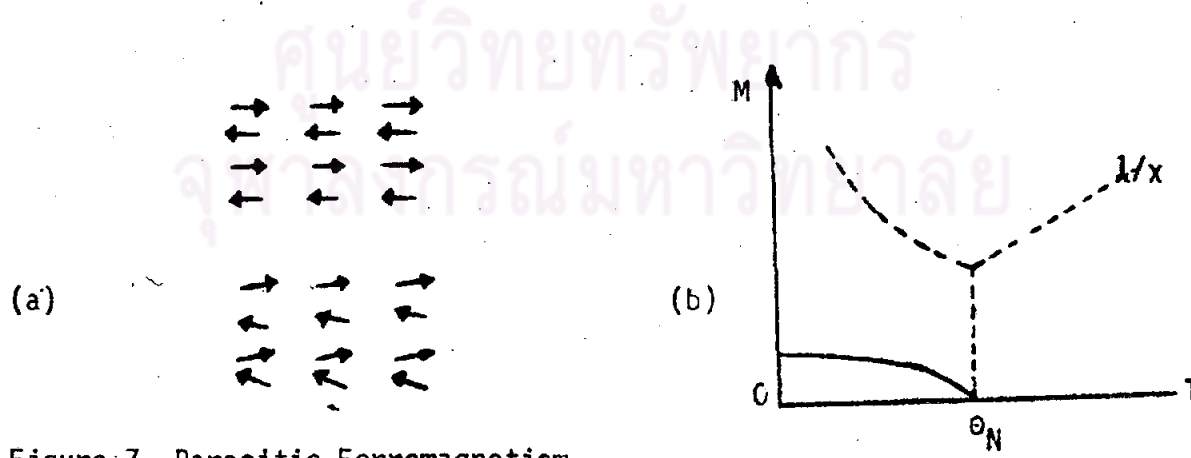
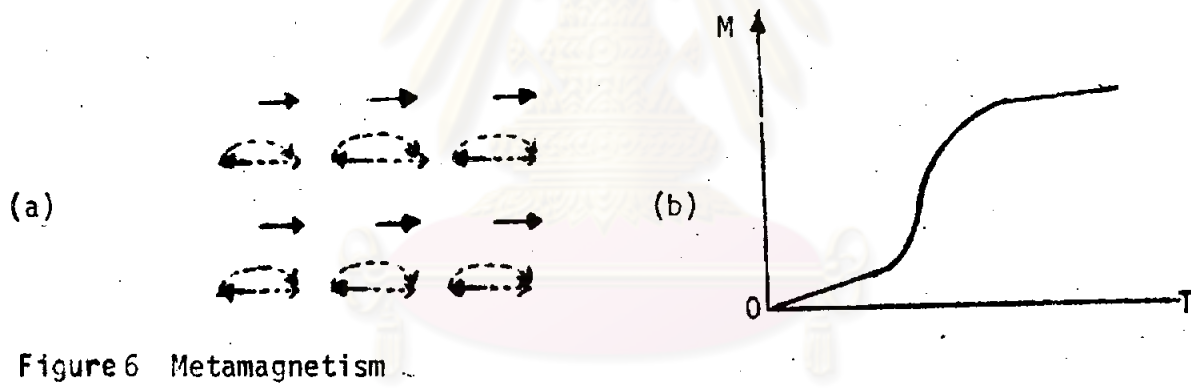
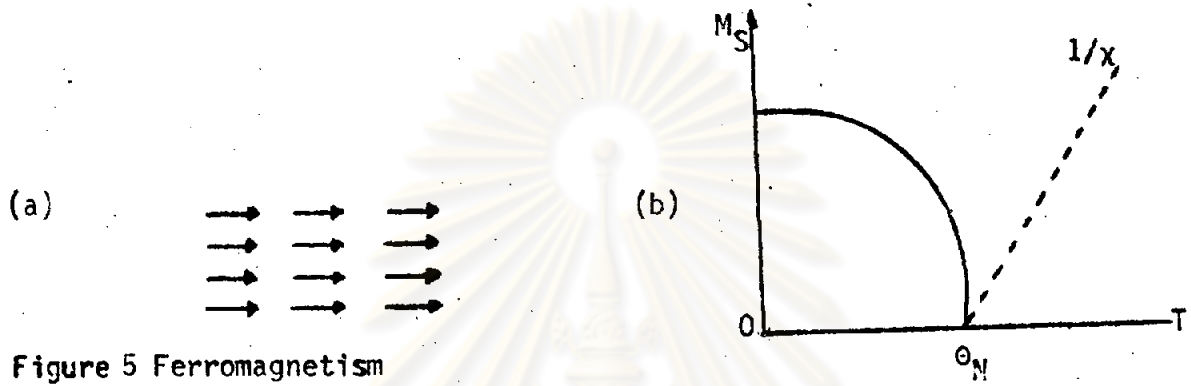


