

Non - Metallic Materials
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Module - 05

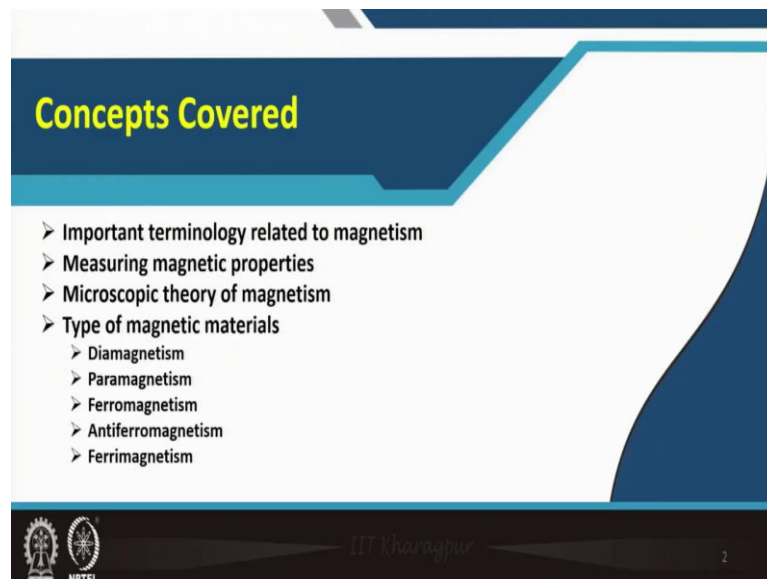
Electrical, magnetic and thermal properties of non - metallic materials

Lecture - 25

Magnetic properties: Origin of magnetism, para, dia, ferro, and ferrimagnetism

Welcome to my course Non-Metallic Materials and today we are in module number 5 Electrical, magnetic and thermal properties of non-metallic materials. And today's lecture is lecture number 25 where I will be talking about Magnetic properties specifically origin of magnetism and then different types of magnetic material including paramagnetic, diamagnetic, ferromagnetic and ferrimagnetic materials.

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Now, first I will cover certain important terminology. Sometimes it is quite confusing for you to understand about various types of terminology which are relevant for magnetic properties. Then I will explain a simple experiment to know what type of magnetic material it is. So, that experimental details will be described.

And then we will take some time to understand the microscopic theory behind magnetism and finally, I will be talking about different types of magnetic material

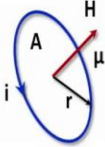

including diamagnetic, paramagnetic, ferromagnetic, anti-ferromagnetic and a special type of magnetism which is ferrimagnetism that will be covered.

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Important terminology related to magnetism

- **Magnetic field intensity or applied field (H)** – At the center of a circular loop of radius r , through which a current i is flowing, $H = i / 2r$ A/m. 1 A/m field is produced when 1 A is passed through a loop of 1 m diameter. Direction of the magnetic field w.r.t current flow is as shown.
- In vacuum H will result in a magnetic field B ; where $B = \mu_0 H$, where μ_0 is permeability of free space; μ_0 is $4\pi \times 10^{-7}$ Wb /A.m.
- B is expressed as $\text{Wb/m}^2 = \text{T (Tesla)}$, $1 \text{ T} = 10^4 \text{ Gauss}$.
- A magnetic induction of 1T will generate a force of 1 N on a conductor carrying a current 1 A perpendicular to the direction of induction.
- In the presence of a solid $B = \mu_0 (H + M)$, where M is the magnetization of the solid defined as the net magnetic moment μ_{ion} per unit volume

$$M = \mu_{\text{ion}} / V$$
- The atomic origins of μ_{ion} will be discussed shortly. The unit of μ_{ion} is $\text{A/m} \cdot \text{m}^3 = \text{A} \cdot \text{m}^2$. Thus a μ_{ion} of $1 \text{ A} \cdot \text{m}^2$ experiences a torque of $1 \text{ N} \cdot \text{m}$ when oriented perpendicular to a B field of 1 T

Now, let us consider a simple loop here made by a wire where current is flowing; the direction of the current flow is in accordance to the arrow. So, once this coil carries an electric current, then at the center of this circular loop and we have assumed the loop radius is typically r and i current is flowing through it. So, magnetic field is in perpendicular to the plane of the loop where from in in which this current is passing.

So, the magnetic field direction is in this direction and the magnetic field is current flowing divided by the diameter of the loop. So, 1 ampere meter i is in ampere and the diameter is in meter; that field is produced when 1 ampere current is passed through the loop of 1 meter of diameter. And direction of the magnetic field with respect to the current is exactly as shown in the figure.

Now, in vacuum this magnetic field or this magnetic field intensity or the applied field that will result a magnetic field which I have termed as B where B is proportional to H and the proportionality constant is permeability of the free space. And in the unit of this permeability is 4π into 10 to the power 7 , I guess. I guess I have missed it here, Weber per ampere into meter.

So, the field B is expressed as Weber per meter square from this relation and this Weber per meter square is nothing, but Tesla and 1 Tesla is equal to 10^4 Gauss. So, a magnetic induction of 1 Tesla field will generate a force about 1 Newton on a conductor which is carrying a current about 1 ampere and this field is perpendicular to the direction of the current flow.

Now, if you put a solid material inside this loop, then this field relation is changed. This field relation B is permeability into the field which is induced and the magnetization which is being generated due to the solid instead of vacuum. So, the magnetization that is defined by the net magnetic moment per unit volume.

