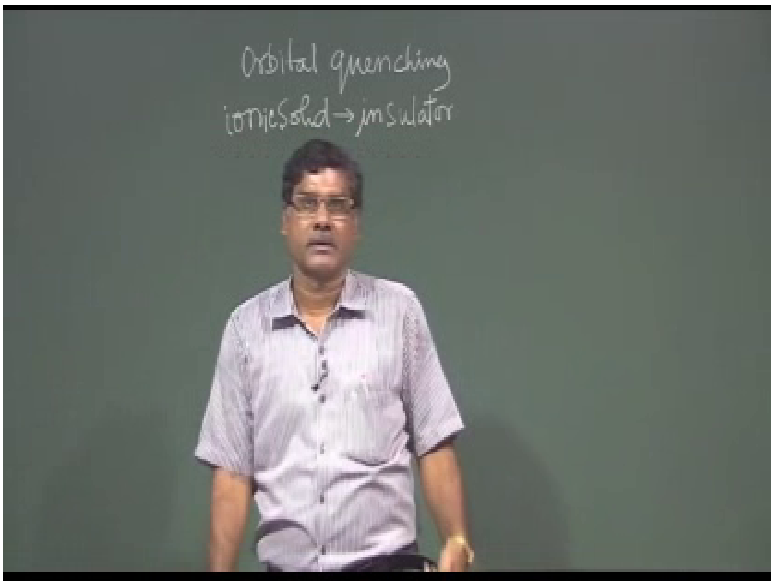
Solid State Physics
Prof. Amal Kumar Das
Department of Physics
Indian Institute of Technology, Kharagpur

Lecture – 65
Magnetic Property of Solids (Contd.)

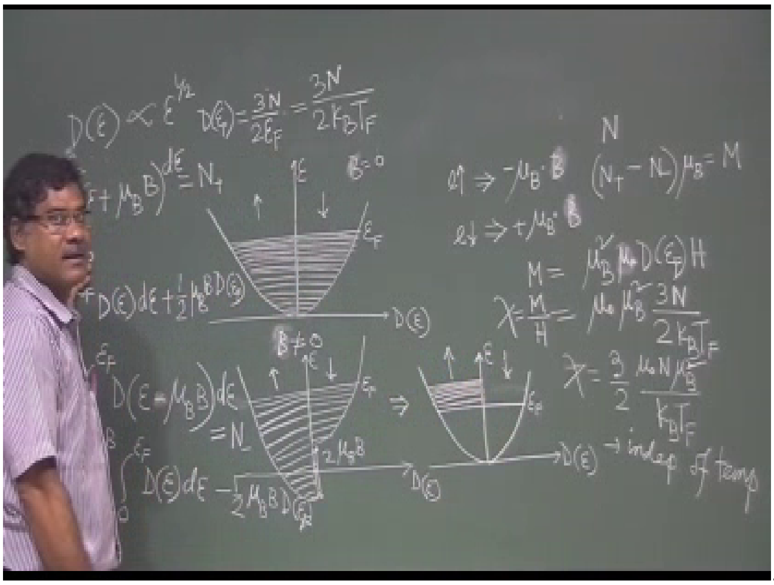
So, we have discussed about the orbital quenching of para magnetic salt.

(Refer Slide Time: 00:27)



So, in case of iron salt iron group salt; so, this orbital quenching was found; whereas, in case of rare earth salt; so, in that case which there is no orbital quenching. So, why it happens; that we have discussed. So, these paramagnetism; whatever we have discussed, that is for ions; ion solid or ionic solid, that is basically insulator, it is basically insulators material.

(Refer Slide Time: 01:56)



Today, I will discuss about the paramagnetism for metal. So, this paramegnetism in metal; so, we have familiar with metal and as we have seen that metal have the free electrons, and using the quantum theory, we can see that these electrons are arranged in different energy levels, and near the Fermi level, Fermi energy those electrons participate in conduction. So, in this case also, when we discuss about the paramagnetism in metal. So, this is similar behavior will be considered means electrons near the Fermi level will contribute in paramagnetism.

So, experimentally it is found that this paramagnetism in metal; this chi susceptibility, it is independent of temperature. It is independent of temperature and experimental result is nicely agree with this mu 0 N mu square divided by 3 kb. So, in case of paramagnetism we have seen, in case of paramagnetism of insulator material that we have seen this chi is like this. It depends on temperature. But in case of metal, this is not the case. So, it has to be independent of temperature. So, this temperature dependent will not be there. So, that is what we want to see here, how it is independent of temperature.

