Solid State Physics
Lecture 65
Introduction to Superconductivity

Hello. We have come to the last module of this course. So, the last module is superconductivity that we are going to discuss now. (Refer Slide Time: 00:34)

Many of you are familiar with superconductivity, but for the sake of completeness we will go through a formal description of the phenomenology of superconductivity that many of you know. Then we will go into the theoretical aspects of superconductivity. The electrical resistivity of many metals, alloys and compounds; they drop suddenly to 0 perfect 0, when the specimen is cooled to a sufficiently low temperature. This phenomenon is called superconductivity. This was first observed in 1911 by Kamerlingh Onnes. This was 3 years after he could liquefy helium. Before liquefying of helium, which is about 2 kelvin temperature at which helium can be liquefied. Before liquid helium being available, there was no possibility of discovering superconductivity or knowing that something like that existed. At a critical temperature we call it T_c; T critical, the specimen undergoes a transition from a state of normal electrical resistivity to a superconducting state. $T < T_c$, it is superconductor and for $T > T_c$, the material is a normal conductor. Now, looking at this so far what we have described. You may have an impression that superconductor is just like a normal conductor with the resistivity 0, but that is not the case. There is a certain difference between normal conductor with exact 0 resistance, if that existed although it does not exist. If that existed, a normal conductor with exact 0 resistance and superconductor; these two things would still be different. There is a significant difference between these two and we will come to that discussion. Let us go to an experimental survey of superconductivity the phenomenology of superconductivity. In the superconducting state, the DC electrical resistivity is 0 or close to 0 that persistent electrical currents have been observed to follow to flow without attenuating in superconducting rings for more than a year, until the experiment was stopped. So, the current does not stop even if even though there is no electric field, which should have happened provided there is no resistance. Therefore, this clearly is the case of no resistance. And just like the dramatic electrical properties, superconductors also process dramatic magnetic properties where it differs from a normal conductor with exact 0 resistance. The magnetic properties cannot be accounted for by assuming superconductors at normal conductors with 0 electrical resistivity. Bulk superconductor in weak magnetic field act as a perfect diamagnet. What do we mean by perfect diamagnet? That means, whatever magnetic field is applied, nothing enters the material in its superconducting state. So, the interior has no magnetic field no magnetic induction in the interior of a superconductor. And this happens up to a maximum threshold of the external magnetic field applied magnetic field beyond which it the magnetic field penetrates the material at the same time the superconducting property is also lost. So, it remains in superconducting state and allows the magnetic field to pass through that does not happen. If the magnetic field is sufficiently large to force invade the material, then the superconductivity is killed. Now, when a specimen is placed in magnetic field and is then cooled through the transition temperature T_C for superconductivity, the magnetic flux originally present is ejected from the specimen. We have a specimen at a temperature $T > T_c$. Now, we are cooling this material and bring it to $T < T_c$. And during the process, we had some magnetic field external magnetic field applied in the material. Now, as soon as we cooled it below T_C, the magnetic field would be expelled of this material and this kind of effect is called the Meissner effect. And this is very interesting. (Refer Slide Time: 07:13)

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So, here we discuss some properties of superconductivity. Superconductivity occurs in many metallic elements, alloys and intermetallic compounds and doped semiconductors as well. And it has a very varying range of critical temperature $YBa_2Cu_3O_3$. This compound has a superconducting $T_C = 90K$

kelvin pretty high. And rhodium on the other hand, has a tiny superconducting critical temperature which is 0.001 kelvin. Silicon can become superconducting at a moderate temperature of 8.3 K at 165 kbar of pressure which is extremely high pressure. Foreign paramagnetic impurities can superconductivity also a strong external magnetic field can destroy superconductivity. (Refer Slide Time: 08:17)

And this is the Meissner effect that we were talking about. If we have the temperature above the critical temperature, the magnetic field passes through this material here this blue material. And as soon as we bring this temperature below T_C by cooling the material, the magnetic field is expelled. The field lines move outside the material. It cannot penetrate through the material. Meissner effect shows that a bulk superconductor behaves as if the magnetic field is 0 inside the specimen. We obtain a particularly useful form of this result, if we limit ourselves to long thin specimen with long axis parallel to the applied magnetic field B_a. Now, the demagnetizing field contribution will be negligible. So, the magnetic field can be written as $B = B_a + \mu_0 M$in the material. And as we describe the Meissner effect this magnetic field has to be 0 inside the material; that means, $\frac{M}{B_a} = -\frac{1}{\mu} = -\epsilon_0 C^2$. The result B = 0 cannot be derived from the characterization of the superconductor as a medium of 0 resistivity; that is how superconductor is different from a normal conductor of 0 resistance. (Refer Slide Time: 10:09)

Now, let us consider Ohm's law. Ohm's law tells us that applied electric field $\overrightarrow{E} = \rho \overrightarrow{j}$; ρ is the resistivity and $\overrightarrow{j}$ is the current density. We see that if $\rho \to 0$ while the current density $\overrightarrow{j}$ is held finite, then $E = 0$. So, if $\rho \to 0$ j is finite, we must have $\overrightarrow{E} \to 0$. Now, let us recall a Maxwell's equation which is also known as Faraday's law, that is $\frac{\partial \overrightarrow{b}}{\partial t} = -\overrightarrow{\bigtriangledown} \times \overrightarrow{E}$. Recalling this, $\rho \to 0$ means $\frac{\partial \overrightarrow{b}}{\partial t} = 0$; that means, there is no change of the magnetic field with time, but that does not require the $\overrightarrow{B} \neq 0$. That means, absolute 0 resistivity does not require the $\overrightarrow{B} \neq 0$ which can be the case, but not necessarily. And by research, we also know that the flux through the metal cannot change on cooling through the transition. The Meissner effect suggests that perfect diamagnetism is an essential property of a superconducting state. We expect another difference between superconductors and perfect conductors defined as a conductor in which the electrons have infinite mean free path. When the problem is solved in detail, it turns out that a perfect conductor when placed in a magnetic field cannot produce a permanent eddy current screen. The field will penetrate about 1 centimeter per hour, but in superconductor that does not happen. (Refer Slide Time: 13:07)

Then we discuss about type 1 and type 2 superconductors. So, type 1 superconductivity is abruptly killed beyond the critical magnetic field as shown in this red curve here red lines. Here, H is the external magnetic field applied. And $-\mu M$ that is proportional to magnetization. If we have a type 1 superconductor then, the superconductivity sustains up to this much that is H_c critical field and then it is abruptly killed. And it cannot resist the magnetic field beyond this value of the magnetic field. But, if we have type 2 superconductor, then there are two different critical fields. Up to the first critical field, the magnetization keeps on changing linearly and then it increases linearly then, beyond this field there is an exponential decay in the magnetization or negative of magnetization to be more precise. And then and after beyond the second critical field, the superconducting property is completely killed. So, this part below H_{c1} that is absolute superconducting state, beyond H_{c1} and below H_{c2} that is a mixed state and beyond H_{c2}, it is a normal metallic state. (Refer Slide Time: 14:43)

There are other properties of superconductors like we can discuss we can talk about heat capacity, which is lower in superconducting state and decreases with decreasing temperature. We have there are energy gap there is an energy gap in a superconductor which is a correlation gap not at all like the band gap in a band insulator and this gap is observed around the Fermi level. If we consider different isotopes of an element, if that element is superconducting and has a critical temperature that change so, different isotopes will have different critical temperature for super conductivity. And if we mix these isotopes that superconducting critical temperature varies smoothly as a function of mixing.