PYL 102

Thursday, Oct. 24, 2024

Magnetic properties of solids

All materials are magnetic. This means that every material responds to an externally applied magnetic field in a specific manner. The origin of magnetism lies in a fact that a moving charge produces a magnetic field. There are two types of electron motions, namely spin and orbital.

A charged particle rotating in an orbit creates a magnetic moment (μ), which is given by

$$\boxed{\mu = \frac{qL}{2m}}$$

In this equation, *q* is the charge, *L* is the angular momentum, and *m* is the mass of the charged particle. The angular momentum of an electron is quantized.

$$\boxed{L = \frac{nh}{2\pi}}$$

Basic unit of magnetic moment is known as a *Bohr magneton* (μ_B)

$$\mu_B = \frac{\hbar e}{2m} = 9.27 \times 10^{-24}\ A\,m^{-2}$$

The total magnetic dipole moment per unit volume of a material is known as the *magnetization* (*M*). Total magnetization of a material will be the vector sum of different magnetizations of electrons and nuclei that make up the atom. The magnetization that develops in a material is similar to the development of polarization (*P*) in dielectrics.

What is important is to recognize that most "free" atoms possess a net magnetic moment. The atoms are isolated and do not form part of any solid or liquid. Although most *free* atoms have a magnetic moment, most often when atoms bond to other atoms to form a solid or liquid, the electrons of different atoms interact, and the resultant material has no net magnetic moment. This is why, although all atoms contain electrons and each electron can be viewed as a magnet, most materials behave essentially as nonmagnetic materials.

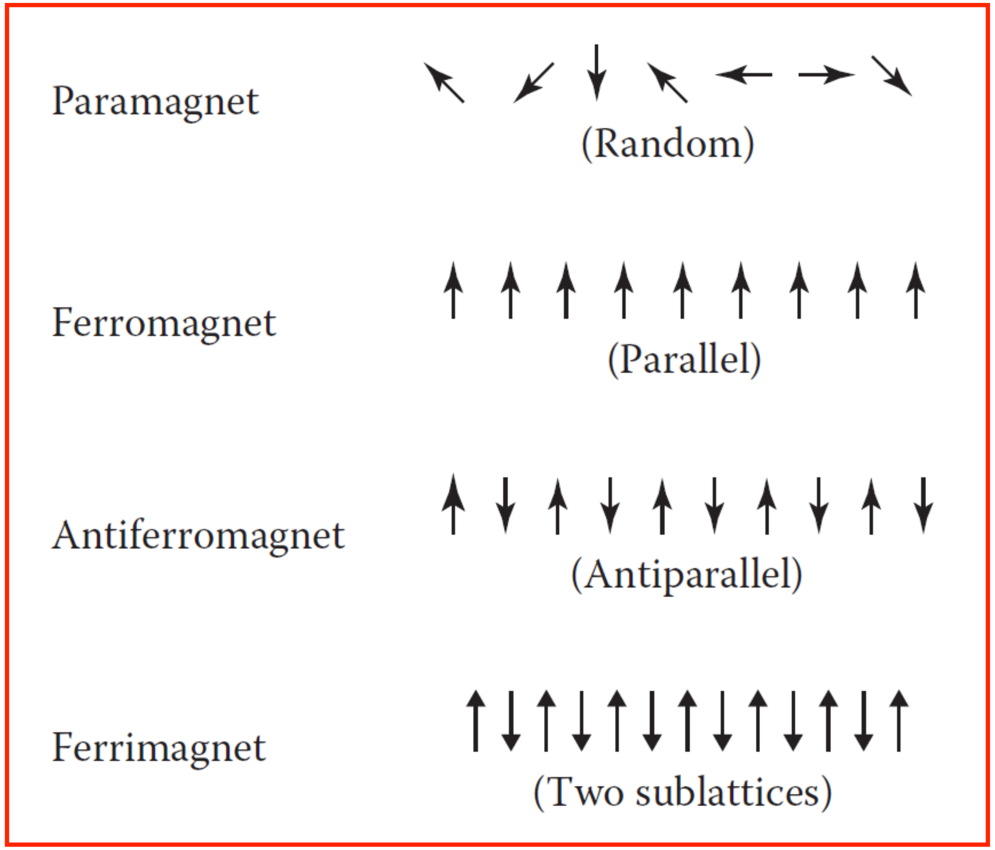
Few materials, such as transition elements (with incomplete 3d, 4d, or 5d orbitals), lanthanides (partially filled 4f orbital), or actinides (partially filled 5f orbital), some of the electron shells are incomplete. In these materials, even after the atoms form a solid, the atoms in the resultant structure have a net effective magnetic moment.