It is something similar to the ferroelectric material although the mechanism is entirely different in case of ferroelectricity is related to the cation movement as I have described in one of my earlier lectures.

But as we will see that this magnetic moment is related to electron spin. So, the nature is different, but magnetization and polarization something similar; something similarity you will get and this is the μ ion I have defined is magnetization per unit volume. So, that is actually sorry the magnetic moment per unit volume that gives you the magnetization.

So, the unit of your μ ion is ampere per meter into meter cube that comes from the volume. So, it is ampere into meter square. So, μ ion of 1 ampere meter square will finally, experience a torque of 1 Newton into meter when oriented perpendicular to a field of B at 1 Tesla.

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Important terminology related to magnetism

Symbol	Quantity	Value	Units
H	Magnetic field intensity or magnetizing field		A/m ²
M	Magnetization		A/m
B	Magnetic field		Wb/m ² = T = Vs/m ² = 10 ⁴ G
μ_0	Permeability of free space	$4\pi \times 10^{-7}$	Wb/(A-m) = Vs/(A-m)
μ	Permeability of a solid		Wb/(A-m) = Vs/(A-m)
μ_r	Relative permeability		Dimensionless
χ_{mag}	Relative susceptibility		Dimensionless
μ_{on}	Net magnetic moment of an atom or ion		A-m ² = C-m ² /s
μ_s	Spin magnetic moment		A-m ²
μ_{ob}	Orbital magnetic moment		A-m ²
μ_B	Bohr magneton	9.274×10^{-24}	A-m ²

^a It is unfortunate that both μ_s and μ_{ob} have the same symbol, but they will be clearly marked at all times to avoid confusion.

^b 1 A/m = 0.0126 Oersted (Oe).

- In paramagnetic and diamagnetic solids B is a linear function of H; $B = \mu H$ (μ is permeability)
- For ferromagnetic and ferrimagnetic materials B is a non-linear function of H
- Magnetic susceptibility (χ_{mag}) is defined as $\chi_{mag} = M/H$
- Relative permeability μ_r is given as $\mu_r = \mu/\mu_0$
- It can be shown that $\mu_r = (\chi_{mag} + 1)$



So, here in this table, you will find the different quantity what exactly I have described. Some you will be able to understand like H is defined magnetic field intensity magnetization is defined, then magnetic field is defined permeability of the free space μ_0 is defined. And this is as I said 4π into 10 to the power minus 7 . So, earlier slide I missed this indices part and the relevant units also I have tabulated here.

So, in paramagnetic and diamagnetic material the solid material, this field is a linear function of H. So, B equal to proportionality constant this is known as permeability into H. For ferromagnetic and ferrimagnetic materials, this B is a non-linear function of H. So, that is the prime difference between paramagnetic diamagnetic and ferro and ferromagnetic.

And magnetic susceptibility you can defined is the ratio between magnetization and magnetic field intensity M by H. This is both are vector quantity M and H. Relative permittivity this is defined as a ratio of the magnetic permeability and the permeability in vacuum. And one can show that this relative permittivity is related to the value of the magnetic susceptibility plus 1. This can also be evaluated.

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Measuring magnetic properties

- A solenoid of n turns per meter, through which a current i flows so as to produce a magnetic field intensity, H that is in same direction as that of the permanent magnet (N pole pointing up)
- Axially uniform H of strength $H = n i$. H induces **magnetic moments** in the material to align themselves either with or against the applied field
- Magnetic force on the material $F_z = \mu_{\text{ion}} dB/dz$

$$F_z = M V dB/dz$$

$$= V \chi_{\text{mag}} H dB/dz$$

- Force on the sample is directly proportional to χ_{mag} and H
- Since dB/dz is $-ve$, for attractive force χ_{mag} is $+ve$.

Now, I was talking about this experiment, let us understand the experiment. A solenoid you can see here a solenoid which is having n turns per meter. So, this is a metallic coil. So, inside this metallic coil which is having a turn of n per meter; I am assuming i current is flowing. So, direction of i is there and it produce a magnetic field intensity that is in the same direction of the permanent magnet. So, I have put a permanent magnet here.

So, the field direction is in this direction. So, it is flowing in the clockwise direction this current. So, magnetic field is in the same direction as that of the permanent magnet where this n pole North Pole is facing up. So, actually uniform H of strength, I can get the strength is number of coil n into the current flowing into it so, that will induce a magnetic moment in the material. So, this is my sample. So, it will induce a magnetic moment.

And the nature of this material, I am not disclosing at this moment. So, depending on the nature of the material either it will attract towards the magnetic field or it will repel towards the magnetic field. So, if you estimate the magnetic force of the material which is defined as F_z in z direction that is μ_{ion} the magnetic moment and the gradient of the field dB by dz .

So, here you put you know that this magnetic moment is magnetization into the volume of the material and dB/dz is there. So, you know the relation between the susceptibility

and M and H . So, you just put this value here. So, force on the sample you can see here it is directly proportional to the susceptibility; magnetic susceptibility and magnetic field intensity. Now, this field gradient is negative. So, for attractive force the magnetic susceptibility must be positive, then only it is valid.

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Case – I Sample is weakly repelled, χ_{mag} is -ve. Weight appear to diminish. Increasing H by increasing current in the solenoid will linearly increase the repulsive force. Material is **diamagnetic** (most ceramics)

Case – II The sample is weakly attracted to the permanent magnet, with a force of attraction that is proportional to H . The sample gains weight, χ_{mag} is +ve. Sample is **paramagnetic**. χ_{mag} decreases with increasing temperature. Both for diamagnetic and paramagnetic materials weight changes are completely reversible.

