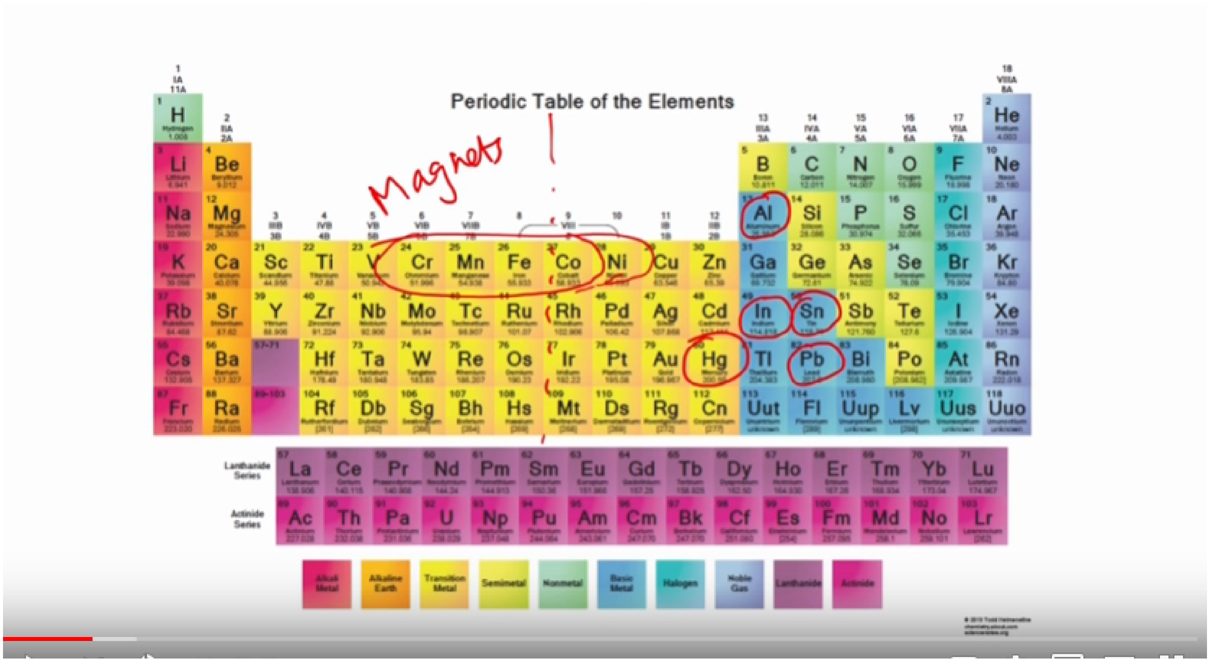
Lecture 1:
Historical Introduction of Superconductivity

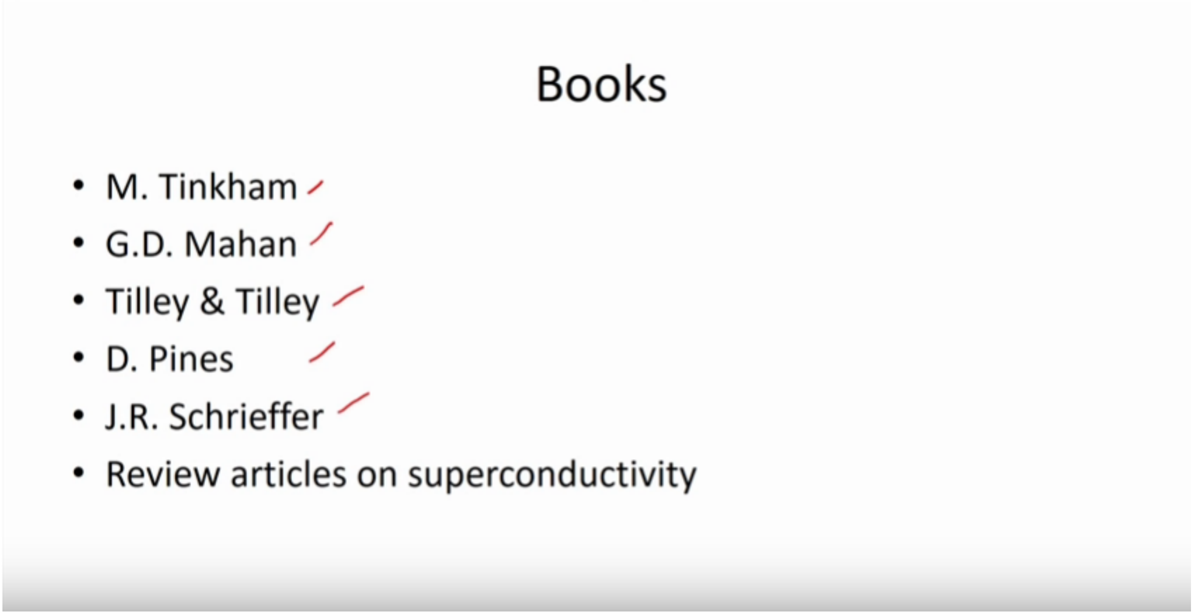
So, we are going to talk about super conductivity. So, having seen a various phenomena in condensed matter physics such as magnetism then metallic behaviour insulating behaviour ferromagnetism ant ferromagnetism and doing a thorough analysis, with regard to the greens function let us now talk about superconductivity 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 will try to give you some recent experiments on superconductivity, which are not very recent but still 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's look at the periodic table.

Refer slide time :(01:48)



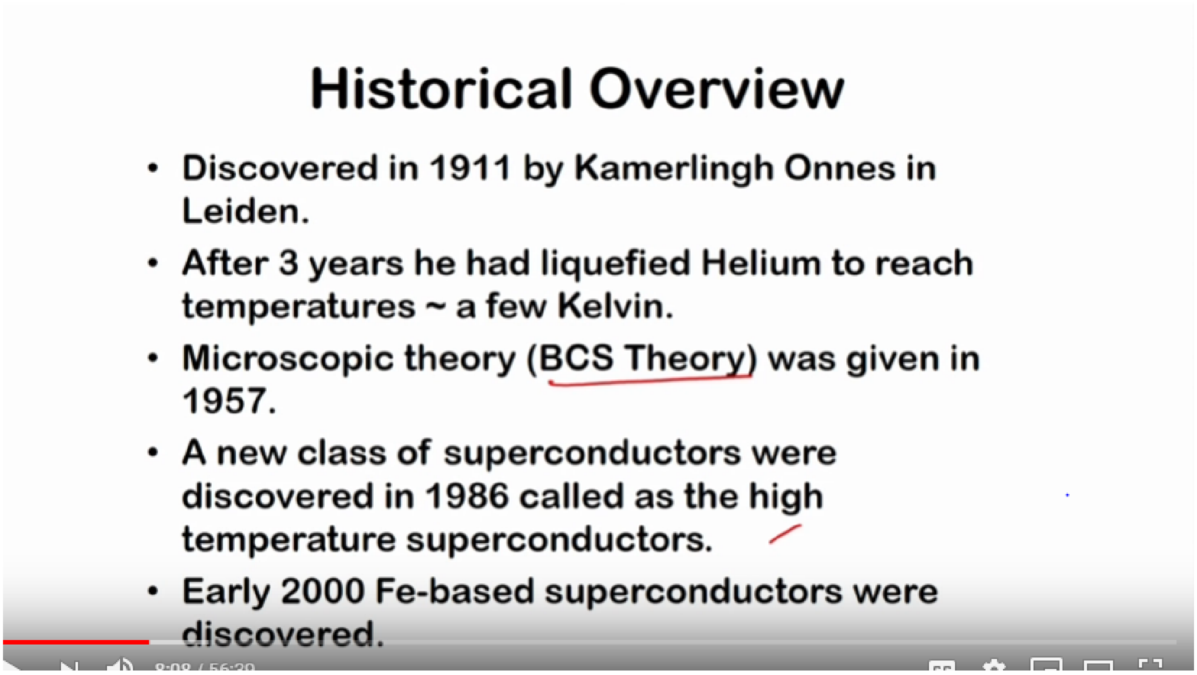
And which are the superconductors or which form which has this phenomenon of super conductivity which is vanishing of electrical resistance below a certain temperature certain characteristic temperature, which is a characteristics to that particular system. If you look at it there are examples of superconductor the first superconductor was in, in mercury and they are in lead and in team and in indium antimonide. And so, on and also some pallium based compound and in aluminium for example and so, there are examples of superconductivity here. So, if we and 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, these are nice magnets and, and there are superconductors which are denoted by the circles. So, superconductivity in the earlier days have been seen in these materials and they're from the colour 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's what pretty much distinguishes metals or other the magnets or the elements which show magnetism with the ones that show superconductivity.

Refer slide time :(04:21)



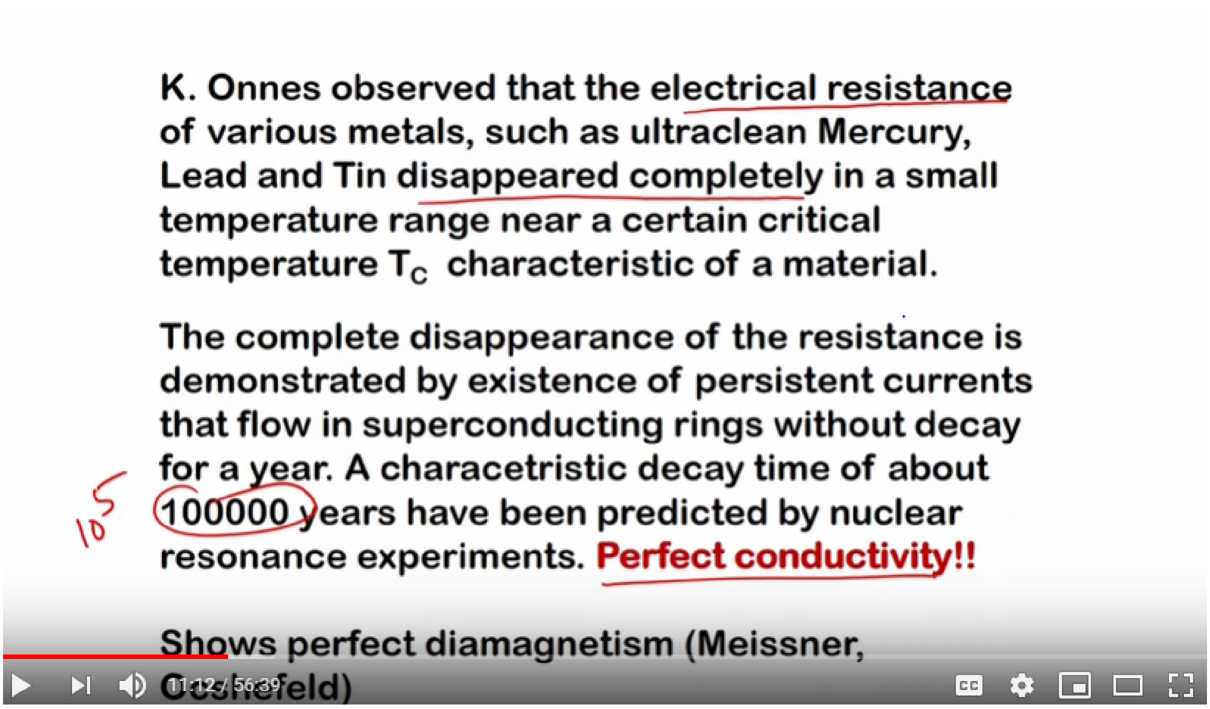
So, let us go ahead with this and let us talk about a few books that are of importance one can look at books such as Tinkham is a very good book Mahan we have already been talking about there's a book called 'Tilley and Tillie', their book called as by David's Pines J.R. Schrieffer one of the discoverer of this BCS theory and there are numerous review articles on super conductivity which you might want to look at it. So, these are our starting point

Refer slide time :(05:00)



