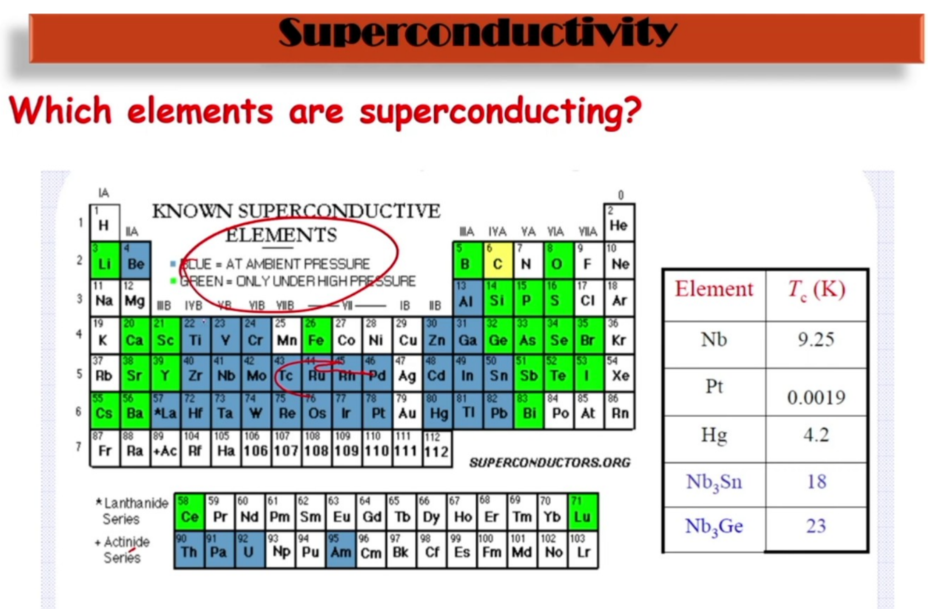
ELEMENTS OF MODERN PHYSICS

Prof. Saurabh Basu
Department of Physics
IIT Guwahati

Lec 27: Superconductivity, Meissner Effect, Type I & II Superconductors

Welcome to this last module on superconductivity. This is the solid-state physics course, which will end after this. And this will be done as briefly as possible and will not have the flexibility or freedom to go very deep into this. But if you are interested in superconductivity, I have another MOOC course which deals only with superconductivity and the BCS theory. In particular, it has been done with some rigor.

So, we are, you know, again presenting you with this periodic table where, you know, there are these materials which are shown here. These materials that are present really here that you see there, so not the ones that are here, but on this top row. And they are either magnets or superconductors. Okay, so the left side is more like superconductors and the right ones are like more like magnets. And of course, there is some superconductivity on the right side as well.



So, this looks like that they exist on the same row, which means that there are a lot of properties that are common and indeed there are properties that are common. So, there are these niobium, which are one of the first, you know, known superconductors, niobium with a TC of less than 10 Kelvin, platinum with very low TC, you know, a fraction of a Kelvin. This mercury which was 4.2 Kelvin and then there were more complicated or rather compound materials or there are combination of different elements which gave rise to superconductivity. The NB3SN and NB3GE were known for quite some time and these TCs that you see 18 and 23, these were the highest known TCs. Till about the mid-1980s, okay.

And there are more; there are other superconductors, and this has been taken from superconductors.org. And so, this Kemerling Owens, who discovered superconductivity, this shortly, you know, after this liquid helium was discovered, And he passed current, so his name is Kemmerlingh Onnes, K. Onnes, passed a current through a very pure mercury wire and measured the resistance as he steadily lowered the temperature. So the temperature of the substance is steadily lowered, and he was... measuring the resistivity of very pure mercury.

