Advanced Condensed Matter Physics
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Lecture – 18
Introduction to electrodynamics Meissner effect

So, we are going to talk about super conductivity. So, having seen a various phenomena in condensed matter physics such as magnetism then metallic behavior, insulating behavior ferromagnetism, anti ferromagnetism and doing a thorough analysis with regard to the greens function, let us now talk about superconductivity and initially we are going to give you a glimpses of the historical achievements of superconductivity, that is how it got developed in the earlier years.

And also we will try to give you some recent experiments on superconductivity which are not very recent, but still the compared to the time that it was discovered there are some recent developments and then we will talk about the most important thing which is called as a BCS theory, the microscopic theory about superconductivity.

So, in these few slides we have tried to first give you the outline and then discuss with a little more details and let us look at the periodic table.

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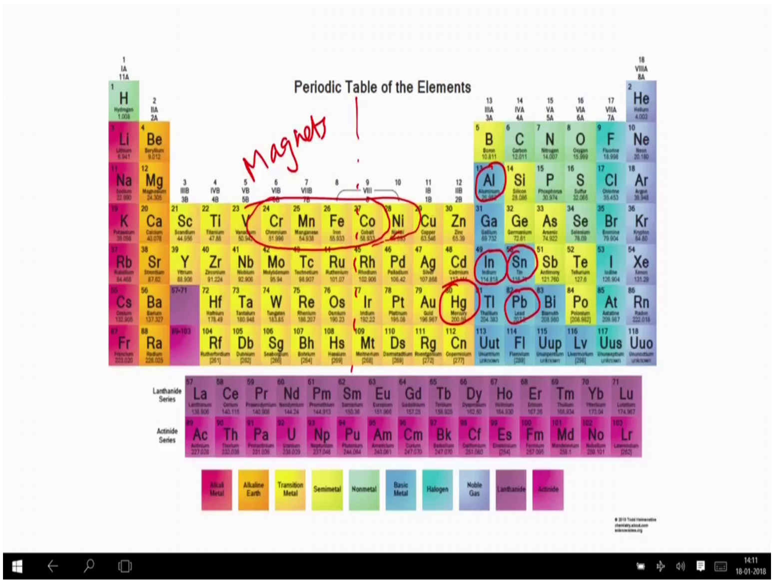

And which are the superconductors or which form which has this phenomenon of super conductivity, which is vanishing of electrical resistance below a certain temperature certain characteristic temperature, which is a characteristics to that particular system. If you look at it there are examples of superconductor the first superconductor was in mercury and they are in lead and in tin and in indium antimonide and so on and also some thallium based compound and in aluminum for example and so there are examples of superconductivity here.

So, if we a nicely you know split the periodic table into two halves, the superconductivity occurs at the right half of the periodic table; whereas the left half if you see that there are nice magnets I mean including these are nice magnets and there are superconductors which are denoted by the circles. So, superconductivity in the earlier days have been seen in these materials and they from the color code that is presented in this periodic table, there are basically basic metals are they form superconductors and there are these are somewhat like transition metals and semi metals and so on. However, both of the magnets and the superconductors they have a lot of electrons at the Fermi level.

However, in magnets the wave function of the electron or the you know the range over which the electrons electronic wave function are distributed, have a certain range whereas, for the superconductors the range is quite large and that is what pretty much distinguishes metals or other the magnets or the elements which show magnetism with the ones that show superconductivity.

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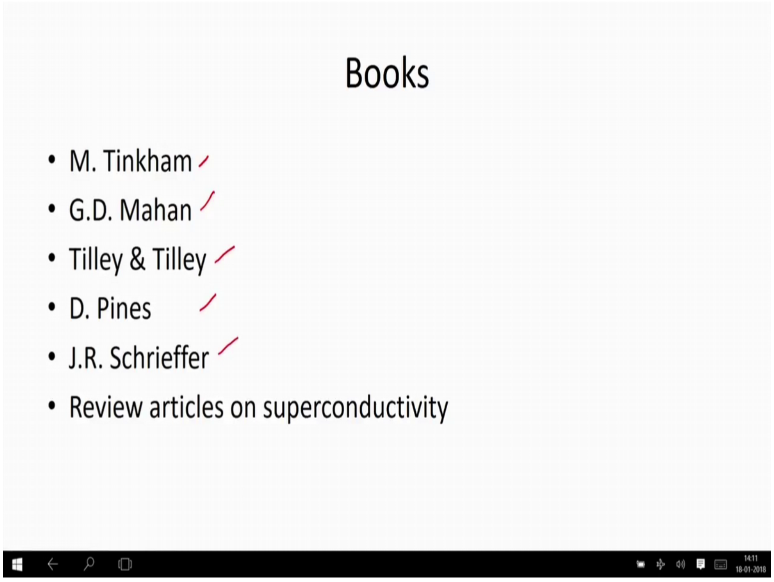

So, let us go ahead with this and let us talk about a few books that are of importance, one can look at books such as M. Tinkham is a very good book, G.D. Mahan we have already been talking about there is a book called Tilley and Tilley their book called as by David's, D. Pines J.R. Schrieffer 1 of the discoverer of this BCS theory and there are numerous review articles on superconductivity which you might want to look at it. So, these are our starting point and let us have a historical overview superconductivity was discovered in 1911 by gentleman called Kamerlingh Onnes in Leiden that is the name of the place this in Europe and so after 3 years he had liquefied helium to reach temperatures of the order of a few Kelvin.

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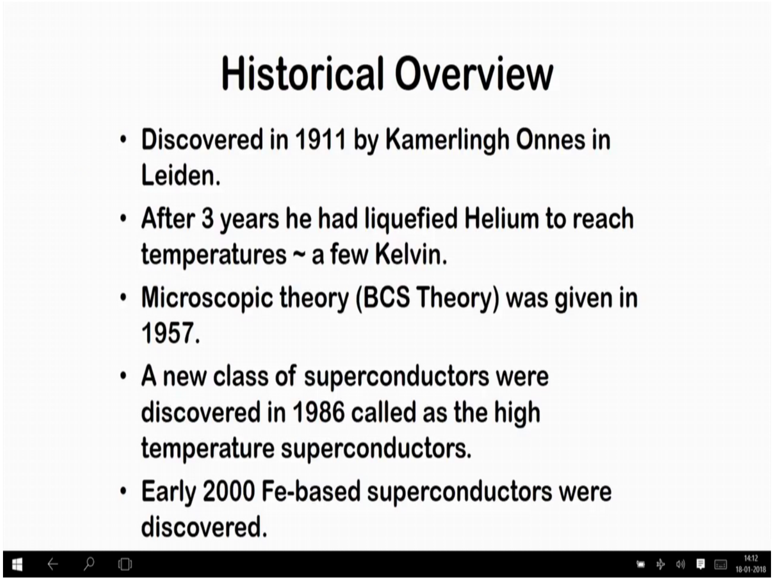

Now why are they related or they have been placed one0 after another is that it is important to achieve low temperatures in order to see superconductivity, superconductivity does not occur at any temperature or at room temperature it happens at very low temperatures. So, 1 has to cool system a metal, so to say to that temperature below which it shows superconductivity and it is intimately related to the liquid helium temperature, which is why it is mentioned which is about 4 Kelvin 4.2 Kelvin.

So, a liquid helium temperature is needed in order to cool a system and that is why the superconductivity discovery of superconductivity is also intimately related to the ability, to our ability of achieving low temperatures. Then the microscopic theory which is known as the BCS theory, goes after the name we will talk about this a burden cooper and Schrieffer that was given out in 1957, which is just about you know 60 years back from now and then a new class of superconductors were actually discovered in 1986 they are called high temperature superconductors. So, the super conductivity in these conventional materials which are which are seen above in the sense that discovered by can came early moans and then a few years the researchers have dealt with superconductivity around with at most transition temperatures to be 20 Kelvin.

So, below 20 Kelvin they showed superconductivity and above that the superconductivity was discovered, by the way the disc the chameleons see saw super conductivity in ultra coal ultra clean sorry ultra clean mercury samples, which had shown a sudden drop in resistivity at certain temperature below certain temperature other and we did a very small narrow temperature range. So, this was about this was about 1986 and then early 2000 there are superconductors which are based on iron. So, iron and superconductivity they do not seem to go hand in hand because, irons are supposed to be Ferro-magnets good Ferro-magnets and the Ferro-magnets imply that there are the spins are all pointing in the same direction, that is what a Ferro magnetism is about.

However a superconductor requires a pairing of up and down electrons, I mean 2 electrons 1 having an up spin with a momentum k and the other with a momentum minus k and a down spin. So, apparently there is an ambiguity, but there are instances and experimental evidences of iron based superconductors.

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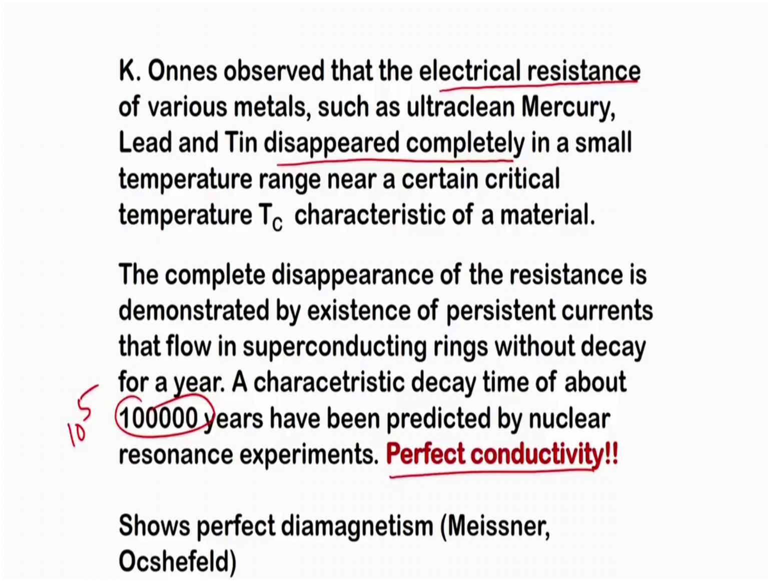

So, what Kamerlingh Onnes did is that while he was doing an experiment with ultra clean mercury and then subsequently with lead and tin, we have shown in the periodic table that there are lead and tin etc showing superconductivity. So, the electrical resistance electrical resistance that disappeared completely in a very small range of temperature, we have some supporting figures for that you will see and that particular temperature below which the resistivity vanishes is a characteristic of that particular material and the complete disappearance of the resistance is demonstrated by the existence of persistent currents, that flow in superconducting rings without any decay for a year and in fact, the nuclear resonance experiments are predicted that they would only be decaying in a time scale of 10 to the power 5 years, which is this is like 10 to the power 5 years and that is why they are they are called as Perfect conductivity.

