Electroceramics
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Lecture - 33

So, we will start a new module here in this lecture. So, we have finished about I think 5 modules, first one was based on structure then we moved onto defects. And then we moved onto conduction or movement of defect diffusion and conduction, and then we looked at insulating a dielectric ceramics with the focus on linear dielectrics. And then in module 5 in the last module, we discussed non linear dielectrics which show extraordinary properties like ferroelectricity, piezoelectricity and pyroelectricity. Now, moving on forward in this module, we will discuss basically magnetic ceramics.

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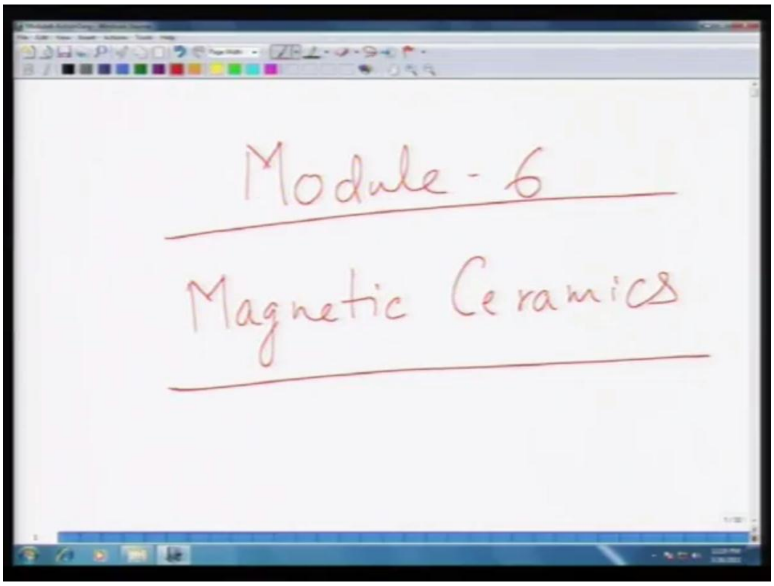

Now, this magnetic ceramics is a very important topic from applications point of view, because magnetic ceramics like ferrites and various other oxides. They have special properties in terms of magnetism and their transition temperatures which make them useful for variety of applications. You can use them in applications starting from data storage, you can make them make tunnel junctions spin walls; you can use them in variety of frequency applications. So, lot of and as you know some of them are already used in transformer course, etcetera. So, varieties of applications are there for magnetic materials especially magnetic ceramics. And this is because of peculiar properties of magnetic ceramics. And typical magnetic ceramics when we talk about it come one of which come to your mind is iron oxide.

Now, of course the magnetism in materials is very old phenomena for centuries people have been observing magnetism in specially in materials containing iron. So, iron itself and iron oxides have been giving rise to various kinds of stories about magnetism. However, the physics of magnetism took off only when we got quantum mechanics, classical mechanics or classical physics was not able to explain the origins of magnetism, because magnetism in the end as we will see is a quantum phenomena. And that is where quantum mechanics start off 1900 or so when quantum mechanics started being explained by people like Einstein, Nielsbohr, and Heisenberg etcetera then of course, magnetism was explained in a much better way.

So, what we will do is in this module is we will first discuss the basics reasons of magnetism, what basically? What kind of magnetism? What gives rise to magnetism? What kinds of magnetism are there? And then slowly we will move onto magnetic ceramics with most of the emphasis on ferrites, because ferrites are the most common magnetic ceramics.

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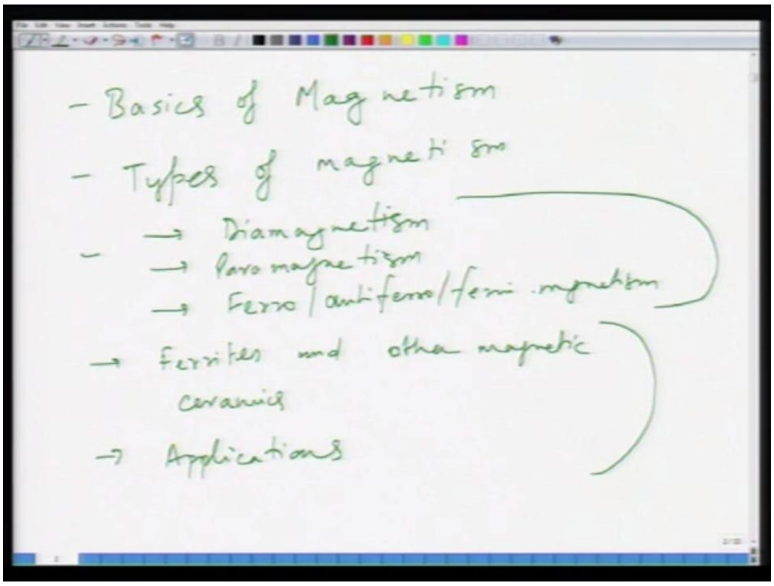

So, the way we will follow is we will just first. So, we will first study basics of magnetism. And then we will look at types of magnetism and then we will look at essentially. So, this will be followed by discussion on for instance diamagnetic, diamagnetism, paramagnetism. These are various kinds of magnetisms ferro, antiferro and ferrimagnetism and followed by we will discuss basically ferrites and other magnetic ceramics followed by application. Now, here we will spend quite of lot of time here, because these are important concepts and then of course, lot of sometime will be spent here. So, we will cover this module in roughly 5 to 6 lectures. So, stay tune for the next few lectures.

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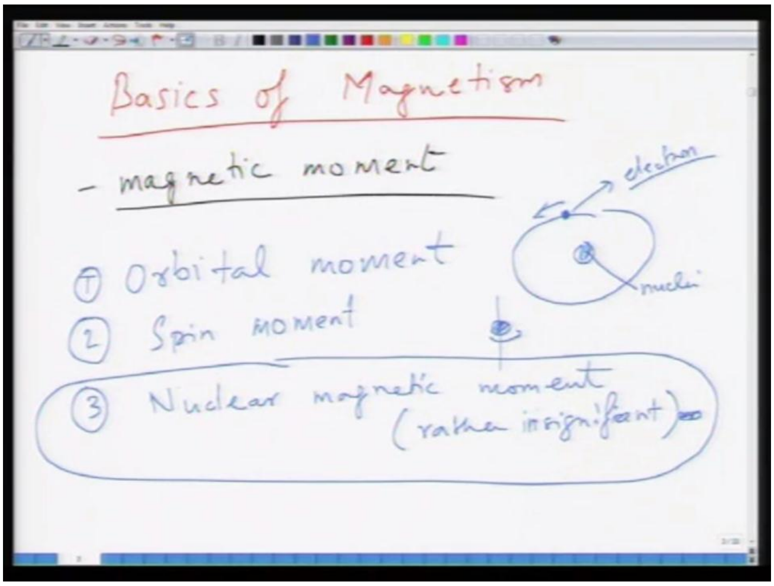

So, we will first look at the basic magnetic properties and basic magnetic properties. Now, basics of magnetism are basically magnetism as we know is an effect which is most commonly understood by ability of materials to attract to each other. So, you have 2 pieces of material which either attract or repel each other. And this is what is the basically this is what is because of magnetic effect inside this. Now this, this effect of magnetism is quite complicated in nature it is not very simple in nature. But what it is quantified by is a quantity called magnetic moment, and this magnetic moment is a quantity as we will see. And this magnetic moment is the quantity which quantifies the extent of magnetism.

So, when you are worried about, when you have 2 pieces of material. Now, how much what is the attractive force or repulsive force between them is determined by the determined by the magnetic moment inside the material. So, magnetic moment is a fundamental quantity of the material, and this is you should not confuse this magnetic moment with the dipole moment. In module 4, we looked at the dipole moment which is because of separation of charges from each other as a result you have dipole moment. Now, here this magnetic moment is not, because of separation of charges it is rather because of different reasons. So, the contributors to magnetic moment in the material can be variety different types. So, the first contribution comes from orbital moment the orbital moment comes from basically you have here, you have to look at the structure of atom.

So, when you go inside an atom you have electrons orbiting in the orbitals. Now, this is because of motion of electrons in an atom in the orbit of an atom that gives rise to essentially the orbital moment. And this orbital moment you can the most simple analogy that you can think to explain this is like motion of a current in a loop of a wire and this wire of course, has a very zero resistance. So, basically you can assume this orbital to be as if it was a loop carrying a current I. Now, second of course, is your spin moment? So, not only electron in the first case, you have this orbit around the nucleus, and you have these electrons spinning this gives rise to their own moment. In the second case, you have electrons which are rotating about their own axis. So, as we know from the quantum physics that electron has a spin up or spins down, but what is spin? Basically it is about its rotation of electron about its own axis. And this rotation of electrons about its own axis gives rise to another moment called as spin moment.

