Advanced Ceramics for Strategic Applications
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Lecture - 34
Magnetic Ceramics

Welcome. The topic of today's lecture is magnetic ceramics, although our focus is on ceramic materials. To understand the properties of the ceramic, this group of ceramics, we need to understand the basics, some of the basic concepts of magnetism and compare the properties of the ceramics with other group of materials like metals and alloys.

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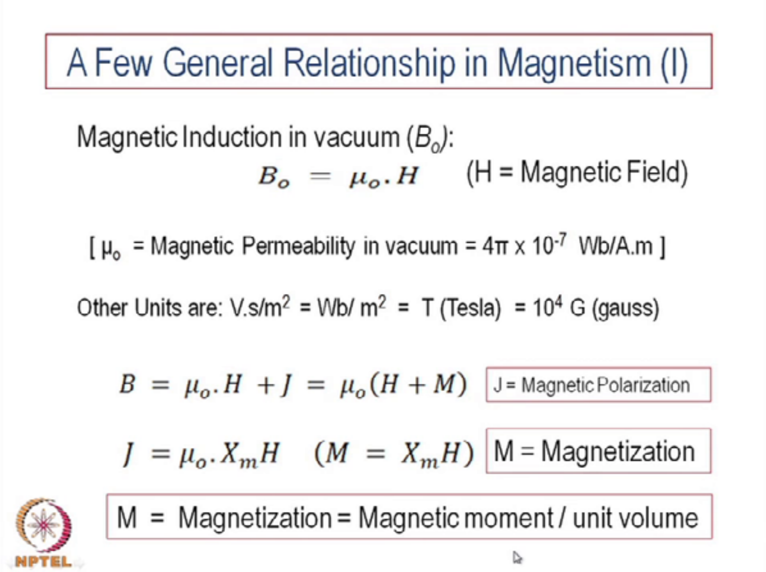

So, to start with, as I mentioned our topic is the magnetic ceramics and we will first consider a few general concepts in magnetism. These are basic physics from the undergraduate physics, one can go through this and some of the relationships, they are just strong co-relation between magnetism and dielectric properties which we will take it up in a minute.

So, magnetic induction is basically dependent on the magnetic field we apply, particularly when the environment is vacuum, we can write an equation B 0 equal to mu 0 multiplied by H. H is the magnetic field and B 0 is the result of that. So, it is a magnetic flux density or sometimes, it is also called magnetic induction. So, B 0 is mu 0

H. H is the magnetic field and mu 0 is the magnetic permeability. We have seen earlier, a similar term epsilon 0 in case of dielectric property or dielectric behavior or dielectric polarization. Here, very similar term is that mu 0 is the magnetic permeability in vacuum. The sub script 0 denotes vacuum here again and it is constant with a value of 4 pi into 10 to the power of 27, 10 to the power of 7 web ampere meter.

Now, there are various different units used not only for this particular parameter, but in the context of the magnetic behavior or magnetic, other parameters in magnetism. Other units are volts second per meter, that is the same permeability is also written as web per meter square and the g also tesla which is nothing but 10 to the power gauss. So, the measure of magnetic field impact magnetic field is, there are various different units used in the literature. Instead of vacuum, we have a material, magnetic material which responds to the magnetic field in some form or the other, then we can write the magnetic induction B mu O H plus J which is J is magnetic polarization and J also has a relationship with M. M is the magnetization and by that one can write mu 0 H plus M and from this relationship, one can get J. The magnetic polarization equal to mu 0 chi M introduce another parameter is very similar to the dialectic behavior. Chi M is the susceptibility, magnetic susceptibility and it is written as chi M equal to M by H.

So, the magnetic polarization here also we are bringing in a term is called magnetic polarization. J is mu 0 multiplied by chi M multiplied by H, M as I mentioned just now is magnetization and in other words, magnetic moment per unit volume. So, this is also a kind of relationship between magnetic movement and the magnetization.

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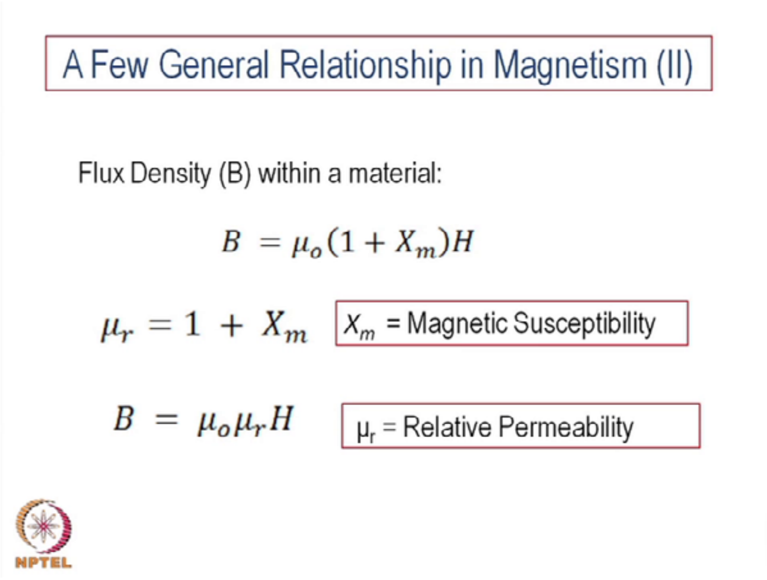

As I have told you that flux density B with a material equal to B equal to mu 0 1 plus chi M H. That is an important relationship from which we derive another permeability term, that is the relative permeability mu R into 1 plus chi M. This 1 plus chi M is the mu R. So, this also has magnetic susceptibility as we mentioned and finally, the magnetic induction is mu 0 mu R H. So, it is a proportional, the magnetic induction is proportional to the magnetic field we apply. Here of course one could also notice that it is a very closely related to the dialectic phenomena we have studied earlier.

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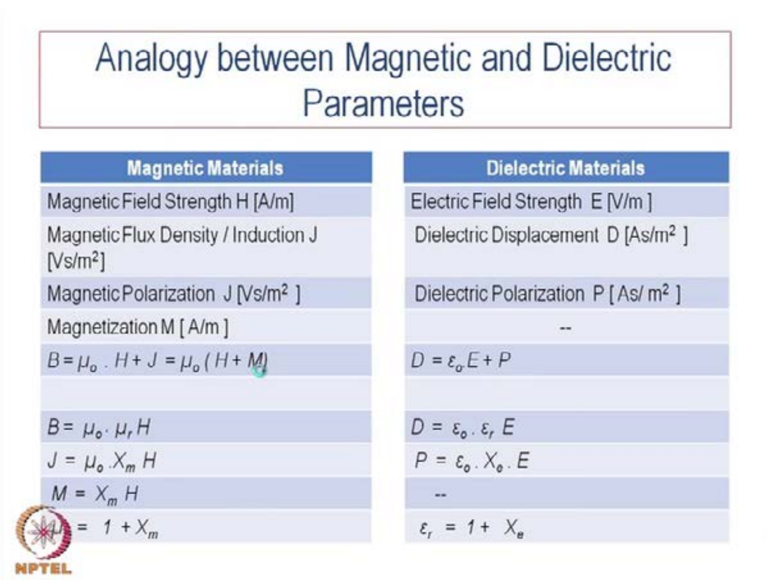

Magnetic Materials	Dielectric Materials
Magnetic Field Strength H [A/m]	Electric Field Strength E [V/m]
Magnetic Flux Density / Induction J [Vs/m²]	Dielectric Displacement D [As/m²]
Magnetic Polarization J [Vs/m²]	Dielectric Polarization P [As/m²]
Magnetization M [A/m]	--
$B = \mu_o \cdot H + J = \mu_o(H + M)$	$D = \varepsilon_o E + P$
$B = \mu_o \cdot \mu_r H$	$D = \varepsilon_o \cdot \varepsilon_r E$
$J = \mu_o \cdot X_m H$	$P = \varepsilon_o \cdot X_e \cdot E$
$M = X_m H$	--
$= 1 + X_m$	$\varepsilon_r = 1 + X_e$

So, that gives us a comparison analogy between magnetic and dielectric properties or dielectric parameters. This is magnetic field strength H and that is ampere per meter, whereas this is electric field strength. So, that is the external field, magnetic field we apply. Of course, there is a co-relationship between the magnetic field and the electrical current. Normally, it is the magnetic field is generated by a solinite or by a permanent magnet from outside. So, magnetic flux density the induction we are basically talking about how this material response to the external field H. Here also, the dielectric displacement is D. They have an analogy between each other. Magnetic polarization j and here is the dialectic polarization P and the units are ampere second per meter square that is volts seconds per meter square.

So, magnetization M this particular term does not have a real analogy with the dielectric phenomena; otherwise all the terms have some parallel phenomena in both the types of interactions. B equal to mu 0 H plus J, that is mu 0 H plus M and that I have written earlier and here also, the similar expression is dielectric displacement is equal to epsilon naught E plus P. The polarization here J is the polarization, here P is the polarization and then once again one can write this expression. We have also seen mu 0 mu r h here also dielectric displacement is equal to epsilon 0 epsilon RE, the polarization can be also expressed in the form of susceptibility that is mu 0 chi MH here, and here is dielectric susceptibility. This is magnetic susceptibility and that is dielectric susceptibility and the relationships are very similar.

