2.0 **MACROSCOPIC MAGNETIC PROPERTIES OF MATTER**

The macroscopic magnetic properties of matter are due to the following atomic properties:

1. An atom is made up of a number of charged particles in constant motion. Electrons orbit round the nucleus continually whilst within the nucleus protons orbit round each other.
2. These two forms of orbital motion may be considered flowing electric currents. These electric currents generate corresponding magnetic fields.
3. In addition to the orbital motions the charged particles within the atom also rotate (or spin) about their axes. Thus, the electrons, protons and neutrons all spin about their axes. These spin motions may also be regarded as flowing electric currents which generate magnetic fields.
4. The magnetic fields arising from the currents flowing in loops within the atom, nuclei and atomic particles can be described in terms of their corresponding magnetic dipole moments.
5. These small magnetic dipole moments within a material sample can be aligned to produce a strong magnetic field especially in the presence of an external magnetic field e.g. from an electromagnet.
6. The strength of the magnetic field produced, however, depends on how readily the atomic and subatomic dipoles respond to the external magnetic field.
7. Depending on their magnetic response, materials may be put into the following categories:

    i. Diamagnetic Materials
    ii. Paramagnetic Material
    iii. Ferromagnetic Materials

An isolated electron can be viewed classically as a tiny spinning negative charge with *an intrinsic spin angular momentum S.* Associated with this spin angular momentum is intrinsic *magnetic moments* μ_s.
The magnitude of the spin angular momentum, as predicted by quantum theory and as measured in the laboratory, is

$$S = \frac{h}{4\pi} = 5.2729x10^{-35}\, J.s$$

where h is the Planck constant, the central constant of quantum physics.
When we deal with magnetism at the level of the electrons and atoms, we find it convenient to adopt a non-SI unit for measuring magnetic moments. It is called the *Bohr magneton* (μ_B)

$$1\mu_B = \frac{eh}{4\pi m} = 9.27x10^{-24} J/T$$
$$\mu_s = 1.001159652193\mu_B$$
$$\mu_s \approx 1\mu_B$$

in which *e* is the elementary charge, and *m* is the electron mass. Expressed in these units, the magnitude of the spin magnetic moments of the electron is*[1]

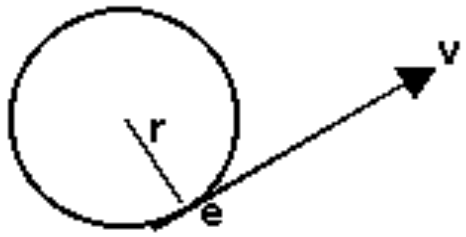
$$\mu_s = 1\mu_B$$

Like essentially all physical properties examined at the atomic level, the orbital magnetic moment of the electron is quantized, being restricted to integral multiples of the Bohr magneton.

2.1 **ATOMIC AND NUCLEAR MAGNETIC MOMENTS**

An electron moving in an orbit around a nucleus produces an average current along its orbit. If the electron has a circular orbit with radius *r* and speed *v*, then the time taken for one complete circular motion is $2\pi r/v$. The charge moved in this time is *e*

Let us consider the simple case of an electron *e* in a circular orbit of radius r around the nucleus with a speed v. The time for one complete cycle (called periodic time T) is given by $T = 2\pi r/v$.



An electron in a circular orbit

Let I = current generated along the orbit, then,

$$I = \text{charge/time} = e/(2\pi r/v) = ev/2\pi r \qquad (2.1)$$

The circulating current I (2.1) will give rise to an orbital magnetic dipole moment μ_m.

[1] The quantum theory of the electron (called *quantum electrodynamics*, or QED) predicts that the 1 front of μ_B should be replaced as 1.001 159 652 193. This remarkable prediction has been verified by equally remarkable experiments. However, for our purpose, 1 will do nicely.

$$\mu_m = I \times (\text{area of orbit})$$

$$= ev/2\pi r \times \pi r^2 = evr/2 \qquad (2.2)$$

Let m_e = mass of the orbiting electron.

