University of Anbar

College o Science – Dept. of Physics

Lectures of

NanoScience #1

for 4th level of physics students

by

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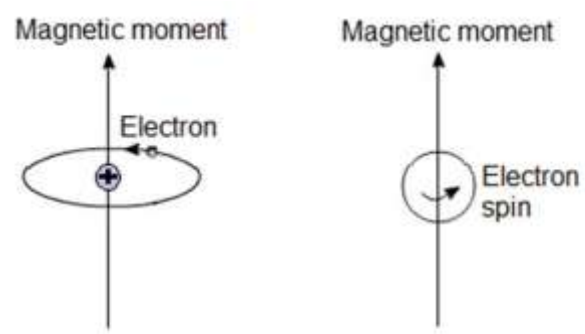
Chapter Three

<u>Magnetic Properties of Nanomaterials</u>

3- *Magnetic Properties of Nanomaterials*

There are two magnetic effects, one results with the orbital motion of an electron around an atom, that relates to the quantum number (l). The other is the spin of an electron, which relates to the quantum number (s). Beside figure shows tow related movement with the two magnetic effects of electron that gives an electron the magnetic dipole properties, which will be affected in the atom totally. The magnetic properties of an electron differ depending on the location of an electron from the ionic cores or in the energy band.



Orbital moments of the electron:

Magnetism relates with the angular momentum of the elementary particles strongly. Then, the magnetic properties relate with the quantum angular momentum.

All protons, neutrons, and electrons have an angular momentum equal to $(\frac{1}{2}\hbar)$, is called spin. The magnetic effects of nucleus are ignored because of its large nucleonic mass. Therefore, the main acquired magnetic properties of the atom come from the magnetic activity of electrons.

When electron round around the nucleus, an orbital moment results, that written as;

$$m = -\frac{e}{2m_e}\ell \quad ; \ell = m_e r \times v \dots \dots (2-109)$$

where r is the radius of orbital, v is a linear speed of electron into the orbital. The quantum orbital moment in Z- direction can be given as;

$$m_z = -\frac{e}{2m_e} m_\ell \hbar \quad ; m_\ell = 0, \mp 1, \mp 2 \dots \qquad \dots (2-110)$$

where m_ℓ is the quantum orbital magnetic number.

Bohr's magneton is the measurement unit of the magnetization, which is given as;

$$\mu_B = \frac{e\hbar}{2m_e} \dots \dots \dots (2-111)$$

where $1\mu_B = 9.274 \times 10^{-24} A.m^2$

Spin moment:

An electron has a quantum angular momentum number equal to ($s = 1/2$), that relates with the magnetic moment, not relates with the orbital motion of the electron. Its direction depends on the magnetic field direction, where the quantum angular momentum number has two values ($s = \mp 1/2$).

We can write the spin moment as;

$$m = -\frac{e}{2m_e} m_s \quad ; m_s = \mp {}^{1}/_{2} \dots \qquad \dots . (2-112)$$

That is meaning, there are two possibilities for angular momentum in z- direction.

$$m_z = -\frac{e}{2m_e} m_s \hbar \qquad \dots \dots \dots \dots \dots \dots . \dots . (2-113)$$

Therefore, the magnetic moment will arise, the orbital angular momentum value equal to half the angular spin momentum.

Spin- Orbit coupling:

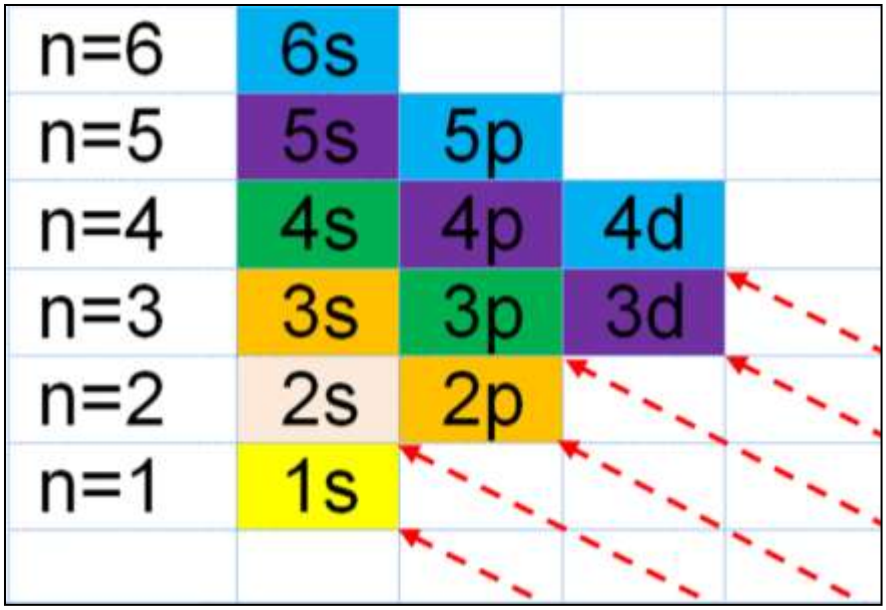
Total angular momentum is produced by reaction of both momentums, which is equal to;

$$m = -\frac{e}{m_e} j \,, \quad \hat{j} = \hat{s} + \hat{\ell} \qquad \dots \dots \dots \dots \dots \dots \dots \dots . (2-114)$$

To understanding the magnetic properties of materials, some fundamental basics of electronic distribution in the sub-orbital of the energy bands of material must be reviewed.