Figure 4 Ferrimagnetism



1.3 The Weiss Molecular Field Theory⁽³⁾

The idea that spontaneous magnetization is due to interactions between magnetic atoms was first proposed by Pierre Weiss⁽⁴⁾ in 1907. The Weiss molecular field approximation considers only one magnetic atom and replaces its interaction with the remainder of the crystal by an effective field which is proportional to the average net magnetic moment of the crystal, that is

$$\vec{H}_{\text{eff}} = \gamma \vec{M} \quad (1.8)$$

where γ is the Weiss molecular field coefficient. Heisenberg⁽⁵⁾ showed that the interactions were quantum mechanical exchange interaction in origin. The exchange interaction which expresses the difference in Coulomb interaction energy of the system when the electron spins are parallel or antiparallel, tends to orient the magnetic moments of the atoms. The simplest example of this effect can be seen in the quantum mechanics of a two-electron system. Suppose that we have two electrons subject to field derived from similar potential functions. The Hamiltonian operator for the pair is then

$$\begin{aligned} H &= -\frac{\hbar^2}{2m} \nabla_1^2 - \frac{\hbar^2}{2m} \nabla_2^2 + V(1) + V(2) + \frac{e^2}{r_{12}} \\ &= H^0 + \frac{e^2}{r_{12}} \end{aligned} \quad (1.9)$$

where numbers 1 and 2 refer to the spatial coordinates of the two electrons and r_{12} is the separation of the two electrons. Neglecting the



interaction between the two electrons, we have a wave function of the form

$$H^0 \psi = E^0 \psi \quad (1.11)$$

which can be separated into independent wave equations involving each electron. The solutions are

$$\psi = \psi_i(1) \psi_j(2) \quad (1.12)$$

$$E^0 = E_i + E_j \quad (1.13)$$

where ψ_i and ψ_j are solutions for a single electron moving in the potential V . If we apply first order perturbation theory to calculate the effect of the interaction, we find

$$E = E_0 + \int \psi_i^*(1) \psi_j^*(2) \frac{e^2}{r_{12}} \psi_i(1) \psi_j(2) d\tau \quad (1.14)$$

$$E = E_0 + C_{ij} \quad (1.15)$$

where C_{ij} has the physically reasonable interpretation as the average Coulomb interaction of two electrons in state i and j , respectively. The Pauli principle requires that the total wave function be antisymmetric with respect to exchanging the space and spin coordinates of the two electrons. The two spins of $S = \frac{1}{2}$ combine to give two states which may be characterized by the total spin S' . The singlet state ($S' = 0$) is antisymmetric and the triplet state ($S' = 1$) is symmetric in the spin coordinates, the appropriate total wave functions are then

$$\psi_S = \frac{1}{\sqrt{2}} [\psi_i(1)\psi_j(2) + \psi_i(2)\psi_j(1)] \phi_0, \quad E_S^0 = E_i + E_j \quad (1.16)$$

$$\psi_T = \frac{1}{\sqrt{2}} [\psi_i(1)\psi_j(2) - \psi_i(2)\psi_j(1)] \phi_1, \quad E_T^0 = E_i + E_j \quad (1.17)$$

where ϕ_0 ($S' = S_1 + S_2 = 0$ and $S' = 1$) is the spin function. When we recalculate the first order perturbation contribution to the energy, we find

$$E_S = E^0 + C_{ij} + J_{ij} \quad (1.18)$$

$$E_T = E^0 + C_{ij} - J_{ij} \quad (1.19)$$

where $J_{ij} = \int \psi_i^*(1)\psi_j^*(2) \frac{e^2}{r_{12}} \psi_i(2)\psi_j(1) d\tau$ (1.20)

is the exchange energy of two electrons in state i and j . As we see the singlet and triplet energies are different; whether the singlet state (spins "antiparallel") or triplet state (spins "parallel") has the lower energy and is the ground state depends on the sign of J_{ij} .

