INTRODUCTION

Modern technology would be unthinkable without magnetic materials and magnetic phenomena. Magnetic tapes or disks (for computers, video recorders, etc.) motors, generators, telephones, transformers, permanent magnets, electromagnets, loudspeakers, and magnetic strips on credit cards are only a few examples of their applications. At least five different kinds of magnetic materials exist. They have been termed para-, dia-, ferro-, ferri-, and antiferromagnetics. A qualitative as well as a quantitative distinction between these types can be achieved in a relatively simple way by utilizing a method proposed by Faraday. The magnetic material to be investigated is suspended from one of the arms of a sensitive balance and is allowed to reach into an inhomogeneous magnetic field (Figure 1). Diamagnetic materials are expelled from this field, whereas para-, ferro-, antiferro-, and ferrimagnetics are attracted in different degrees. It has been found empirically that the apparent loss or gain in mass, that is, the force, ***F***, on the sample exerted by the magnetic field, is:

$$F = V \chi \mu_0 H \frac{dH}{dx},$$

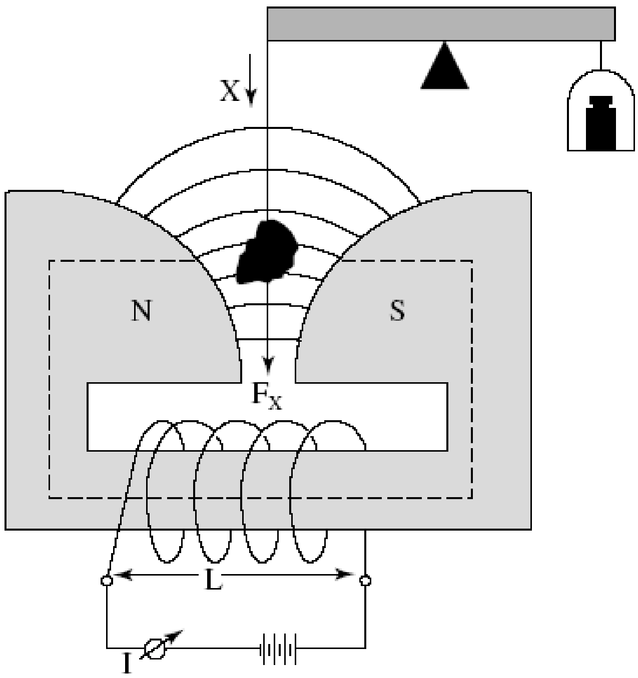

Figure 1

Where ***V*** is the volume of the sample, μ_0 is a universal constant called the **permeability** of free space (1.257×10^{-6} H/m or Vs/Am), and χ is the **susceptibility**, which expresses how responsive a material is to an applied magnetic field. Characteristic values for χ are given in Table 1. The term (***dH/dx)*** is the change of the **magnetic field strength *H*** in the ***x***-direction. The field strength ***H*** of an electromagnet (consisting of helical windings of a long, insulated wire as seen in the lower portion of Figure 1) is proportional to the current, *I*, which flows through this coil, and on the number, ***n***, of the windings (called ***turns***) that have been used to make the coil.

Further, the magnetic field strength is inversely proportional to the length, ***L***, of the ***solenoid***. Thus, the magnetic field strength is expressed by:

$$H = \frac{In}{L}.$$

The field strength is measured (in SI units) in "Amp-turns per meter" or shortly, in (A/m). The magnetic field can be enhanced by inserting, say, iron, into a solenoid, as shown in Figure 1. The parameter which expresses the amount of enhancement of the magnetic field is called the **permeability μ**. The magnetic field strength within a material is known by the names **magnetic induction** (or ***magnetic flux density***) and is denoted by ***B***.

