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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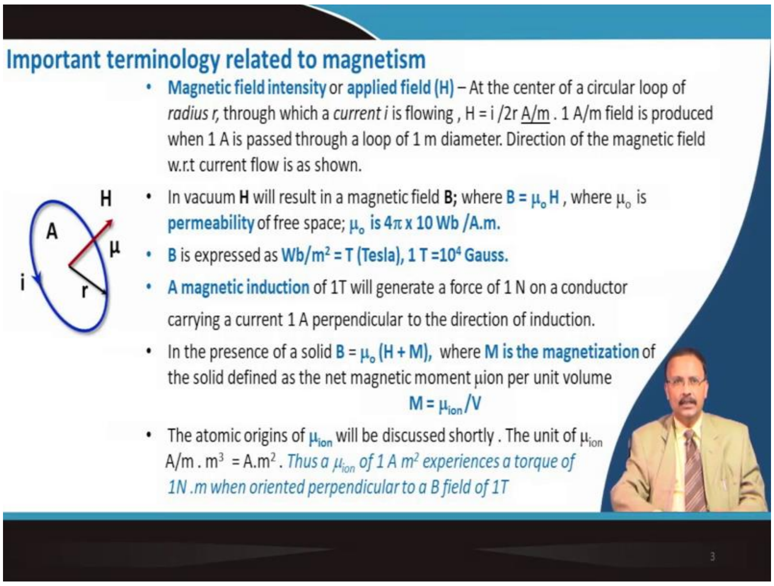

Now, let us consider a simple loop here made by a wire where current is flowing; the direction of the current flow is in accordance to the arrow. So, once this coil carries a an electric current, then at the center of this circular loop and we have assumed the loop radius is typically r and i current 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 4 pi 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 to the power 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 mu 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 mu ion is ampere per meter into meter cube that comes from the volume. So, it is ampere into meter square. So, mu 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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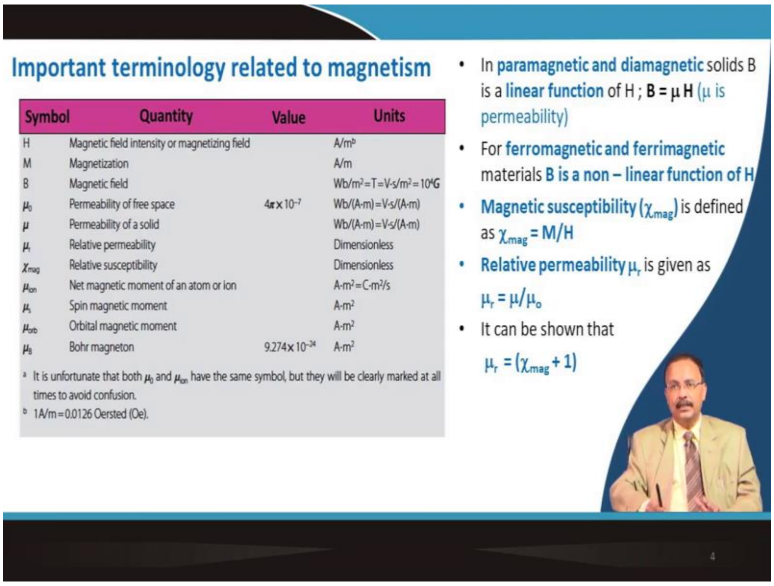

