University of Babylon
College of Material Engineering
Department of Methlogical Engineering

Class: 3^{rd}

Subject: Electronic and Magnetic Materials

Lecturer: Magnetic Materials

Lecturer: Dr. Qabas Khalid Naji

Magnetism

This comprises those physical phenomena involving magnetic fields and their effects upon materials.

- Magnetic fields may be set up on a macroscopic scale by electric currents or by magnets. On atomic scale, individual atoms cause magnetic fields when their electrons have a net magnetic moment as a result of their angular momentum.
- A magnetic moment arises whenever a charged particle has an angular momentum. It is the cooperative effect of the atomic magnetic moments which causes the macroscopic magnetic field of a permanent magnet. However, the underlying principles and mechanisms that explain the magnetic phenomenon are complex and subtle, and their understanding has eluded physicists until relatively recent times.

- Several of our modern technological devices rely on magnetism and magnetic materials; these include electric motors, electric power generators and transformers, components of sound and video reproduction systems, telephones, radio, television, computers, etc. Well known examples of magnetic materials which exhibit magnetic properties are: iron, some steels and the naturally occurring mineral lodestone.

The important facts about the magnetic materials are:

1. There are some materials which exhibit magnetic properties even without the application of any magnetic field and become more magnetic when a weak magnetic field is applied to them.

2. There are many other materials which lose their initially strong magnetism when heated above a certain critical temperature and become comparatively weakly magnetised.

3. There are some materials which show a magnetic response in a direction opposite to that of any externally applied field.

Magnetic materials:

are all media capable of being magnetized in a magnetic field, i.e. of creating their own magnetic field. According to their magnetic properties, such materials are divided into three principal groups: diamagnetic, paramagnetic and ferromagnetic materials. From the applications point of view all the magnetic materials can be placed under two groups:

(i)Soft

(ii)Hard magnetic materials.

Iron, some steels, and the naturally occurring mineral lodestone are well-known examples of materials which exhibit magnetism. Ferro and ferrimagnetic materials are the most important magnetic materials from the point of view of practical applications. We will first consider the terms and definitions used in magnetism.

Terminology

(i) Magnetic Induction or Magnetic Flux Density (B): In the presence of magnetic field in vacuum, the magnetic induction (B) is related to the field strength H (in units of A–m^{-1}) as follows:

$$B = \mu_o H \qquad (30)$$

where μ_o is called the *permeability of free space*. B is expressed in units of *tesla* or Weber per square metre. The units of permeability are

$$\mu_o = \frac{B}{H} = \frac{\text{Wb} - \text{m}^2}{\text{A} - \text{m}^{-1}} \qquad (\because\ \text{Wb} - \text{m}^2 = \text{NA}^{-1}\text{m}^{-1})$$

$$= H - m^{-1}\ (\text{H} = \text{Wb} - \text{A}^{-1} \text{ where H} \rightarrow \text{Henry})$$

In SI units, the permeability of free space (μ_o) has a value of $4\pi \times 10^{-7}$ H-m^{-1}.

(ii) Magnetic Field (H): It is said to occupy a region when the magnetic effect of an electric current or of a magnet upon a small test magnet which is brought in the vicinity is detectable. Magnetic field strength is denoted by *H*. When a magnetic material is placed in a magnetic field *H*, it becomes magnetized, i.e., it becomes itself a magnet. Magnetic field strength (*H*) is expressed in units of A-m^{-1}.