Now this word also has to be taken with caution because, very good metals have perfect conductivity or rather infinite conductivity as T goes to 0 the temperature goes to 0; however, they are different from superconductors in the sense that perfect conductors do not show a property called as Meissner effect, which is said later and superconductors show this property of Meissner effect and superconductors show perfect diamagnetism, which is again what we was discovered by Meissner and auction felt and this is something that we are going to discuss; this is the electromagnetic properties of superconductors which are very important.

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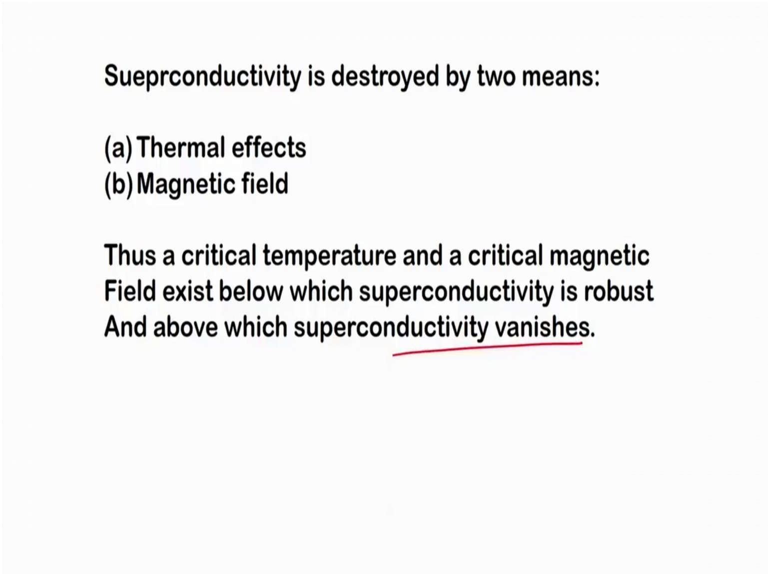

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So, super conductivity can be destroyed, why we are talking about destruction of superconductivity is that then we understand how robust the superconducting state is.

So, there it can be destroyed by 2 means, that is one is thermal effects that is if you raise the temperature of the system or if you apply an external magnetic field, both these can actually destroy superconductivity and the system will go on to a so called metallic state. It does not have to we will see that in high Tc superconductors they do not go on to a state which is exactly metallic, but there are some deviations there as well. In any case so there is a critical temperature and a critical magnetic field that exists below is the superconductivity is robust and above which superconductivity vanishes, which means that we have metallic state that emerges beyond that. So, one superconductivity is destroyed there is a emergence of a metallic state.

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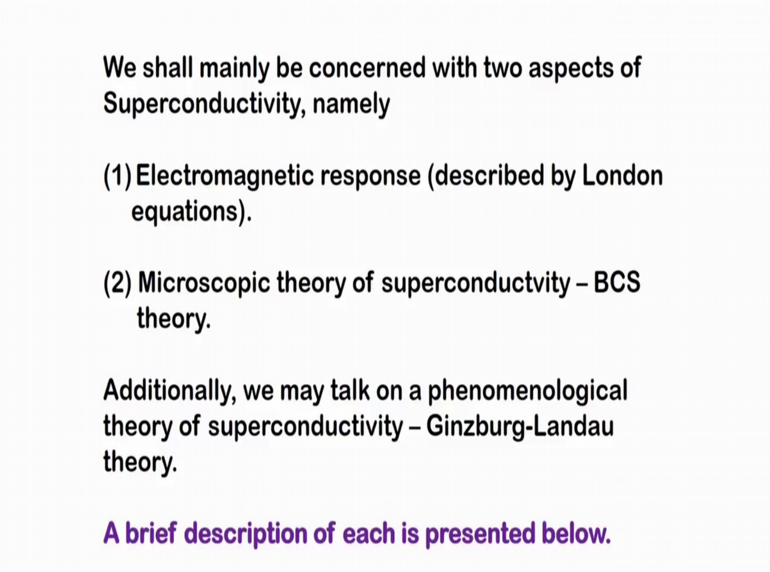

So, we are going to be concerned about mainly 2 aspects of superconductivity and one of them being the electromagnetic response as we have just said which takes care of the meissner auction field effects and so on and this was discovered by or rather they are described by Landau equations, will give us a small overview now and then we will do it later on in an elaborate fashion.

And then also we would be concerned about the microscopic theory of superconductivity, which is known as BCS theory and you will see that how it was actually coopers problem it is called cooper instability. It is shown that 2 electrons which are known to be having the same charge and hence would repel they can be shown that they actually have an attractive potential operative between them, when they are in presence of a filled pharmacy and this attractive interaction is mediated by via phonons.

So, also we may talk on the phenomenological theory of superconductivity which are known as Ginzburg Landau theory. So, this phenomenological theories in general are very good starting points when microscopic theories are unavailable and they provided you take into account the correct symmetries of the problem and you know that how a system loses superconductivity, then you can write down a free energy functional in terms of some wave functions or rather some order parameters which are going to give you the; I mean particularly this the phase transition is captured by writing down the free energy functional in terms of the order parameters. So, a very brief a description is first presented about each 1 of them and then we will go on for a little elaborate discussion.

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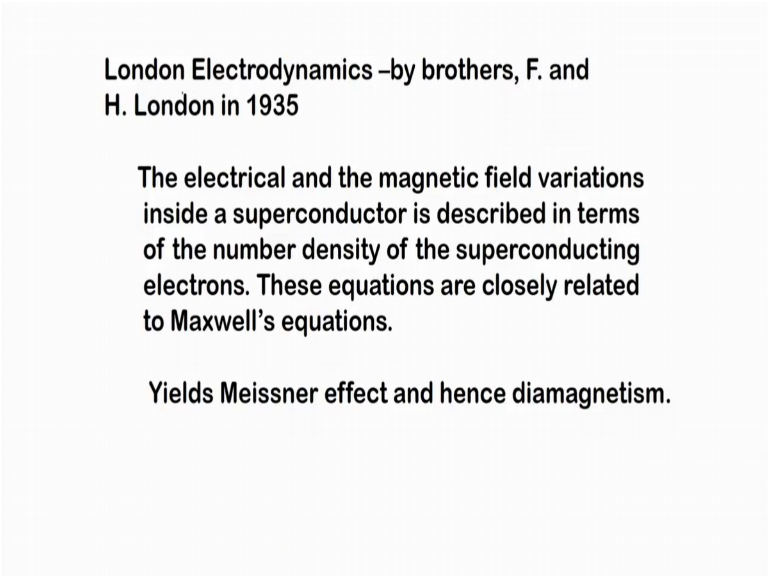

So, to start with it was we said that it is a electrodynamics. So, these were by 2 brothers F. and H. London F. London and H. London in 1935. So, they actually were wrote down equations where the electric field and the magnetic field variations, inside a superconductor can be described in terms of the number density of the superconducting electrons or the super current density.

So, it is important to say that normal current does not flow through a superconductor, because of this super conductors being perfect dia magnets; the normal currents will be killed and they cannot penetrate into the superconducting sample. Whereas, the super currents what we actually mean by super currents will be explained later, they can be they can propagate or rather they can they flow in the superconducting sample and it nicely eels starting from these equations, which are nothing but some variations of the Maxwell's equations of electrodynamics. 1 can get diamagnetism from and hence meissner effect this is what we have talked about.

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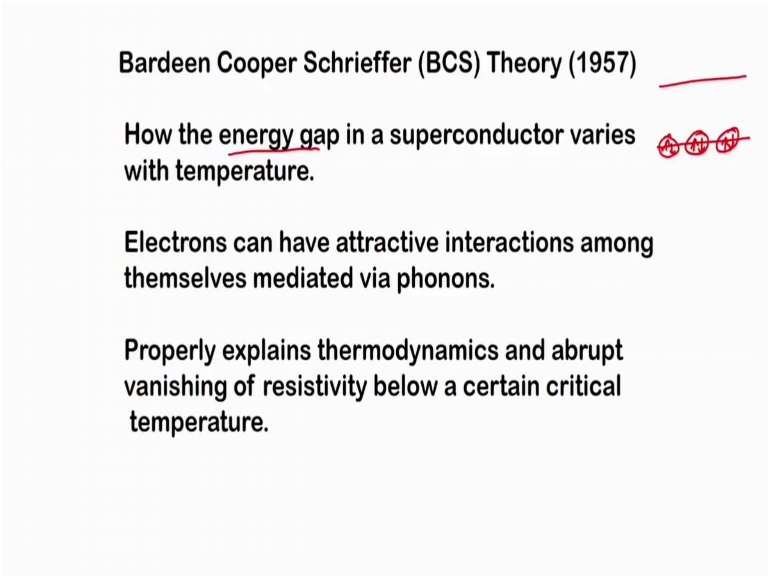

Then we have this microscopic theory that should come into the discussion, which was again put forward in 11957 by 3 people called Bardeen cooper and Schrieffer and the superconductor. So, it will show that how the energy gap in a superconductor varies with temperature. So, what we mean by an energy gap is that there is a ground state and there is a first I mean there is an excited state, where superconductivity is disco is basically destroyed. So, when the system is in the superconducting state, the ground state becomes occupied by all these pairs of electrons. So, they form pairs which are actually pairs of up and down electrons and then there are many of these pairs that are present and the ground state is actually a many body ground state of all these pairs.