If **L** is the angular momentum of the orbiting electron, then

$$\mathbf{L} = m_e v r$$

$$\therefore \mu_m = -(e/2m_e).\mathbf{L} \quad \text{(orbital motion)} \qquad (2.3)$$

μ_m is called the *orbital magnetic dipole moment* and **L** refers to the *orbital angular momentum* of the orbiting electron. The minus sign arises because the orbiting electron carries a negative charge.

The orbital magnetic dipole moment for an orbiting electric charge is thus proportional to the orbital angular momentum.

Equation 2.3 is also valid for periodic orbits and can be obtained using quantum mechanics. The net magnetic moments of the atoms are the sum of the magnetic moments of all its electrons. Hence Eq. 2.3 can also be regarded as a relation between the net orbital angular momentum and the net magnetic moment of the entire atom.

The magnitude of the orbital angular momentum is always some integer multiple of the constant $\hbar = \frac{h}{2\pi}$. Thus, the possible values of the orbital angular momentum are

$$L = 0, \hbar, 2\hbar, 3\hbar, 4\hbar, \ldots\ldots \qquad (2.4)$$

Because angular momentum exists only in discrete packets, it is said to be *quantized*. The constant $\hbar$ is the fundamental quantum of the angular momentum, just as *e* is the quantum of electric charge.

Besides the magnetic moment generated by the orbital motion of the electrons, we must also take into account that generated by the rotational motion of the electrons. An electron may be thought of as a small ball of negative charge rotating about an axis at a fixed rate. This kind of rotational motion again involves circulating charge and gives the electron a magnetic moment. The net magnetic moment of the atom is obtained by combining the *intrinsic orbital* and

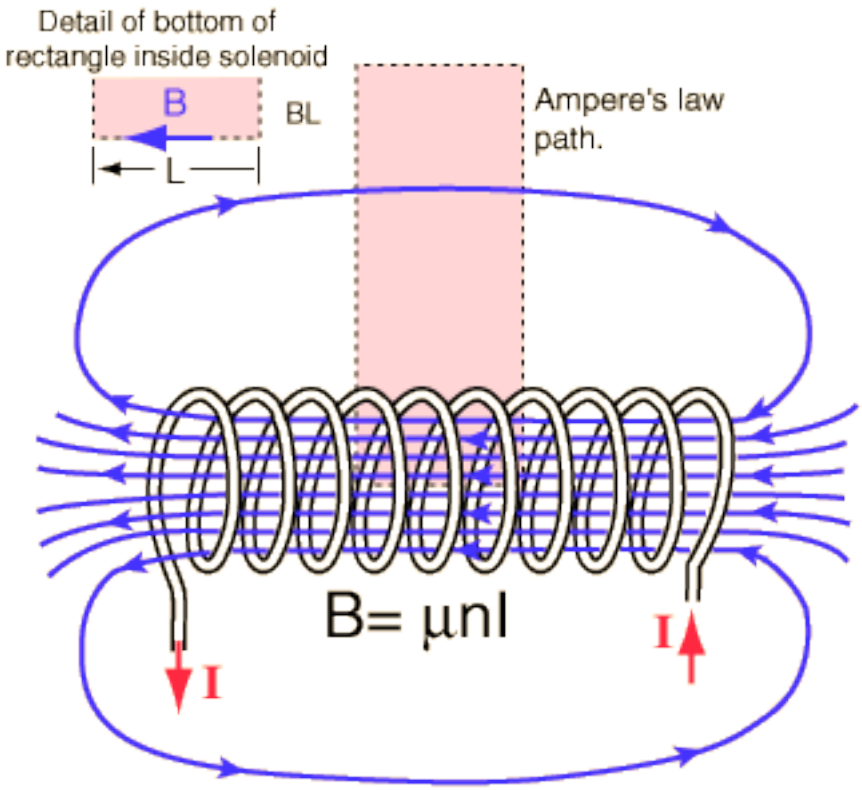
intrinsic spin moments of all the electrons, taking into account the directions of these moments.

The nucleus of the atom also has a magnetic moment. This is due to (i) the orbital motion of the protons inside the nucleus, and (ii) the rotational motion of individual protons and neutrons. The magnetic moment of a proton or neutron is small compared with that of an electron, and in reckoning the total magnetic moment of an atom, the nucleus can usually be neglected.