It the magnetic field is applied to a solid medium, the magnetic induction in the solid is given by a relationship

$$B = \mu \mathrm{H} \tag{31}$$

where μ is the permeability of the solid material through which the magnetic lines of force pass. In general μ is not equal to μ_0. The ratio μ/μ_0 is the relative permeability of the medium and designated by μ_r. Mathematically,

$$\mu_r = \frac{\mu}{\mu_0} \tag{32}$$

(iii) Magnetization: This may be defined as the process of converting a non-magnetic bar into a magnetic bar. This term is almost analogous to the polarization in dielectric materials. The flux density

$$B = \mu H = \mu_0 \mu_r H$$

$$= \mu_0 \mu_r H + \mu_0 H - \mu_0 H$$

$$= \mu_0 H + \mu_0 H (\mu_r - 1) \quad (33)$$

$$= \mu_0 H + \mu_0 M$$

$$= \mu_0 (H + M) \quad (34)$$

where $M = \mu_0 (H + M)$ is called the magnetization of solid and expressed in ampere/metre. From the above relation, we find that if a magnetic field is applied to a material, the magnetic flux density is equal to the effect on vacuum and on the material. The magnetization (M) may thus be defined as the magnetic dipole moment per unit volume of the bar.

(iv) Magnetic Susceptibility (χ): The magnitude of the magnetization, M is proportional to the applied field as follows:

$$M = \chi H \tag{35}$$

where χ is called the magnetic susceptibility, which is *unitless*. The magnetic susceptibility and the relative permeability are related as follows:

$$\chi = \mu_r - 1 = M/H \tag{36}$$

We may note that B, M and H are vectors. Magnetic units and conversion factors for SI and CGS – emu systems are given in Table 14.8. We may note that magnetic units may be a source of confusion because there are really two systems in common use. The ones used thus far are SI [rationalized MKS (metre-kilogram-second)]; the others come from the CGS-emu (centimetre-gram-second-electromagnetic unit) system.

Table : magnetic units and conversion factors for the SI, CGS, emu systems.

Quantity	Symbol	SI units: Derived	SI units: Primary	CGS-emu unit	Conversion
• Magnetic induction (flux density)	B	tesla (Wb/m^2)	kg/s–C	gauss	$1 \frac{Wb}{m^3} = 10^4$ gauss
• Magnetic Field Strength	H	$\frac{amp-turn}{m}$	C/m–s	oersted	$\frac{1\ amp-turn}{n} = 4\pi \times 10^{-3}$ oersted
• Magnetization	M (SI) I (CGS – emu)	$\frac{amp-turn}{m}$	C/m–s	$maxwell/cm^2$	$\frac{1\ amp-turn}{m} = 10^{-3}$ $maxwell/cm^2$
• Permeability of a vacuum	μ_o	henry/m	$kg–m/C^2$	unitless	$4\pi \times 10^{-7}$ henry/m = 1emu
• Relative permeability	μ_r (SI) μ'(CGS-emu)	unitless	unitless	unitless	$\mu_r = \mu'$
• Susceptibility	χ (SI) χ' (CGS-emu)	unitless	unitless	unitless	$\chi = 4\pi\chi'$

Note: units of Weber (Wb) are volt-seconds, units of heary are Webers per ampere *(v) Magnetic Dipoles:* Magnetism is *dipolar*, i.e. magnetism is characterized by having two opposite poles: north (N) and south (S). Magnetic dipoles are found to exist in magnetic materials, which, in some respects are analogous to electric dipoles. The strength of a magnetic dipole is measured by the product of the pole strength and the distance between the poles. This is called *magnetic moment*. Magnetic dipoles are influenced by magnetic fields and within a magnetic field, the force of the field itself exerts a torque that tends to orient the dipoles with the magnetic field. One source of magnetism in an atom is the orbital motion of electrons. Each electron revolving around the nucleus in a atom constitutes a circulating electric charge or current and thus produces a small magnetic field. Moreover, each spinning electron on its axis also can be conceived as a circulating charge and also produced a small magnetic fields. Many times it is convenient to think of magnetic forces in terms of fields. Imaginary lines of force may be drawn to indicate the direction of the force at positions in the vicinity of the field source.

Origins of Magnetic Moments

The macroscopic magnetic properties of a substance are a consequence of magnetic moments associated with individual electrons. Each electron in an atom has magnetic moments that originate from the following two sources:

(i) orbital magnetic moment of electrons

(ii) spin magnetic moment of electrons.