So, here in this table, you will find the different quantity what exactly I have described. Some you will be able to understand like H is defined magnetic field intensity magnetization is defined, then magnetic field is defined permeability of the free space mu 0 is defined. And this is as I said 4 pi 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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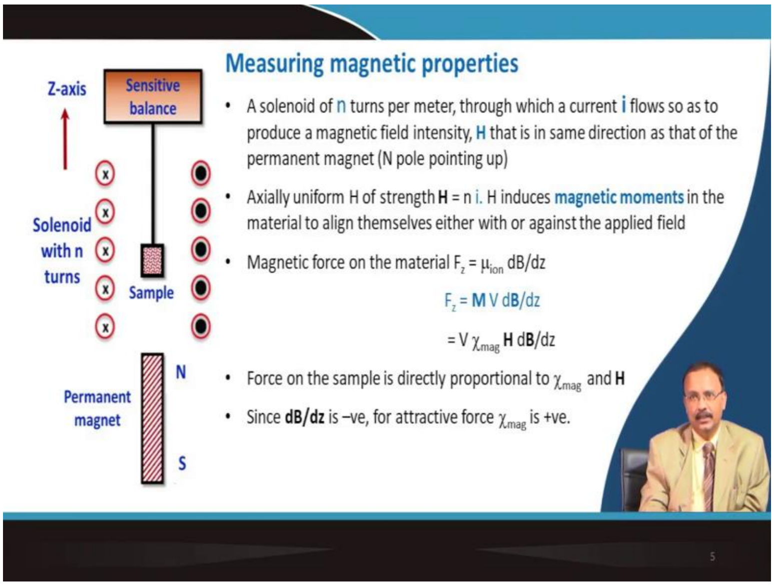

Now, I was talking about this experiment, let us understand the experiment. A solenoid you can see here a solenoid which is having n turns per meter. So, this is a metallic coil. So, inside this metallic coil which is having a turn of n per meter; I am assuming i current is flowing. So, direction of 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 mu 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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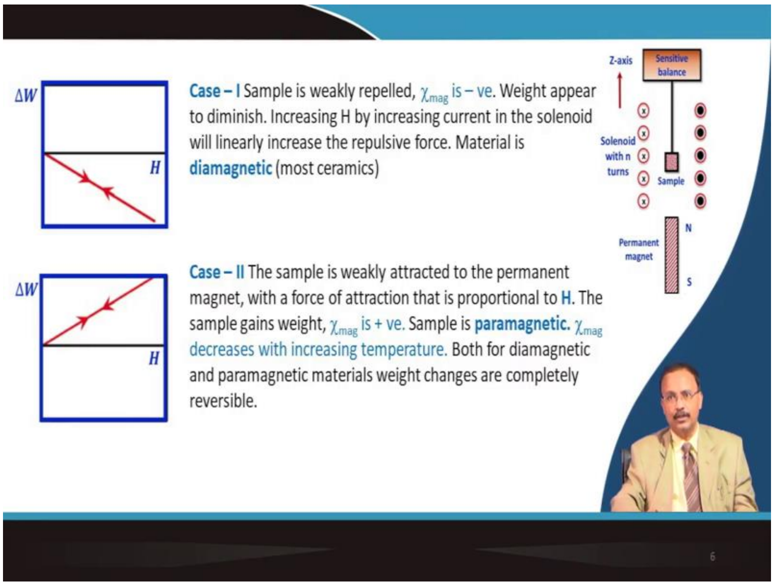

So, let us consider now the nature of the sample. So, case I that sample is weakly repelled. So, susceptibility is negative. So, weight appear to diminish. So, it will repel it. So, magnetic field will repel the sample so, the weight will diminish. So, if you plot the change in weight versus field of 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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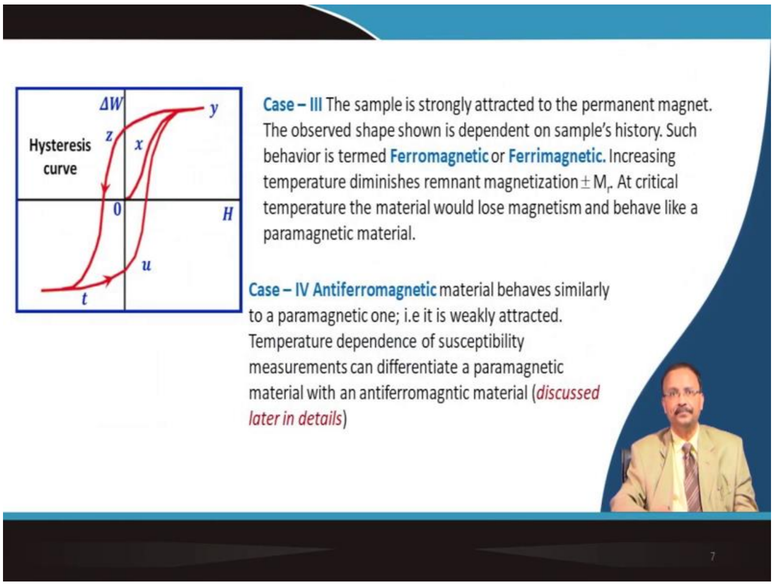

