Condensed Matter Physics

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Module - 01
Lecture - 27
Superconductivity- Perfect Electrical Conductivity and Perfect diamagnetism

Exactly a hundred years ago something happened something of an (()) making proportions happens in a physics this event is the discovery of superconductivity.

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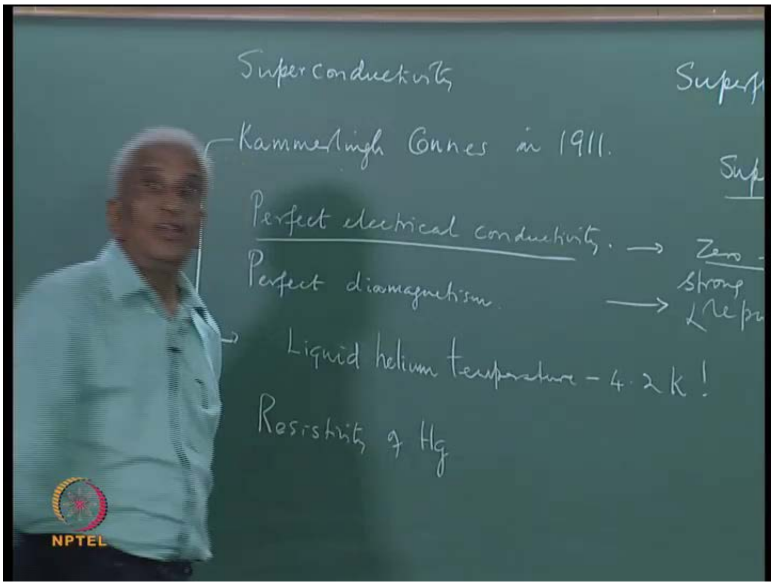

The phenomenon of superconductivity discovered by a person called a Dutch physicist called Kammerlingh Onnes in 1911. So, today is a 100 years of superconductivity and in these hundred years a lot of things have happened. In particular investigation of superconductivity and on in metals as well as the discovery and study of the phenomenon of super fluidity in a liquid helium both these phenomena have opened up a completely new domain in the history of condense matter physics that of super fluids. Even a superconductor is considered as a super fluid only it is a charged fluid that is the main difference.

So, these both are quantum fluids, which means that unlike in the case of atoms and molecules their quantum effects can only be inferred from the phenomena, here you can witness quantum phenomena actually on a microscopic scale. So, you have the area of quantum fluids, which is a completely new area in the history of condense matter physics. So, the discovery of superconductivity in 1911 by Kammerlingh Onnes in this sense marks beginning of an entirely new chapter and opened up a completely new area in the domain of condense matter physics. So, from now on we are going to spend some time discussing this very fascinating phenomenon.

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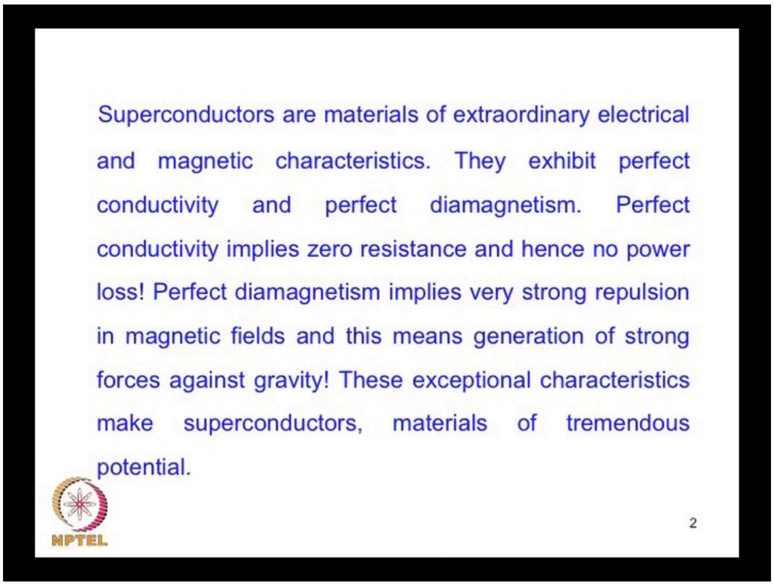

Superconductors are materials with extraordinary electrical and magnetic properties. We will see how, very soon.

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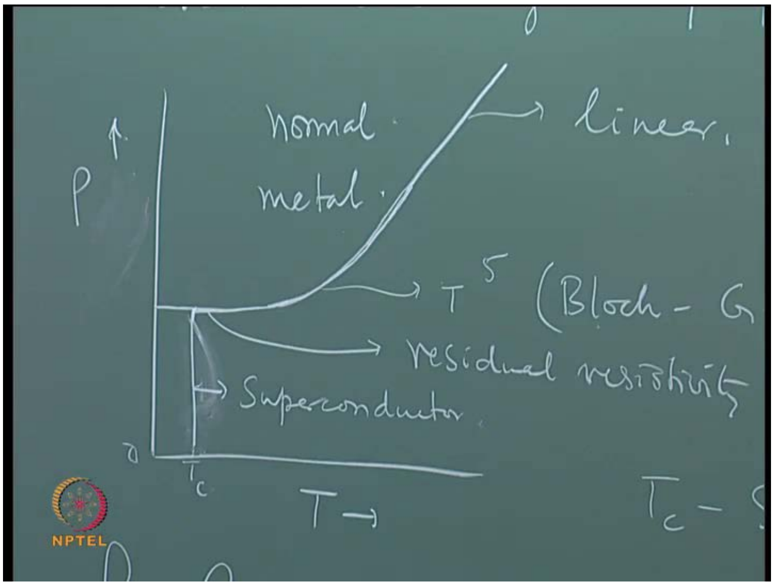

They exhibit for example, a superconductor exhibits the characteristic of perfect electrical conductivity this is the discovery by Onnes. In addition a superconductor also exhibits perfect diamagnetism. This will be the topic of our discussion today. Now, what do you mean by perfect electrical conductivity? It means zero electrical resistance, well in physics there is nothing called zero, zero is a mathematical concept, in physics you measure and find out whether something is zero or not and that zero will depend on how sensitive your measurement can be. So, if your instrument can measure milliohms then you can only say it is milliohms, if it can measure micro ohms you say this zero resistance is it close to zero and it is of the order it cannot be more than a few micro ohms.

