Solid State Physics
Lecture 55
Introduction to Diamagnetism

(Refer Slide Time: 00:32)

Hello, after finishing our discussion on lattice vibrations, now we shall discuss about magnetism. We are aware of a bit of the magnetic properties of materials some materials are diamagnetic, where if we apply an external magnetic field the material develops the magnetization in the direction opposite to the external magnetic field and of course the magnetization is weak. There is a paramagnets, paramagnetic materials where the magnetization is induced in the direction of the external magnetic field, but it is pretty weak. Then there is ferromagnetic material, ferromagnetic materials if an external magnetic field is applied then develop a strong magnetic moment along the direction of the magnetic field, but even if there is no external magnetic field it may have some magnetization in its ferromagnet form not all ferromagnetic materials are magnets, but there are magnets that are made of ferromagnetic materials. There are also antiferromagnetic materials have spins in the system that are opposite in orientation opposite to each other and that makes it antiferromagnetic. So, ferromagnetic, antiferromagnetic these two are long range orders of spins in a particular material and this order takes place in a certain up to a certain temperature not at any arbitrarily high temperature. There are also ferrimagnets, ferrimagnetic material are just like antiferromagnetic material where the spins are oppositely aligned, but then not all spins are of equal length something like this, that is ferrimagnet. It is also a long range order and survives up to a maximum limit diamagnetic and paramagnetic materials these properties survive up to very high temperature. So, let us start our understanding with diamagnetism and paramagnetism. Magnetism is a completely quantum phenomenon its inseparable from quantum mechanics, for a strictly classical system in thermal equilibrium it cannot display any magnetic moment, even if a magnetic field is applied. So, what contributes to magnetism? The first thing that contributes is the spin of an electron, electrons have spins that is that has only quantum mechanical origin there is no classical analog to it and this contributes hugely in the magnetic properties of materials. Then there is orbital angular momentum of an electron, and finally, the change of orbital angular momentum due to applied magnetic field. So, if we consider magnetization and denote this with capital M that would be the magnetic moment per unit volume and then we can define another quantity called magnetic susceptibility, which is expressed with $\chi = \frac{M}{B}$ in CGS units and in SI units its given as $\chi = \frac{M}{B}$, these are the expressions for the susceptibility, magnetic susceptibility. (Refer Slide Time: 07:42)

Now, let us understand Langevin's theory of diamagnetism. We want to find out how diamagnetism appears and we will first go through the theory that Langevin developed in this. Langevin's theory is rather a classical theory diamagnetism is associated with the tendency of electrical charges to partially shield the interior of a body of a material from an applied magnetic field. What do we mean? We mean, if an external magnetic field is applied on a material then the material itself tries to somewhat shield that is insulate the that is minimize the effect of the external magnetic field inside the material, hence comes diamagnetism. So, when we try to understand the diamagnetism then we consider the atoms and ions they employ Larmor theorem. That means in a magnetic field the motion of the electrons around the central nucleus is at least to the first order in the magnetic field the same as a possible motion of the electrons in the absence of the magnetic field except for the superposition of a precision of the electrons with an angular frequency. That means because of the application of external magnetic field the electrons presses and this precision is with a frequency ω, which is given as e electrons charge times the magnetic field $\omega = \frac{eB}{2mc}$, c is the velocity of light this is in CGS unit. This precision happens to obstacle the external magnetic field and in SI unit this is given as $\omega = \frac{eB}{2m}$. If the field is applied slowly the motion in the rotating reference system will be the same as the original motion in the rest system before the application of the field. The average electron current around the nucleus is initially 0. The application of magnetic field will cause a finite current around the nucleus because all of the electrons are moving in the same direction. The current is equivalent to a magnetic moment, but this time opposite to the applied electric applied magnetic field. And it is considered that the Larmor frequency that we have got the expression here is much lower than the frequency of the motion under the central field. The Larmor precision of Z electrons is equivalent to an electric current. So, the current is $I = (-Ze)(\frac{1}{2\pi}\frac{eB}{2m})$ in SI units. So, the magnetic moment that is μ of a current loop is given by $\mu = IA$ of the loop the area. If we have a radius ρ of the loop, then the area is given as $A = \pi\rho^2$. Then the magnetic moment $\mu = -\frac{Ze^2B}{4m}\langle\rho^2\rangle$. This is of course, in SI unit and in CGS unit $\mu = -\frac{Ze^2B}{4mc^2}\langle\rho^2\rangle$. So, we are considering row vector in a plane we can call it x y plane. That means, $\langle\rho^2\rangle = \langle x^2\rangle + \langle y^2\rangle$, this is the mean square of the perpendicular distance of the electron from the field axis passing through the nucleus. The mean square distance of the electron from the nucleus is given as $\langle r^2\rangle = \langle x^2\rangle + \langle y^2\rangle + \langle z^2\rangle$. (Refer Slide Time: 14:30)

And if we have spherically symmetric charge distribution, then we can write $\langle x^2\rangle = \langle y^2\rangle = \langle z^2\rangle$and if we have that then we can clearly write $\langle r^2\rangle = \frac{3}{2}\langle\rho^2\rangle$. So, after doing all these we can find out the diamagnetic susceptibility per unit volume as $\chi = \frac{N\mu}{B}$, μ is the magnetic moment equals $\chi = -\frac{NZe^2}{6mc^2}\langle r^2\rangle$ this is in CGS unit. If we write down the equivalent in SI unit we will get , $\chi = \frac{\mu_0 N\mu}{B}$ μ_0 is the free space permeability,μ is the magnetic moment one must be careful about this over $\chi = \frac{\mu_0 N\mu}{B} == -\frac{\mu_0 NZe^2}{6m}\langle r^2\rangle$ in SI unit and this is the classical Langevin result.