Now the interesting thing appears in certain sample when they are strongly attracted to the permanent magnet. So, once they strongly attracted, the shape of the change in weight with respect to the magnetic field, it is something like this it starts from here in the origin state then it is going like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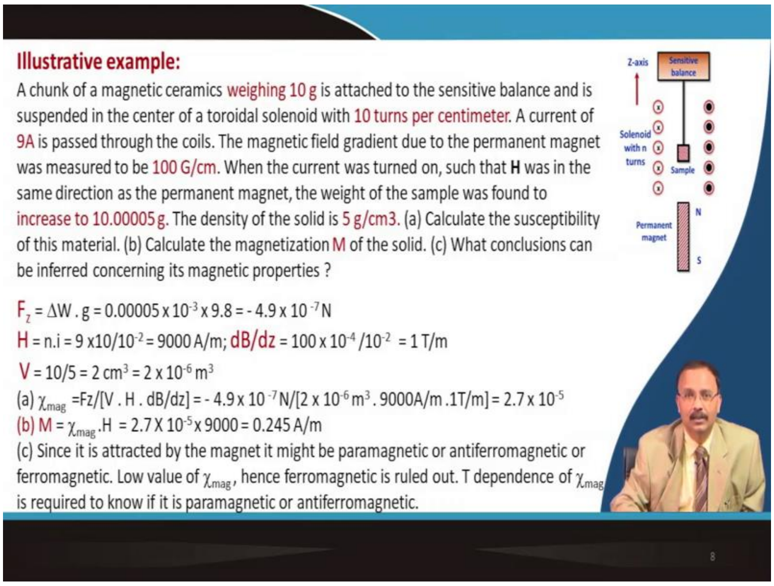

So, let us have an illustrative example just to understand the basic concept. So, the same experiment if you remember, there is a solenoid coil and we are passing a current through it. So, it induce magnetic field. We have hung a sample and the sample is connected to a very sensitive balance which can 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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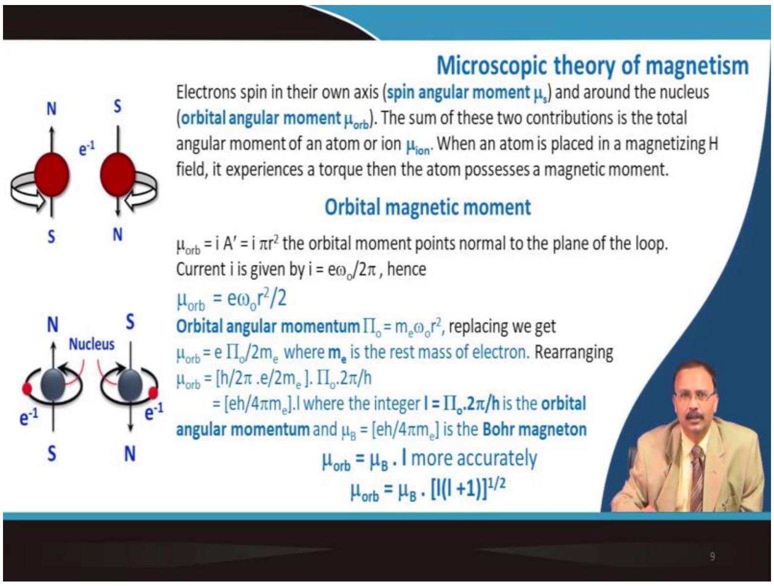

Now, this microscopic theory of magnetism is related to electron spin as you know that electron can spin in its own axis and then we call this is a spin angular momentum and it can also rotate along around the nucleus. So, we call its orbital angular momentum mu orbital.