In the third moment is a nuclear magnetic moment and this is essentially due to the presence of nuclei, because not only. So, you have nuclei here, and this is electron. So, presence of nuclei itself gives rise to a magnetic moment, but this magnetic moment is rather insignificant or very small as compared to the above 2. As a result in most of the discussion on magnetism this nuclear magnetic moment is neglected, and we will neglect this in our discussion as well. So, what we will do in the next few slides is we will look at the effect of each of these moment orbit or we will quantify these moments orbital and spin moment.

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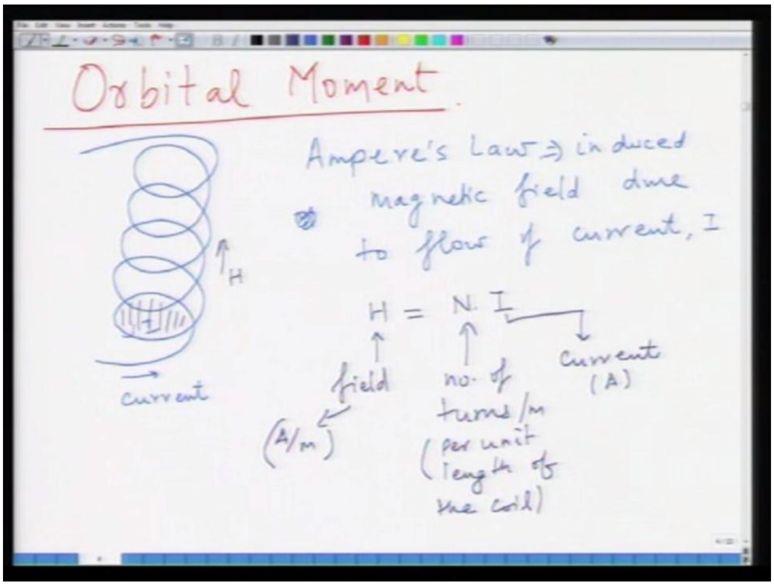

So, as I said that orbital moment can be thought of as if you have you have a loop of the wire, and in this wire you have a current I which is flowing. So, if you have a picture like this something like that. So, you have a loop of a wire and in this wire you have a current flowing. So, of course, you have current I which is flowing through this and this flow of current in the in this loop of wire can be related by Ampere's law. So, according to Ampere's law, Ampere's law when a current I flows through a coil or a loop of wire it gives rise to a magnetic field and this magnetic field. So, basically you have induced magnetic field due to flow of current I in an in a wire. And this magnetic field is perpendicular to the plain of the loop.

So, you can see this is the plain of the loop. So, if I just share it a little bit. So, this is the plain of the loop. So, this is perpendicular to this plain. So, you have this field H and this field H is related to the current by N multiplied by I. So, H is the field, N is the number of turns and this I is the current. So, number of turns you can say per unit length of the otherwise you have to take l length into account as well and I is the current in Ampere and H is the field in Ampere per meter, because this is number of turns per meter or per unit length. So, this field is essentially it has units of Ampere per meter now, so based on this analogy, so this I can also be related to so what we will do now is we will consider this orbit or the loop of the wire as in orbit and then we will move on further.

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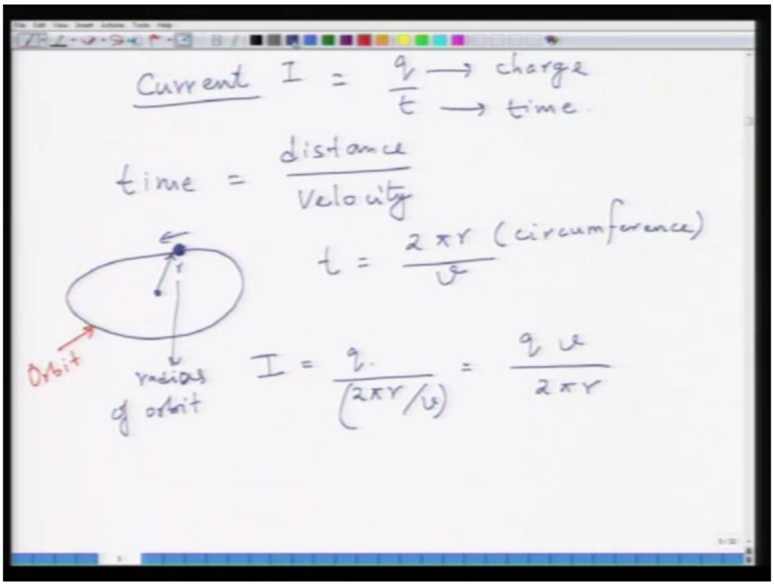

Now, according to classical physics this current I is related to charge and this is related to q by t so q is charge and t is time. So, basically current is nothing but charge per unit time. So, what is now, here if I want to what is the quantity that you can express in other parameters? The only quantities that you can express in other parameters are time. So, time is what, time nothing but distance by velocity is, and if you know that your orbit is of radius r and your electron is moving. Let us say that way then so your or that way or this way it does not matter only the field direction will change. So, this time will be t will be given as distances the whole circumference which is 2 pi r and velocity is nothing but v. So, this has the unit of time. So, as a result i becomes q divided by 2 pi r divided by v or q v divided by 2 pi r. So, this is the, so where r is nothing but your radius of orbit and this is your orbit.

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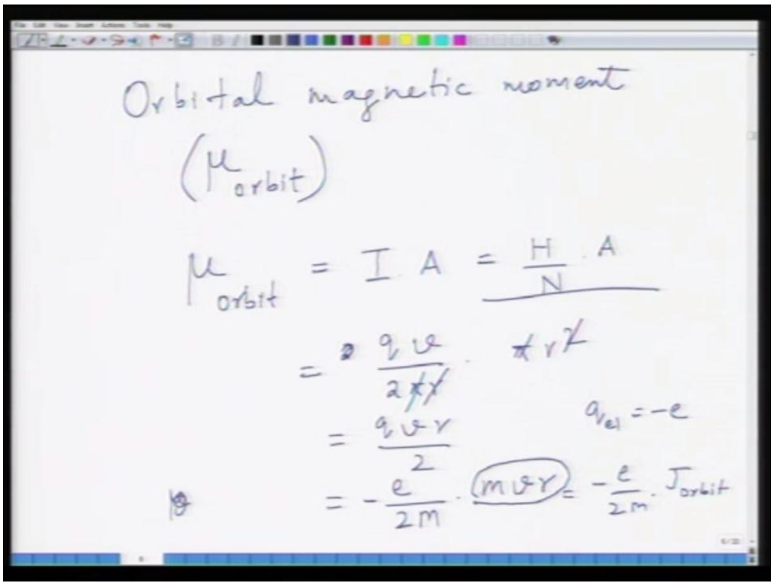

So, now therefore, the orbital magnetic moment we define it as mu orbit. So, mu orbit is related to current I multiplied by area. So, you can see that there is relation to field as well, because we know H is equal to nothing but N into I. So, if you replace I by H it also becomes equal to H divided by N into A and N was nothing but N divided by l number of turns per unit length. So, this has a relation. So, let us forget about this at the moment, let us just focus on I multiplied by A. So, basically the orbital magnetic moment is current multiplied by the area of the loop. So, this I is nothing but 2 pi from the previous slide if you go to previous slide I is q v divided by 2 pi r. So, this is q v divided by 2 pi r and A is nothing but equal to pi r square which is the area of the loop. So, this is you can cancel r r here pi cancel each other again.

So, this becomes q v r divided by 2 and I can further modify it a little bit. So, this becomes equal to now q is equal to minus e and if I take the 2 on this side multiply it by m on both the sides. So I can write this as, so q for an electron is minus e. So, q electron is equal to minus e. So, mu orbit becomes minus e by 2 m multiplied by m v r and what is m v r? m v r is nothing but your orbital moment. So, minus e by 2 m multiplied by J orbit and this, this as we know is nothing but the orbital moment.