Z-axis
Sensitive balance
Solenoid with n turns
Sample
Permanent magnet (N, S)

So, let us consider now the nature of the sample. So, case I that sample is weakly repelled. So, susceptibility is negative. So, weight appear to diminish. So, it will repel it. So, magnetic field will repel the sample so, the weight will diminish. So, if you plot the change in weight versus field of the applied magnetic field that will be linear in nature and it is repulsive. So, then this kind of material is called diamagnetic material. Most of the ceramic material oxide materials, they are diamagnetic in nature.

Second case is the sample is weakly attracted to the permanent magnet with a force of attraction that is proportional to H . Again as I told that it will be linear in nature in case of diamagnetic and paramagnetic material. So, in that case when it is attracted, then the sample gains weight. So, your magnetic susceptibility is positive.

So, we call the sample is paramagnetic and usually this magnetic susceptibility decreases when the temperature is increased. Both diamagnetic and paramagnetic material weight changes are completely reversible. So, whenever you take off the field magnetic field, you will see that the weight change is again 0; it will go back to its original condition.

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Case - III The sample is strongly attracted to the permanent magnet. The observed shape shown is dependent on sample's history. Such behavior is termed **Ferromagnetic** or **Ferrimagnetic**. Increasing temperature diminishes remnant magnetization $\pm M_r$. At critical temperature the material would lose magnetism and behave like a paramagnetic material.

Case - IV **Antiferromagnetic** material behaves similarly to a paramagnetic one; i.e it is weakly attracted. Temperature dependence of susceptibility measurements can differentiate a paramagnetic material with an antiferromagnetic material (*discussed later in details*)

Now the interesting thing appears in certain sample when they are strongly attracted to the permanent magnet. So, once they strongly attracted, the shape of the change in weight with respect to the magnetic field, it is something like this it starts from here in the origin state then it is going like this; it is saturated and then it follows the path as shown by this red line.

So, once this happens when it is strongly attracted then the material could be either ferromagnetic or ferrimagnetic ; ferrimagnetic I will define later. So, increasing the temperature if you increase the temperature, then the remnant magnetization I have not defined what is magnetization, but something similar curve you will get if you plot magnetization versus magnetic field.

So, at 0 magnetic field you have still the magnetization left. So, here it is still attractive. So, you get the weight difference, at critical temperature this remnant magnetization will be 0 for this type of material and it will start behaving like a paramagnetic material. So, this is interesting magnetic material and we term this as either ferromagnetic or ferrimagnetic. The difference between these two will be clear in the subsequent slides.

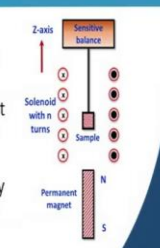
The final case is antiferromagnetic material that behaves exactly similar like the paramagnetic one that is in the weak in the field, it is weakly attracted and the temperature dependence of the susceptibility measurements can in fact differentiate

between a paramagnetic material with an anti ferromagnetic material and this I will discuss subsequently.

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Illustrative example:

A chunk of a magnetic ceramics weighing 10 g is attached to the sensitive balance and is suspended in the center of a toroidal solenoid with 10 turns per centimeter. A current of 9A is passed through the coils. The magnetic field gradient due to the permanent magnet was measured to be 100 G/cm. When the current was turned on, such that H was in the same direction as the permanent magnet, the weight of the sample was found to increase to 10.00005 g. The density of the solid is 5 g/cm³. (a) Calculate the susceptibility of this material. (b) Calculate the magnetization M of the solid. (c) What conclusions can be inferred concerning its magnetic properties ?



$F_z = \Delta W \cdot g = 0.00005 \times 10^{-3} \times 9.8 = -4.9 \times 10^{-7} \text{ N}$
 $H = n \cdot i = 9 \times 10 / 10^{-2} = 9000 \text{ A/m}; dB/dz = 100 \times 10^{-4} / 10^{-2} = 1 \text{ T/m}$
 $V = 10/5 = 2 \text{ cm}^3 = 2 \times 10^{-6} \text{ m}^3$
 (a) $\chi_{\text{mag}} = F_z / [V \cdot H \cdot dB/dz] = -4.9 \times 10^{-7} \text{ N} / [2 \times 10^{-6} \text{ m}^3 \cdot 9000 \text{ A/m} \cdot 1 \text{ T/m}] = 2.7 \times 10^{-5}$
 (b) $M = \chi_{\text{mag}} \cdot H = 2.7 \times 10^{-5} \times 9000 = 0.245 \text{ A/m}$
 (c) Since it is attracted by the magnet it might be paramagnetic or antiferromagnetic or ferromagnetic. Low value of χ_{mag} , hence ferromagnetic is ruled out. T dependence of χ_{mag} is required to know if it is paramagnetic or antiferromagnetic.

So, let us have an illustrative example just to understand the basic concept. So, the same experiment if you remember, there is a solenoid coil and we are passing a current through it. So, it induce magnetic field. We have hung a sample and the sample is connected to a very sensitive balance which can measure very small amount of weight change and we have a permanent magnet whose field direction is something similar to the field that you are getting out of this solenoid.

So, the magnetic material a ceramic material, it weighs 10 gram. This is attached to the sensitive balance and suspended at the center of the toroidal solenoid and the number of turns 10 is given per centimeter. Remember it is given per centimeter for the dimensional control you will have to take it in meter. A current of 9 ampere is passed through the coil. The magnetic field gradient due to the permanent magnet was measured to be 10 Gauss per centimeter. So, this field gradient you need to know.