The sum of these two contribution is a total angular moment. So, that is for one single atom or ion, it is mu 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 pi r square orbital moment points normal to the plane of the loop. And this current is actually given by its charge into omega 0 and divided by 2 pi from elementary physics concept.

So, your mu orbital you can calculate e omega r square by 2 orbital angular momentum is nothing, but this rest mass of electron into omega 0 r square. So, we replace this equation and rearrange it. So, I am introducing this term h by 2 pi. So, I can get this relation.

So, out of this relation this is e h by 4 pi m e into the another integer l that is the angular momentum. The first term is known as Bohr magneton e h by 4 pi into rest mass and l value is given as this pi 0 into 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 into l plus 1 root over. So, that is the expression for your orbital magnetic moment.

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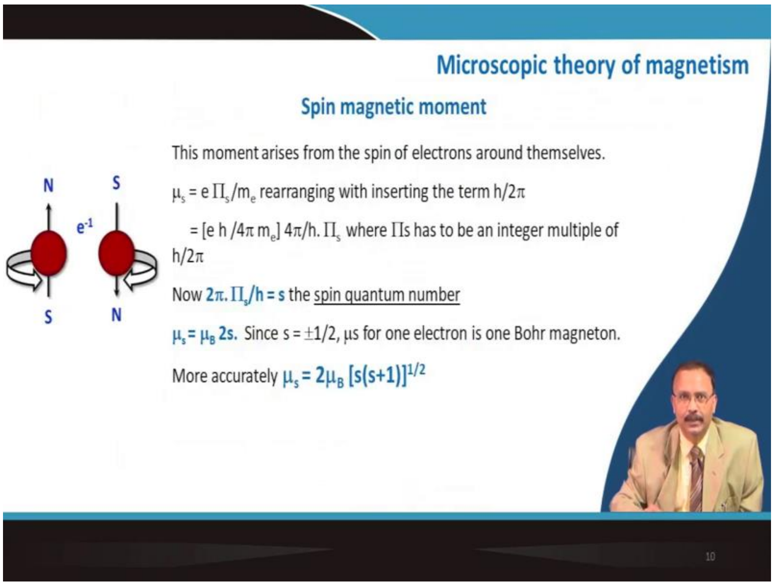

Similarly you can estimate the spin magnetic moment and this arises from the spin of the electron around themselves, it is rotating in its own axis. So, similarly this spin moment is also e into pi s by rest mass of electron. So, again we are rearranging by putting the term g by 2 pi from fundamental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

So, here this pi s that has to be an integer multiple with h by 2 pi from the basic quantum mechanics theory. So, this 2 pi into pi s by h, it is equal to s small s where s is the spin quantum number. So, your mu s mu related to the spin is now Bohr magneton into 2 s 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 plus 1 to the power half.

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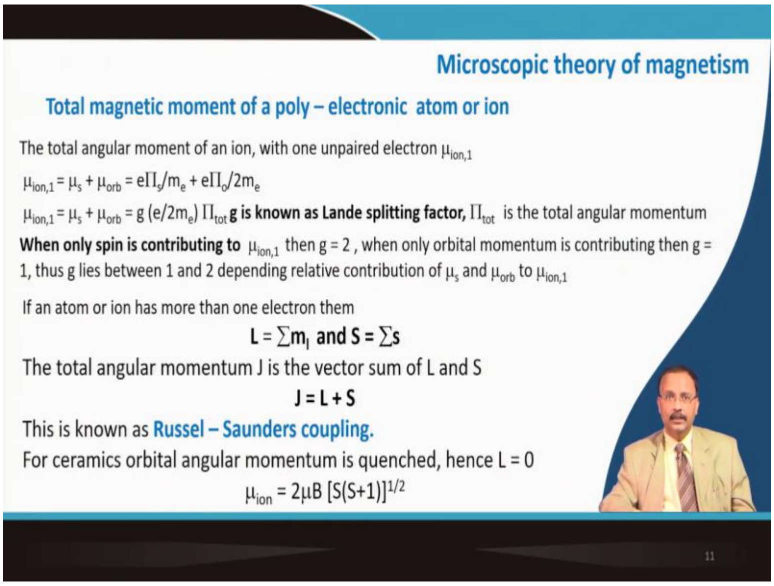

So, now, the total magnetic moment is for 1 ion with 1 unpaired electron. If I consider that so, that mu ion will be the spin an orbital moment. So, I just put the relevant values and then I just introduce a term g which is known as Lande splitting factor. So, this total pi total is the total angular 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 are 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 mu ion is nothing, but 2 into Bohr magneton mu B and the value of the contribution of all spin. So, capital S into S plus 1 to the power half so, root over of that.