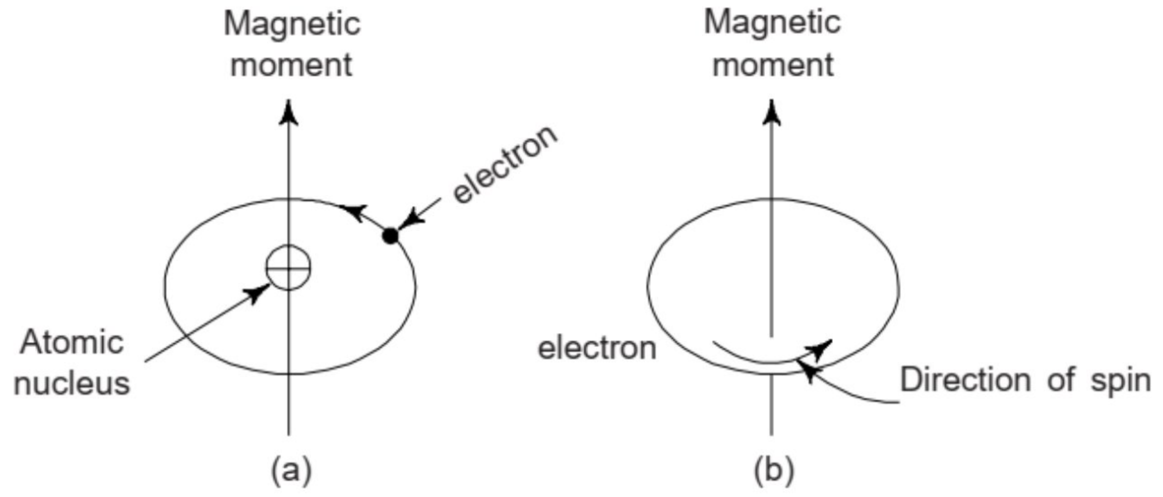

Fig. 14.17 Magnetic moment associated with (a) an orbiting electron and (b) a spining electron

We may note that permanent magnetic moments can also arise from spin magnetic moment of the nucleus. Of the three, spin dipole moments of electrons are important in most magnetic materials. Magnetic moments associated with (a) an orbiting electron and (b) a spinning electron is shown in Fig. 14.17. Electron in an atom is continuously orbiting around the nucleus; being a moving charge, an electron may be considered to be a small current loop, generating a very small magnetic field, and having a magnetic moment along its axis of rotation (Fig. 14.17(a)). Moreover, each electron may also be thought of as spinning around an axis; the other magnetic moment originates from this electron spin which is directed along the spin axis as shown in Fig. 14.17(b).

We may note that spin magnetic moments may be only in an “up” direction or in an antiparallel “down” direction. Obviously, each electron in an atom may be thought of as being a small magnet having permanent orbital and spin magnetic moments. The net magnetic moment due to electron spin in a sodium atom is one unit, called a Bohr magneton $\mu\text{-}B$, which is of magnitude 9.27×10^{-24}A-m^2. For each electron in an atom the spin magnetic moment is $\pm\ \mu\text{-}B$(+sign for spin up and–sign for spin down). The orbital magnetic moment contribution is equal to $m\text{-}l\ \ \mu\text{-}B$, $m\text{-}l$ being the magnetic quantum number of the electron.

Classification of Magnetic Materials

There are three classes into which all the magnetic materials may be grouped according to their magnetic behaviour, although there is some overlap among groups:

1. Diamagnetic substances (Fig. 14.18a)
2. Paramagnetic substances (Fig. 14.18b)
3. Ferromagnetic substances (Fig. 14.18c)