(Table 1)

Material	χ (SI) unitless	χ (cgs) unitless	μ unitless	Type of magnetism
Bi	-165×10^{-6}	-13.13×10^{-6}	0.99983	
Ge	-71.1×10^{-6}	-5.66×10^{-6}	0.99993	
Au	-34.4×10^{-6}	-2.74×10^{-6}	0.99996	Diamagnetic
Ag	-25.3×10^{-6}	-2.016×10^{-6}	0.99997	
Be	-23.2×10^{-6}	-1.85×10^{-6}	0.99998	
Cu	-9.7×10^{-6}	-0.77×10^{-6}	0.99999	
Superconductors[a]	-1.0	$\sim -8 \times 10^{-2}$	0	
β-Sn	$+2.4 \times 10^{-6}$	$+0.19 \times 10^{-6}$	1	
Al	$+20.7 \times 10^{-6}$	$+1.65 \times 10^{-6}$	1.00002	Paramagnetic
W	$+77.7 \times 10^{-6}$	$+6.18 \times 10^{-6}$	1.00008	
Pt	$+264.4 \times 10^{-6}$	$+21.04 \times 10^{-6}$	1.00026	
Low carbon steel	Approximately the same as μ because of $\chi = \mu - 1$.		5×10^3	
Fe–3%Si (grain-oriented)			4×10^4	Ferromagnetic
Ni–Fe–Mo (supermalloy)			10^6	

Magnetic field strength and magnetic induction are related by the equation:

$$B = \mu \, \mu_0 H.$$

The SI unit for ***B*** is the tesla (T) and that of μ_0 is henries per meter (H/m or Vs/Am). The relationship between the susceptibility and the permeability is

$$\mu = 1 + \chi.$$

For empty space and, for all practical purposes, also for air, one defines ($\chi = 0$) and thus ($\mu = 1$). The susceptibility is small and negative for diamagnetic materials. As a consequence, **μ** is slightly less than (1). For para- and antiferromagnetic materials, **χ** is again small, but positive. Thus, **μ** is slightly larger than (1). Finally, **χ** and **μ** are large and positive for ferro- and ferrimagnetic materials. The magnetic constants are temperature-dependent, except for diamagnetic materials, Further; the susceptibility for ferromagnetic materials depends on the field strength, ***H***. In free (empty) space, ***B*** and $\mu_0 H$ are identical. Inside a magnetic material the induction ***B*** consists of the free-space component ($\chi_0 H$) plus a contribution to the magnetic field ($\mu_0 M$) which is due to the presence of matter [Figure 2(a)], that is,

$$B = \mu_0 H + \mu_0 M,$$

Where ***M*** is called the ***magnetization*** of the material. Which relate with χ and ***H*** by:

$$M = \chi H.$$

H, ***B***, and ***M*** are actually vectors. Specifically, outside a material, ***H*** (and ***B***) point from the north to the South Pole. Inside of a ferro- or paramagnetic material, ***B*** and ***M*** point from the south to the north;