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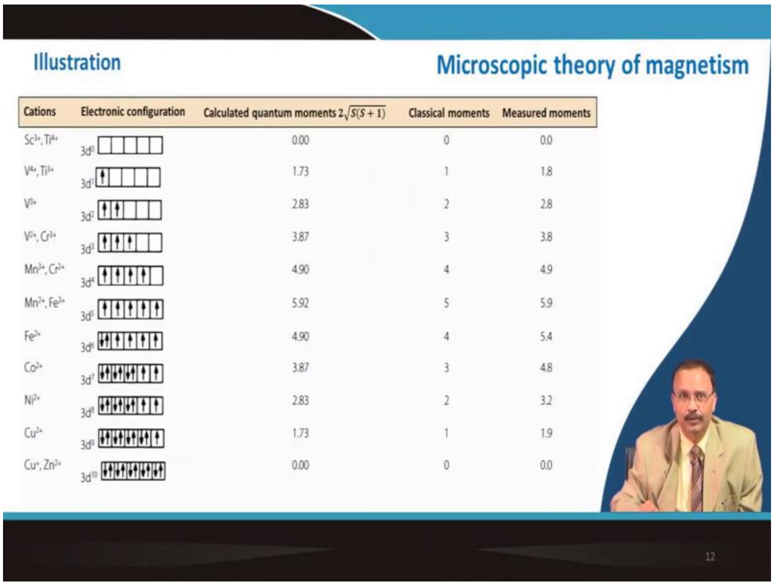

So, now, you can consider various types of cations as you can see and you can configure the electron from elementary chemistry idea 1 S 2, 2S 2 2p 6. So, the final you will find that the d shell is either unfilled or it is partially filled or it is coupled something like that. So, the calculated quantum 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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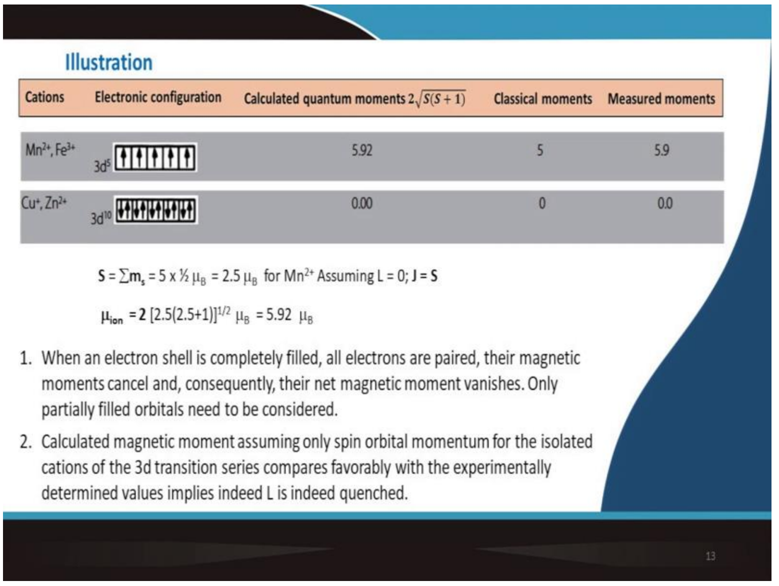

