Lecture - 36

So, this is again a new class on the same module of magnetic ceramics and we were at the end of discussing the ferromagnetism. In the ferromagnetism, one of the important concepts is to explain the ferromagnetism and to explain the curie transition or Curie Weiss transition.

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Then, what is proposed is molecular field theory. Now this molecular field theory was proposed by Weiss in 1907 and this was essentially to explain that why in ferromagnets the atomic spins align in one direction, because the picture the microscopic picture of moments is like this in ferromagnetic materials, you have spontaneous alignment of magnetic dipoles. Now, this gives rise to a spontaneous magnetization that to large.

So, the question was why does it happen? Now, the basis for this came from Weiss in 1907, who proposed that this is, this ordering, this ordering of a spins in one direction is because of some neighbourhood effect and this neighbourhood effect is nothing but, is nothing but, having some internal field inside the material, because of presence of neighbours around each atom and this internal field is something which helps in keeping

these spins align in one direction. Although this concept is proven wrong little later, because when we go into details, we find that the field requirements to satisfy this, the field requirement to satisfy this condition is extremely large. You need to require fields of the order of the latest labs which is extremely large field, and which has, which cannot be generated even by the best of the machines.

So, but this sought of laid the foundation of finding the fundamental aspects of this magnetic ordering in ferromagnets, so what he postulated in 1907, something called as internal field and this internal field is similar to what we saw in dielectrics in module 4 as a, as an internal field which helps in, which acts on top of the applied field. And this is again because of presence of surrounding ions on the on the particular atom. So, this internal field modifies the total expressions for the total expressions of the field. Now, if you write this internal field expression, let us say this is H i, and this H i is now modified by this is applied field H, and then you have what is called as H w which is nothing but Weiss field or molecular field, some sort of molecular field because of presence of ions. Now, this molecular field was later conceived by Weiss as gamma M where gamma is nothing but, a Weiss constant or a molecular constant.

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So, this gamma was molecular constant and as a result what you have now is, so for a ferromagnetic material, now susceptibility is M by H, and if you replace this H by the modified expression for H, so it becomes M by H divided by H plus gamma M and what

was this equal to from the curie's behaviour? This was equal to C by T. So, what you get after modifying this expression is M by H to be equal to C divided by T minus gamma C. Now, this gamma C turns out to be equal to what is called as Curie temperature. Now this Curie temperature is same as transition temperature for most practical purposes. But when you look at it microscopically in the vicinity of this transition temperature, they are a little different. As a result, this particular expression is called as Curie Weiss law or Curie Weiss behaviour. So, what you have in the in the plot of magnetism in magnetization and susceptibility now is.

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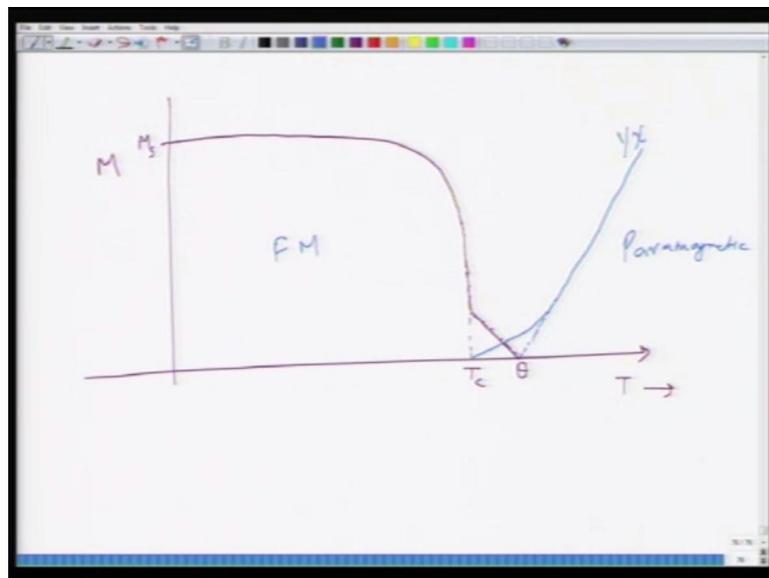
When you plot magnetization first, as a function of temperature, so magnetization, it starts from M s which is a saturation magnetization and then it drops near the temperature, which is let us say the transition temperature T c, the Curie temperature, the most the temperature, which we conceived best. But what happens is that, there is a diversion near the T c and it dives off slowly. So, it comes up to this point and then it dives off slowly and it goes to temperature theta and this is what, this is now, now you can understand what is theta and what is T c. And this is best reflected in the susceptibility part. So, what you have in susceptibility part is essentially, so this is your 1 over chi term and what you have is a divergence or the susceptibility which leads to slow move towards T c. So, what you have is, so this region will of course, be paramagnetic and this would be of course, the ferromagnetic.

So, this little discrepancy in T c and theta is because of Curie Weiss behaviour and although for most practical purposes in all the books, you will find that this M s curve drops right at T c itself. So, this is this is one of the differences from the Curie behaviour as we saw earlier for paramagnets. So, what you have here is, you call theta as a temperature for paramagnetic transition temperature, and then T c can be called as a ferromagnetic transition temperature. And in between the lines, remain little fussy. So, these are the two lines which demarcate the difference between ferromagnetic and paramagnetic behaviour.

Now, if you now you can, you can sort of roughly work out what is the value of this applied field, and before we do that just to remember the theta is greater than T c in most of the cases and what this means is that, that the molecular field is acting in the direction of applied spins. So, this sought of helps, because this is what you should explain, you should expect for ferromagnets, because the moments are aligned parallel to each other. And so now, if you calculate, you can, you can roughly calculate estimate the direction of this applied field and this applied field.

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Let us say near the, near the transition temperature, the thermal energy is T c and the moment magnetization which is because of this molecular field is mu B H w and if you now calculate this, H w which is k T c divided by mu B, this works out to be for most ferromagnets. The transition temperatures which are reasonably well above room

temperature, this is of the order of kilotesla and this very large field. You cannot achieve even, this one very good machine. So, as a result there was something wrong with this concept of molecular field. So, later what emerged was what helps in aligning these atomic spins is the concept of exchange energy, and this exchange energy is because of exchange interaction between this spins which is a purely quantum mechanical concept.

And what this says is that, you have exchange energy which is, which is given by this Hamiltonian expression, Heisenberg Hamiltonian expression which is where, which says that H e x the Hamiltonian is equal to minus of sigma i j, and then you have J multiplied by S i S J. So, you calculate the overall energy for all the spins multiplied by a factor which is called as a J exchange or exchange interaction constant or exchange integral. Lot of times, you can approximate both of them and which depends upon the interaction between the electron proton and so on and so forth, we will not go into details of that and you have take the wave functions into account. But nevertheless it depends upon the atomic structure.

An atomic, an atomic inter, atomic interactions and the sign of this J x determines what kind of ordering are you going to have. So, a positive value will mean that the energy will be minimum and this positive value means that you have a spins aligned in the same direction, and this gives rise to what is called as a ferromagnetic interaction. And when you look at J exchange, which is negative and this negative means, this negative means that energy is essentially S i S J are antiparallel. So, as a result this is the expression. So, this is your another kind of ordering which is called as antiferromagnetic ordering which we see in the, in the next few minutes.