Magnetization again does not have a particular analogy within the dielectric phenomena IMH. This is not there. So, as far as the dialectic phenomenon is concerned, this mu R equal to 1 plus chi m and epsilon R is 1 plus chi E. So, the two phenomena, magnetic phenomena and dialectic phenomenon are very similar in nature, although there are certain differences and it will be clear when we discuss further.

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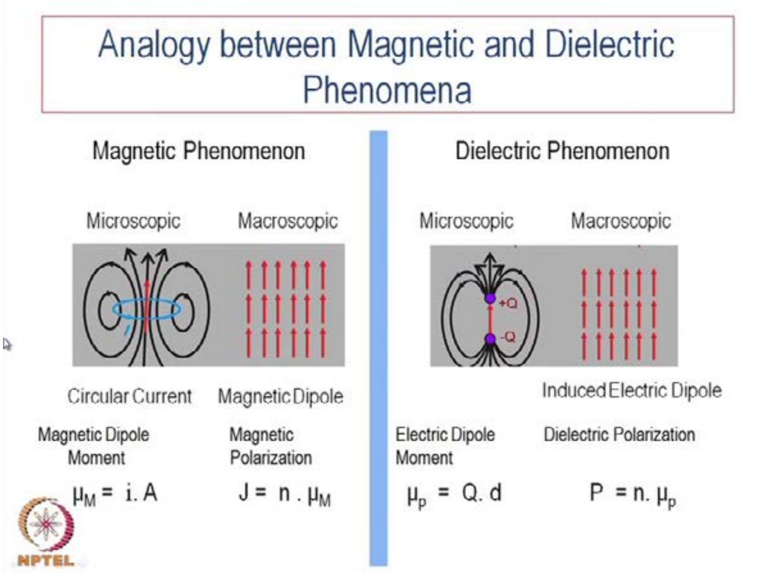

So, those are some of the phenomenological description of the magnetic behavior of material and here is we like to understand from where this magnetic behavior comes from, and as we have seen there are different mechanisms of polarization in dielectric material. Here also, there is an addition of magnetism in any material. Of course, dielectric phenomena comes only when we apply an electric field from outside, but in magnetism, the magnetic phenomena or magnetic behavior arises from within the materials because magnetism basically is a result of some current flow, electrical current flow or in the form of solenoid and so on.

So, whenever there is an electric current flow or movement of charge in a continuous manner, we will have some magnetic field generated and that is the reason in any material you have magnetic field within the system itself primarily because there is charge species like electrons which are moving and which is a going in a circular path around the nucleus, and that is equivalent to a flow of current. So, there is major difference there. So, as far as the dialectic phenomena and magnetic phenomena is concerned, dielectric phenomena only when there is external field applied to it and the charged particles or the charge species respond to the external applied field in a particular manner, and that gives rise to dielectric phenomena or dielectric constant dielectric permittivity and so on or dielectric polarization.

Similar thing happens here when we apply an external dielectric external magnetic field in a magnetic material, but in addition or any material fact, but in addition all materials because they have some electrons within them and the electrons within them flow of electrons are basically equivalent to a flow of current. So, there is some magnetism or there is a magnetic field generated within and that is what we would like to understand in addition to the external magnetic field. So, they respond to the external magnetic field, but they have some worry in magnetism from the inside. So, in a magnetic phenomena what happens is you have a current flowing because these are the flow of current electrons are flowing and therefore, you generate a magnetic field, magnetic lines of force and this is a continuous magnetic lines of force. The current is flowing in this horizontal path, the electron is moving in this path and so there is a magnetic field perpendicular to that and the magnetic lines of force are depending on the intensity and the surroundings, either they will be circular or it may pass through the centre of the coil.

So, the flow of electrons or the circular orbit actually acts like a current flowing through a wire, conducting wire. So, you have a magnetic dipole generated even in the absence of an electric field from magnetic field from outside. So, you have a macroscopic view. Magnetic dipoles are already there in the material. Of course, we will find out. Some of them are effective and all of them are not really effective. In that sense this is a microscopic scale, but in a microscopic scale, you have some magnetic lines of force already all the time present where as in this case, only some dipoles are prepared. Dipoles are generated only when there is an applied electric field except in some material where we have spontaneous magnetic polarization.

What spontaneous polarization? Here a spontaneous magnetization is always present in a magnetic field in a magnetic material or almost all the material. So, that is the origin of the magnetism. From material itself, the relationship here magnetic dipole moment is mu M is equal to i current flowing through that and A is the area of the circular path and magnetic polarization J equal to N into mu M. Mu M is the magnetic dipole moment multiplied with the number of dipoles present. The same thing here also we have dipole moment. This is Q multiplied by D. That means, Q is the charge and the distance of separation is D and the dipole polarization is P, capital P equal to a small n into mu P is the dipole moment multiplied by the number of dipoles present per unit volume. So, these are some kind of correlation or some kind of analogy between magnetic phenomena and dielectric phenomena.

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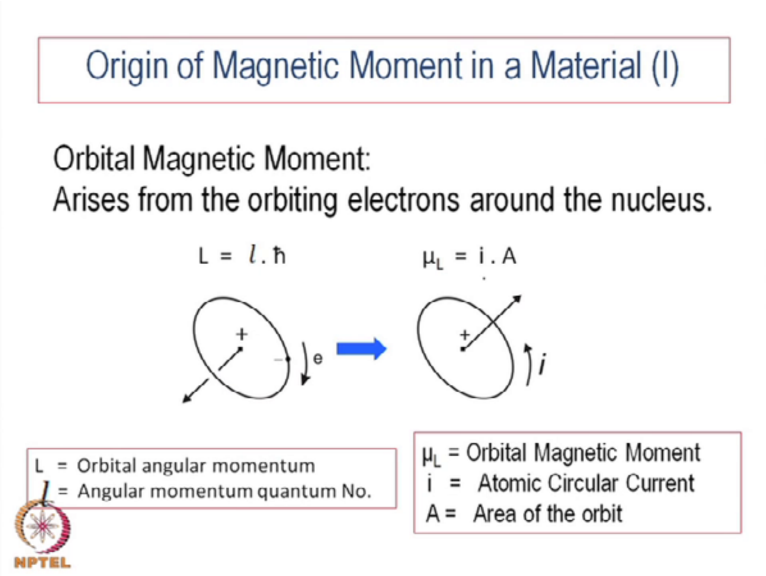

As I mentioned that since current is flowing in around the nucleus in a circular path, the electrons are moving in a circular path. So, it is equivalent to a flow of current. So, if you have an orbit, so that gives rise to some magnetic field or magnetic dipole movement magnetic. This is if this is the current flowing in this direction. This will be perpendicular to that to the magnetic lines of force and orbital dipole moment. Orbital magnetic moment arises from the orbiting of the electrons around the nucleus. So, this is one kind of a motion of the electrons which gives rise to the magnetic dipole movement and that can be expressed as l, the orbital angular momentum equal to l, the angular moment quantum number l multiplied by H bar. H is the planck's constant or in other words, mu l the dipole moment is equivalent to i into A i is the current flowing and A is the area that also can be mentioned.

So, mu l is the orbital dipole magnetic, dipole movement magnetic movement, i is the atomic circular current which is flowing because of the flow of movement of the electrons and A is the area of the orbit. So, this is one kind of origin of the magnetic moment in any material. In fact, wherever is the nucleus electrons is moving surrounding the nucleus, you have a current flowing equivalent which is equivalent to a current and that gives rise to a dipole moment or magnetic movement. So, this is one kind of origin of magnetism in any material.

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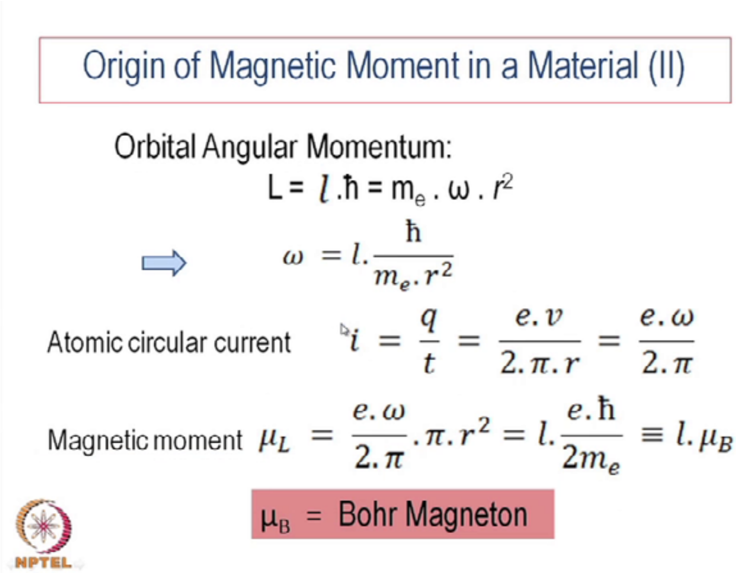

This can be further calculated or expressed in different quantities in terms of other quantities. So, the orbital angular momentum is equal to l h bar. This has been mentioned earlier which is again equivalent to m e omega r square. Omega is the velocity, angular velocity with is the electron is moving. So, omega is the angular velocity with which is electron is moving. So, omega is the angular velocity with which the electron is moving and that is the orbital angular momentum and magnetic moment. So, m e is the mass of the electron, r is the radius of the circle in which the electron is moving from this one can also write omega equal to l h bar m e r square and i is the current atomic circular current within an atom and q is the charge, and t is the time. We have a velocity here, angular velocity. So, e multiplied by v and then 2 phi r that is a circular path. So, e omega 2 phi e is the electronic charge, e is the electronic charge.