So, when the current is turned on such that H was in the same direction to the permanent magnet that already I have mentioned. The weight of the sample was found to increase. So, suddenly it will not be diamagnetic, it is increased and see that change is very very small; it is in microgram level. So, the balance needs to be very very sensitive.

Density of the solid is given as 5 gram per centimeter cube. Now you are supposed to calculate the susceptibility of the material from this experiment, you can calculate the magnetization of the solid and finally, you are asked that what conclusion you can make out of the nature of the magnetic properties.

So, it is straight forward you know the force is nothing, but change in weight into g , gravitational constant. So, it is in Newton you can calculate, then you can calculate the magnetic field intensity number of coil into current passing and remember this was in centimeter I have transformed into meter. And the field gradient is given as 1 Tesla per meter and the value of V is given not really given, but the weight is given and density is given.

So, you can calculate the volume also in meter. So, the susceptibility is given by this relation. This already I defined and you can calculate the susceptibility value which is having a very small, but positive value. Magnetization is the susceptibility into the magnetic field intensity. So, you can calculate the magnetization and since it is attracted by the magnet, it might be a paramagnetic material or it could be antiferromagnetic.

So, the low value of this magnetic susceptibility; hence ferromagnetic is ruled out. So, it is attracted. So, it can be ferromagnetic as well, but it is ruled out and temperature dependence of this susceptibility is required to know if it is really paramagnetic or it is antiferromagnetic in nature.

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Microscopic theory of magnetism

Electrons spin in their own axis (**spin angular moment μ_s**) and around the nucleus (**orbital angular moment μ_{orb}**). The sum of these two contributions is the total angular moment of an atom or ion μ_{tot} . When an atom is placed in a magnetizing H field, it experiences a torque then the atom possesses a magnetic moment.

Orbital magnetic moment

$\mu_{orb} = i A' = i \pi r^2$ the orbital moment points normal to the plane of the loop.
Current i is given by $i = e\omega_e/2\pi$, hence

$$\mu_{orb} = e\omega_e r^2/2$$

Orbital angular momentum $\Pi_o = m_e \omega_e r^2$, replacing we get
 $\mu_{orb} = e \Pi_o/2m_e$ where m_e is the rest mass of electron. Rearranging
 $\mu_{orb} = [h/2\pi \cdot e/2m_e] \cdot \Pi_o \cdot 2\pi/h$
 $= [eh/4\pi m_e] \cdot I$ where the integer $I = \Pi_o \cdot 2\pi/h$ is the **orbital angular momentum** and $\mu_B = [eh/4\pi m_e]$ is the **Bohr magneton**

$\mu_{orb} = \mu_B \cdot I$ more accurately
 $\mu_{orb} = \mu_B \cdot [(I + 1)]^{1/2}$

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Now, this microscopic theory of magnetism is related to electron spin as you know that electron can spin in its own axis and then we call this is a spin angular momentum and it can also rotate along around the nucleus. So, we call its orbital angular momentum μ_{orbital} .

The sum of these two contribution is a total angular moment. So, that is for one single atom or ion, it is μ_{ion} . So, when atom is placed in a magnetizing field of intensity H it experiences a torque then the atom poses a magnetic moment.

So, the orbital magnetic moment, you can calculate it is current into the area and if it is circular you can talk about πr^2 orbital moment points normal to the plane of the loop. And this current is actually given by its charge into ω and divided by 2π from elementary physics concept.

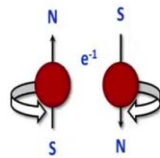
So, your μ_{orbital} you can calculate $e \omega r^2$ by 2 orbital angular momentum is nothing, but this rest mass of electron into ωr^2 . So, we replace this equation and rearrange it. So, I am introducing this term $\frac{h}{2\pi}$. So, I can get this relation.

So, out of this relation this is $\frac{e h}{4\pi m_e}$ into the another integer l that is the angular momentum. The first term is known as Bohr magneton $\frac{e h}{4\pi m_e}$ and l value is given as this $\frac{h}{2\pi}$ by h . So, I am getting an expression of Bohr magneton into l and for a precise calculation this l is actually replaced by $l + \frac{1}{2}$. So, that is the expression for your orbital magnetic moment.

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Microscopic theory of magnetism

Spin magnetic moment



This moment arises from the spin of electrons around themselves.

$$\begin{aligned}\mu_s &= e \hbar \pi_s / m_e \text{ rearranging with inserting the term } \hbar / 2\pi \\ &= [e \hbar / 4\pi m_e] 4\pi / \hbar \cdot \pi_s \text{ where } \pi_s \text{ has to be an integer multiple of } \hbar / 2\pi\end{aligned}$$

Now $2\pi \cdot \pi_s / \hbar = s$ the spin quantum number

$\mu_s = \mu_B 2s$. Since $s = \pm 1/2$, μ_s for one electron is one Bohr magneton.

More accurately $\mu_s = 2\mu_B [s(s+1)]^{1/2}$



Similarly you can estimate the spin magnetic moment and this arises from the spin of the electron around themselves, it is rotating in its own axis. So, similarly this spin moment is also $e \hbar \pi_s$ by rest mass of electron. So, again we are rearranging by putting the term g by 2π from fundamental quantum mechanics. So, I am getting this relation.

So, here this π_s that has to be an integer multiple with \hbar by 2π from the basic quantum mechanics theory. So, this $2\pi \pi_s$ by \hbar , it is equal to s small s where s is the spin quantum number. So, your μ_s related to the spin is now Bohr magneton into $2s$ and you know that s can have only two value plus half and minus half for 1 electron is 1 Bohr magneton.

