Advanced Ceramics for Strategic Applications

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Lecture - 35
Magnetic Ceramics (Contd.)

In this lecture, we will continue our discussion on magnetic ceramics material. In the earlier lecture, we have already discussed the basics of magnetism, the origin of magnetism particularly in atoms due to the orbital movement of the electrons and also the spin movement of the electrons. So, we had seen there are two basic origins or basic nature of the magnetic moment in an atom. One is orbital and another is spin, and we have also seen the phenomenological magnetic behavior of different materials and based on that, we have grouped the different materials or the whole (( )) materials in 4-5 different groups. Diagrammatic, paramagnetic, ferro magnetic and anti-ferromagnetic. These are basically five different groups.

We have also seen how they respond to the external magnetic field. Some of them very weakly respond, quite quickly, other very strongly and their origin of this response are also little different. So, we have seen it is up to the ferromagnetic behavior, ferri magnetic behavior in also there. Now, ferromagnetic basically arises from the unfilled D cells and one can find out what kind of behavior is expected from what different kind of elements have been unfilled D cells.

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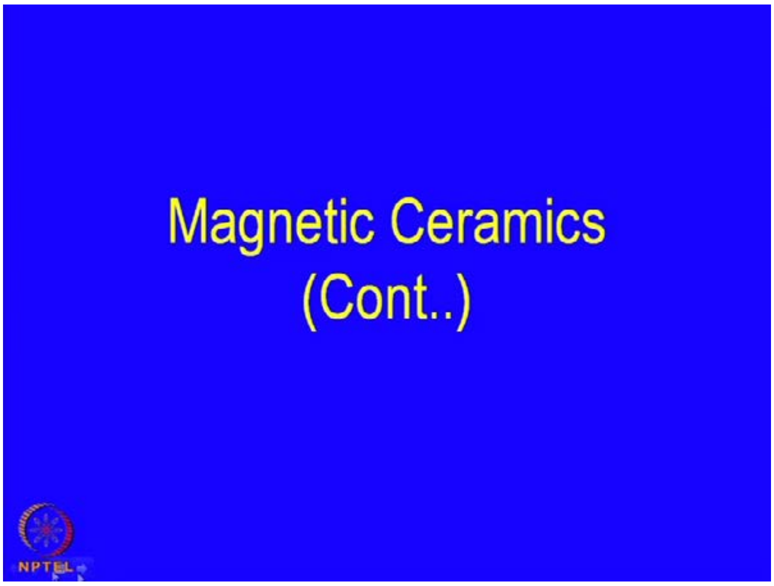

Magnetic Ceramics
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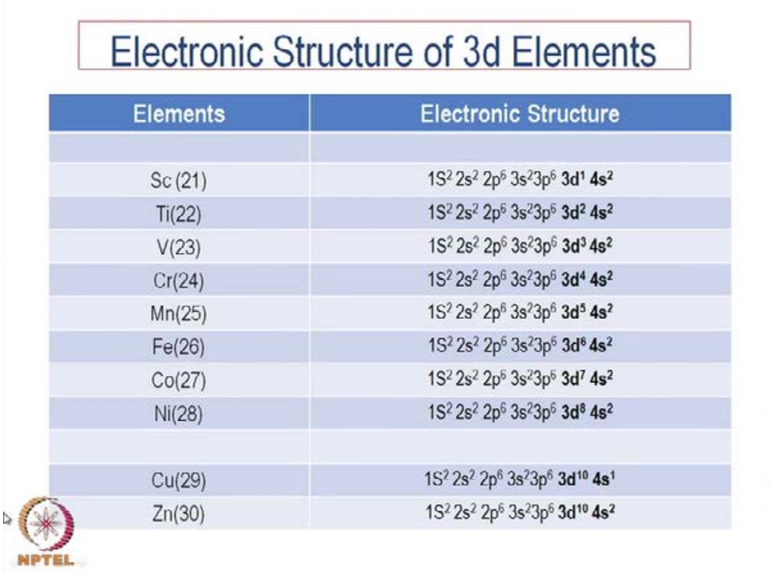

Electronic Structure of 3d Elements

Elements	Electronic Structure
Sc (21)	$1S^2 2s^2 2p^6 3s^2 3p^6$ **$3d^1$ $4s^2$**
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Cu(29)	$1S^2 2s^2 2p^6 3s^2 3p^6$ **$3d^{10}$ $4s^1$**
Zn(30)	$1S^2 2s^2 2p^6 3s^2 3p^6$ **$3d^{10}$ $4s^2$**

So, that is one of our first discussions in this lecture and therefore, we first look at the so-called electronic structures which we have learned in the school chemistry. What is the distribution of the different electrons in the different elements, particularly the transmission elements having unfilled D cell. To start with, the scandium which is the atomic number is 21 and this is how they are distributed, and one can see the first one in the last two columns, these all are 4s 2 and one can see keeping d can have over total number of 10 electrons. So, before d is filled up, the s has been filled up and that is why, it is called the unfilled d cells or d electrons, d elements.

So, in all these cases, particularly this group, we can see 4 s is already filled up whereas d is slowly getting filled up from scandium to nickel. So, scandium has 21 electrons and this is 22, 23, 24, iron is 26, cobalt is 27 and nickel is 28. One can remember that iron, cobalt, nickel, around the strongest ferromagnetic materials whereas, copper and zinc, once again it is a filled d cell, but unfilled s cell. So, this is the distribution of the electron between DMSL.

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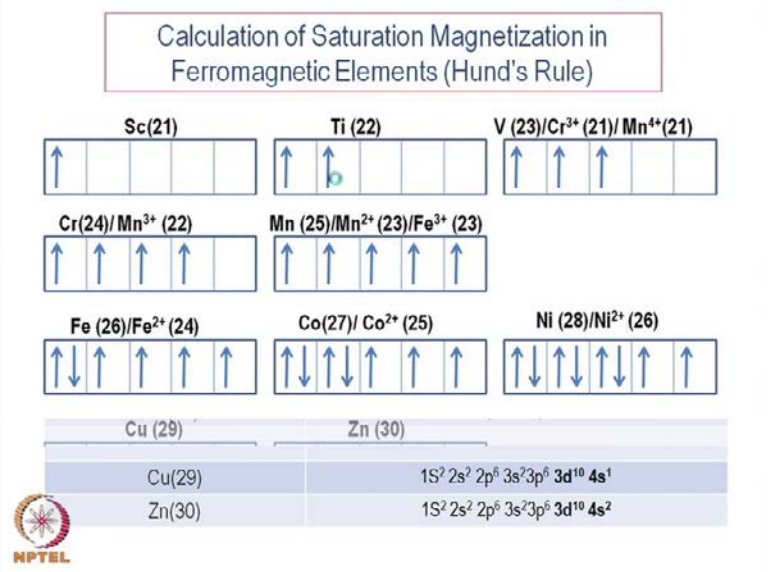

Calculation of Saturation Magnetization in Ferromagnetic Elements (Hund's Rule)

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So, that is one of the major sources or that is one of the causes of strong magnetism in some of these ions. Now, with this background, we would also like to look at some other principle. This is called the calculation of saturation magnetization in ferromagnetic elements and that is the Hund's rule. Some of designs do give rise to ferromagnetism and we have seen the d cell is slowly filled up from one electron here to nickel, which is about 8 electrons, but what is the speed. Because we have also mentioned earlier that in all these cells, unfilled d cells, it is the spin magnetic moments which dominates the contribution of the orbital magnetic moment is almost negligible. So, we are not so much concerned about the orbital magnetic moment.

In these cases, our main concern is how the spin magnetic movement is behaving and how much its contribution is in the overall magnetism. So, here we have only one magnetic, one electronic, the d cell. Then, in titanium, there are 2 electrons and benedium 23 has 3 electrons, chromium has 4, manganese has 5 and then, iron has 6 and so on. So, one thing you have to notice that is what we call Hund's rule.