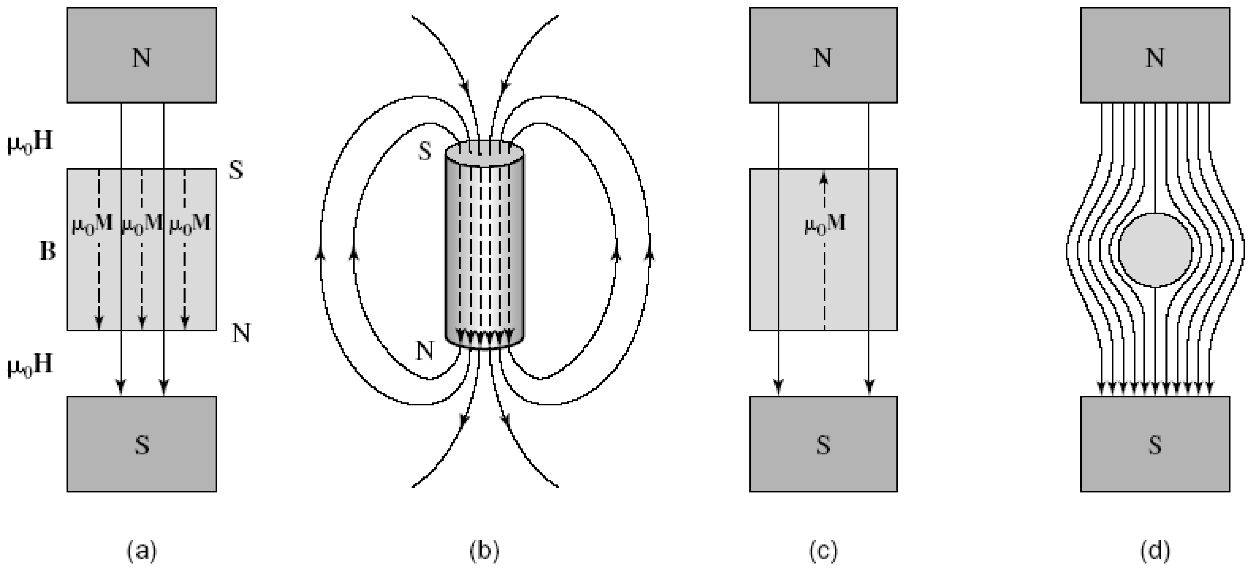

Figure 2

B was called above to be the magnetic flux density in a material, that is, the magnetic flux per unit area. The **magnetic flux** (Φ) is then defined as the product of ***B*** and area ***A***, that is, by

$$\phi = B\,A.$$

Finally, we need to define the magnetic moment $\boldsymbol{\mu}_m$ (also a vector) through the following equation:

$$M = \frac{\mu_{\rm m}}{V},$$

Which means that the magnetization is the magnetic moment per unit volume.

<u>Diamagnetism</u>

Ampère postulated more than one hundred years ago that so-called ***molecular currents*** are responsible for the magnetism in solids. He compared these molecular currents to an electric current in a loop-shaped piece of wire which is known to cause a magnetic moment. Today, we replace Ampère's molecular currents by ***orbiting valence electrons***. To understand diamagnetism, a second aspect needs to be considered. A current is induced in a wire loop whenever a bar magnet is moved toward (or from) this loop. The current thus induced causes, in turn, a magnetic moment that is opposite to the one of the bar magnet (Figure 3). Diamagnetism may then be explained by postulating that the external magnetic field induces a change in the magnitude of the atomic currents, i.e., ***the external field accelerates or decelerates the orbiting electrons,*** so that their magnetic moment is in the opposite direction to the external magnetic field. In other words, the responses of the orbiting electrons counteract the external field [Figure 2(c)].