So this mercury has been, all kinds of defects, etc., impurities have been removed as far as possible, and it's in a very pure form, and he was measuring this resistivity. And what he found is that there's no resistance below a certain temperature, 4.2 Kelvin, and implying that there's a very good resistance conduction or there is, you know, this name superconductivity arose there itself or thereafter and one gets these extremely good conduction where he saw these thing to go to 0, nearly to 0, 10 to the power minus 5. And the question is that is the resistance really become equal to 0 and it is really because a lower limit of the decay time of current that flows in the system is equal to 10 to the power minus, I mean 10 to the power 5 years. Current that starts in a superconductor will go on for 10 to the power 5 years.

So it is that kind of precision we are talking about in terms of defining the resistivity to be equal to 0. So, what can kill superconductivity, or what are the agencies that can kill superconductivity? Of course, you know, you need to provide enough energy for all the pairs that cause superconductivity. We will come to that. All pairs within some coherence length.

Superconductivity

What kills superconductivity?

Need to provide enough energy to break up *all* pairs within a coherence length:

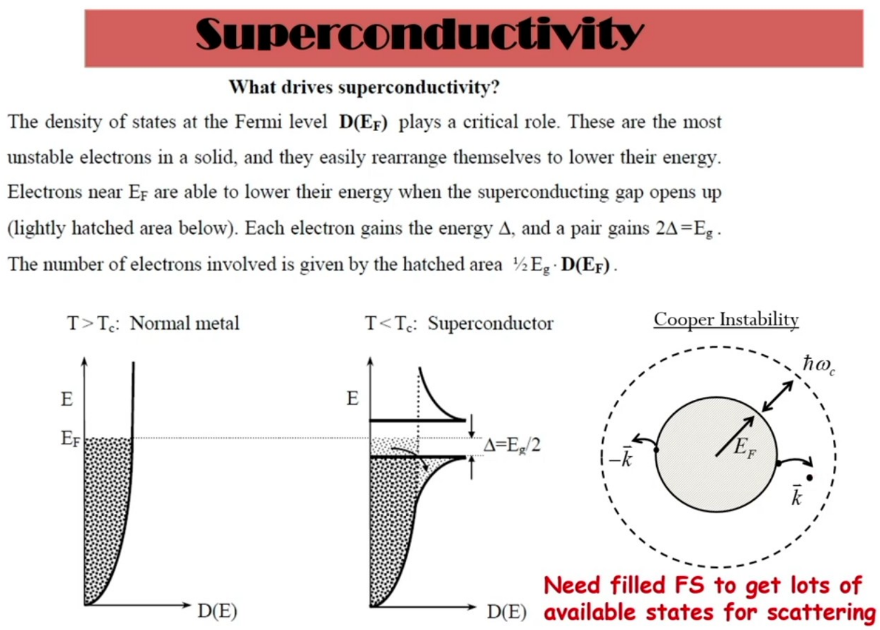
1. Thermal energy: → Critical temperature $\mathbf{T_c}$
2. Kinetic energy: → Critical current density $\mathbf{J_c}$
3. Magnetic energy: → Critical field $\mathbf{H_c}$

So the pair should be broken, and the superconducting state should be lost. It can be done using thermal energy, which is—there's a critical temperature TC—or you can actually give current in the system, pass a current in the system. If the current exceeds some critical current density JC, then also superconductivity will be destroyed. Or the superconductivity can also be destroyed by using a critical magnetic field Hc. So, what is superconductivity?

What happens in a superconductor? How does a superconductor form? What is the microscopic picture, and so on and so forth? So, we start from this right picture, as you see there. So, there is an inner circle which is slightly shaded or striped.

That is the filled Fermi sphere. So, the filled Fermi sphere, we have these two electrons. Now we are showing it in k-space. So, they correspond to the two momenta having this momentum k and minus k. That is why they are shown on opposite sides. they just go out of this and remain in the vicinity of these, you know, this Fermi sphere.