So, in the same way you can only say a set of an upper limit to the resistance and say that it cannot be more then. So, that is the kind of sense in which we can say it is zero, but there are ways of actually proving to a great extent that the electrical resistance actually vanishes. What is the implication of this electrical resistance is the basic mechanism for dissipation of energy in a conductor and loss of electrical power. So, when you say zero electrical resistance; that means, there is absolutely no loss of electrical energy in a superconductor.

So, this is what fired the imagination of electrical engineers and physicist alike about the possibility of generating, transmitting and utilizing electrical energy with no loss. This is one of the holy grails of material science in a superconductor gives you the possibility, the promise of realizing such a situation in this sense it is the matter of, it is the subject of science fiction.

A lot of science fiction has been written based on such a characteristic, but as you will see like every other dream of a getting something out of nothing this dream is also dashed in physics to a great extent and we have limitations to this argument about perfect conductivity. In addition if you have a combination of perfect diamagnetism also, if a material is perfect diamagnet then it means that, if you apply magnetic field there is going to be an extremely strong repulsion. This means you can generate very strong forces, repulsive forces, which can work against gravity.

So, you can have a barring, which is frictionless which is contactless and which sustains which supports something against gravity. Strong repulsive forces, which can be employed against gravity for example, superconductors have been envision and actually it has been realized of fast ground transportation of trains. Super conducting trains, which go at very high speeds without any contact with the ground. So, they are just levitated above ground and this mean that a major source of resistance friction is not there to be contended with therefore, you can reach very high speeds this again has been realized to some extent. So, you can see that the exceptional characteristics of superconductors render them to be materials of tremendous technological importance.

Of course like every dream there are drawbacks. Superconducting behaviour as you see was discovered by Onnes in 1911, but only when the material is cool to liquid helium temperatures, very low temperatures 4.2 Kelvin to be exact, just 4.2 degrees above absolute zero. So, you require a lot of power in order to provide this refrigeration unless you have a superconductor, which is superconducting close to room temperature, which is yet to be found. So, the need for refrigeration to low temperatures offsets the energy gained that you get from perfect electrical conductivity.

So, this is a major drawback of super conducting devices. Of course, there is a very incidentally, there is a very fascinating story about the discovery of superconductivity. Kammerlingh Onnes actually was a recipient of two noble prizes in physics. One in 1908 for his discovery for his a liquefaction of helium, he was the first one to liquefy helium and to realize this low temperature. For this in fact, it may be of interest to know that he utilized helium gas which was derived by heating monazite sands which were obtained from coast of Kerala in India.

We are still today not producing liquid helium gas of our own even though we have tremendous resources of helium gas natural resources. The monazite sands are full of alpha particles, which are nothing, but helium nuclear, but still we have not produced our own source of helium gas, we are still importing helium gas for liquefaction and other purposes. Well because he had the monopoly of access to liquid helium temperatures, which was realized by him in 1908. He could use this temperature to investigate the electrical behaviour of metals at such low temperatures and that is what let him on to the discovery of superconductivity in 1911. Three years later and that won him a second noble prize. So, one thing led to another.

Today, we will discuss the characteristic properties of superconductors and their interpretation based on thermo dynamic as well as quantum theories. We will also touch briefly on applications of superconductors.

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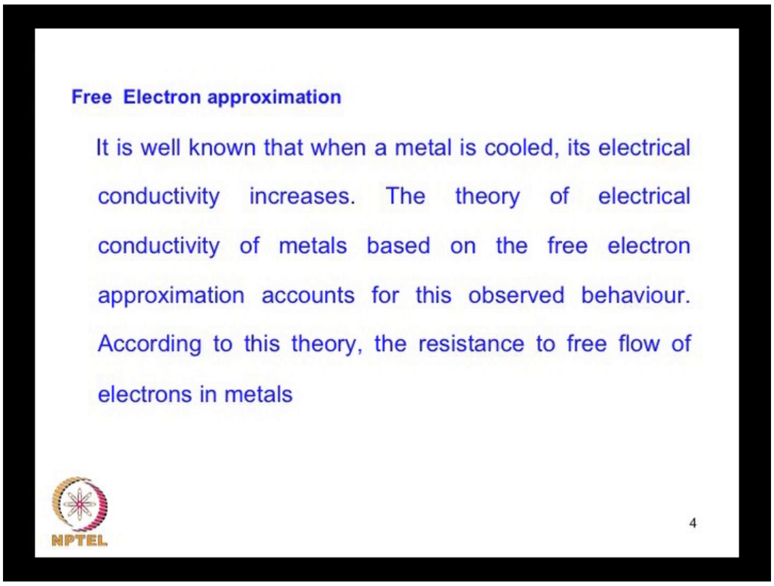

Let us return to the phenomenon of perfect electrical conductivity or zero resistivity. Let us recall, what we said about the electrical resistance of a metal or electrical resistivity better still it is temperature dependence of any metal. In general follows a behaviour like this at sufficiently high temperatures the electrical resistivity increases with an increase in temperature a well known example is that of platinum, which is used as a resistance thermometer for this reason.

So, this is a linear region at high temperature, we also saw that as the material as the metal is cooled there is a region, where it becomes nonlinear and obeys the so, called Bloch Gruneisen law, which is at it is power five dependence due to Bloch Gruneisen law. Which predicts an approximately fifth power dependence on temperature and then it soon tapers off and reaches a constant value which is nonzero and this is due to not phonon scattering, but by scattering defects and impurities. So, this is the so, called residual resistivity. So, if I take this, I can write rho equals rho 0 plus rho of T, there is a part of the resistivity, which is temperature independent which is constant which is due to impurity scattering and then a part, which depends on temperature as given by this. This is the normal behaviour of the temperature dependence of the electrical resistivity.