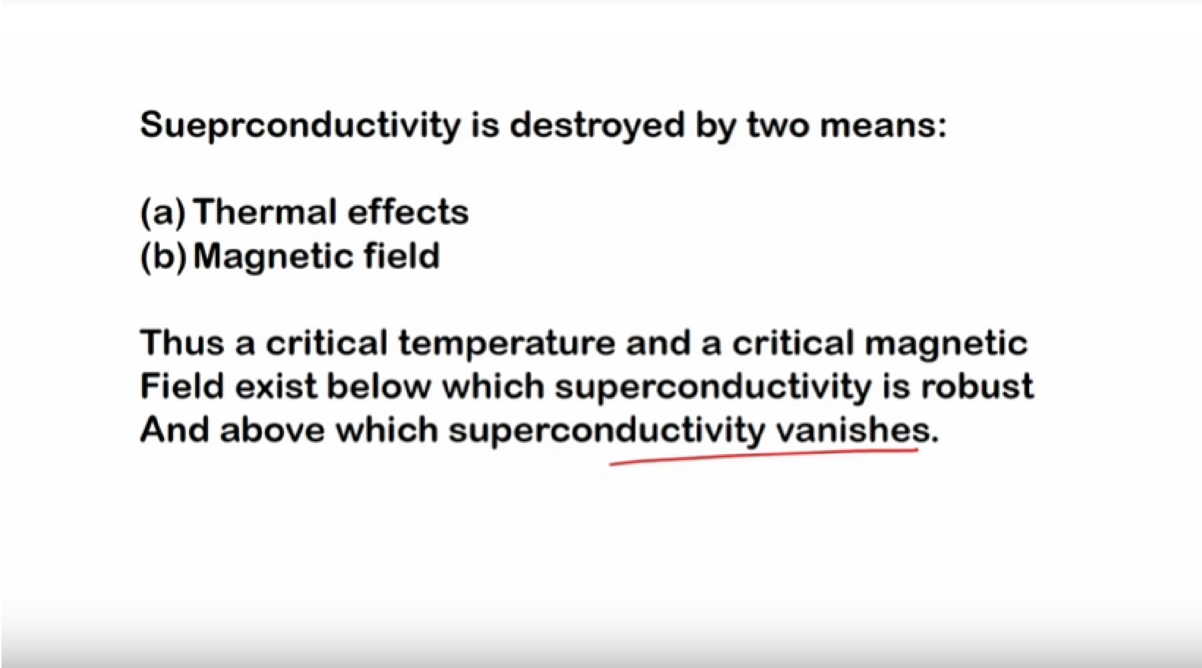
And let us have a historical overview superconductivity was discovered in 1911 by gentleman called kamerlingh onnes in Leiden, that's the name of the place this in Europe and so, after three years he had liquefied helium to reach temperatures of the order of a few Kelvin now why are they related or they have been placed one 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, one has to cool a 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's mentioned which is about 4 Kelvin 4.2 Kelvin. So, a liquid helium temperature is needed in order to cool a system and that's 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'll talk about this a burden cooper and Schrieffer that was given out in 1957 which is just about you know sixty years back. From now and then a new class of superconductors were actually discovered in nineteen hundred and eighty-six they are called high-temperature superconductors. So, the superconductivity in these conventional materials, which are which are seen above in the sense that discovered by can came only 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 discover the chameleons see saw superconductivity in ultra cool ultra clean sorry ultra clean mercury samples, which had shown a sudden drop in resistivity at certain temperature below certain temperature rather and within a very small narrow temperature range. So, this was about this was about 1986 and then early 2000 there are other 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 ferromagnets, good ferromagnets. And the ferromagnets imply that there are the spins are all pointing in the same direction. That's what Ferro magnetism is about however a superconductor requires a pairing of up and down electrons I mean two electrons one having an up spin with a momentum K and the other with a momentum minus K and a down spin so, apparently there's an ambiguity but there are instances and experimental evidences of iron based superconductors.

Refer slide time :(08:53)



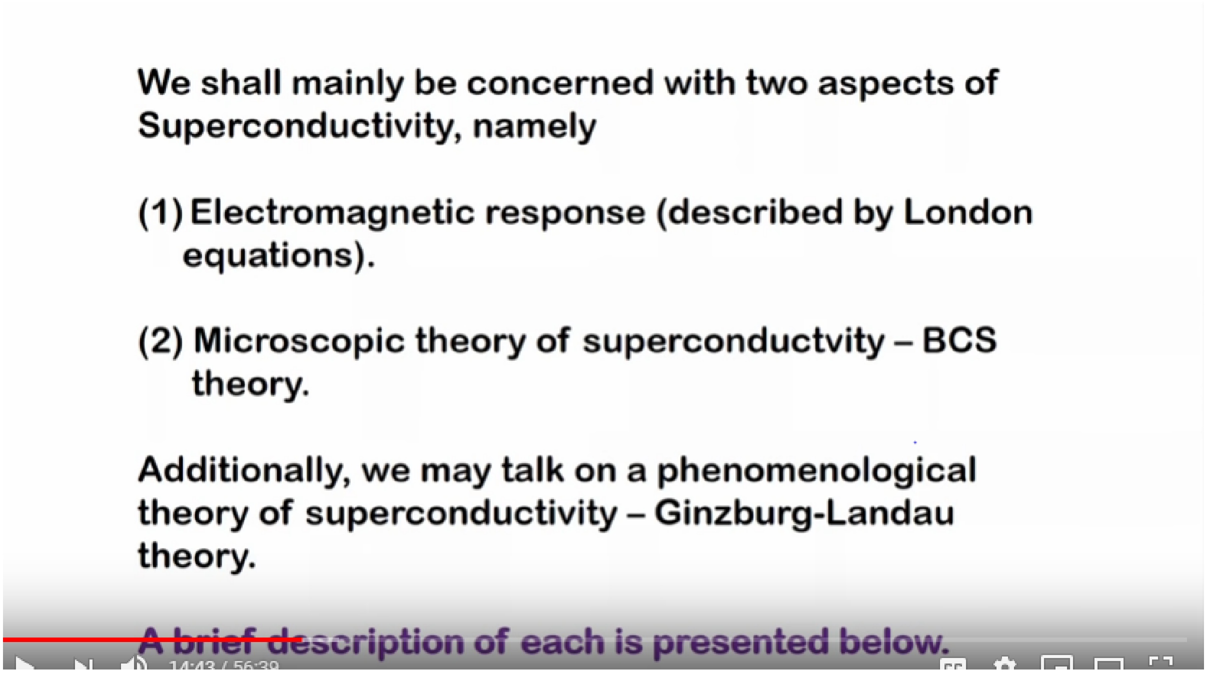
So, what came aliens did is that while he was doing an experiment with ultra-thin mercury. And then subsequently with lead and team we have shown in the periodic table that there are LED and teen etc showing superconductivity. So, the electrical resistance, electrical resistance that disappeared completely in a very small range of temperature, we have some supporting figures for that you 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 have 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's why they are they're 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 zero the temperature goes to zero 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.

Refer slide time :(11:16)



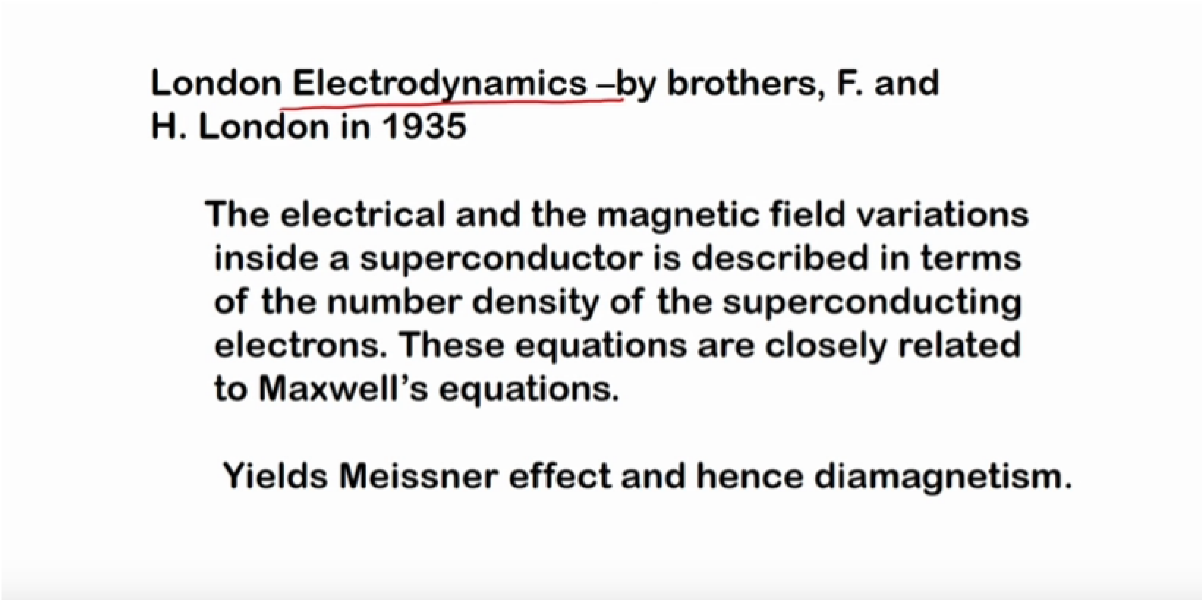
So, superconductivity can be destroyed why we are talking about destruction of superconductivity is that then we understand how robust superconducting state is so there it can be destroyed by two means, that is one is thermal effects that is if you raise the temperature of the system or if you apply an external magnetic field, both these can actually destroy superconductivity and the system will go on to a so-called metallic state, it doesn't have to we'll see that in high TC superconductors they don't 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, once superconductivity is destroyed there's a emergence of a metallic state.

Refer slide time :(12:29)



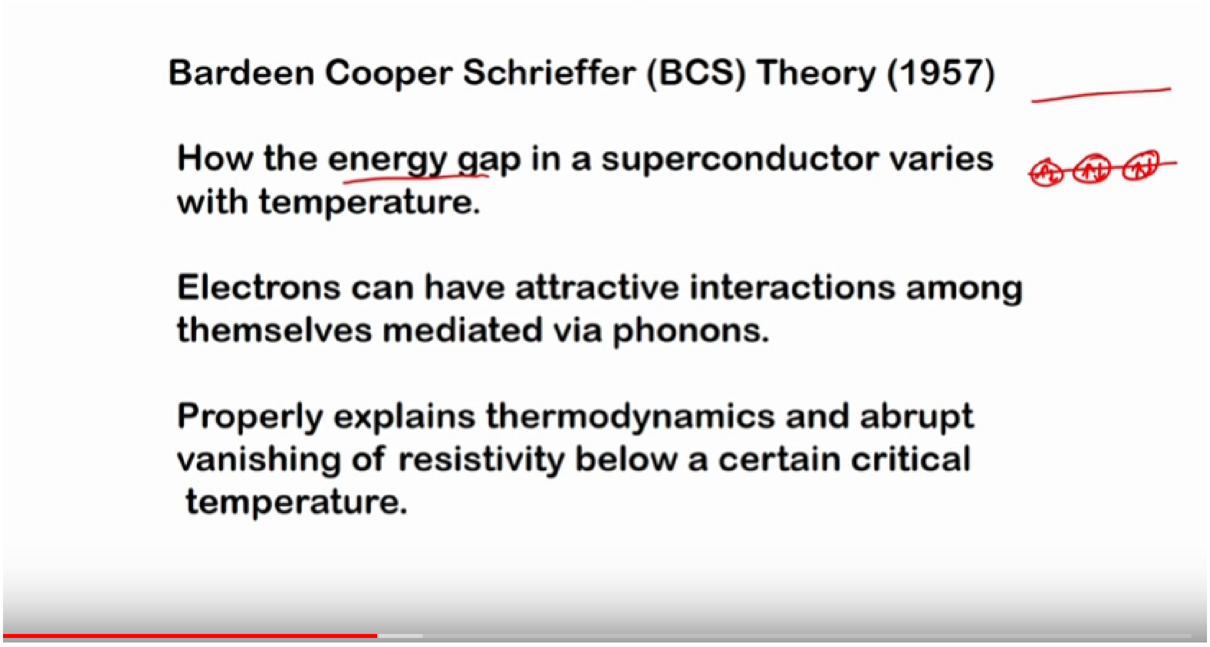
So, we are going to be concerned about mainly two aspects of superconductivity and one of them being the electromagnetic response as we have just said which takes care of the Meissner auction Fled effects. And so, on and this was discovered by or rather they are described by London equations will give us a small overview now and then we'll 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 TM and you'll see that how it was actually Cooper's problem it's called ‘Cooper instability’, it is shown that two 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 Fermi sea .Okay? 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 function and in terms of some wave functions or rather some order parameters which are going to give you 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 description is first presented about each one of them and then will go on for a little elaborate discussion.

