CHAPTER I

INTRODUCTION

Materials which are magnetized, more or less, by a magnetic field are called magnetic materials. There are several kinds of magnetic materials, each characterized by how they response to the applied field and their magnetic structure. The magnetic materials can be categorized as being paramagnetic or diamagnetic, depending on whether the magnetic moments induced by an external magnetic field align parallel or antiparallel to the field. They can also be categorized as being ferromagnetic, ferrimagnetic or antiferromagnetic in those materials in which the magnetization occurs spontaneously.

The magnetic moment per unit volume of a magnetic material is called the intensity of magnetization and is denoted by the vector **M**. This vector points from the south pole to the north pole of the magnetic moment. The unit of **M** is the weber per square meter (1 wb/m^2 = (1/4) * 10^4 gauss). The magnetic induction or magnetic flux density **B** is also commonly used to describe the magnetization. The relationship between **B** and **M** is

$$B = \mu_0 H + M \qquad (1.1)$$

where μ_0 is the permeability in vacuum. The unit of μ_0 is henry per meter. The relationship between the intensity of magnetization (**M**) and the magnetic field (**H**) can be expressed as

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

where χ is the magnetic susceptibility. The unit of χ is the henry per meter, the same as μ_0(making it possible to measure χ in units of μ_0). The susceptibility thus measured is the relative susceptibility and denoted as $\bar{\chi}$

$$\bar{\chi} = \chi/\mu_0 \qquad (1.3)$$

and is a dimensionless quantity. Substituting eqn. (1.2) into eqn. (1.1), we get

$$B = \chi H + \mu_0 H$$

$$B = (\chi + \mu_0)H = \mu H \qquad (1.4)$$

where μ is the permeability of the material. Dividing μ by the permeability of vacuum, we get the relative permeability $\bar{\mu}$ defined as

$$\bar{\mu} = \mu/\mu_0$$

$$\bar{\mu} = \bar{\chi} + 1 \qquad (1.5)$$

The observed value of the relative susceptibility ranges from 10^{-5} for very weak magnetic materials to 10^{6} for very strong magnetic materials. Often, the relation between M and H is not linear. Then $\bar{\chi}$ depends on the intensity of the magnetic field.

There are two possible atomic origins to magnetism; the orbital motion of the electrons and the spins of the electrons. An atom which has a magnetic moment due to the spin of the electron or to the orbital motion of the electrons or to both are called magnetic atoms. Since the magnetic moments of the more important magnetic atoms such as iron, cobalt and nikel, are caused by the spin motion of the electrons, we normally refer to the atomic moments as "spin". As we have already mentioned, magnetic substances can be categorized into five groups(1);