And if that happens, then if they sort of stay within a distance h cross omega d, where omega d is a Debye frequency, then such a thing, the pairing of these electrons can be formed. And we just talking about two electrons and we can talk about two more electrons independent of these two electrons and two more and so on. So if you have n such electrons there and n by two pairs are formed, then it will result in a superconducting state. So we crucially need a filled Fermi surface, and we should have a lot of available space for scattering or states for scattering. Okay, so this is a metal T greater than TC and we have, you know, so these all these in metals, the electrons are filled all the way up to the Fermi energy and in a superconductor as you lower the temperature, what happens is that A sort of gap is created—an energy gap is created at the Fermi level, okay?



And the density of states gets slightly modified there, and these electrons, which were earlier there, sort of occupy this state, okay? Now, if you switch on certain kind of interaction or rather, you know, certain kind of attractive interaction, normally attractive interactions do not occur between electrons. Electrons are known to give rise to repulsive interactions because they have the same charge. So, the Coulomb interaction between them is positive and will not give rise to superconductivity.

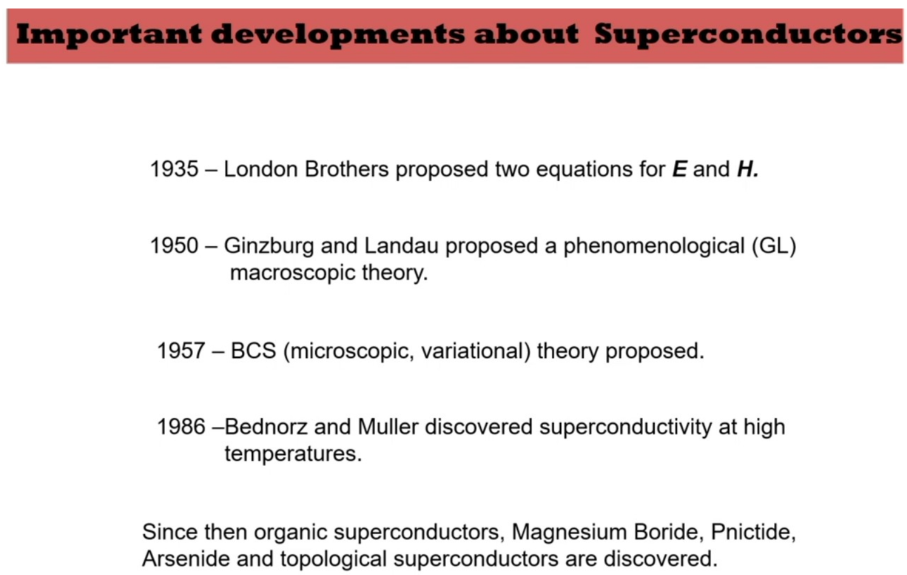
But there is another agency—or sort of a third party—which plays an important role in pairing. And this third party is nothing but the lattice or the phonons. So, let us see what is written here. So, the density of states at the Fermi level—we can denote it by dEF— It plays a crucial role.

These are the most unstable electrons in a solid. The ones that are, you know, here are the most unstable electrons. The ones that are here showing. So, laser pointer. Yeah.

So these are the most unstable electrons. And these electrons would want to sort of be easily rearrange themselves to lower their energies. And so the electrons near the Fermi level are able to lower their energy when the superconducting gap opens up. That is this area that you see here. That is this area here.

Each electron gains this energy delta, and a pair gains this energy 2 delta. And the number of electrons that are involved is proportional to this hatched area, which is something like half Eg into density of states at the Fermi level. Okay. So what is important is that you should have a filled Fermi level, and then certain mechanisms can create these attractive or induce this attractive interaction, which will cause superconductivity. Let us see some development of superconductors.

In 1935, the London brothers proposed two equations, which are known as the London equations. They are very important in the study of the electrodynamics of superconductors. In 1950, Ginzburg and Landau, two Russian physicists, proposed a phenomenological macroscopic theory. These are called the GL theory.