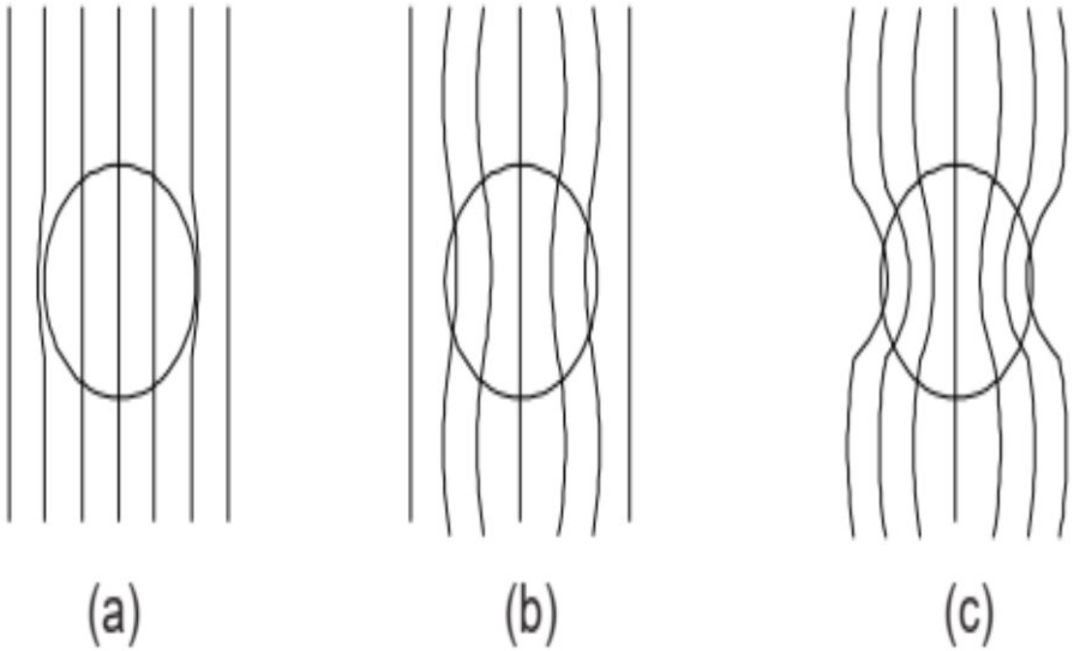

Fig. 14.18 (a) Diamagnetic solid: Lines of forces are slightly repulsed. Relative permeability is less than 1 (b) Paramagnetic solid: Lines of forces are attracted weakely. Relative permeability is slightly greater than 1. (c) Ferromagnetic solid: Lines of forces are attracted very strongly. Relative permeability is much greater than 1

1. Diamagnetism

Diamagnetism is a very weak form of magnetism exhibited by substances with a negative magnetic susceptibility ($X= \mu°$ M/B), i.e., by substances which magnetize in a direction opposite to that of an applied magnetic field. A diamagnetic substance has a magnetic permeability less than 1, and is repelled when placed near a magnet. The examples are organic solids like naphthalene, benzene, etc.; metals like silver, gold and copper; atoms with rare gas configurations like, A, He, Ne, etc. The magnetization of diamagnetic substances is associated with the currents induced on application of a magnetic field. According to Lenz's law, the flow of an induced current is in such a direction as to oppose the change of flux of inducing field; this accounts for the negative susceptibility.

The diamagnetic susceptibility is invariably small, of the order of $10^{-5}\ cm^2$ /mole.

When placed between the poles of a strong electromagnet, diamagnetic materials are attracted toward regions where the field is weak. The atomic magnetic dipole configuration for a diamagnetic material with and without an external field is shown in Fig. 14.19. The arrows in the figure represent atomic dipole moments. Figure 14.20 shows the dependence of B on the external field H for a material which exhibits diamagnetic behaviour. Susceptibilities of several diamagnetic materials are given in Table 14.9.