Refer slide time :(14:47)



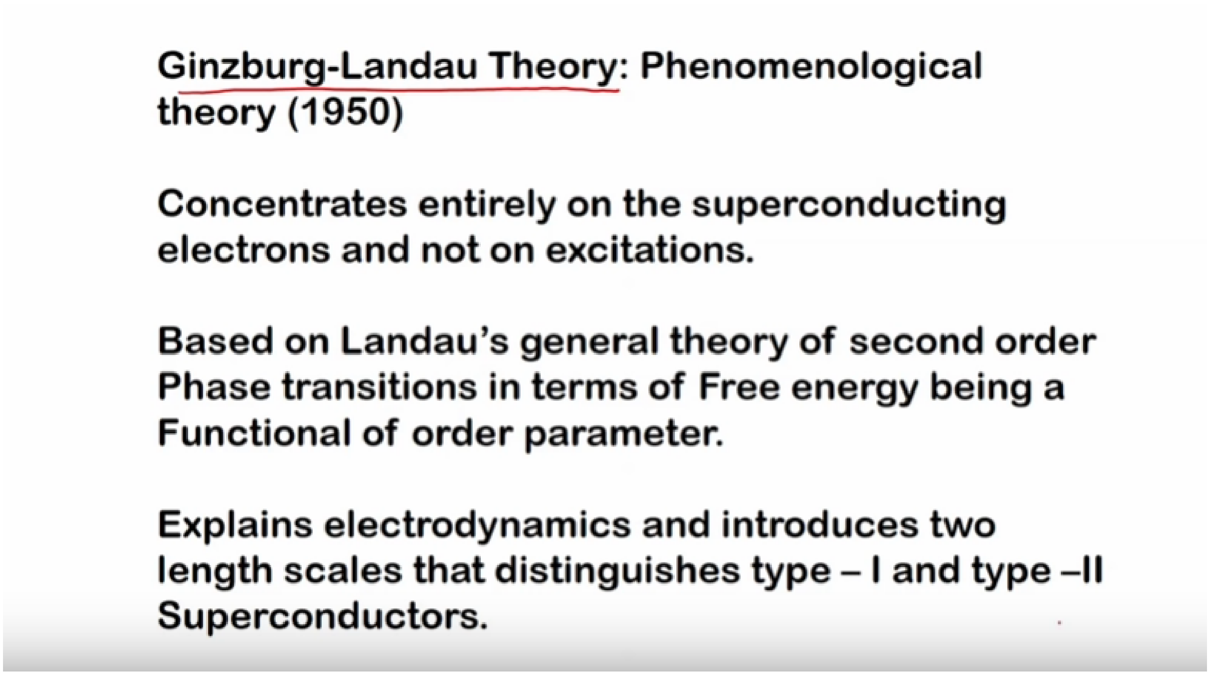
So, to start with it was we said that it's a electrodynamics so, these were by two brothers F and H London F London and H London in 1900 and 35. So, they actually were wrote down equations where the electric field and the magnetic field variations inside a superconductor can be described in terms of the number density of the superconducting electrons or the super current density. So, it is important to say that normal current doesn't flow through a superconductor because, of this super conductors being perfect diamagnets 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 yields starting from these equations which are nothing but some variations of the Maxwell's equations of electrodynamics one can get diamagnetism from and, and hence Meissner effect this is what we have talked about.

Refer slide time :(16:12)



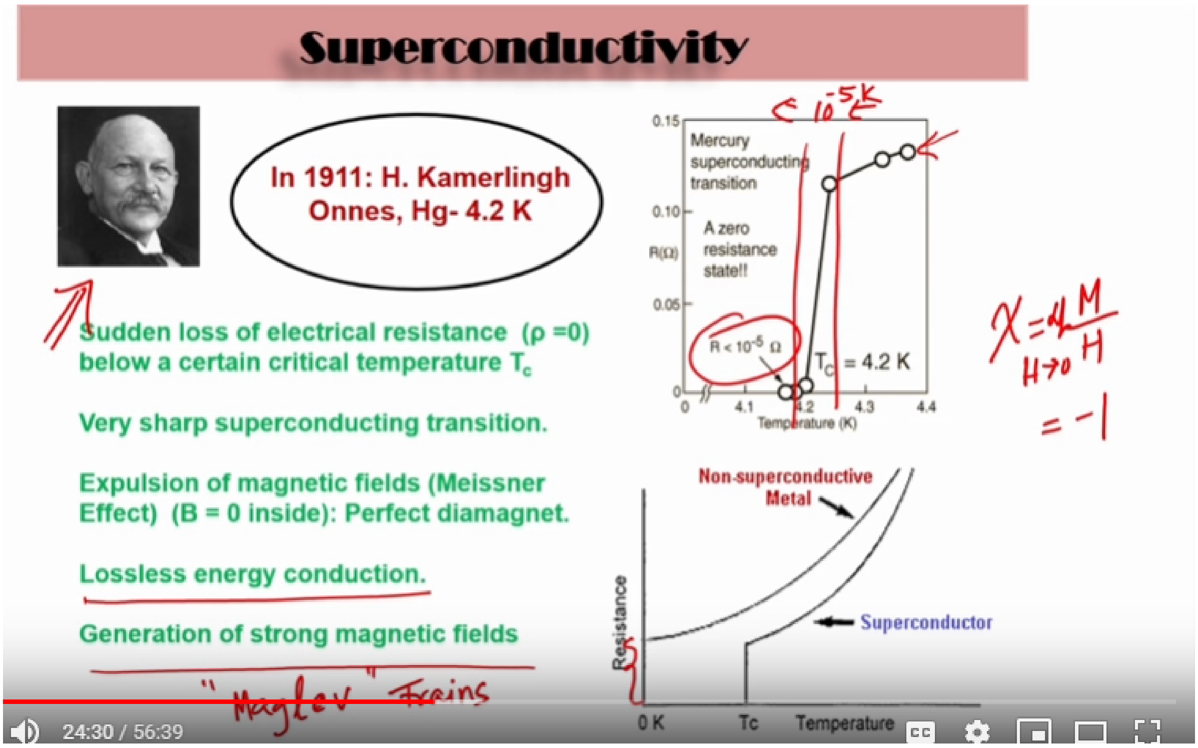
Then we have this microscopic theory that should come into the discussion which was again put forward in 1957 by three people called ‘Bradeen cooper and Schrieffer’. And the superconductor so, it will show that how the energy gap in a superconductor varies with temperature. So, what we mean by an energy gap is that there is a ground state and there is a first I mean there is an excited state where superconductivity is discovered 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, there are Supes 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.

Refer slide time :(18:02)



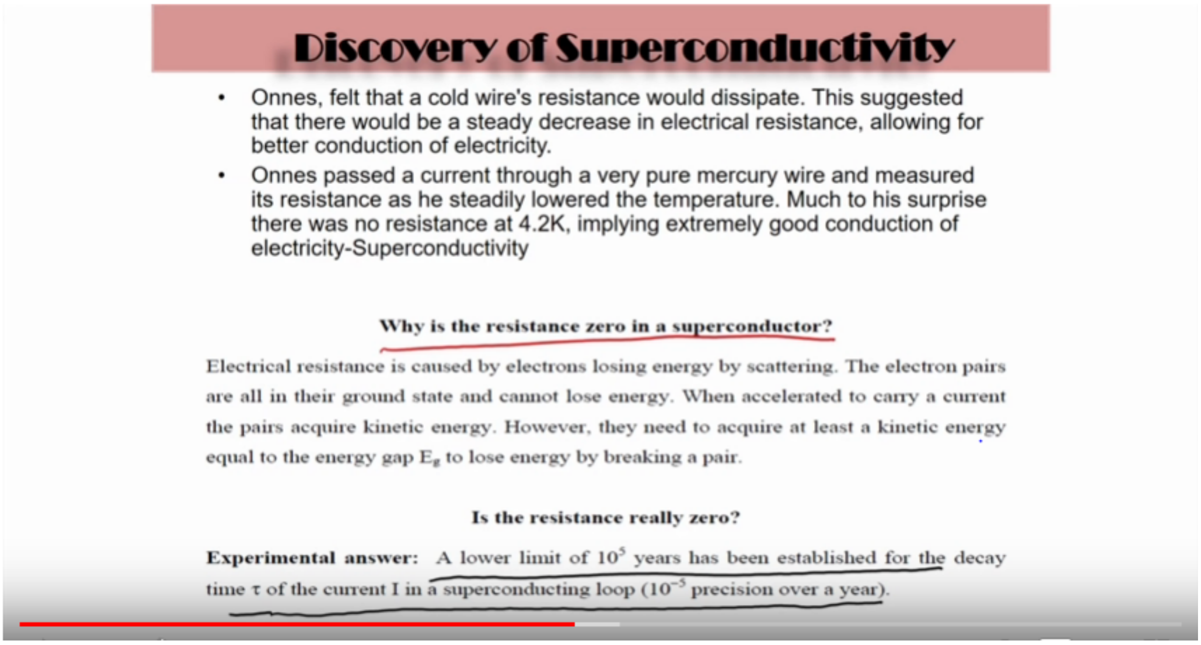
And then the Ginsburg Landau theory as we told it's a phenomenological theory, it doesn't have any microscopic basis and it was put forward ahead of BCS Theory when BCS theory was unavailable and what it did is that it is it wrote down the free energy functional in terms of powers of the order parameter or basically the complex wave functions that describe a transition from one state to another. So, it concentrates on the superconducting electrons and not on, on its excitations it's based on the Landau's general theory of second order phase transition that's why this name Ginsburg Landau it's coming and in terms of free energy and, and so, free energies is a functional of the order parameter. So, one is to identify the order parameter and know that how it vanishes at the phase transition then one can write down a free energy functional and do calculations of say electro dynamics and it also very importantly introduces two 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 one of the other type of superconductors.

Refer slide time :(19:35)



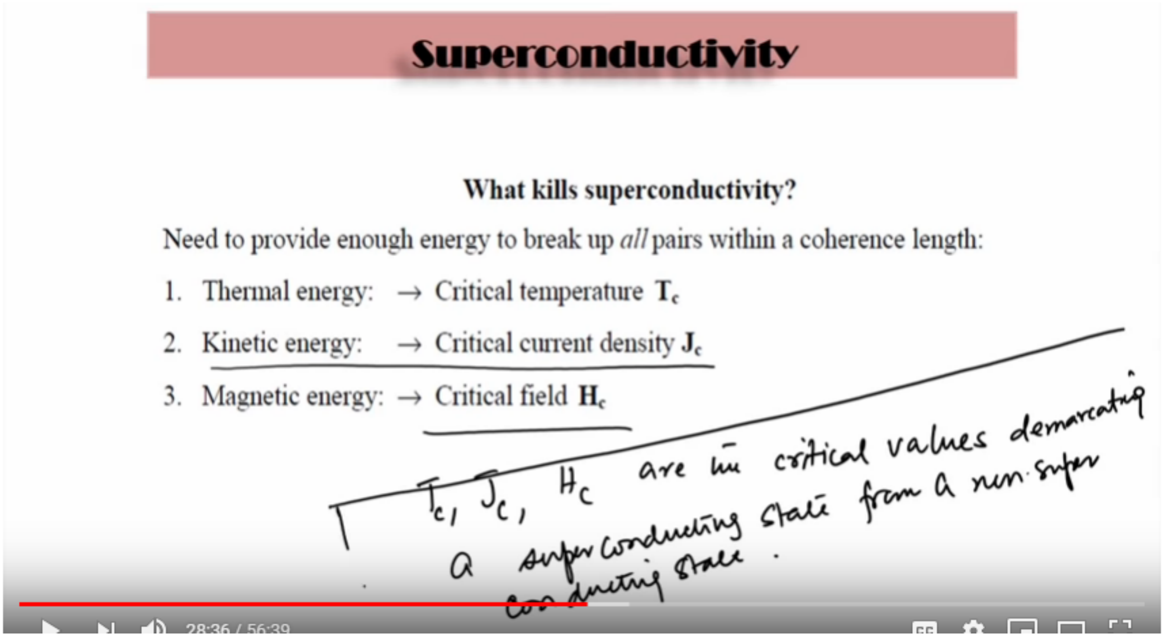
And so, let us go to slightly more elaborate discussion of superconductivity. So, it is this gentleman which we said HK modelling owns and he was working with very clean absolutely clean mercury and it found he found that the resistivity above 4.2 Kelvin it has a linear behaviour here. And suddenly in the vicinity of 4.2 Kelvin in fact within a temperature range very, very narrow it is of the order of 10 to the power minus 5 Kelvin it doesn't show it that way but it is it is true that there are so this, 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. So, the left of this transition is called as a zero 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 zero 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 row 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's why because, there is absolutely no magnetic field. So, that's why they are called as perfect diamagnets 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 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 chi is really small it's 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 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 2020 27 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 zero it takes it gives you a value which is finite. So, this is R equal to R naught equal to zero whereas for a superconductor it decreases and then it suddenly drops to zero at a temperature which is equal to T equal to TC. So, that's the basic difference between good metal and a superconductor.