So this exchange energy is essentially the driving force behind this ferromagnetic interaction, unfortunately we cannot go into details of exchange energy, because of it is a little bit more complicated than what you would, what you would require to understand in this course. However, if you are interested to know about exchange energy, there are plenty of books available such as you can read for example, Rehammel electronic and magnetic properties of material, they have reasonably theta is on the exchange interaction and you can also read Hench and Wesel Elecroceramics. Then you have about they have a section on the description of this exchange energy. So, essentially this exchange energy is an energy which is responsible for this ferromagnetic interaction in the materials.
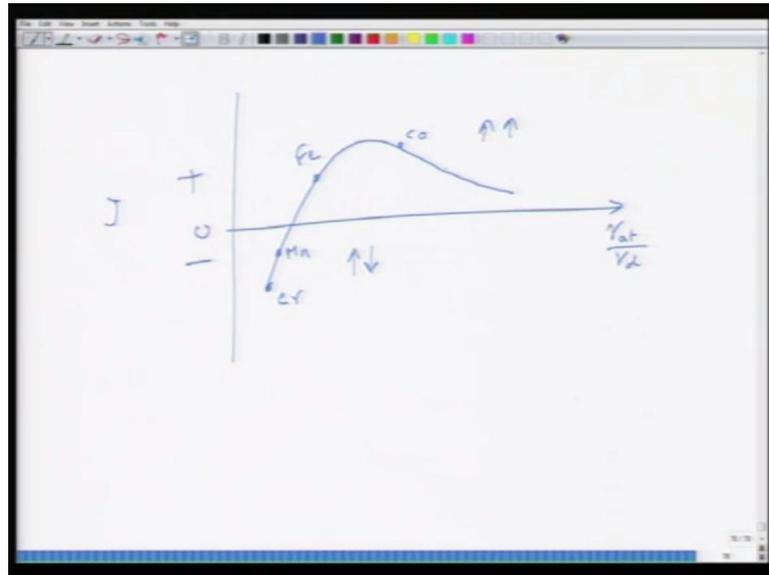
And if you plot this, for instance, this J as a function of atomic parameters, which is let us say r a t by r d which is essentially the atomic radius divided by the radius of the 3 d orbital of for 3 d elements. And if you plot J is around 0, when you see J goes something like this, and here, somewhere here you find manganese, somewhere here you find chromium. So, this is the negative value of J which describes antiferromagnetic ordering. So, you have a spin alignment like this. But, if you go here somewhere, iron, cobalt and so on and so forth, so the ferromagnetic d elements fall in this category of J which is positive. So, this sought of explains the reasons for ferromagnetic interaction in the materials. So, what we will do is that we will and so this sought of finishes the discussion on ferromagnetic material.

So, what you, so what basically ferromagnets are… Ferromagnets are the materials which show a spontaneous magnetization. They show what is called as presence of a hysteresis loop and this hysteresis loop is as a result of spontaneous alignment of magnetic dipoles. But also the shape of the loop and the values of coercive field, etcetera, depends upon how easily or how difficult the how easy or how difficult the domain movement is. And this domain concept is again similar to ferroelectric materials is, which is nothing but region of uniform magnetization or uniform magnetic alignment, and again, because of energy reasons, you have a multi domain structure and the way this domain structure changes as a function of applied field, you get a correct restrict hysteresis loop.

So, and these ferromagnetic materials, also follow what is called as a Curie Weiss behaviour which is nothing but transition from the ordered ferromagnetic state to a ordered paramagnetic state across a transition temperature which is called as T c. Although if you look at it more carefully in the vicinity of T c, you have 2 temperatures T c and theta, and theta is slightly above T c but nevertheless for all practical purposes, it is taken to be similar. Now, what we what I will do now is, I will just, I will show you couple of animations based in the domain movement in ferromagnetic materials and then, we will move on to another kind of Ferromagnetic ordering in materials which is important before we move into the discussion on magnetic ceramics things like ferrites and granites etcetera.

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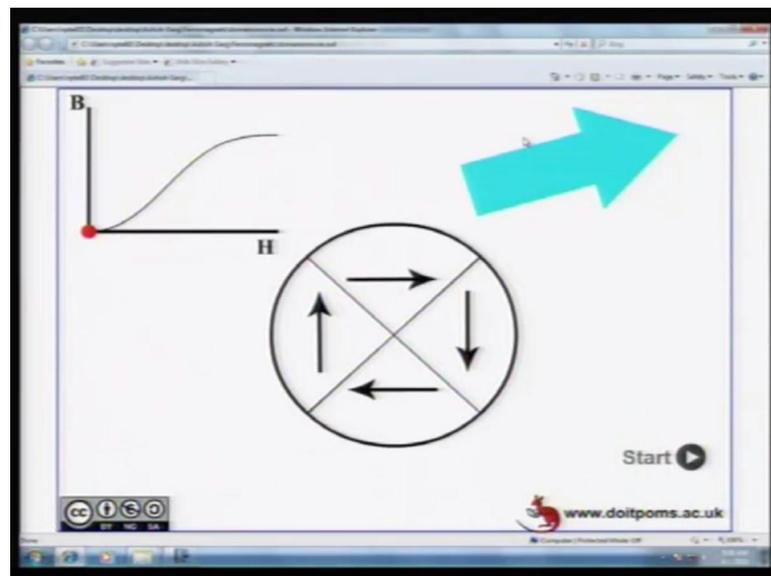
So, essentially I will first show you this one which is nothing but, a movie on the domain. Again, we acknowledge the support of help of doitpoms.ac.uk, who have put it that on their website for free circulation. So, we thank for their, we thank for their help. Now, you have a situation like this, you start at this point in the virgin material where zero magnetization is observed and this is the idealised domain structure where you get zero magnetic moment, and this is let us say the applied field direction.

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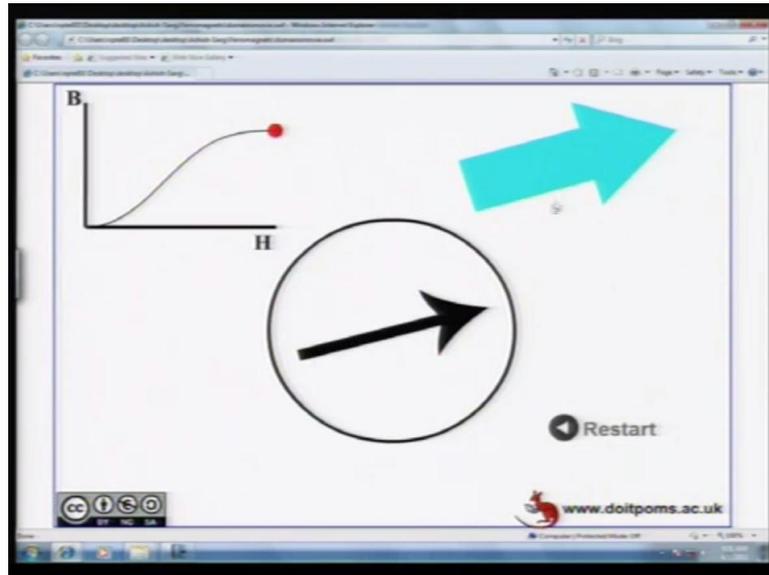
So you start increasing the field strength in this direction, and you can see how the domain structure changes. So, what you get is, what you get is this vector which is now turned in direction applied field. Initially, it was horizontal, but this was the most conducive domain alignment and this has grew, this has grown at the expense of other domains giving rise to domain growth in these ferroelectric materials. I will just play it again for the sake of illustration. So you can see that the unfavourably oriented domains slowly get wiped out.