So, again more accurately you can write that the spin magnetic moment is related to 2 into Bohr magneton and this parameter s into $s + 1$ to the power half.

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Microscopic theory of magnetism

Total magnetic moment of a poly – electronic atom or ion

The total angular moment of an ion, with one unpaired electron $\mu_{ion,1}$

$$\mu_{ion,1} = \mu_s + \mu_{orb} = e\hbar/m_e + e\hbar/m_e$$
$$\mu_{ion,1} = \mu_s + \mu_{orb} = g (e/2m_e) \hbar \Pi_{tot}$$

g is known as Lande splitting factor, Π_{tot} is the total angular momentum

When only spin is contributing to $\mu_{ion,1}$ then $g = 2$, when only orbital momentum is contributing then $g = 1$, thus g lies between 1 and 2 depending relative contribution of μ_s and μ_{orb} to $\mu_{ion,1}$

If an atom or ion has more than one electron then


$$L = \sum m_l \text{ and } S = \sum s$$

The total angular momentum J is the vector sum of L and S

$$J = L + S$$

This is known as **Russel – Saunders coupling**.

For ceramics orbital angular momentum is quenched, hence $L = 0$

$$\mu_{ion} = 2\mu_B [S(S+1)]^{1/2}$$


So, now, the total magnetic moment is for 1 ion with 1 unpaired electron. If I consider that so, that μ_{ion} will be the spin and orbital moment. So, I just put the relevant values and then I just introduce a term g which is known as Lande splitting factor. So, this total μ_{ion} is the total angular momentum when only spin is contributing then g is actually 2 and when orbital momentum is contributing then g is equal to 1.


And when both are contributing, then it is in between 1 and 2 for solving certain problems; these concepts will be required. But in a solid there are multiple number of atoms or ions. So, I can define this value of L , it is a summation of m_l and value of S that is the summation of s . So, the total angular momentum is a vector sum of this L and S .

So, this is actually known as Russell-Saunders coupling. Usually for ceramic material the angular momentum is quenched. So, you can safely take L equal to 0. So, your μ_{ion} is nothing, but 2 into Bohr magneton μ_B and the value of the contribution of all spin. So, capital S into $S + 1$ to the power half so, root over of that.

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Illustration **Microscopic theory of magnetism**

Cations	Electronic configuration	Calculated quantum moments $2\sqrt{S(S+1)}$	Classical moments	Measured moments
Sc ³⁺ , Ti ⁴⁺	3d ⁰ [] [] [] []	0.00	0	0.0
V ⁴⁺ , Ti ³⁺	3d ¹ [↑] [] [] []	1.73	1	1.8
V ³⁺	3d ² [↑] [↑] [] []	2.83	2	2.8
V ²⁺ , Cr ³⁺	3d ³ [↑] [↑] [↑] []	3.87	3	3.8
Mn ²⁺ , Cr ²⁺	3d ⁴ [↑] [↑] [↑] [↑]	4.90	4	4.9
Mn ³⁺ , Fe ³⁺	3d ⁵ [↑] [↑] [↑] [↑] [↑]	5.92	5	5.9
Fe ²⁺	3d ⁶ [↑] [↑] [↑] [↓] [↓]	4.90	4	5.4
Co ³⁺	3d ⁶ [↑] [↑] [↓] [↓] [↓]	3.87	3	4.8
Ni ²⁺	3d ⁸ [↑] [↑] [↓] [↓] [↓] [↓]	2.83	2	3.2
Cu ²⁺	3d ⁹ [↑] [↑] [↓] [↓] [↓] [↓] [↓]	1.73	1	1.9
Cu ⁺ , Zn ²⁺	3d ¹⁰ [↑] [↑] [↓] [↓] [↓] [↓] [↓] [↓]	0.00	0	0.0





So, now, you can consider various types of cations as you can see and you can configure the electron from elementary chemistry idea 1 S 2, 2S 2 2p 6. So, the final you will find that the d shell is either unfilled or it is partially filled or it is coupled something like that. So, the calculated quantum moment is given by 2 into root over of S into S plus 1. So, if you calculate that for unpaired electron, then you can get the quantum moments like this; you can do that I will so, show one of the examples.

And the classical moment calculation based on the elementary quantum mechanics, they are something similar not exactly similar and the measured moment they resemble to this calculated quantum moment.

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Illustration

Cations	Electronic configuration	Calculated quantum moments $2\sqrt{S(S+1)}$	Classical moments	Measured moments
Mn ²⁺ , Fe ³⁺	3d ⁵ 	5.92	5	5.9
Cu ⁺ , Zn ²⁺	3d ¹⁰ 	0.00	0	0.0

$S = \sum m_s = 5 \times \frac{1}{2} \mu_B = 2.5 \mu_B$ for Mn²⁺ Assuming L = 0; J = S
 $\mu_{ion} = 2 [2.5(2.5+1)]^{1/2} \mu_B = 5.92 \mu_B$

- When an electron shell is completely filled, all electrons are paired, their magnetic moments cancel and, consequently, their net magnetic moment vanishes. Only partially filled orbitals need to be considered.
- Calculated magnetic moment assuming only spin orbital momentum for the isolated cations of the 3d transition series compares favorably with the experimentally determined values implies indeed L is indeed quenched.