Hund's Rule:

Simply, every orbital in the sub-shell is singly occupied with one electron before any one orbital is doubly occupied, and all electrons in a singly occupied orbital have the same spin. That means, add an electron to the equivalent orbital must be filled all orbital in one direction before add electrons in the opposite direction.



Pauli Exclusion Principle:

Pauli Exclusion Principle is the quantum mechanical principle which states that two or more identical fermions (particles with half-integer spin) cannot occupy the same quantum state within a quantum system simultaneously.

Since the electron is a small magnet has a moment in one direction, then, the presence of two electrons in the same orbital will be in opposite directions, thus, one completely remove the effect of anther.

Generally, there are three types of the materials as the magnetisms;

Paramagnetic materials.

Diamagnetic materials.

Ferromagnetic materials (Atoms of these materials have not a primary magnetic moment).

For paramagnetic and diamagnetic materials, the magnetism proportional with the magnetic field (H).

$$\mathbf{M} = \chi H \ldots\ldots\ldots\ldots\ldots..(2-115)$$

where χ is the magnetic susceptibility of material. Generally, paramagnetic materials have positive magnetic susceptibility values. Thus, the magnetism value is in the same direction as the applied field. While, the diamagnetic have negative values, that results a magnetism factor in the opposite direction as the applied field.

Magnetic Susceptibilities of Some Paramagnetic and Diamagnetic Substances at 300 K

Paramagnetic Substance	χ	Diamagnetic Substance	χ
Aluminum	2.3×10^{-5}	Bismuth	-1.66×10^{-5}
Calcium	1.9×10^{-5}	Copper	-9.8×10^{-6}
Chromium	2.7×10^{-4}	Diamond	-2.2×10^{-5}
Lithium	2.1×10^{-5}	Gold	-3.6×10^{-5}
Magnesium	1.2×10^{-5}	Lead	-1.7×10^{-5}
Niobium	2.6×10^{-4}	Mercury	-2.9×10^{-5}
Oxygen	2.1×10^{-6}	Nitrogen	-5.0×10^{-9}
Platinum	2.9×10^{-4}	Silver	-2.6×10^{-5}
Tungsten	6.8×10^{-5}	Silicon	-4.2×10^{-6}

Where the relation between the magnetic permeability and susceptibility is;

$$\mu_m = \mu_o(1+\chi) \ldots\ldots\ldots\ldots\ldots (2-116)$$

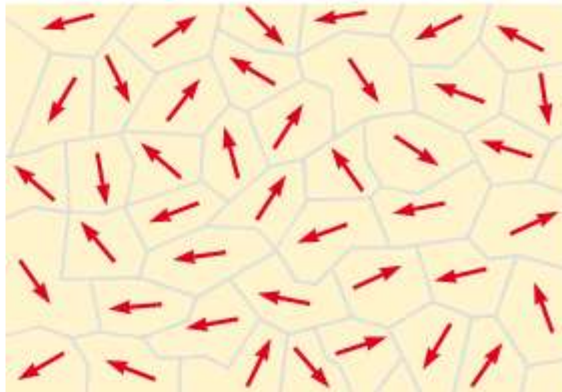
Where comparing, we found that,

Paramagnetic Materials	$\mu_m > \mu_o$
Diamagnetic Materials	$\mu_m < \mu_o$

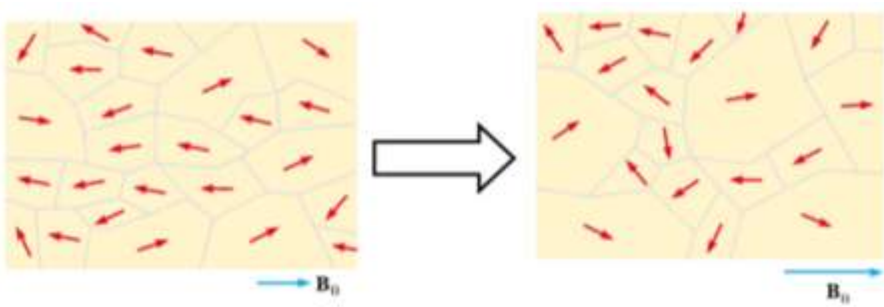
To both types have a small value of χ, then μ_m is closed to μ_o. While μ_m of ferromagnetic be greater than other types by many thousands times as result, these crystalline solids have strong magnetic effects,

Iron Fe^{26}	[Ar] $3d^6\,4S^2$	↑↓	↑	↑	↑	↑
Cobalt Co^{27}	[Ar] $3d^7\,4S^2$	↑↓	↑↓	↑	↑	↑
Nickel Ni^{28}	[Ar] $3d^8\,4S^2$	↑↓	↑↓	↑↓	↑	↑

These materials have atomic moments parallel with each other even with a weak external magnetic field be found. All ferromagnetism include micro-regions are called domains. Each domain has a magnetic moment in a direction depend on the crystalline direction. These domains are surrounded by boundaries like the grain boundaries, shown in below figure.