So, this expression for paramagnetism in in ionic salt like a iron group salt, or for this the rare earth salt. So, here paramagnetism in metal that is basically called Pauli paramagnetism of metal; so, basically mainly for conduction electron, this paramagnetism mainly for conduction electron. So, this so if you take a metal. So, it has free electrons, now it is electrons are we can consider that the electrons are arranged in energy level.

So, this type of diagram frequently we will see in book. So, this basically energy E and this axis is density of states. So, density of states, you know this number of states per unit energy. So, that is basically number of electrons per unit energy, if any state this electrons are there. So, here free electrons, if we consider the spin of the electron. So, in normal metal half of the spin is up, and half of the spin is down. So, we can show that if this is the Fermi energy. So, this level; so, this half if we take this, these are the; this, this half is filled up by up spilling. And this half is filled up by down spin.

So, these are density of states. So, at lower energy density of states are less, because this is the density of states. So now, if you go at higher energy, density of states will increase density of states will increase, because it is increasing; right, it is increasing. So, density of states increases. So, these are the basically energy levels. So, here this density of states increases. So, that why I have not drawn this diagram, just it will increase compared to the lower energy. So, half of the electrons have spin up and half of the electron has spin down, now if you do not apply any magnetic field H equal to 0. Now if you apply magnetic field. So, what will happen? So, spin up electron; say it is magnetic moment say it is mu B, and this energy due to magnetic field energy will be mu B dot H and that it is minus right.

So, these; the energy, this is the energy due to applying magnetic field. So, this energy is this energy is for spin of electron, or spin of electron right. This is the energy for spin of electron. Similarly, for spin down electron the energy will be mu B minus H dot H. So, here it is plus sign, because mu B, if in this case is plus up and this other case, it will be down. So, see in the case of applying magnetic field. So, what will happen? This spin of energy of the spin of electron will change, right, for each electron by this. It is independent of energy level. So, it will be shifted it will be shifted by this amount. And this it will be shifted by down on shifted by this amount.

So, this if I draw of a plane magnetic field. So, what I will see? I will see the; if this is the initial level. So, what we will see? So, from this spin up one it will be shifted by minus mu B, it will be shifted by minus mu B, whereas, this one will be shifted by plus mu B; so, but at equilibrium. So, Fermi level here this basically E F Fermi energy, this is the Fermi energy. So now, here you can see this; the spin up electron and this is the spin down electron right.

So, this is for applying; after applying magnetic field H is not equal to 0, H is not equal to 0. So, here we are using B. So, let us write B magnetic induction; let us write B. So, this is the energy separation it is 2 mu B B, right. So now, here is if I just take them in this condition. So, equivalent diagram I can write; I can draw like this, as if such it has to be symmetry. So, as if I just want to find out the net spin up electron, here we can see this spin up electrons are more, because energy here lower energy states are more. So, here is so these are spin down. So, net spin up electron it will be like this, you can represent way like this. So, this minus from this one, then that will be the net spin of electron, near the Fermi energy.

So, these axis of density of states, this is the axis of energy. So, that you should you should write. So now, under by application of magnetic field I have the imbalance between the spin up and spin down electrons. In this case this it was balanced it was 0; net spin up or spin down was electrons are 0, but here we have net spin of electrons are there. So, if N is the number of electrons per unit volume, and N plus is the number of spin up electrons, and N minus is the number of spin down electron. So, per in volume; so, this minus this will give me net spin up electron.

Now, each electron will have the magnetic moment mu B right. So, this will be the magnetization, because this is the net number of spin of electrons per unit volume. So, this is the magnetization. So, spin of now you see density of states; if you remember density of states is proportional to square root of energy that is why it is parabolic right, because of this. So, N; so, number of spin up electrons will be; number of spin up electrons, or density of spin up electrons is D at energy E I think this is the this is the energy for yeah, it will be here it is a I think mu B B. So, total number will get if I integrate total number of states integrate minus mu B B to Fermi energy. So, this will give me N plus.

So, this I can write break it. So, basically, I can write 0 to Fermi energy, due to Fermi energy. So, that is it has to be D E, and then plus plus minus mu B B to 0, 0 minus mu B B to 0, for this will be. So, this for this case each electron will have the; so, mu B B energy, and for this I can write, what will be? The things; it is a total number of electrons is up, right, total number of electrons is half. Means, half coming from this this this onces things I should tell you that total number of electrons N. So, here we have considered for spin up and spin down. So, we have separately so that degeneracy we have taken here, that is in in total number of N. So, N number of that is spin up and spin down both are there is right, for each one, one state is assigned.