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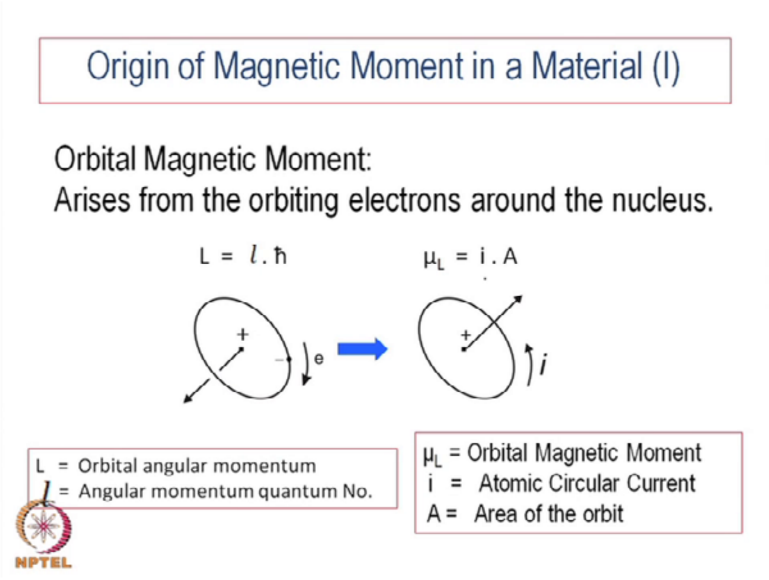

So, magnetic movement mu l which you have defined earlier, mu l that is the magnetic moment or one particular electron which is moving orbiting around the nucleus, then e omega 2 phi into phi r square. That is the area. That is phi r square is the area.

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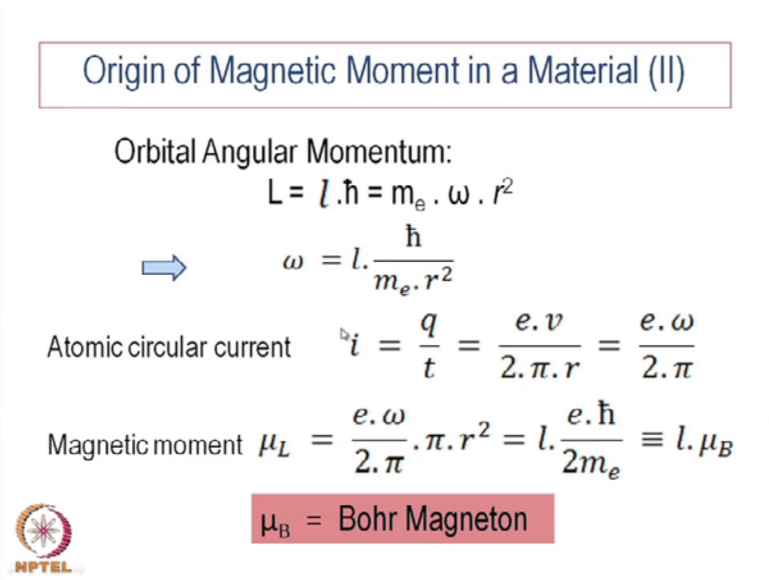

So, l e h prime 2 m e. M e is the mass of the electron and that term comes up in the magnetic calculation, magnetic moment calculation or magnetic property calculation most of the times and that particular term e h bar 2 m e is known as the Bohr magnetron. That is a unit of magnetic moment. So, it is called mu b is equal to Bohr magneton. So, the orbital magnetic moment ultimately comes to l multiplied by mu b, the Bohr magneton. So, depending on the angler quantum number, magnetic quantum number l you have the total magnetic moment multiplied by that number and mu b is this parameter which is fixed which is constant. So, one can see the orbital angular momentum is actually some integer multiple of mu b is particular term. So, depending on the number of depending on the value of l, the total orbital angular momentum will vary to continue.

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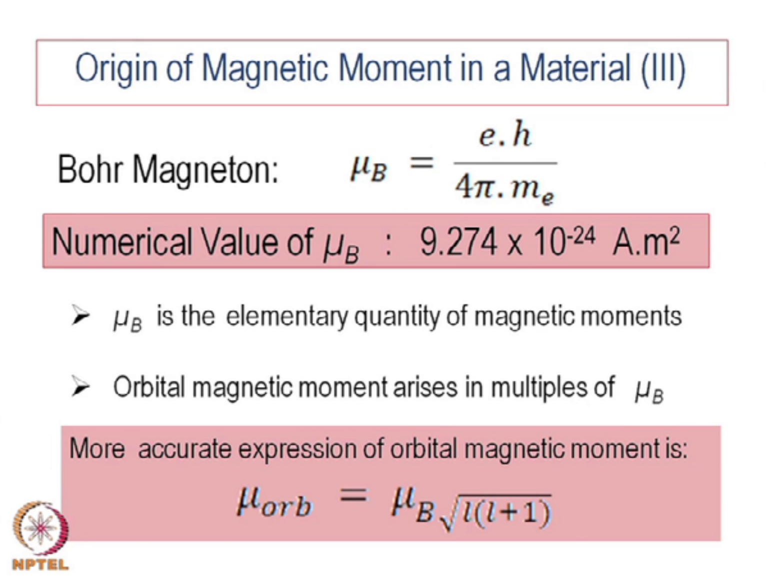

Further, this way of saying this is the expression of mu B and that is as I mentioned is a constant number and that value of that number is 9.274 into 10 to the minus 24 ampere meter square. So, that is a constant which will come across most of the time when you are trying to calculate or understand the magnetic behavior of different materials. Mu B is the elementary quantity of magnetic moments. Orbital magnetic moment arises in multiples of mu B that I have just mentioned. More accurate expression of orbital magnetic moment is, however is just not 1, actually it is more precisely without going to the details of that more precisely one can write orbital magnetic moment is actually mu B root over l into l plus 1. So, it just not l into mu B, but it is actually root over l into l plus 1. That is the more accurate expression of the magnetic moment, orbital magnetic moment, but mu B is certainly an important parameter. Whenever you try to calculate any magnetic moment of any origin, there is one more origin of magnetic moment inside an electron, inside an atom.

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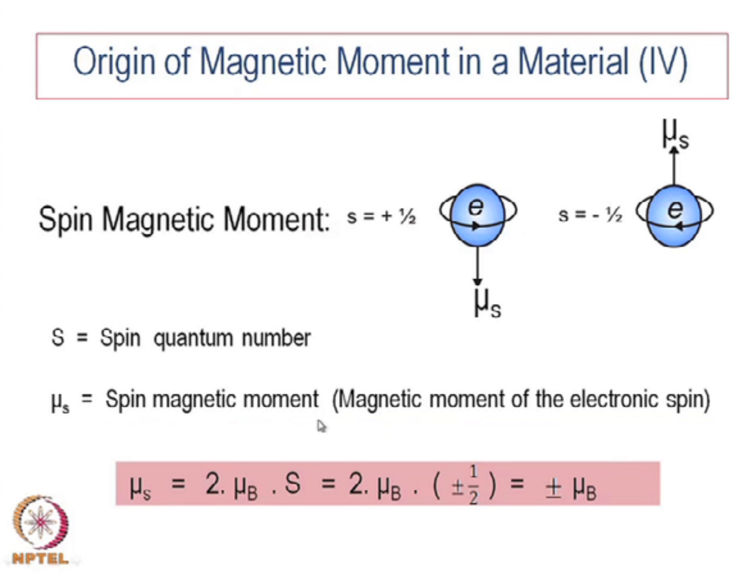

So, atoms of two different origins of magnetic moment from within one, we have discussed already the orbital magnetic moment. The other one is the spin magnetic moment. So, the spin magnet moment S equal to in fact S equal to plus half and minus half. That is the spin of an electron. So, in addition to the orbital motion, it has a spin motion on its own axis and as it is known that it has two possible spin quantum numbers. One is plus half and another is minus half, and that also that spinning on its own axis also gives rise to a magnetic moment and that is called the spin magnetic movement mu S. Once again this mu orbital mu S mu orbital or mu l which you have used earlier, mu S is the spin magnetic movement which is again the magnetic moment of the electronic spin that is arising from the spin of the electron, and that can be expressed as mu S equal to 2 into 2 mu B.

Once again the same number is coming up, some unit is coming up of mu B Bohr magnetron and multiplied by S. S is the spin and then S is plus half minus half. So, it gives rise to the spin magnetic moment is equal to mu B plus minus mu B. So, it is either mu B plus mu B or minus mu B. So, the multiplier is only one. So, for each electron or electronic spin, we will have one Bohr magnetron equivalent one Bohr magnetron magnetic moment and either, 1 or plus minus plus 1 or minus 1.