Refer slide time :(24:31)



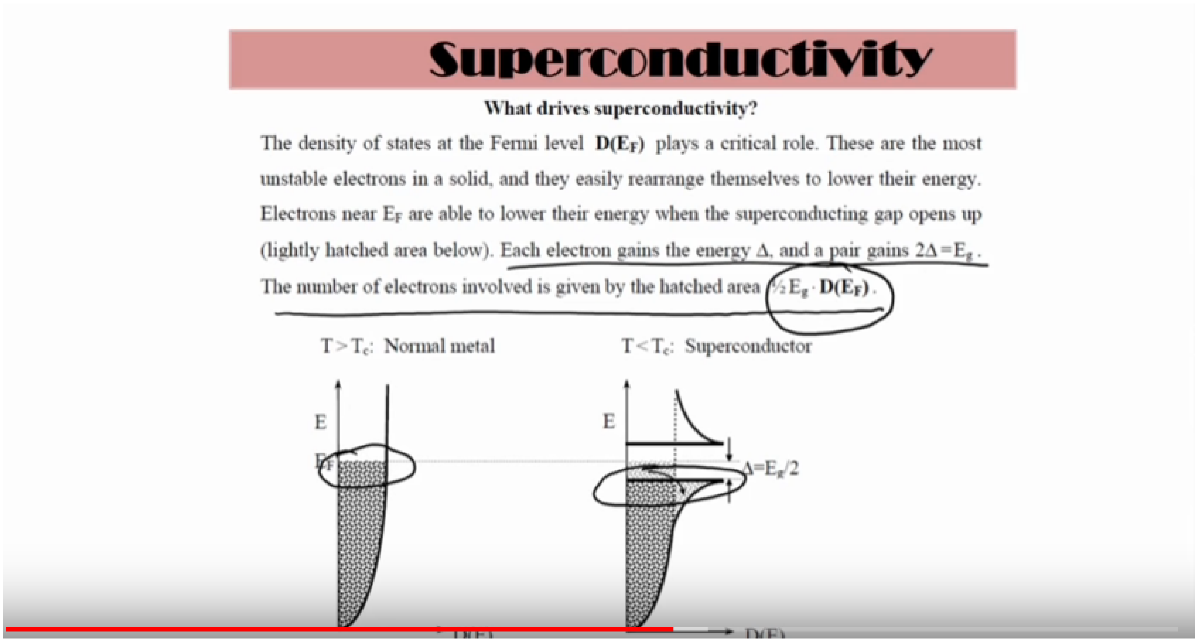
So, there are several things that one had to take care of in experiments and so, geminians felt that the cold wires resistance also would dissipate. So, this suggested that he would there would be a steady decrease in electrical resistance allowing for better conduction of electricity .Okay? And then owns passed a current through a very pure mercury wire and measured the resistance as it steadily lowered the temperature and that's how the experiment went trough 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 zero 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 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, they so there are you need to give it energy, a kinetic energy such that the pairs dissociate and they break and there are some electrons that are made available in them excited energy state. The question is that is the resistance really zero the experimental answer is that a lower limit of what we have what we have said already is 10 to the power 5 years is established for a decay of decay time of current in a superconducting loop which is 10 to the power minus 5 precision over a year, Which is an extremely good signature that resistance is really equal to zero and the current is really persistent.

Refer slide time :(27:09)



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 + HC are the critical values, demarcating superconducting state from a non superconducting state.

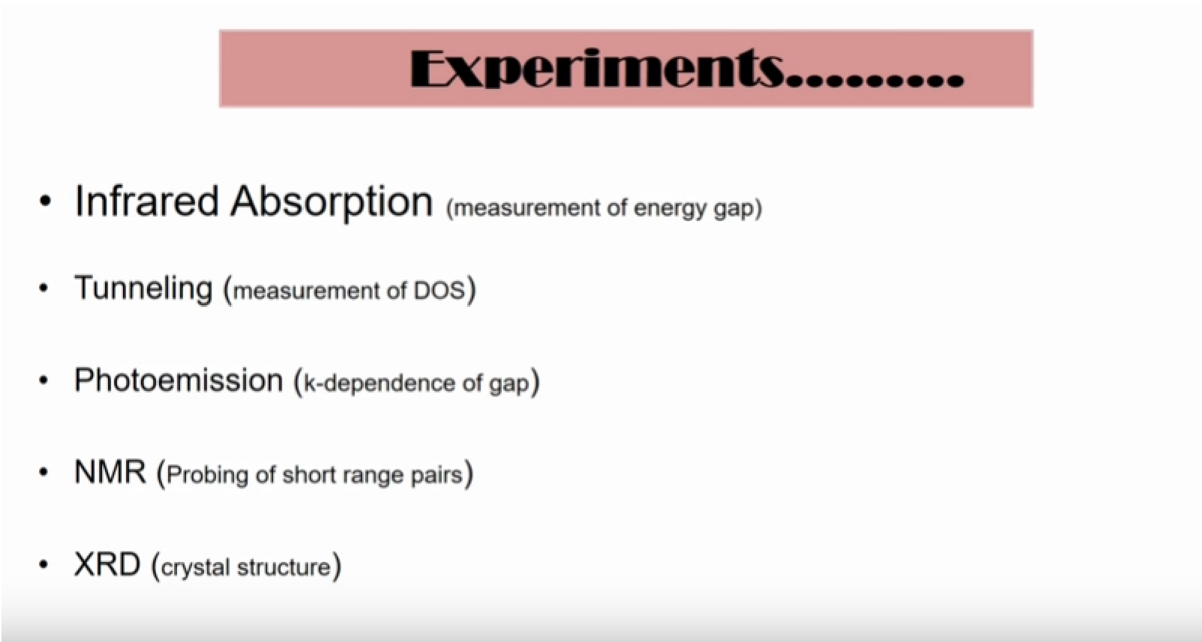
Refer slide time :(28:40)



So, that question is that what drives superconductivity? What causes a superconducting transition? 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 don't 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's only the electrons in the vicinity of this can move into the gap and the other electrons they don't 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.

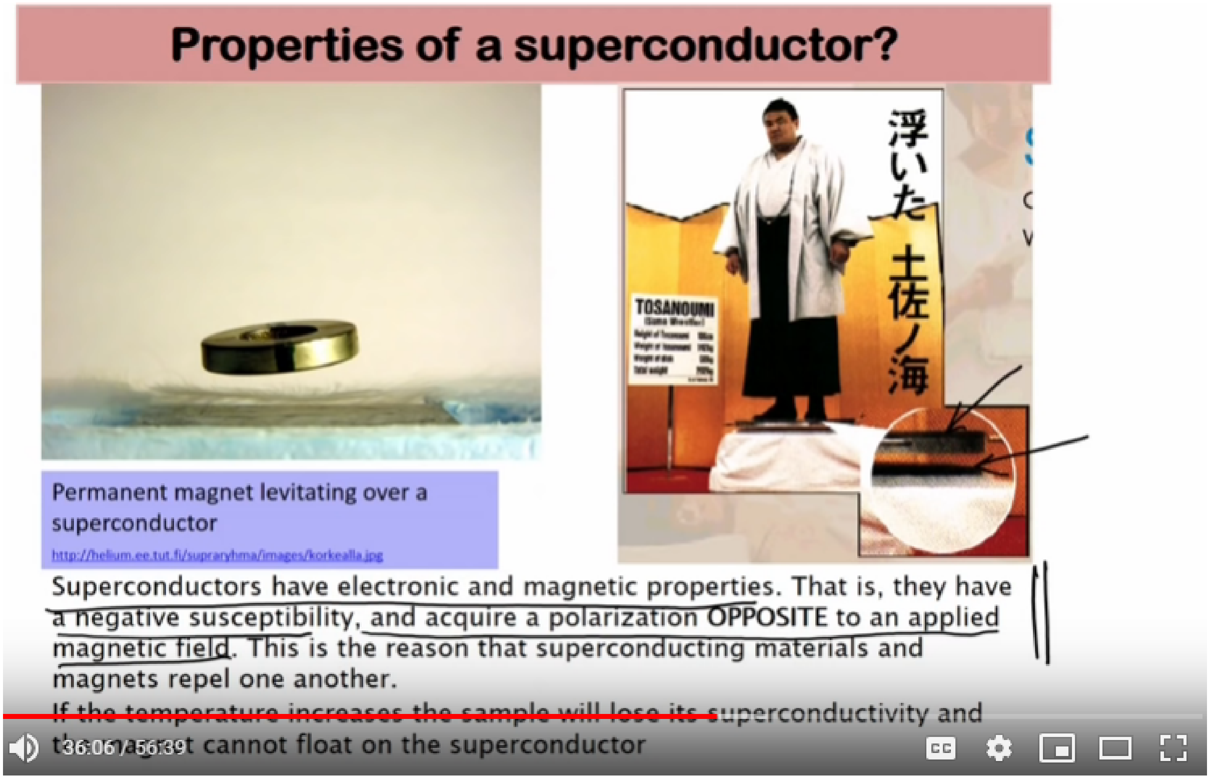
So, this is one typical this thing called diagram called as then for the T greater than TC is for a normal metal where we plotted the density of states on the x axis and E on the y axis in a lot of other books you see that this sorry interchange but they carry the same meaning and for a superconductor 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, 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 this kind of superconductor destroy superconductivity. So, each electron gains Delta and a 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 multiply it 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.

Refer slide time :(32:20)



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're 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, NMR it probes short pairs. So, usually these pairs have are defined by a coherence length which is basically the resulting the, the size of the resulting wave function and there are also smaller pairs in fact this high TC superconductor it is caused by or it's 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.

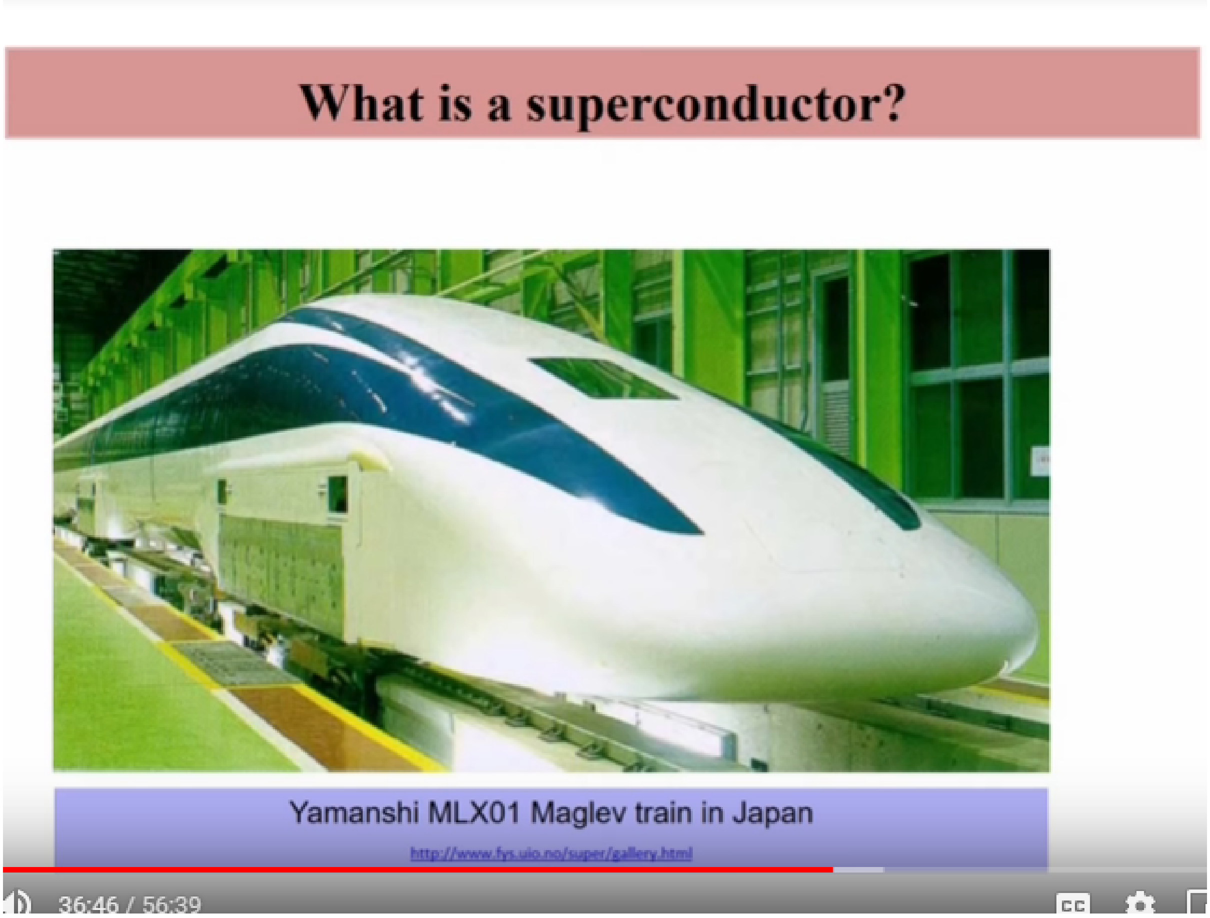
Refer slide time :(33:49)



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 disc 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's 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 its super conductivity and the magnet will not be able to float on the superconductor because, the super conductivity is destroyed.