For example, Mn (Z = 25) with an electronic configuration of $1s^2 2s^2 2p^6 3s^2 3p^6 3d^5 4s^2$ up to and including the level 3p, the shells are completely filled. The rules of quantum mechanics tell us that before filling up the 3d sublevel, the 4s level must be filled. In a manganese atom, there are five unpaired electrons. The spin of each unpaired electron produces a magnetic moment of one Bohr magneton. Therefore, a "free" Mn atom has a net magnetic moment of 5 μ_B .

However, when Mn atoms form an Mn crystal, the magnetic moments of the spin and the orbital motions cancel each other out. Thus, the atoms in a manganese *crystal* do *not* have a net magnetic moment.

Most materials have a relatively weak (but nonzero) response to an external magnetic field.

An iron atom has a net magnetic moment of 4 μB. In iron, when the atoms form a phase with a particular crystal structure only some of these magnetic moments are canceled. Therefore, a material such as iron has a net magnetic moment. In iron, all the magnetic moments of the atoms are in the same direction. A material in which all the magnetic moments of atoms or ions are aligned in the same direction is known as a *ferromagnetic material.*



B = B_0 + B_magnetisation
B_0 = u_0 H
B_mag = u_0 M

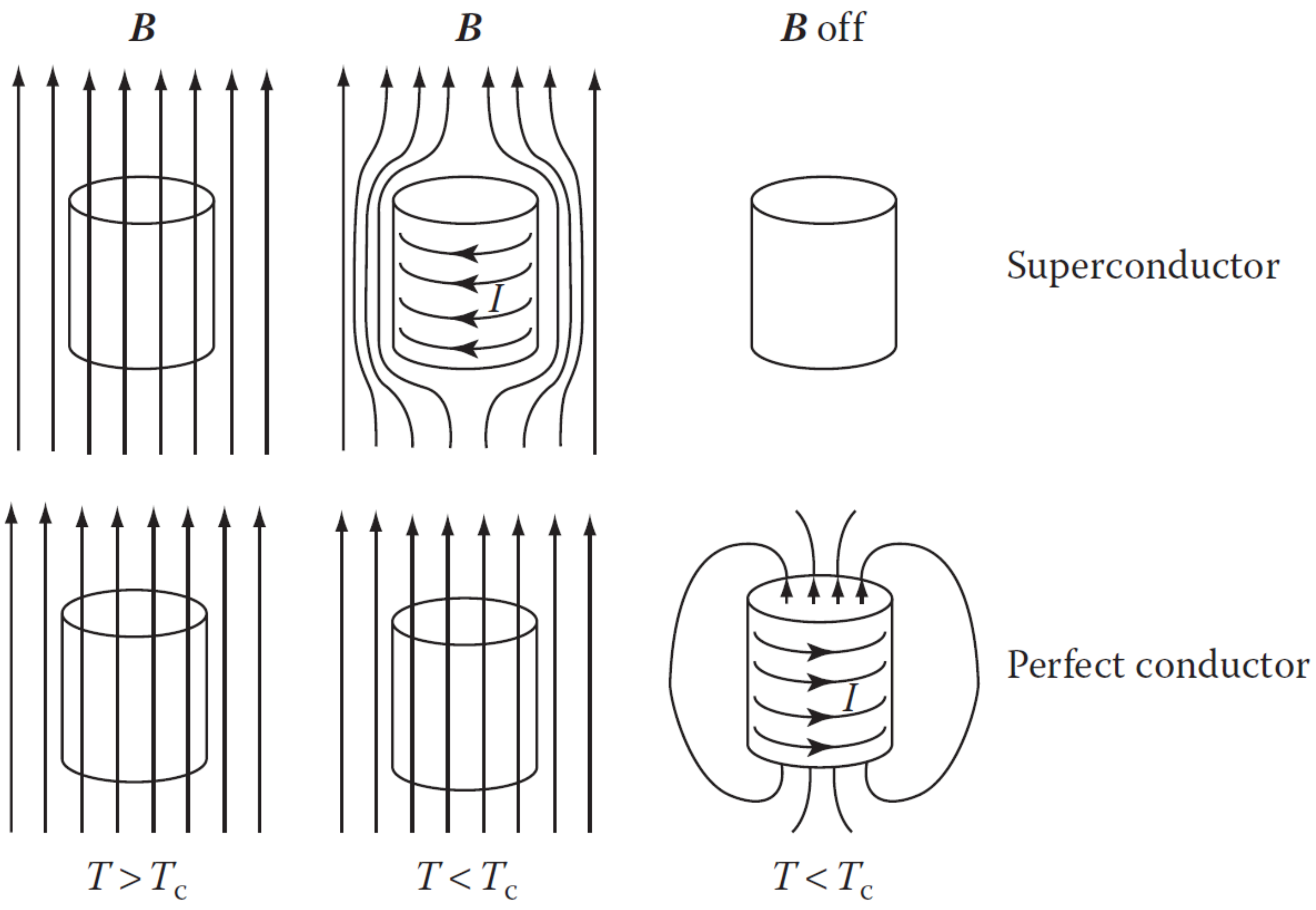
M = XH (only for dia and para)