Now, in the case of a superconductor this behaviour is modified and it becomes this is a metal. Now, in the case of the superconductor all this is the same, but then at a sufficiently low temperature the resistivity falls abruptly to 0 or an immeasurably small value. So, that is the famous discovery of Kammerlingh Onnes. So, this happens at a temperature T c. T c is the superconducting transition temperature. So, this is the behaviour of a superconductor. This is a normal metal non super conducting metal .

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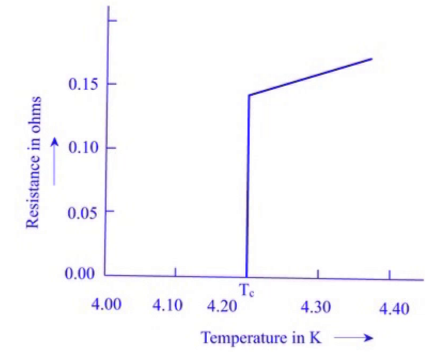

Fig 27.1 Variation of resistivity with temperature in Hg. The resistivity falls abruptly to zero at 4.15 K

So, the figure shows the experimental the observed resistivity variation temperature variation of the electrical resistivity as discovered by Kammerlingh Onnes in mercury. He measured the resistivity of mercury again, Onnes was very lucky because, his choice of mercury was not based on any inspired gases, the simple reason why he chose mercury. Mercury as you know is a liquid, but which is a conductor, a good conductor of electricity. It is metallic therefore, it can be obtained rather readily in extremely purified form you can purify mercury and get rid of all impurities. So, it is for this reason that he chose mercury, but he was a very lucky fellow and it just happened that the superconducting transition temperature of mercury just a, let us plot this for mercury and this was very close to 4.2 Kelvin the boiling point of liquid helium.

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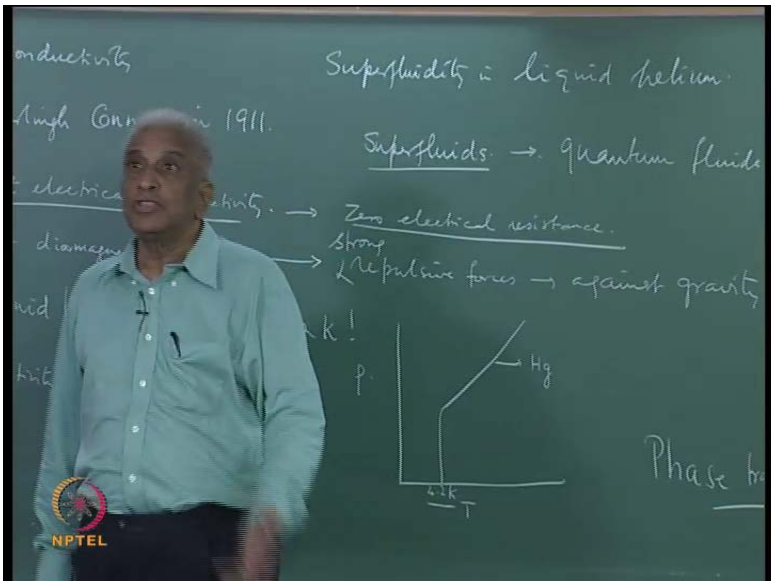

So, Kammerlingh Onnes had a pool of liquid helium a bath of liquid helium whose normal boiling point is 4.2 k and this super conducting transition took place exactly around this point. Therefore he was lucky to this is the curve for mercury. So, he was lucky to discover the phenomenon of superconductivity because, he was lucky enough to choose a material, which became superconducting just at the boiling point of liquid helium. This is one of the accidents of a lucky accident of physics.

Well not only mercury, but many more elements in the periodic table were found later to exhibit superconducting behaviour. The behaviour was observed even in impure metals and the materials which exhibit the property of superconductivity are known as superconductors. This transition temperature is one where the material is said to undergo a transition from the normal state to the superconducting state. So, this is also a phase transition, we discussed phase transition.

Superconducting transition is also an important class of phase transitions, but unlike other phase transitions this does not involve any structural changes. It is not a crystallographic phase transition, for example, one can measure the x-ray diffraction, diffractogram of a material, which become superconducting both above and below the superconducting transition temperature and one, does not find any significant changes. Thus we are able to see that this phase transition does not involve any structural phase transitions. It is not like the vapour to liquid or liquid to solid phase transition either, it is not a magnetic phase transition either. So, all these things are different it is not an order, disorder transition, which takes place in metals, it is a totally new kind of phase transition.

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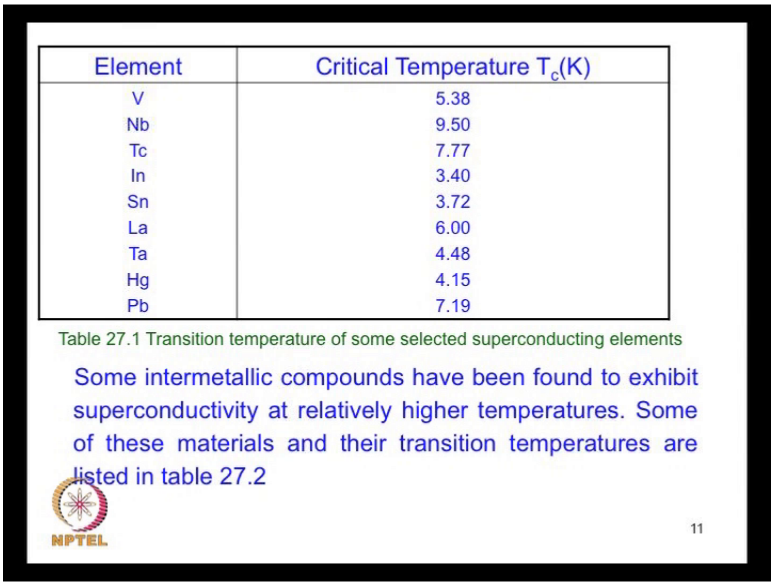