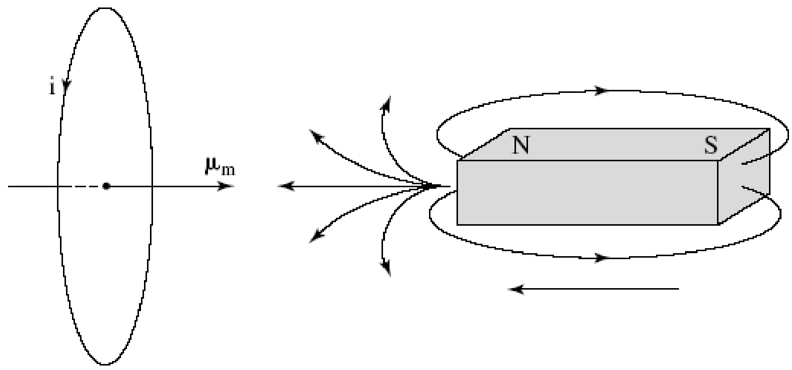

Figure *3*

Paramagnetism

Paramagnetism in ***solids*** is attributed to a large extent to a magnetic moment that results from electrons which spin around their own axis; see Figure 4(a). The spin magnetic moments are generally randomly oriented so that no net magnetic moment results. An external magnetic field tries to turn the unfavorably oriented spin moments in the direction of the external field, but thermal agitation counteracts the alignment. Thus, ***spin paramagnetism*** is slightly temperature-dependent. It is generally weak and is observed in some metals and in salts of the transition elements. Free atoms (dilute gases) as well as rare earth elements and their salts and oxides possess an additional source of paramagnetism. It stems from the magnetic moment of the ***orbiting electrons***; see Figure 4(b). Without an external magnetic field, these magnetic moments are, again, randomly oriented and thus mutually cancel one another. As a result, the net magnetization is zero. However, when an external field is applied, the individual magnetic vectors tend to turn into the field direction which may be counteracted by thermal agitation. Thus, ***electron-orbit paramagnetism*** is also temperature-dependent. From the above-said it becomes clear that in paramagnetic materials the magnetic moments of the electrons eventually point in the direction of the external field, that is, the magnetic moments enhance the external field [see Figure 2(a)]. On the other hand, diamagnetism counteracts an external field [see Figure 2(c)].

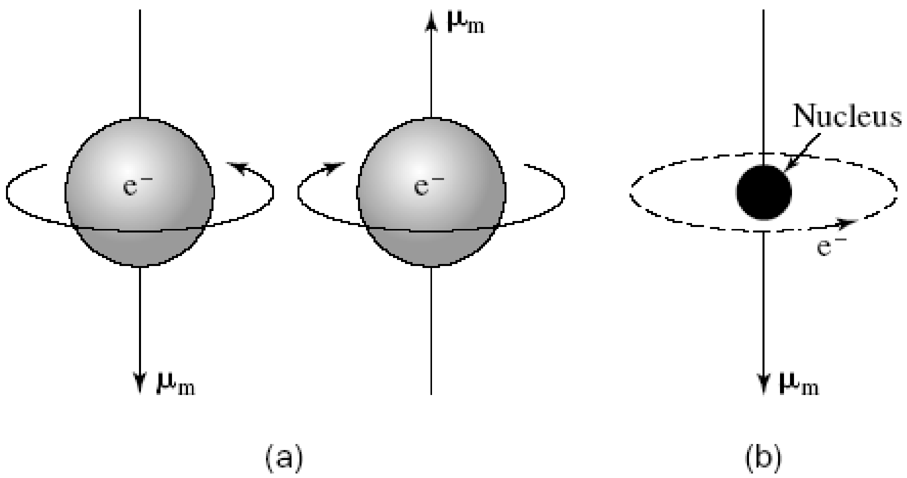

Figure 4

Thus, para- and diamagnetism oppose each other. Solids that have both orbital as well as spin paramagnetism are consequently paramagnetic (since the sum of both paramagnetic compounds is commonly larger than the diamagnetism). Rare earth metals are an example of this. In many other solids, however, the electron orbits are essentially coupled to the lattice. This prevents the orbital magnetic moments from turning into the field direction. Thus, electron-orbit paramagnetism does not play a role, and only spin paramagnetism remains. The possible presence of a net spin-paramagnetic moment depends, however, on whether or not the magnetic moments of the individual spins cancel each other. Specifically, if a solid has ***completely filled electron bands***, then a quantum mechanical rule, called the **Pauli principle**, requires the same number of electrons with spins up and with spins down [Figure 4(a)]. The Pauli principle stipulates that each electron state can be filled only with two electrons having opposite spins. The case of completely filled bands thus results in a cancellation of the spin moments and no net paramagnetism is expected. Materials in which this occurs are therefore diamagnetic (no orbital and no spin paramagnetic moments). Examples of filled bands are intrinsic semiconductors, insulators, and ionic crystals such as NaCl. In materials that have partially filled bands, the electron spins are arranged according to **Hund's rule** in such a manner that the total spin moment is maximized. For example, for an atom with eight valence *d*-electrons, five of the spins may point up and three spins point down, which results in a net number of two spins up; Figure 5. The atom then has two units of (para-) magnetism or, as it is said, two Bohr magnetons per atom. The **Bohr magneton** is the smallest unit (or quantum) of the magnetic moment and has the value:

$$\mu_B = \frac{eh}{4\pi m} = 9.274 \times 10^{-24} \left(\frac{J}{T}\right) \equiv (A \cdot m^2).$$