1. Diamagnetic
2. Paramagnetic
3. Ferromagnetic
4. Ferrimagnetic
5. Antiferromagnetic

1.1 Diamagnetism occurs when the induced magnetization is opposite to the applied field (see Figure 1.1).

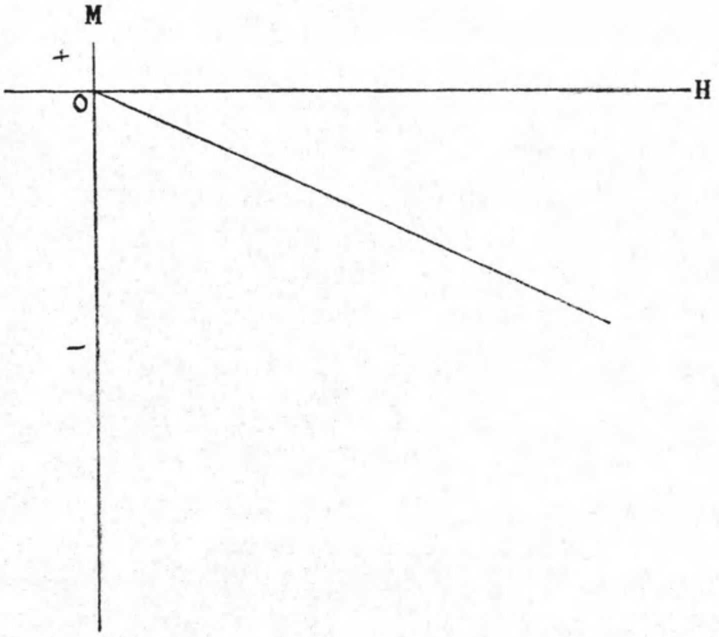
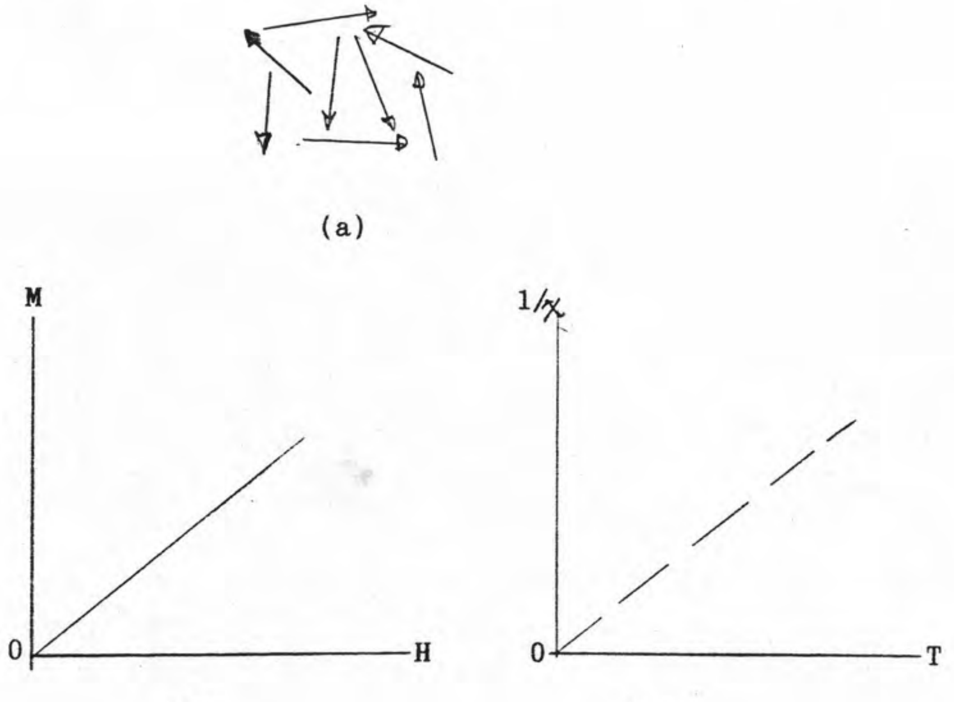


Figure 1.1 Diamagnetic behavior of M vs H.

The susceptibility is negative and the magnitude of the relative susceptibility $\bar{\chi}$ is of order 10^{-5}. Diamagnetism occurs through the deformation of the electric charge distribution when a field is applied and it disappears when the field is removed. The diamagnetic susceptibility is usually independent of temperature. Diamagnetism is exhibited by the inert gases, the elements Zn, Cu, Au, Bi, Ga amoung others.

1.2 <u>Paramagnetism.</u> This occurs when the magnetization is in the same direction as the applied field (see Figure 1.2).



(a)

(b)

(c)

Figure 1.2 Paramagnetism. (a). The arrangement of the magnetic moments in the absence of the field. (b). Plot of **M** vs H. (c). Dependence of $1/\chi$ on the temperature.

The order of magnitude of the relative susceptibilities of paramagnetic materials is between 10^{-3} and 10^{-5}. Ions from the transition metal series and the rare earth series possess a net magnetic moment because they contain electrons in incomplete shells. The magnetic moments arising from the individual electrons in the incomplete shells do not cancel out, leaving the atom with a net magnetic moment. In the absence of a magnetic field, the moments usually point in random directions so that the vector sum of all the moments in the material is zero (the probability that the atom will have a magnetic moment pointing in one direction is the same as the probability of it pointing in the opposite direction). When a field is present, all the magnetic moments tend to line in the direction of the field and this leads to a net magnetization. The susceptibility is positive and usually depends inversely on the temperature (measured in the absolute temperature scale).