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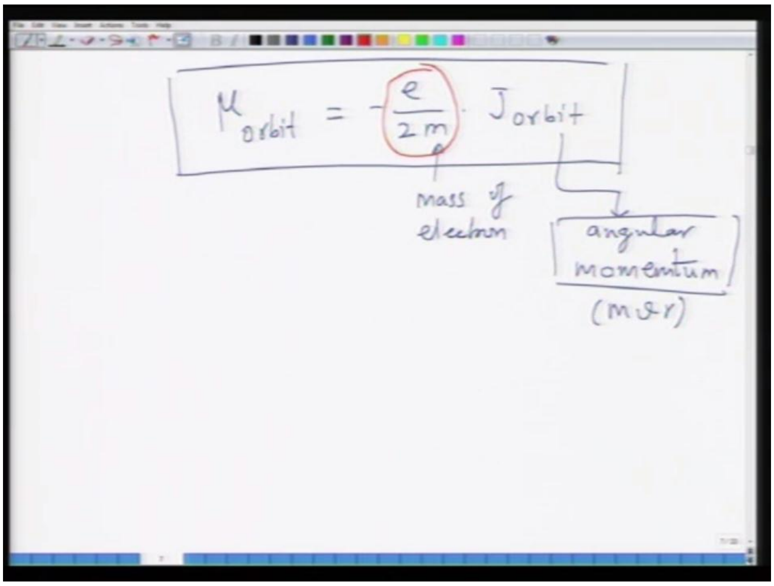

So, mu orbit you got a relation is equal to minus of e by 2 m multiplied by J orbit. This is an important relation which we will be used a little later as well when we talk about. And here m is nothing but mass of the electron and J orbit is nothing but angular momentum m v r which is nothing but m v r. So, we have got an expression for orbital magnetic moment. Now, we have to get an expression for spin magnetic moment and then we get the total magnetic moment.

So, we move to now spin magnetic moment this is very elementary. So, we will try to finish as soon as possible. One thing that you must realize from the previous expression is that orbital magnetic moment can be expressed as multiples of orbital angular momentum. So, this is something which is important, because e by m can be taken as a constant because e is constant m is constant. So, essentially mu orbit is nothing but a multiple of J orbit which is the orbital angular momentum.

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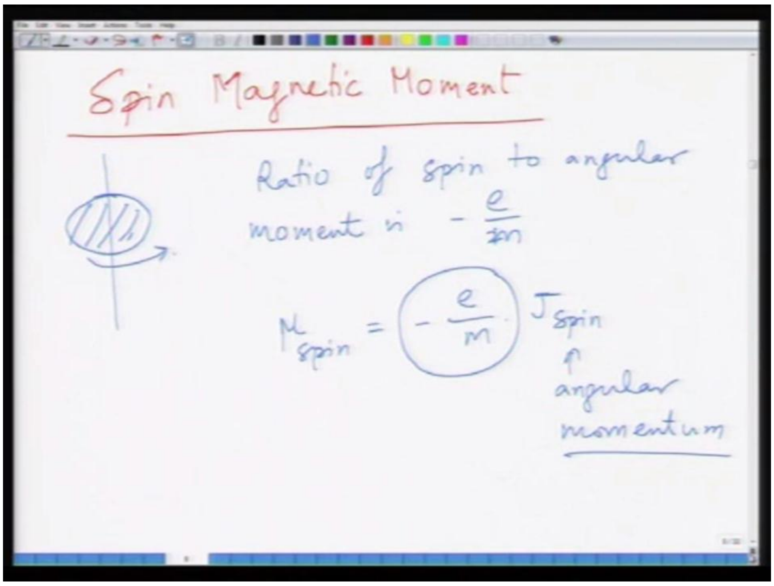

Now, we look at spin magnetic moment spin magnetic moment as we know is because of spin of electron around its own axis. So, this is for purely quantum mechanical reasons, this essentially the ratio of spin to angular moment is minus e by m. So, essentially what it means is that, mu spin is equal to minus of e by m into J and J as we know is nothing but angular momentum. So, angular moment of electron, spin orbit spin magnetic moment of in a material its twice to that of the orbital magnetic moment and this is for purely quantum mechanical reasons which you can go in any standard book on magnetism. So, essentially what it means is that.

So, you have this is the angular momentum and you have this factor which is e by 2 m in case of orbital moment becomes e by m in case of spin moment. And this you can say, because you can you always have you know the spin taking place in one direction then you have a spin in another direction, and both of them sort of add up and gives give rise to a total momentum which is twice to that of the orbital momentum.

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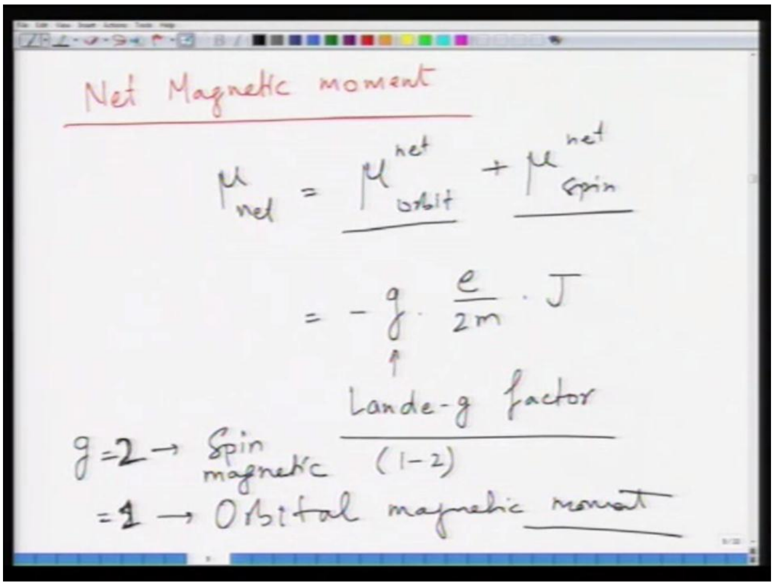

And then having known these two, the net magnetic moment, this net magnetic moment mu net becomes mu orbit. So, mu net, mu orbit plus mu spin. So, total orbital momentum plus total spin magnetic moment orbital magnetic moment plus spin magnetic moment, they give rise to total magnetic moment in a material. And of course, since you have number of atoms, you have number of electrons all of these has have to add together. Now, this quantum mechanically is explained little differently and this is quantum mechanically written as g multiplied by e by 2 m multiplied by J and this g is called as Lande-g factor. And this is again a purely quantum mechanical factor, and this is because the value of g is always between 1 and 2.

So, if this value is one then the magnetic moment is purely contributed by orbital magnetic moment. And if this value is 2 then this magnetic moment is purely contributed by a spin magnetic moment. And this depends upon the type of material for instance in many materials where magnetic moment is thought as quenched and that is where most of the magnetic moment comes from spin magnetic moment. So, if g is equal to 1 then spin magnetic moment dominates and if g is equal to 2, if g is equal to 2 then you have a spin magnetic moment dominates and if g is equal to 1 then it is purely orbital magnetic moment, if it is between 1 and 2. Then of course, it is sum of both of them or mixture of both of them. So, again there is another problem which is because of quantum mechanics.

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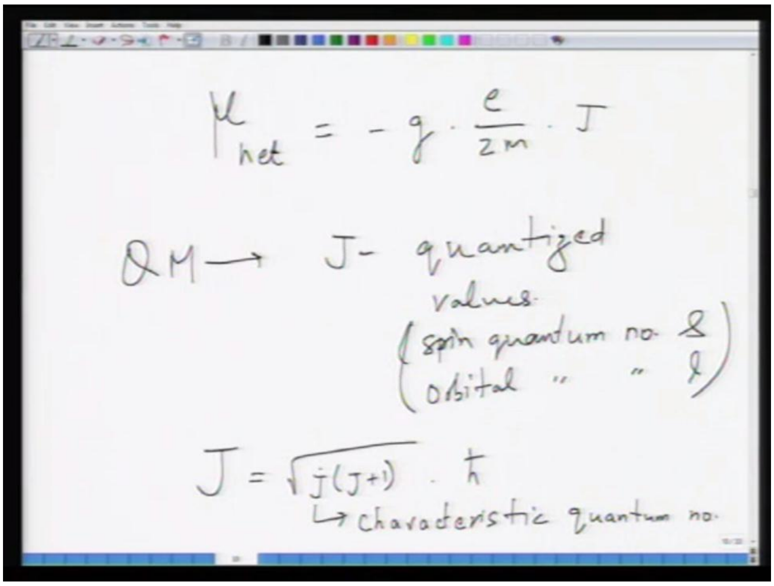

Now, quantum mechanics says that now, first you know that mu total is equal you know that mu. Now, we say that mu net is equal to g e by 2 m J, but according to quantum mechanics this J is also quantized which is the angular momentum for both electron spinning around its own axis as well as spinning in the orbit as well rotating in the orbit. Now, according to quantum mechanics this J cannot take any value it also takes the specific values which are called as quantized values.