2.2 CLASSIFICATION OF MAGNETIC MATERIALS

We have already seen that a current I in a loop of wire of cross-sectional area A produces a magnetic dipole

$$\mu = I\,A.$$



The direction of μ is perpendicular to the plane defined by A. A long solenoid is equivalent to N closely spaced identical loops of wire, each having the same current I. Each loop in the solenoid produces an identical magnetic dipole moment $I*A$. The dipole moment is aligned along the axis of the solenoid. Thus, for a solenoid with N turns, the net magnetic dipole moment is

$$\mu = NIA. \qquad (2.5)$$

If the solenoid is placed in a magnetic field, then the solenoid experiences a torque given by

$$\tau = \mu \ x \ B. \qquad (2.6)$$

In a vacuum, the magnetic field inside a long solenoid is

$$B_E = \mu_o nI \qquad (2.7)$$

Where using $n = N/L$.

which may be rewritten as

$$B_E = \frac{\mu_o NIA}{AL}$$

Using Eq. 2.5, we have

$$B_E = \frac{\mu_o \mu}{V} \qquad (2.8)$$

where $V = AL$ is the volume contained within the windings of the solenoid. If N and A are known, a measurement of the current I determines the magnetic moment μ. The magnetic moment changes with changing current. When the inside of the solenoid is filled with a material, a magnetic dipole moment is then induced, the magnetic dipole moment of the also solenoid changes. That is, when the interior of the solenoid is filled with some material, the induced magnetic moments produce an additional contribution to the magnetic moment. This additional contribution may be denoted as μ_i. Thus,

$$B = \frac{\mu_o(\mu + \mu_i)}{V}. \qquad (2.9)$$

It is found experimentally that the induced magnetic moment depends on the current in the solenoid. This dependence can be written as

$$\mu_i = \chi_m \mu \qquad (2.10)$$

where χ_m is the magnetic susceptibility. Depending on the type of material inside the solenoid, χ_m may be constant (at a particular temperature) or may depend on the current *I*. In terms of χ_m, Eq. 2.9 can be written as

$$B = \frac{\mu_o \mu (1 + \chi_m)}{V} \qquad (2.11)$$

where μ is determined from the characteristics of the solenoid and the current in the solenoid. The magnitude of *B* is determined from measurements of magnetic flux. Thus the magnetic susceptibility is determined from the equation

$$\chi_m = \frac{BV}{\mu_o \mu} - 1 \qquad (2.12)$$

The three main classes of magnetic materials can be described in terms of measurements of the magnetic susceptibility.

(a) *Diamagnetic materials* interact weakly with an imposed magnetic field, weaken the existing magnetic field, and have negative values of χ_m. The magnetic susceptibility is essentially independent of temperature and solenoid current.

(b) *Paramagnetic materials* interact weakly with the imposed magnetic field, strengthen the existing magnetic field, and have positive values of χ_m. χ_m depends on temperature and is essentially independent of solenoid current.

(c) *Ferromagnetic materials* interact strongly with an imposed magnetic field, strengthen the existing magnetic field, and have magnetic susceptibilities that depend sensitively on the solenoid current.

Now, $1 + \chi_m$ is the relative permeability and is denoted by κ_m. That is,

$$\kappa_m = 1 + \chi_m. \qquad (2.13)$$

Equation 2.11 then becomes

$$B = \frac{\mu_O \mu \kappa_m}{V}$$

κ_m is called the *permeability*

2.3 DIAMAGNETISM

A change in magnetic field lines threading a current loop causes a current to be induced in the loop. The magnetic flux produced by the induced current always acts to *oppose the change*.

Whenever a material is subjected to a magnetic field, magnetic field lines thread the path of electrons, and the currents and magnetic dipole moments created by the circulating electrons change. These changes oppose the action of the applied magnetic field, and the induced magnetic moments orient oppositely to the applied magnetic field, in accordance with Lenz's law. Thus the induced magnetic moments reduce the strength of the applied magnetic field. In terms of Eq. 2.9, the induced magnetic moment (μ_i) and the magnetic moment due to the current (μ) have opposite directions. From Eq. 2.10, it follows that χ_m is negative. Diamagnetism is a property of all materials, but it is a very weak property and is observed in materials made of atoms that have permanent magnetic dipole moments.