So, in density of states so that degeneracy is accounted so for each level; so, each level one for the spin up and one for spin down; so, whatever the total density of states; so, half will be for spin up, and half will be for spin down. So, for so half, and then for each one this energy is mu B B and these density of states. So, this for minus mu B to 0 for this you will get. So, here minus sign is there. So, that is why this will get this term for N plus this is for N plus, similarly for N minus for N minus, it will be plus mu B B to Fermi energy. So, this D is basically epsilon plus or energy plus this will be minus; minus mu B B; because here energy will start this energy will start from here; so, E minus E minus this; so, because they are origin ifs origin as if from here; so, E minus mu B; so, starting come from here; so, this up to here.

So, here it started from here. So, that is why E. So, 0 is from here. So, this amount is added with this. So, in density of states, that is why it is E plus mu B B. And then this is D E. So, that will be basically N minus. So, that will be N minus. And in this case, you will get this in same way; you will get in same way that this one can write 0 to epsilon F, then density of states E D E then minus. So, this this is taking 0 to E F means from here to here. So, minus this part which are having mu B B energy; so, here I will get like this here plus because I have to add this part? So, here minus because this above this. So, this plus this minus for this part. So, this half of the density of states, and for each one is mu B; energy mu B B, and then this density of states.

So, density of states for each energy it will give you the number of number of states means number of spin down electrons, and half we are writing this because half of the electron is spin down and half of the electron is spin up. So now, this; from here this N plus minus N minus. So, this will be M. So, I can write M equal to N minor N plus minus N minus. So, here from here, you can see this is the N plus, and this is the N minus if you take difference. So, this will go, because this this gives the same number initially. So, with respect to 0 to E F; so, here whatever 0 to E F; so, this part basically it will cancellation only. This part will remain. So, this is the Fermi energy was basically here’s.

So, spin down just it is decreased and spin up increased. So, does the net spin up will be difference that spin up will be double. So, basically this is the; this is the part. So, this this part from spin down; spin down for this part and this part for spin up. So, if you take difference. So, this plus this right, and this will cancel each other, and this half from the spin up and half from the spin down. So, as a whole this difference is basically this net differences just double. So, this plus this will be the net spin of electrons. So, this is giving me mu B B and density of states and then mu B is there. So, mu B square, that is the M.

Now, this B I can write mu 0 H, and this E F here I should write; because it is near the Fermi level. So, this I should write density of states at Fermi level. Now you remember that density of states at Fermi level D E F equal to 3 N by, I think 3 N by 2 K v, 3 N by 2 E F. And you remember E F equal to K B T F Fermi temperature; so, this equal to 3 N 2 K B T F; that is the Fermi temperature. Then if I put here I will get mu 0 mu B squares, and then basically let me write chi equal to M by H. So, this is mu 0 mu B square density of states that Fermi. And so, it has to be F, this 3 N 2 K B T F.

So, that is giving you chi equal to 3 by 2 mu 0 N mu B square divided by K B T F. So, this is the susceptibility of paramagnetic metal, it is called Pauli susceptibility of paramagnetic metal. So, here you can clearly see that this expression this chi is independent of temperature, it is independent of temperature. So, as I mentioned earlier that; I will show you the expression for paramagnetic susceptibility of metal, which is independent of temperature. So, this is the right time for me to show, and that is clearly you can see ok.

So, this is in this case this; whatever this diagram I have drawn. So, this very useful diagram, you have to be familiar with this diagram, this is energy this is density of states. So, what is the meaning of this, and how I have done drawn this one from here to here right, after applying magnetic field. So, in case of spin up energy goes down, in case of spin down energy goes up. So, net spin up and spin down, it will just with respect to Fermi level if you draw curve corresponding to this diagram. So, it will be this net spin up electron will be this right. And whatever here we have calculated spin up spin down, thus 1 can follow this diagram, and can take the limit of integration, and take the limit of integration and find out.

So, this is the paramagnetic susceptibility of metal of conduction electrons, and which is independent of temperature. But in case of paramagnetic susceptibility of insulator; oxide or real or thought this ion group oxide. So, this ionic solid basically; for that case it is as you have seen this chi is inversely proportional to the temperature. That is chi equal to c by T right, that Curry laws. So, that we have seen. So, I have discussed enough about the paramagnetism. So, next class I will discuss about the ferromagnetism. So, I will stop here.

Thank you.