In 1928, Dirac⁽⁶⁾ showed that for the special case of localized electrons in orthogonal orbits, the exchange interactions between spins caused by two-body system can be taken into account by adding to the Hamiltonian of the form

$$H_H = -2 \sum_{i < j} J_{ij} \vec{S}_i \cdot \vec{S}_j \quad (1.21)$$

where \vec{S}_i, \vec{S}_j are the total spins of atoms i and j , respectively. J_{ij} is

the exchange integral and be positive or negative is favored according to whether parallel or antiparallel alignment of \vec{S}_i and \vec{S}_j . The operator (1.9) is known as the Heisenberg Hamiltonian which was first deduced by Dirac and was used first in magnetic theory by Van Vleck⁽⁷⁾.

The Heisenberg model suggests that spontaneous magnetization arises from a coupling of the spin angular momenta, \vec{S}_i , rather than the total angular momenta, \vec{J}_i . The crystal contains atoms with magnetic moments associated with their spin angular momenta as in the relation

$$\vec{\mu} = g\mu_B \vec{S} \quad (1.22)$$

where μ_B is the Bohr magneton, $(\frac{e\hbar}{2m_e c})$. The magnetic atoms are assumed to interact in pairs according to (1.9) and to be subjected to an external applied field. Thus the Hamiltonian of the crystal becomes

$$H = H_H + H_Z \quad (1.23)$$

$$= -2 \sum_{i < j} J_{ij} \vec{S}_i \cdot \vec{S}_j - g\mu_B H_0 \sum_i \vec{S}_i \cdot \vec{z} \quad (1.24)$$

where the first term is the Heisenberg interaction energy and the second term is the Zeeman energy in an applied field H_0 directed along the z-axis.

In Heisenberg model, we considered only cases in which all magnetic atoms are identical and all magnetic lattice sites are crystallographically equivalent. The model is not sufficiently general to allow for anisotropic or antisymmetric exchange interactions.

In anisotropic exchange, the $\vec{S}_i \cdot \vec{S}_j$ term would have the form $J_x S_{ix} S_{jx} + J_y S_{iy} S_{jy} + J_z S_{iz} S_{jz}$, with at least two of J_x , J_y and J_z unequal. An antisymmetric exchange interaction has the form $\vec{D} \cdot (\vec{S}_i \times \vec{S}_j)$.

We should now consider only crystals with a single kind of magnetic atom and assume that all magnetic lattice sites are equivalent. Therefore all nearest neighbor pairs have identical interactions. As exchange interactions are expected to fall off rapidly with increasing distance, it seems likely that only a few sets of interactions need to be considered. Considering the case of nearest neighbor exchange interactions only, equation (1.24) becomes

$$H = -2J \sum_{nn} \vec{S}_i \cdot \vec{S}_j - g\mu_B H_0 \sum_i S_{iz} \quad (1.25)$$

where J is positive, the exchange interaction favors a parallel alignment of the spins, that is a ferromagnetic interaction. A negative J gives an antiparallel spin alignment, or antiferromagnetic interaction.

Assuming $H_0 = 0$ and extracting the single atom Hamiltonian from (1.25) we get

$$H = -2JS_i \sum_{j=1}^Z S_j \quad (1.26)$$

where the sum is over the Z nearest neighbors of the i th atom.

According to the Weiss effective field approximation, The interaction of the i th atom with its Z nearest neighbors can be replaced by an effective field \vec{H}_{eff} . The Hamiltonian for this i th atom is

$$\vec{H}_{\text{eff}} = -\vec{\mu}_i \cdot \vec{H}_{\text{eff}} = -g\mu_B \vec{S}_i \cdot \vec{H}_{\text{eff}} \quad (1.27)$$