When a diamagnetic material is placed in a magnetic field B, the force experienced by the electron is $-ev \times B$ in addition to the usual electric force within the atom. Assume that the nucleus produces an electric field E. Then the net force on the electron is $-eE - ev \times B$. To keep the electron in a circular orbit of radius r,

$$eE + evB = m_e v^2/r. \tag{2.14}$$

Using $\omega = v/r$, Eq. 2.14 can be written as

$$eE + e\omega rB = m_e \omega^2 r. \tag{2.15}$$

In the absence of the magnetic field,

$$eE = m_e \omega_o^2 r. \tag{2.16}$$

Subtracting Eq. 2.16 from Eq. 2.15, we have

$$e\omega B = m_e(\omega^2 - \omega_o^2). \tag{2.17}$$

The increment of frequency is

$$\Delta\omega = \omega - \omega_o. \qquad (2.18)$$

For small magnetic field, $\Delta\omega$ is small compared with ω_o. Hence

$$\omega^2 - \omega_o^2 = 2\omega_o\Delta\omega + (\Delta\omega)^2 \cong 2\omega_o\Delta\omega. \qquad (2.19)$$

Eq. 2.17 then becomes

$$e\omega B \cong 2m_e\omega_o\,\Delta\omega. \qquad (2.20)$$

ω and ω_o are nearly equal ($\omega \sim \omega_o$). Thus Eq. 2.20 becomes

$$\Delta\omega = eB/2m_e. \qquad (2.21)$$

This frequency is called the *Lamor frequency*; it tells how much faster the electron moves around its orbit as a result of the presence of the magnetic field.

There is a change in the orbital magnetic moment corresponding to the change $\Delta\omega$ in the orbital frequency.

From Eq. 2.2,

$$\mu = evr/2 = er^2\omega_o/2.$$

Hence,

$$\Delta\mu = (er^2/2)\Delta\omega.$$

Thus the fractional change in the magnetic moment is

$$\Delta\mu/\mu = \Delta\omega/\omega_o. \qquad (2.22)$$

Typically, the frequency of an electron in an atom is $\omega_o \cong 10^{16}$ s^{-1}. If the magnetic field is B = 1.5 T, then

$$\Delta\omega = eB/2m_e = 1.6 \times 10^{-19} \times 1.5/(2 \times 9.1 \times 10^{-31})$$

$$= 1.32 \times 10^{11}\ s^{-1}.$$

As a result,

$$\Delta\mu/\mu = \Delta\omega/\omega_o = 1.32 \times 10^{11}/10^{16}$$
$$= 1.32 \times 10^{-5} \cong 10^{-5}.$$

That is, the magnetic moment changes by about 1 part in 10^5. This gives an indication of the small size of the diamagnetic effect.

2.4 PARAMAGNETISM

Magnetism as we know it in our daily experience is an important but special branch of the subject called *ferromagnetism.* Here we discuss a weaker and thus less familiar form of magnetism called Para magnetism.

For most atoms and ions, the magnetic effects of the electrons, including both their spins and orbital motions exactly cancel so that the atom or ion is not magnetic. This is true for the rare gases such neon and for ions such as Cu^+, which makes up ordinary copper.

If we place a sample of *N* atoms, each of which has a magnetic dipole moment μ, in a magnetic field, the elementary atomic dipoles tend to line up with the field. This tendency to align is called *paramagnetism.*

A paramagnetic material is composed of a uniform distribution of atomic magnetic dipoles sufficiently separated so that the magnetic field, of any given dipole does not influence any of its neighbours. In the absence of magnetic field, the dipoles are randomly oriented as a result of thermal motions.

The net magnetic moment of a paramagnetic material is, therefore, zero. However, when an external magnetic field is applied, the dipoles align themselves with the field and produce a net magnetic moment in the material. This alignment is not perfect, because of the disturbance caused by random thermal motions. But even partial alignments of the dipoles have an effect on the magnetic field. The material becomes *magnetized* and contributes an extra magnetic field that *enhances* the original magnetic field. Magnetic alignment can be achieved in two ways: (i) by lowering the temperature of the specimen or (ii) by increasing the applied magnetic field.