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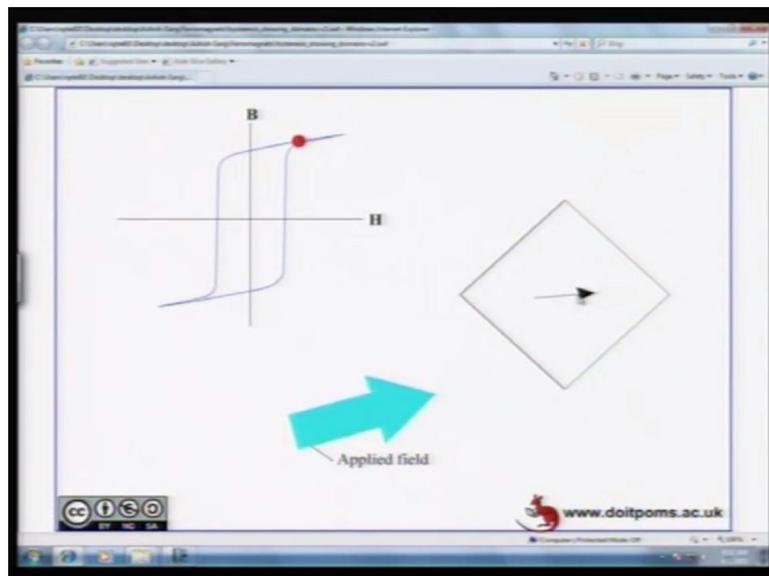
And another animation which I want to show you is this one. So, here you can see that the field is increasing and decreasing. Just focus on the black arrow and focus on the on the on the on this on this view graph on the right, so you see that this increasing in the field strengths. Now you have complete alignment of domains, then slowly it goes back to this point and then you have M R and 0 M R and then going back into negative direction, so this cycle continues and this essentially tells you about the domain growth in ferromagnetic materials. So what I will do now is that, I will now discuss the next class of materials, which is or next class of magnetism which is antiferromagnetism.

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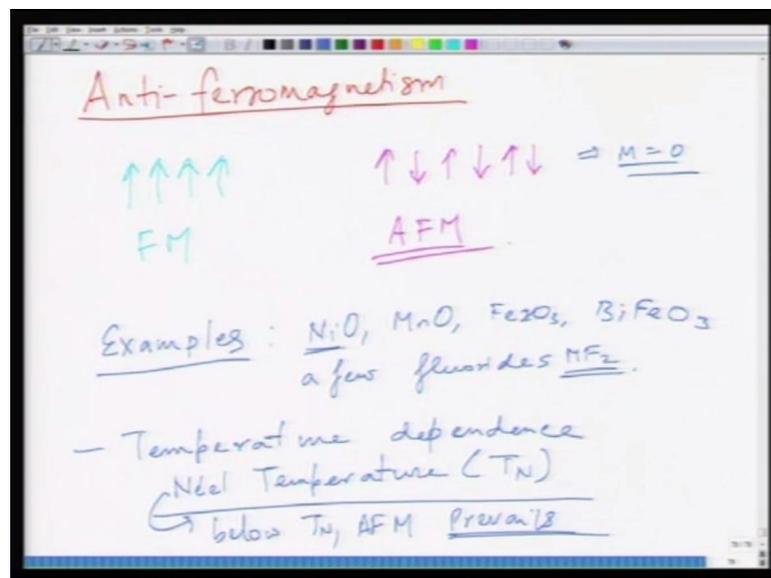
So, now antiferromagnetic materials are opposite to ferromagnetic materials in the sense that, while in ferromagnetic materials, the alignment of spins is in this direction. So, this is, what is ferromagnetism? In antiferro what you have is opposite alignment of spins and this is your antiferromagnetism A F M. And this happens in, this happens in crystallographic materials like. So, examples of this effect could be materials like, you know N i O, M n O, some hematite F e 2 O 3, B i F e O 3 and which is again a new class of materials and some fluorites as well.

So you can say M F 2 type of fluorides. So, they all show what is called as ferromagnetism, antiferromagnetism. So, essentially what happens is that in these materials, you can see that the two kinds of ions; you have one cat ion, one anion. Now anion is typically diamagnetic in nature, it does not contribute any magnetism. So, what

you have is magnetization being contributed or magnetic moments come only from the nickel. So, the question that you are, you can ask is, if they, if the magnetic moment is coming only from one type of atom, then why is that you have a antiparallel ordering and how is the antiparallel ordering happens and essentially this gives rise to zero magnetization as well. So, how does this happen and moreover these materials also have a temperature dependence.

So they have temperature dependence and below a certain temperature which is called as Niel temperature T N, below which these materials remain antiferromagnetic. So, below T N, A F M antiferromagnetism prevails and above T N, these become paramagnet just like your, just like ferromagnet to paramagnet transition. You have an antiferromagnet to paramagnetic transition. But the temperature is not called as Curie temperature. It is called as; it is called as Neil temperature. So, how it happens? So for instance we take example of nickel oxide.

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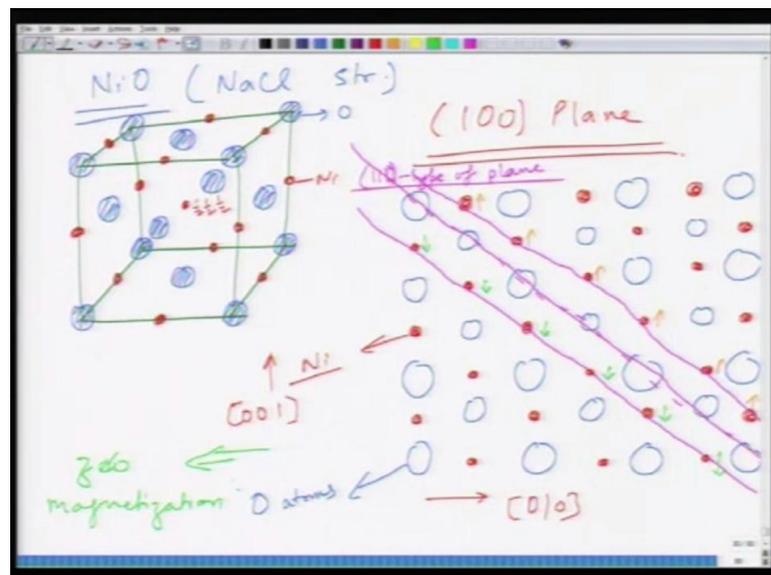
So you take a nickel oxide. Nickel oxide has N a C l structure. So N a C l structure is something like this. So, you have, if you just look at for instance, this is your N a C l. You have to go to module, go back to module 1, to see this. But here I will draw it for you. So you have…

So these are your corner atoms. Now both of the atoms, both of the ions, make F c c lattice. So, typically the base lattice is made by using anions so we make F c c lattice using anions which is chlorine, oxygen in this case. So, this is the base lattice made by oxygen atoms. Now, where does the nickel atom go? Nickel atom goes to the tetragonal tetrahedral sides. These are the tetrahedral sides for nickel and one at the body centre, so that in the middle at half half half. So, you have these all the tetrahedral sides occupied by nickel atoms. So, this is nickel and this is oxygen. So, this is the crystal structure.

Now what happens here is, the best way to represent antiferromagnetism is, is to look at only the nickel ions. Now for the representation of this antiferromagnetism, what we will do is that, we will draw the plan view of 1 1 0 plane. Typically, we are used to drawing 1 0 0 or 0 0 1 plan view. Here, we will take a representation of 1 1 0 plane. And this 1 1 0 plane, you can draw it, you can, you can draw it pretty well yourself. But in any case I will draw it here. What we will have is, or may be; let us, let us draw for the sake of simplicity.