So, their soops of pairs and in order to break a pair, we can populate this the first available excited energy level by breaking the pair and that breaking can be done as we have said either by applying temperature or by the magnetic field. So, how do these electrons have attractive interactions, we have already said that after that that the interaction is mediated via phonons they can still have attractive interaction and these BCS theories they properly explain the thermodynamics and the transport properties such as the vanishing of resistivity below a certain critical temperature and then the Ginzburg landau theory as we told it is a phenomenological theory.

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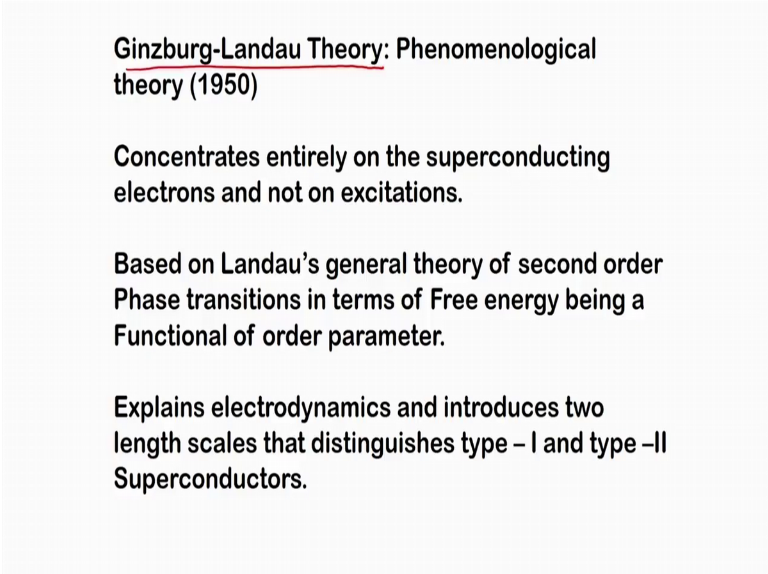

It does not have any microscopic basis and it was put forward ahead of BCS theory, when BCS theory was unavailable and what it did is that it is it wrote down the free energy functional in terms of powers of the order parameter or basically the complex wave functions that describe a transition from 1 state to another.

So, it concentrates on the superconducting electrons and not on it is excitations it is based on the landaus general theory of second order phase transition, that is why this name ginzburg landau; it is coming and in terms of free energy and so free energies is a functional of the order parameter.

So, 1 is to identify the order parameter and know that how it vanishes that the phase transition then 1 can write down a free energy functional and do calculations of say electro dynamics and it also of very importantly introduces 2 length scales of the problem, that distinguishes type 1 and type 2 superconductors we will see what a type 1 and type 2 superconductors. So, broadly all these conventional superconductors which were discovered before 1986, they all can be plugged into 1 of the other type of superconductors and so let us go to slightly more elaborate discussion of superconductivity.

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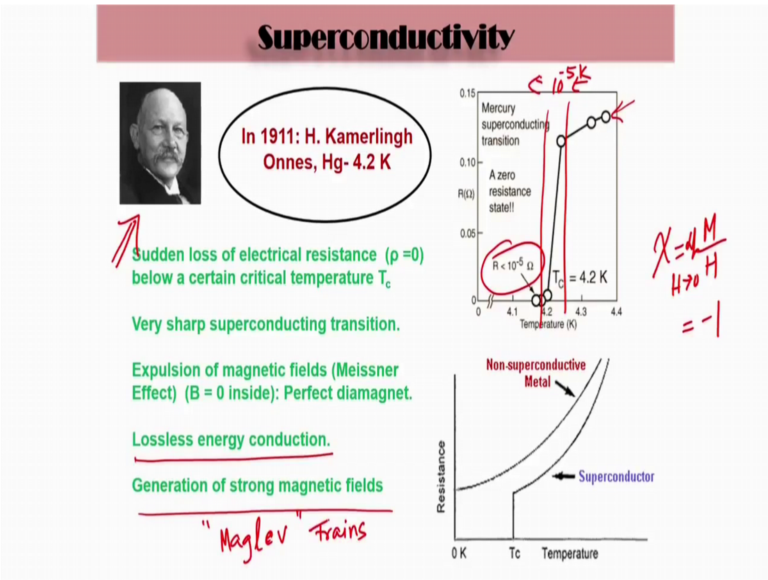

So, it is this gentleman which we said H. Kamerlingh Onnes and he was working with very clean absolutely clean mercury and it found he found that the resistivity above 4.2 Kelvin it has a linear behavior here and suddenly in the vicinity of 4.2 Kelvin. In fact, within a temperature range that is very narrow it is of the order of 10 to the power minus 5 Kelvin, it does not show it that way, but it is it is true that there are. So, this fall off is extremely sharp and so below 4.2 Kelvin the resistivity becomes so small almost negligible, so of the order of 10 to the power minus 5 ohm.

So, the left of this transition is called as a 0 resistance state and this is a mercury the plot is that of a mercury showing transition Tc being, which is the temperature that demarcates metallic regime and 0 such state regime is that temperature is 4.2 Kelvin. So, what happens is that there is a sudden loss of electrical resistance electrical resistance is denoted by the symbol rho, below a certain critical temperature Tc, there are very sharp superconducting transition as we have seen; the magnetic fields are completely expelled from superconductors.

So, if there are magnetic fields that are going to be completely expelled from the material from the specimen and they cannot enter other than a very small depth of the specimen which are called as penetration depth, we will see that and that is why because there is absolutely no magnetic field, so that is why they are called as perfect dia magnets which the diamagnetic susceptibility becomes equal to minus 1. So, M by H limit H tends to 0.

So, this is the susceptibility is defined as M by H in the limit H tending to 0 this becomes equal to minus 1. So, M and H are actually oppositely directed and these this is the definition of perfect diamagnetism, in even the best of the systems that show diamagnetism other than the superconductors the or rather a chi is really small it is of sometimes of the order of 10 to the power minus 4 or 5. However, in superconductors it is equal to 1, then as we have said earlier that there are lost less energy conduction and generation of strong magnetic fields.

So, in the vicinity of the superconductor there are generation of very strong magnetic field we will show you at the end of videos showing that how magnetic field is expelled and Japan is actually making train which would be realizable around 2027 or 2028 these are called as a maglev trains and this maglev's is the short form of magnetically levitated.

So, let us see that what happens for a good metal and a superconductor, in a good metal the resistivity decreases and as T goes to 0 it takes it gives you a value which is finite. So, this is r equal to r naught equal to 0, whereas for a superconductor it decreases and then it suddenly drops to 0 at a temperature which is equal to T equal to Tc. So, that is the basic difference between good metal and a superconductor.

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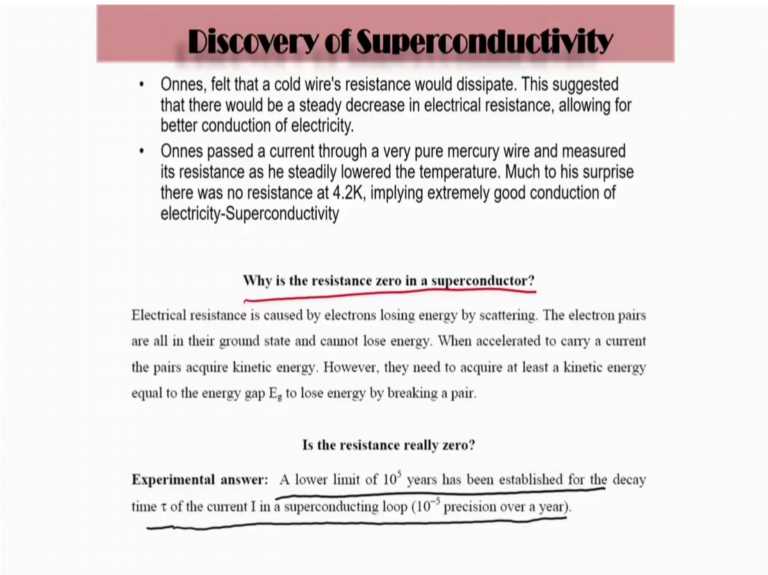

So, there are several things that 1 had to take care of in experiments and so Kamerlingh Onnes felt that the cold wires resistance also would dissipate. So, this suggested that he would there would be a steady decrease in electrical resistance allowing for better conduction of electricity and then owns passed a current through a very pure mercury wire and measured the resistance as it steadily lowered the temperature and that is how the experiment went off; much to his surprise he saw that there was no resistance at 4.2 Kelvin implying extremely good conduction of electricity and this is the discovery of superconductivity.

So, what the question is why is resistance 0 in a superconductor electrical resistance is caused by electrons, that lose energy by scattering between or with each other. So, there are new channels in which the energy can be dissipated that opens up and because of the scattering between electrons the energy dissipates, the electron pairs are all in their ground state and hence cannot lose energy.

For superconductors the electron pairs the they form pairs and they go into the ground state. So, there is no way that they can lose energy, so the super conductivity is a phenomenon of the ground state. However, the need to acquire at least a kinetic energy equal to the energy gap to lose energy by breaking a pair. So, there are you need to give it an energy a kinetic energy such that the pairs dissociate and they break and the there are some electrons that are made available in the excited energy state.

The question is that is the resistance really 0 the experimental answer is that a lower limit of, what we have what we have said already with 10 to the power 5 years is established for a decay of decay time of current in a superconducting loop, which is 1 0 to the power minus 5 precision over a year; which is an extremely good signature that the resistance is really equal to 0 and the current is really persistent.