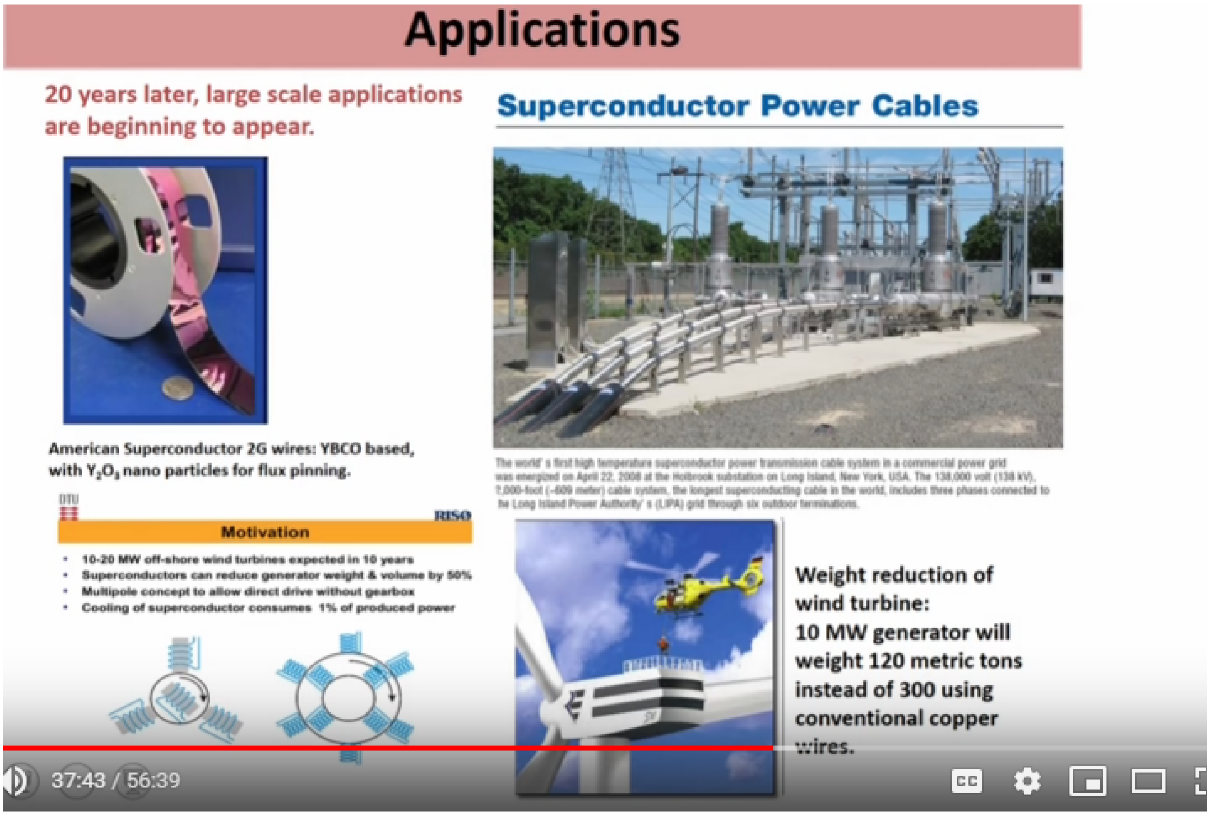
So, the Meissner effect goes along with that so there'll be no more exclusion of the flux and so the magnetic energies go away which used to support the weight of the ring. This is in this cartoon there is a sumo wrestler which is shown that he is standing on a platform and the platform has a small gap as it's shown here between the ground and that so the, the superconducting platform so, because this plank or the layer of the material on which the, the sumo wrestler stands is shown here this one the top one and the bottom one 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.

Refer slide time :(36:10)



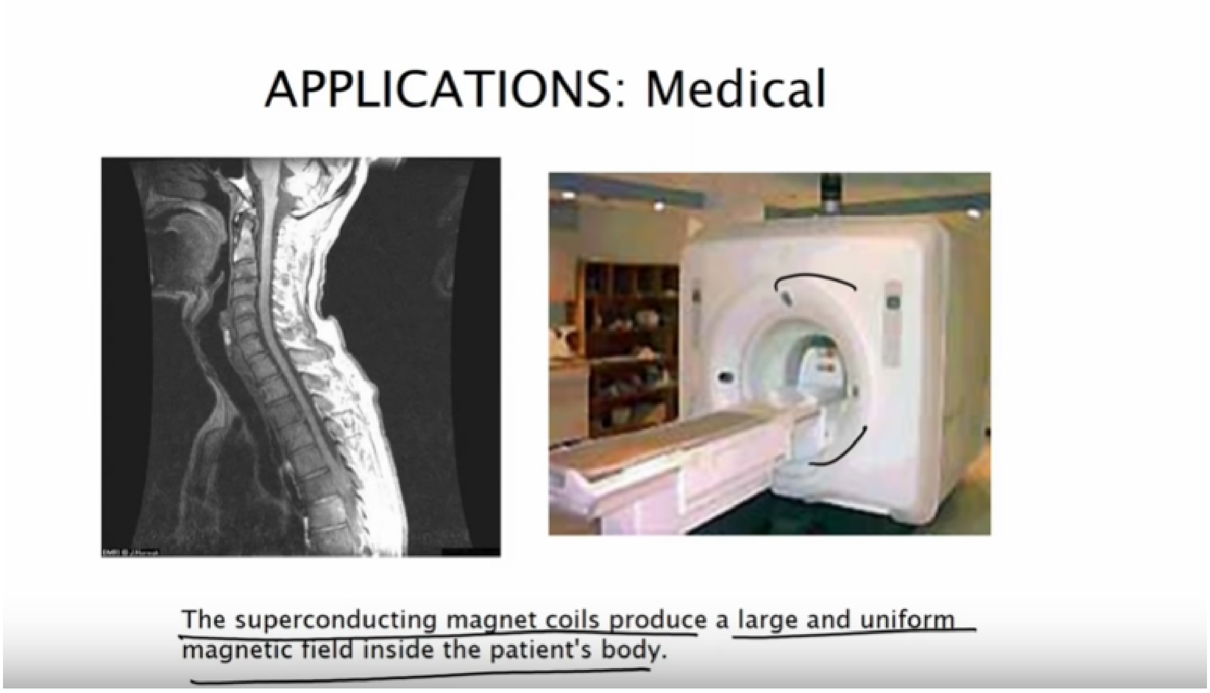
And this is the maglev train which is not yet operational but they are planned to be operational they would reach velocities more than even the bullet trains and the reason, being that they would be levitated and they won't be having any super Canuck or any friction from the rails which usually impede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

Refer slide time :(36:50)



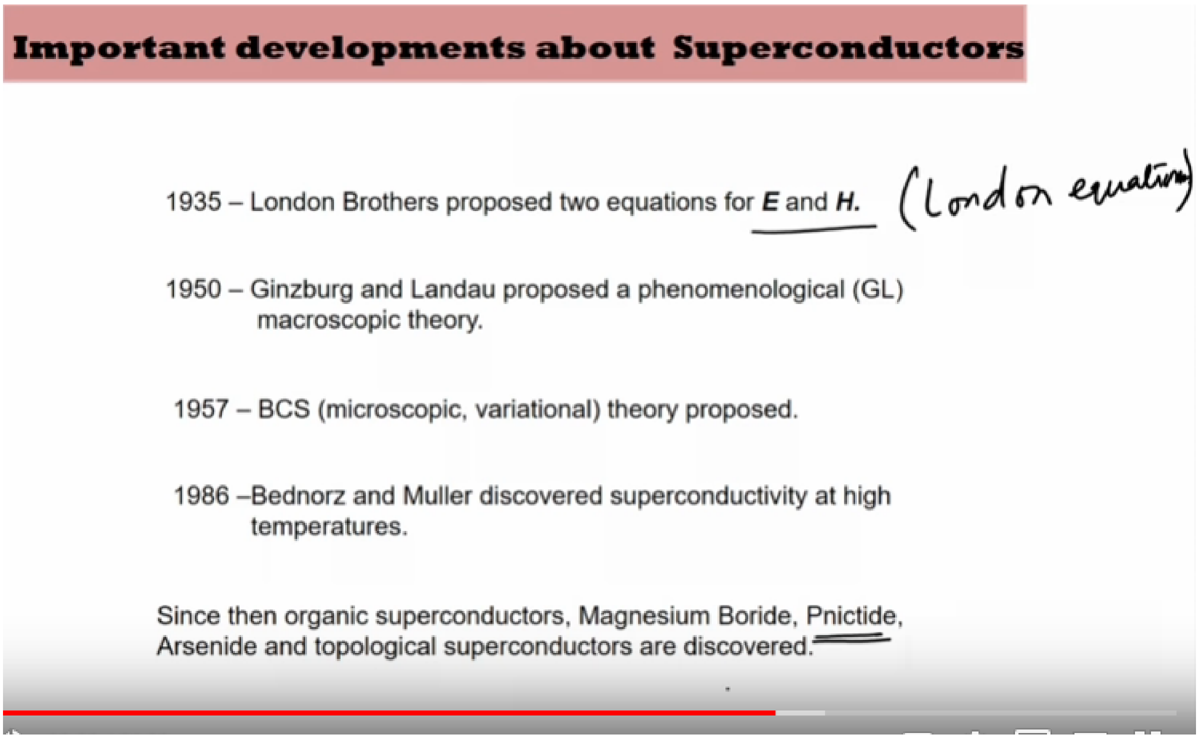
And this is of course some of them are only our futuristic ideas and ambitions that we will have that there are large-scale applications of superconductors which are which can begin to appear like American Superconductor 2g wires. So, there are YBCO that is HM barium copper oxide and why two or three ETM oxide nanoparticles for flux pinning one can have the superconducting power cables such that there are persistent current and you don't have to add sustain the current one 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 tonnes instead of 300 using conventional copper wires and so on. And these are the applications which we can

Refer slide time :(37:47)



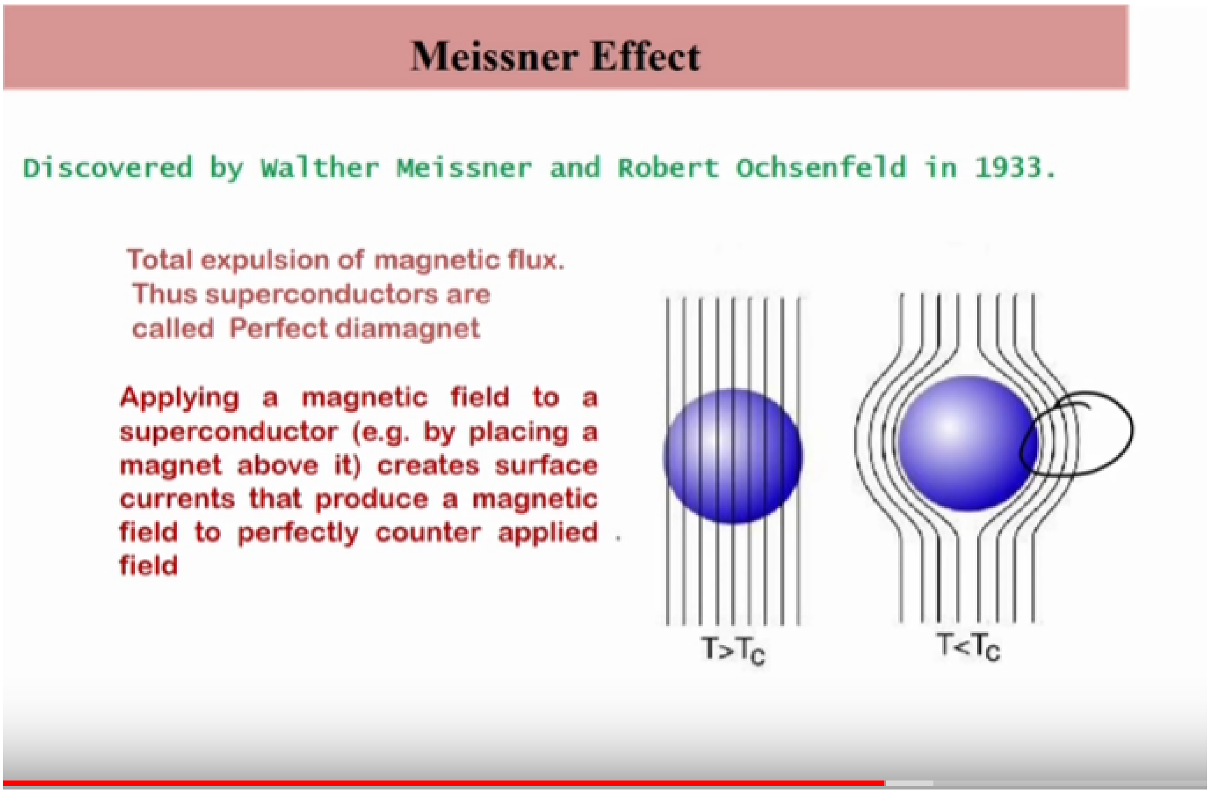
See in the future there are medical applications. So, these are these ones are actually superconducting magnet coils which produce very large uniform magnetic fields that can penetrate through the patient's body and will give information if there is an animal II or there is a pathological defect in the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