Element	Critical Temperature T_c(K)
V	5.38
Nb	9.50
Tc	7.77
In	3.40
Sn	3.72
La	6.00
Ta	4.48
Hg	4.15
Pb	7.19

Table 27.1 Transition temperature of some selected superconducting elements

The table is the phase transition temperature of some of the important elements like vanadium, niobium, tin, indium, mercury, lead and so on. Niobium has the highest a transition temperature of 9.5 Kelvin among the elements. Even lead becomes superconducting at a sufficiently high temperatures, high within quotes. It is not extremely low that is what I mean something like 7.2 Kelvin, but we all know that lead is a very poor conductor; it is used as a fuse material a lead wire.

So, it has very high electrical resistance, but it becomes goes into a state of zero electrical resistance. So, a material, which becomes superconducting whereas, noble metals like silver, gold, copper they do not become easily superconducting, until you cool them to extremely low temperatures. So, you see that there is an anticorrelation between the characteristic of a very good conductor in the normal state and a super conductor. So, a very good conductor is not necessarily a good superconductor and vice versa.

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Alloy	Critical Temperature T_c in K
Nb_3Sn	18.1
Nb_3Ge	23.2
Nb_3Al	17.5
V_3Ga	16.5
V_3Si	17.1
La_3In	10.4
NbTi	10.0

Table 27.2 Transition temperature of some superconducting compounds

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So, this is a very important paradox, which will be explained in the course of our discussion. Even inter metallic compounds and alloys become superconducting.

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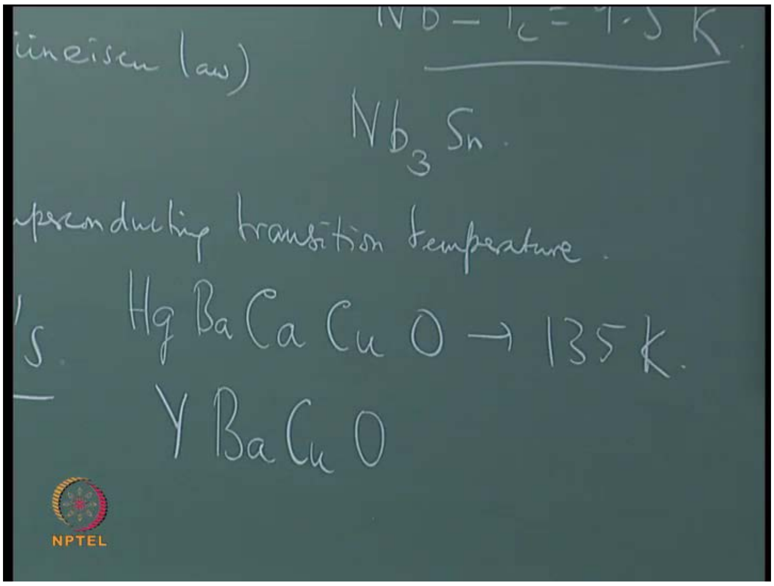

Next table shows some of the important alloys like niobium tin is an important interesting alloy, which has a critical temperature or superconducting transition temperature of 18.1 k. You can have similarly niobium germinate, niobium aluminium Nb 3 Al you can also V 3 Ga, V 3 Si and so on. Niobium titanium, which is again, has a critical temperature of 10 k; these are niobium titanium and niobium tin. Niobium tin is an intermetallic compound, niobium titanium is an alloy. So, both are extensively used as superconductors because, of their high transition temperatures as well as favourable metallurgical characteristics and other superconducting characteristics, which we will see presently.

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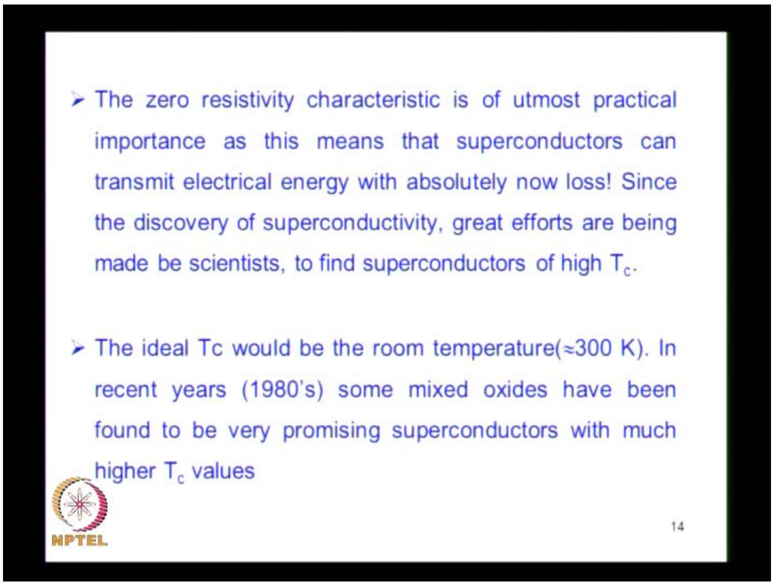

So, although the transition temperatures of the superconducting compounds are much higher than those of superconducting elements, these temperatures are still too low to be attained easily. The necessity it is still necessary to use liquid helium in order to cool them below T c. So, that is there for even the intermetallic compounds and alloys. So, the zero resistivity characteristic is of utmost practical importance because, this means that superconductors can be employed to transmit electrical energy with absolutely no loss. So, scientists as well as engineers have been engaged, since the discovery of superconductivity in 1911. During these hundred years to find materials, which becomes superconducting at a relatively high temperature or close to the room temperature, the ideal transition temperature would of course, be room temperature.