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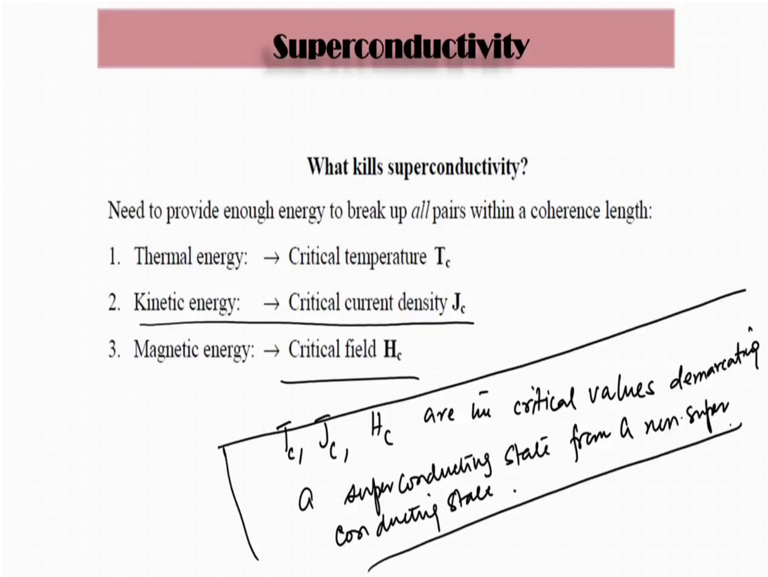

So, we have said this that what kill superconductivity, so we need to provide enough energy for the pairs to dissociate and the pairs remain within the coherence length of each other.

So, there is a thermal energy that can be given and there is also a critical current density this is something that we have not said earlier, there is also a critical current density which superconductor can hold and there is also a critical magnetic field which is needed for it to the break super conductivity. So, Tc Jc and Hc are the critical values demarcating a superconducting state from a non superconducting state. So, that question is that what drives superconductivity what causes a superconducting transition.

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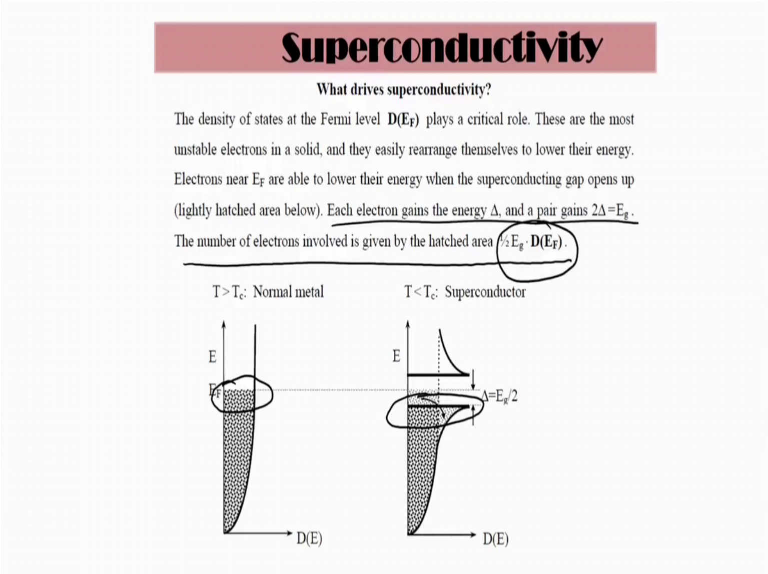

So, the density of states at the Fermi level call it D Ef or n Ef depending on which book you are following. So, the density of states at the Fermi level plays a critical role, these are the most unstable electrons in a solid unstable because they can actually cross the barrier and go on to energy levels that are available to them.

Whereas the ones that are actually much farther away from the Fermi energy are very robust they do not make any transition. So, these unstable electrons they can easily rearrange themselves to lower their kinetic or lower their energies. So, electrons near the Fermi level are able to lower their energy when the superconducting gap opens up. So, these electrons in the vicinity of this thing can actually lower their energies and. So, this is like acting like a refrigeration because so when there is a superconducting gap that opens up.

So, what we are trying to say is that it is only the electrons in the vicinity of this can move into the gap and the other electrons they do not make any transition and make any attempt to go and occupy other energy levels, that is there is a selective cooling which are the most energetic electrons that are near the Fermi surface and these electrons are actually going into states which are which are occupied and thereby causing cooling to the rest of the system.

So, this is 1 typical this thing called diagram called as then for the T greater than Tc is for a normal metal, where we plotted the density of states on the x axis and E on the y axis in a lot of other books, we will see that this is access an interchange but they carry the same meaning and for a superconductor there is a Fermi energy at the Fermi energy there is a gap that opens up and that gap has to be some you know accessed or rather it has to be overcome, in order to have the electrons going into the normal state or rather the superconductivity is destroyed and this corresponds to a gap which is given by the metallic gap or rather the gap that we see in usual cases. So, this is the gap energy and we need to get over the gap energy or rather have supply larger energies than the gap energy in order to describe super conductive destroy superconductivity.

So, each electron gains delta and the pair gains to delta and so the number of electrons that are involved in this in this process is half of Eg because, this is for the twice of the gap and then multiplied by the density of states at the Fermi level. So, these are the number of electrons that are available for causing superconductivity in a sample.

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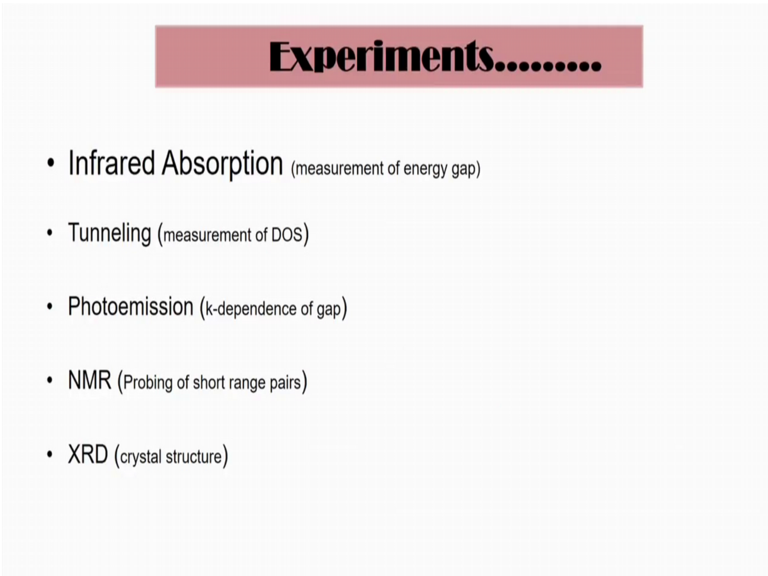

So, what are the experiments which see super conductivity or sort of make inferences about superconductivity, they are infrared absorption which does the measurement of the energy gap, they are tunneling which are which do the measurement of the superconducting density of seeds and show these that a superconductor has a gap that appears at the Fermi level photo emission. Photo emission tells you that if there is a momentum dependence of the gap whether the gap is homogeneous at all k values or there is a particular fashion or rather an orientation in which the gap is smaller along some direction of k or it is bigger in some other direction, NMR it probes short pairs.

So, usually these pairs have are defined by a coherence length, which is basically the resulting the size of the resulting wave function and there are also smaller pairs. In fact, this high Tc superconductivity is caused by or it is believed to be caused by shorter pairs. So, NMR probes this existence of shorter pairs and of course XRD which is x ray diffraction it does the crystal structure determination of all materials including the superconductor.

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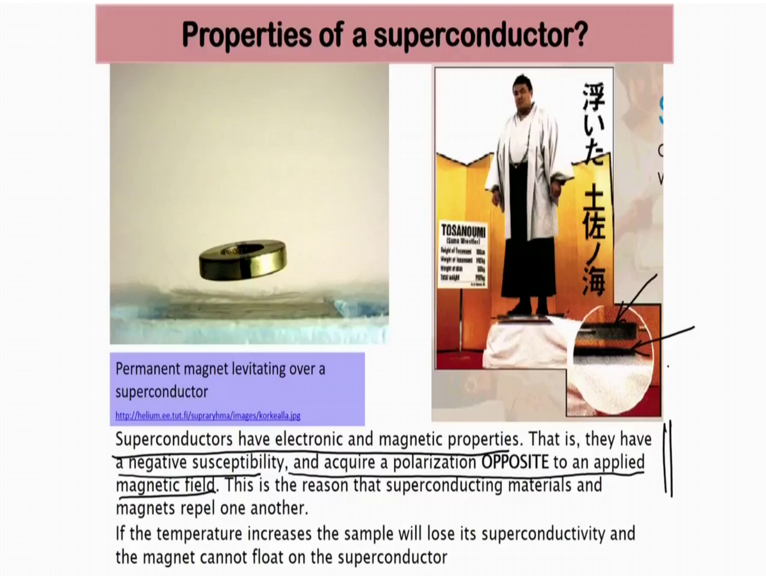

So, we will see this magnetic levitation in a video that we have said and this is one of the properties, now how does the magnet levitate in presence of a superconducting sample because, there is a very large magnetic field density in the vicinity of the superconducting sample; that is because the magnetic flux is very large in the vicinity because all the magnetic field lines are pushed out of the superconductor and they bunch together.

So, much so the magnetic energy is able to lift with the weight of such a disk or a ring, superconductors also have electronic and magnetic properties. So, that is we already have said that they have a negative susceptibility and they acquire a polarization opposite to that of the applied magnetic field and that is why the superconducting materials and magnet they actually repel each other, so this is the reason for that. If the temperature increases the sample would lose it is super conductivity and the magnet will not be able to float on the superconductor because, superconductivity is destroyed so the meissner effect goes along with that. So, there will be no more exclusion of the flux and so the magnetic energies go away which used to support the weight of the ring. this is in this cartoon there is a sumo wrestler which is shown that he is standing on a platform and the platform has a small gap as it is shown here between the grounds and that so the superconducting platform.

So, because this plank or the layer of the material on which the sumo wrestler stands is shown here this 1 the top 1 and the bottom 1 is a superconducting sample. So, this levitation can actually support the weight of a sumo wrestler this is what is being said in this diagram.