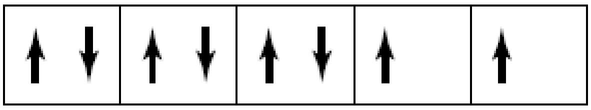

Figure 5

Ferromagnetism

Figure (6) depicts a ring-shaped solenoid consisting of a newly cast piece of iron and two separate coils which are wound around the iron ring. If the magnetic field strength in the solenoid is temporally increased (by increasing the current in the primary winding), then the magnetization (measured in the secondary winding with a flux meter) rises slowly at first and then more rapidly, as shown in Figure (7) (dashed line). Finally, ***M*** levels off and reaches a constant value, called the **saturation magnetization**, ***Ms***. When ***H*** is reduced to zero, the magnetization retains a positive value, called the ***remanent magnetization***, or **remanence**, ***Mr***. It is this retained magnetization which is utilized in permanent magnets. The remanent magnetization can be removed by reversing the magnetic field strength to a value ***Hc***, called the **coercive field**. Solids having a large combination of ***Mr*** and ***Hc*** are called ***hard magnetic materials*** (in contrast to ***soft*** magnetic materials, for which the area inside the loop of Figure(7) is very small). A complete cycle through positive and negative ***H***-values as shown in Figure (7) is called a **hysteresis loop**. The saturation magnetization is temperature-dependent. Above the **Curie temperature**, ***Tc***, ferromagnetics become paramagnetic. the spins of unfilled ***d***-bands spontaneously align parallel to each other below ***Tc***, that is, they align within small domains (1–

100μm in size) without the presence of an external magnetic field; Figure 8(a). The individual domains are magnetized to saturation. The spin direction in each domain is, however, different, so that the individual magnetic moments for virgin ferromagnetic materials as a whole cancel each other and the net magnetization is zero. An external magnetic field causes those domains whose spins are parallel or nearly parallel to the external field to grow at the expense of the unfavorably aligned domains; Figure 8(b). When the entire crystal finally contains only ***one*** single domain, having spins aligned parallel to the external field direction then the material is said to have reached ***technical saturation magnetization***, ***Ms*** [Figure 8(c)]. An increase in temperature progressively destroys the spontaneous alignment, thus reducing the saturation magnetization, Figure 8(d).