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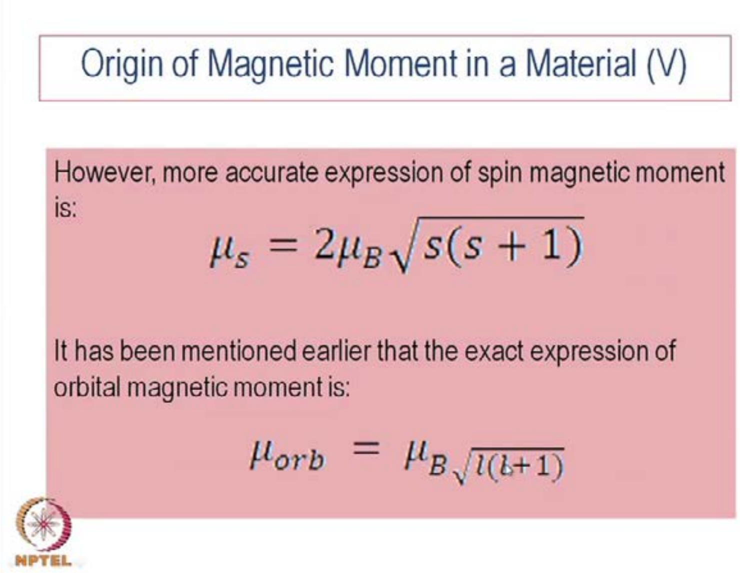

Once again just like the mu orbital or mu l, we have used earlier, it is not exactly the integer or just multiplied by l. It is l root over l into l plus 1. That is the multiplying integer. A multiplying number here also in case of spin magnetic moment, it is just not S into 2 mu B, but instead of it is the more accurate expression is a root over S into S plus 1. So, these are the two expressions of the two types of magnetism which is origins from the movement of the electrons within an atom. So, all atoms have this kind of a magnetic moment present in them, but depending on the type of the atom and their combination, their crystal structure, they actually come up the outs from the outside in their microscopic scale. The magnetic moments will be quite different and that we like to see next.

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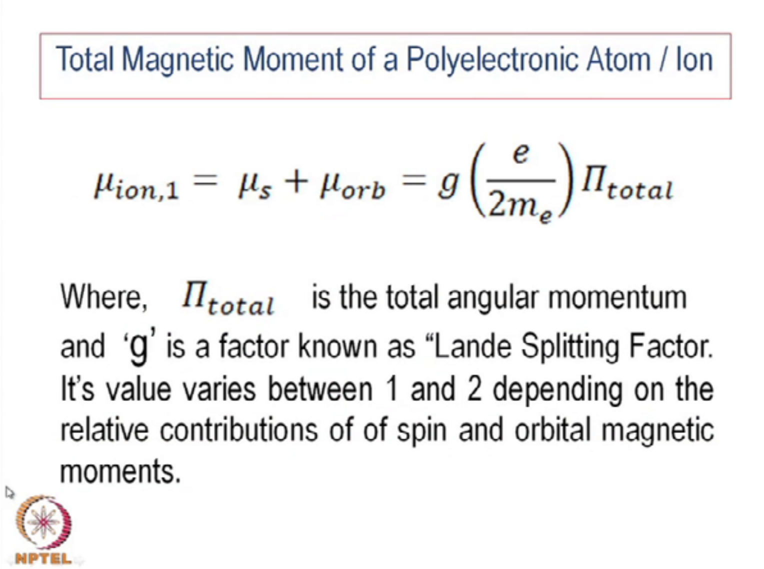

The total magnetic moment of a poly electronic atom which you have discussed over in terms of the orbital magnetic moment or the spin magnetic moment, basically we talked about only one electron. However, if obviously atoms have more number of electrons and they will combine each other and they will interact and the overall magnetic moment of the atom from the electron will upgrade it to atom integrating it to the atom. So, this is an expression for the total ion having one electron and mu S mu orbital equal to g multiplied by e by 2 m e is the electronic charge. Again m e 2 or m e is the mass and g is known as the Lande Splitting Factor, once again a constant.

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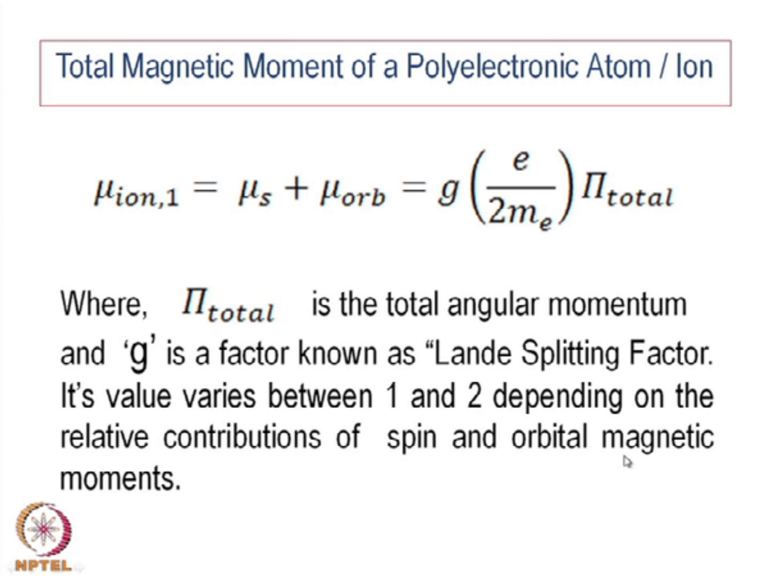

However, it is an integer value varying between 1 and 2 depending on the relative contributions of the spin, sorry there are mistake over there, right, their contributions of spin and the orbital magnetic moments. That means in each electron, each atom we have two different contributions. One is the orbital contribution and another is spin contribution. So, the overall contribution is some kind of an additive term and that additive term is not as simple that is addition, but it is a little complex, and this is how it is added up. So, there is a g factor Lande Splitting Factor and this phi total is called total angular momentum. So, this is the kind of an expression of the two terms, the orbital magnetic moment and the spin magnetic moment.

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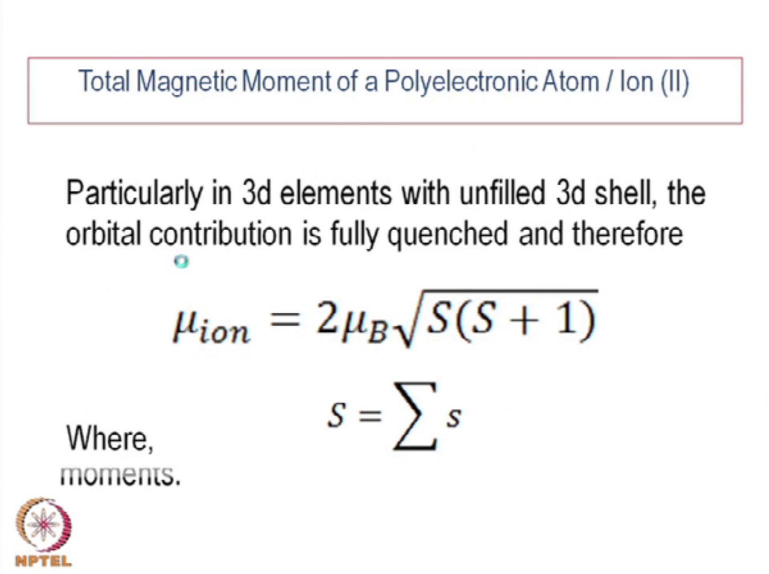

Now, particularly we will see later on or one of our major interests is in the particular group of elements that is 3d elements, the transition metal elements and these 3d elements with unfilled 3d shell, the orbital contribution is fully quenched which means when you are talking about this group of irons or atoms with unfilled 3d cell, then the orbital magnetic moment is almost negligible and we did not consider compared to the spin magnetic moment. That is negligible and that is what we call the orbital contribution is fully quenched and therefore, the irons contribution or the atoms contribution is 2 BS the root over 2 B.

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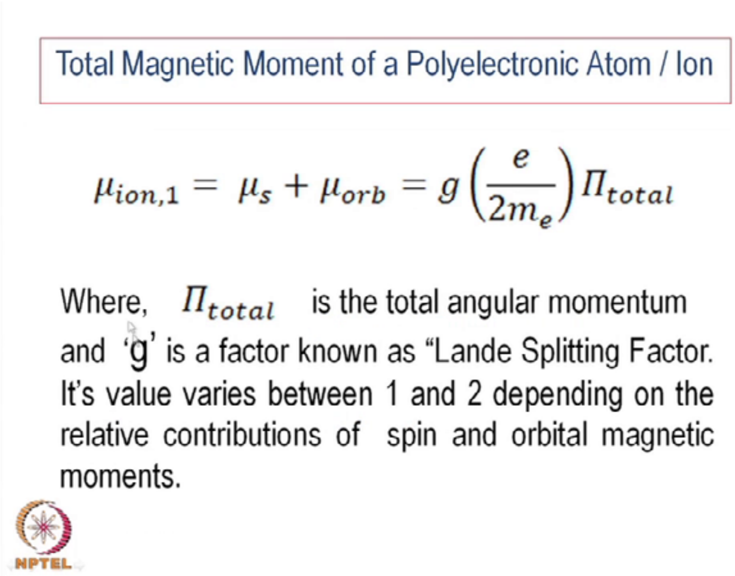

One of the terms is dominating as we have seen it earlier. This one is the spin magnetic moment contribution and this is the orbital magnetic moment contribution. This is almost negligible compared to that.