Let us draw 1 0 0 plane, so if you draw 1 0 0 plane now, so 1 0 0 plane would be, so this is your, I will just draw few rows, not all the rows and the nickel atom goes. So, this is your nickel and then you have one at this position. Then of course, you have at these positions and you have of course, another nickel atom sitting at the centre of these phases. So, this is oxygen atom, all of them, so these are all oxygen atoms and these are all nickel atoms.

Now what happens here is, so this direction is, your let us say 1 0 0 direction and this direction would be, so this is we have taken 1 0 0. So, this would be 0 1 0 and this would be 0 0 1. Now what would be this kind of plane? So, if I draw a line like this, along just connecting these atoms, so this is nothing but, your diagonal across the phase and this diagonal, if you, if you take it inside, this diagonal will represent what is called as a 1 1 0 plane 1 1 0 type of plane.

So these along this direction, all the atoms are oxygen. They do not contribute to magnetism. But, below but, you have this series of these 1 1 0 planes. So, another plane is this, another plane is this. So, remove the oxygen from there, do not, do not count the oxygen, what you have now in these 1 1 0 planes is, in one of the planes these in one of the planes these nickel atoms, let us say here are spin up, but in the other planes they are

spin down. So, what you have here is spin down. Since you have to maintain the stoichiometry of material the net up spins cancel the net down spins as a result what you have is zero magnetization.

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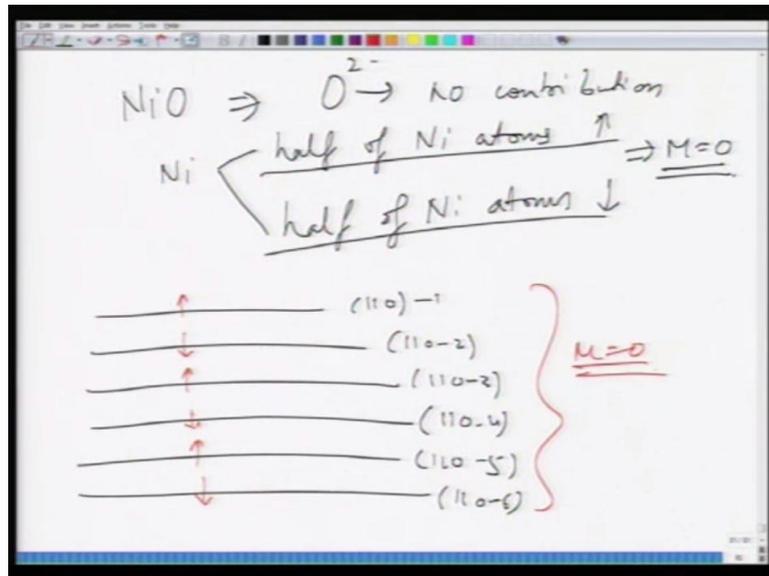
So you can say essentially that in N i O, oxygen no contribution nickel half of nickel atoms spin up half of other half of nickel atoms spin down. And this gives rise to M is equal to 0 and this is along 1 1 0. In the alternating 1 1 0 plane, so if you, if you draw now, like this, this is 1 2 3 4 5 6, so this is 1 1 0 1, this is 1 1 0 2, this is 1 1 0 3, this is 1 1 0 4, 1 1 0 5, 1 1 0 6. So, the nickel atoms here would give rise to positive, here it would be negative, it would be positive negative positive negative.

So essentially it is a same picture, it is it is a same picture I have just turned it around by 45 degrees. So, that 1 1 1 0 planes are now parallel to our view. So, now this gives rise to M is equal to 0. So, essentially you can say that there are in the F c c's sub lattice of nickel, there are 2 sub lattices; one sub lattice has a spin orientation up, another sub lattice has spin orientation down. And this gives rise to zero magnetization. So, I hope it is clear now. So, this is what is antiferromagnetism. Now these materials also a have temperature dependence as I said.

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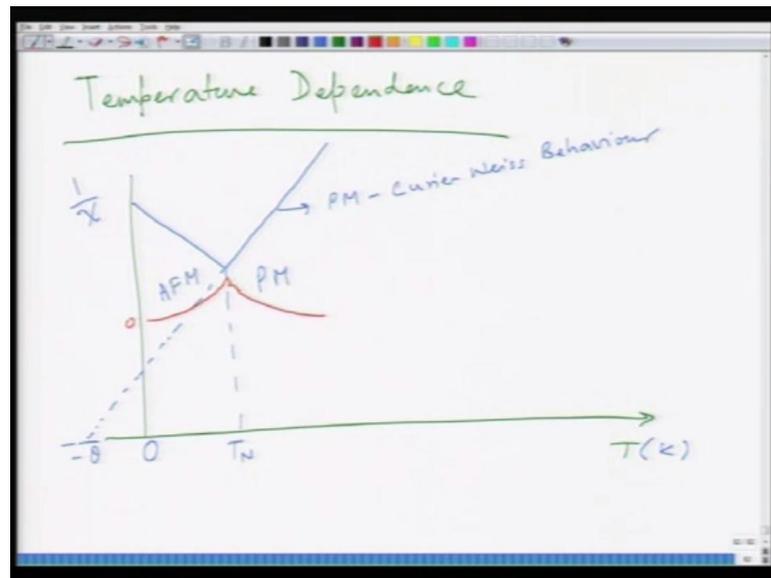
So, if you plot as a function of temperature, the first thing that you plot is let us say the T plot, what we call is 1 over chi versus T. Since they do not have any magnetization, it is meaningless to plot in terms of magnetization. So, what you have is, which increases little bit up to transition limitation and then it falls back again into paramagnetic regime. So, what you have here is essentially behaviour like this, and this line, you can extra pull it back and this is in Kelvin. So, this is zero Kelvin, so this is your T N, this is your paramagnetic Curie Weiss behaviour and this is your, and this is, so this region is antiferromagnetism, antiferromagnetic region. So, of course, nothing is below zero Kelvin, you cannot reach a temperature below zero Kelvin. But, you can extra pull it to the temperature axis, what you get a temperature like minus theta which does not have any practical significance although it is of some theoretical interest to theoreticians.

And then on the right, you have paramagnetic region. So, antiferromagnetic material, if you plot 1 by chi versus temperature, it falls down to until Niel temperature is reached and then it increases again for a as a as you increase the temperature. So of course, if you plot, if you plot chi, so chi would be something like this. This would be the behaviour of chi of course, the inverse behaviour it is not, so you so it sought of increases from 0 to some value. So, you would actually start at 0, very close to 0, because you do not have any magnetic moment and then it increases to some value near T N, and it falls off again. So, this is what your temperature dependence of antiferromagnetic materials. Now in antiferromagnetic materials, some materials do show some magnetization and which is

essentially because of deviation from the ideal spin configuration of perfect antiparallel configuration.