So, I will just show certain examples. So, I have taken the example of manganese 2 plus and iron 3 plus. So, here you can see that there are 5 unpaired electron. So, it is having plus half. So, the total S is 5 into half Bohr magneton so, 2.5 Bohr magneton and the L is quenched as I said. So, the J value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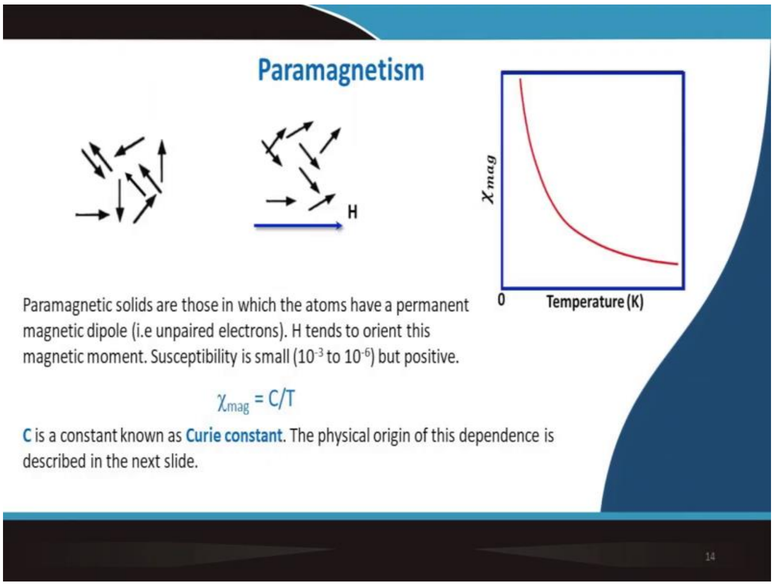

Now, let us have a look about paramagnetism as such paramagnetic solids are those solids in which the atoms have permanent magnetic dipoles; that means, unpaired electrons are there and H the magnetic field intensity tends to orient this magnetic moment. Susceptibility is usually small 10 to the power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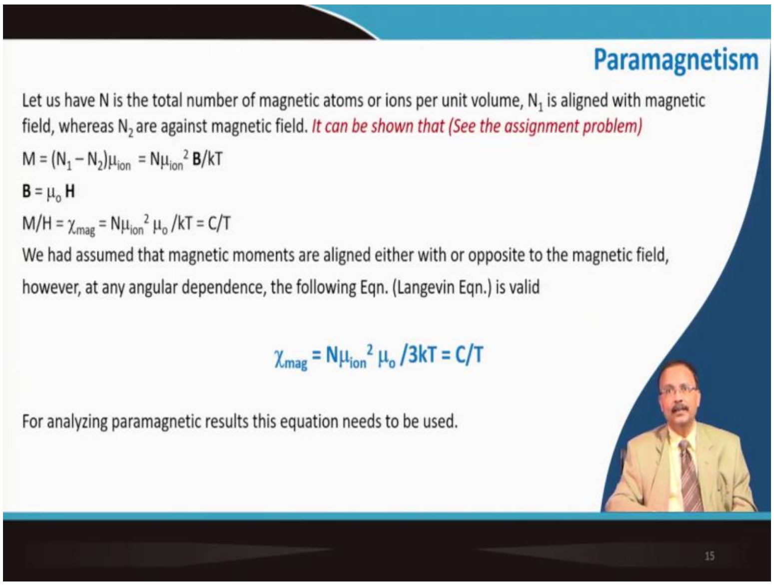

So, let us consider there are N total number of magnetic atoms per unit volume and N 1 out of that is aligned with the magnetic field and N 2 are against the magnetic field. So, you can show that the magnetization is N 1 minus N 2 into the magnetic moment mu ion.