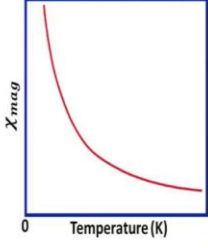
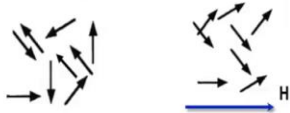
So, I will just show certain examples. So, I have taken the example of manganese 2 plus and iron 3 plus. So, here you can see that there are 5 unpaired electron. So, it is having plus half. So, the total S is 5 into half Bohr magneton so, 2.5 Bohr magneton and the L is quenched as I said. So, the J value is equal to S. So, you can estimate the mu ion is 2 into this value S into S plus 1 to the power half into Bohr magneton. So, it is coming 5.92 Bohr magneton this value.

And classical calculation will give you only 5 because these are 5 unpaired electrons into Bohr magneton. So, it is slightly modified and the experimental value measured moment is very close to it. So, similarly for copper Cu plus, they are all coupled I mean there is no unpaired electron. So, as expected the magnetic moment is 0 here. So, this does not have any magnetic moment in it.

So, when the electron shell is completely filled all electrons are paired their magnetic moments cancel and consequently net magnetic moment vanishes only partial field orbitals need to be considered in this kind of calculation. And calculated magnetic moment only assuming spin orbital moment for isolated cations of 3d transition series compares favorably well with the experimentally determined values that implies that indeed the L value is quenched.

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Paramagnetism



Paramagnetic solids are those in which the atoms have a permanent magnetic dipole (i.e. unpaired electrons). H tends to orient this magnetic moment. Susceptibility is small (10^{-3} to 10^{-6}) but positive.

$$\chi_{\text{mag}} = C/T$$

C is a constant known as **Curie constant**. The physical origin of this dependence is described in the next slide.

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Now, let us have a look about paramagnetism as such paramagnetic solids are those solids in which the atoms have permanent magnetic dipoles; that means, unpaired electrons are there and H the magnetic field intensity tends to orient this magnetic moment. Susceptibility is usually small 10 to the power minus 3 to 10 to the power minus 6 and we have just estimated.

It was around 10 to the power minus 5 , but it is having a positive value for this paramagnetic material the susceptibility varies with temperature following this Curie relation this relation C by T . So, C is a Curie constant and the physical origin of this dependence, I will just describe in a moment.

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Paramagnetism


Let us have N is the total number of magnetic atoms or ions per unit volume, N_1 is aligned with magnetic field, whereas N_2 are against magnetic field. *It can be shown that (See the assignment problem)*

$$M = (N_1 - N_2)\mu_{\text{ion}} = N\mu_{\text{ion}}^2 B/kT$$
$$B = \mu_0 H$$
$$M/H = \chi_{\text{mag}} = N\mu_{\text{ion}}^2 \mu_0 /kT = C/T$$

We had assumed that magnetic moments are aligned either with or opposite to the magnetic field, however, at any angular dependence, the following Eqn. (Langevin Eqn.) is valid

$$\chi_{\text{mag}} = N\mu_{\text{ion}}^2 \mu_0 /3kT = C/T$$

For analyzing paramagnetic results this equation needs to be used.



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So, let us consider there are N total number of magnetic atoms per unit volume and N_1 out of that is aligned with the magnetic field and N_2 are against the magnetic field. So, you can show that the magnetization is N_1 minus N_2 into the magnetic moment μ_{ion} .

In fact, this is part of an assignment problem for you to estimate it and this relation is valid. N is the number total number of magnetic atoms and it is related to magnetic moment square into field intensity divided by kT .

Now, you know that this B value for paramagnetic material is μ_0 into H . So, M by H is nothing, but your magnetic susceptibility. So, you get the relation like this which is nothing, but C by T the remaining part is C . So, we had assumed that the magnetic moments are aligned either with or opposite to the magnetic field; either it is along with the magnetic field or exactly opposite to the magnetic field.

So, it can be not like this or this, but it can be anything in between. So, if that is the case then, there is a simple relation Langevin, he introduced it only a factor 3 is coming here remaining everything remains same. It is same like this relation. So, for analyzing any paramagnetic result, you can safely used this relation as shown. So, only a factor 3 is in extra.


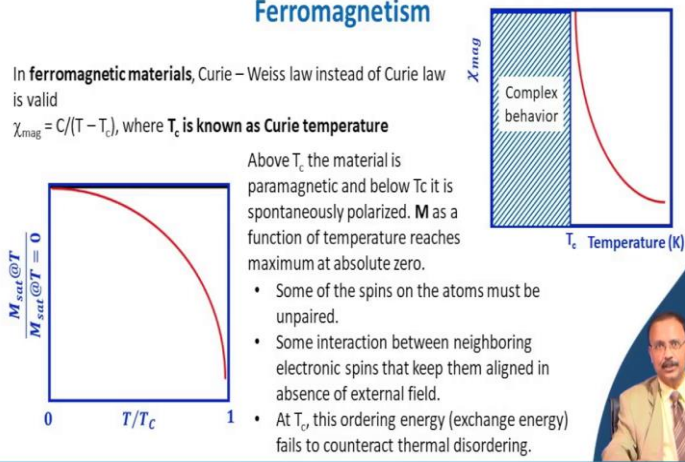
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Ferromagnetism

In **ferromagnetic materials**, Curie – Weiss law instead of Curie law is valid
 $\chi_{mag} = C/(T - T_c)$, where T_c is known as **Curie temperature**

Above T_c the material is paramagnetic and below T_c it is spontaneously polarized. M as a function of temperature reaches maximum at absolute zero.