How does such an increase of magnetic field come about? Consider a piece of paramagnetic material placed between the poles of an electromagnet. Figure 2.1 shows the alignment of the magnetic dipoles in such a material.

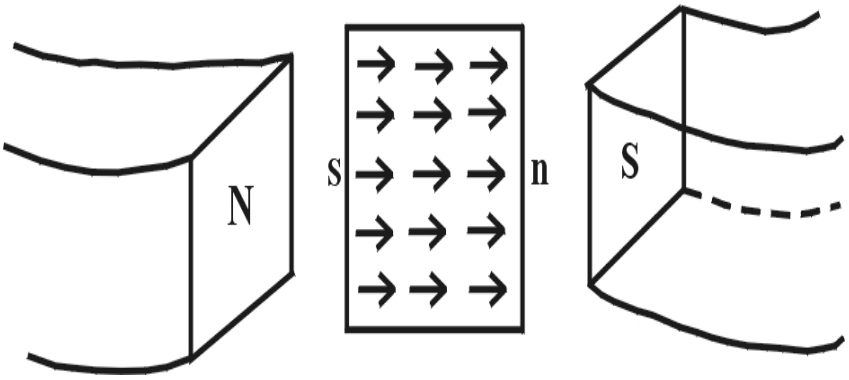


Fig. 2.1: A piece of paramagnetic material in an electromagnet.

For the sake of simplicity, Fig. 2.1 shows a case of perfect alignment. The magnetic dipoles are due to small current loops within the atoms. Figure 2.2a shows the alignment of current loops. Now look at any point inside the material where two of these current loops (almost) touch. The currents at this point are opposite and cancel. Thus, everywhere inside the material, the current is effectively zero. However, at the surface of the material, the current does not cancel. The net result of the alignment current loops is therefore a current running along the surface of the magnetized material (Fig. 2.2). The material consequently behaves like a solenoid; it produces an extra magnetic field in its interior. This extra magnetic field has the *same* direction as the original, external magnetic field. Hence, the total magnetic field in a paramagnetic material is larger than the original magnetic field produced by the currents of the electromagnet.

The alignment of atomic dipole moment in a paramagnetic specimen enhances the magnetic dipole moment, and the magnetic field increases. It follows that χ_m is positive.

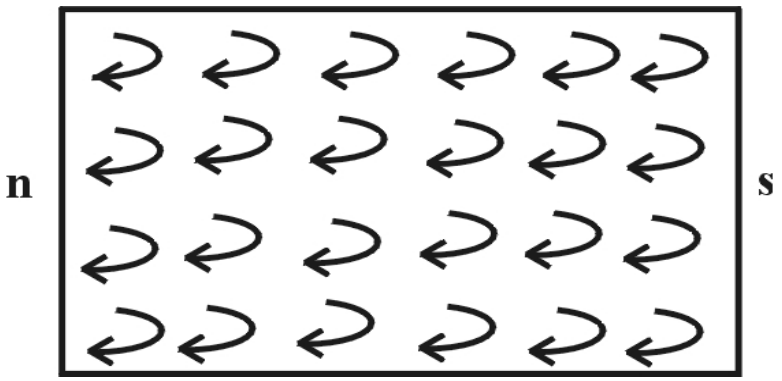


Fig. 2.2: Alignment of current loop.

We can express the extent to which a given specimen of a material is magnetized by dividing its measured magnetic moment by its volume., is called the magnetisation **M** of the sample.

In 1895 Pierre Currie discovered experimentally that the magnetization **M** of a paramagnetic specimen is directly proportional to **B**, the effective magnetic field in which the specimen is placed, and inversely proportional to the kelvin temperature T. In equation form

$$M = C\left(\frac{B}{T}\right) \text{ (Curie's law)}$$

in which C is a constant.

2.5 FERROMAGNETISM

Ferromagnetism is exhibited by five elements - iron (Fe), nickel (Ni), cobalt (Co), dysprosium (Dy), and gadolinium (Gd) - and some alloys, which usually contain one or more of these five elements.
The intense magnetization in ferromagnetic materials is due to a strong alignment of the *spin magnetic moments of electrons*. In these materials, there exists a special force that couples the spins of the electrons in adjacent atoms in the crystal. This force (known as *exchange coupling*) serves to align the atomic dipoles in rigid parallelism, in spite of the randomizing tendency to the thermal motions of the atoms. This is phenomenon, called *ferromagnetism,* is a purely quantum effect and cannot be explained in terms of classical physics.