1.3 <u>Ferromagnetism.</u> In these magnetic materials, the magnetic moments of the individaul ions are strongly coupled, leading to spontaneous parallel alignment of the magnetic moments even in the absence of the applied field. This often results in a very large net magnetization in the material. As the temperature of the material is increased, the thermal motion of the magnetic moments causes the directions of the individual magnetic moments to fluctuate. At high enough temperatures, the fluctuation becomes sufficient so that the moments are pointing in random directions.

When this happens, the spontaneous magnetization is destroyed. The temperature at which this occurs is called the Curie temperature. Application of an externally applied field above this temperature causes the random (due to the thermal agitation) orientated magnetic moments to align themselves just as in the case of paramagnetism (see Figure 1.3).

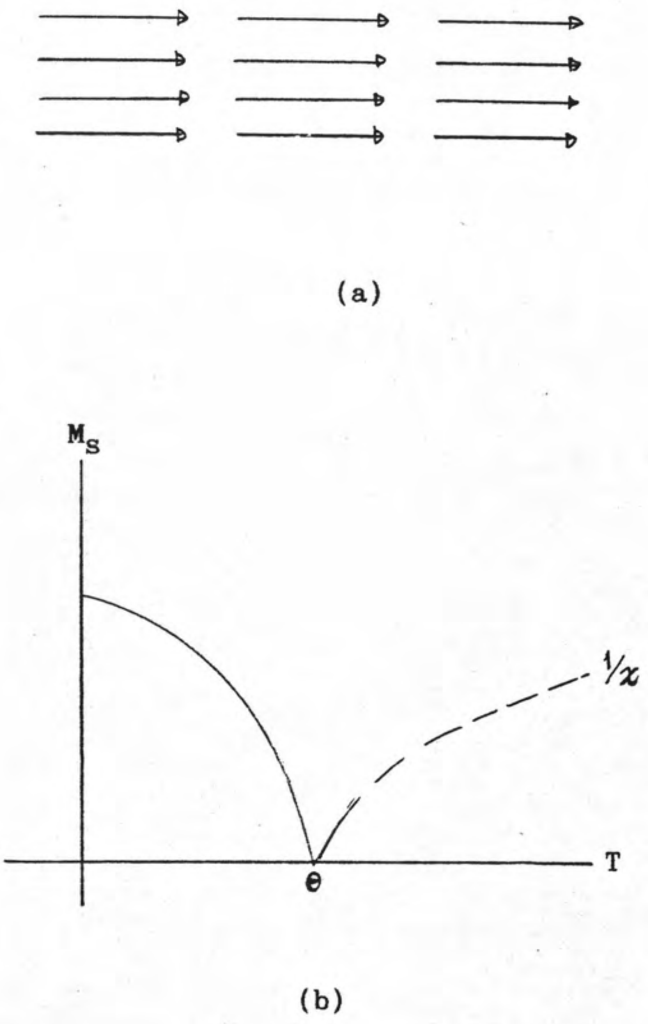
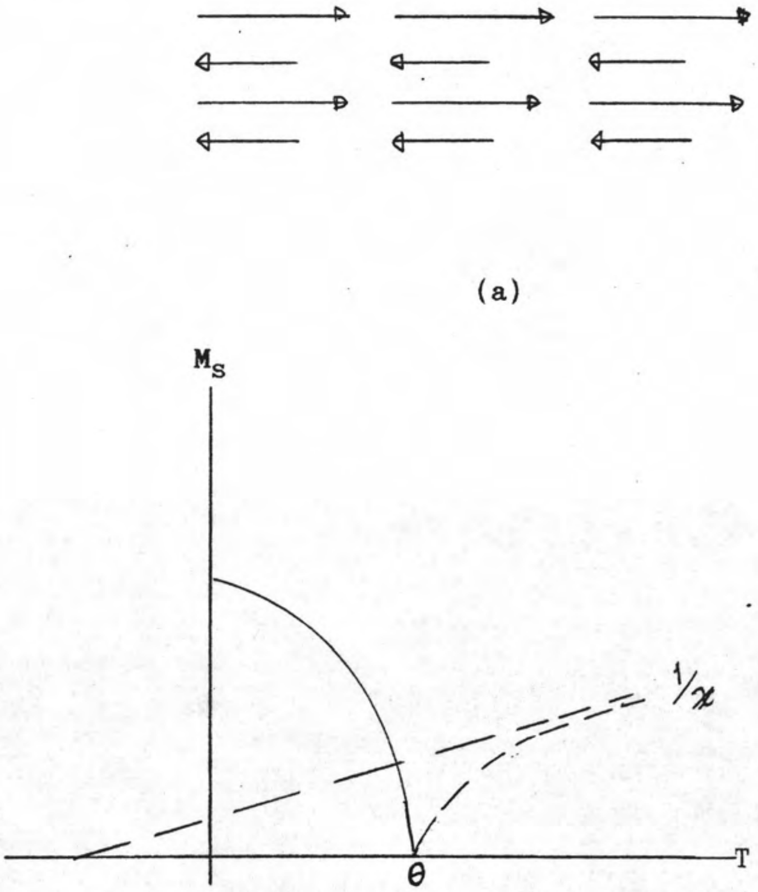