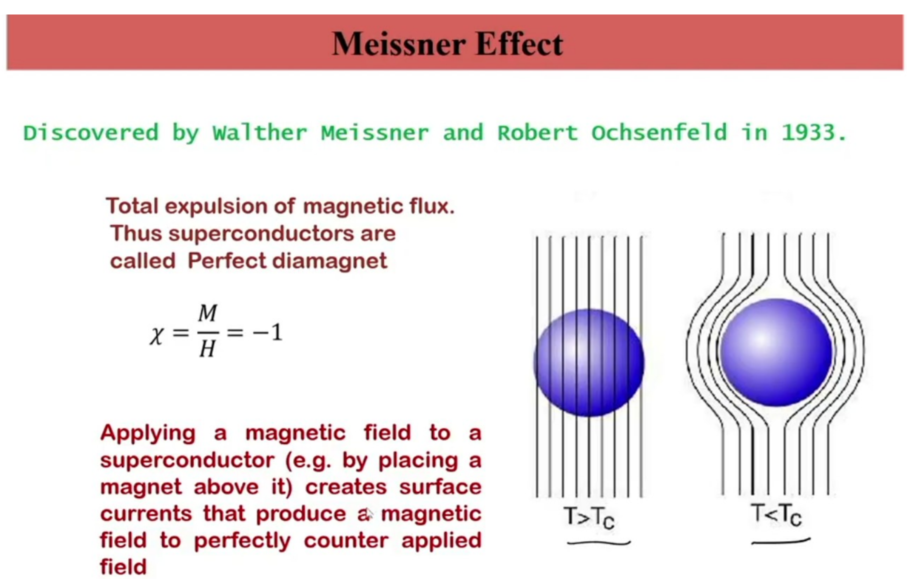
In 1957, the BCS theory, which is a microscopic and variational theory, was proposed. In 1986, there were Bednorz and Müller. They discovered superconductivity at very high temperatures, and these are called cuprate superconductors. And since then, there are a large number of superconductors that are discovered, organic superconductors, magnesium boride, niktide, arsenide, several topological superconductors, they are discovered. Superconductivity has always been at the forefront of research.

Because it has shown many surprises. Some of them were understood using microscopic theory. Some of them could not be explained using microscopic theory. And we had to be contended with whatever application they had to offer. And each time there is a discovery of a new superconductor, there is a surge in the research interest from all across the world, where people either want to recreate or reproduce that superconductor, fabricate that superconductor, or want to find out whether the theory aligns with the well-known BCS theory, or there is something more that is required.

And that's why it's always at the helm of affairs in terms of research. One of the main effects of superconductors, this was discovered by Meissner and Ochsenfeld in 1933, and it's called as Meissner effect or it's also called as Meissner-Ochsenfeld effect. And what it says is that if at T greater than TC, you have these flux to be penetrating through the sample. If you lower the temperature below TC and it becomes superconducting, then the flux will be pushed out. So you'll have a large flux density in the sample.

near vicinity of these superconductors. And that's why these superconductors are known as perfect diamagnets. And what is meant by perfect diamagnets is that their susceptibility is nearly equal to 1. Even for the best known, the ones that are known in solid state physics, diamagnetic susceptibility is 1. is weakly, you know, diamagnetic.

These, all of them are accepting the superconductors. So they have susceptibility of the order of 10 to the power minus 4, 10 to the power minus 3, and so on. So if you apply a magnetic field to a superconductor or by placing a magnet above it, it creates surface current and this surface current will produce a magnetic field to expel the magnetic applied field from inside the specimen. This is called as a Meissner effect as we told. Let me show a small animation again downloaded from the Internet.