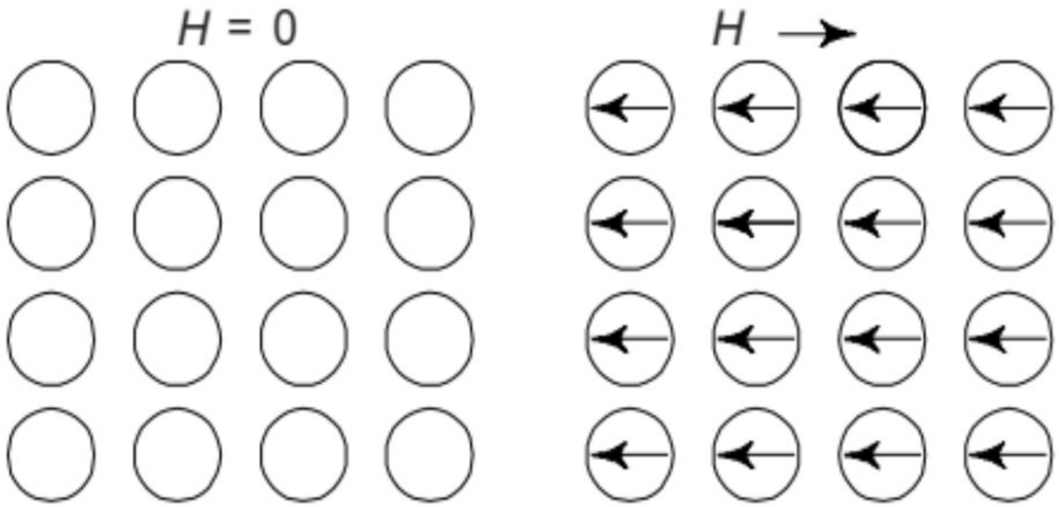

Fig. 14. 19 **Schematic illustration of the atomic dipole configuratin for a diamagnetic material with and without a magnetic field. No dipoles exists in the absence of an external field, whereas in the presence of a field, dipoles are induced that are aligned opposite to the field direction**

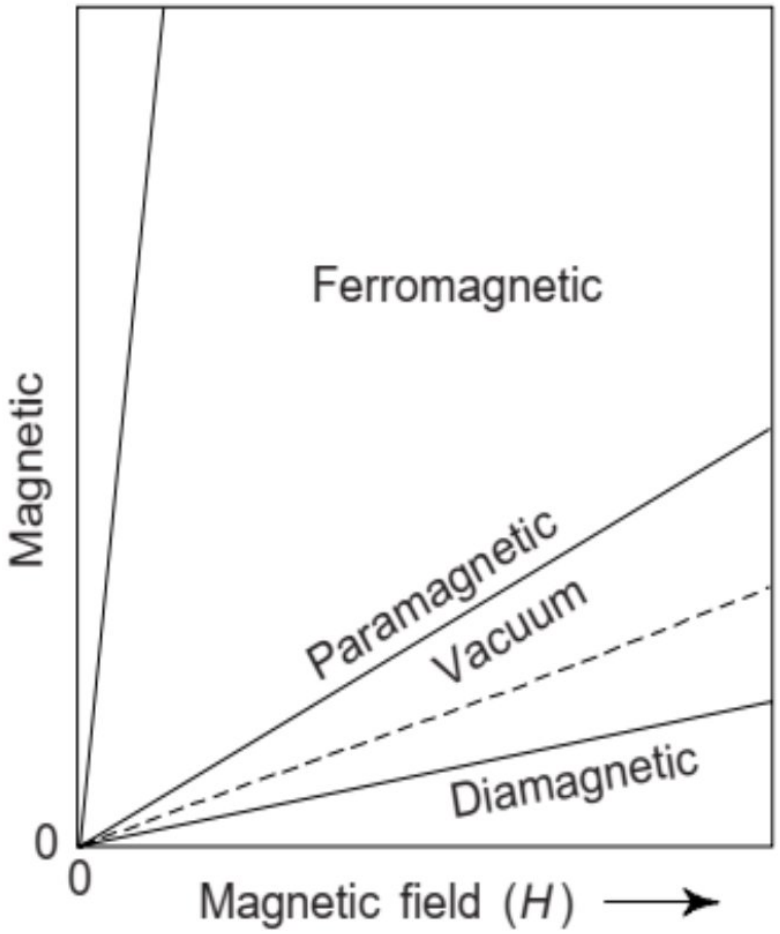

Fig. 14.20

Table 14.9 Magnetic susceptibilities for diamagnetic materials at room temperature