In recent years in the 19 late 1980s a revolution of stars took place in this respect some of the mixed oxides have been found to be very promising superconductors with very much higher substantially higher T c values. We have for example, the mixed oxide, mercury barium calcium copper oxide. So, that is an oxide, which has mercury barium calcium copper oxide is a queen, it is a compound with five different elements, it is not even ternary. This has the highest known temperatures, transition temperature of 135 Kelvin, which is substantially higher than, this we can use liquid nitrogen, which is relatively easily available to cool such a material below T c.

The more extensively studied superconducting oxide is Y Ba Cu O. So, a ternary compound involving yttrium barium copper oxide, which has a T c of about 90 Kelvin, which is still very much higher than liquid nitrogen temperature. So, these oxide superconductors, so, they are all oxides. So, they are all known as high temperature superconductors HTSCS. So, their discovery sort of galvanizes the interest in the area of superconductivity they are the high temperature superconductors. So, these materials will also be discussed a little later.

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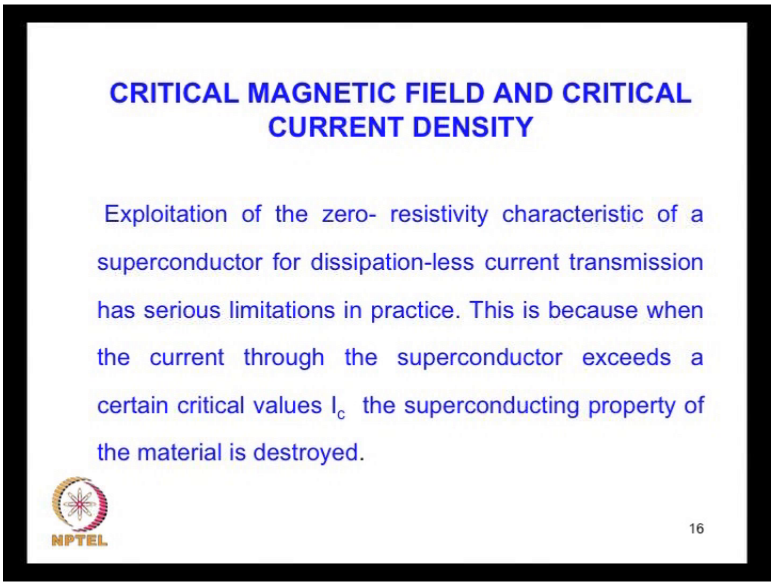

Now, in addition to a critical temperature below, which a superconductor becomes superconducting. We also have additional parameters, which characterize the superconductivity, superconducting state. One of these parameters is known as a critical magnetic field.

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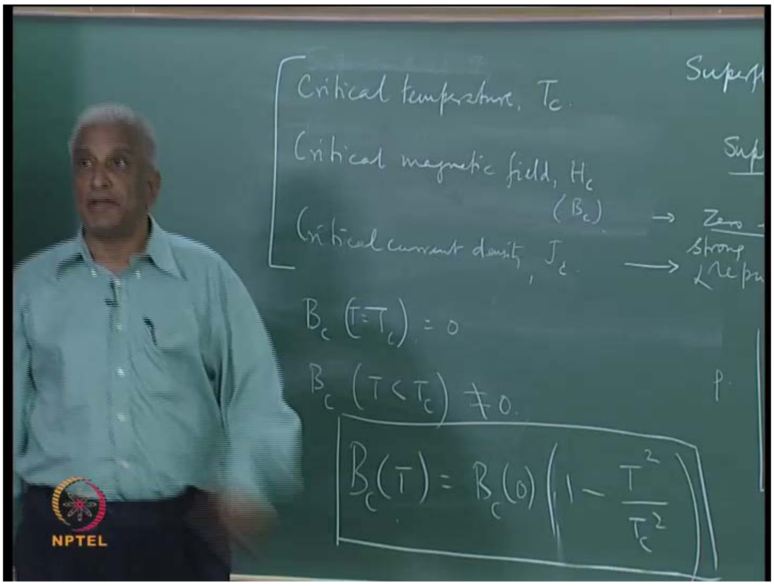

So, we have already the critical temperature or the superconducting phase transition temperature, which should be as high as possible. In addition we have a critical magnetic field H c or B c as well as a critical current density known as J c these are the three parameters, which are necessary to characterize these, this figure of merit of a superconductor for technical applications.

For example, 0 resistance characteristic below T c has is seriously limited because, if you make use of that and try to pass a current through the superconductor, this current also has the automatic consequence that it produces a magnetic field. So, when people tried to pass a very high current thinking that it is a zero resistance. So, you can pack a lot of current inside and use it as a high current device, use a thin wire and send a high current through it then people thought like that and started sending.

For example in a lead wire below 7 k it becomes superconducting and so, you try to send say 50 amperes or 100 amperes in the ends. And what happens is, this current generates automatically a magnetic field and when this magnetic field goes above a certain value called the critical magnetic field superconducting property is lost. That means that the current is also limited because, the magnetic field is produced by the current and is proportional to the current. So, it means that you cannot send a current which exceeds this so, called critical current which corresponds to the critical magnetic field.

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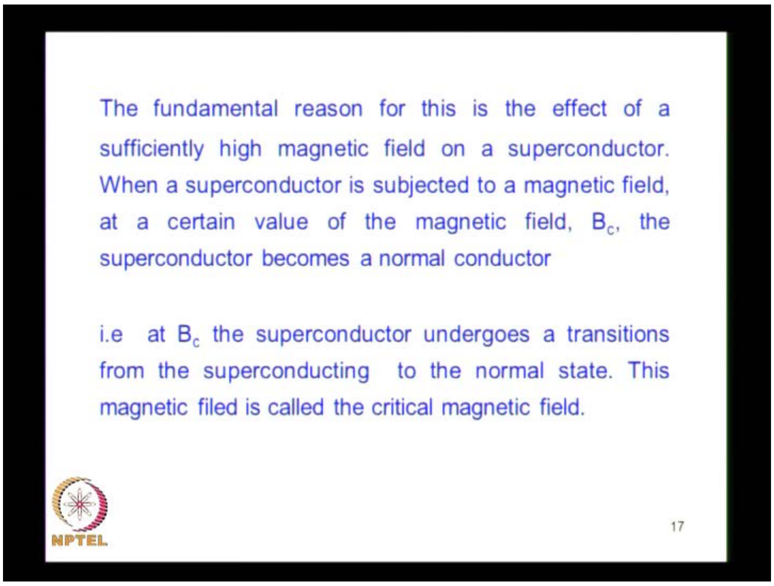

So, the superconductivity is destroyed and the material is driven normal. This is because a sufficiently high magnetic field drives the superconductor normal. Again the superconductor goes back and undergoes a phase transition back from the superconducting to the normal state.