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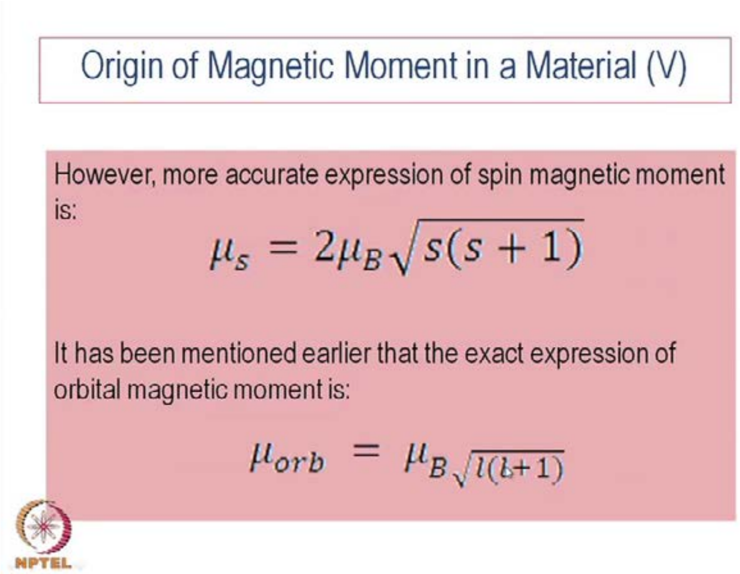

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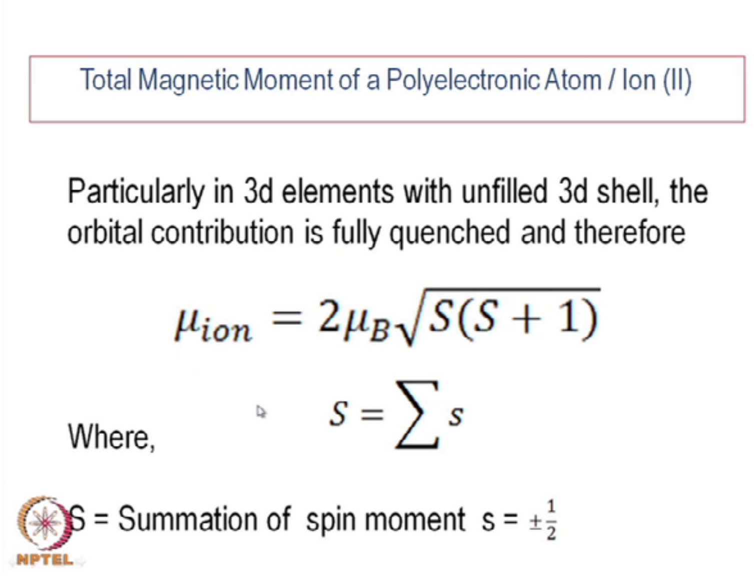

So, we have the magnetic moment the overall magnetic moment of the ion consisting of several electrons is 2 B. What is the spin quantum number and that is the root over of is into S plus 1, where S is the summation of now all the electrons, so S summation of this, the spin moment of all the electrons available. So, that leads you to the total spin quantum number, a spin magnetic moment and that is the predominating term. The orbital magnetic moment is negligible in group of these groups of materials with this little background there.

So, we have learnt there in any atom, there is an origin of magnetism or magnetic moment. There are two types of two different origins. One is from the movement of the electrons, the orbital moment of the electrons around the nucleus and other is the movement of the electrons around its own axis. So, one is called the orbital magnetic moment and the other is called spin magnetic moment.

Well, with this background, let us keep that aside and let us go to the phenomenological description of different kind of materials based on what we discussed initially, and that is the permeability and the susceptibility terms, two different terms and that is the kind of response of the different materials or the atoms or the structure, crystals to the external magnetic field. So, both mu r and chi m. Mu r is the permeability and chi m is the susceptibility. These two are the phenomenological description or phenomenological parameter of the materials response to the external magnetic field, and these based on that how the response to the external magnetic field.

Based on that, there are different kinds of materials, there are different types, classified materials can be classified under different groups. These are the four or three, in fact three different groups, but they have subgroups. We will find them and we will discuss them in details.

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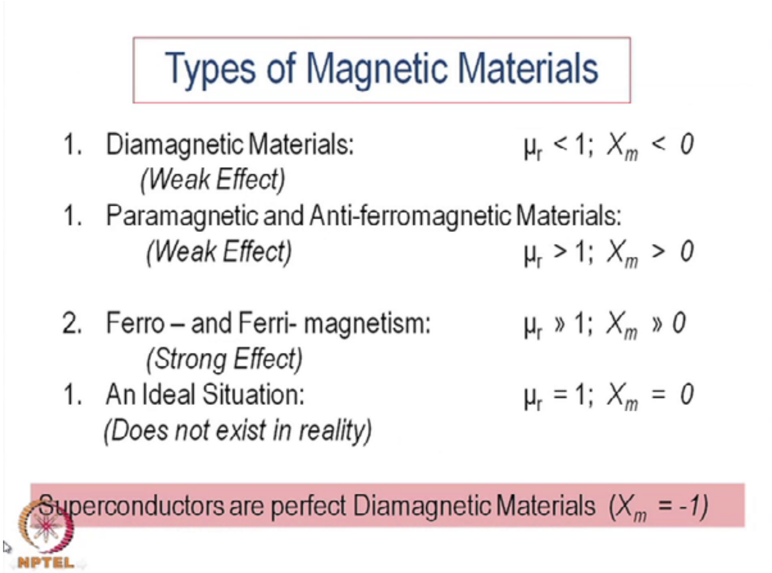

So, the first group is diamagnetic material weak effect. That means, they have effect to the external magnetic field is fairly low and they do not respond strongly and mathematically, one can say that the mu r, the relative permeability is less than 1 is negative, chi m is negative and this is less than 1. This group of material is called diamagnetic material and they have a weak effect, they do not respond to the external magnetic field so strong.

The second group is called the paramagnetic and anti ferromagnetic materials. It is anti-ferromagnetic as well as anti-paramagnetic. They respond more or less in similar manner and once again have a weak effect, and here mu r is no longer negative. No not less than 1, but is positive. Sorry is more than 1. So, mu r is more than 1. That means mu r is basically mu by mu 0. So, it is more than 1 and chi m is greater than 0 that is here it is negative and this is positive and this is less than 1. This is more than 1.

There is third group ferro and ferri-magnetism and here, it has a very strong effect. That means, it is strongly affective and strongly respond to the external magnetic field and that is because it is relative permeability is much greater than 1, and chi m is also greater than 0, much greater than 0. So, by that they are characterized. So, this group of magnetic materials is of tremendous importance from the application point of view. We will look into that later. Now, ideally there may be one group because here you have seen it is less than 1 less than 0. These are all more than 1 more than 0 and this is much more than this value.

So, ideally there should be the situation where it is somewhere in between. That means mu r is exactly 1 and chi m is exactly 0. Ideally that should be there, but in reality does not exist. Either it is slightly below or slightly above 1 and 0 values. So, ideally it should have, but in reality it does not exist. So, this is not a group of materials of our interest obviously because such materials do not exist. We have only these three groups and these. I am sorry once again. There is 1. Sorry, I should correct that there are two problems of serial numbers. Then this should be four, right.

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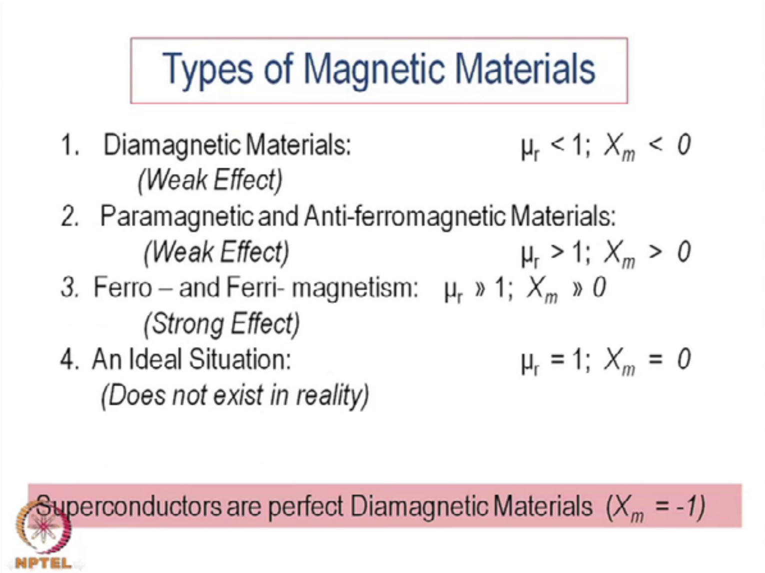

Sorry, there are some problems of serial numbers. So, we have four groups. Actually fourth does not exist. Other three really exist and out of these three groups, two of them have two subgroups as it is mentioned here, paramagnetic and anti-ferromagnetic as far as these parameters are concerned is same, but their behaviors are different, their many other properties are quite different. We will look into that later. Similarly, you have two groups here. As far as these properties are concerned, they are identical, but they again have different properties. We will look into that later. We have to correct it once more.