How the spin is getting arranged? There are two different spins. Half-half plus and minus half. So, the first electron is plus half and the second must have the minus half. That is the normal expectation. However, in this case that is really not so and that is given or that is the rule of Hund's. First of all, all the electrons still all the filled because you have 5 sub cells and each sub cell can accommodate 2 electrons of two different spins. So, if the second electron comes or is present, there in titanium for example, the spin will be same as that of the first. So, it is not this electron will fill up the sub cell first and then, the additional electron will go to the next sub cell. It is not so till all the 5 sub cells 10 electrons have been subdivided or grouped under two each.

So, you have 5 sub cells and then, all the 5 sub cells must be filled up with electrons of the same spin. So, if this is positive, these two are also positive, the third electron will also have a positive spin and fourth electron and so on, till the fifth electron is added. Fifth electron is the manganese. So, manganese have d 5 and all the five will be filled up first, the same spin as sixth electron will fill up with a reverse spin. So, in iron for example, the sixth electron d 6, this will have the same spin. Sorry, the different spin as in the first one and so on. So, the seventh one will have in the second cell and third one will be in the third cell. So, this will have one kind of orbital moment. Sorry, the spin magnetic moment. This will also have seen same spin magnetic moment in the same direction.

So, up to the fifth, up to d 5, the magnetic moment will increase and each magnetic moment, you remember our discussion earlier. Each electron will give rise to 1 bohr magneton k. This gives you 1 bohr magneton. This is another more 2 bohr magneton and 3 bohr magneton, 4 and 5 and so on. However, when we add sixth one, then this will have a positive spin and this will have a negative spin and they will cancel each other. So, the result will be 4 bohr magnetons. So, up to this, the number of electrons will increase the same spin and therefore, magnetic moment will also increase and after that, this will decrease and this will decrease.

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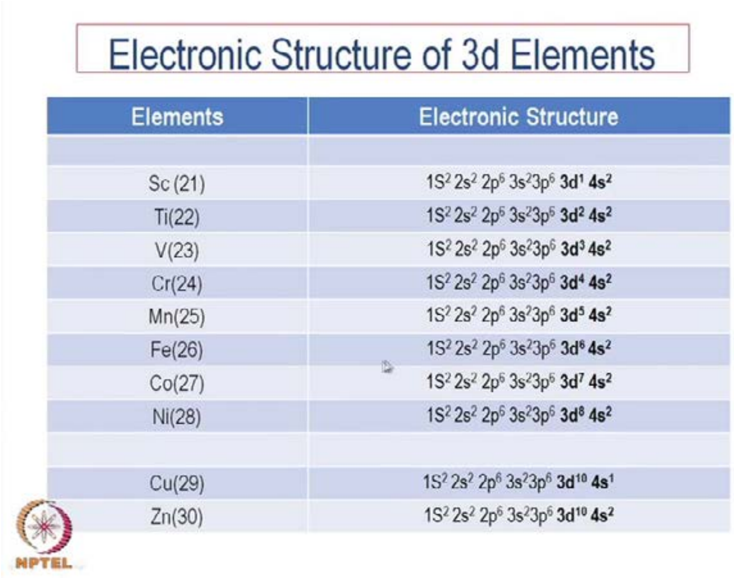

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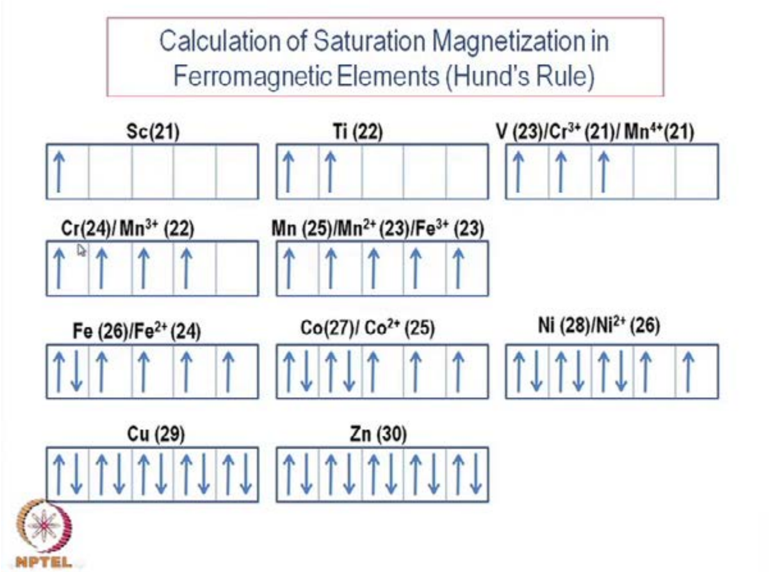
Calculation of Saturation Magnetization in Ferromagnetic Elements (Hund's Rule)



So, d 6, we will have only 4 resultants bohr magnetons, d 7 will have 3 and d 8 will have only 2, right. There is no d 9. It will be that after nickel. Actually, it comes d 10, both copper and manganese. As we have seen earlier, both copper and manganese actually d 10. So, there is no d 9 here, right because after this, this is 4 s 2 and then, once again it becomes 4 s 1. So, d 10 and 4 s 2 d 10. So, these are basically supposed to be diamagnetic without any resultant magnetic moment. So, this is what we call the Hund's law. How the additional electrons are getting filled up or providing, in which particular sub cell it is going and initially, all the five, till the five, this d electron; all the five will have the same spin. Then, the reversal will take place one after the other.

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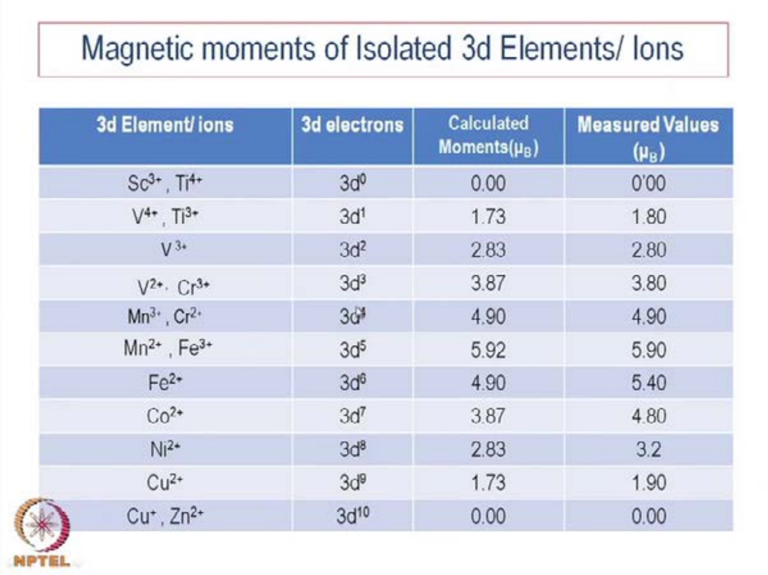

Magnetic moments of Isolated 3d Elements/ Ions

3d Element/ ions	3d electrons	Calculated Moments(μ_B)	Measured Values (μ_B)
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V^{4+} , Ti^{3+}	$3d^1$	1.73	1.80
V^{3+}	$3d^2$	2.83	2.80
V^{2+}. Cr^{3+}	$3d^3$	3.87	3.80
Mn^{3+} , Cr^{2+}	$3d^4$	4.90	4.90
Mn^{2+} , Fe^{3+}	$3d^5$	5.92	5.90
Fe^{2+}	$3d^6$	4.90	5.40
Co^{2+}	$3d^7$	3.87	4.80
Ni^{2+}	$3d^8$	2.83	3.2
Cu^{2+}	$3d^9$	1.73	1.90
Cu^{+} , Zn^{2+}	$3d^{10}$	0.00	0.00