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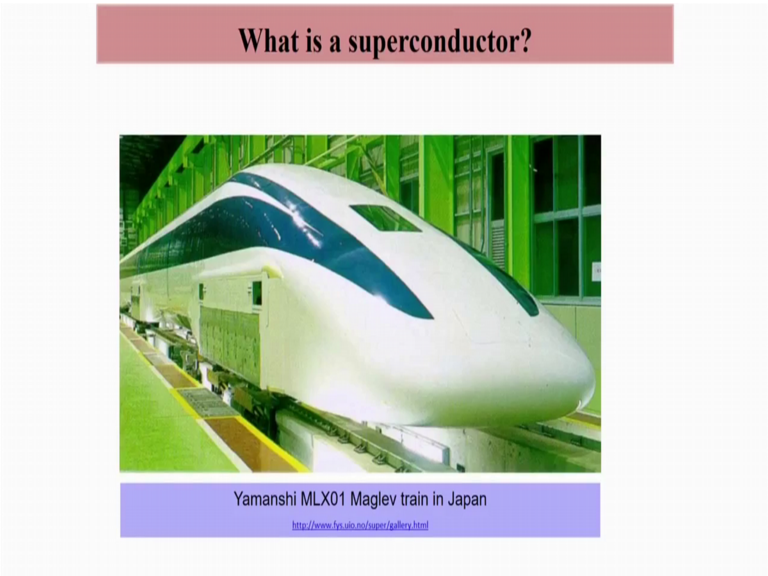

And this is the maglev train which is not yet operational, but they are planned to be operational they would reach velocities more than even the bullet trains and the reason being that they would be levitated and they would not be having any super conduct or any friction from the rails which usually impede the velocities; these are nice looking trains and they are probably artists impressions of how the trains are going to look like.

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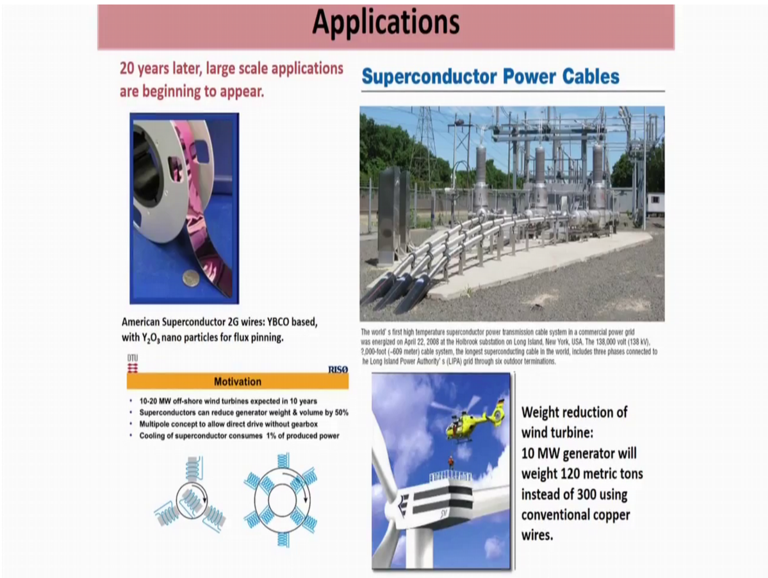

And this is of course some of them are only our a futuristic ideas and ambitions that we will have that there are large scale applications of superconductors which are which can begin to appear, like American superconductor 2G wires.

So, there are ybco that is yttrium barium copper oxide and Y2O3 yttrium oxide nano particles for flux pinning, one can have the superconducting power cables such that there are persistent current and you do not have to add sustain the current 1 starts it will keep going on and various other things I mean there are you know weight reduction of the wind turbine, 10 megawatt generator which will weight 120 metric tons instead of 300 using conventional copper wires and so on and these are the applications which we can see in the future.

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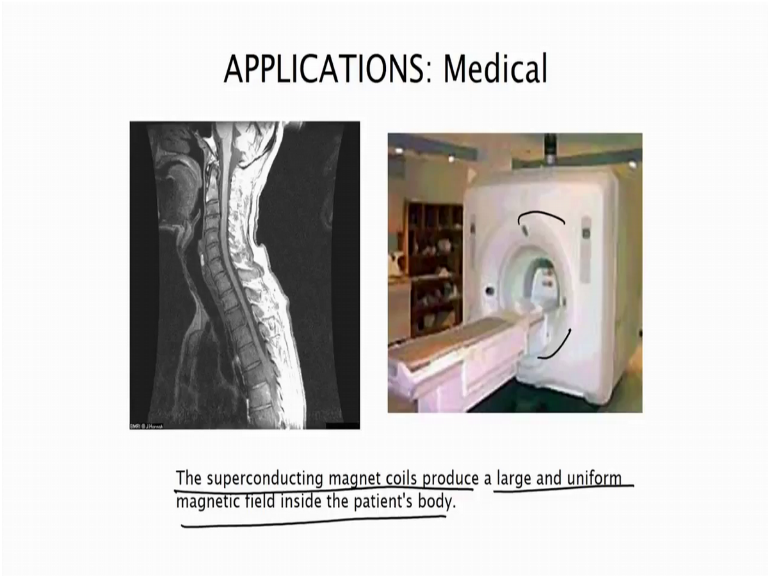

There are medical applications, so these are these ones are actually superconducting magnet coils, which produce very large uniform magnetic fields that can penetrate through the patient's body and will give information if there is an anomaly or there is a pathological defect in the human body and then the actual treatment can proceed a lot of medical diagnostics are now dependent on MRI doing MRI and so they crucially have lot of applications in the medical sector.

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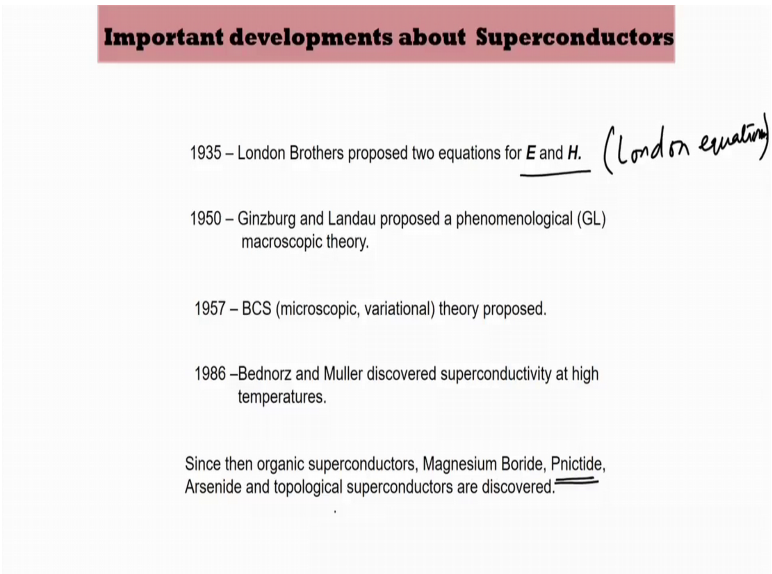

So, to talk about those important developments and some dates etc, 1935 a London brothers proposed these equations on E and H and these are called as the London equations, 1950 Ginzburg and Landau proposed a phenomenological called as the Ginsburg landau theory, 1957 is a BCS theory microscopic it is a variational theory and cannot be obtained by doing any finite order of perturbation theory and 1986 is Bednorz and Muller discovered superconductivity at high temperatures and then there are lot of other, like the iron based superconductors are called as a Pnictide superconductors, they are being discovered including the magnesium boride and the arsenide and now 1 is talking about the topological superconductors.

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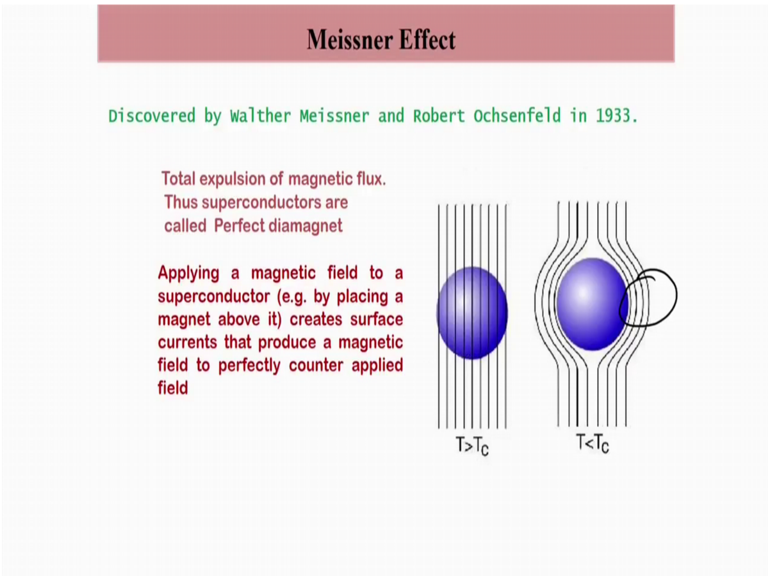

So, pictorially what happens in the meissner effect, we will do all these calculations as we go along. So, the meissner effect it was discovered by Walther Meisner and Robert Ochsenfeld in 1933, so this is the total expulsion of the magnetic flux. So, that is why the superconductors are called as the perfect dia magnets, applying a magnetic field to the superconductor by replacing the magnet above, it creates surface current that produces a magnetic field to perfectly counter the applied field.

So, this is T greater than Tc though the magnetic fields penetrate as T is lowered below Tc this it becomes this blue ball becomes superconducting and this it starts repelling the magnetic fields and now you see that in this region there is a large flux of the magnetic fields because it is bending around the obstacle and this as it says that what happens is that it creates some surface currents and the surface currents produce a magnetic field in a direction that exactly cancels the applied field.