Equating (1.26) and (1.27), we find

$$\vec{H}_{\text{eff}} = \frac{2J}{g\mu_B} \sum_{j=1}^Z \vec{S}_j \quad (1.28)$$

In the spirit of the Weiss approximation⁽³⁾, each \vec{S}_j can be replaced by its average value $\langle \vec{S}_j \rangle$. As all magnetic atoms are identical and equivalent, $\langle \vec{S}_j \rangle$ is related to the total magnetic moment of the crystal by

$$M = Ng\mu_B \langle \vec{S}_j \rangle \quad (1.29)$$

then

$$\vec{H}_{\text{eff}} = \frac{2ZJ}{g\mu_B} \langle \vec{S}_j \rangle = \frac{2ZJ}{Ng^2\mu_B^2} \vec{M} \quad (1.30)$$

agrees with the Weiss molecular field model if

$$\gamma = \frac{2ZJ}{Ng^2\mu_B^2} \quad (1.31)$$

1.4 The Two-Sublattice Model⁽³⁾

Historically, the first theory of antiferromagnetism was developed by Néel. However, Landau was the first person to actually predict a phase transition analogous to that in ferromagnetism. In Néel's theory, which is a generalization of the Weiss molecular field theory, a completely ordered arrangement is predicted at absolute zero, with the lattice of magnetic atoms divided into two spontaneously magnetized equivalent sublattices set antiparallel to each other. As

the temperature increases, the spontaneous magnetization decreases and vanishes at a transition temperature (the Néel point). Above the Néel point the susceptibility follows the Curie-Weiss law with $\theta = -T_N$

The most obvious antiferromagnetic arrangement is a lattice which can be subdivided into two equivalent, interpenetrating sublattices, A and B, such that A atoms have only B atoms for nearest neighbors and vice versa, even though this is not possible for all lattices. At any low temperature, the A and B sublattices will become spontaneously magnetized in opposite directions. Two different molecular fields, H_{eA} and H_{eB} which act on the A and B sublattices, as A or B atoms interact only with B or A atoms respectively. The relation is

$$\vec{H}_{eA} = \frac{4ZJ}{Ng^2\mu_B^2} \vec{M}_B = 2\gamma\vec{M}_B \quad (1.32)$$

$$\vec{H}_{eB} = \frac{4ZJ}{Ng^2\mu_B^2} \vec{M}_A = 2\gamma\vec{M}_A \quad (1.33)$$

In the applied field H_0 , the total fields acting on A and B atoms should be

$$\vec{H}_A = \vec{H}_0 + 2\gamma\vec{M}_B \quad (1.34)$$

$$\vec{H}_B = \vec{H}_0 + 2\gamma\vec{M}_A \quad (1.35)$$

According to statistical mechanics, the magnetization of the sublattice A is given by



$$\begin{aligned}
 M_A &= \frac{N}{2} \langle \mu_z \rangle \\
 &= \frac{N}{2} g \mu_B \sum_m \exp\left(\frac{m X_A}{S}\right)
 \end{aligned}
 \tag{1.36}$$

where $X_A = \frac{g \mu_B S H_A}{kT}$ is the ratio of the magnetic and thermal energies.

However, the expression (1.36) can be reduced to the useful form

$$M_A = \frac{N}{2} g \mu_B S B_S(X_A) \tag{1.37}$$

where $B_S(X)$ is the Brillouin function,

$$B_S(X) = \frac{2S+1}{2S} \text{Coth}\left(\frac{2S+1}{2S} X\right) - \frac{1}{2S} \text{Coth}\left(\frac{X}{2S}\right) \tag{1.38}$$

and similarly to the sublattice B

$$M_B = \frac{N}{2} g \mu_B S B_S(X_B) \tag{1.39}$$

Equations (1.37) and (1.39) are coupled by the fact that H_A depends on M_B and H_B on M_A . Thus they must be solved simultaneously. Considering only the high temperature approximation in which $x \ll 1$:

and $B_S(X) = \frac{S+1}{3S} X \tag{1.40}$

then $M_A = \frac{1}{2} N g \mu_B S \frac{S+1}{3S} \frac{g \mu_B S (H_0 + 2\gamma M_B)}{kT}$

$$= \frac{1}{2} \frac{C}{T} (H_0 + 2\gamma M_B) \tag{1.41}$$

and $M_B = \frac{1}{2} \frac{C}{T} (H_0 + 2\gamma M_A) \tag{1.42}$

where $C = \frac{Ng^2\mu_B^2 S(S+1)}{3k}$ is Curie's constant. Moreover, the total magnetic moment $M = M_A + M_B$ can be obtained by summing (1.41) and (1.42), which reduces to

$$M = \frac{C}{T - C\gamma} H_0 \quad (1.43)$$

003942

Hence the susceptibility is given by

$$\chi = \frac{C}{T - \theta} \quad (\text{Curie-Weiss law}) \quad (1.44)$$

$$\text{where } \theta = T_C = C\gamma = \frac{2gS(S+1)}{3k} \quad (\text{Curie temperature}) \quad (1.45)$$

However, this number is negative since $J < 0$.

