Solid State Physics
Lecture 64
Antiferromagnetism and Ferrimagnetism

Lecture - 64

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Now, let us move on to Antiferromagnetism and Ferrimagnetism. (Refer Slide Time: 00:32)

Let us start with antiferromagnetism which is actually a special case of ferrimagnetism. So, what is antiferromagnetism? In an antiferromagnet the spins are ordered in anti parallel arrangement with no net magnetic moment, if we have a temperature below the ordering temperature. So, antiferromagnets are ordered kind of a magnet where the spins are aligned this way and there is no net magnetic moment, no net magnetization. And, it is a particular order, so there is an ordering temperature for this phase which is also called the Neel temperature, after the person who developed this idea who discovered this phenomenon, below which the antiferromagnetic order exists and above which the material becomes paramagnetic. So, how does this thing occur, this kind of situation takes place? Let us consider a part of a lattice, part of a system. I am drawing a rough picture here. We have drawn 16 intersections here and now let us mark them with up and down spin. This one has up spin, this one has up spin, no this one will not have up spin, sorry. Then the nearest one does not have up spin. So, this one has up spin, this one has up spin like this and the down spins are located here, here, here, here. A repetition of this in space will give us an antiferromagnet. So, we have clearly seen here a red sublattice and a blue sublattice. The reds. The blue sublattice, let us call it sublattice A and the red sublattice we call sublattice B. So, we have got two sublattices A and B. So, all the points where this blue spin is located are A sublattice points and all points where the red spin is located are the sub B sublattice points. This is the situation and this brings us antiferromagnetism, if we have the magnitude of these magnetic moments on the individual atoms; that is the size of this vector, the magnitude of this blue vector and the red vector equal and opposite to each other. The Neel temperature in the mean field approximation as we discussed earlier can be given as $T_N = \mu C$, C is the curie constant. But, now comes an interesting thing there is no net magnetization, so this C refers to one of the sublattices. In case of antiferromagnet it is the same, because the spin the magnetic moments on each sublattice is the same, there is no difference. The susceptibility in the paramagnetic region, that is when we go $T > T_N$, we can obtain the susceptibility in this region as $\chi = \frac{2CT - 2\mu C^2}{T^2 - (\mu C)^2} = \frac{2C}{T+\mu C} = \frac{2C}{T+T_N}$. Above the Neel temperature, this is the susceptibility in the paramagnetic region. How about the susceptibility below the T_N? That could be something interesting. (Refer Slide Time: 06:26)

There are two situations in this consideration. If we have the applied magnetic field that can be perpendicular or parallel to the spins, that it can be aligned in different ways as well, but then it will have a perpendicular and parallel component. So, considering the perpendicular and parallel components that is sufficient for our purpose. At and above Neel temperature, the susceptibility is nearly independent of the direction of the field relative to the spin axis. Now, if we have the applied magnetic field $\overrightarrow{B_a}$ perpendicular to the spin, what is going to happen? We can calculate the susceptibility by elementary considerations. Let us try doing that. Let us calculate the energy density. Energy density and we symbolize $M = |\overrightarrow{M_A}| = |\overrightarrow{M_B}|$as the magnetic moment coming from one sublattice. This is M in our definition. So, the energy density $U = \mu \overrightarrow{M_A} \cdot \overrightarrow{M_B} - \overrightarrow{B_a} \cdot (\overrightarrow{M_A} + \overrightarrow{M_B})$. Here, everything is in proper vector form. Which is $U \approx -\mu M^2[1 - \frac{1}{2}(2\phi)^2] - 2B_a M\phi$. So, what is ϕ? 2ϕ, this is the angle between the spins. The spins make some angle with each other and this is the angle, relevant in the situation where all the spins are not aligned along the same direction which is more general a situation in above absolute 0 temperature. If we have absolute 0 temperature, then this thing does not come normally. This thing still can come in special conditions, but otherwise the spins will not point exactly along the same direction, it will have it will make some angle ok. The energy is minimum when $\frac{dU}{d\phi} = 0 = 4\mu M^2\phi - 2B_aM$. From this we find that $\phi = \frac{B_a}{2\mu M}$, then the susceptibility, the perpendicular component of the susceptibility $\chi_\perp = \frac{2M\phi}{B_a} = \frac{1}{\mu}$ in CGS units. (Refer Slide Time: 11:06)

Now, if we consider the parallel orientation of the spins and the applied magnetic field then the magnetic energy is not changed. If the spin system A and B make equal angle with the field, then the $\chi_{\parallel}(T = 0) = 0$. Chi parallel at absolute 0 temperature must be 0 from this argument. The parallel susceptibility increases smoothly with temperature up to the temperature reaching the Neel temperature, T_N and beyond that the yeah the not the anti ferromagnetic susceptibility the paramagnetic susceptibility takes over. Now let us discuss about ferrimagnetism. Ferrimagnetism, as we discussed earlier, if we look into the if we make that kind of a picture once again, we will see something like this. This is the lattice under consideration, just a representative 1, the lattice does not have to be like this. Here we have up spin sublattices, the blue sublattices and the down spin sublattices. That is red, but the size of the vector differs. That means, the magnitude of the spin, magnetic moment that differs. If we have this kind of an arrangement of the magnetic moments on each atom then we can clearly see that the net magnetization $\neq 0$. And, this kind of a magnetic arrangement is seen in a compound Fe_3O_4, which is the ferrimagnetic compound. Why this kind of situation arises in this compound? Fe_3O_4 is actually a combination of $FeO + Fe_2O_3$. An ordered combination, here iron has an oxidation state of +2 and here it is +3. If you make an ordered arrangement of this, you can clearly see that because two different kind of ions will give different amount of spin moment in the lattice. And therefore, and so these this ion +2 ion, this magnetic moment aligns with other plus 2 ion in parallel, and +3 ion they align with other +3 ions in parallel, but then these 2 ions align anti parallely giving rise to this kind of a sublattice structure that we have drawn here. So, in with this kind of an arrangement, we can understand ferrimagnetism in this material, with two different oxidation states and its not really shared electron between them, these two are quite stable +2 and +3 oxidation states are quite stable. So, this is like a charge disproportionation and in this kind of a situation we realize ferrimagnetism. That is all of our discussion about magnetism. Next, we will move on to superconductivity.