If the temperature is raised above a certain critical value, called the *Curie temperature*, the exchange coupling ceases to be effective and most such materials become simply paramagnetic.
Ferromagnetism is evidently a property not only of the individual atom or ion but also of the interaction of each atom or ion with its neighbours in the crystal lattice of the solid.

Since spin-spin force is fairly strong, we must ask, why is it that ferromagnetic materials are ever found in none magnetized state? Why is it that not every piece of iron is a permanent magnet? The answer is that, on a small scale, ferromagnetic materials are always magnetized. There are regions in every ferromagnetic specimen that have near perfect alignment of magnetic dipole moments even when there is no applied magnetic field. These regions are called *magnetic domains*. The direction of alignment of the dipoles varies from one domain to the next (Fig. 2.3). For the crystal as a whole, however, the domains are so oriented that they largely cancel each other as far as their external magnetic effects are concerned.

The formation of domains results from the tendency of the material to settle into a state of least energy (equilibrium state). The state of least energy for the spins would be a state of complete alignment. But such a complete alignment would generate a large magnetic field around the material. Energetically, this is an unstable configuration. The domain arrangement is a compromise - the magnetic energy is then small because there is little magnetic field and the spin-spin energy is then also reasonably small because *most* adjacent spins are aligned.

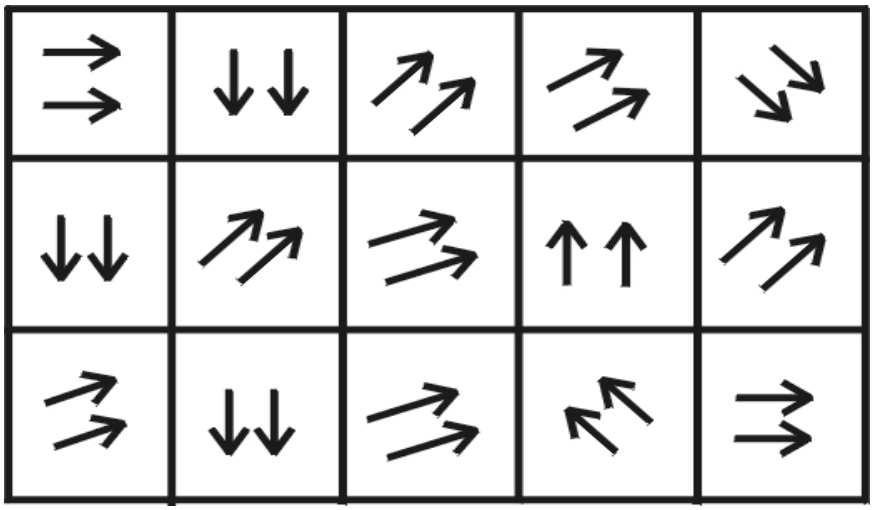


Fig. 2.3: Magnetic domains in a ferromagnetic material.

However, if the material is immersed in an external magnetic field, all dipoles tend to align along this field. The domains then change in two ways:

1. Those domains with magnetic dipole moments parallel to the magnetic field grow at the expense of the neighbouring domains (Fig. 2.3). This effect is responsible for producing a net magnetic dipole moment in a weak applied magnetic field.
2. The magnetic dipole moments of the domains rotate toward alignment with the applied magnetic field. This is the mechanism of magnetic dipole alignment when the applied magnetic field is strong.

If all the magnetic dipoles in a piece of ferromagnetic material align, their contribution to the magnetic field will be very large.

Hysteresis loop

When a ferromagnetic material is magnetized in one direction, it will not relax back to zero magnetization when the imposed magnetizing field is removed. It must be driven back to zero by a field in the opposite direction. If an alternating magnetic field is applied to the material, its magnetization will trace out a loop called a hysteresis loop see figure below. The lack of retraceability of the magnetization curve is the property called hysteresis and it is related to the existence of magnetic domains in the material. Once the magnetic domains are reoriented, it takes some energy to turn them back again. This property of ferromagnetic materials is useful as magnetic "memory".