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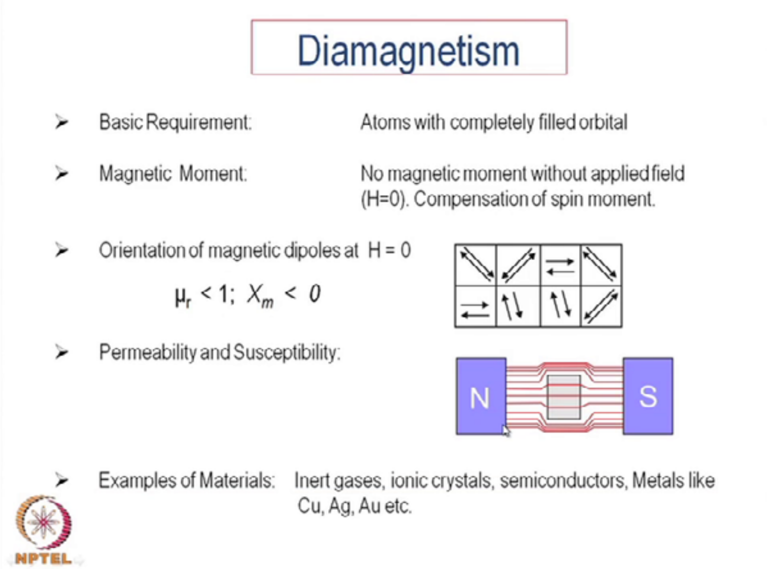

Now, we will look at some of the other aspects of these groups. First of all the diamagnetic or diamagnetism. The basic requirement is atoms with completely filled orbital. So, one of the requirements the elements which have a completely filled orbital like inert gases. They do have this kind of behavior, diamagnetic behavior. That means their mu r is less and chi m is also less than, sorry mu r is less than 1 and chi m is less than 0. No magnetic moment without applied electric field just because they have filled cells in principles. They should have a magnetic moment, but they do not generate any magnetic moment. So, the compensation of spin moments. So, each one of them has a negative and positive component. Obviously, they cancel each other.

The orientation magnetic dipole. This is the kind of orientation in the absence of a magnetic external magnetic field. So, since there are all filled cells, there are no unfilled cells, so there is no internal magnetization or magnetic moment and in absence, whatever small magnetic moment of their from the dipolar magnets, they are aligned anti-parallel aligned with each other. However, when you apply magnetic field, if there is a magnetic filled, this is your material.

Well, magnetic aligns of force because of this value and because the chi m is negative. So, the magnetic lines of force are repaired by the diamagnetic material. So, diamagnetic material really does not like the magnetic lines of force. They on the other hand repel and the inert gases and crystals semiconductors metals like this which is mostly the field orbital will have this kind of a property. So, the most important thing is rare reflection of the magnetic lines of force through the diamagnetic material.

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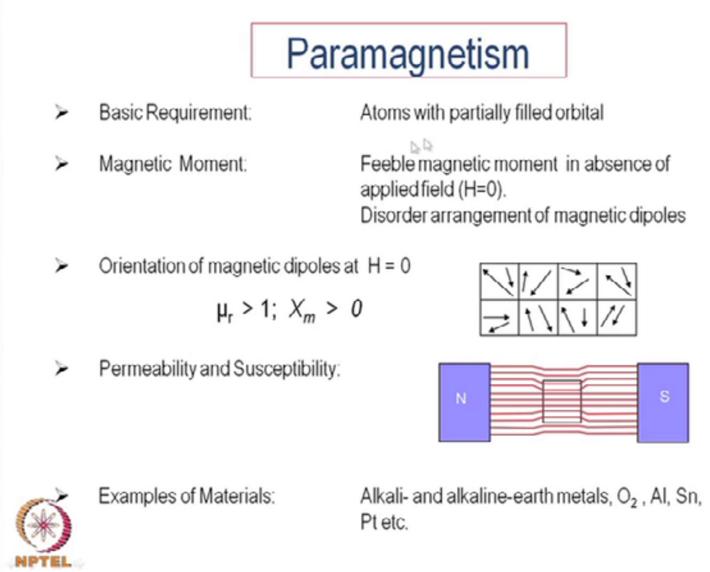

Comparison to that paramagnetism is like this and this is the kind of orientation of the dipoles or in absence of the external magnetic field. This is the dipole moments. Whatever is there, they are kind of random orientation. The atoms with partially filled orbital here. Earlier it was completely filled. Here, it is partially filled feeble magnetic moment in absence of applied field. So, even in the absence of magnetic field, they have a very feeble magnetic moment and the disorder arrangement of the magnetic dipoles. So, mostly the magnetic dipoles which is at there each atoms there the disorder form and in the presence of a magnetic field when we apply magnetic field, they like to concentrate around within the material.

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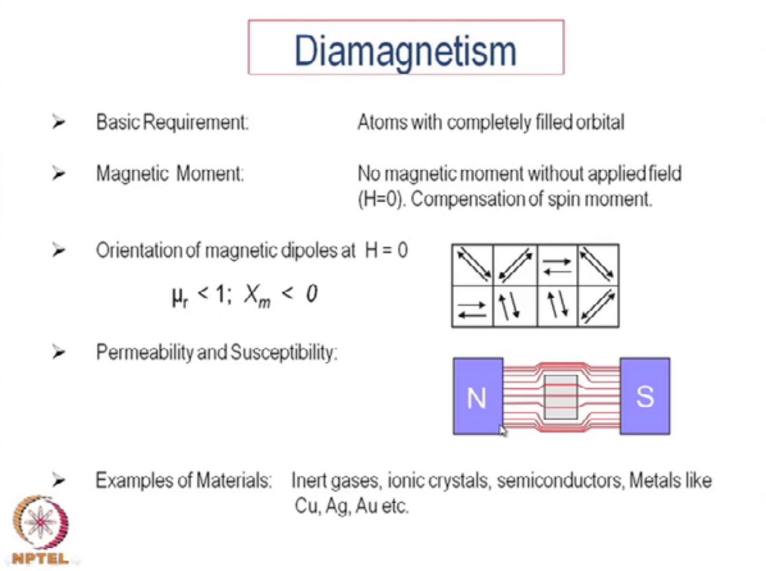

So, compared to the diamagnetic material where it was repelling, the magnetic lines were repelled here. So, there is a little bit of concentration around or within the magnetic paramagnetic material.

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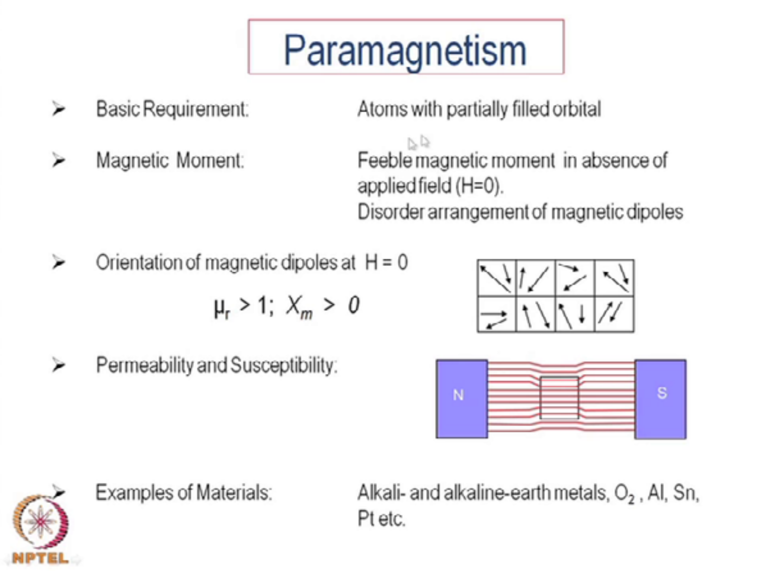

The example of such material is alkali and alkaline-earth metals, oxygen, aluminum, tin and platinum etcetera. So, these are some of the materials which have very weak magnetic materials.

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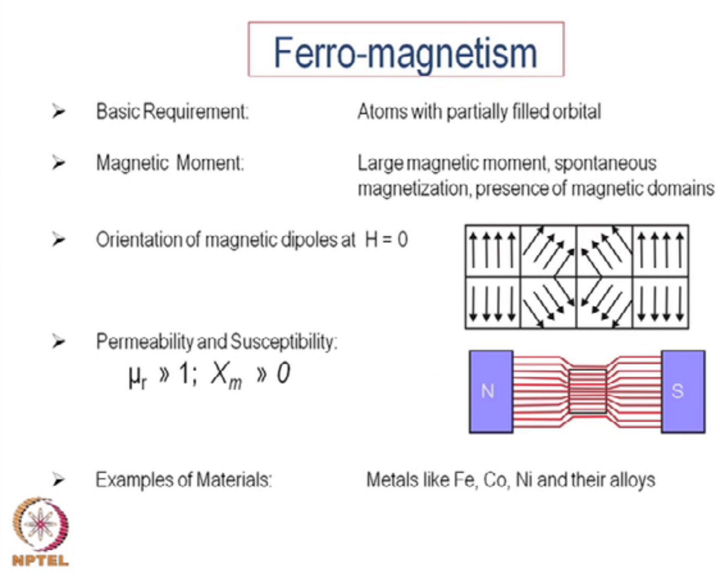

Next is ferro ferromagnetic material. Here, of course there are strong magnetic effect atoms with partially filled orbital primarily the d-cell orbital and then large magnetic moment, spontaneous magnetization presence of magnetic domains. It is identical or analogous to ferroelectric material in presence of the electric field. So, they have a large magnetic moment spontaneous magnetization. So, even in the absence of the magnetic field, they are magnetized and the presence of magnetic domains that also give rise to magnetic domains just like ferroelectric domains we have seen earlier. So, within this domain, the magnetic moments are aligned in a particular direction. However, the neighboring domains may have a different orientation. Most important thing in the presence of a magnetic field is they get strongly coupled with the ferromagnetic material.