So, according to that now and these quantized values are defined by your spin quantum number which is s and orbital quantum number which is l. So, the magnitude of J is going to be determined by whether it is a spin dominated or orbital dominated. But the whole point is according to quantum mechanics is J has to be quantized and this J is given as capital J is given as small j multiplied by small j plus 1 under root of whole thing multiplied by h cross. And this small j is nothing but a characteristic quantum number which is equal to s when everything is dominates when spin magnetic moment dominates and it is equal to l when orbital magnetic moment dominates.

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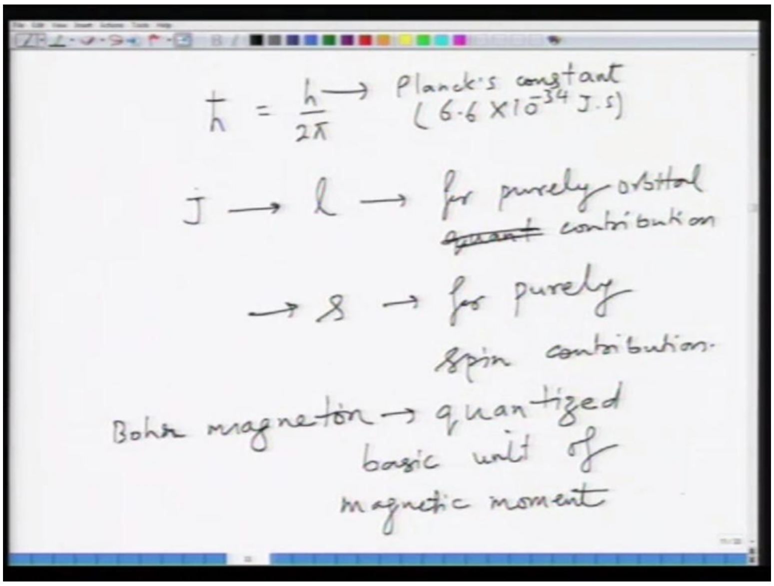

And h cross here is equal to h divided by 2 pi, h is nothing but you Planck's constant which is 6.6 into 10 to the power minus 34 Joule second and so this is h cross. So, j small j can take l for purely orbital contribution and it can be equal to s for purely spin contribution. And based on this, if we are saying that the orbital moment is also quantized then the whole magnetic moment of the material is also quantized. So, as a result the net magnetic moment of the material can be expressed in terms of a quantized unit and this quantized unit of magnetism is called as Bohr Magneton, quantized basic unit of magnetic moment.

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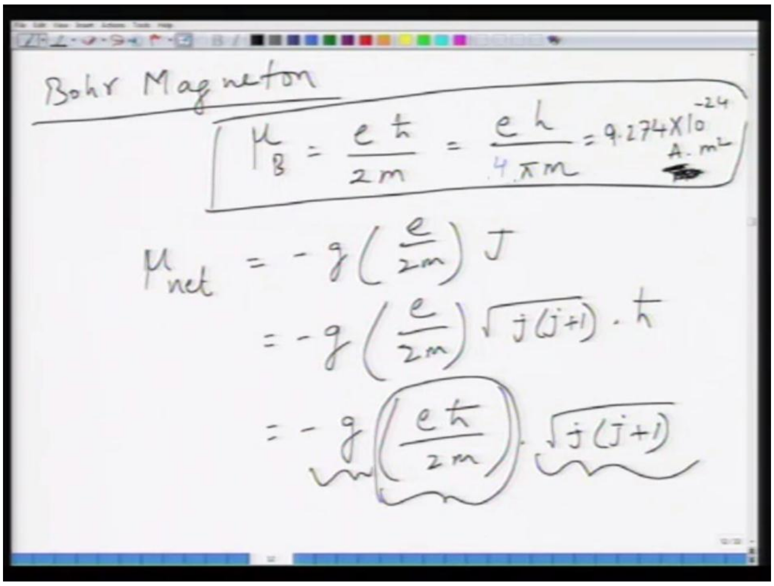

So, this mu b is written as this is called as so Bohr Magneton, mu b is written as e h cross divided by 2 m or e h divided by 4 pi m. So, this is the basic unit and you can see how it comes from, because you know that mu net was equal to minus of g e by 2 m into J. And now, I am saying that this is equal to minus of g e by 2 m into root of small j j plus 1 into h cross. So I can make it minus g e h cross divided by 2 m into root of j j plus 1.

Now, these are going to be determined by whether the contribution is purely orbital or purely spin or mixture of them, but this remains a constant. So, as a result this becomes a fundamental unit a basic or a smallest unit of magnetism which is called as Bohr Magneton. And this value is equal to 9.274 multiplied by 10 to the power minus 24 Ampere per meter square. So, this is a fundamental quantity that you must remember and now probably, you understand where does it come from?

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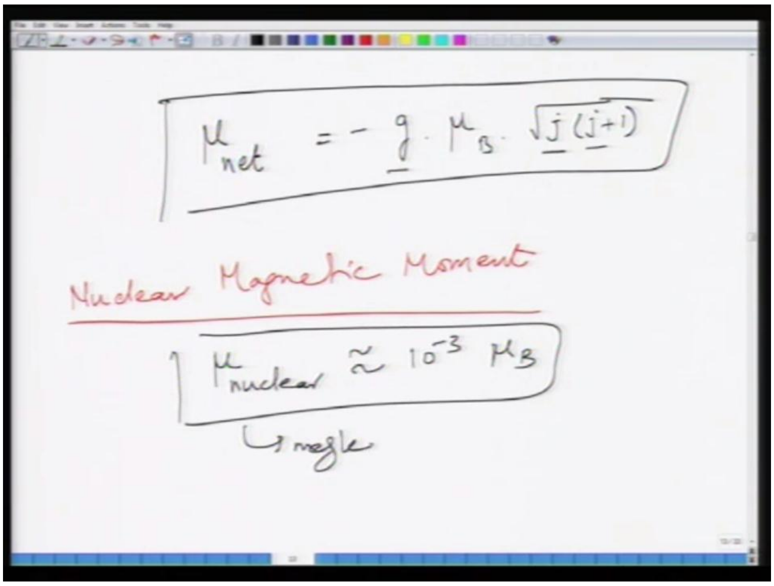

So, essentially your net magnetic moment mu net now becomes minus g into mu B into root of small j into small j plus 1. And this is your mu net expression and this is essentially a quantum mechanical expression and this tells you that the net magnetic moment in the material is although it is composed of orbital spin moment. Now, magnetism is always a quantized it is it can only take a specific value it cannot take any arbitrary value which it likes. And those values are determined by the values of g and the values of j and j which are determined by whether it is pure orbital or whether its spin contribution. So I hope you take this.

And the third contribution that we then talk about is nuclear magnetic moment and this is very small in number. So, mu nuclear is of the order of ten to the power minus three mu b, so if for most of the materials. So, as a results it is neglected. So, we just worked with a orbital and a spin contributions for most of the materials. So, this is the microscopic view of magnetization there is also another view of magnetization. So, this is something which we inside the material which we get which we see inside the material. But this total magnetic moment can also be seen in terms of what you see outside? And this is the total magnetic induction or total magnetization that comes of the material comes out of the material that you can measure.