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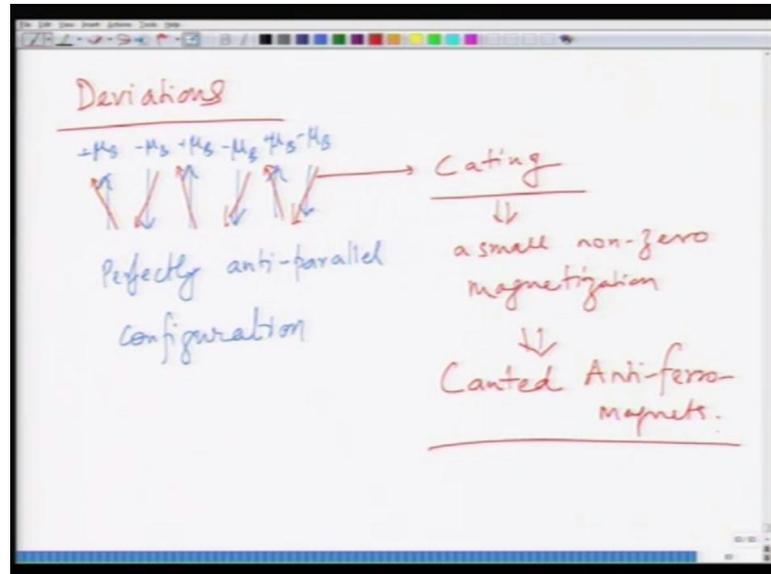
So, the perfect configuration is this perfect antiferromagnetism. So, you can say perfectly, I have plotted little wrong here, so these would be spin down, so each of these have mu B magnetization, some mu B. So, let us say, this is plus, this is plus, this is plus and another thing become minus minus minus. So, all of them cancel each other. So, perfectly antiparallel configuration and this is what is perfect antiferromagnetism. In some materials, what happens is that, you can have little deviation. So, this for instance may go little bit like this, this for instance may be little bit like this.

Similarly here this may be like this, like this and so on and so forth. And this configuration is called as canting. So this canting is little bit deviation from the perfect antiparallel configuration and this gives rise to a small non zero magnetization and these are and materials which show this are called as canted antiferromagnets. So, this is little deviation from perfect antiferromagnetism. So, I will not go into details of any of this, but it is just to explain some deviations from eye reality. Next type of magnetism in this class is called as ferrimagnetism.
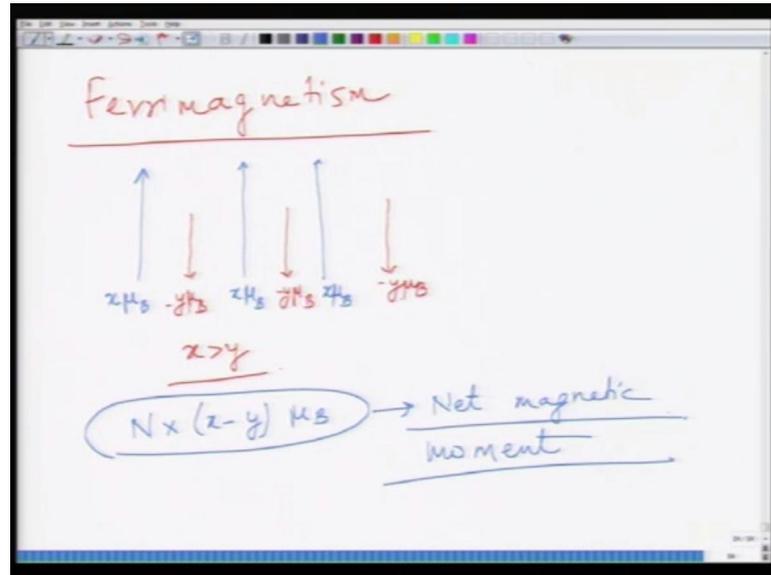
Now, ferrimagnetism is similar to, similar to antiferromagnetism it is just that so. In antiferromagnetism, what you saw was, you have one spin like this, another equivalent opposite like this, another equivalent opposite, so you have equivalent opposite spins which means they have equivalent opposite magnetic moments and they are perfectly antiparallel to each other. So, you have plus mu B minus mu B plus mu B minus mu B plus mu B minus mu B.

Now in antiferrimagnetism, what happens is this; so if this was, let us say x mu B plus x mu B, I will just rub it. So, let us say this is x mu B, what you have in the other direction is not exactly equal. So, what you have in the other direction is rather something like this. The length of the vector shows the length of the arrow shows the magnitude. So, this is let us say y mu B minus y mu B minus y mu B minus y mu B and here for the sake of illustration x is greater than y. Now, when you calculate the overall magnetization of course, overall magnetization would be number of atoms multiplied by x minus y mu B.

And this is not as long as x is bigger than y, this is not 0. So, this would be the net magnetic moment. So, ferrimagnetic materials are those materials which have antiparallel alignment of spins. But, these atomic spins are not equal in the magnitude which means a spin up in one direction have magnitude which is different from a spin down in another direction. Now this results in a net magnetic moment and this gives rise to what is called as a ferrimagnetism and so essentially what you have here is different.

So, as you can see the moment, you have different kinds of magnetic moments. You need to have different kind of atoms, so you have atoms which are of different types and these 2 atoms are sit at 2 different sub lattices and they give rise to what is called as what is what results in a net magnetization? So, examples of this kind of behaviour are materials like ferrites. So, these are all ferromagnetic ceramics.

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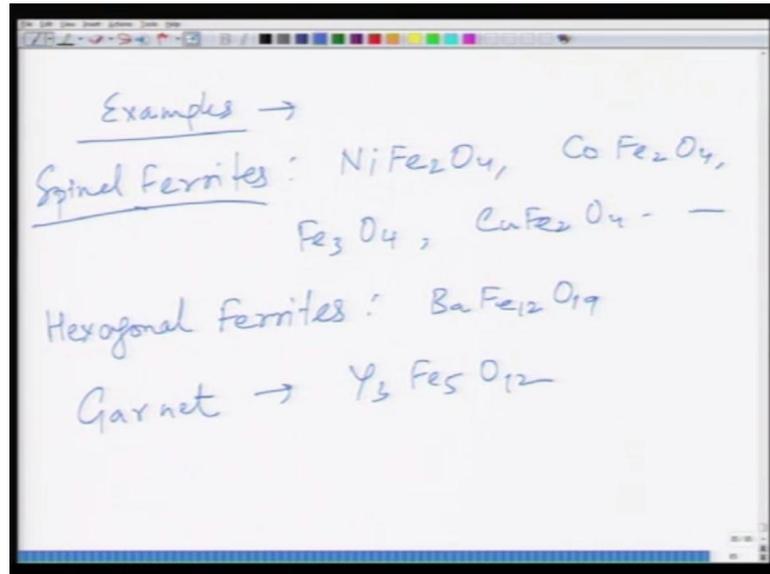
So, like $NiFe_2O_4$, $CoFe_2O_4$, Fe_3O_4 and $CuFe_2O_4$ and so on and so forth. Many of these ferrites have magnetism which is finite and so. On top of ferrites you have some other materials as well. So, these are all called as actually they are called as Spinel ferrites. So, I will just a word add Spinel ferrites, then you can also have hexagonal ferrites in this category such as a barium ferrite $BaFe_{12}O_{19}$. You can have garnets $Y_3Fe_5O_{12}$ example. So, you can see that most of these have ions which are magnetic in nature and they have and they have ions sitting on different sub lattices and they contribute differently to the total magnetic moment. It is not necessary that you have 2 different magnetic ions sometimes only 1 magnetic ion does the job but, it is the distribution of these ions on 2 different sub lattices which is important that we will see in detail when we discuss ferrites. So at the moment, I will, I will just, I will not discuss it too much, so I will just draw a picture. So you have basically 3 kinds of magnetic orderings.