Figure 1.3 Ferromagnetism. (a). Alignment of the magnetic moments in the absence of an applied field. (b). Temperature dependence of $1/\chi$

The inverses susceptibility rises from zero at the Curie temperature and increases linearly with the temperature. Ferromagnetism is usually exhibited by most transition metals, most rare earth metals and oxides such as CrO_2.

1.4 Ferrimagnetism. In these substances magnetic ions occupy two kinds of lattice sites, A and B, and spins on A sites point in the plus direction, while those on B sites point in the minus direction because of a strong negative interaction acting between the two spin systems on A and B. Since the number of magnetic ions and also the magnitude of spins of individual ions are difference on the A and B sites, such an ordered arrangement of spins gives rise to a resultant magnetization. Again as the temperature is increased, the directions of the magnetic moments at sites within each sublattice begin to fluctuate, thus leading to a reduced net magnetization within each sublattice. Since the field produced by each sublattice can induce the magnetic moments in the other sublattices to align in a preferred direction, the temperature at which the magnetization in one sublattice disappears, is also the temperature as which all the magnetization disappears. This temperature is also called the Curie temperature. Above the Curie temperature, the inverse susceptibility varies linearly with T (see Figure 1.4). The extrapolation of the linear T proportion of the inverse susceptibility usually intercepts the $M_s = 0$ axis at a negative temperature (M_s is the spontaneous magnetization).

Many materials are ferrimagnets, the most commonly known is magnetite Fe_3O_4. In this study, we are interested in ferrimagnetism in the garnets.