- Some of the spins on the atoms must be unpaired.
- Some interaction between neighboring electronic spins that keep them aligned in absence of external field.
- At T_c , this ordering energy (exchange energy) fails to counteract thermal disordering.



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In ferromagnetic material, it will follow a Curie Weiss law instead of a Curie law which I just defined. So, Curie Weiss law is given by C divided by T minus T_c . So, this T_c is a Curie temperature something similar to your ferroelectric material which I have talked about. Above T_c the material is paramagnetic in those cases, it was paraelectric in nature and below T_c , it is spontaneously polarized. So, M is the spontaneous polarization. Now M is a function of temperature, it reaches a maximum at absolute zero.

So, if you take the value of saturation magnetization with respect to the saturation magnetization at 0 field, you see the maxima is here. So, some of the spins of the atoms must be unpaired.

So, therefore, you will get this spontaneous polarization. Some interaction between the neighboring electron spins that keep them aligned in the absence of electric field. So, nature of this magnetic interaction is very important because it is only in one particular ion. So, it has a cooperative phenomena.

So, this ordering energy is called exchange energy. So, exchange energy is very prominent or it contributes more when the temperature is less at near the Curie temperature, they are all randomized. So, you get a paramagnetic nature. So, above the paramagnetic above the Curie temperature this follows the Curie Weiss law. But below it, it is really a complex behavior and this is not part of this description so, that is why the shaded area we are not talking much about it.

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Understanding the temperature dependence of ferromagnetic materials

Ferromagnetism

A local electric field B_{loc} is operative which has the following form
 $B_{loc} = \mu_0 (H + \lambda M)$, λ is the mean field constant or coupling coefficient and is a measure of the strength of the interaction between neighboring moments. Larger is λ stronger is the interaction.

In our earlier relation
 $M = N \mu_{ion}^2 B/kT$, replacing B by B_{loc} , we get
 $M = N \mu_{ion} (\mu_0 H \mu_{ion} + \lambda M \mu_{ion} \mu_0) / kT$


Defining $M_{sat} = N \mu_{ion}$
 $M/M_{sat} = \mu_0 H \mu_{ion} / kT + \lambda M \mu_{ion} \mu_0 / kT$

If T_c is defined as $\lambda M_{sat} \mu_{ion} \mu_0 / k$
 $M/M_{sat} = \mu_0 H \mu_{ion} / kT + M T_c / M_{sat} T$

$M/M_{sat} [(T - T_c)/T] = \mu_0 H \mu_{ion} / kT$
 $M/M_{sat} = \mu_0 H \mu_{ion} / [k(T - T_c)]$, we have defined $\chi_{mag} = M/H$

$\chi_{mag} = M_{sat} \mu_0 \mu_{ion} / [3k(T - T_c)]$ (The digit 3 appears due to same reason as earlier)

$\chi_{mag} = C / (T - T_c)$



So, we can understand the ferromagnetic behavior just in terms of a local electric field that be localized is operative. So, the form is something like this. So, it is the applied field intensity and with magnetization, you have a mean field constant that is a coupling coefficient and it is a measure of the strength of the interaction between the neighboring moments; larger the value of lambda, stronger will be the interaction.

So, we have already deduced this relation magnetization is this. So, now, we are replacing the value of B with B localized. So, this relation is valid. So, saturation magnetization is nothing, but number of this atom or ion and individual magnetic moment so, N into mu ion. So, M by M sat is given by this relation and we have tacitly assumed that T C is the value which is shown in the green color.

So, I replace this M by M sat is something like this. So, you just derive this relation yourself so, it will be relatively clear. So, this value gets me to this relation and finally, we have defined that magnetic susceptibility is M by H. So, I have this relation here and again this three appears because of the same reason as earlier and this is nothing, but your Curie Weiss law which I just defined.

So, this was an attempt just to understand the felt constant or what we called the coupling coefficient of the exchange energy which actually helps the magnetic moment to be oriented in one particular direction.

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Antiferromagnetism

In some magnetic material the coupling coefficient is negative and magnetic moments on adjacent ions are antiparallel. Net magnetic moment is zero. These solids are **antiferromagnetic**. Note T_c is negative for antiferromagnetic materials.

$\chi_{mag} = C / (T + T_N)$

A maximum in susceptibility is observed at a temperature T_N , known as **Neel temperature**. Above T_N the material is paramagnetic, the Curie Weiss law holds again (NiO, CoO etc)

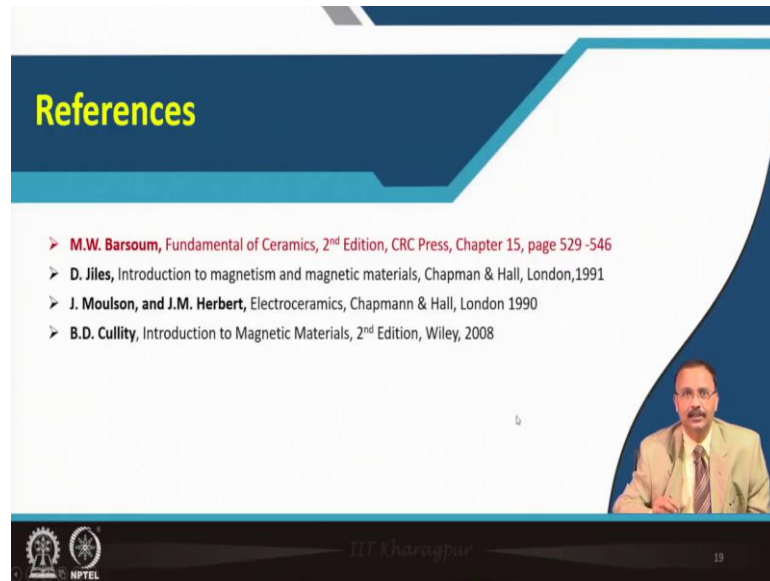
In certain material the coupling is negative, but adjacent moments are unequal, and they do not cancel and a net moment results. These materials are called **ferrimagnetic**