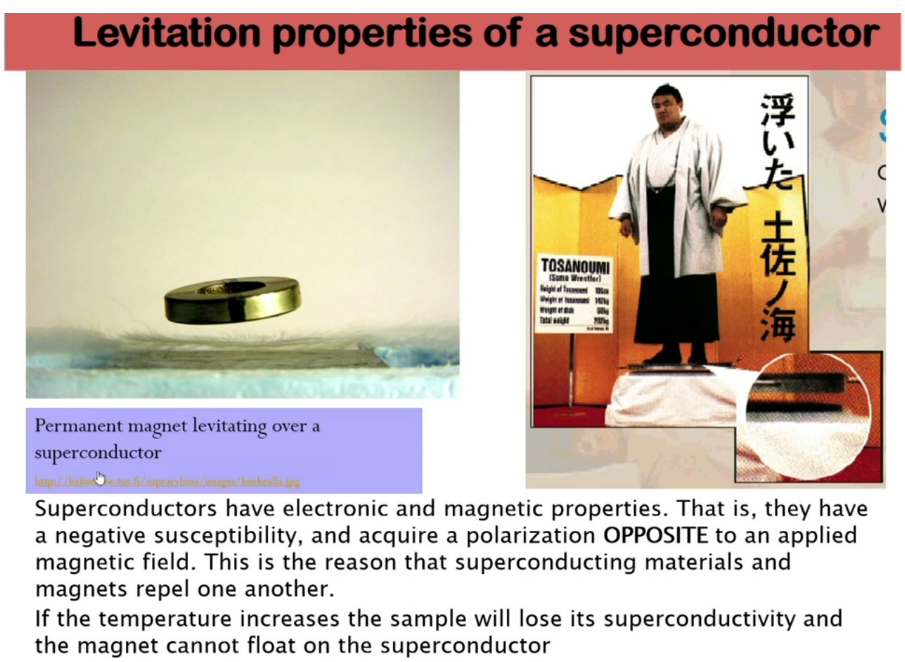


And it's a magnetic levitation experiment. And you see that there is a black superconductor. In fact, this is also a problem because it's a high-temperature superconductor. It becomes superconducting at liquid nitrogen temperature. Nothing happens when it is just a metal.

And this is a problem that is black because if it's shiny, then probably the theory would have been better understood. And shiny means it's metallic. And because it's dull and black, it's probably not metallic. And that's where it creates a problem. We'll just give a small, you know, illustration of that.

Now you see that there is an object which is put on the on the superconductor and it's not collapsing down under gravity. It's been, you know, been pushed by the superconductor and further demonstration that there is nothing inside. It is nicely floated or floating there and even if you give it a spin, nothing happens. If you try to put it close to that, it gets repelled.

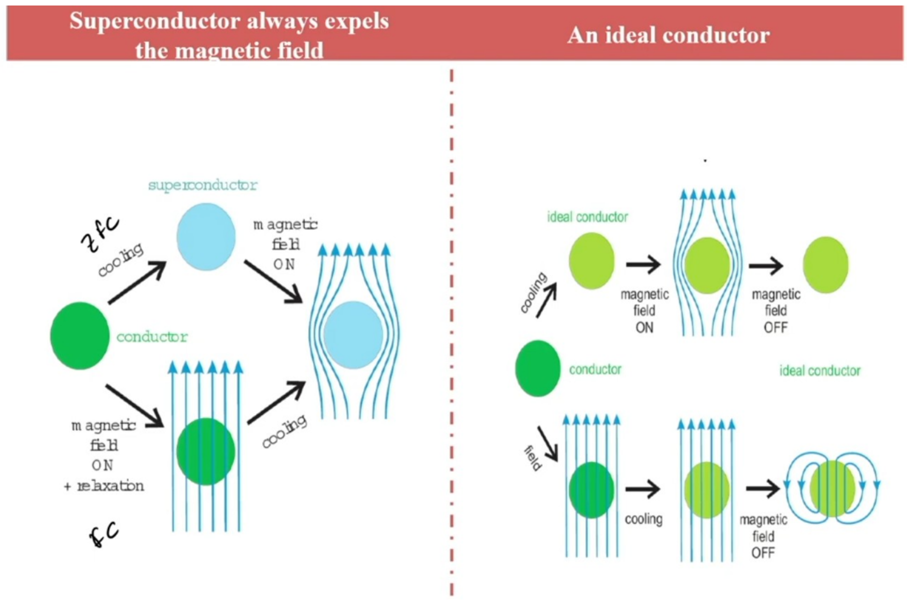
And that you can actually use it to sort of lift this superconductor and that means that it is actually capable of doing some or lifting some weight you see that weight is being lifted. And once the superconductivity is destroyed, then of course it collapses then onto the superconductor. I mean, which was earlier a superconductor at a lower temperature. Now you see that superconductivity is gone because the temperature is basically increasing. Okay, so let us see this levitation experiment we have shown.