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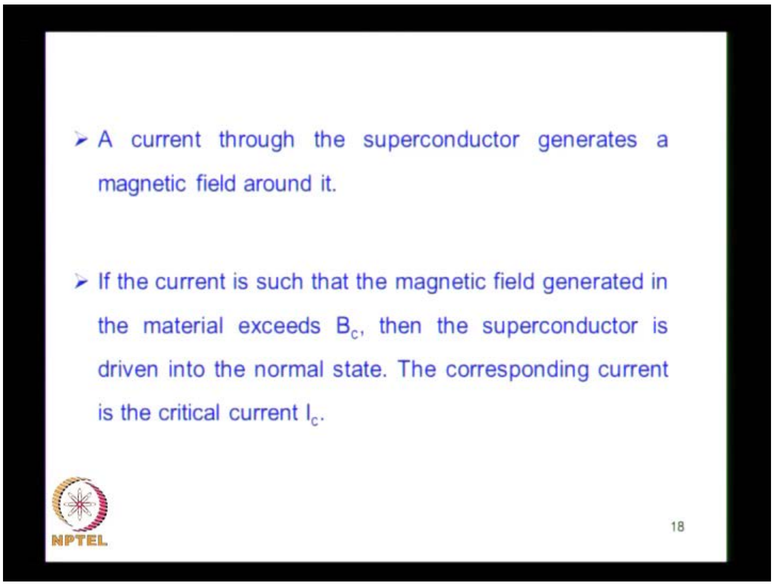

So, the magnetic field, which corresponds to this, is called the critical magnetic field. If the current, which flows through the superconductor is such the magnetic field generated inside it is cease the critical magnetic field then the superconductor is driven normal and the corresponding current is called the critical current. So, in practical technical applications of a superconductor it is this trio the T c, B c and J c, which together determine the usefulness of a good superconductor. So, you must have a high enough T c, which is close to room temperature and a high enough B c critical magnetic field and correspondingly a high enough critical current J c and such materials if they have to serve as superconductors in practical devices they have to also be cheaply produced and easily processed.

So, these are main characteristics which are desirable for technical applications of superconductivity Now, this critical magnetic field B c is also a function of temperature, this can also be readily seen because, when you come to the T c then you do not require a magnetic field to destroy superconductivity. If you have formed the material above T c it becomes normal therefore, B c T at T c is zero, but if you go below T c for T less than T c it is not zero.

So, you can immediately see that B c the critical magnetic field is the function of temperature. So, one can measure the value of the critical magnetic field, which is necessary to drive a superconductor into the normal state at a given temperature below T c and when this is done, it is found that this is a quadratic function and it actually obeys a law like this.

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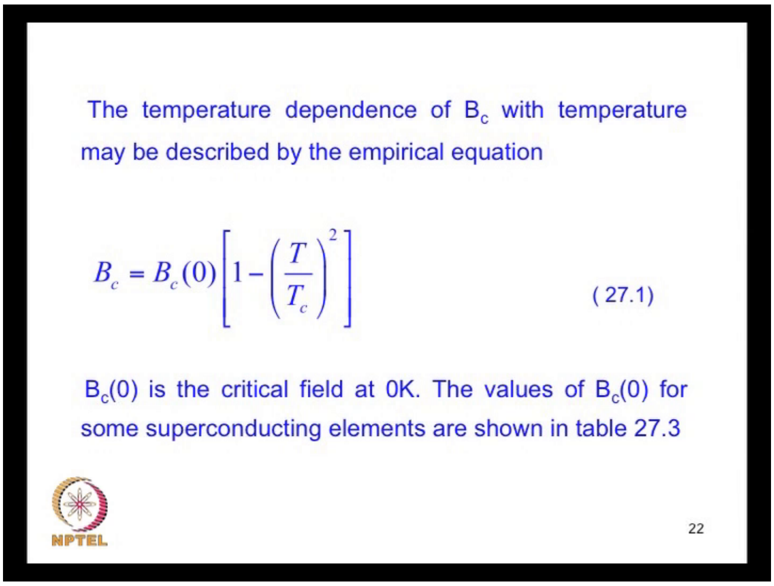

This is a quadratic or parabolic behaviour, which is illustrated in the next figure. For different materials like lead, mercury, tin, indium and so on. So, this is the actual temperature dependence of the critical magnetic field. So, B c 0 is the value of the critical magnetic field at 0 Kelvin. So, this value is a characteristic of the super conduct.

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Element	Critical Field at 0 K (milli Testa) $B_c(0)$
V	142.0
Nb	198.0
Tc	141.0
In	29.3
Sn	30.9
La	110.0
Ta	83.0
Hg	41.2
Pb	80.3

Table 27.3 Critical magnetic fields of some elemental superconductors

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So, this critical field at 0 k has been listed in the next table for different materials like vanadium, niobium, indium, tin etcetera. You can see that the critical magnetic field in milli tesla is of the order of 100 or 200 in the best cases. And they can be as low as 2 or 30 milli tesla for materials like indium or tin. So, this means that, if we go above this field the superconductivity is lost.