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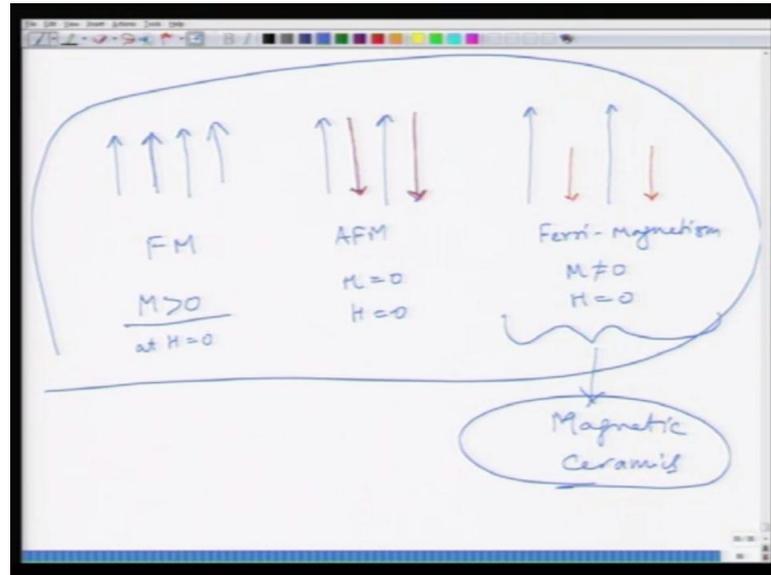
So you have ferromagnetic ordering which is like this, so this is your ferromagnetic ordering, antiferromagnetic ordering is this kind of ordering, this is antiferromagnetic ordering, and I will just use a different colour here. So, this is your antiferromagnetic ordering. So, you can say that M is much greater than 0 at H is equal to 0, M is equal to 0 when H is equal to 0.

And then you have second kind of ordering which is ferrimagnetic ordering. So, basically unequal spin moments and what you have here is then ferrimagnet. So, M is not equal to 0 when H is equal to 0. So, this is the 3 different type of magnetic orderings that you come across in variety of magnetic materials and this is the class which is typically magnetic ceramics. Typically all the antiferromagnetics are magnetic ceramics as well. But they are of a little use because of zero magnetization, so as a result you do not really technologically then they are very they are not studied that well by scientists. So, ferrimagnets also follow a similar curie transition just like ferromagnets.

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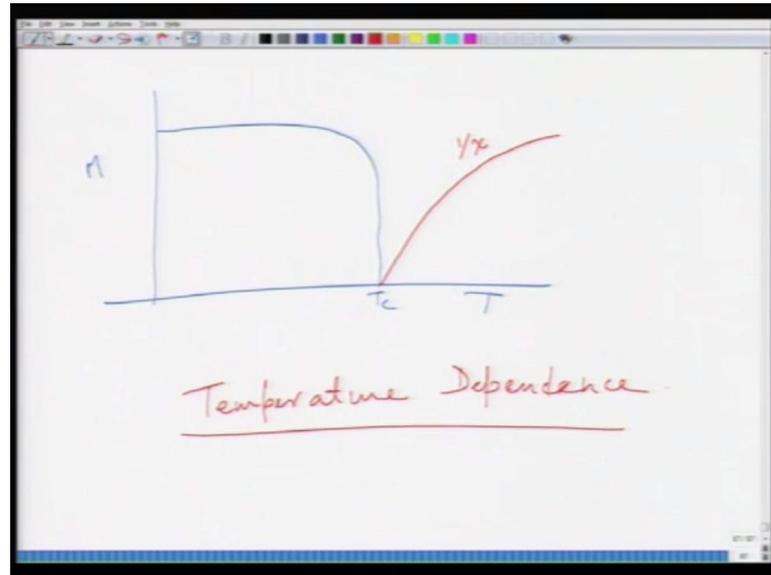
So, when you draw a transition magnetization versus temperature, so magnetization goes like this, near T c and and if you, if you plot susceptibility, the susceptibility 1 by chi goes like this, this is 1 over chi. So, again you might have some deviation from the behaviour which is perfect. But, this is how the behaviour typically is for a ferrimagnet. So, what I will do now is, I will just summarize all these different kind of magnetization before we go into the next part of this lecture. So, what essentially you have, you have we have discussed 4 various kinds of magnetism.

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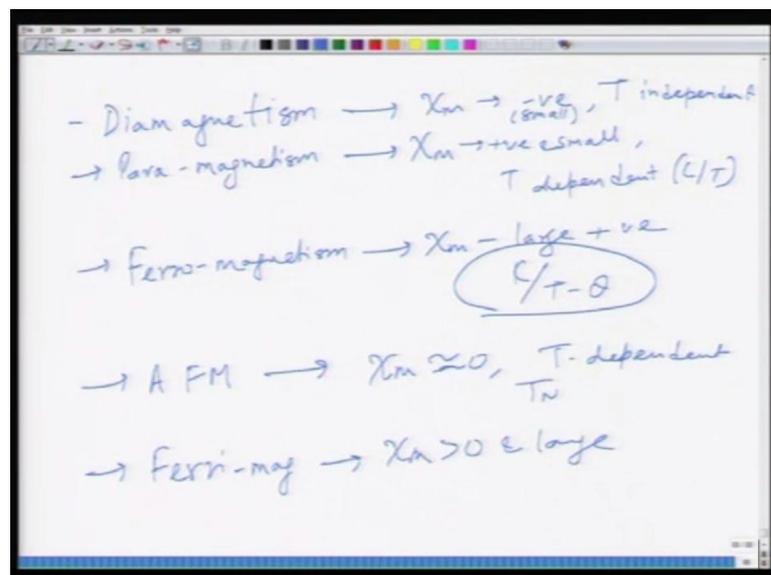
So, you have diamagnetism which is essentially due to response of electrons upon the application of electric field and this gives rise to susceptibility which is negative and temperature independent. Then, you have paramagnetism where each atom has a net magnetic moment, but all these magnetic moments are randomly placed with respect to each other as a result you have chi which is positive. But, small similar in case of diamagnetic it is a small typically but, it is temperature dependent. So, it follows a behaviour of C by T. But, another class of material is ferromagnetism, where atoms are atoms do have net magnetic moment. But these spins are also aligned in one direction at the below a certain temperature called as curie temperature and as a result chi M is large and positive and this also has a temperature dependence of C divided by T minus theta.

So this is the temperature dependence that you see in ferromagnets and then you have antiferromagnets which have chi M equal to 0, very small or very tiny and then but, positive it could be positive because of canting and they also have a temperature dependent behaviour and they have what you call as Neil temperature and then you have what is called as finally ferrimagnetism, which is sort of antiferromagnetism but different because the atomic spins spin magnetic moments are unequal in the magnitude as a result chi M is 0 and large and this is also temperature dependent. So, these are the 5 different kinds of magnetism that we discussed. And if you plot;