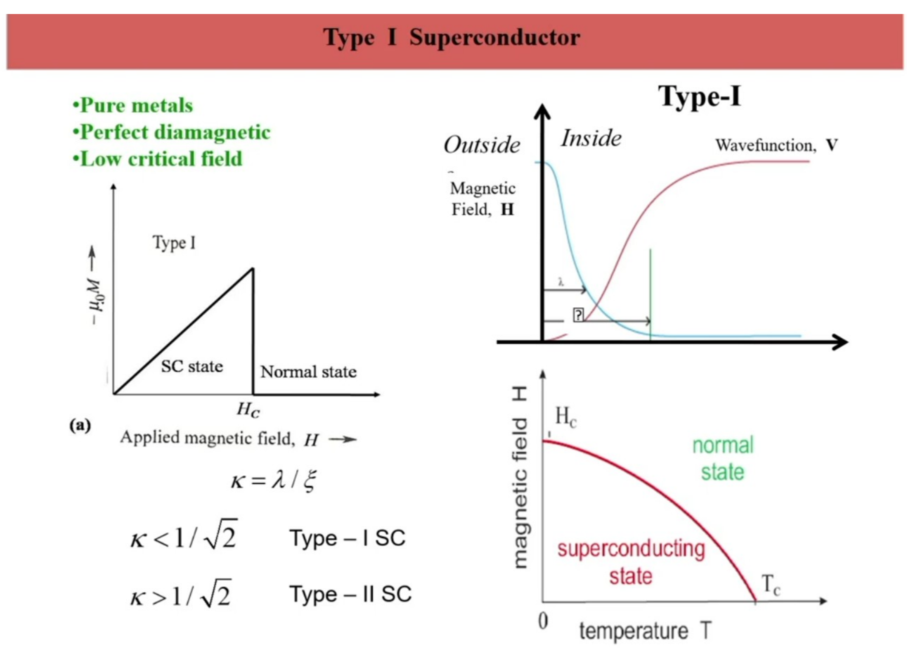
And if you want to know how much of weight it can actually lift, you see this thing that there is a sumo wrestler which is standing on top of this thing and there is a superconductor below. So it can actually lift very large weights. That is what it is saying. So superconductors have electronic and magnetic properties, that is they have a negative susceptibility which is what we have seen, acquire a polarization opposite to an applied magnetic field and this is the reason that superconducting materials and magnets they repel each other. When the temperature increases, the superconductivity is lost, and we have seen that these are different agencies that can kill superconductivity.

Basically, these pairs that are formed are broken because of this additional energy coming from either the heat or from a current or from a magnetic field. How can you distinguish between perfect conductor and ideal conductor from a superconductor? So, on the left, we see an experiment for a superconductor. So, this is called as the ZFC, which is a zero field cooled and this is called as a field cooled, okay, so FC. So if you take a superconductor and cool it, simply cool it, becomes a superconductor, then you put a magnetic field, it gets expelled.

If you do it under the field-cooled condition, that is, put in a field and then cool it, the result is the same. It gives you the same, these superconductors at the end, which means that irrespective of whether you take a ZFC or a FC, you get this picture that is the magnetic field is pushed outside. This is called as a Meissner effect. So, what we are trying to come to is that the ideal conductors or good conductors do not show Meissner effect whereas superconductors do. So for an ideal conductor, if you do a ZFC, that is a zero field cool, it becomes an ideal conductor.