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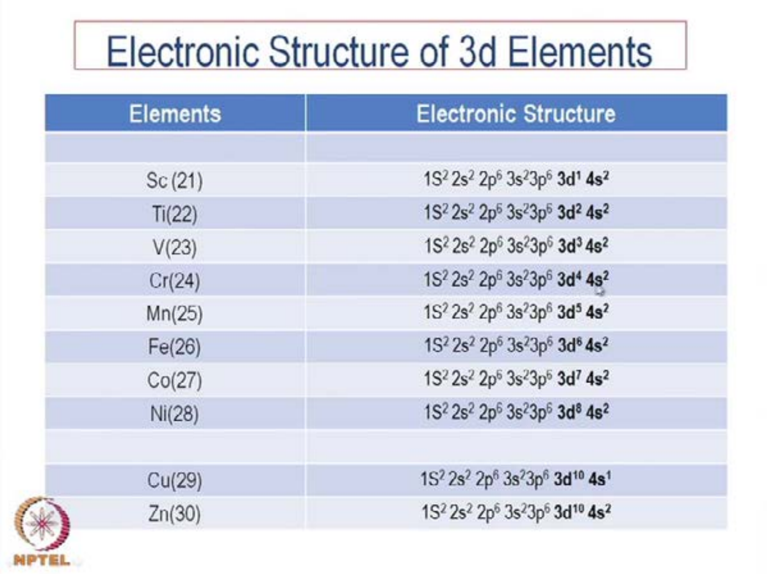

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So, this is an important concept and important criteria one must remember. Now, in addition to the element, this is scandium 21, titanium 22 electrons. We have benedium 23. Now, there are few other ions also mentioned and the numbers of electrons are actually 21. If you go back to the earlier table, chromium actually has 24 and if you have chromium 3 plus, that means 3 electrons have been removed. So, it becomes actually 24 minus 3, it becomes 21 electrons and this 21 electrons, sorry not this one, 23 electrons. Chromium has also 21 electrons. 3 have been removed from here and these 3 are actually this 2 and this 1.

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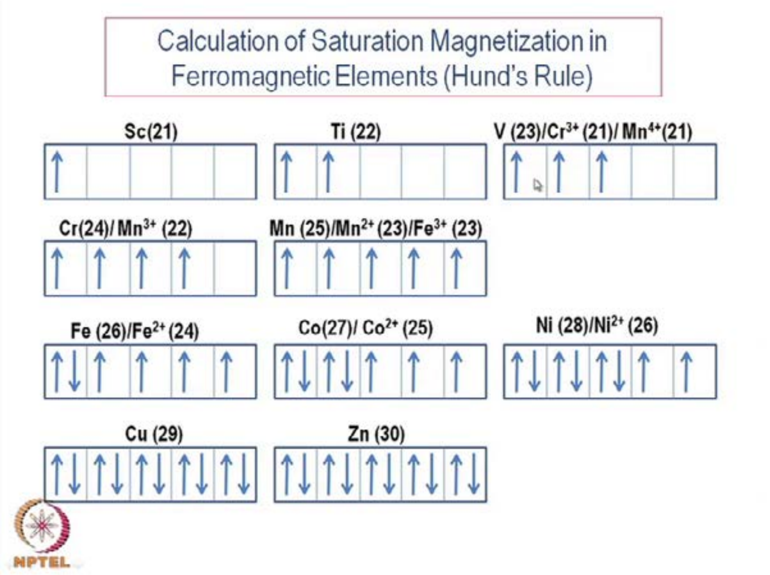

Calculation of Saturation Magnetization in Ferromagnetic Elements (Hund's Rule)

So, it becomes d 3. That is why it is mentioned here. It is 21 electrons, but it is a d 3. So, this is actually 3 d electrons are there. Similarly, the case with manganese. 4 plus manganese is actually 25. Here, it is 25. You can see the element has 25 electrons, where as 4 plus have 21 electrons and out in which we have 3 d electrons. So, it is 3 d structure and similarly, here chromium, the elemental chromium has 24 and it is a d 4 configuration, whereas m n 3 plus is also d 4 configuration. Although, it has only 22 electrons. Manganese has basically 25 and 3 electrons are removed. So, it becomes 22 whereas, if it is manganese 2 plus, then it is 23, 22, 25 minus 2 is 23 and that also have the same configuration of the d 5 Fe 3 plus is 23 electrons as such Fe is 26.

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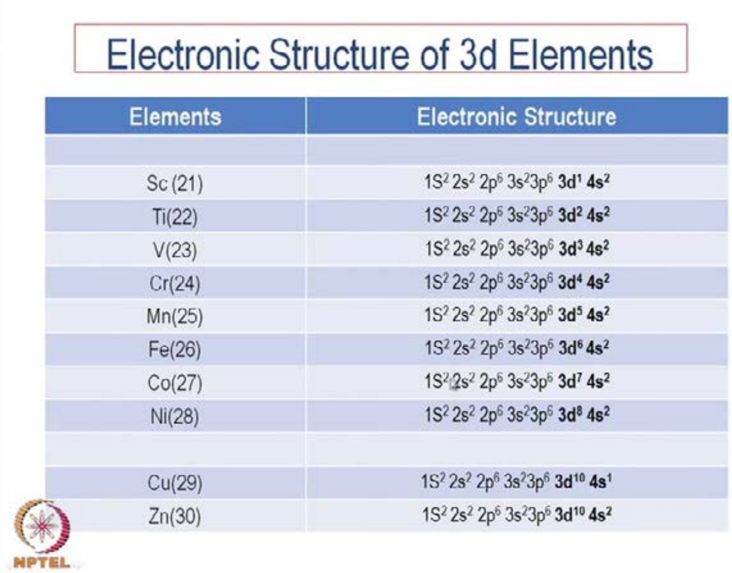

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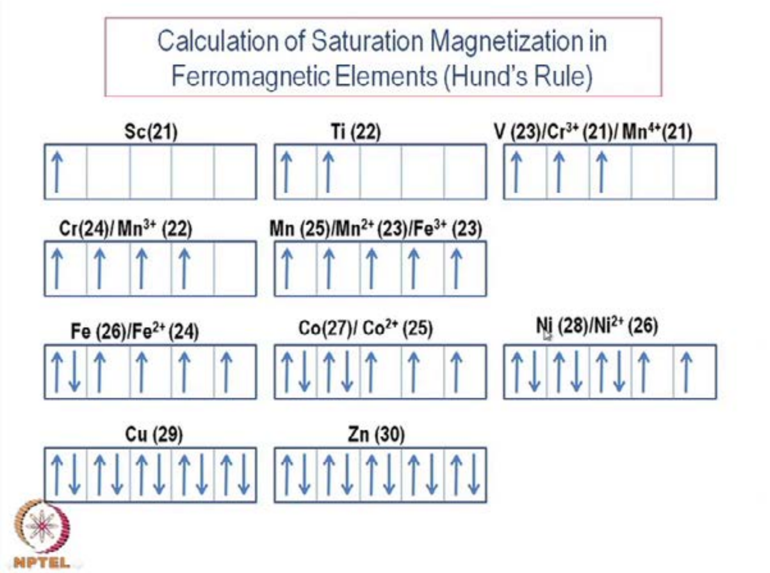

Calculation of Saturation Magnetization in Ferromagnetic Elements (Hund's Rule)

So, if we remove 3 electrons, it becomes 3 plus and it becomes again a d 5 configuration and that is how few more ions have been mentioned. Fe 2 plus also have the same Fe elemental and Fe 2 plus of the same configuration of d 6. That is clear from here. This is d 6. So, Fe 2 plus these two electrons will go away and it will be d 6. So, copper 29 and zinc 30 are completely filled cells whereas, nickel 28 has d 2, sorry it is d 8 and this nickel 2 plus also has same configuration. As far as d cell is concerned, number of electrons will be different because s cells electrons are actually getting removed, but the d cell configuration remains unchanged.