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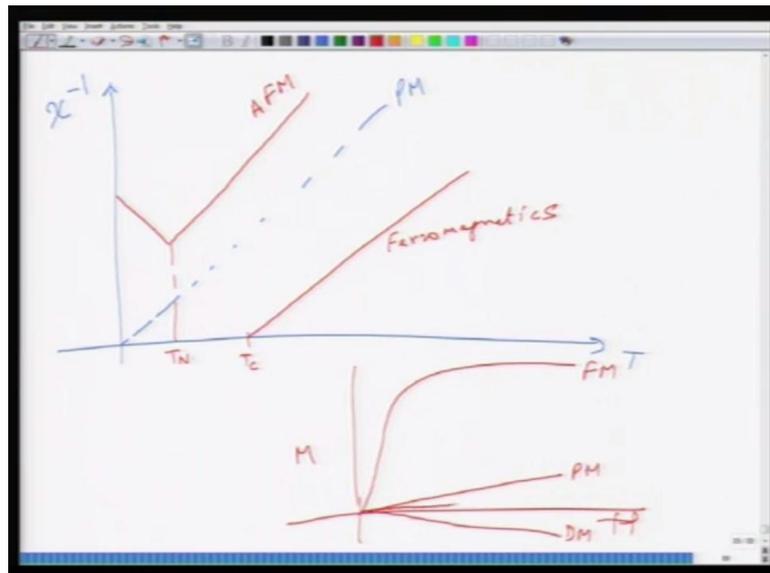
Now if you plot magnetic response of these materials individually, so for a paramagnet so for a empty ferro, we will start from paramagnet. So, for paramagnet of course, for a diamagnetic it is temperature independent, so we do not need to do that. So, you we just plot chi inverse for the temperature for the practically useful magnetic materials. So, we have paramagnet whose susceptibility is like this, it goes so this is your paramagnet and then you have antiferromagnet, antiferromagnet is something like this. So, this is your antiferromagnetic material behaviour at transition T N and then you have ferromagnet and ferromagnet has a response typically like this. So, this is your T C and this is so what you have here is essentially large susceptibilities below T C. So, that is why you do not plot it before below T C, so this is your ferro magnet and that is how ferrimagnet also look like. So, this is the typical comparison of ferromagnetic response like magnetization of ferromagnets is much larger as compared to rest of these materials.

So, when you plot magnetization M versus for instance H, M versus H for ferro ferrimagnet ferromagnets something like this very large ferri is also similar so this is ferromagnetic paramagnetic is very small linear response and diamagnetic will go other way round. So, this is D M diamagnetic and and antiferromagnetic would be very very small close to 0, this is a F M as a function of magnetic field. So, this is how the behaviour of all these different kind of magnetic materials compares with respect to each other.

So, this brings us to another topic before we go into discussion on ferrites is, the moment you have this hysteresis loop, you also have these what is called as a magnetic loses inside the material and these magnetic loses are not only aided by because the domain walls require energy for their movement as a result so it is something so you have domain wall growth. And the moment you have growth, you have friction inside the material you have energy dissipation, but also these materials also tend to be conducting and they tend to have certain they tend to have a small resistivity as a result you have large eddy current loses.
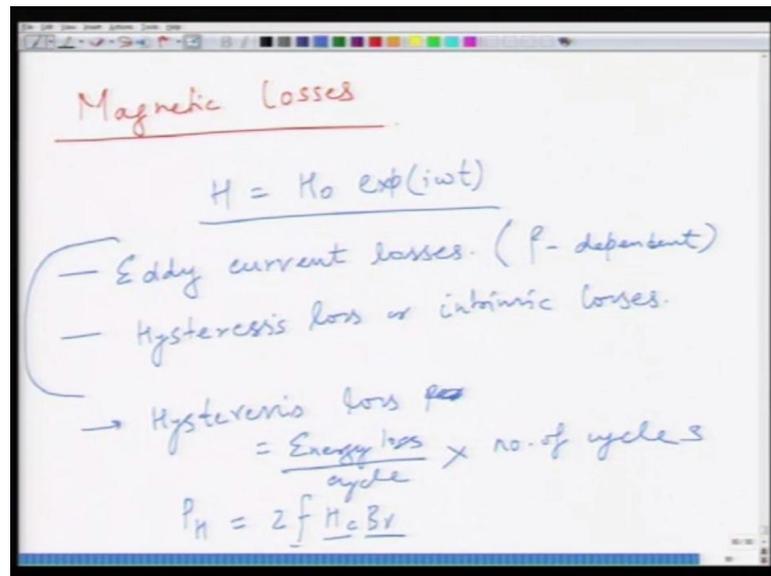
So the magnetic loses in these materials typically they are more important actually when these materials are used in frequency dependent applications. Because in frequency dependent applications you have switching of magnetic field as a function of time and then of course, you generate you have, you have back and forth movement of domains and this gives rise to large dissipation of energy. So, you can have alternating electric just like alternating electric field you have alternating magnetic field which is given by H is equal to H naught exponential of i omega t and in this alternating magnetic field is applied you have, you have dissipation of energy inside the material.

So you have essentially two coins of loses; one is the eddy current loss which are dependent upon the resistivity so you can say resistivity dependent and then you have second kind of loss which is you can say hysteresis loss or intrinsic loses. So, these are intrinsic to a ferromagnetic material and these are essentially because of domain wall movement, because the domain wall movement requires energy and as a result you have some dissipation of energy. So, the sum of these two loses governs how lossy a material is, so this basically the energy which is dissipated that dissipates as heat and this is what you do not want especially in the A C applications.

So typically what you see is that, while parameters like frequency magnetization coercivity they govern the second kind of loss. The resistivity of the material governs the first kind of loss. So, the total hysteresis loss, so the hysteresis essentially we will look at

2 both of these loses individually. So, hysteresis loss per, so let hysteresis loss essentially, hysteresis loss is the energy loss basically per cycle multiplied by. So, you have essentially this is energy loss per cycle multiplied by number of cycles and this is given essentially. So, P H is given as 2 f H c B r, so B r is the magnetic remanence H c is the course of field f is the frequency of applied field. So this is a P H factor which is due to hysteresis loses.

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The second loss is the eddy current loss and this eddy current power loss are given as what is called as P e and this is given as pi d square divided by 6 rho into f into B max and here you can see that this is the resistivity, and as the resistivity increases as the material gets more insulting, the power loss eddy current due to eddy current loss decrease, so that is why in applications like transformer cores etcetera where eddy currents are significantly, they are vey, they are very important. One must use materials with slightly higher resistivity.

So, total power loss P total is equal to P eddy plus P hysteresis. This is the total power loss and the characteristic of each of these governs in the choice of material govern the choice of materials. So, that the loss can be minimised especially in the applications where losses are crucial parameter, another thing that emerges from by use of A C field is that just like in dielectrics when you used A C field expression, you got expression for dielectric susceptibility which was complex in nature just similarly, in these materials.

When you use that kind of expression, you get you come up with a situation where the magnetic permeability also becomes complex in nature.

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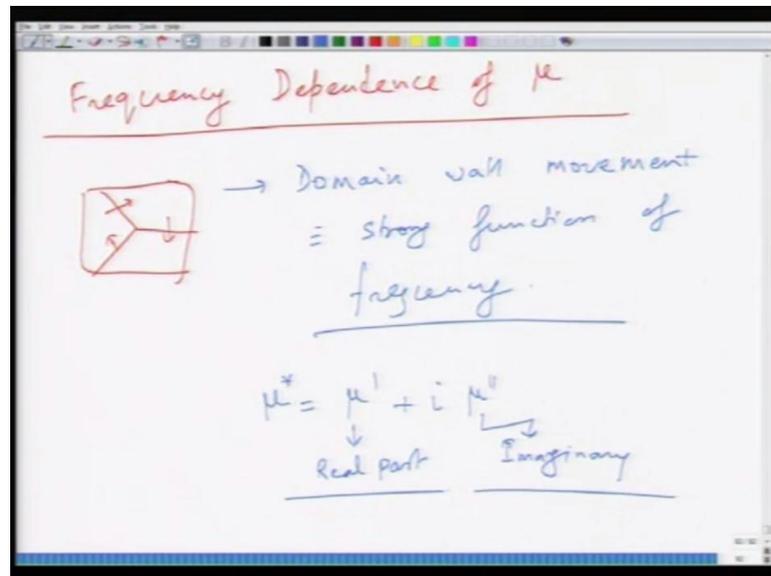
So, essentially you are looking at frequency dependence of mu which is the magnetic materials permeability and so since these materials have permanent magnetic moments and which result as a result of domain alignment and these 2 and these domains are also separated by domain wall movement of this domain wall is governed by coercivity. So, typically is easier the domain wall movement is what it means is that lower the coercivity of the material is so essentially what it means is that so the moments you are concerned with domain wall movements. So this is your domain wall structure. So the moment you are concerned with this domain wall movement, this domain wall movement can be back and forth. So, it can be made faster and slower depending upon the frequency of applied field.