So, this is how the fascination for using a superconductor as a lossless electrical conductor was dashed because, the moment you pass a current, if you have a long thin cylindrical superconducting wire the critical current I c produces a critical magnetic field because, we have the relation B equal to Mu nought I by two pi r, where r is the radius of the wire. So, you see that a current here produces the magnetic field. So, the critical current corresponds to critical magnetic field.

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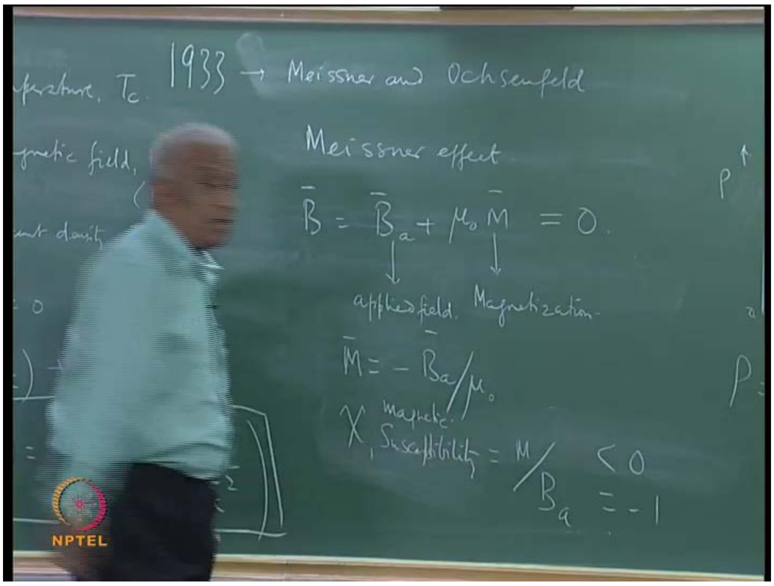

In 1933 another very important development took place in the history of superconductivity that is because of an experiment conducted by Meissner and Ochsenfeld. They discovered that, if you have a superconductor, which is placed in a uniform magnetic field below B c then the magnetic lines of force, which pass through the material when the temperature are pushed out of the superconductor. When the material is in the normal state, the magnetic lines of force enter, but when you cool it down below the transition temperature the magnetic flux is completely expelled out of the bulk material. So, this is known as the Meissner effect. This is shown in the next figure.

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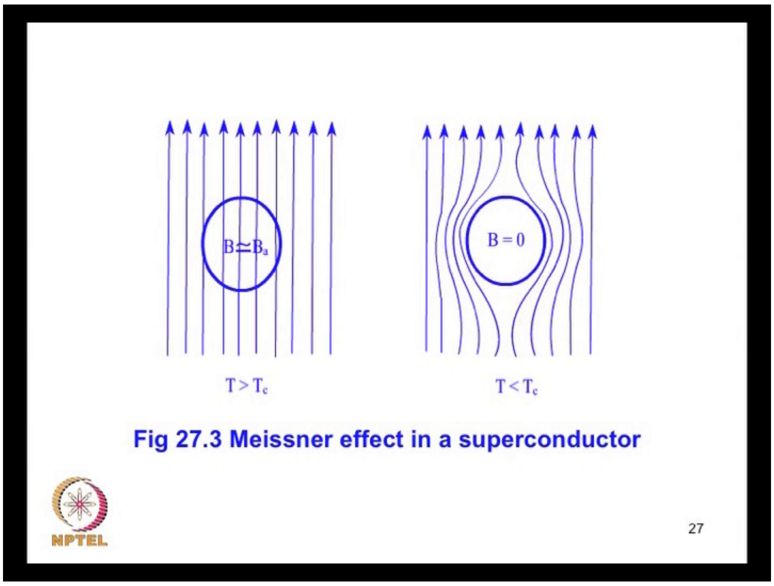

You have T greater than T c, you have a spherical or ellipsoidal specimen of the superconductor into which the magnetic flux lines completely penetrates magnetizing the specimen, but when you cool the superconductor below T c the flux lines are expelled as shown in the second part of the figure. So this is the basic effect called Meissner effect. So, if you have B, which is B applied plus Mu nought M, where M is the magnetization. So, M is the magnetization and B a is the applied field, this is the actual magnetic induction. So, this means that the B inside a superconductor vanishes because; it is the flux lines are completely expelled from the superconductor.

So, if you go into the bulk of the superconductors the B is 0; that means, M is minus B a by Mu nought. So, you have a magnetization, which opposes the effect of the applied field. So, it is negative. So, the susceptibility, magnetic susceptibility, which is just the ratio of M by B a is negative, in fact it is minus one. So, it is a diamagnetic susceptibility, a negative magnetic susceptibility is known as diamagnetic susceptibility. The negative science shows that the induced magnetization opposes the applied magnetic field.

So, it is a diamagnetic susceptibility and it has the values of one, which is it is maximum value. So, that means that it is a perfect diamagnet. So, the discovery of the Meissner effect, show that a superconductor is not only a perfect electrical conductor, but also it is a perfect diamagnetism. In the sense that, the magnetic susceptibility is negative and has the maximum value of unity. So, the perfect diamagnetism is not just an automatic (()) of the perfect conductivity, electrical conductivity, it is an additional property electro dynamic characteristic of a superconductor. So, perfect electrical conductivity and perfect diamagnetism or the signatures of superconductivity. We will discuss this in the next class. Now, we will talk about what happens to the magnetization graph.