So, the line of force gets concentrated and passes through the magnetic material. So, they are coupling is quite strong. In the other cases, the coupling is quite weak. The materials like iron, cobalt, nickel, these are three transition metal elements of a strong ferroelectric effect, ferroelectric property and of course, these are alloys. Also, these are ferromagnetic materials and iron is one of the major, the most important element or member of this group, and in addition to cobalt and nickel, also have the similar properties. So, this is where the strong magnetic coupling takes place with the external magnetic field and that is why mu r is much greater than 1 and chi m is also more than 0. It is actually positive.

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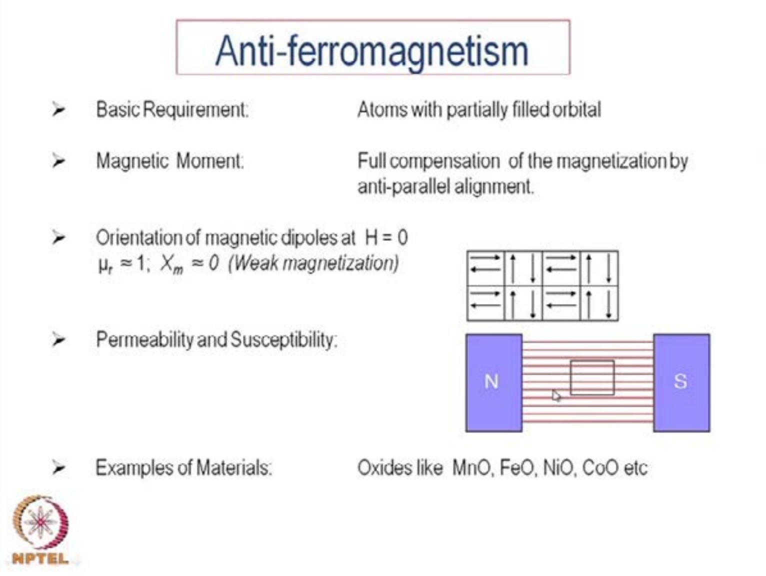

This is anti ferromagnetism. In fact, earlier we had three groups and now, we have five groups including the two subgroups. So, anti-ferromagnetism was coupled with or combined with para magnetism which has very similar behavior so far as the external magnetic field is concerned. However, their origins are little different here. Once again the atoms with partially filled orbital.

The magnetic moment full compensation of the magnetization by anti-parallel alignment. We will look into this what exactly it means, but basically it is given here to some extent that each magnetic movement has an anti-parallel pair. So, each of them are cancelling each other. So, exactly the same magnet quantitative value, but the direction is different. Direction is just anti-parallel. So, there are pairs of magnetic moments having the exact same value, but in opposite direction. So, individually they have magnetic moments, but for some reason or other they have an anti-parallel ordering and because of the anti-parallel ordering, the overall magnetic moment is 0, almost very close to 0 and that is why chi m is very close to 0.

So, it is weak magnetization very similar to parallel paramagnetic materials. So, that is the reason they were combined together, but individually each atom has a strong magnetic moment result in magnetic moment, but when it is combined in the crystal structure in a particular structure, get them aligned in opposite directions. So, the examples are basically not metals or elements. In this case, primarily is the oxides like a kind of oxides in MnO, FeO, NiO, CoO, all of them. If I remember, all of them have a rock solid structure, sodium chloride structure. So, they have identical structures and because of their interaction between them, the magnetic moments are aligned in a anti-parallel manner, and that is the reason this group of materials is called anti-ferromagnetism. So, compared to ferromagnetism where there is a parallel alignment, here is an anti-parallel alignment and therefore, it is given as anti-ferromagnetism.

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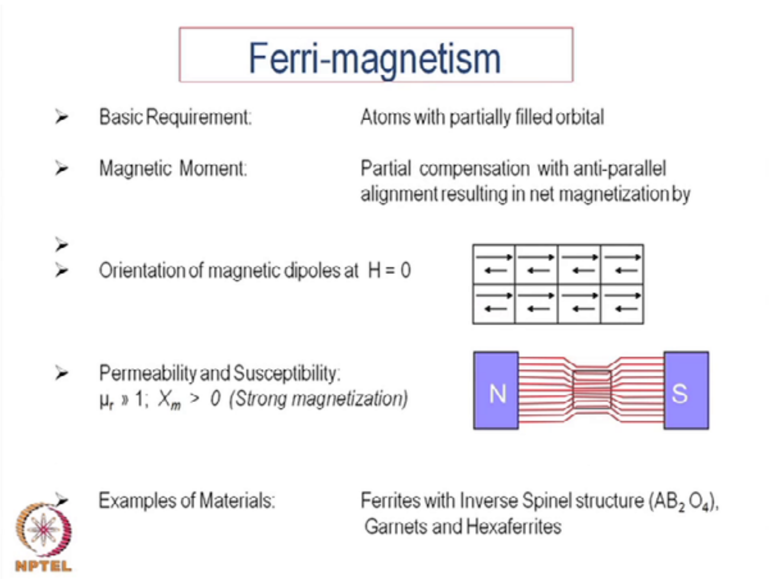

The last group in this series is actually called ferri-magnetism. This is very close to ferromagnetism, but their relation, the origin of this magnetic behavior is slightly different and that is why although they are strong magnetic material like ferromagnetic materials, strong magnetization mu r is much greater than 1 and chi m is also more than 0. So, very similar to that of ferromagnetic material, but they are not called ferromagnetic material. This is called ferri-magnetic material. So, these things must be remembered that although their behavior is more or less same in many ways, but the origin of the magnetism or the response to the external magnetic field is slightly different. Sorry, response to the magnetic field is different, but the origin response to the magnetic field is same, but the origins are different and that is why they have not been termed in with the same name.

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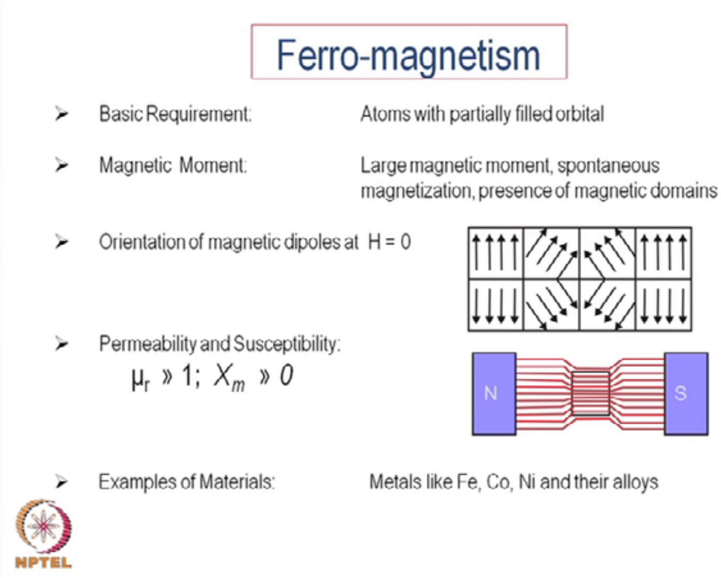

There are one is ferro-magnetism, another is ferri-magnetism. You will see one thing here. You can see the coupling with the external magnetic field with ferro-magnetism and ferri-magnetism is almost identical. So, they can be used more or less the same purpose because they have the same kind of properties.

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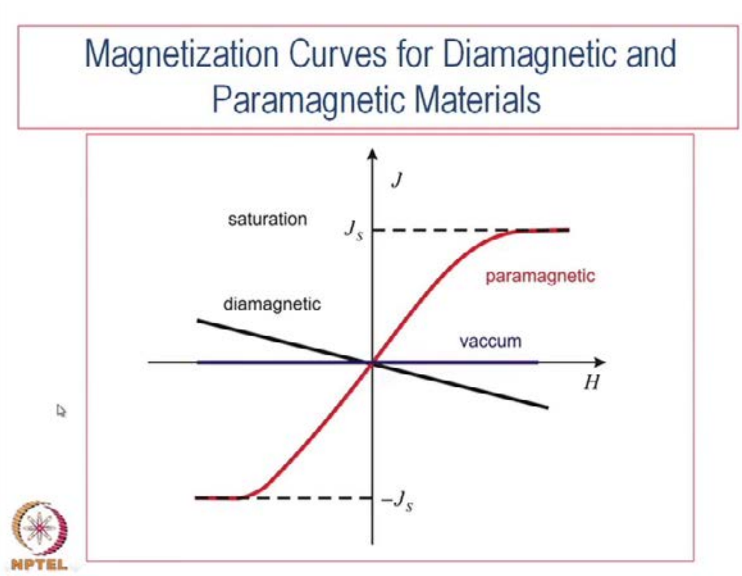

Now, coming back to the paramagnetism and diamagnetism which are weak magnetic materials and therefore, they have some kind of linear magnetism or non-linear just like linear dielectrics. Here also can say linear magnetic materials because the polarization versus the external magnetic field, h j versus h curve is linear. However, there is one difference between the two magnetic materials is that one is the paramagnetic material. It is a positive slope and the black one is diamagnetic. It is a negative slope. So, that is one of the major distinctions in addition to what we have discussed earlier.