Consequently, if $X \gg 1$ then

$$B_S(X) = 1 - \frac{1}{S} e^{-g\mu_B H_0 / kT}$$

As $T \rightarrow 0$, $B_S(X) \rightarrow 1$ and $M_A = M_B = \frac{N}{2} g\mu_B S$ which is the saturation behavior where each atom has the maximum z component of the magnetic moment, $g\mu_B S$.

To locate the transition temperature, we set $H_0 = 0$ in equation (1.41) and (1.42). The condition required for M_A and M_B to have non-zero values is

$$\frac{C\gamma}{T_C} = 1, \quad M_A = M_B \quad (1.46)$$

or
$$\frac{C\gamma}{T_N} = -1, M_A = -M_B \quad (1.47)$$

The first condition is obviously that for a ferromagnet which will have a negative transition temperature, the negative value indicates the ferromagnetism is unstable if $J < 0$. The second condition give the antiferromagnetic arrangement, $M_A = -M_B$ and a positive transition temperature $T_N = -\theta$. In the absence of interactions between magnetic atoms, the Curie-Weiss law with $\theta = 0$ reduce to the Curie's law for purely paramagnetic substances, $\chi = C/T$. However, a quantum mechanical treatment shows that at low temperature, a term independent of temperature should be added to the Curie's law, and so we get

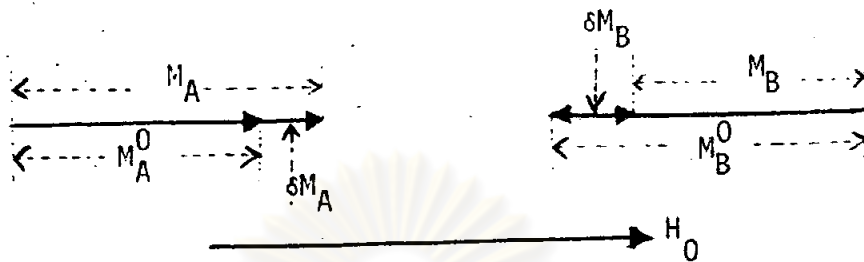
$$\chi = \frac{C}{T} + N_a(\bar{J}) \quad (1.48)$$

where \bar{J} is the total angular momentum $\vec{J} = \vec{L} + \vec{S}$.

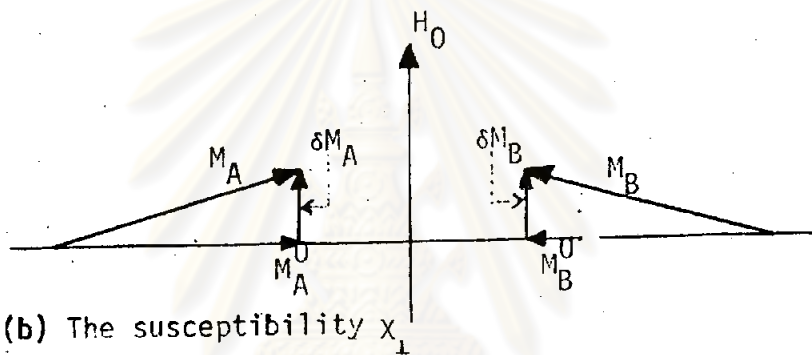
1.5 The Susceptibility Below The Néel Point⁽³⁾

In an antiferromagnet below the Néel point, each of the sublattices acquires a spontaneous magnetization and the molecular field becomes very large. This means that in calculating the susceptibility below the Néel point we can no longer use the approximation $g\mu_B S H_i \ll kT$ which leads to the Curie-Weiss law for $T > T_N$.