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 mu 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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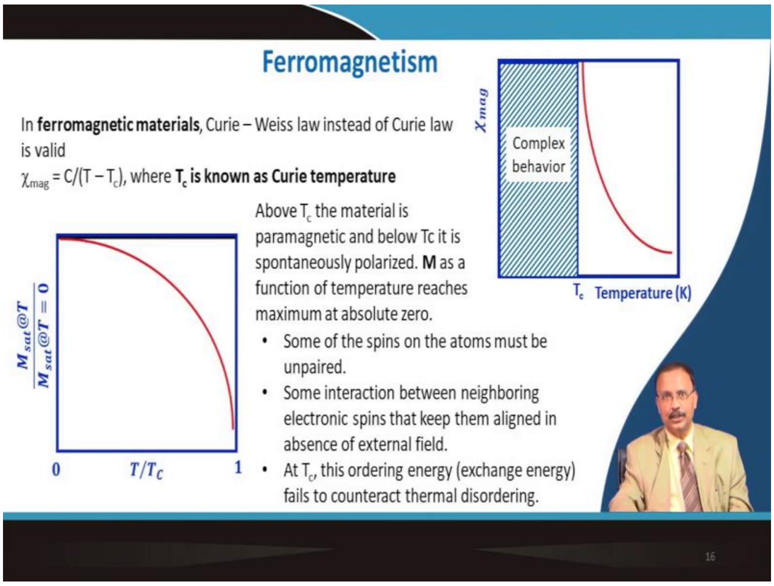

In ferromagnetic material, it will follows a Curie Weiss law instead of a Curie law which I just defined. So, Curie Weiss law is given by C divided by T minus T c. So, this T c is a Curie temperature something similar to your ferroelectric material which I have talked about. Above T c the material is paramagnetic in those case, 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 for this description so, that is why the shaded area we are not talking much about it.

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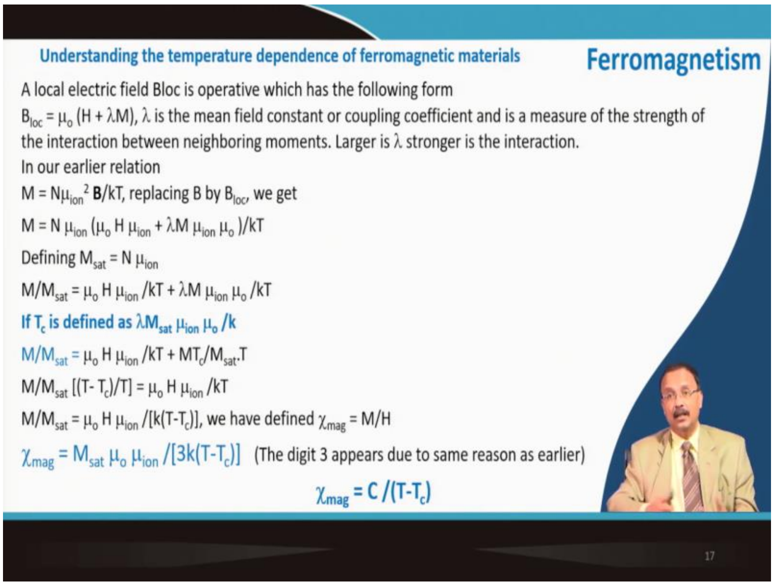

So, we can understand the ferromagnetic behavior just in terms of a local electric field that be localized is operative. So, the form is something like this. So, it is the applied field intensity and with magnetization, you have a mean field constant that is a coupling coefficient and it is a measure 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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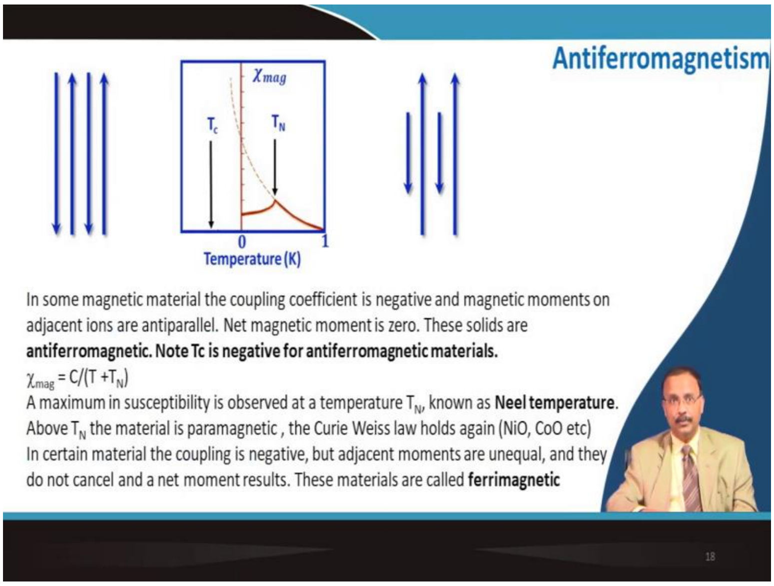