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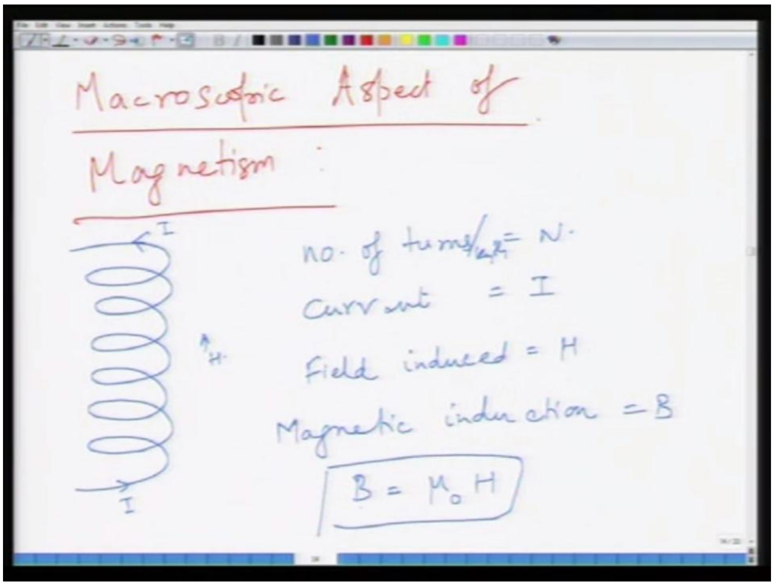

So, what we are going to see now is basically a macroscopic nature of not nature, but macroscopic aspect of magnetism. Now, again we consider here the same geometry. So, we take a current carrying coil like this, and this current carrying coil of course, have so you have a current flowing I. And this current gives rise to a field H and we will see what happens when. So, at the moment this current; this coil does not carry this coil does not consist of anything inside it. So, this coil has number of turns are equal to n the current which flows is equal to I.

Now, because of the field induced you have a magnetic induction. So, this field induced is H, and as a result of this field you have what is called as magnetic induction, which is called as B and B and H are related as B is equal to mu naught H and the H is related to I and N number of turns per unit length and. So, B is related to H by mu naught and this is again a fundamental relation.

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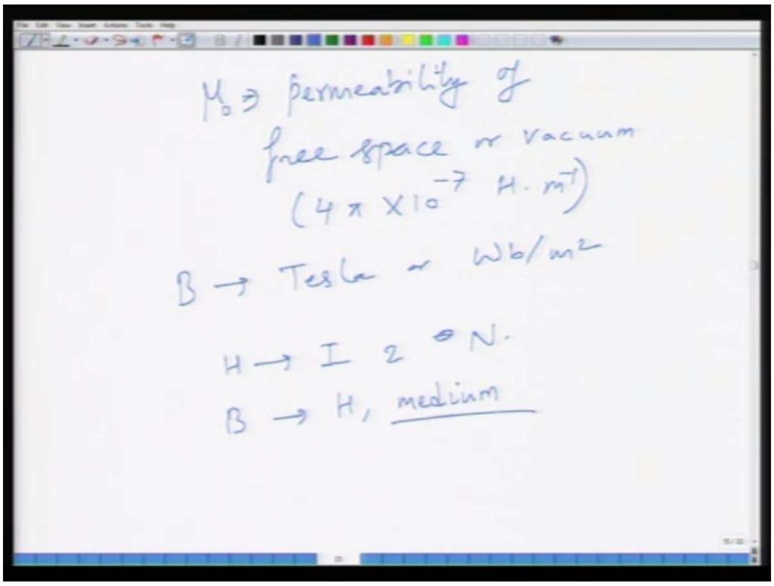

And this mu naught here is nothing but permeability of free space or vacuum and its value is given as 4 pi into 10 to the power minus 7 Henry per meter and B is given as either tesla or weber per meter square depending upon the convention. And this also explains that while H depends only on current and number of turns or the length of the coil, B depends upon not only H, but also on a medium which is inside the coil, so also the medium. And this medium at the moment when there is nothing inside the coil its free space, what happens when you put something in it something which has ability to magnetize?

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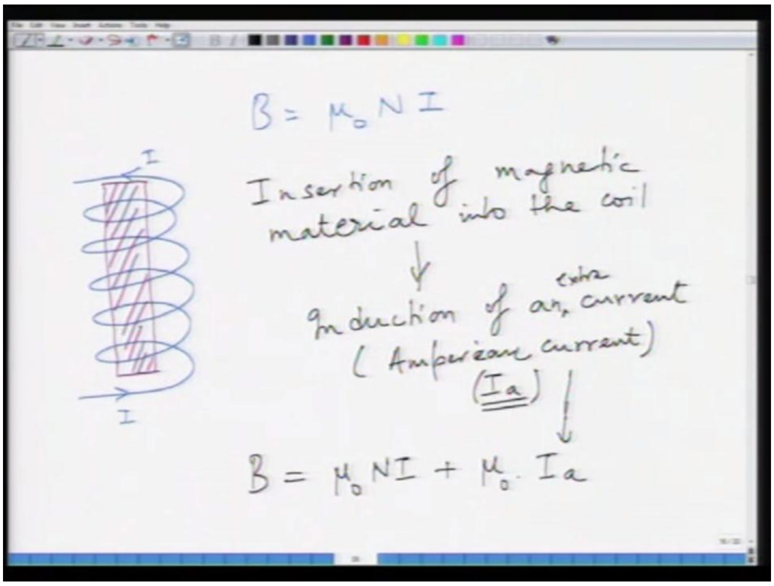

So, rewriting this equation B can be written as mu naught into N I, if you replace H. Now, imagine in the in that picture. So, again I redraw this. So I have a current flowing I. Now, what I do now is I insert a coil I insert a magnetic bar inside this coil. Now, this is just like what we did with capacitors. So, we had a capacitor which was a vacuum capacitor and then when we inserted inside that vacuum capacitor a dielectric material there was an extra effect of inserting a dielectric. So, as a result of insert insertion of a dielectric, insertion of a magnetic material now this insertion of a magnetic material which gives rise to a current which is induced in the magnetic material as well and this current, so basically induction of a, because it is a magnetic material. So, it is going to get effected, because of induced field, because if you already had field H.

Now, when you insert a magnetic material that gets amplified? So, you have an extra current because of that. So, induction of an extra current which is called as Amperian current so and this is defined by let us say I a, a quantity and this modified this equation. So, you insert a magnetic material inside the coil and coil this magnetic material induces its own additional magnetism. And this gives rise to B to be written as so you had mu N I from the earlier one. And what you have now on top of it is mu naught multiplied by I a, and this I a is the extra induced current which all which is because of insertion of a magnetic material. So, net magnetic induction has gone up this is for a typical magnetic material.

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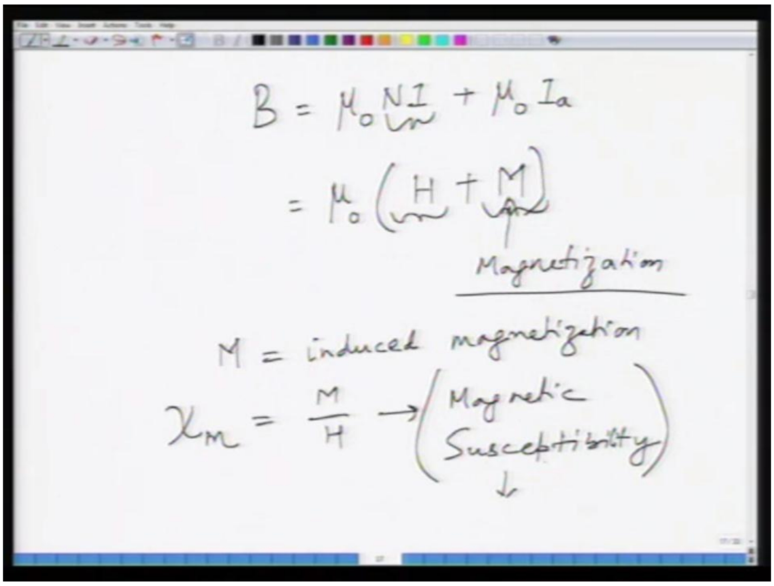

So, what you have here is this is of course, you can you can replace this amperian current. So, this B was equal to mu naught N I plus mu naught I a, this is also written as N I can be replaced by H and this I a can be explained by another quantity which is called as magnetization. So, just by inserting a magnetic material in the coil the net magnetic induction has additional component which is because of magnetization which is induced inside the material. So, this not, so on top of, on top of field H. Now, you have extra term which is M just like polarization term in the electric case.

What you need to do now is, so if magnetization you can assume this to be. So, this magnetization is essentially nothing but and this is related to field by another quantity which is called as chi M. So, just like, so the ratio of M versus H determines the magnetic response of the material and this and this is nothing but your magnetic susceptibility. So, this determines the magnetic response of the material. So, just like chi as we saw in case of dielectric materials you have similar equivalent term which is called as chi M.