In the two-sublattice model, below T_N and in the absence of any applied field, the magnetization of the two-sublattices are antiparallel. Whenever the external field \vec{H}_0 is applied along the axis



(a) The susceptibility χ_{\parallel}



(b) The susceptibility χ_{\perp}

Figure 8 The susceptibility: χ_{\parallel} , χ_{\perp}

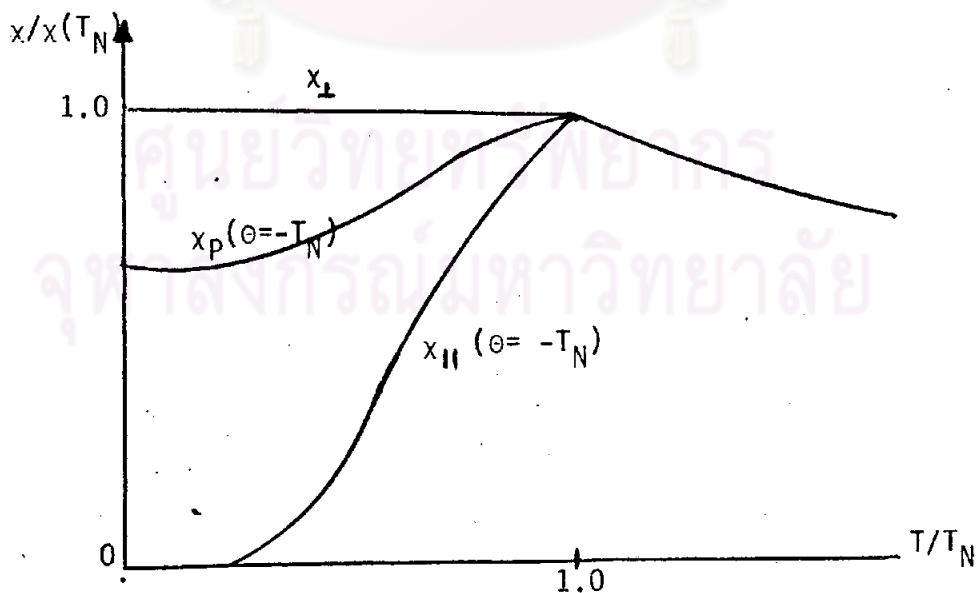


Figure 9 Temperature dependence of the magnetic susceptibility of an antiferromagnetic substance

of \vec{M}_A and \vec{M}_B , this will increase the magnetization of one sublattice and decrease the magnetization of the other, in figure 8(a). This susceptibility is referred to as χ_{\parallel} . In the case of the field being perpendicular to their axis, the magnetizations will not be changed but will be rotated slightly away from their axis into the direction of the field, in figure 8(b). This susceptibility is called of χ_{\perp} . According to the calculation by Van Vleck for the simple A-B type antiferromagnet with nearest neighbor interactions only, χ_{\perp} is constant for $T < T_N$; while χ_{\parallel} is zero at absolute zero and rises monotonically to χ_{\perp} at $T = T_N$. This behavior is shown in figure 9. As $\chi_{\perp} > \chi_{\parallel}$, the minimum energy configuration in a magnetic field will occur with the antiferromagnetic axis perpendicular to H_0 . Consequently, for the simple Heisenberg model, we should expect the moments to rotate until the perpendicular configuration is achieved, so that the susceptibility observed for $T < T_N$ will always be χ_{\perp} . However, Nagamiya⁽⁸⁾ has pointed out that such rotations are opposed by an anisotropy field which tends to keep the moments aligned along a particular crystal axis. It is not until the applied field reaches a critical value, $\sim \sqrt{2}H_e H_a$, where H_a is the anisotropy field, that the moments suddenly flip into the perpendicular configuration. For powder samples, some sort of average over possible orientations is given by (in fig. 9)

$$\chi_p = \frac{1}{3}\chi_{\parallel} + \frac{2}{3}\chi_{\perp} \quad (1.49)$$

By using Van Vleck's calculation for the two-sublattice model, we can generalize the molecular field treatment for the susceptibility of



a single-axis antiferromagnet below the Néel point. For an applied field small in comparison to the molecular field, the magnetization of each sublattice is not very different from the spontaneous value and can therefore be written as

$$M_A = M_A^0 + \delta M_A \quad (1.50)$$

which is the same as the magnetization of sublattice B. However, when H_0 is applied perpendicular to the antiferromagnetic axis, the sublattice magnetizations will be rotated through a small angle α until the decrease in Zeemann energy is counterbalanced by the increase in exchange energy.