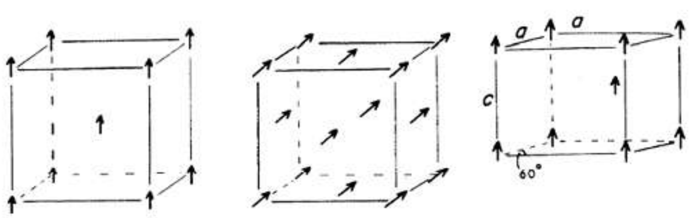
The equivalent moment in these materials is zero normally because of the random direction of the magnetic moments, but these moments become in the same direction and increasing in the domain size when the external magnetic field is applied. When the external field is greatly increased, the domains that are not in the line with the field direction begins to decrease in size, thus, its effect is blocked on the total result.



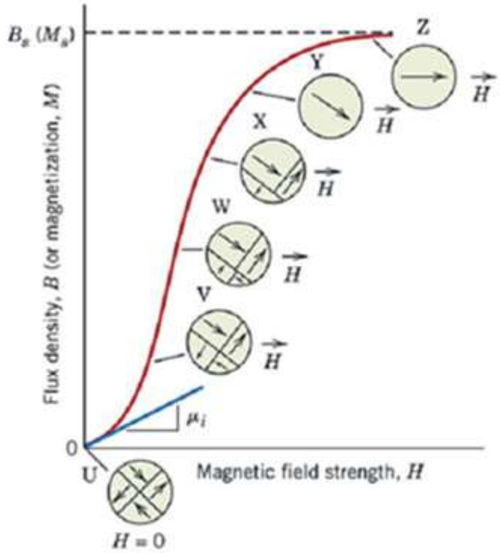
The distribution of the domains depends on;

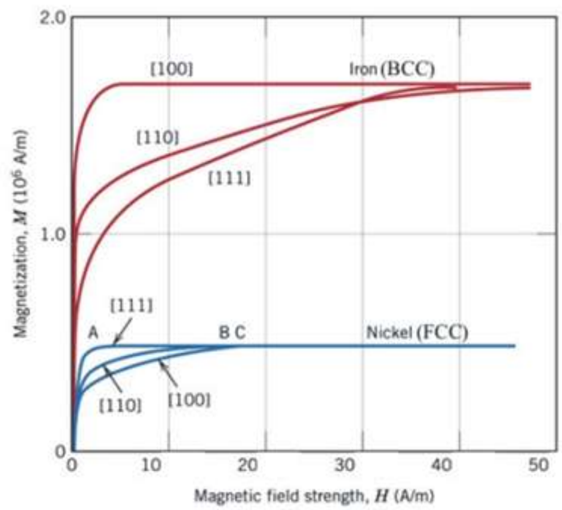
1. Crystalline type.
2. Crystalline shape.
3. Crystalline direction.

Thus, one grain may be contains on more one of domains in deferent directions, that results deference in the magnetic hysteresis behaviour.



α-Fe, T_c = 1043 K   Ni, T_c = 631 K   Co, T_c = 1404 K





Size Reduction effect on the magnetic properties:

Generally, the magnetic energy of any ferromagnetic materials can be described by;

$$E_{total} = E_{exch} + E_{ani} + E_{dem} + E_{app} \dots \dots (2-117)$$

Where E_{exch} is the change energy, E_{ani} is the demagnetization energy, and E_{app} is related energy with applied magnetic field.

The first term in equation (2-117) generates due to correlation between quantum mechanics and the atomic moment, describes the alignment of the magnetization vector in one direction, while the second term describes the alignment of the spin in the same direction of the crystalline axes direction. Thus, the soft materials will appear low symmetry energy, while the hard materials will be contrasted. In nanoscales, these energy can negated, where equation (2-17) can be written as;

$$E_{total} = \boldsymbol{M}H \dots \dots \dots \dots (2-118)$$

One of the important consideration be taken with dealing with ferromagnetic materials is interaction between the exchange and the loss energies.

For small particles or small grains, change's energy is dominant because of the coupling forces that lead to arrange the moments of the neighboring grains. Therefore, in the critical size, the particle is an individual domain.

$$D_{crit} = \frac{9\gamma_B}{\mu_o M_s^2} \dots \dots (2-119)$$

Where $\gamma_B = 4(AK_1)^{1/2}$, A is the exchange stifles, K_1 anisotropic constant, and M_s is the magnetic saturation.

The critical size of iron and cobalt is around (70, 15) nm respectively.

When the size will decrease less than the critical size, the material be unstable magnetically and lose its magnetization because of the thermal fluctuation (i.e. it's unstable thermally), which is called Superparamagnetic, addition to other magnetic effects). Physically, when studying the hysteresis behavior, where the coercive field increases with the size reduction to critical size (to its greatest value), then it begins decreasing even to magnetization becomes unstable because of the superparamagnetic behavior.