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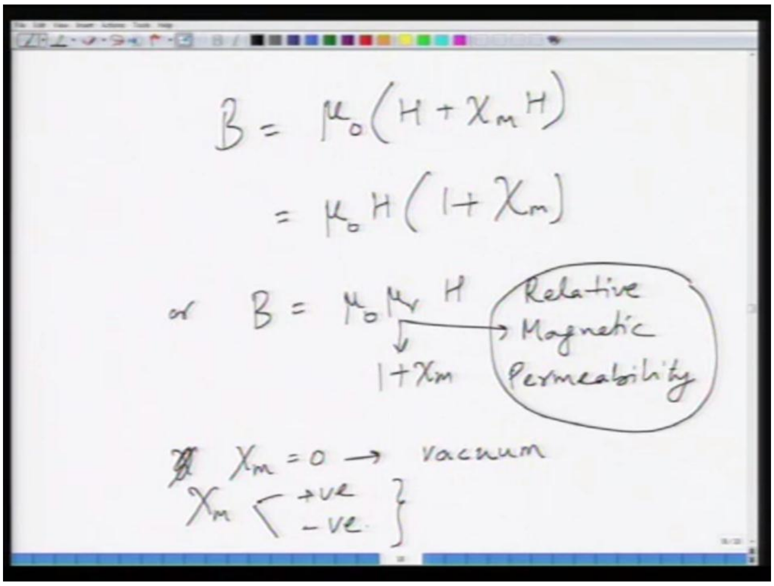

So, this equation now modifies as B is equal to mu naught into H plus chi m H and this is mu naught H into 1 plus chi m or this is also written as mu naught mu r H, where mu r is equal to 1 plus chi m and this is called as magnetic permeability or relative magnetic permeability. So, just like mu r you had in case of dielectrics which were called as dielectric susceptibility, here you have which was related to dielectric constant. Of course, here you have what is called as a relative magnetic permeability, which is which again expresses the response of electrons in the material to the applied magnetic field as a result of flowing current inside the circuit and this chi m as you can see from this is a dimensionless. So, if you go to previous slide. So, this chi m again is dimensionless and it basically quantifies the magnetic response of the material and it is related to mu r, so in the same manner as we saw in case of dielectric material. So, now in general both a permeability as well as susceptibility are vector quantities.

So, as a result there are tensors in most cases what we assume is that these vectors are co linear. So, as a result we do not a typically take the vector notation, but as strictly speaking you got to use the vector notation. Now, naturally chi m is equal to 0 for vacuum however, unlike dielectric materials chi m can be both positive and negative. And this is the fundamental crucial difference between magnetic and dielectric materials that while in dielectric materials chi is always greater than 0, here it could be both greater and smaller than 0 it could be positive and negative both.

So, this is one of the major differences between with the dielectric materials. So, based on this understanding, what we do now is we need to classify this magnetism on the basis of chi. The story so far is we have established the fundamental basis of magnetism the fundamental basis of magnetism is because of magnetic moments those magnetic moments could be, because of rotation of electron in an orbit. So, that is called as orbital magnetic moment and then of course, the rotation of electrons around its own axis which is the spin magnetic moment. You have a third contribution nuclear magnetic moment as well but that is very small.

And this sum of these 2 or magnetic moments gives rise to the net magnetic moment and this net magnetic moment is nothing but it is a quantized quantity. And this is related to orbital and a spin contribution, but also its product it is in the multiples of mu B which is the fundamental quantity of magnetism and this is called as your Bohr Magneton. And further by taking a microscopic view, we can see that this magnetic moment can also be expressed in terms of magnetic in terms of magnetic induction. And as a result we have this expression which gives rise to another quantity which is called as susceptibility or magnetic susceptibility which is similar. So, this magnetic susceptibility is similar to dielectric susceptibility in the sense that represents the magnetic response of the material, but it is different, because it can take positive or negative values.

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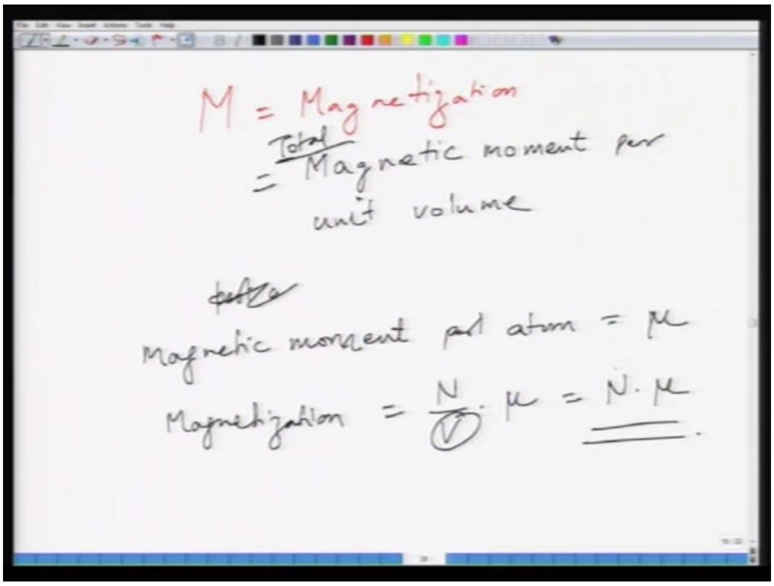

Now, more over this magnetic magnetization M is nothing but so it is magnetization and this is related to magnetic moments by what is called as so just like per unit volume of the material. So, just like we saw in case of ferroelectrics or dielectrics we had these definitions of magnetic moment which is nothing but related to. So, you have you can have per atom. So, you can have magnetic moment per atom as mu. So, magnetization of the material will be number of atoms per unit volume multiplied by mu. So, if this is unit volume you can take it N multiplied by mu.

So, this is how you can say total magnetic moment per unit magnetization is nothing but total magnetic moment per unit volume of the material. So, this is the relation between magnetization which is the macroscopic quantity and magnetic moment which is the microscopic quantity. And these two are related by number of atoms in a material. So, this is we have evolved a concept of important magnetic quantity which is nothing but your magnetic susceptibility.

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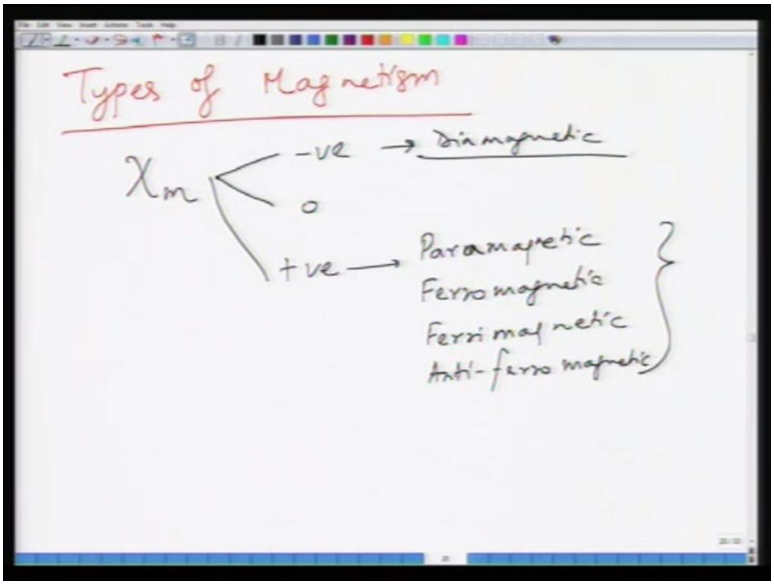

Now, based on this magnetic susceptibility we can classify this magnetism in a very nice manner. So, as I said that this chi m can be negative can be 0 and it can be positive and depending upon the magnitude it could be different kind of material. So, for materials which have negative susceptibility they are called as diamagnetic material or this kind of effect is called as or materials which show negative susceptibility have an effect which is called as diamagnetism. And the materials which have and of course, chi m is equal to 0 means then you do not have any magnetic material or material is non magnetic in nature.

So, essentially it means that you have no magnetic materials being used and this positive would mean that material could be either paramagnetic, or it could be ferromagnetic, it could be ferromagnetic. So, any of these effects can be or it could be antiferromagnetic. Now, depending upon the type of magnetic material, you can have the magnitude of chi which can vary quite a quite a lot, but in all these 4 cases the chi is essentially a positive quantity, it could be very small value and it could be very large value it depends upon the type of material.