Thus the total magnetization is given by

$$M(1-\theta/T_N) = CH_0/T_N \quad (1.51)$$

Then the susceptibility χ and χ_{11} which are reduced from the generalized field theory are

$$\chi(T_N) = \frac{C}{T_N - \theta} \quad (1.52)$$

$$\chi_{11} = C \frac{3S(S+1)^{-1} B'_S(X_0)}{T - 3S(S+1)^{-1} \theta B'_S(X_0)} \quad (1.53)$$

which goes to zero at absolute temperature.

In general, the experimental data tends to resemble the curve for $\theta/T_N = -1$. Some experimental data shows two deviations from the molecular field predictions; the perpendicular susceptibility is not

quite temperature independent and χ_{11} does not vanish at absolute zero.

1.6 Other More Advanced Theories (3)

In the molecular field theory, all the exchange interactions in the crystal are replaced by an effective field, the detailed properties of the spin-spin interaction are completely lost. Since the discussion of magnetism on the microscopic level is unmanageable if all exchange interactions are taken into account, one usually looks only at the interactions present in a small volume of the magnetic material and approximate all the interactions occurring in this volume by a limited number of interactions. The simplest approach is the Oguchi method. Here we consider a pair of nearest neighbor atoms selected at random. The exchange coupled pair in an effective field is proportional to the average magnetization of the sample

$$H_e = \gamma M \quad (1.54)$$

where $\gamma = \frac{2(Z-1)J}{Ng^2\mu_B^2}$ is the molecular field coefficient. This coefficient

differs from Weiss' only with Z is replaced by $(Z-1)$ because each atom in the pair has one interaction treated exactly and $(Z-1)$ interactions treated in the molecular field approximation. As the pair is chosen arbitrarily, the average magnetic moment per atom must be the same as that of any other pair. Consequently, we have

$$M = \frac{N}{Z} g\mu_B \langle S'_Z \rangle \quad (1.55)$$

where

$$\begin{aligned} \langle S_z' \rangle &= \langle S_{iz} + S_{jz} \rangle \\ &= \frac{\text{Tr}\{(S_{iz} + S_{jz}) \exp(-H_p/kT)\}}{z_p} \end{aligned} \quad (1.56)$$

here H_p is the Hamiltonian for such a pair and z_p is the partition function.

For the special case of spin $\frac{1}{2}$ atom, above the transition temperature, the paramagnetic susceptibility is

$$\chi = \frac{M}{H_0} = \frac{C}{T} \frac{4}{e^{-2j} + 3 - 2(Z-1)j} \quad (1.57)$$

where $j = J/kT$.

For antiferromagnetic solution below the Néel point and the applied field being zero, we have

$$H_A = -H_B, \quad H_0 = 0 \quad (1.58)$$

where

$$S_A = \langle S_{Az} \rangle = \frac{M_A}{\frac{1}{2} Ng\mu_B} \quad (1.59)$$

$$S_B = \langle S_{Bz} \rangle = \frac{M_B}{\frac{1}{2} Ng\mu_B} \quad (1.60)$$

Thus the Oguchi⁽⁹⁾ molecular field approximations for H_A and H_B are :

$$H_A = \frac{2(Z-1)J}{g\mu_B} S_B \quad (1.61)$$

$$H_B = \frac{2(Z-1)J}{g\mu_B} S_A \quad (1.62)$$

The antiferromagnetic condition requires that

$$[1-(Z-1)^2 (S_A - S_B)^2]^{1/2} (e^j + \cosh \frac{D}{2}) + (Z-1) \sinh \frac{D}{2} = 0 \quad (1.63)$$

The above equation can be solved to give $(S_A - S_B)$ as a function of T . At the Néel point $(S_A = -S_B = 0)$, $p = 2j$, we have

$$e^{2j_N} = \frac{Z-2}{Z+2} \quad (1.64)$$

which shows that there is no Néel point unless $Z > 2$.

At temperature below the Néel point, the Oguchi method gives results for the susceptibility similar to those of the Weiss theory.

Therefore, χ_{\perp} is nearly constant but decreases by a few percentage points in going from T_N to 0°K , and the parallel susceptibility is given by

$$\chi_{\parallel} = \frac{C}{T} \frac{2}{(1+e^{-j} \cosh \frac{D}{2}) - (Z-1)j} \quad (1.65)$$

ศูนย์วิทยทรัพยากร
จุฬาลงกรณ์มหาวิทยาลัย