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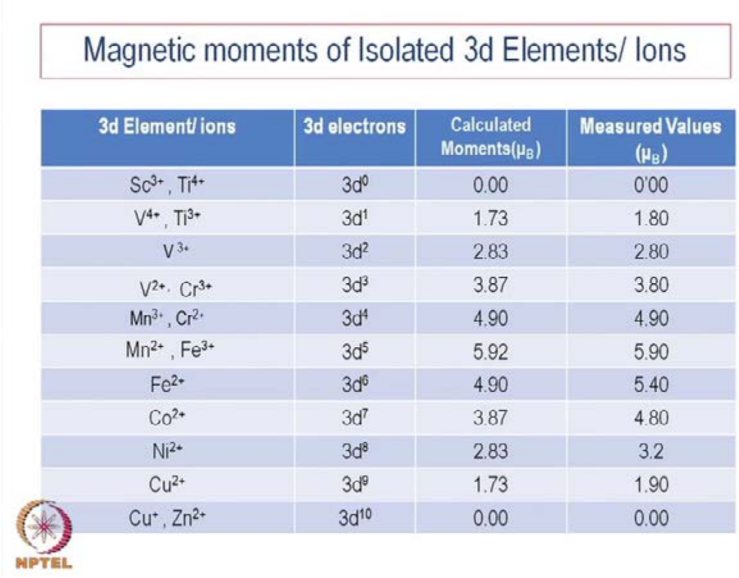

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Ni^{2+}	$3d^8$	2.83	3.2
Cu^{2+}	$3d^9$	1.73	1.90
Cu^{+} , Zn^{2+}	$3d^{10}$	0.00	0.00

So, this is a very important consideration when you are discussing about the magnetic moment of d cell electrons, d cell atoms, unfilled d cells atoms, here is a list. Based on that, here is a list of magnetic moments of isolated 3 d electron elements or ions depending on the number of electrons available in the d cell. These are some of the ions scandium 3 plus is d 3 is d 0 configuration. So, there is no magnetic moment, orbital magnetic moment as I mentioned is not playing any role in this. It is only the spin magnetic moment which is imported. So, it is the number of electrons in the d cell which is of our concern. Benedium 4, titanium 3 is 3 d 1 and calculated moment magnetic moment is 1.73 by the formula which you have shown earlier that mu b into s into s minus 1. If you do that, that gives you this kind of 1.73 is the calculated value and the resultant, the experimental value is very close to that. So, it is 1.80.

Similarly, benedium 3 plus is a 3 d 2 configuration 2.83 is calculated and the theoretical is 2.8. It is very good agreement. B 2 plus and chromium 3 plus is d 3 configuration. So, it is 3.87 and 3.80. This is theoretically calculated value and the actual measurement is 3.8 manganese 3 plus and chromium 2 plus is d 4 configuration and 4.90 bohr magneton. Remember these are 4.90 bohr magneton mu b multiplied, the actual value is multiplied by the value of mu b. So, 4.9 multiplied by mu b. Similarly, it is exactly same 4.9 multiplied by mu b m n 2 plus and Fe 3 plus 3 d 5. This is configuration. This is 5.92 and 5.9 iron 3 iron 2 plus iron 2 plus is 3 d 6 is 4.9. Now, 4.9 and 5.0, there is a slight difference here. It is not exactly same. The reason of course is different, not from here, but it is not too different. Cobalt 2 plus 3.87, 4.8 again once again beyond this is the difference or matching is not that well, but above this, the matching is quite well.

So, it depends on the total number of electrons here beyond 3 d 5. The matching is not that good. For example, 2.83 and 3.2 copper 2 plus 3 d 9 and copper plus as well as zinc 2 plus is 3 d 10. So, 0, this is certainly quite expected and that is what we get in the measurement, experimental measurement. Also, this is not a ferromagnetic material. Neither this is a ferromagnetic material, but some of these transition metal oxides do contribute to the ferromagnetic oxide because most of them are ions.

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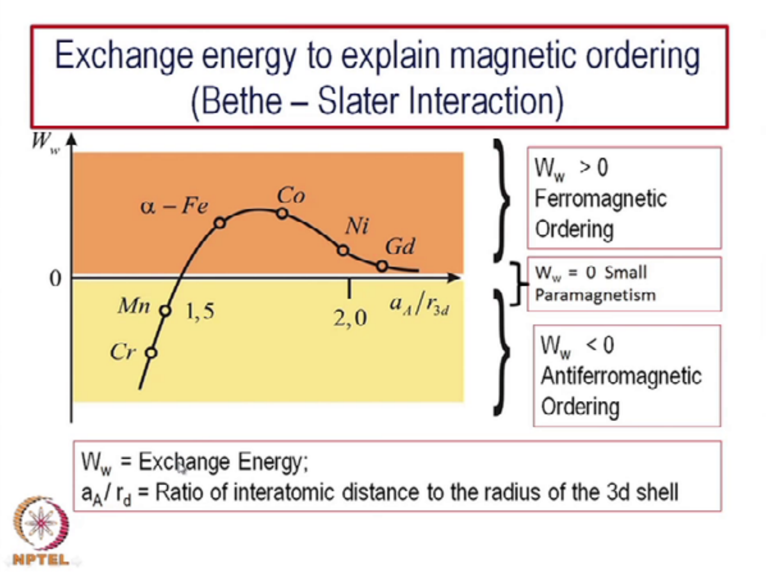

Exchange energy to explain magnetic ordering (Bethe – Slater Interaction)

$W_w > 0$ Ferromagnetic Ordering

$W_w = 0$ Small Paramagnetism

$W_w < 0$ Antiferromagnetic Ordering

W_w = Exchange Energy;
a_A / r_d = Ratio of interatomic distance to the radius of the 3d shell

So, there contribution comes in the form of oxides and that we will see in the form of ferromagnetic materials. Well, to continue our discussion on ferromagnetic materials, we have seen that these three elements, iron, cobalt and nickel are the strong ferromagnetic materials whereas, the other elements in the transition metal says, although they have unfilled the cell and they have their individual magnetic moments of each of the atoms, but the overall magnetic moment form a solid in the crystal. It is not that strong and that comes from the consideration of what we call the exchange energy term. It is the exchange energy to explain magnetic ordering of this is called the Bethe-Slater interaction. So, it is the interaction within the atoms, within the particular crystal structure depending on d cell diameter of the d cell. That means, the number of the d cell electrons and there are arrangement and also, the inter-atomic spacing between the two atoms.

So, these are two different parameters which play a very important role in actually providing the magnetic behavior, to explain the magnetic behavior of some of these elements and not the oxides. Oxide will consider later. So, it is exchange energy term which is W w. We are going to details of that. This is an important plot from this, be the Slater interaction and that very well explains why some of the unfilled d add cell electron or d cell elements have a strong magnetic interaction or very strong magnetic moment whereas, the others do not. So, once you plotted, once you plot this exchange interaction energy or exchange energy against this ratio, the ratio is a A by r d. a A is nothing, but the ratio of the inter atomic distance, a A is the inter atomic distance of that particular crystal structure and then, the radius of the 3 d cell, obviously the radius of the 3 d cell depends on the number of electrons available in the cell and their interaction with each other.