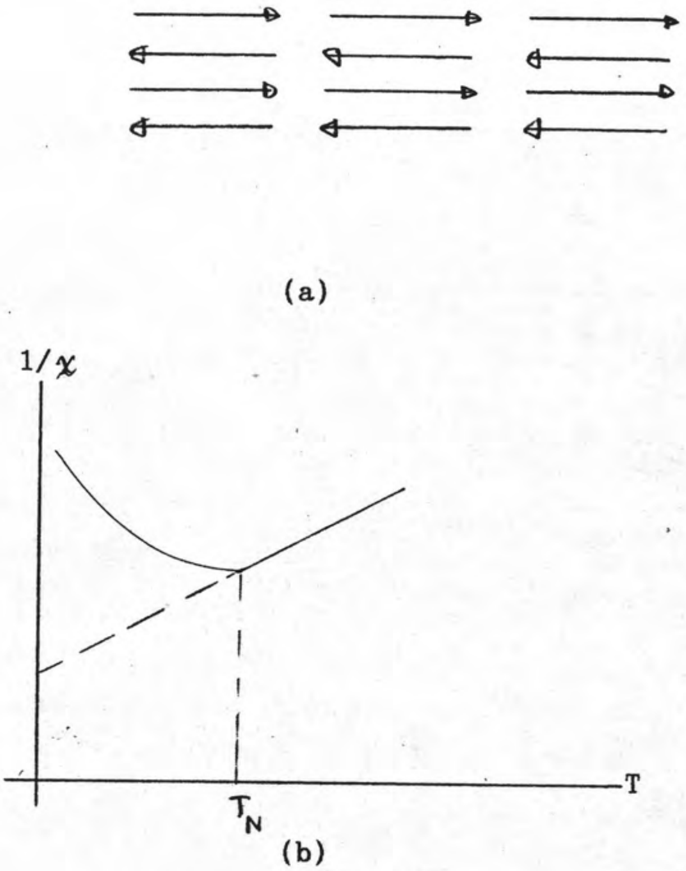


(a)

(b)

Figure 1.4 Ferrimagnetism. (a). The arrangement of the spins in the absence of the magnetic field. (b). Temperature dependence of the inverse susceptibility.

1.5 <u>Antiferromagnetism</u>. Another example of weak magnetism is antiferromagnetism. Like paramagnetism, the magnetic susceptibilities of antiferromagnetic materials are small. The magnetic structures of these materials consists of two or more magnetic sublattices in which the spins within a sublattice are aligned. The susceptibility versus temperature plot exhibits by the occurrence of a kink in the $1/\chi$-T curve at a temperature called the "Néel temperature T_N". Below this temperature, the directions of the aligned spins within one sublattice are opposite to those of the spins on the other sublattice, leading to completely cancel the magnetization (see Figure 1.5).



(a)

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Figure 1.5 (a). The arrangement of the spins in an antiferromagnetic material. (b). The inverse susceptibility versus the temperature of a typical antiferromagnetic material.

Since the tendency of the spins to aligned with an external field is opposed by the strong negative interaction (needed to give rise to the antiparallel alignment of the spins) between the spins, the susceptibility decreases with decreasing temperature. Above the Néel temperature, the spin arrangement tends to be random. The susceptibility therefore decreases with increasing temperature. Examples of antiferromagnetic materials are NiO and FeS.

Of these five groups of magnetic materials, the ferrimagnets are the most commonly used. Among these are the garnets and the ferrites (spinel and hexagonal). In 1909, Wilpert was able to fabricate several ferrites in the laboratory(2). Since these ferrites had high energy losses when they were subjected to an alternating magnetic field, they has little commercial value. In 1946, Snoek of Philips Laboratory (Holland) was able to produce ferrites having strong magnetic properties, high electrical resistivity and low hysteresis loss. These ferrites proves to be of high commercial value and there provided the stimulus to the study of both the experimental and theoretical aspects of the ferrites. 1956 saw the successful fabrication of garnets in the laboratory. These proved to be of even higher commerical value. More recently, hexagonal ferrites having even better commerical values have been fabricated in other laboratory.

We are interested here in the garnet material, in particular the yttrium iron garnets $Y_3Fe_5O_{12}$ (YIG). These magnetic materials have magnetic properties which make them very useful in microwave application and thus are very important commercially. In Chapter II, we review the properties of the yttrium iron garnets, especially their crystal structure. The preparation of polycrystalline samples of these materials will be presented in Chapter III. We will see that the bulk magnetic properties of the garnets are not too sensitive to the fabrication processes the dynamical response properties of the garnets are, however, sensitive to the fabricaton processes. We will see that the X-ray diffraction patterns of the YIG, $Y_3Fe_5O_{12}$, fabricated in this study show the crystal structure to be the same as that listed on the data file of YIG. In Chapter IV, we will study the magnetic hyperfine fields within these materials. The Mössbauer method was used to measure the hyperfine fields.