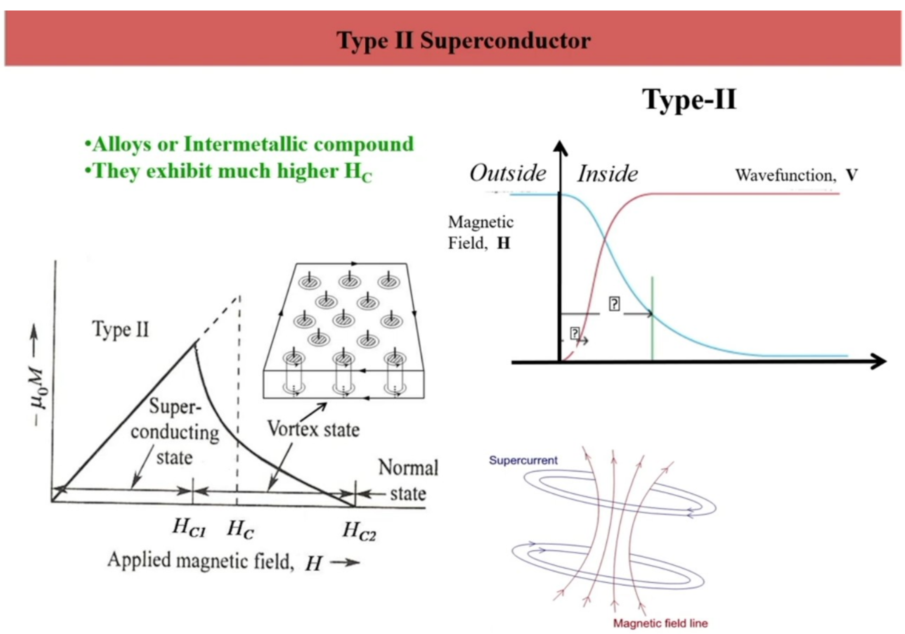
If you put a magnetic field, these flux lines are still expelled. If you put the magnetic field off, it just goes on to the conductor that we have started with. Now, if you do in a field cool, so this is in, first you put it in a field and then you cool and you withdraw the field, you have these, you know, the flux lines are trapped inside. And this is the hallmark difference between a superconductor and a perfect conductor. So if one actually has discovered a superconductor, one of the main experiments that establishes superconductivity being there is the Meissner effect.



There are, you know, type one and type two superconductors and so on. So this type one superconductors, these are the M versus or minus M versus H. So you see that there is a superconducting state sharply, you know, sort of. designating from a normal state at a given HC. These are called A type 1 superconductors. And there, you know, the magnetic field versus temperature dependence is pretty much what we have shown for the magnets.

And outside it's normal metal and inside these region there is a superconducting state. And these are some of these things which are, you know, how magnetic field actually enters into the specimen. And magnetic field does not enter into the specimen. It just sort of falls within this lambda called as a penetration depth. And the wave function actually is, you know, it kind of builds up and becomes a coherent wave function inside a superconductor.

Type II superconductors are more interesting and they are more common in nature. It has, you know, a sort of HC1 where the superconducting state actually sort of persists from between HC1 and HC2 if you see the triangular region there. So this dotted line is basically the type I superconductor whereas the type II superconductor bends down and continues to a different direction. HC2, a larger HC2 and from there of course it is a metallic state. And one gets a vortex-like state where the flux is actually trapped inside in the form of a vortex in this regime, in this regime where, you know, beyond the HC1.



So, this is again minus M shown as a function of field. And again, we show that how H actually varies inside a metal. It has slightly larger penetration depth. And the penetration depth, you know, by xi, that is xi is the coherence length, which is the size of the Cooper pair wave function. And lambda is the penetration depth, that is how much of depth it can penetrate inside a sample.