So, if you plot that, you will find these three elements, alpha iron, cobalt and nickel. They have a very positive interaction energy or positive exchange energy. So, W w when it is positive, there is a strong ferromagnetic ordering. We will see what is exactly ferromagnetic ordering, but individual atoms may have magnetic moments when they are combined in the form of a crystal structure or crystal, the ordering may vary. That means some of them are more disorder than the others and more order means more resultant magnet moment. So, that is what we get when exchange energy is positive. There is a ferromagnetic ordering. That means, all the atoms with a particular spin, there is a particular resultant magnetic moment order gets aligned in a particular direction and in a parallel way. Therefore, you have a strong coupling. There is strong magnetic effect if it is negative. For example, manganese and chromium. Although, they have unfilled cells, the electrons, but even then because of the exchange interaction is negative, there is an anti-ferromagnetic ordering is prevailing. So, if it is less than 0, there is a anti-ferromagnetic order which neutralizes each other and therefore, the overall magnetic moment is almost nil. If it is very close to 0, W w equal to 0 small and this kind of material is basically paramagnetic.

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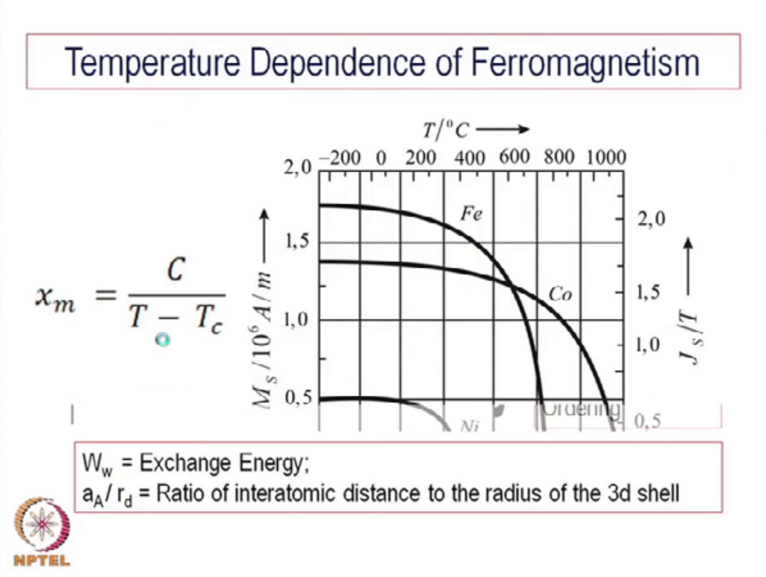

Temperature Dependence of Ferromagnetism

$$x_m = \frac{C}{T - T_c}$$

W_w = Exchange Energy;
a_A / r_d = Ratio of interatomic distance to the radius of the 3d shell

So, if it is fairly low than 0 like this, they have an anti-parallel ordering. If it is close to 0, then it is para magnetism. There is a random ordering and then, if it is more positive, then you have a ferromagnetic ordering or parallel ordering alignment. This is anti-parallel alignment, this is random and then, this is parallel alignment. We will see this little more clearly later on.

So, ferromagnetism means a very strong magnetization and they respond to the external magnificate very intensely, and they have a permanent some kind of spontaneous polarization, spontaneous magnetism polarization. However, this spontaneous magnetic polarization what we called saturation magnetizations here is very strongly temperature dependent according to the Curie wise law. At the Curie law and this relationship, this is the temperature dependence, basically the temperature dependence of ferromagnetism because all magnetism, all magnetic behavior has some temperature dependence because temperature higher is the thermal energy or thermal vibration more is the disorder.

So, even at a lower temperature if you have a strong parallel orientation or anti-parallel orientation or less magnetic moment, so all of them have some temperature dependence. We have seen earlier that the paramagnetic, in case of paramagnetic, there is an inverse law which determines the temperature dependence. Here, it is also the kind of universal law, but with the slight difference earlier in case of paramagnetic property or paramagnetic materials, the k m, the (()) was c by t. That was the relationship. Here, it is more or less same, but with slight difference, there is a critical temperature T c.

So, the critical temperature is the temperature, where it becomes nil. The magnetic saturation or magnetic magnetization curve ultimately drops off. So, at t equal to 0, k m becomes very high almost infinity, otherwise if you plot the magnetization that is the saturation maximum magnetization available from material as a function of temperature, we will see at room temperature, close to room temperature, it does not vary so much more or less remains constant and then, as the critical temperature is reached, this is the critical temperature. The T c as the critical temperature is the polarization or the magnetization drops off quite certainly, quite happening.

So, for nickel, these are the three important ferromagnetic materials one can see. There is a critical temperature. In each case, this temperature is slightly higher than 1000 k. This is about 1400 k and this is around 650 k. So, nickel has a low Curie temperature. This T c is called the critical temperature or sometimes, also referred to as curie temperature. So, each ferromagnetic material has a characteristic temperature beyond which the ferromagnetism is lost because of the thermal vibration or there is no magnetic ordering and the atoms get disorder so far as the magnetic line of magnetic moment is concerned. So, cobalt has a highest curie temperature about 1400 k. Then, iron is around 1050 and this is about 650 k. So, lower temperature is more or less constant and that is the reason it is called saturation magnetic magnetization. This is polarization versus temperature, ok.

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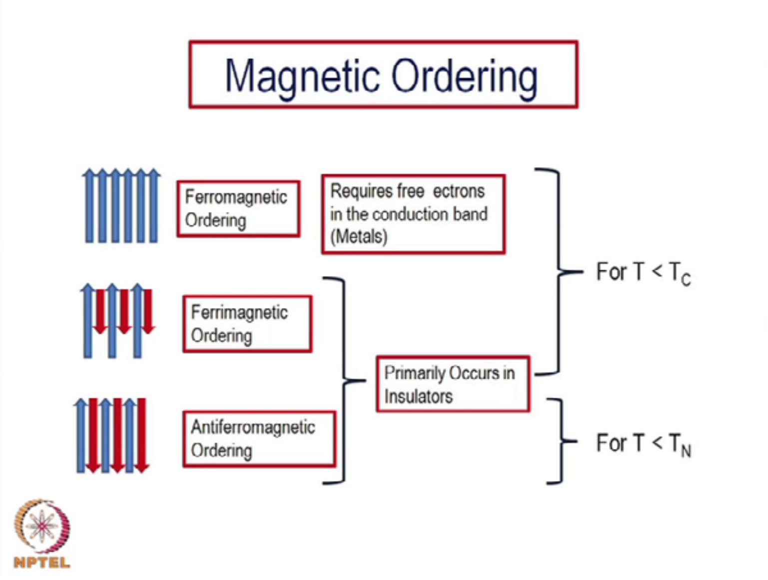

Magnetic Ordering

Ferromagnetic Ordering

Requires free ectrons in the conduction band (Metals)

Ferrimagnetic Ordering

Antiferromagnetic Ordering

Primarily Occurs in Insulators

For T < T_C

For T < T_N

So, this is the relationship of ferromagnetism against temperature. This is what I was talking about, the magnetic ordering. We have seen there is magnetic movement originating either from the orbital magnetic moment, orbital phenomena or the spin phenomena, but for our purpose, orbital phenomenon is not that much of importance. Spin phenomena is more important and that is the major contributor to the magnetic moment, overall magnetic moment or macroscopic magnetic moment of the material, but well, those spin magnetic moment or actually not the macroscopic, but it is more when atom is contributing to the overall magnetic movement from its spin situation.

Now, in case of ferromagnetic, this is what we call ferromagnetic ordering, this is anti-ferro ferrimagnetic ordering and this is anti-ferromagnetic ordering. In ferromagnetic ordering, each of the atoms are, each of the magnetic movement is aligned in such a way that there is parallel orientation look into this what exactly means, but there is a parallel, all the magnetic moment are parallel oriented. That means, they are pointing out in the same direction and therefore, an additive effect, there is an additive effect. So, all of them actually combine to give you the macroscopic property and therefore, that is the reason for it becomes stronger magnetic moment. Overall magnetic movement, resultant magnetic movement is strong, are very hard and that is reason the k a is also more than 1 and more permeability is certainly because while this is if you have a anti-ferromagnetic ordering, last one in this case, we will see the same thing, but each one has an opposite speak or each one has an opposite melody moment in their aligned the opposite direction. Therefore, there is a cancellation.