Material	*Susceptibility, χ (volume) (SI units)*
Copper	-0.96×10^{-5}
Gold	-3.44×10^{-5}
Mercury	-2.85×10^{-5}
Silicon	-0.41×10^{-5}
Silver	-2.38×10^{-5}
Zinc	-1.56×10^{-5}
Aluminium oxide	-1.81×10^{-5}
Sodium Chloride	-1.41×10^{-5}

2. Paramagnetism

A property exhibited by substances which, when placed in a magnetic field, are magnetized parallel to the field to an extent proportional to the field (except at very low temperatures or in extremely large magnetic fields).

Paramagnetic materials always have permeabilities greater than 1, but the values are in general not nearly so great as those of ferromagnetic materials. For some solid materials, each atom possesses a permanent dipole moment by virtue of incomplete cancellation of electron spin and/or orbital magnetic moments. In the absence of an external magnetic field, the orientations of these atomic magnetic moments are random, such that a piece of material possesses no net macroscopic magnetization. These atomic dipoles are free to rotate, and paramagnetism results when they preferentially align, by rotation, with an external field as illustrated in Fig. 14.21.

These magnetic dipoles are acted on individually with no mutual interaction between adjacent dipoles. In as much as the dipole align with the external field, they enhance it, giving rise to a relative permeability μr that is greater than 1, and to a relatively small and positive susceptibility. Susceptibilities for few paramagnetic substances are given in Table 14.10. Susceptibilities for paramagnetic substances range from about 10^{-5} to 10^{-2}. A schematic B-H curve for a paramagnetic substance is also shown in Fig. 14.20.