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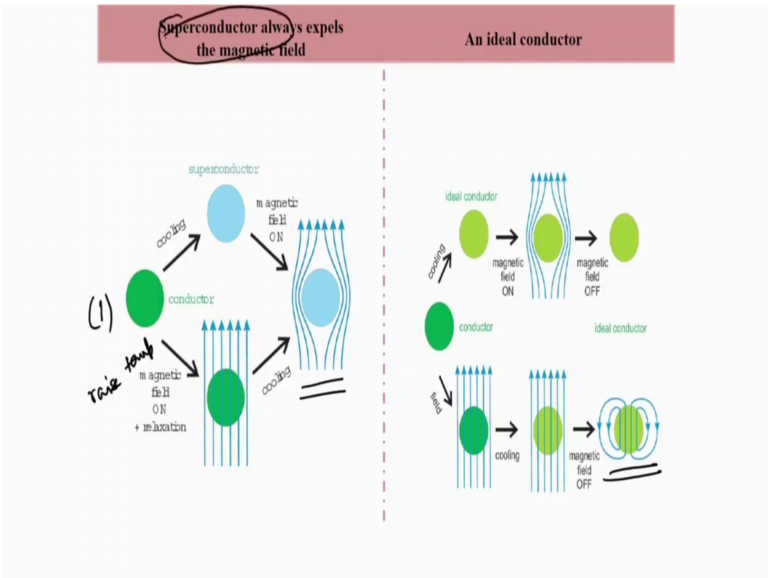

So, let us have a distinction between the perfect conductor and the super conductor. So, this is a superconductor so it is a superconductor or rather let us start with 1. So, it is a conductor upon cooling it becomes a superconductor, if you switch on the magnetic field the magnetic fields get say expelled and these are called meissner effect and the magnetic field if you on. So, if we relaxed that is if we raise the temperature so this is raising temperature. So, superconductivity is destroyed and the flux lines will penetrate.

Now what happens for an ideal conductor if it is an ideal conductor the magnetic field is on, so it is cold magnetic field is on the magnetic field is off that it is it completely the flux lines completely vanish and if it is put in a magnetic field then the magnetic field will penetrate if you cool, the magnetic fields will still penetrate and when we switch off the magnetic field.

Then for an ideal conductor we will have that these things will make circles the magnetic field lines will make circles whereas, this step is different than what we have for superconductors. So, superconductors it completely sort of. So, if we switch off the magnetic field then we do not have such trapping of the flux lines and that distinguishes a superconductor from an ideal conductor.

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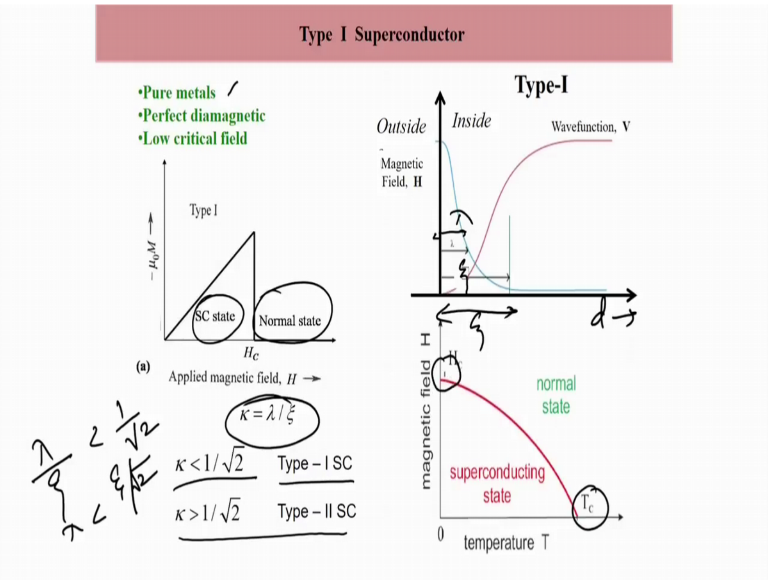

Now, there are 2 kinds of superconductors we have already said type 1 and type 2 superconductors. So, type 1 superconductor is that they are pure metals which is what we have seen in the periodic table, they are perfect dia magnets and they have lower critical field. So, the M versus H diagram which is called as a phase diagram of superconductors it, as you increase H the M keeps going linearly and then suddenly it drops as you further increase eight.

So, as we know that if we give if you apply magnetic field superconductivity is destroyed and then it gives rise to a normal stage. So, this is the superconducting state inside and there is a normal state here. So, this is another sort of this thing for how the magnetic field falls off inside the, so this is the distance inside the superconducting material. So, it falls off magnetic field falls off within a length scale lambda, whereas the wave function actually grows like this.

So, this is called as psi this length is called as psi and this length is called as lambda as you can see this length is called as lambda and this called as a penetration depth and this is called as a coherence length. So, 1 can actually talk about a single quantity kappa, which is ratio of psi by lambda by psi; where kappa less than 1 by root 2 gives you a type 1 superconductor whereas, kappa greater than 1 by root 2 gives you type 2 superconductor.

Which means that if lambda is less than psi, so lambda by psi less than 1 by root 2 which means lambda is lambda is less than psi over root 2, then we have a type 1 superconductors and if there is lambda is greater than psi over root 2 there is a root 2 there, then we have a type 2 superconductors and similarly the magnetic field versus temperature shows that this the regime bounded by the red line is called as a superconducting state and above that which is the normal state.

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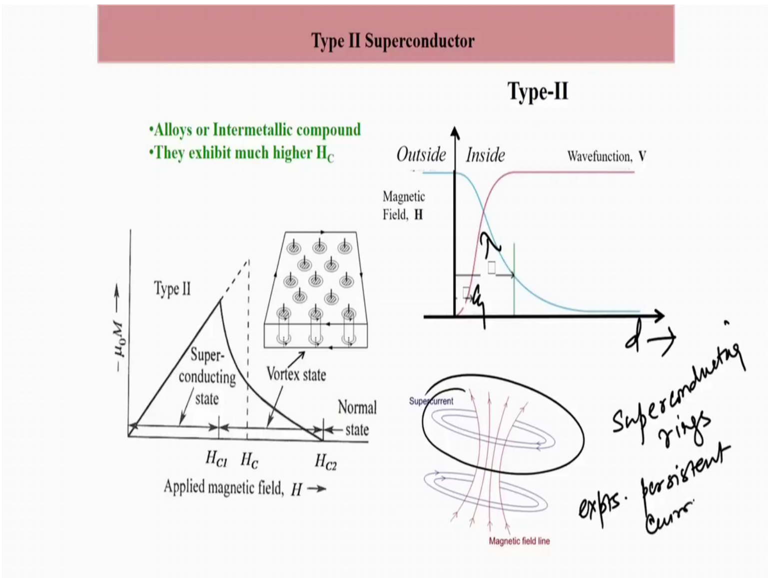

So, there is a Tc beyond which superconductivity destroys and there is also a Hc beyond which superconductivity destroys and sothis is a type 2 superconductors it occurs in alloys. So, there is a combination of different elements it is alloys or inter metallic compounds and they exhibit a much higher Tc. So, the phase diagram is not exactly like what we have seen here it is dissimilar and there is a linear increase and then there is a fall off like this, inside is a superconducting state a part of it; but a part of it what is called as a vortex state and beyond that it is a normal state.

So, what happens is that the magnetic field can partially penetrate into the sample and beyond that when the magnetic field is increased beyond the super conductivity is destroyed; however, the magnetic flux lines that get trapped and this trapping also happens in some nice regular ordering and in particular it happens in a form of a hexagonal lattice, which is called as the abric course of lattice. So, this is the lambda and this is the psi and now you see that it penetrates much larger into the superconducting sample.

So, this is D is the distance inside the superconducting sample, whereas the wave function of the of the electrons are smaller and this is a typical diagram showing that there are superconducting rings these are superconducting rings and there is there is a magnetic field lines that are that are applied and so the current super current goes in these superconducting rings or in the ring fashion the current actually circulates in about the magnetic field lines and these are the experiments demonstrating persistent current.

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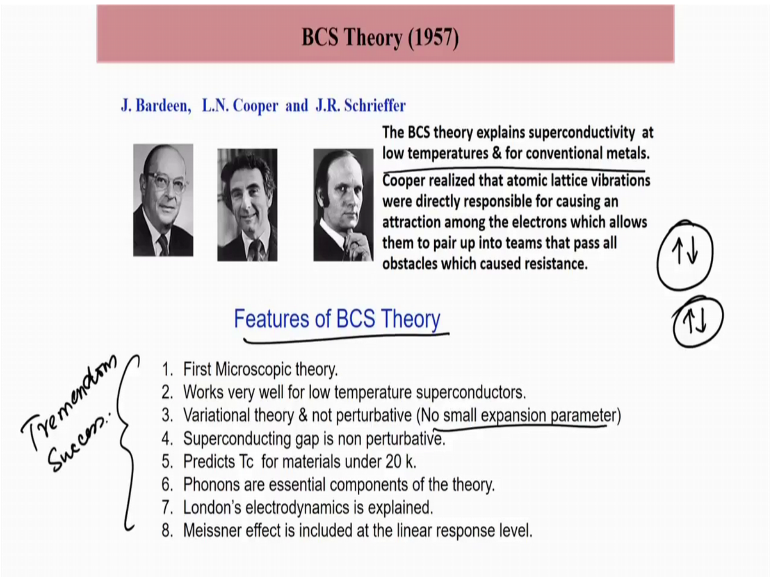

So, finally just small glimpse of what came from Bardeen cooper and Schrieffer, so these are the photographs of them and this explains superconductivity at low temperature for all conventional metals and it was started with coopers work he realized that the atomic lattice vibrations were directly responsible for causing attraction among the electrons, which allow them to pair up into teams pairs that is that parcel ops all obstacles which cause resistance.

So, when an electron pairs up with another electron forms a bound pair, this bound pair seamlessly move without having any resistance or rather without having any collision suffering any collision from another pair. So, this team or the pairs of the electrons which are called as the cooper pairs, they move without any resistance through the sample. The features of BCS theory the first microscopic theory it works well for low temperature superconductors, it is variational and non perturbative we will say all that.

So, no small expansion parameter the superconducting gap is non perturbative, the predicts Tc for materials under 20 Kelvin; the phonons are essential components of the theory London's electrodynamics is explained meissner effect is included at the linear response level. So, there is a tremendous success including all these things.