The overall magnetic moment of the assembly becomes very close to 0 and therefore, it is more or less where the permeability is concerned is more or less like paramagnetic. It is although individual element, individual atoms has a strong magnetic moment, but overall resultant magnetic moment still is very close to 0. That is why this anti-ferromagnetic property are, anti-ferromagnetic materials are grouped along the paramagnetic materials. They also have same thing, but for a different reason. Because of the more random nature or less magnetic movement for individual atoms parallel, there is a ferrimagnetic ordering which is mostly presenting oxides. Mostly presenting oxides are not in elements. Incidentally, this is also in oxides primarily focusing insulators and oxide insulators. So, this occurs primarily in metals and requires free electrons as in the conduction bank. So, that is another requirement which gives rise to the strong parallel alignment.

Now, ferrimagnetism is also anti-parallel, very close to anti-ferromagnetism, but in the two directions, they are unequal, there magnitudes are unequal. Although, there alignments are anti-parallel identified and mannerisms, but the magnitude cell is different and therefore, there is a resultant magnetic mount. So, the downward directions are smaller whereas, the upward alignments are upward as oriented magnetic moments are larger and therefore, there is a positive output, positive resultant, positive magnetic moment in a particular direction. So, like this a light ferromagnetism, they are also strongly coupled with the external magnetic field, but unlike this anti-ferromagnetism wherein this can weakly coupled. So, these are three different kind of ordering. This is available in different materials are these requests mal-adjustments and requires free electrons in the conduction bands show mostly available in metals. They are primarily insulated and these two groups are primarily oxides.

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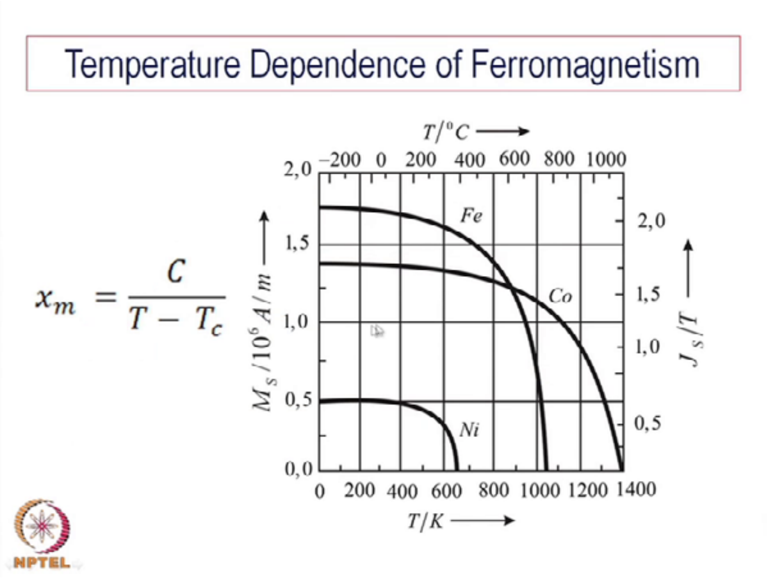

Temperature Dependence of Ferromagnetism

$$x_m = \frac{C}{T - T_c}$$

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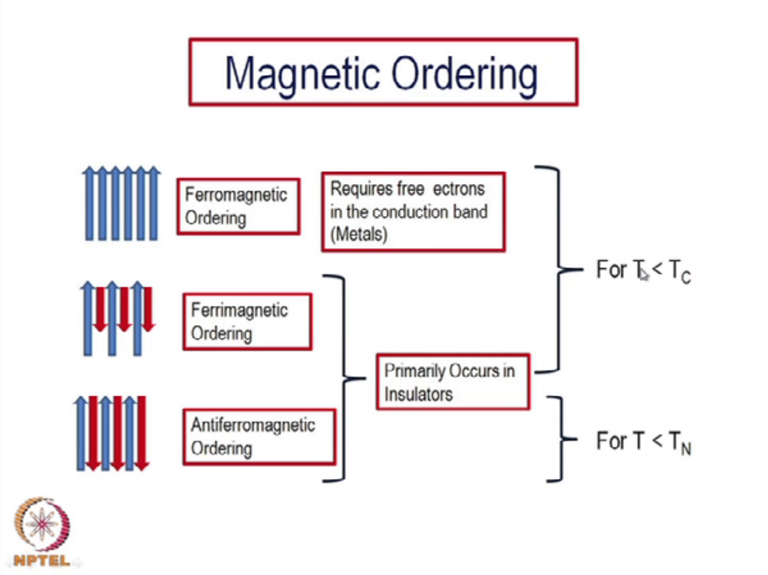

Magnetic Ordering

Ferromagnetic Ordering

Requires free ectrons in the conduction band (Metals)

Ferrimagnetic Ordering

Antiferromagnetic Ordering

Primarily Occurs in Insulators

For T < T_C

For T < T_N

So, when we talk about magnetic ceramics, we are talking about basically these sub ideal, either ferromagnetic or anti ferromagnetic, the temperature dependence is concerned in both these ferrimagnetic because they are strongly coupled and they have some kind of a critical temperature which the curie temperature and this is available both ferromagnetic. We have seen the example of ferromagnetism or ferromagnetic materials how this temperature dependence saturation magnification becomes nil above a temperature. This is a thermal vibration. They no longer become parallel orientation parallel alignment. The atoms are randomly oriented and therefore, we use the magnetic property whereas, here in case of anti-ferromagnetic ordering which is they have a critical temperature, there are also critical temperature which is called nil temperature T n and that happens below the critical temperature again beyond the temperature, this alignment.

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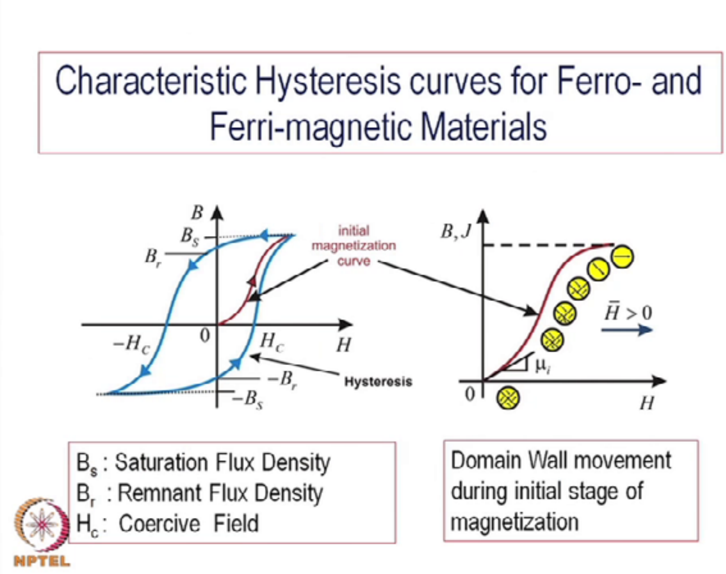

Characteristic Hysteresis curves for Ferro- and Ferri-magnetic Materials

B_s : Saturation Flux Density
B_r : Remnant Flux Density
H_c : Coercive Field

Domain Wall movement during initial stage of magnetization

So, to get a random orientation and main end up with paramagnetic for both of them, all the materials are changeover through a paramagnetic behavior shortening temperature. This is a very important phenomena of a ferromagnetic and ferrimagnetic. So, the correct history cause plot. We have seen earlier for the pair parallel paramagnetic diamagnetic, there is a linear magnetic material used to plot the magnetic induction on magnetic polarization against end up with a linear relations. Here are particularly for these two groups of magnetic material whether it is ferromagnetic or ferrimagnetic. They have identical properties so far as the external magnetic field is concerned here.