In some magnetic material the coupling coefficient is negative and the magnetic moments of adjacent ions are antiparallel in nature. So, the net magnetic moment is zero. This kind of solids are called antiferromagnetic and the variation of susceptibility is given by $\chi_{mag} = C / (T + T_N)$ where T_N is a nil temperature. It denotes the maximum of the magnetic susceptibility as you can see.

You can just extend this curve and here you can see the T_c value. So, called T_c this is negative for this type of material. So, antiferromagnetic material is having a nil temperature. Above the nil temperature it is of course, paramagnetic it follows the Curie Weiss law nickel, oxide cobalt, oxide iron, oxide FeO. They are the examples of antiferromagnetic material.

So, in certain material the coupling is negative and of course, below the nil temperature it is antiferromagnetic in nature. So, the magnetic moment cancels to each other, but in certain materials it does not cancel. So, there are a remnant magnetization remains and this type of material is called ferrimagnetic material. And typical example schematic is shown here in case of antiferromagnetic this and this will cancel, but in case of ferrimagnetic this will remain. So, some net magnetization is there.

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References

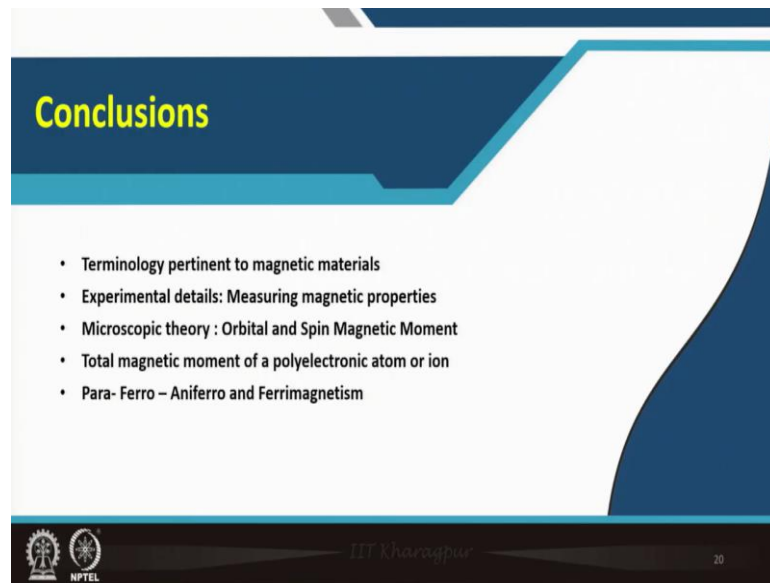
- **M.W. Barsoum**, *Fundamental of Ceramics*, 2nd Edition, CRC Press, Chapter 15, page 529 -546
- **D. Jiles**, *Introduction to magnetism and magnetic materials*, Chapman & Hall, London,1991
- **J. Moulson, and J.M. Herbert**, *Electroceramics*, Chapman & Hall, London 1990
- **B.D. Cullity**, *Introduction to Magnetic Materials*, 2nd Edition, Wiley, 2008

The slide features a dark blue header with the word 'References' in yellow. Below the header is a white area containing a bulleted list of references. In the bottom right corner, there is a small video inset showing a man in a light-colored suit and tie speaking. At the bottom of the slide, there are logos for IIT Madras and NPTEL, along with the text 'IIT Madras' and the number '19'.

So, in this particular lecture I have talked about the basics of the magnetic material and the study material for this is Barsoum, the book by Barsoum Chapter 15 and the page number is also given. So, that you can read and you have a better idea understanding about the fundamental concepts that I have covered.



Other than that you can have nice book by D Jiles and B. D, Cullity, they are fundamentally very good book on magnetic properties of the material and for the application of this magnetic material you can consider the book by Moulson and Herbert named Electroceramics.

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Conclusions

- Terminology pertinent to magnetic materials
- Experimental details: Measuring magnetic properties
- Microscopic theory : Orbital and Spin Magnetic Moment
- Total magnetic moment of a polyelectronic atom or ion
- Para- Ferro – Aniferro and Ferrimagnetism

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So, in this lecture I just described the terminology which are pertinent to magnetic materials and then we have defined an experimental details to probe the magnetic properties. And remember that while I described this particular experiment, I never assumed any kind of magnetic ordering in the solids; I just mentioned that it is a solid sometimes it is repelled by the induced magnetic field.

They are diamagnetic sometimes the magnetic susceptibility is very weak, but positive value we talked about those material which are paramagnetic in nature. Sometimes it is very strong that is ferromagnetic in nature. We also talked about antiferromagnetic and ferrimagnetic materials. Those kind of material nature cannot be identified by the experiments that I just described.

So, in order to understand that you will have to understand the microscopic theory which covers the orbital and spin magnetic moment as well as total magnetic moment we have defined and the l is quenched. So, only the spin quantum number is valid for estimation of the magnetic moment and finally, the paramagnetic, ferromagnetic, ferrimagnetic, antiferromagnetic characteristics of the material is described.

Thank you so much for your attention.