B = u_0 (M + H) = u_0 (XH +H)
= u_0 (1 + X)H = u_0 u_r H

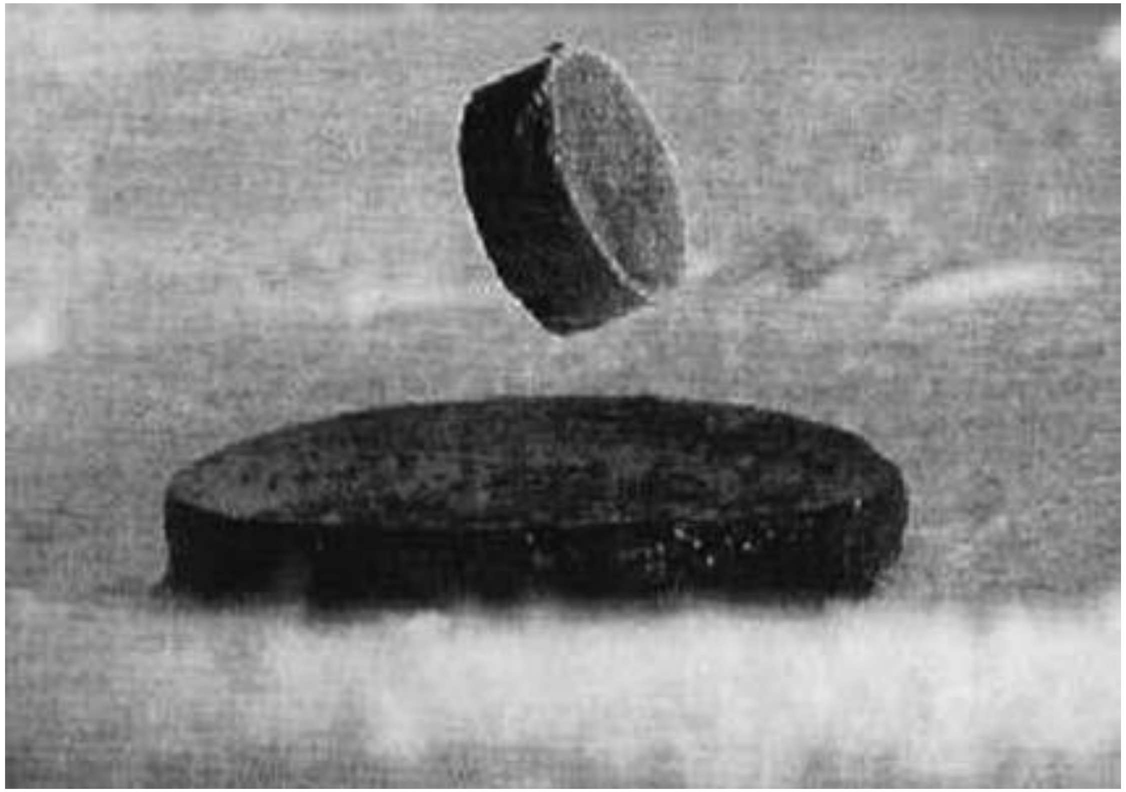
Schematic representation of the alignment of magnetic moments in different materials.