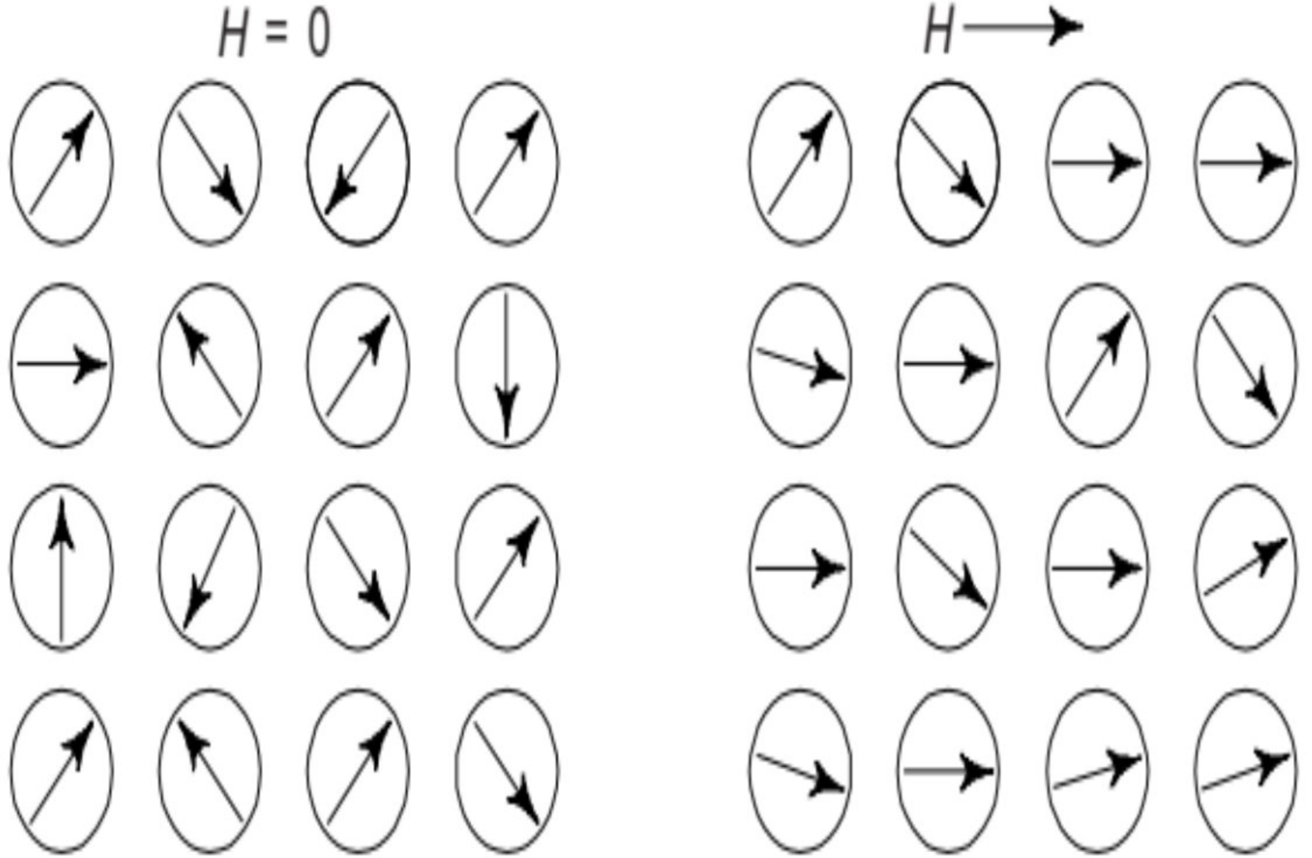

Fig. 14.21 **Atomic dipole configuration with and without an external magnetic field for a paramagnetic material**

Table 14.10 Magnetic susceptibilities for paramagnetic materials at room temperature

Materials	*Susceptibility χ (volume) (SI units)*
Aluminium	2.07×10^{-5}
Chromium	3.13×10^{-4}
Chromium chloride	1.51×10^{-3}
Manganese sulphate	3.70×10^{-3}
Molybdenum	1.19×10^{-4}
Sodium	8.48×10^{-6}
Titanium	1.81×10^{-4}
Zirconium	1.09×10^{-4}

The following types of substances are paramagnetic:

1. All atoms and molecules which have an odd number of electrons. According to quantum mechanics, such a system cannot have a total spin equal to zero; therefore, each atom or molecule has a net magnetic moment which arises from the electron spin angular momentum. Examples are organic free radicals and gaseous nitric oxide.
2. All free atoms and ions with unfilled inner electron shells and many of these ions when in solids or in solution. Examples are transition, rare-earth and actinide elements and many of their salts. This includes ferromagnetic and antiferromagnetic materials above their transition temperatures.
3. Several miscellaneous compounds including molecular oxygen and organic biradicals.
4. Metals, in this case, the paramagnetism arises from the magnetic moments associated with the spins of the conduction electrons and is called the Pauli paramagnetism.

Relatively few substances are paramagnetic. Aside from the Pauli paramagnetism found in metals, the most important paramagnetic effects are found in the compounds of the transition and rare-earth elements which have practically filled 3*d* and 4*f* electron shells respectively.

Most paramagnetic substances at room temperature have a static susceptibility which follows a Langevin-Deby law (Eq. (37)),

$$\chi = \frac{Np^2\,\mu_B^2}{3kT + N\alpha} \tag{37}$$

where N is the number of magnetic dipoles per unit volume, p is the effective magneton dipoles per μ_B is the Bohr magneton, k is Boltzmann's constant, T is absolute temperature and α is the temperature independent contribution of Van-Vleck paramagnetism.

Both paramagnetic and diamagnetic substances are considered to be non magnetic because they exhibit magnetization only in the presence of an external field. Moreover, for both, the flux density B within them is almost the same as it would be in vacuum.