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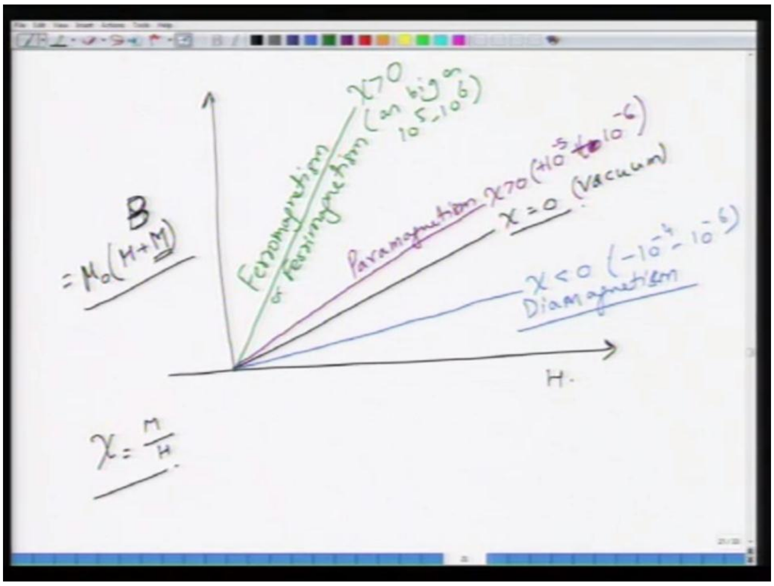

So, if you plot now this. So, we know that chi is equal to M by H. So, if you just plot M versus H and let us say, so for vacuum it would be something like that and chi is equal to 0. Let us say B, because b is nothing but equal to mu naught multiplied by H plus M, because for chi is equal to 0, M will be equal to 0. So, as a result it would only be equals to mu naught H otherwise it would have been a flat line. So, let us plot B versus H and for chi is equal to 0 it would of course, be equal to mu naught H only.

So, as the H increases it will proportionately increase. Now, when you have negative chi what it would mean is that, this m would be negative. As a result this B would decrease. So, what you have here is let me use a different color line. So, this line would be chi less than zero and this kind of and typically these values are of the order of minus 10 to power minus 4 to 10 to the power minus 6 and this is called as diamagnetic magnetism or materials which show this effect are called as diamagnetic materials. Now, you can have chi slightly larger, if you have slightly larger value of chi, then this is chi greater than 0 but again the small number plus 10 to the power 5 minus 5 to 10 to the power to 10 to the power minus 6 and this kind of material is called as paramagnetic material or effect is called as paramagnetism and this of course, is vacuum.

And then of course, you have very large chi and this gives rise to large magnetic induction and this is again chi is greater than 0 but it could be a quantity which can be as big as 10 to the power 5 to 10 to the power 6 and this typical effect is called as ferromagnetic, ferromagnetism or ferrimagnetism and so this is essentially the classification of magnetic materials which is based on the sign of magnetic permeability which is very different from what we saw in dielectric materials. You do not have a negative value there; you only have a positive value there. More over dielectric materials are little bit more non linear in nature, you have lot of other interactions which play around the dielectric materials.

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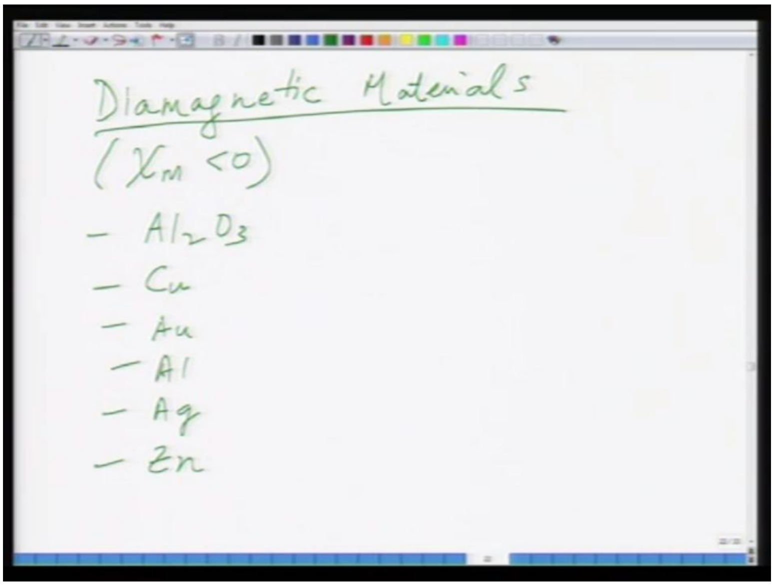

So, the diamagnetic materials typically which have chi m less than 0. So, examples of such materials are ceramics likes alumina, you have copper, gold, aluminum, silver, zinc, many other materials. They are all diamagnetic which means they have a negative susceptibility on what and what it essentially means is that when you apply a field then the induced magnetic moment in the material is not along the direction of field. But rather it opposes the direction of field. So, as a result you have a reduced magnetic induction.

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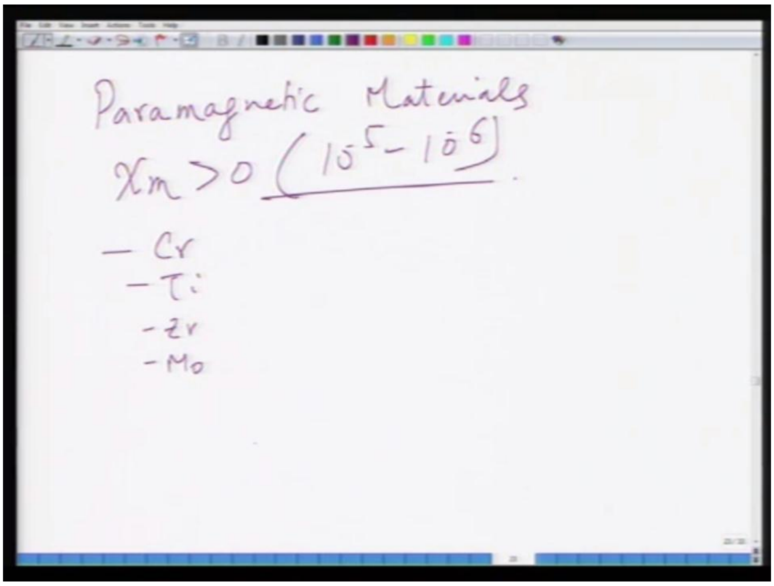

On the other hand second thing is what is paramagnetic material? So, chi m is greater than 0, but 10 to power minus 5 to 10 to the power minus 6 very small in number. So, you have a very small induction inside the material and these materials are for instance your chromium, titanium, zirconium, moly, variety of materials follow this kind of paramagnetic behavior.

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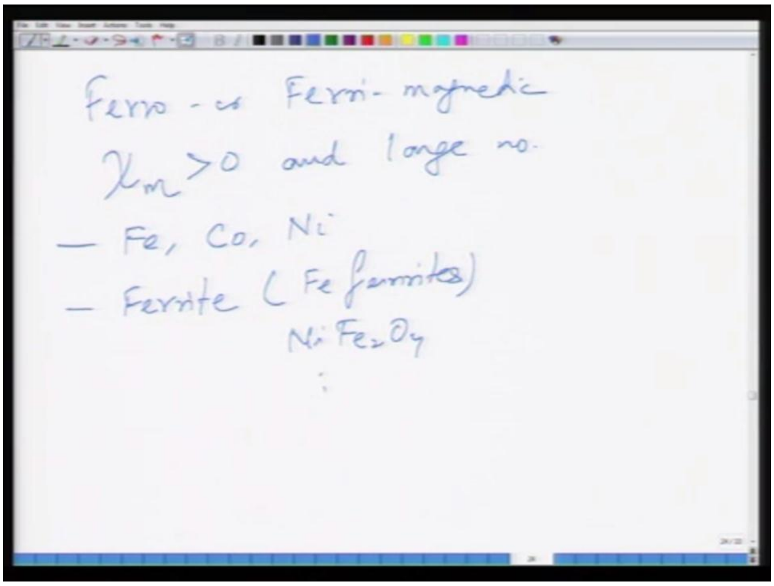

And then of course, what you have is the ferromagnetic ferro or ferri magnetic and these have chi m which is greater than 0 and large number. And here you can have materials like iron, you can have cobalt, you can have nickel materials like this or you can have ferrites, variety of ferrites typically iron ferrites examples for example or you can have materials like nickel ferrite N i F e 2 O 4 etcetera, etcetera. So, these guys have very large these materials have very large magnetic response to the applied field. So, this is the classification of magnetic material I will give you certain values for this.