Diamagnetism

- When an external magnetic field is applied to a diamagnetic material, it tries to exclude the magnetic flux. Diamagnetism is an inherent property of the orbital motion of individual electrons in a field.
- This may be viewed as an atomic version of Lenz's law induced magnetic fields tend to oppose the change which created them.
- All materials are inherently diamagnetic, but if the atoms have some net magnetic moment as in paramagnetic materials or in ferromagnetic materials, these stronger effects are always dominant.
- Certain materials known as superconductors are perfect diamagnetic materials. This means that in superconductors, the magnetic field can be completely expelled. The magnetic susceptibility of superconductors is $\chi_m = -1$. This important difference between a conductor and a superconductor.
- The expulsion of magnetic flux lines due to the diamagnetic behavior of a superconductor is known as the *Meissner effect*, which is the basis of magnetic levitation using superconductors.



Expulsion of magnetic flux lines in a superconductor at $T < T_c$. In a conductor, the magnetic flux lines continue to penetrate.



Paramagnetism

- Some materials exhibit a magnetization which is proportional to the applied magnetic field in which the material is placed.
- These materials are said to be paramagnetic and follow Curie's law:

$$\boxed{M = C\left(\frac{B}{T}\right)}$$

M = magnetization
B = magnetic field
C = Curie's constant
T = Temperature in Kelvins

The paramagnetic response is so small that, for all practical purposes, these materials are also considered nonmagnetic.

Ferromagnetism

- Ferromagnetic materials exhibit a long-range ordering phenomenon at the atomic level which causes the unpaired electron spins to line up parallel with each other in a region called a domain.
- Within the domain, the magnetic field is intense, but in a bulk sample the material will usually be unmagnetized because the many domains will themselves be randomly oriented with respect to one another.
- Iron, nickel, cobalt and some of the rare earths (gadolinium, dysprosium) are most common examples.
- Samarium and neodymium in alloys with cobalt have been used to fabricate very strong rare-earth magnets.

$$B = H + 4\pi M$$

In SI units

B = B_0 + B_magnetisation
B_0 = u_0 H
B_mag = u_0 M

M = XH (only for dia and para)

B = u_0 (M + H) = u_0 (XH +H)
= u_0 (1 + X)H = u_0 u_r H
= uH

H is magnetic field strength and is reserved for field solely from free currents, such as electric current flowing in a wire. *M* is magnetization per unit volume and results from orbital and spin motion of e's. *B* is defined as magnetic induction. For example, an electromagnet made by winding Cu coils around Fe rod and passing current through wire has *H* from this current and *M* from e's orbital and spin motions in Fe and *B* as sum of these two quantities.

Magnetic susceptibility and permeability

The measure of how effective an applied field is for producing a magnetic dipole is the susceptibility of the material and is defined as $\chi = M/H$. ~~Permeability is defined as~~ μ = B/H. ~~So, $\mu = 1+4\pi\chi$.~~

The nature of interaction with the applied field allows us to classify magnetic field in three major categories.

1. Paramagnetic $\chi > 0$ (10^{-3} to 10^{-5})
2. Ferromagnetic $\chi > 0$ (up to few thousands)
3. Diamagnetic $\chi < 0$ (10^{-5} to 10^{-6})

It is important to note that all equations are in cgs units.