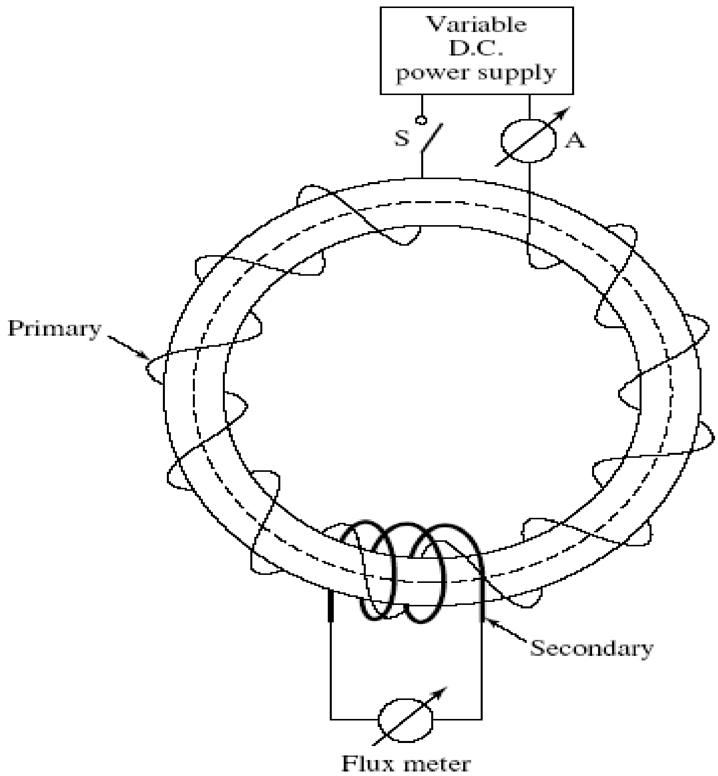

Figure 6

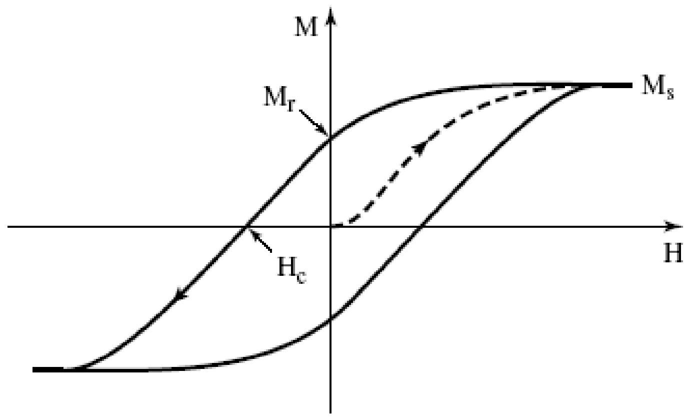

Figure 7

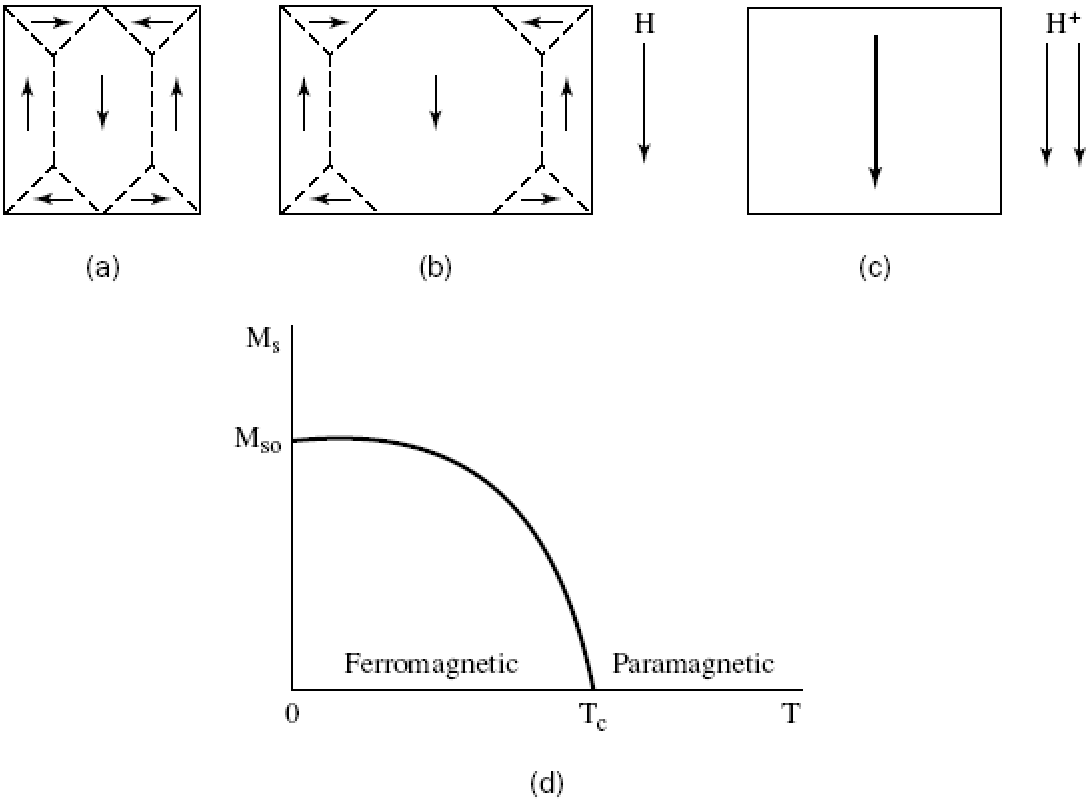

Figure 8

Antiferromagnetism

Antiferromagnetic materials exhibit, just as ferromagnetics, a spontaneous alignment of spin moments below a critical temperature (called the **Néel temperature**). However, the responsible neighboring atoms in antiferromagnetics are aligned in an antiparallel fashion (Figure 9). Actually, one may consider an antiferromagnetic crystal to be divided into two interpenetrating sublattices, A and B, each of which has a spontaneous alignment of spins. Figure (9) depicts the spin alignments for two manganese compounds. (Only the spins of the manganese ions contribute to the antiferromagnetic behavior.) Figure (9(a)) implies that the ions in a given **{110}** plane possess parallel spin alignment, whereas ions in the adjacent plane have antiparallel spins with respect to the first plane. Thus, the magnetic moments of the solid cancel each other and the material as a whole has no net magnetic moment. Most antiferromagnetics are found among ionic compounds such as MnO, MnF_2, FeO, NiO, and CoO. They are generally insulators or semiconductors. Additionally, manganese and chromium are antiferromagnetic.

Ferrimagnetism