Refer slide time :(38:32)



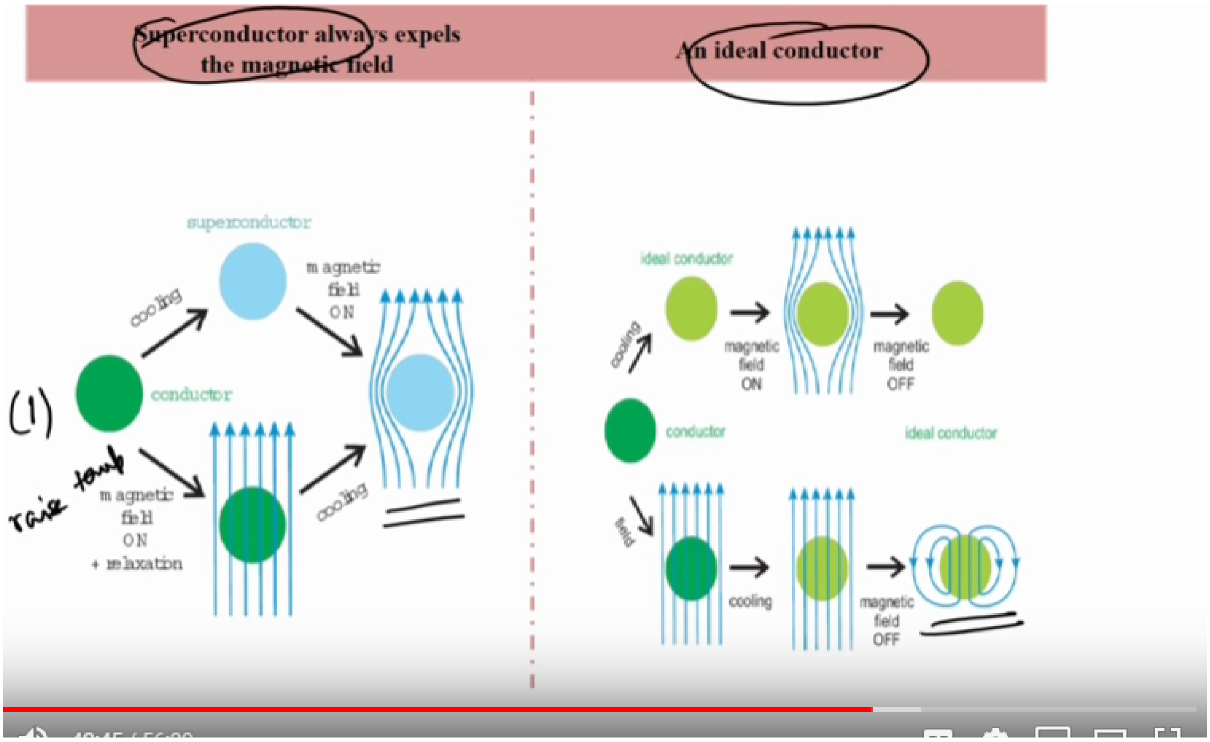
So, to talk about those important developments and some dates etc 1935 a London brothers proposed these equations on ENH and these are called as the London equations 1950 Ginsburg and Landau proposed a phenomenological called as the Ginzburg, Ginzburg landau theory 1957 as a BCS theory microscopic it's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

Refer slide time :(39:33)



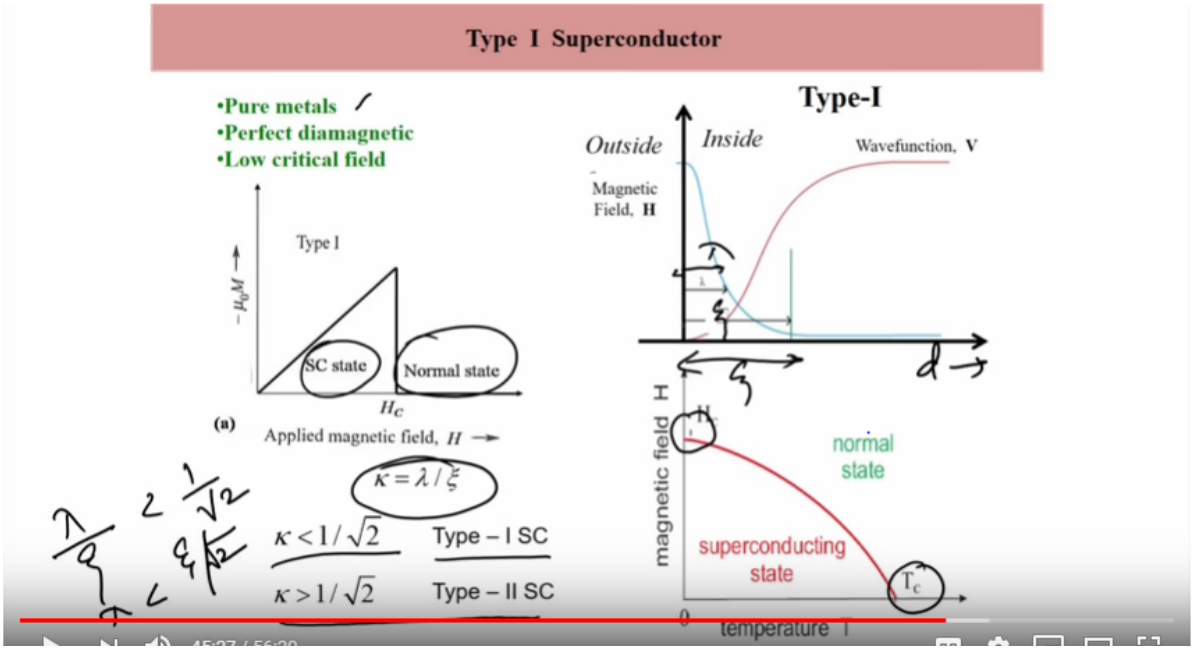
So, pictorially what happens in the Meissner effect will do all these calculations as we go along so, the Meissner effect it was discovered by Walter Meissner and Robert oxygen felt in 1900 and 33 so, this is the total expulsion of the magnetic flux. So, that's why the superconductors are called as the 'perfect diamagnets', 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's 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.

Refer slide time :(40:49)



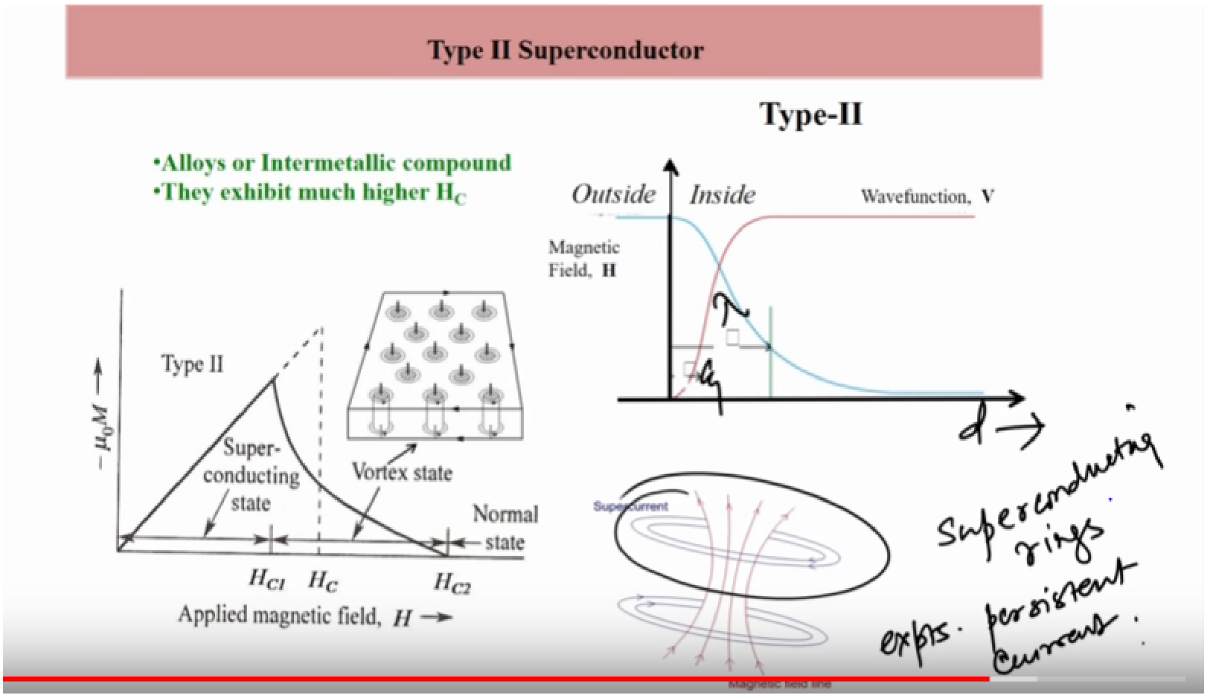
So, let us have a distinction between the perfect conductor and the superconductor. So, this is a superconductor so, it's a superconductor or rather let's start with one so. it's a conductor upon cooling it becomes, a superconductor if you switch on the magnetic field the magnetic fields get expelled and these, 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's an ideal conductor the magnetic field is on so it, 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 will have there 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.

Refer slide time :(42:47)



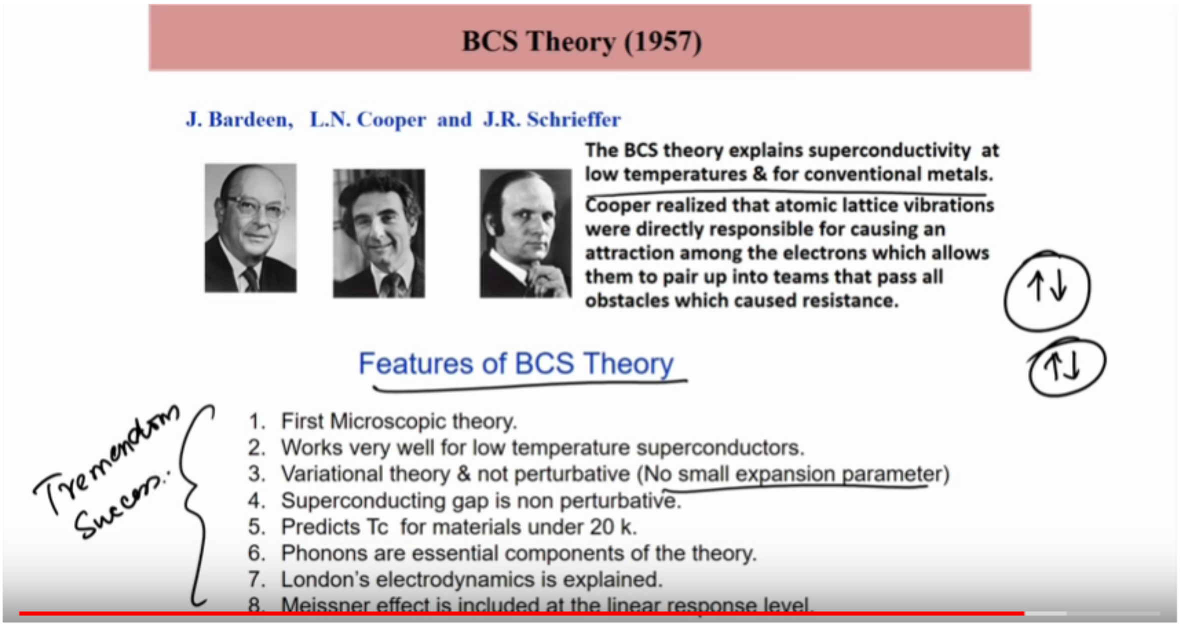
Now there are two kinds of superconductors we have already said type 1 and type 2 superconductors. So, type 1 superconductor is that they are pure metals which is what we have seen in the periodic table they are perfect diamagnets and they have lower critical field. So, the M versus H diagram which is 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 8. So, as we know that if we give magma 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's a normal state here. So, this is another sort of this thing for how the magnetic field falls off inside so this is the distance inside a 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 I this length is called a ZI 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 called as a coherence length. So, one can actually talk about a single quantity Kappa which is a ratio of ZI by lambda by Z 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 superconductors which means that if lambda is less than ZI. So, lambda by Z less than 1 by root 2 which means lambda is lambda is less than ZI over root 2 then we have a type 1 superconductors and if the lambda is greater than ZI over root 2 there's 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. So, there's a TC beyond which superconductivity destroys and there is also a HC beyond which superconductivity destroys.