In some magnetic material the coupling coefficient is negative and the magnetic moments of adjacent ions are antiparallel in nature. So, the net magnetic moment is zero. This kind of solids are called antiferromagnetic and the variation is given by susceptibility is C divided by T plus T N where T N is a nil temperature. It depends I mean 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 the. 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 F e O. 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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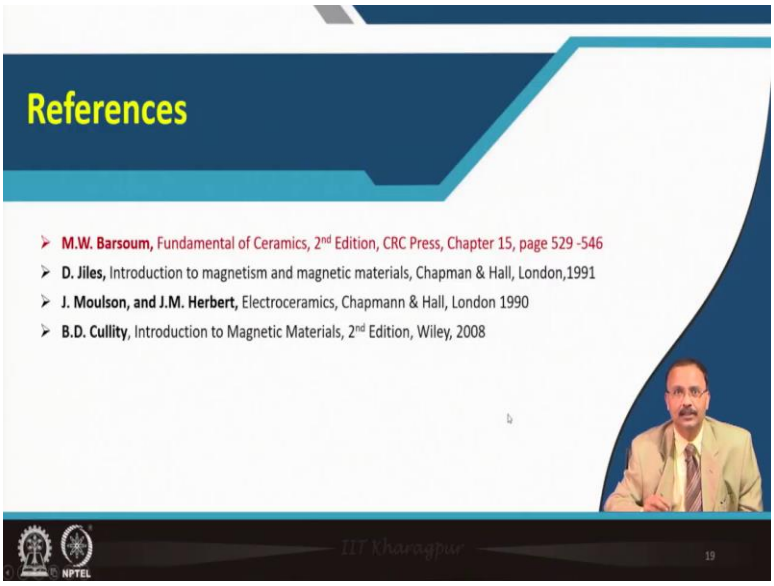

So, in this particular lecture I have talked about the basics of the magnetic material and the study material for this is Barsoum, the book by Barsoum Chapter 15 and the page number is also given. So, that you can read and you have a better idea understanding about the fundamental concepts that I have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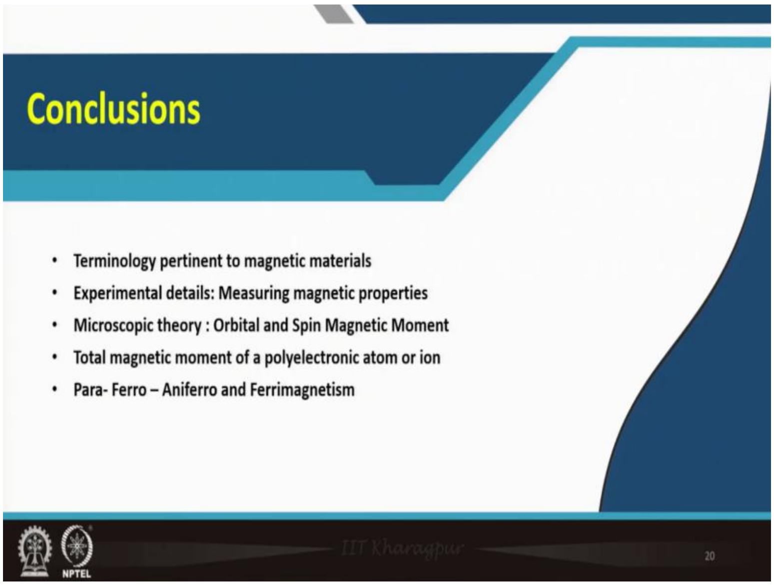

So, in this lecture I just described the terminology which are pertinent to magnetic materials and then we have defined an experimental details to probe the magnetic properties. And remember that while I described this particular experiment, I never assumed any kind of magnetic ordering in the solids;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