So, this is one way to distinguish between paramagnetic material and diamagnetic material. Both of them are weak magnetic materials. Their response to the external magnetism is fairly weak. However, one responds completely differently than the other. Paramagnetic material has a positive slope so far as the polarization is concerned, magnetic polarization is concerned. On the other hand, diamagnetic has a negative slope, but both of them have a linear slope. These are some of the examples and specific values of susceptibility for a group of diamagnetic as well as paramagnetic materials.

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A Few Typical Values of Susceptibility for Diamagnetic and Paramagnetic Materials

Diamagnetic Materials		Paramagnetic Materials	
Material	Susceptibility(X_m)	Material	Susceptibility(X_m)
Al_2O_3	-1.81×10^{-5}	Aluminium	2.07×10^{-5}
Copper	-1.96×10^{-5}	Chromium	3.13×10^{-5}
Gold	-3.44×10^{-5}	Molybdenum	1.19×10^{-5}
Silver	-2.38×10^{-5}	Sodium	8.48×10^{-5}
Silicon	-0.41×10^{-5}	Titanium	1.81×10^{-5}
Zinc	-1.56×10^{-5}	Zirconium	1.09×10^{-5}
Sodium Chloride	-1.41×10^{-5}	Manganese Sulphate	3.70×10^{-5}

This is you can see here most of them values are in the range of 10 to the power minus 5, but negative and there is slight variations, but more or less in the same range. Aluminum oxide, copper, gold, silver, silicon, metallic zinc, sodium chloride.

Aluminum oxide two compounds they also have the similar range of susceptibilities and there are diamagnetic materials here. On the other side, aluminum sorry the paramagnetic materials are aluminum and another set of elements and compounds like aluminum, chromium, molybdenum, sodium, titanium zirconium. As you can see, one thing is you can see the susceptibility in both the cases in the order of 10 to the minus 5, whereas one is positive and another is just negative. Otherwise, they have certain amount of similarity and even manganese sulphate is 3.70 into 10 to the minus 5. So, this is just to give you an idea what is the range of susceptibility of different groups of materials like particularly the weak magnetic.

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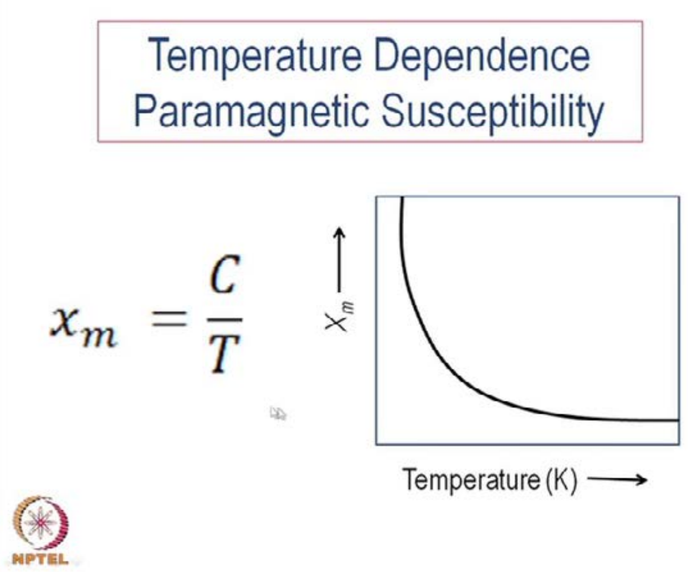

Materials like diamagnetic and paramagnetic susceptibility temperature dependence of particularly the paramagnetic materials, paramagnetic susceptibility it is as temperature increases, the chi m or the susceptibility decreases which is quite understandable. It is basically in a crystal or in a solid. There are atoms and each atom has some magnetic moments aligned in a particular direction and these atoms because of the temperature range, temperature rise, there is a more of randomness because of the thermal vibration and that decrease the susceptibility. So, whatever small susceptibility it has, still it further decreases and it is a kind of parabolic relationship or inverse relationships or parabolic inverse relationship.

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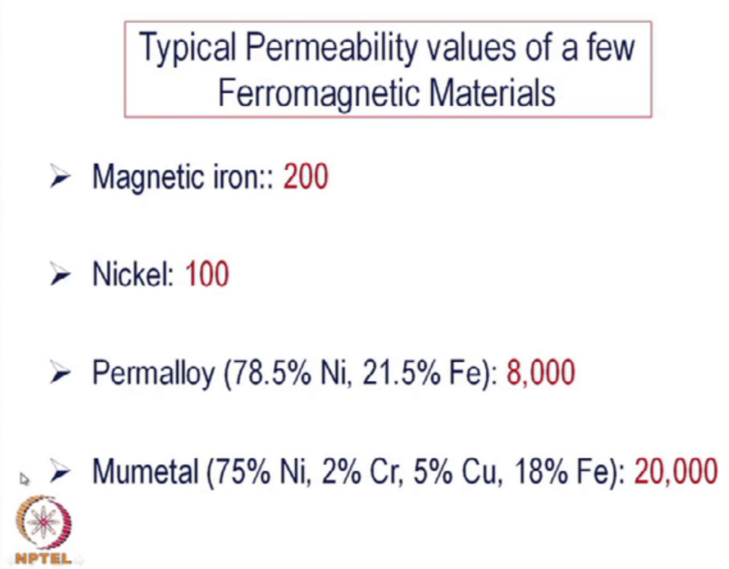

So, one can plot and express this chi m as a constant, C is a constant and T is the temperature in Kelvin compared to that whatever we have seen earlier in a table or the susceptibilities of the order of 10 to the minus 5, either positive or negative compared to that.

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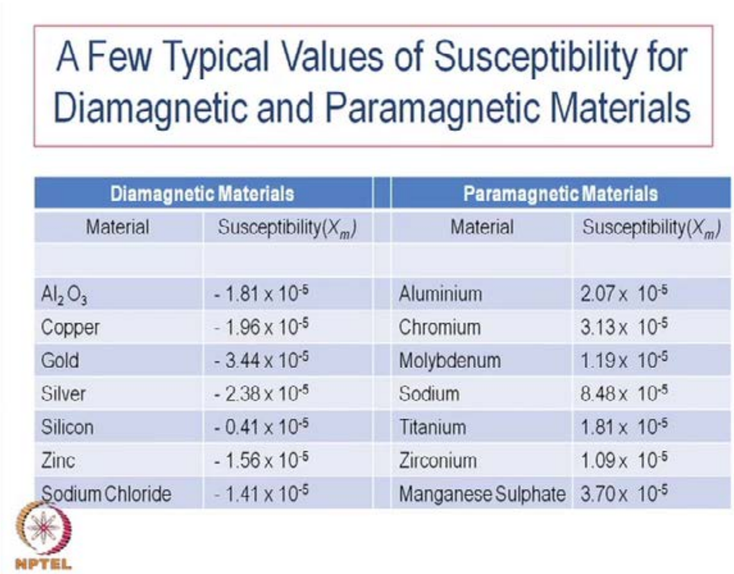
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Strong magnetic materials like ferromagnetic materials are also there. We will look into that later.

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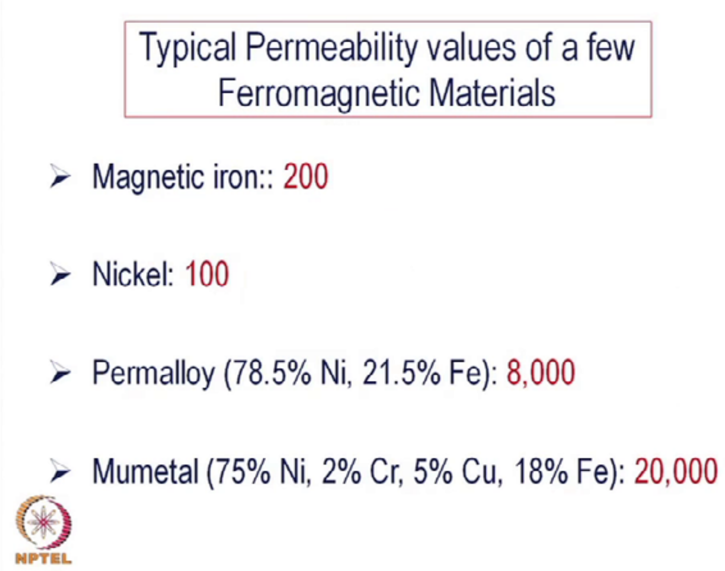

If you go to some of the ferromagnetic materials, the susceptibilities or these are not susceptibilities. I am sorry, this is permeability. Mu is as mentioned is much greater than 1 and these are of this order. Magnetic iron is 200, nickel is 100, permalloy is a permanent magnet alloy of nickel and iron about 8000 and another alloy, again a permanent magnet is 75 percent nickel, and 18 percent iron and in addition to about chromium and copper. These are different phases. These are not pure elements and different crystallographic phases will have different property, and one can buy that process, one can increase the magnetic permeability to the order of about 20,000.

So, that is very important. So, they can respond to the external magnetic very strongly and they can be basically ferromagnetic materials and they can convert it into permanent magnet where the magnetic lines of force will remain there, and it will not destroy. So, in other cases because of the weak magnetic response only, when the magnetic field is applied to get an inductional polarization, whereas here the polarization will be permanent and one can get a magnetic field generated out of it. So, the time is almost up. So, we will discuss this further in the next lecture.

Thank you. Thank you for your attention.