So, to start from here, it has non-linear characteristics like this. It goes to a saturation value, a highest value where it saturates the magnetic induction and not the polarization gets saturated at the sum value of external magnetic field, but then if you reduce the magnetic field, reverses the magnetic field, it follows a different kind, different path. So, initially from zero field, it follows this red line and then, goes to the blue line and follows a different path altogether and even at zero field, when the reverse direction and the field is 0, have a value off the magnetic induction or organization. So, when the material is still magnetized and magnetize is remnant flux density, one can say remnant magnetization or remnant flux density and this is Br. So, it does not come back, it does not follow the original path and then, you need additional or negative bias or negative field. Opposite direction would apply field in the opposite direction to bring the value to 0 and this is a valuable magnetic field like needed to neutralize the remnant flux density is called square c field and these are all the terminologies which is also being used for ferromagnetic, ferroelectric material impact.

Ferroelectric have been discovered much later than the ferromagnetic group of materials. So, ferromagnetic was no much earlier. We have discussed in inverse way in our discussion, ferromagnetic comes later than ferro electricity and that is why I am referring to the earlier discussion of electricity. So, the origin is same. The reasons of this kind of loop hysteresis called exactly same and it follows the similar pattern and also terminology is very similar. In their case, we will have a remnant polarization, here was electric polarization, there are the tool electric polarizations, magnetic polarization causes a field, the dialectic material. It was electric field. Here is a magnetic field. Otherwise, it is same in case of dielectric material. It is basically this kind of hysteresis called or on the origin of the course of field, the origin of the relevant here eminent flux density remnant polarization is primarily because the habit domain structure are seeing a minute.

What is a domain structure? So, that domain structure changes as from zero field to higher fields and this is to some extent much sluggish in nature. This movement is much sluggish, this changeover is much sluggish than the rate of change of the electric magnetic field and therefore, it has a memory effect. So, change is from a more or less random structure, random domain moving domain alignment to almost a fully aligned and domains that has it takes time. Therefore, immediately it does not come back to random less. So, the alignment exists even after the withdrawal of the magnetic field.

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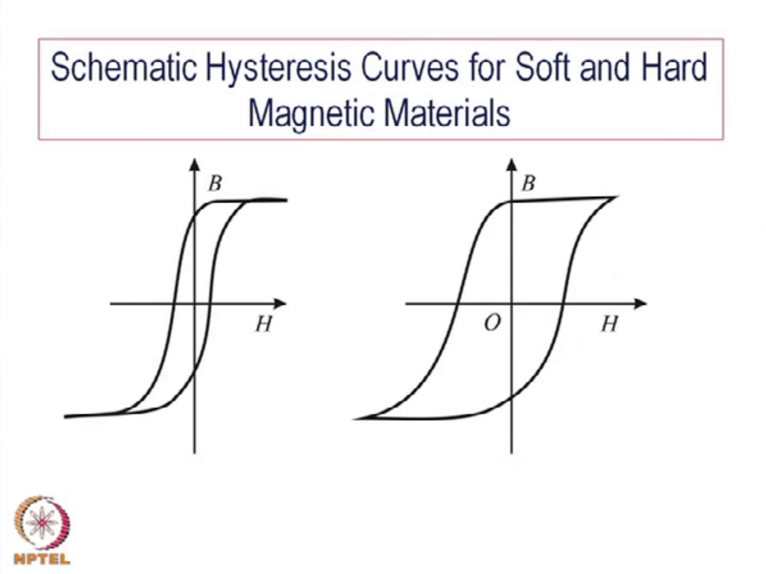

Schematic Hysteresis Curves for Soft and Hard Magnetic Materials

So, that is the origin of the hysteresis loop called particularly for ferroelectric, sorry ferromagnetic and ferrimagnetic fields. This is carved for soft and hard magnetic materials while when you are talking about and ferromagnetic materials as the two types of ferromagnetic. One is this half magnetism, hard magnetism. That means, in hard material, it is difficult to magnetize and also difficult to demagnetize whereas, soft magnetic material which is fairly easy means you need much less external faint to fully magnetize it, saturate the magnetization and also need much less reverse magnetic field to demagnetize. So, these are the two basically depending on the area of the hysteresis loop and at two different routes are the area under carve because the area under the carve measures the total amount of energy needed to magnetize or demagnetize.

So, this is a much fatter of the very high energy hysteresis loop which is much larger and also, the coercive field is large and these distances is large from zero and to magnetize is, fully magnetize, that is also quite large. Their remnant magnetization is also very large and you need more magnetic fields in the reverse direction to neutralize it. So, the total overall cell is a large, a hysteresis loop as I mentioned and it is difficult to demagnetize and so difficult to leave its player's wild is a possibility that it retains the magnetization after the external field is withdrawn. It can get converted to a permanent magnet. So, such type of material will be used, can be used as permanent whereas, these are soft magnetic materials and they need now cannot be used permanent magnet managing be lost with very little of the magnetizing force. Therefore, they can be used more of an electromagnetic, electromagnets where the magnetic field will carry with the application of the external magnet on the magnetic moment or polarization and magnetic induction will vary almost in phase with the applied magnetic fields that has its own application, particularly in many of the electronic device as including the memory for computers, but these days of course, this kind of a memories are not used, but it can be used for miniatures, transformer course, spot course so on.

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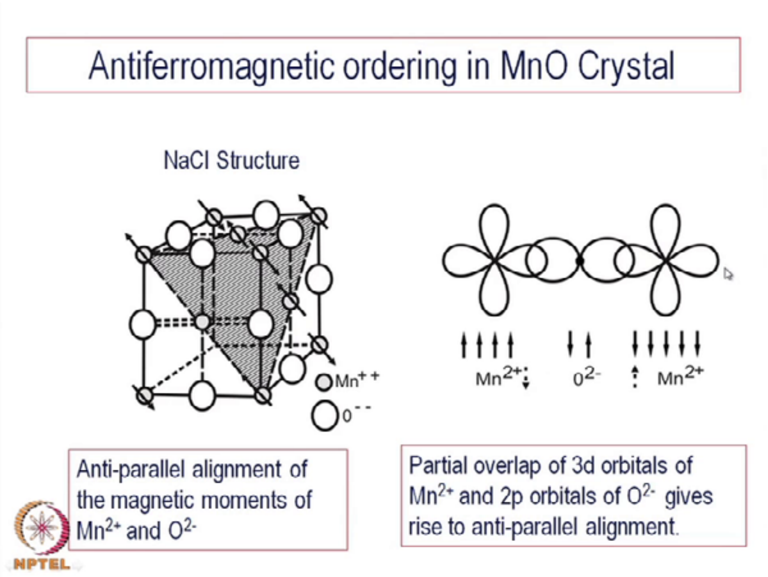

Antiferromagnetic ordering in MnO Crystal

NaCl Structure

Anti-parallel alignment of the magnetic moments of Mn^{2+} and O^{2-}

Partial overlap of 3d orbitals of Mn^{2+} and 2p orbitals of O^{2-} gives rise to anti-parallel alignment.

We will come to that later. Both of both these varieties of magnetic materials have their own usefulness and one can design different devices based on this particular characteristics of whether it is largest or a small hysteresis one. This is an example. We are talking about the anti-ferromagnetic material and this is an example of anti-ferromagnetic will also mention that from the oxides as do have this property and this is an example of manganese oxide MnO which is having a sodium to chloride structure. These positions of the manganese and oxygen ions are this as a cubic symmetry. It is a cubic symmetry enlarges the oxygen ions and corner ions.