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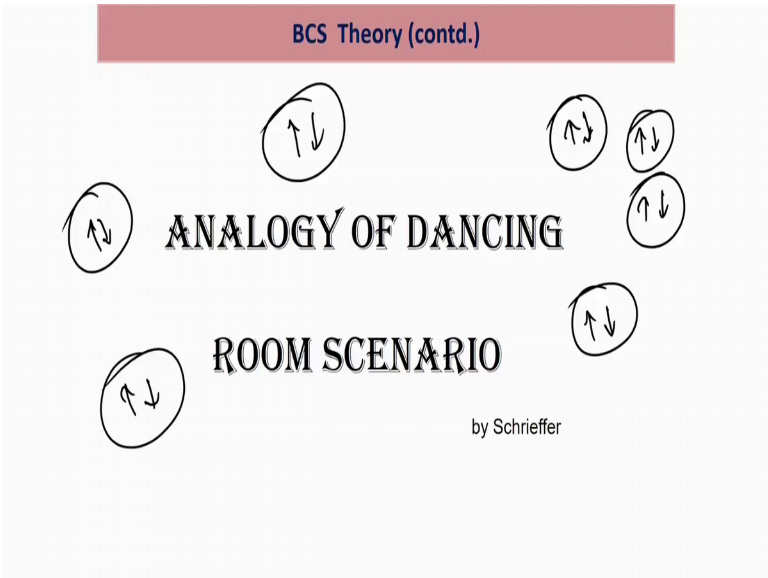

just to have to make the discussion ongoing discussion a little more interesting, there is an analogy of dancing room scenario that was given by Schrieffer; that there are these males and females pairs that are dancing on a dancing floor and they are completely un mindful of another and they keep dancing without suffering any collision from each other. So, there are a large number of them and they can you know they pass on without suffering any collision between each other, the super conducting ground state is exactly like that.

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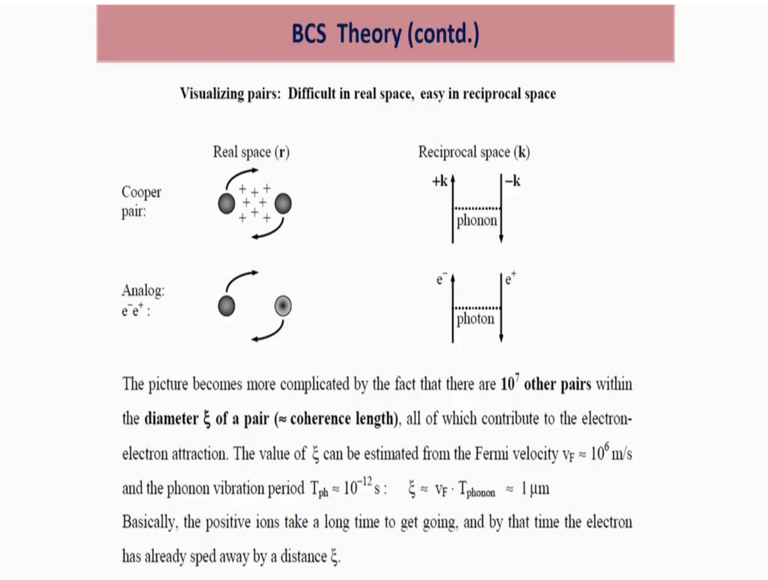

We can talk about this in details later we will do that, but it is just that there are. So, these electrons actually can form a pair in presence of phonons, that is what is said here we will come to this.

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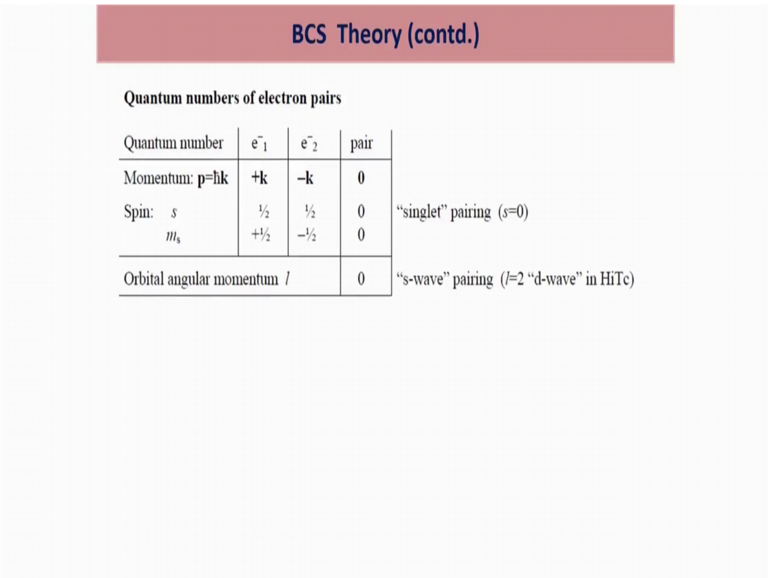

Similarly this ones.

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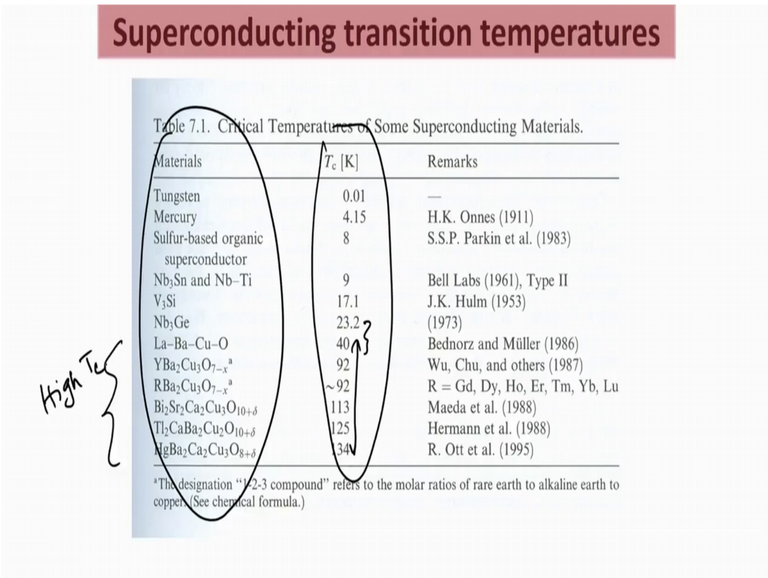

Superconducting transition temperatures

Table 7.1. Critical Temperatures of Some Superconducting Materials.

Materials	T_c [K]	Remarks
Tungsten	0.01	—
Mercury	4.15	H.K. Onnes (1911)
Sulfur-based organic superconductor	8	S.S.P. Parkin et al. (1983)
Nb_3Sn and Nb–Ti	9	Bell Labs (1961), Type II
V_3Si	17.1	J.K. Hulm (1953)
Nb_3Ge	23.2	(1973)
La–Ba–Cu–O	40	Bednorz and Müller (1986)
$YBa_2Cu_3O_{7-x}$[a]	92	Wu, Chu, and others (1987)
$RBa_2Cu_3O_{7-x}$[a]	~92	R = Gd, Dy, Ho, Er, Tm, Yb, Lu
$Bi_2Sr_2Ca_2Cu_3O_{10+\delta}$	113	Maeda et al. (1988)
$Tl_2CaBa_2Cu_2O_{10+\delta}$	125	Hermann et al. (1988)
$HgBa_2Ca_2Cu_3O_{8+\delta}$	134	R. Ott et al. (1995)

[a]The designation "1-2-3 compound" refers to the molar ratios of rare earth to alkaline earth to copper. (See chemical formula.)

And these are some of the superconducting transition temperatures that are listed here, for materials which are like tungsten mercury sulfur based organic superconductors Nb3Sn and so on.

So, you see that suddenly from 23 to 40 there is a large jump and from of course 40 to 92 there are large jumps and so on. Now this is that these are these high Tc, so high Tc superconductors.

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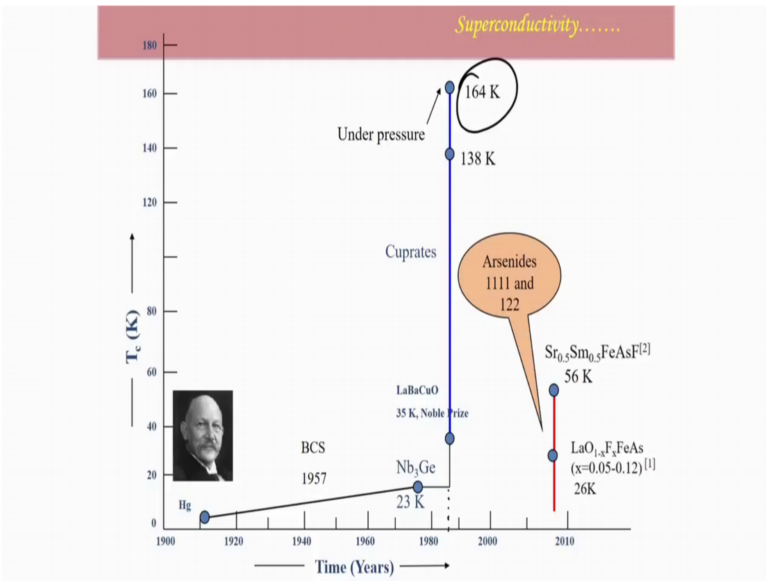

this is how the transition temperature has increased since 1908 it was going fine till about 1986, this is where 1986 is then it shot up and went all the way up to 164 Kelvin. So, there are you know arsenide's which are discovered around this time.

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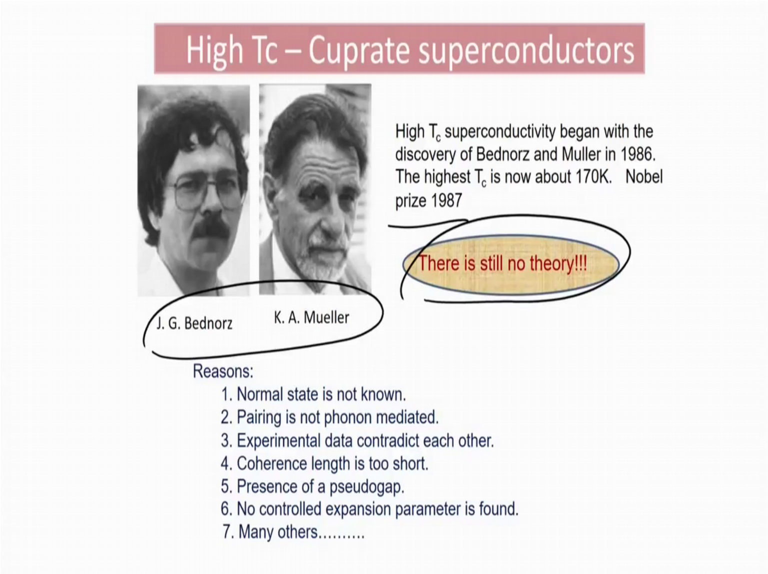

these are the people who discovered this Bednorz and Muller, this these high Tc superconductors the they actually got a Nobel prize in 1987 and there are still no theory because of a number of reasons one of them being that the normal state is not known, pairing is not phonon mediated, experimental data contradict each other coherence length is too short there is something called a pseudo gap.