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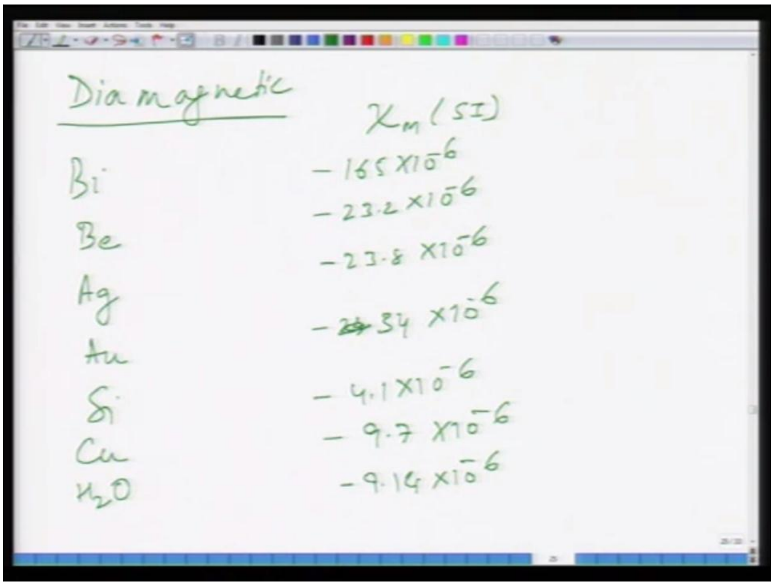

So, for instance, if you look at diamagnetic material. So, if you look at Bismuth, Bismuth has chi of the order of this is chi m minus 165 into 10 to the power minus 6 and this is in S i units. And then you have beryllium, beryllium also has minus 23.2 into 10 to the power minus 6. And then you look at more common material like silver it has minus 23.8 into 10 to the power minus 6 and you have gold which has minus 34 point, 34 point something 10 to the power minus 6. And if you look at silicon for instance, silicon is also a diamagnetic material it is minus 4.1 into 10 to the power minus 6 copper has about minus 9.7 into 10 to the power minus 6. And of course, you have water which is also a diamagnetic and this has minus 9.14 into 10 to the power minus 6.

So, these are the classes, some books also includes super conductors in this category. But super conductors are not diamagnetic the reason books include is that, because the super conductor in the super conducting state completely expel the magnetic field which is sort of analogy to diamagnetic material, but that effect is completely different. So, as a result super conductors are not diamagnetic in nature. So, however as a part of analogy if you just compare them then since they completely expel the magnetic field. So, as a result the susceptibility is close to 1. So, in that sense a super conductor is a perfectly diamagnet, but it is not a diamagnet the effect is completely different which we will discuss later in some module. So, we will not include super conductor here as you might find in some other books.

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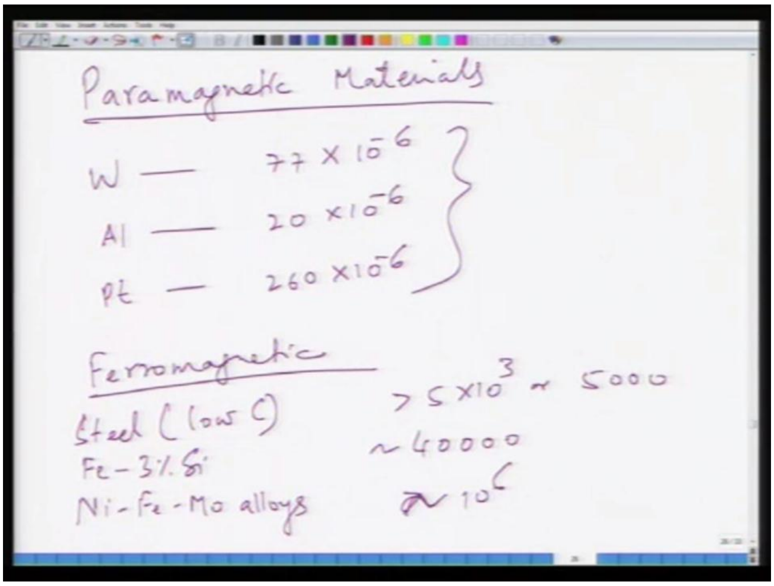

And then you have paramagnetic materials, and here you can have for instance tungsten 77 into 10 to the power minus 6 again the S i unit of chi, you can have aluminum which is hang on. So I think we can replace aluminum here, and it is not diamagnetic it is paramagnetic. So, aluminum is 20 something into 10 to the power minus 6 and then you have platinum which is also something 260 something into 10 to the power minus 6.

So, these are the values for paramagnetic material similarly, if you look at ferromagnetic then you have of course, a steel and you can say low carbon steel. And this has values exceeding 5 into 10 to the power 3 or 5000 and then of course, you have iron silicon and iron 3 percent silicon, again around 40000. And then you can have what is called as N i nickel iron moly alloys and they have of the order of 10 to the power 6, so very large magnetic response to the applied magnetic field. So, this is the classification of material. Now, you should also note that except in case of diamagnetic materials in all other cases that the susceptibilities are temperature dependent as we will see in case of as we will see in the analysis.

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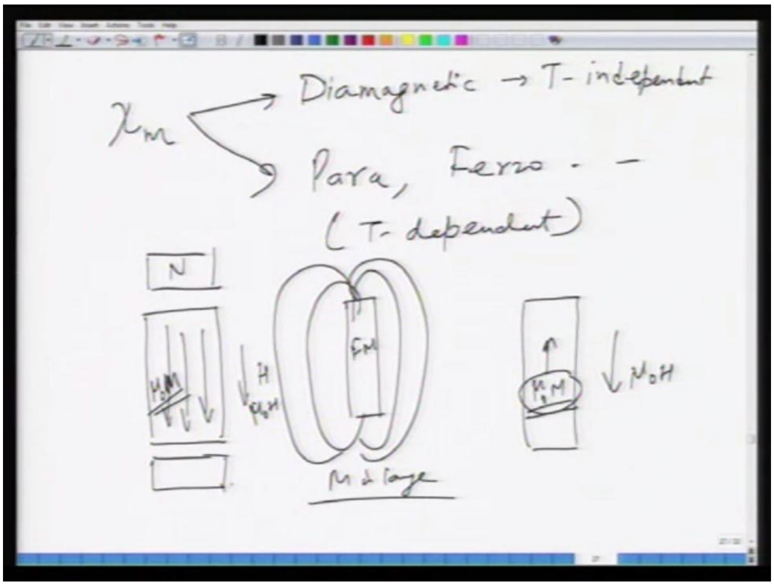

So, here just as information, so chi m for diamagnetic is temperature independent, but para, ferro its temperature dependent. So, this is an important difference again which we will also see in the later part of the in may be the next slide next lecture. And sign of susceptibility it classifies the type of material and sign of susceptibility essentially means that how much the magnetic flux of field is penetrating inside the material. So, when you have a diamagnetic material when you apply a field. So, this diamagnetic material, so essentially what you have is you have a magnetic material and you keep it inside the magnetic field let us say north south pole here.

So, in case of, so let us say this is the field applied field H. So, you have some induction mu naught H mu naught M and this is mu naught H and this M is a smaller. So, little bit penetration of the field if you have a super if you have a ferromagnet in case of ferromagnet you have very strong flux lines on the surface. So, this M is large complete penetration, but large induction in case of diamagnetic material what you have is you have a diamagnetic material. So, this is your mu naught H, but this is your mu naught M. So, you have some opposition to the applied field. So, this induced magnetic magnetization is in opposite direction. So, this is the qualitative description of how magnetic field penetrates inside the. So, this means that magnetic field does not completely penetrate inside the diamagnetic material and it has tendency to be repulsed in that sense in the sense of magnetic flux lines, whereas in case of ferromagnet it completely gets. So, you have these flux lines going inside the material completely. So, as a result it has very deep penetration and in large induced magnetization.

So, what we will do is that, we will stop here today. In the next class, what we will do is that we will do the mathematical treatment of diamagnetism, paramagnetism and followed by treatment of ferromagnetism, and other kind of magnetism before we move on into the ferrites. So, this lecture was essentially about explaining the origins of magnetism looking at it at the microscopic level looking at it the macroscopic level. And the then relating them each other and then evolving the quantity called as susceptibility which is the fundamental quantity dimensionless quantity which whose magnitude and sign determines the kind of magnetic behavior of the material. And that way you qualitatively noticed, and based on this we defined different materials and diamagnetic material which has a negative susceptibility. And then you have para, ferro, ferri which have positive susceptibility.

Thank you.