Here are the manganese and manganese 2 plus ions along the diagonal here and on the area's or on the centre of the ages, we have oxygen ions. Of course, it can be, no it can be reversed also. Reversed in the sense, it can be drawn basically it is the same distribution, but the units cell can be drawn either with the (()) at the cube ages where cube corners or oxygen at the cube corners, both on resistance are cubilant basically.

So, these are manganese ions and these are the oxygen ions using a so-called owns rule. We can find that each manganese ions has a positive magnet or strong magnetic moment is positive and the strong positive moment, a magnetic moment. Therefore, all have certain amount of magnetic moments from the ions and some of them in between, each in between the two cartels will always have some oxygen ions and is basically a raw magnetic, or if there is anti-ferromagnetic kind of coupling within the oxygen ions, this oxygen is the overlap of this 3 d orbitals of the 2 p orbitals of the oxygen ions. So, this is a little detail of the electronic configuration. It is the 2 p orbital and low one this side and the low one this side. These are the orbitals of the d cell of the manganese 2 plus ions, you have a 4 orbital's and there is always structure is such that there is an overlap between the 3 d orbitals of the m n 2 plus and 2 p orbitals. On the oxygen, 2 minus gives rise to anti-parallel alignment.

We are not going to the details as why it exactly happens, but this much information is acceptable means for our purpose that this overlapping the orbital schemes rise to the anti-parallel alignment of the numbering m n 2 plus ions. This is m n 2 plus iron 1 m n 2 plus iron here and another, m n 2 plus ion here. We have oxygen in between. So, because of this overlap, this is directed in this particular direction towards front whereas, this towards back. So, the next one, all this particular set of m n ions m n 2 plus ions all directed are I mean, alternate ones are directed to the different directions. So, these are actually d 4 electrons and these are the end. There is an exchange of electrons here. So, this mn 2 plus and this mn 2 plus directed into different direction. This is the basic reason and because of this, we will have anti-parallel orientation and it is called the anti-ferromagnetic material. Although, the individual cattern have a strong magnetic movement. The same is the case with other rock solid structure oxides like a few cobalt oxide.

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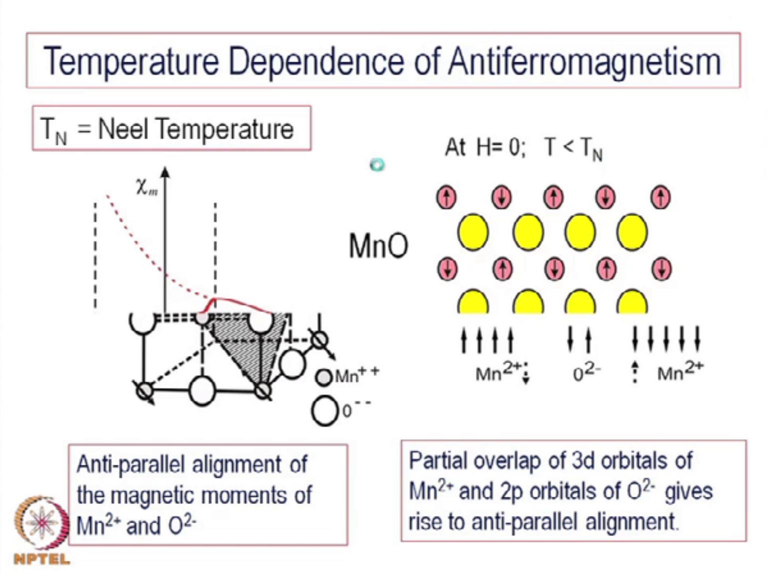

Temperature Dependence of Antiferromagnetism

T_N = Neel Temperature

At H= 0; T < T_N

Anti-parallel alignment of the magnetic moments of Mn^{2+} and O^{2-}

Partial overlap of 3d orbitals of Mn^{2+} and 2p orbitals of O^{2-} gives rise to anti-parallel alignment.

So, nickel oxide, the anti-ferromagnetic material is also strongly magnetic material, but sorry, the weekly magnetic material and we have some kind of paramagnetic way as this is another picture giving rise to the orientation. You can see this. If you look at this layer of atom, each one of them may bring ions different orientation. These are course oxygen ions, these are again manganese ions oriented opposite directions and so on and there is a temperature called nil temperature and the ferromagnetic ordering takes place at a temperature below the nil temperature. Here is the nil temperature and the ordering is lost due to thermal vibration at temperature greater T N. So, very similar to T c in case of where ferromagnetic material, the curie temperature you have a nil temperature and then, the higher ordering can be or the temperature dependence can be expressed in this manner. See, bar T minus theta of course is sometimes is also written as T plus T c over. T c is the negative value and this is called T N. So, this is the key revise law with negative curie temperature. That is this one you can take T N. It becomes T plus T N.

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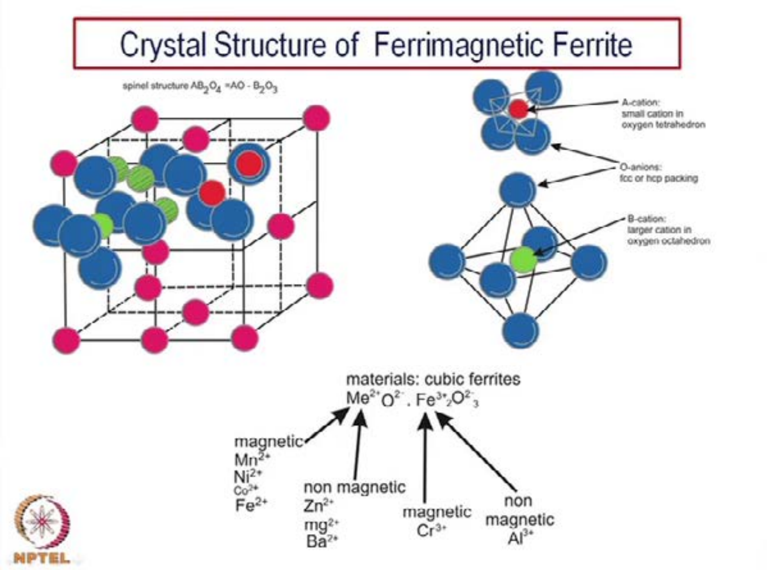

Crystal Structure of Ferrimagnetic Ferrite

spinel structure $AB_2O_4 = AO \cdot B_2O_3$

A-cation: small cation in oxygen tetrahedron

O-anions: fcc or hcp packing

B-cation: larger cation in oxygen octahedron

materials: cubic ferrites

$Me^{2+}O^{2-} . Fe^{3+}{}_2O^{2-}{}_3$

magnetic
Mn^{2+}
Ni^{2+}
Co^{2+}
Fe^{2+}

non magnetic
Zn^{2+}
mg^{2+}
Ba^{2+}

magnetic
Cr^{3+}

non magnetic
Al^{3+}

So, that is the characteristics of the anti-ferromagnetic oxides, particularly the oxide with rock style structure. While we complete this discussion here, because next discussion will be on a separate group of materials that is called ferrimagnetic materials, which are actually the most important group of magnetic ceramic materials. They have enormous application potentiality and just to give an idea, these are ferrimagnetic materials; once again oxide's and they have a particular crystal structure.

Later on, there are three particular structures, in which these oxides crystallize, and they are all very strong magnetic materials having very similar characteristics as that of ferromagnetic characteristics. Although, I mentioned earlier that region is different and they are coupling between the atoms are quite different than that of ferromagnetic materials. Here only on elements like transition metal is iron, cobalt, nickel and there alloys is whereas, a large group of oxides do have a ferrimagnetic ordering and there are also strongly magnetic materials with tremendous application potential. We will discuss further about these materials in general, in greater detail in the next class.

Thank you. Thank you for your attention.