It is like a gap but it violates other properties of an energy gap, there is no controlled expansion parameters and many others and that is the reason that even the best of the minds working in the field have not been able to come up with the general consensus that what the theory that should be there, which would explain all experiments.

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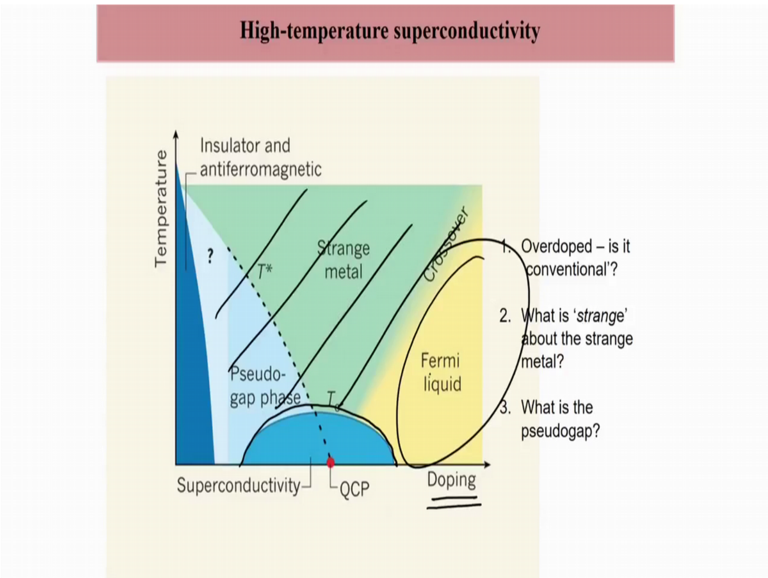

And if one looks at the phase diagram which is a temperature versus doping, so this doping gives the holes which are rather the carriers of superconductivity in this case. there is a superconducting dome that is here, but as you go up you go into a place which is most of it is not known and that is the reason that the theory is not known; whereas, in BCS superconductors all these form nice metals which are pretty much here. So, had all these area here would have been like the Fermi liquid, we would have already had a theory these are some layered structures of these high Tc.

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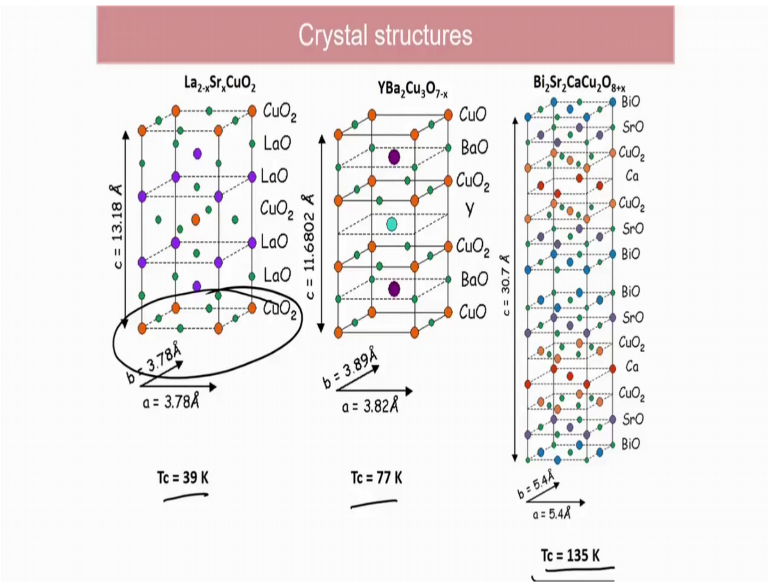

So, basically the essential ingredient is a copper oxide plain in all these things. So, it has a Tc of about 40 Kelvin 77 Kelvin and 135 Kelvin is a lanthanum strontium copper oxide this is called ybco this called lsco this is called ybco, this is a yttrium barium copper oxide and this is called bisco it is abysmal strontium calcium copper oxide and so on.

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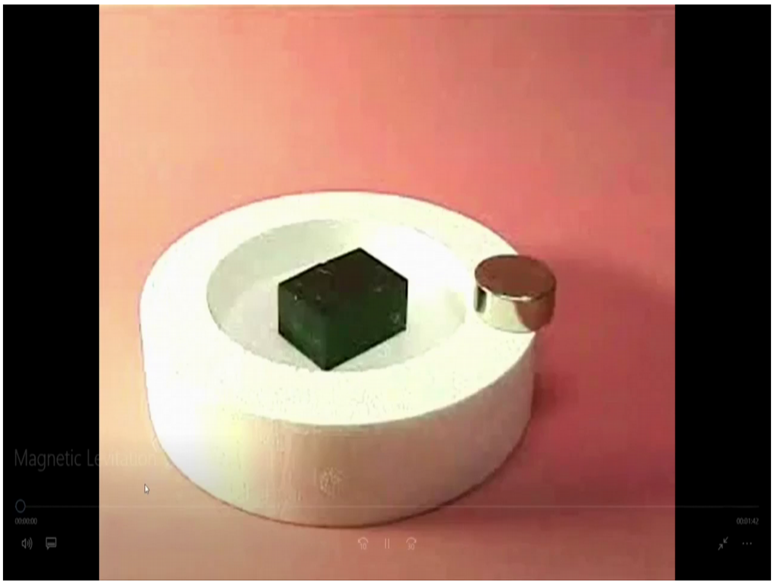

So, let us show you some cartoon for this for the levitation and magnetic levitation in lab experiments and.

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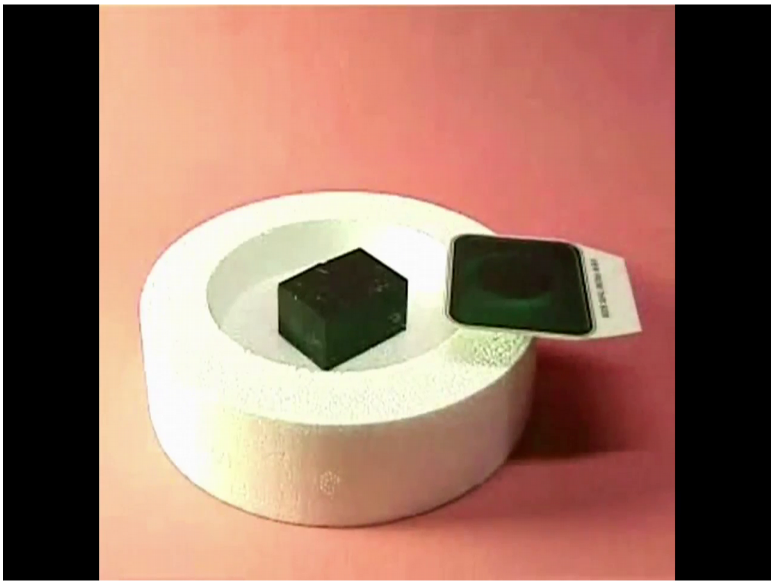

So, this is a superconducting sample that black thing and now there is a coin like thing is kept their, it is kept on top of it. Now this superconducting specimen is just a metal, now they are as if the temperature is being lowered by liquid helium or some other coolant, now it became superconducting now you see placing it on top.

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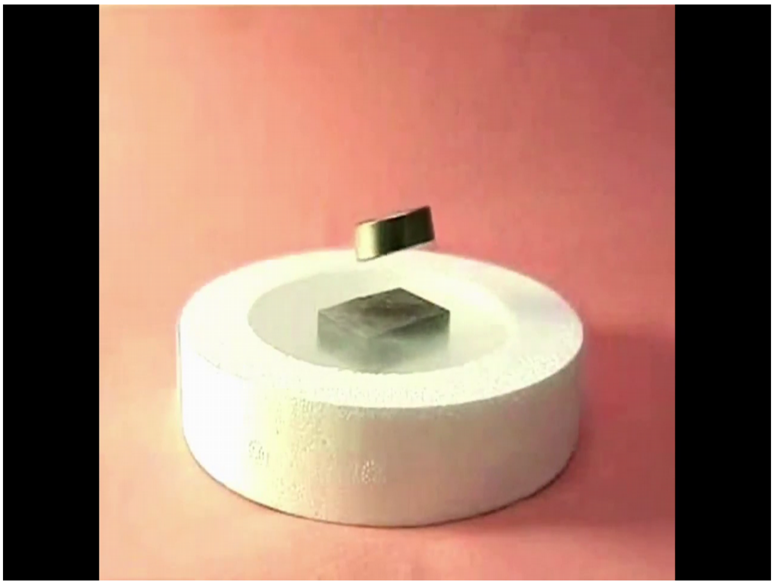

It is just floating this is called as superconducting levitation and it is simply levitating and if you just move it still does not fall off onto the material. So, this black thing that I see is a superconductor now because, the temperature is lowered and you see there is no trick there. So, it is been there is a film has been swiped in order to show that there is nothing there so and now it is spinning also it is still floating as you try to bring it closer it gets repelled, because the magnetic flux lines that has enough magnetic energy in order to support the weight.

Now because it is kept in a kind of open container the temperature is being raised, it lifted that thing itself the material itself and now you have kept taken it out slowly the superconductivity is destroyed and meissner effect is gone the flux are no more expelled and the material just falls crashes on top of the superconducting specimen.

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So, this is the direct lab demonstration of meissner effect.