3. Ferromagnetism

A property exhibited by certain metals, alloys and compounds of the transition (iron groups as BCC α ferrite and cobalt and nickel), rare earth metals such as gaddolinium (Gd), and actinide elements in which, below a certain temperature called the Curie temperature (Eq. 38),

$$T_c = \frac{C}{T-\theta}$$

We must note that the general behaviour of the susceptibility of ferromagnetic materials above the Curie temperature, TC , follows the Curie-Weiss law (Eq. (38)). The behaviour is followed in the region well above the ferromagnetic curie temperature TC . The paramagnetic curie temperature θ is usually slightly greater than the temperature of transition TC . Comparison of TC and for three ferromagnetic metal is given below comparison of θ and Tc.

Comparison of θ and T_c

Parameter	*Fe*	*Co*	*Ni*
θ(K)	1093	1428	650
T_c(K)	1043	1393	631

In a region just a fraction of degree above the "critical point", or Curie temperature T_c, the susceptibility is found to approximate the following relation,

$$\chi = \frac{C'}{(T - T_c)^{\gamma}}$$

Table 14.10 Some selected physical properties of ferromagnetic elements

Element	*Electronic configuration*	*Crystal structure*	*Magnetization at 0 K (Amp/m)*	*Ferromagnetic curie temp. T_c (K)*	*Melting temp. (K)*
Fe	$3d^6\ 4s^2$	bcc	1.7×10^6	1043	1810
Co	$3d^7\ 4s^2$	hcp	1.4×10^6	1404	1750
Ni	$3d^8\ 4s^2$	fcc	0.48×10^6	632	1732
Gd	$4f^7\ 5d^1\ 6s^2$	hcp	5.66×10^6	290	1586

Problems:

Example 6 *The saturation magnetization of BCC Iron is 1750 kA/m. Show that the net magnetic moment per iron atom in the crystal is 2.2. Given lattice parameter of BCC iron = 2.87Å* [B.E., M.Sc.(M.S.)]

Solution Volume of unit cell of BCC iron = $(2.87)^3 \times 10^{-30}$ m^3

Number of atoms in the unit cell = 2

$\therefore$ Net magnetic moment per atom $= 1750 \times 1000 \times (2.87)^3 \times 10^{-30} \times 1/2$

$= 2.068 \times 10^{-23}$ A-m^2

$$\text{The magnetic moment (in units of } \mu_B) = \frac{2.068 \times 10^{-23}}{9.273 \times 10^{-24}} = 2.2$$

Example 7 *The density of nickel is* 8.90×10^3 *kg/m*^{3}*. Avogadro's number* $N_A = 6.023 \times 10^{23}$ *atoms/mol. Atomic weight of Ni is 58.71 gm/mol. Calculate (i) the saturation magnetization (ii) the saturation flux density.* [B.E., Diploma]

Solution

(i) $M_s = 0.60\ \mu_B N$

$$\text{and } N \text{ (number of atoms/m}^3) = \frac{\rho N_A}{A}$$

$$= \frac{8.90 \times 10^6 \text{ gm/m}^3 \times 6.023 \times 10^{23} \text{ atoms/mol}}{58.71 \text{ gm/mol}}$$

$$= 9.13 \times 10^{28} \text{ atoms/m}^3$$

$$\therefore \quad M_s = \left(\frac{0.60 \text{ Bohr magneton}}{\text{atom}}\right)\left(\frac{9.27 \times 10^{-24} \text{ A-m}^2}{\text{Bohr magneton}}\right)\left(\frac{9.13 \times 10^{28} \text{ atoms}}{\text{m}^3}\right)$$

$$= 5.1 \times 10^5 \text{ A/m}$$

(ii) Saturation flux density,

$$B_s = \mu_o M_s$$

$$= \left(\frac{4\pi \times 10^{-7}\ H}{m}\right)\left(5.1 \times 10^5\ \frac{A}{m}\right)$$

$$= 0.64 \text{ tesla.}$$

Thank you