Refer slide time :(45:31)



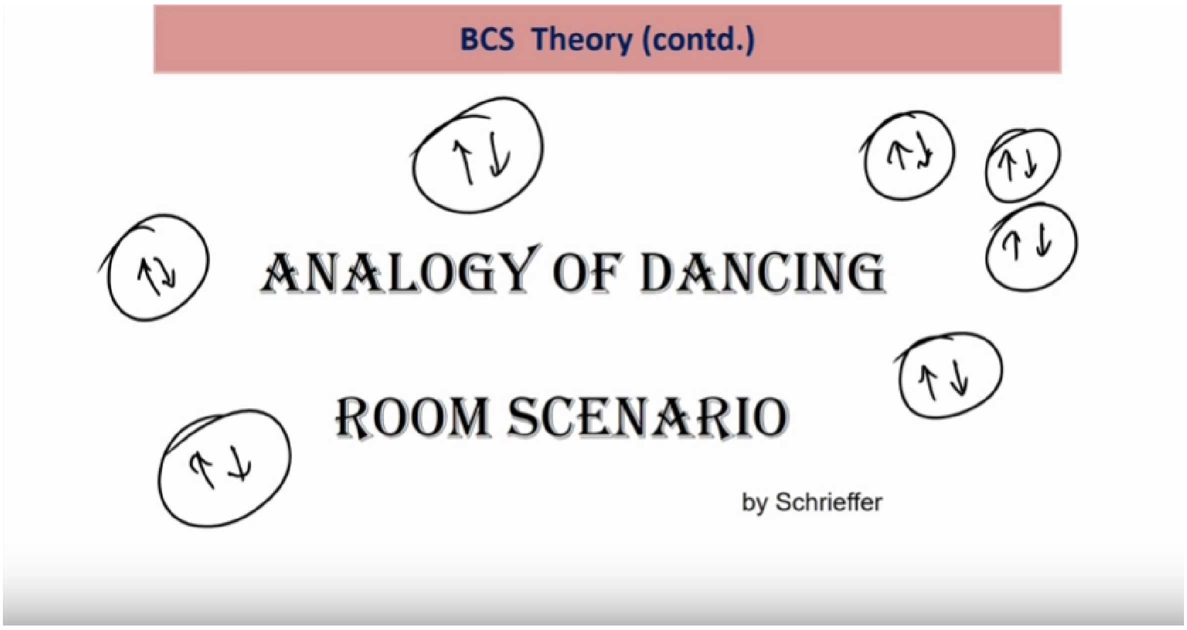
And so, this is a type 2 superconductors it occurs in alloys so, it is a combination of different elements its alloys or inter metallic compounds and they exhibit a much higher TC. So, the phase diagram is not exactly like what we have seen here, here it is dissimilar and there is a linear increase and 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's a normal state. So, what happens is that? The magnetic field can partially penetrate into the sample and beyond that when the Superman the magnetic field is increased beyond the super conductivity is destroyed however the, 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 Abra course of lattice. So, this is the lambda and this is the ZI. And now you see that it penetrates much larger into the superconducting sample. So, this 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's, there's 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.

Refer slide time :(47:56)



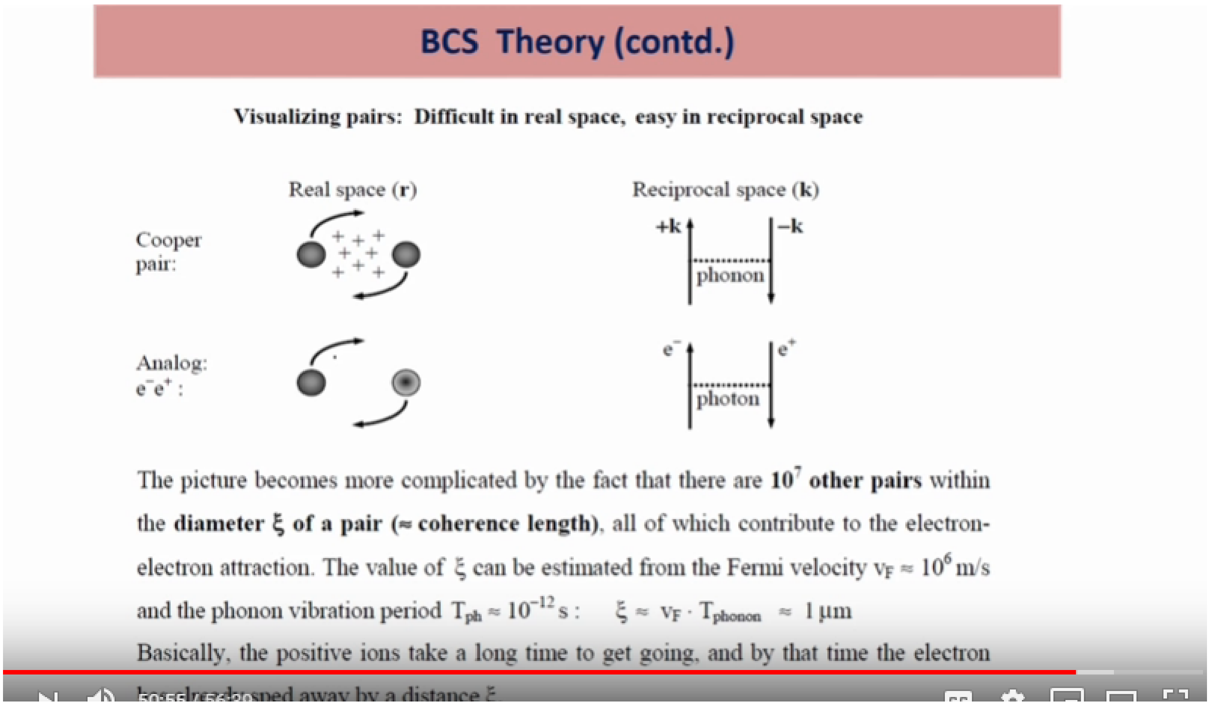
So, finally just small glimpse of what came from Bardeen cooper and Schrieffer. So, these are the photographs of them and this explains superconductivity at low temperature for all conventional metals. And it was started with Cooper's work he realized that the atomic lattice vibrations were directly 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 bear 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, for low temperature superconductors it is variational and non perturbative 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's a tremendous success including all these things.

Refer slide time :(49:55)



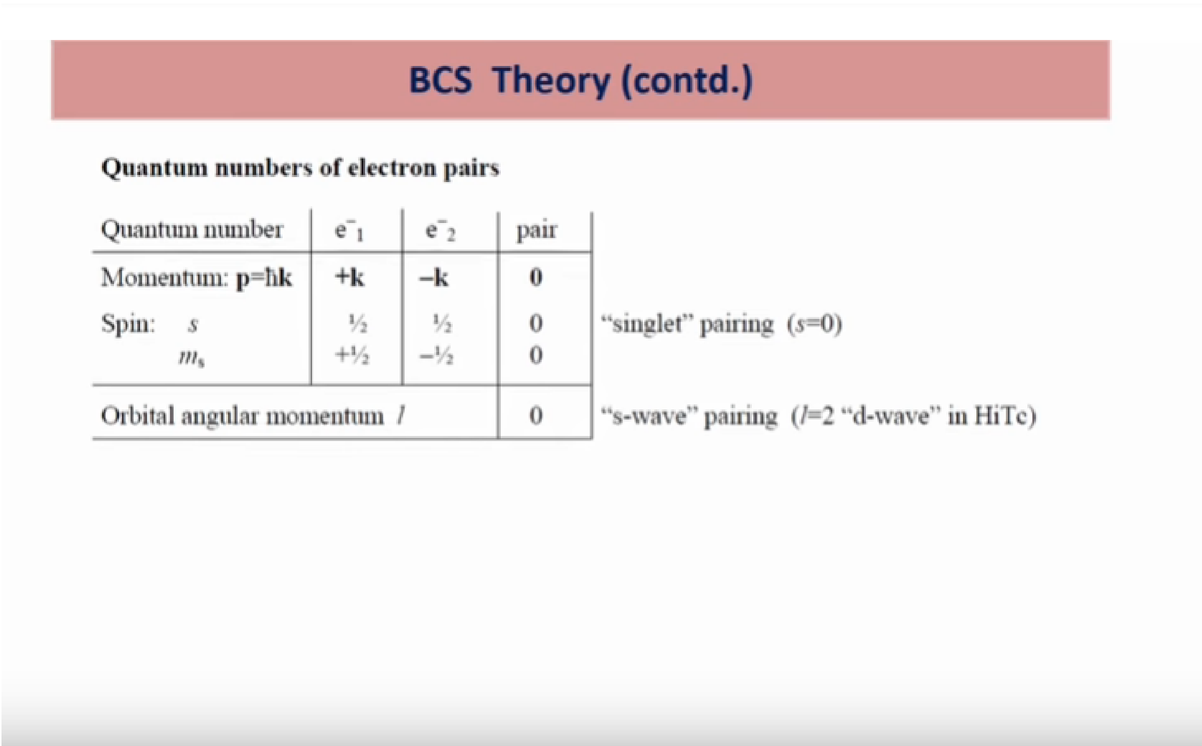
Just to have to make the discussion ongoing discussion a little more interesting there is an analogy of dancing room scenario that was given by Schaefer, that there are these males and female's pairs that are dancing on a dancing floor and they are completely on mindful of another and they keep dancing 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.

Refer slide time :(50:43)



We can talk about this in details later we'll do that but it's just that there are so; these electrons actually can form a pair in presence of phonons that is what is said here.

Refer slide time :(50:55)



We'll come to this

Refer slide time :(51:04)