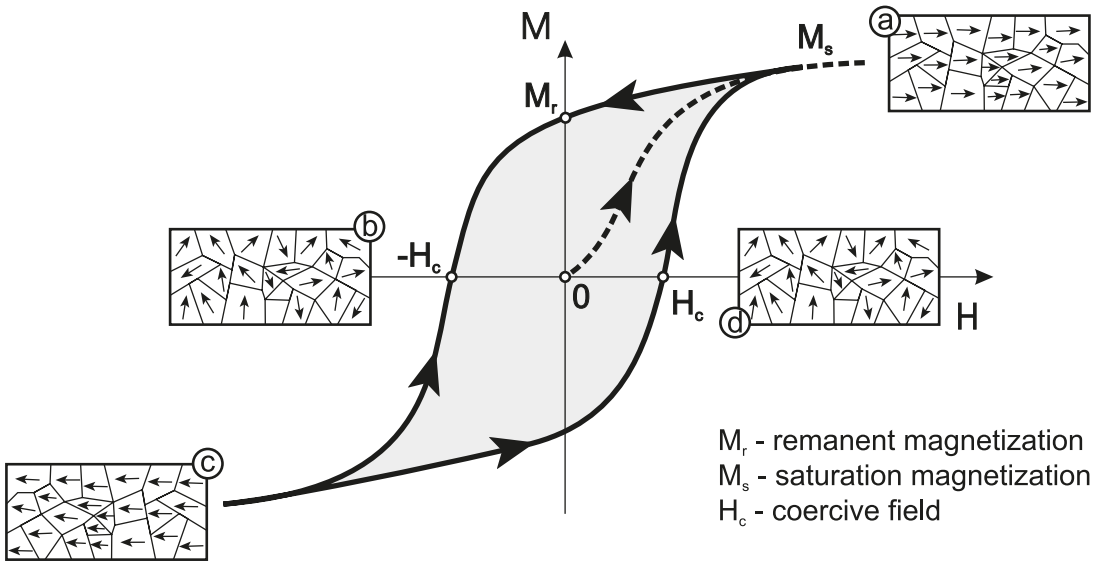


Fig. 2.4: The magnetization 'M' vrs magnetic field strength 'H' for a ferromagnetic:

(a)Starting at zero the material follow at first non-linear magnetization curve and reaches the saturation level, when all the magnetic domains are aligned with the direction of a field; when afterwards driving magnetic field drops to zero, the ferromagnetic material retains a considerable degree of magnetization or "remember" the previous state of magnetization;
(b) at this point, when H= 0 a ferromagnet is not fully demagnetized and only the partial domain reorientation happened;
(c) saturation level in the opposite direction of applied field;
(d) in order to demagnetize a ferromagnetic material the strong magnetic field of the opposite direction (called "coercive field, H_c")has to be applied.

At a critical value *H*, called the *coercive force (H_c)*, the magnetic field is zero. The larger the coercive force, the more difficult it is to demagnetize a ferromagnetic specimen. *Ferromagnetic materials having a large coercive force are said to be magnetically "hard", those having a small coercive force are said to be magnetically "soft"*. Ordinary iron is magnetically soft and has a coercive force of about 10^{-4} T. A hard magnetic material used in the speaker of a high-fidelity system may have a coercive force 20-50 times that of ordinary iron.

As a ferromagnetic specimen is cycled around a hysteresis loop, irreversible changes occur in its domain structure. The magnetizing field does work in order to alter the domains, and the temperature of the specimen increases. The greater the hysteresis loop, the greater the amount of work required and the larger the temperature rise in the specimen.

Many practical electromagnetic devices utilize one or more coils of wire wound around a ferromagnetic medium. The current in the coil often varies cyclically in

direction and magnitude. This means that the ferromagnetic medium is continually cycled through a hysteresis loop; energy is lost in each cycle. In order to minimize the energy loss, materials having a small loop area are used. This condition is generally satisfied by soft materials. Iron is magnetically soft and is widely used in electromagnetic devices such as transformers. New alloys with superior magnetic properties have been developed.