So this domain wall movement is significantly dependent on the frequency of applied field. So, you can say domain wall movement strong function of frequency of applied field and these materials these materials are often used in gigahertz frequency applications. So, while some materials can happen easy switching at gigahertz frequency many other materials do not typically ferrites have very good gigahertz frequency response. As a result, these materials are used quite a lot in gigahertz frequency region. So, essentially just like the electric materials this mu is essentially a complex quantity,

that is why its mu star and this is represented as mu prime plus i mu double prime. So, you have this mu prime as a real part of permeability and mu double prime is the imaginary part and we will see that the ratio of these 2 is significant in determining the power losses in the magnetic materials and this is this is of immense practical importance. So, we will look at the proof of this in the next class, so what I will do is that I will now summarize the overall picture of magnetism that we have got.

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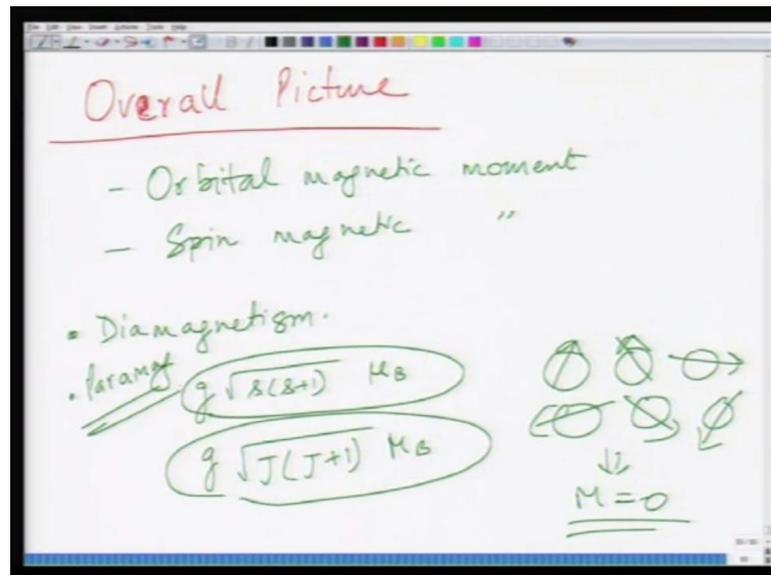
So, overall picture that emerges is, overall picture that emerges is, you have the magnetic moment in the material emanates from 2 sources essentially 2 important sources; first is the orbital magnetic moment and second is the spin magnetic moment. Now, depending upon the magnetic now depends upon, what contributes to what extent in a material gives rise to a type of the magnetism.

And when we discussed the type of the magnetism, the first category in this case was diamagnetism and diamagnetism is essentially about. So, you have a it was essentially a negative response of or the magnetization induced by the materials is negative to the to the applied field as a result they have what is called as a negative susceptibility. Typically the susceptibility is smaller in nature but, this is this response is inherent to all the materials the moment you have atoms and electrons you have diamagnetic behaviour. So, this is something which is intrinsic to all the materials.

Secondly, we discussed paramagnetism. Paramagnetism essentially in most 3 d materials emanates from spin magnetic contribution because the orbits in 3 d metals are believed to be or are thought to be quenched. So, as a result they coupled with the lattice they do not contribute, so they do not switch back and forth when you apply magnetic field. So, as a result the magnetic field which is essentially root s into s plus 1 mu b. So, this is what or you can include a land e g factor as well. So, this is what is the spin magnetic moment for three d materials if you want to go for 4 f material then you have bring the orbital term into picture as well then you make it J J plus 1 mu B. So, this J includes the contribution of both spin and orbital contributions.

However in paramagnetism you have random alignment of spins. So, as a result M is equal to 0 at a finite temperature and this so paramagnetism essentially does not give rise to any magnetization. But it follows a temperature dependent behaviour as a result the susceptibility decreases as the temperature increases.

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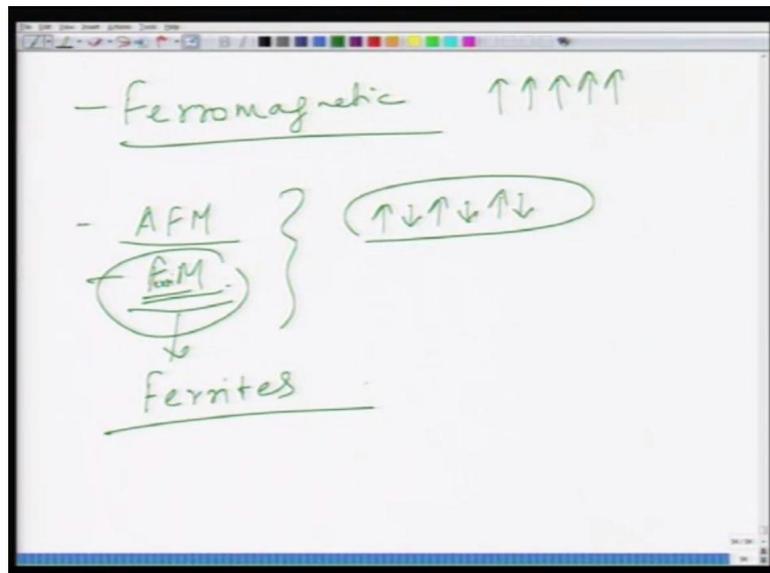
Now the third magnetic ordering was ferromagnetic ordering which is one of the most important and most studied ferromagnetic aspect of the materials and this is because of interesting nature of alignment of ferromagnetic spins. You have completely parallel alignment of spins and as a result you have a domain structure which gives rise to a hysteresis loop and switching under the magnetic field of course, gives rise to hysteresis

loop and this the shape of this hysteresis loop size and shape of this hysteresis loop governs what kind of ferromagnetic materials material it is.

And this is really a very important material aspect of magnetic materials and this is shown by most of the many 3 d elements and such as iron, nickel, cobalt, etcetera and most of these materials are used as permanent magnets memories etcetera. And then we came across antiferromagnetic and ferrimagnetic materials and this is a different kind of magnetic ordering you have you have opposite alignment of spins. But, the magnitude of these equal magnitudes of these opposite, these two oppositely oriented spins determines whether you have an antiferromagnetic behaviour or a ferrimagnetic behaviour so you can say ferrimagnetic behaviour.

And this typically most of these materials which show this kind of behaviour they happen to be ceramics and this is where we will take this case of ferrimagnets which are typically ferrites in nature. Ferrites or ferrimagnets in nature, and we will take the examples of these ferrites, you can have cubic ferrites you can have hexagonal ferrites. You can have garnets most of them contain magnetic all of them contain magnetic ions but, the distribution of these magnetic ions on various cations sub lattices determine what kind of matter response you get. So, what we will do in the next class is, we will complete the discussion on the, a frequency dependence of permeability to look at how the how the losses can be explained in terms of real and imaginary part of permeability.

And we will then look at the microscopic determination of magnetization in the ferrites which are nothing but ferrimagnet ferromagnetic ceramic antiferro you can say ferrimagnetic ceramics. So, we will close this class here and we will take up these issues in the next class, we will have about two lectures to go forward, before we finish this module and enter the next phase of this module.