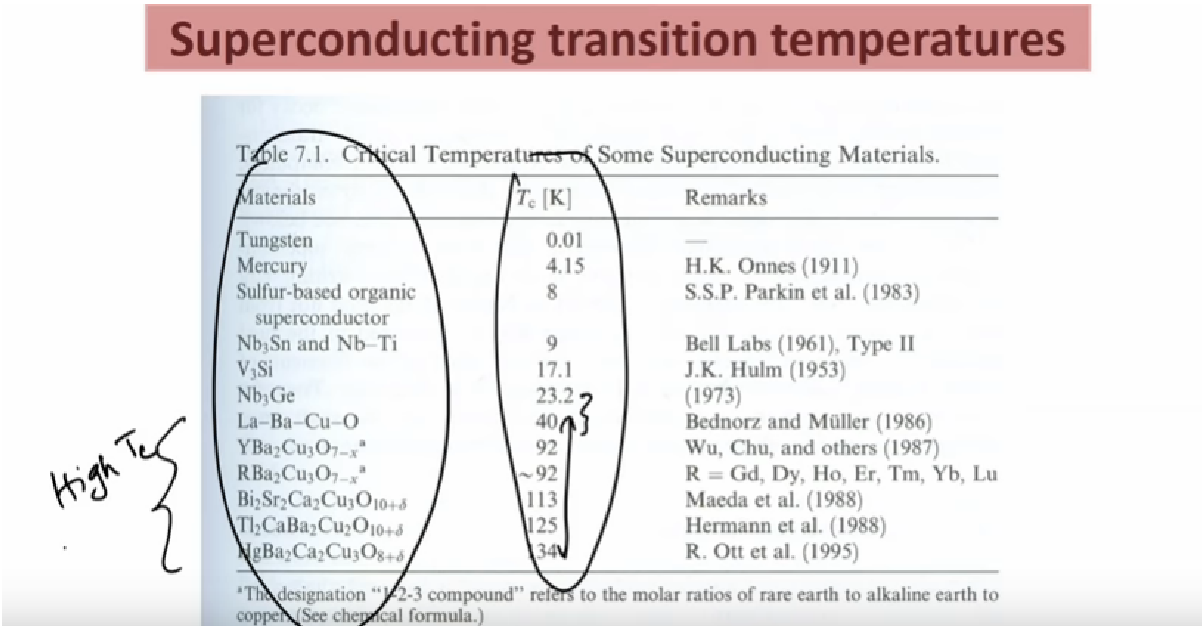


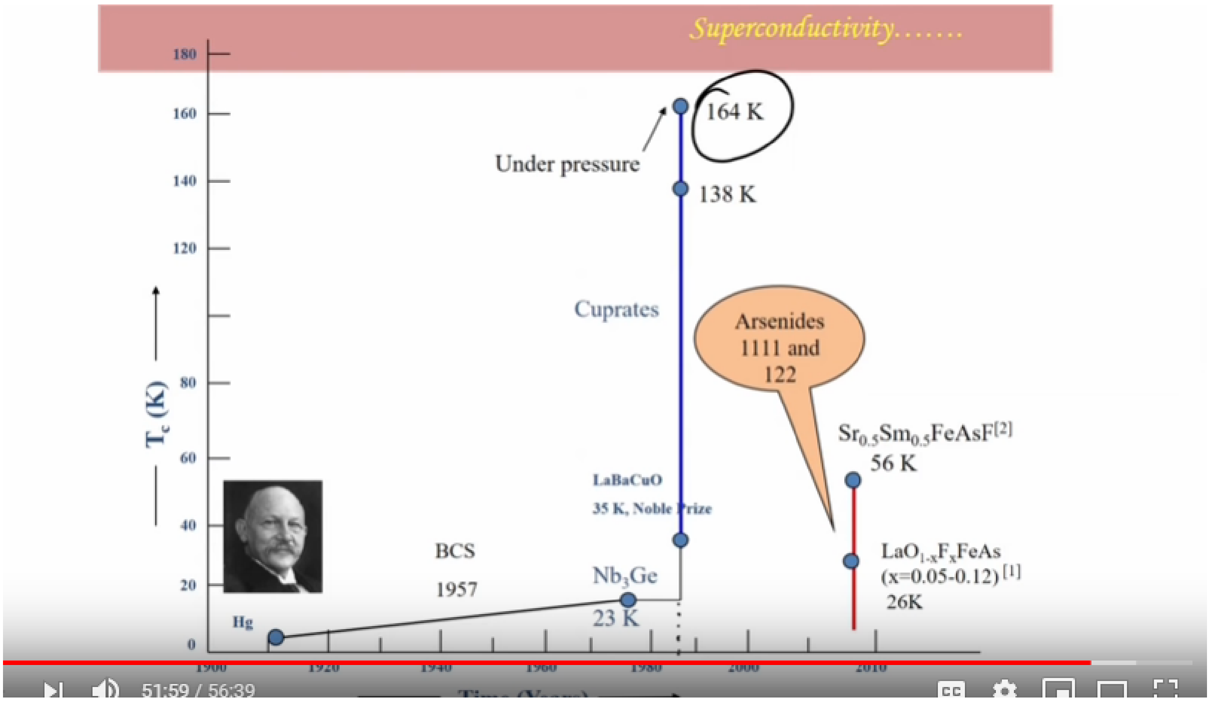
Table 7.1. Critical Temperatures of Some Superconducting Materials.

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.)

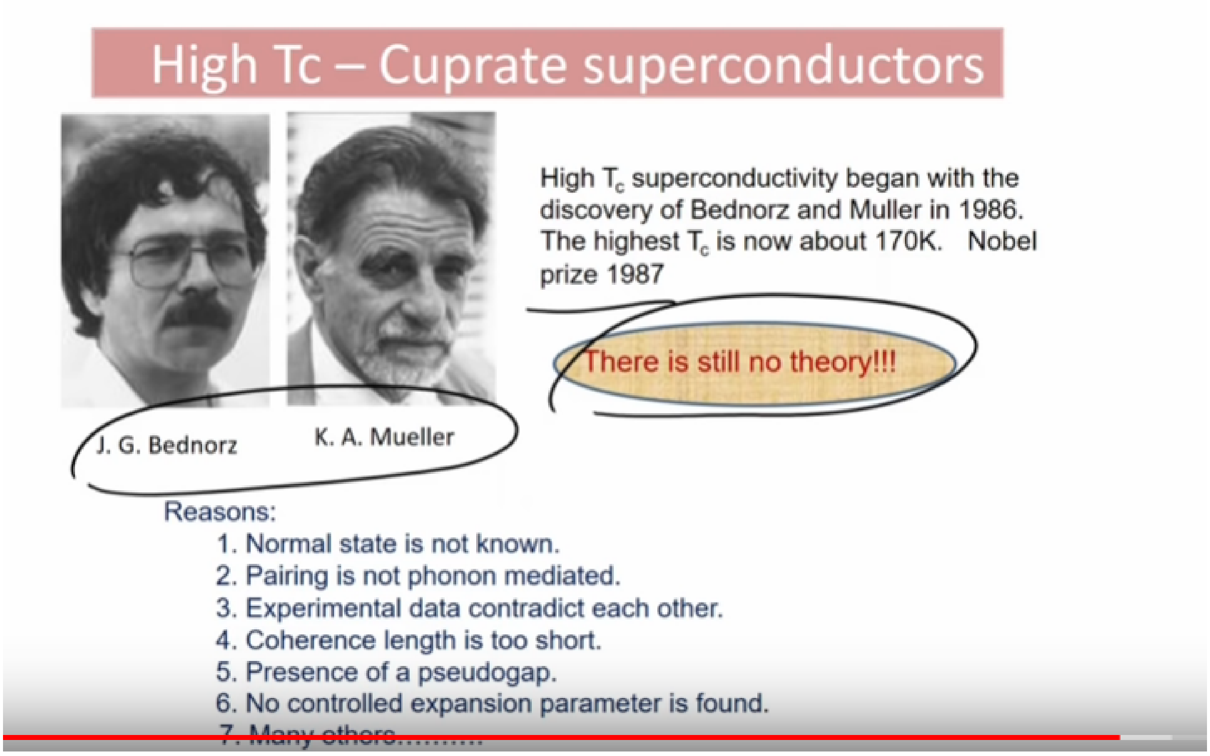
Similarly this one's and these are some of the superconducting transition temperatures that are listed here for materials which are like tungsten mercury sulfur based organic superconductors NB 3 SN and so on. So, you see that suddenly from 23 to 40 there is a large jump and from of 42 92 there are large jumps and so on but this is that these are these high TC. So, high TC superconductors

Refer slide time :(51:38)



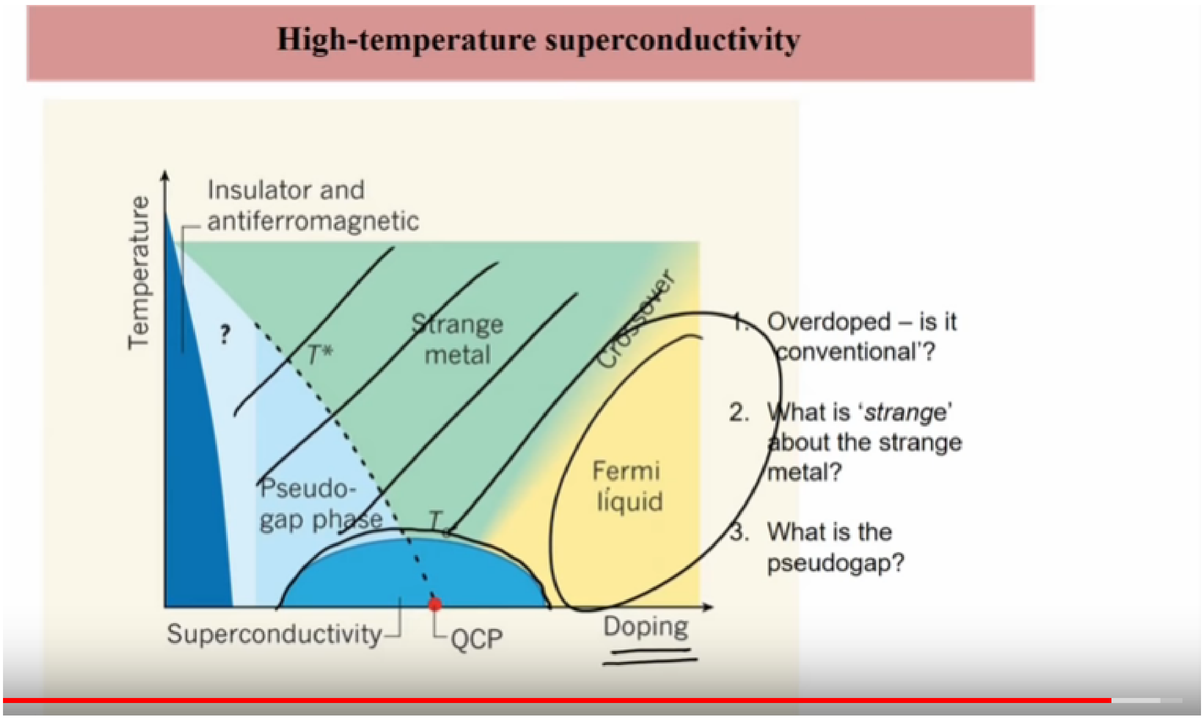
This is how the transition temperature has increased since 1908 it was going fine till about 1986 this is where 1986 is then it's shot up and went all the way up to 164 Kelvin. So, there are you know Arsenal's which are discovered around

Refer slide time :(52:02)



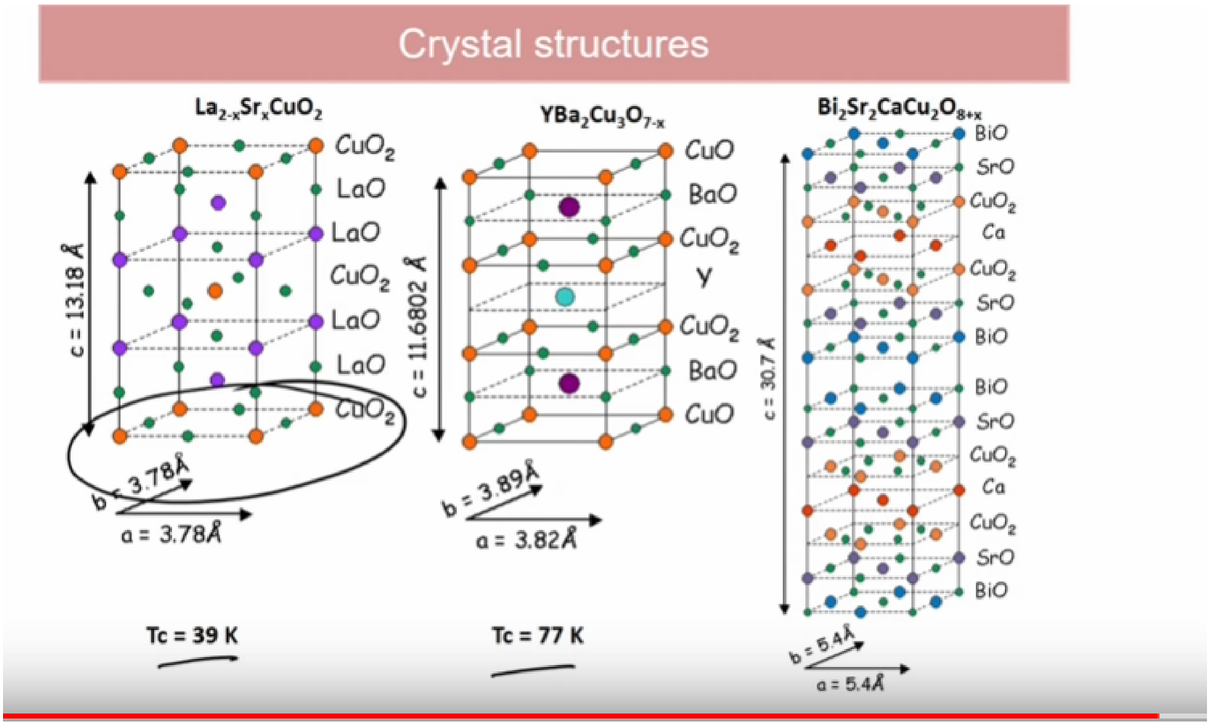
This time these are the people who discovered this Bednorz and Mueller this these high TC superconductors they actually got a Nobel Prize in 1987 and there are still no theory because, of a number of reasons one of them being that the normal state, is not known pairing is not phonon mediated experimental data contradict each other coherence length is too short there is something called a pseudo gap it's like a gap but it violates other properties of an energy gap there's no controlled expansion parameters and many others and that's the reason, that even the best of the minds working in the field have not been able to come up with a general consensus that what the theory.

Refer slide time :(52:51)



That should be there which would explain all experiments 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's 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 areas here would have been like the Fermi liquid we would have already had up here theory.

Refer slide time :(53:38)



These are some layered structures of these high TC 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, Kelvin and 135 Kelvin there's a lanthanum strontium copper oxide this is called 'YBCO', this called LS co this called YBCO this is a hmm barium copper oxide and this is called BISCO it's abysmal strontium calcium copper oxide and so on. So, let us show you some cartoon for this for the levitation and magnetic levitation in lab experiments. And so, this is a superconducting sample that black thing and now there is a coin like thing is kept there it's kept on top of it now the superconducting specimen is just a metal now there 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 it's just floating. This is called as superconducting levitation and it is simply levitating and if you just move it, it still doesn't fall off onto the material. So, this black thing that you see is a superconductor now because, the temperature is lowered and you see there is no trick there so; it's been there's a film has been swiped in order to show that there is nothing there. So, and now it's spinning also it's 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's kept in a kind of open container that 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. So, this is the direct lab demonstration of mice and effect.