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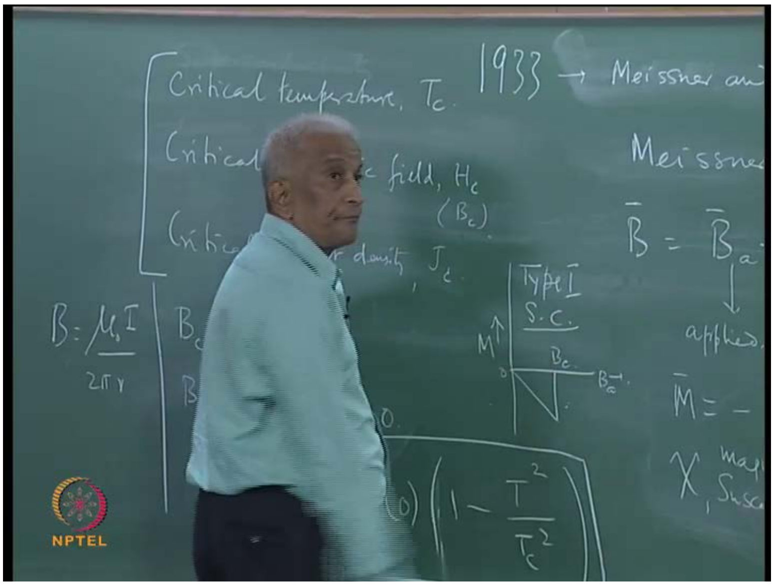

So, this means, if I plot the magnetization M here is 0, these are negative values then it goes like this and then at the critical magnetic fields this is B. So, the magnetization has negative values and this is the B c. So, it falls the diamagnetic magnetization drops to 0 driving the material normal at the critical field. So, this is a straight line with a slope with an angle of 45 degree with a slope of unity. So, that is the magnetization behaviour of a superconductor.

This is not the case with all superconductors. If this was so, superconductivity would have remained an academic curiosity because, a material, which has a once you send a current, which a produces magnetic field equal to the critical magnetic field the superconductivity is lost. Fortunately we have materials, which exhibit a slightly different characteristic these are known as type two superconductors. We just discussed them today; the magnetisation curve that I have shown here belongs to what is known as is that of what is known as a type one superconductor. all elemental superconductors except niobium and vanadium exhibit this behaviour.

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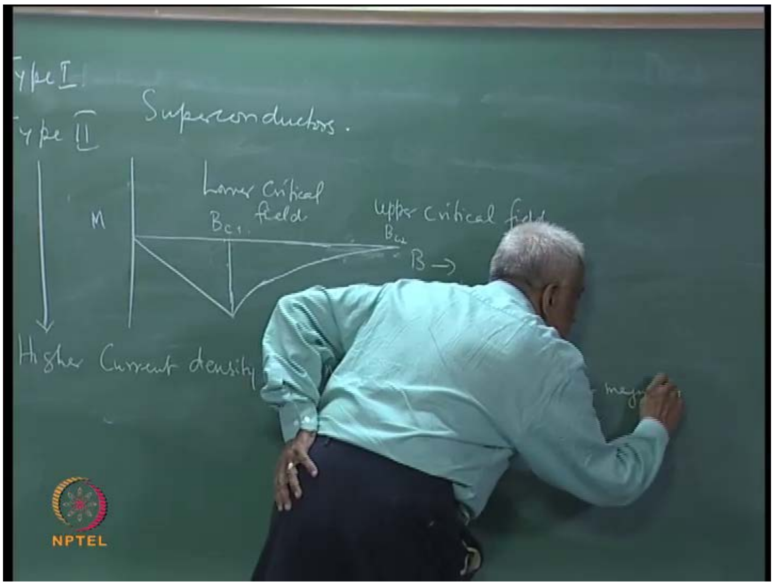

But in addition to type one, you have also a class of superconductors known as a type two superconductors. They were discovered a little later and there many of the intermetallic compounds and alloys belong to the type two and they have a magnetization graph, which is substantially different from that of a type one superconductor. It is also going like this, but at when it would reach this value a maximum value for the magnetization starts dropping with a further increase in the field like this till it reaches zero value somewhere here.

So, the field at which it starts to drop is known as the lower critical field B c1 and the field at which the material actually the magnetization actually becomes zero is a much higher value known as B c 2. So, this is the upper critical field and this is the lower critical field. So, a type two superconductors is characterized by a magnetization graph, which starts falling at a lower critical field which is relatively low, but magnetization the negative magnetization actually become zero and the material becomes normal only at a much higher field corresponding to the upper critical field which can be very high.

So, in this region still there is a negative magnetization and the material is superconducting. So, until you reach the upper critical field value you can use the perfect conductivity characteristic of a superconductor. So, a type two superconductor can carry much higher currents. So, the critical current density can be very high. So, they can carry and these are the materials, which are technically useful they are used for example, in the in making high field electromagnets.

High field superconducting magnets. Niobium titanium is a material, which is a type two superconductor. Niobium tin is also a material, which is a type two superconductor, which can be used in the construction of high field superconducting magnets. For example, one of the very important medical applications of this behaviour is in the magnetic resonants imaging MRI scan which is extensively used.

In order to produce this magnetic resonance response of the human body you require a very high magnetic fields and these are not produced by ordinary magnets, which get electromagnets, which get saturated. So, if you want fields is the order of 10 tesla or even 100 tesla, you can realize it only with high field superconducting magnet using a type two superconductor, whose critical field is above this value. Then you can produce such high magnetic fields. All the magnets which are used in MRI scans today are high field superconducting magnets. They have also the advantage that you need very small amount of power. In fact, once you energize the magnet you can turn off the power because, of the perfect electric conductivity.

So, this is what happens in a superconducting magnet, which is an extremely compact one because, of the fact that you can send very high power current densities into a relatively small volume of the small diameter of the wire. So, you can have the material the superconducting magnet can be bound out of thin wires relatively thin wires. And then the magnet becomes extremely compact and transportable and you energize it in the factory at liquid helium temperature or below transition temperature using a power supply and freeze the magnetic value field value at a high value by sending in the required current.

Then you come a turn off the power supply close the superconducting loop and then you can take the magnet and come across the globe where ever you want the MRI scan to be made and you do not need a power supply for that. As long as you do not want to change that magnetic field it can stay there and most of the MRI scan equipment consists of a superconducting magnet, but there is no power supply. So, you can have a magnet, which operates without any power. So, that is the advantage of a superconducting magnet. So, we will see about the characteristics, these characteristics of type one and type two superconducting materials in subsequent discussions.