Ferrimagnetic materials such as $NiO.Fe_2O_3$ or FeO $.Fe_2O_3$ are of great technical importance. They exhibit a spontaneous magnetic moment (Figure 8) and hysteresis (Figure 7) below a Curie temperature, just as iron, cobalt, and nickel do. In other words, ferrimagnetic materials possess, similar to ferromagnetics, small domains in which the electron spins are spontaneously aligned in parallel. The main difference to ferromagnetics is, however, that ferrimagnetics are ceramic materials (oxides); they are therefore poor electrical conductors. To explain the spontaneous magnetization in ferrimagnetics, Néel proposed that two sublattices, say A and B, should exist in these materials (just as in antiferromagnetics), each of which contains ions whose spins are aligned parallel to each other. Again, the spins of the ions on the A sites are antiparallel to the spins of the ions on the B sites. The crucial point is that each of the sublattices contains a different amount of magnetic ions. This causes some of the magnetic moments to remain uncancelled. As a consequence, a net magnetic moment results. Ferrimagnetic materials can thus be described as ***imperfect antiferromagnetics*** nickel ferrite has two uncancelled spins and therefore two Bohr magnetons per formula unit. This is essentially observed by experiment.

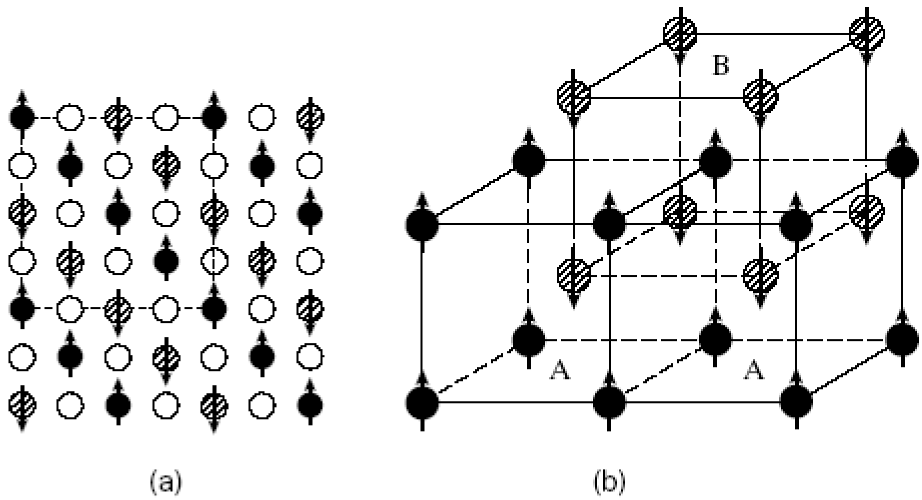

Figure 9