Magnetic domain and domain walls

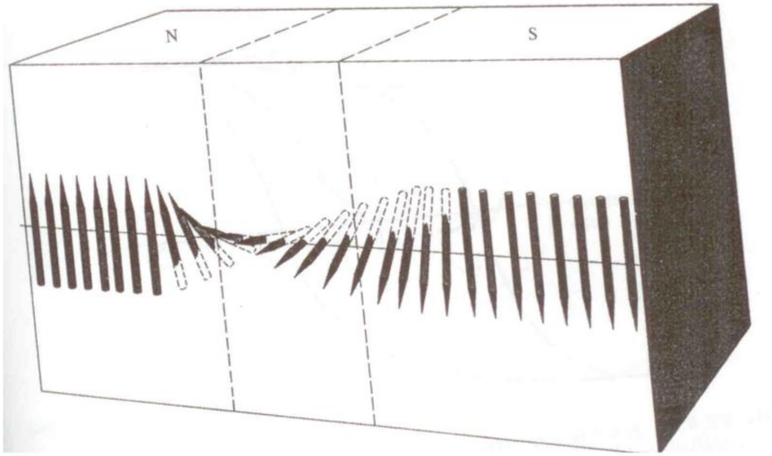
For a ferromagnetic material, all the moments are aligned as result of the exchange force, then why not a piece of iron behave as permanent magnet?

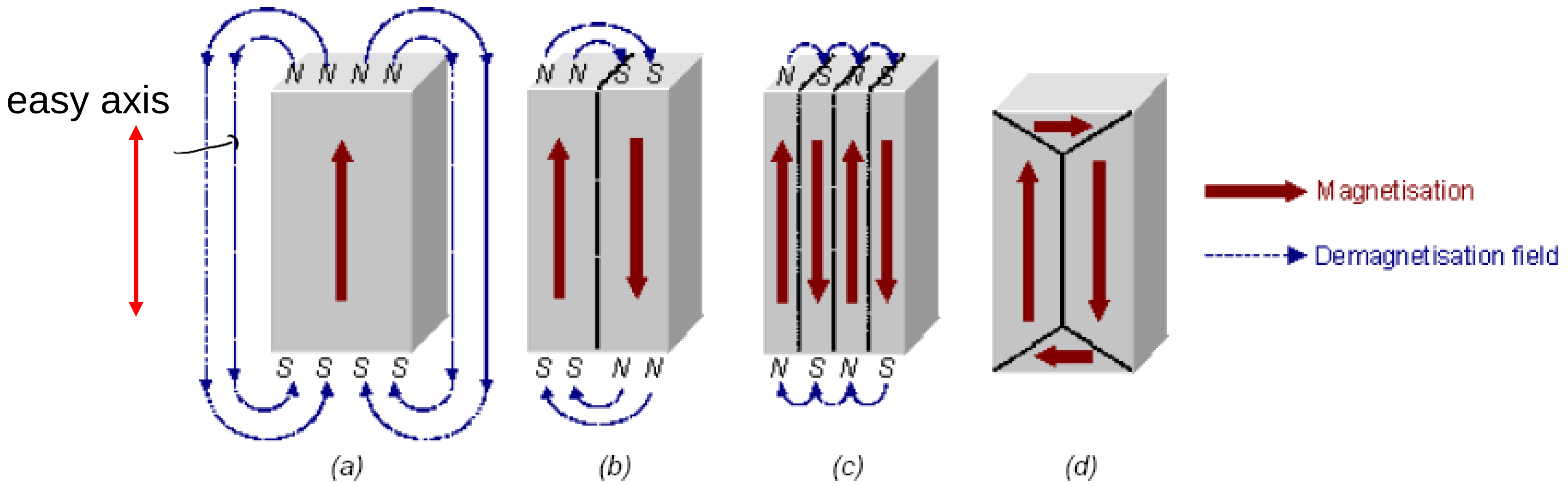
A macroscopic magnetic material will break up into domains that align themselves in a manner as to minimize the total effective moment of the material.

The magnetostatic energy for a sample volume V is given by

$$\boxed{E_s = \frac{\mu_0 N_d M^2 V}{2}}$$

Thus, a magnetostatic energy of a single domain of parallel spins can be decreased by breaking it into smaller oppositely aligned domains. This beneficial decrease would continue with further breaking into more yet smaller domains until it cost more energy to create another wall than gained by division.





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Breakup of magnetization into domains a) single, b) two, c) four, and d) closure doamins.

The size of these domains are of the order of 10^{-3} to 10^{-5} mm.

The exchange interaction between two antiparallel spins in a ferromagnet is so unfavorable that the material tends to develop a wall of finite thickness, hence a thick wall is favored. However, only two antiparallel spins are along the material's easy axis, others are tipped away from the easy axis. This gives rise to magnetocrystalline energy which is not favorable and hence tends to minimize the wall thickness. This competition leads to an optimal wall thickness *l*.