Some compositions of ferromagnetic materials will retain an imposed magnetization indefinitely and are useful s permanent magnets. The magnetic memory aspects of iron and chromium oxides make them useful in audio tape recording and for the magnetic storage of data on computer disk.

Magnetically hard materials are used as permanent magnets. For example, magnets in stereo speakers, magnets in some types of electric motors, and magnets in mechanical ammeters and voltmeters are made from "hard" materials. Some alloys, which consist mostly of nickel, iron, cobalt and aluminium, also make good permanent magnets. "Hard" materials are characterized by broad hysteresis loops. They are hard to magnetize and hard to demagnetize.

2.6 FERRIMAGNETISM

A **ferrimagnetic** material is one in which the magnetic moments of the atoms on different sublattices are opposed, as in anti-ferromagnetism; however, in ferrimagnetic materials, the opposing moments are unequal and a spontaneous magnetization remains. This happens when the sublattices consist of different materials or ions (such as Fe^{2+} and Fe^{3+}).

Ferrimagnetism is exhibited by ferrites and magnetic garnets. The oldest-known magnetic substance, magnetite (iron(II,III) oxide; Fe_3O_4), is a ferrimagnet; it was originally classified as a ferromagnet before Néel's discovery of ferrimagnetism and antiferromagnetism in 1948 [1].

Some ferrimagnetic materials are YIG (yttrium iron garnet) and ferrites composed of iron oxides and other elements such as aluminum, cobalt, nickel, manganese and zinc.

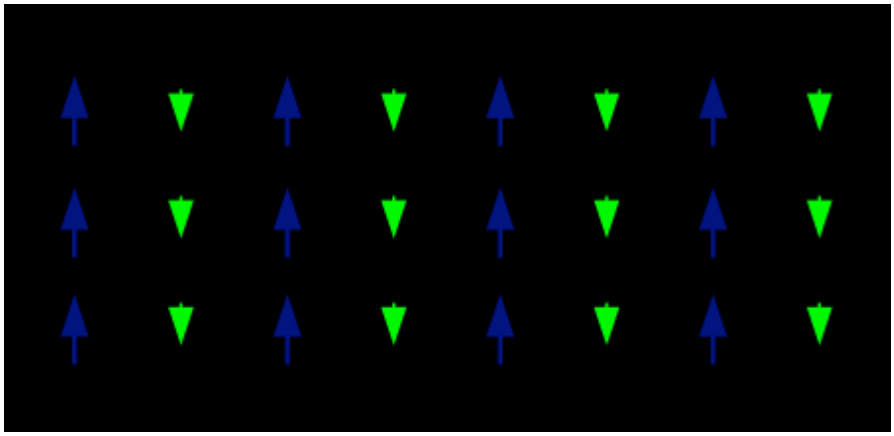


Fig. 2.5 Illustration of Ferrimagnetism

Effects of temperature

Ferrimagnetic materials are like ferromagnets in that they hold a spontaneous magnetization below the Curie temperature, and show no magnetic order (are paramagnetic) above this temperature. However, there is sometimes a temperature *below* the Curie temperature at which the two sublattices have equal moments, resulting in a net magnetic moment of zero; this is called the *magnetization compensation point*. This compensation point is observed easily in garnets and rare earth - transition metal alloys (RE-TM). Furthermore, ferrimagnets may also exhibit an *angular momentum compensation point* at which the angular momentum of the magnetic sublattices is compensated. This compensation point is a crucial point for achieving high speed magnetization reversal in magnetic memory devices

Properties

Ferrimagnetic materials have high resistivity and have anisotropic properties. The anisotropy is actually induced by an external applied field. When this applied field aligns with the magnetic dipoles it causes a net magnetic dipole moment to precess at a frequency controlled by the applied field, called *Larmor* or *precession frequency*. As a particular example, a microwave signal circularly polarized in the same direction as this precession strongly interacts with the magnetic dipole moments; when it is polarized in the opposite direction the interaction is very low. When the interaction is strong, the microwave signal can pass through the material. This directional property is used in the construction of microwave devices like isolators, circulators and gyrators. Ferrimagnetic materials are also used to produce optical insolators and circulators.