So, this K is equal to this kappa, which is a dimensionless quantity—the ratio of lambda by xi. This lambda by xi is small or less than 1 by root 2 for type 1 superconductors, and for type 2 superconductors, it is greater than 1 over root 2, okay. And coming to the BCS theory, this was proposed in 1957 by three people: John Bardeen, Leo Cooper, and J.R. Schrieffer. And it explains superconductivity at low temperatures and for conventional metals. And Cooper realized that the atomic lattice vibrations—that is, phonons—are actually responsible for

causing an attraction between the electrons, which allows them to pair up into pairs or teams that pass all obstacles and which cause this resistance-less—or, I mean, there is no resistance basically—that is, no resistance because of this pair. So the picture becomes something similar to this: there were electrons earlier, and because of the lattice playing a role somehow, these individual electrons form a bound pair. Once they form a bound pair, they become non-interacting and do not see one another. And they, if you put on a small voltage or a bias, then the current will keep flowing and this current will, there will be, it is going to be a persistent current with no decay of that current in a very long time.

And Cooper really understood that there is some way these lattice vibrations play a role. And possibly, the way he got this idea is from the isotope effect. And if there is an option or rather opportunity, I'll explain what is isotope effect. And so, basically, you know, these phonon frequencies have the mass of the ions in the denominator as 1 by the square root of m. Remember the lattice vibrations that we have done. And the TC also has some behavior which is 1 by root over m or inverse of this m to the power half.

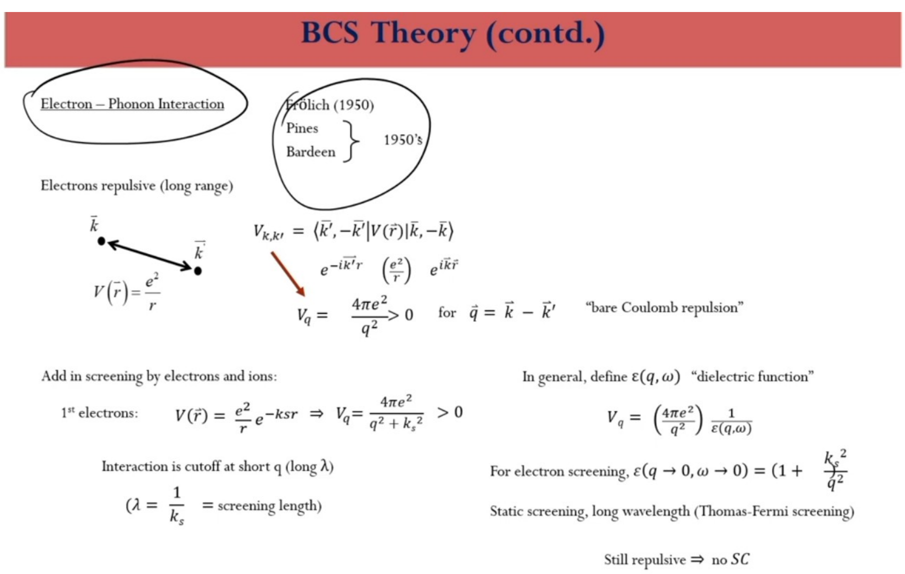
So that way, he might have inferred, and then, of course, his intuition was correct. And it gave rise to this BCS theory, where there is a first microscopic theory, and it works very well for low-temperature superconductors. It is a variational theory, it is not perturbative, there is no small expansion parameter. Superconducting gap is non-perturbative which means that by doing any order of perturbation theory you cannot solve this superconductivity problem. Just like magnets, we have solved magnets or at least paramagnets and diamagnets using this perturbation theory.

Here, it is not possible. It predicts Tc, which is typically under 20 Kelvin or around 20 Kelvin at most. Phonons are important, as we have said. It explains London's electrodynamics, the Meissner effect, etc. Everything is explained using this BCS theory.

This is the BCS paper. You see that it's from 1957. And so it's here. That's the date of this. It's published in Physical Review.

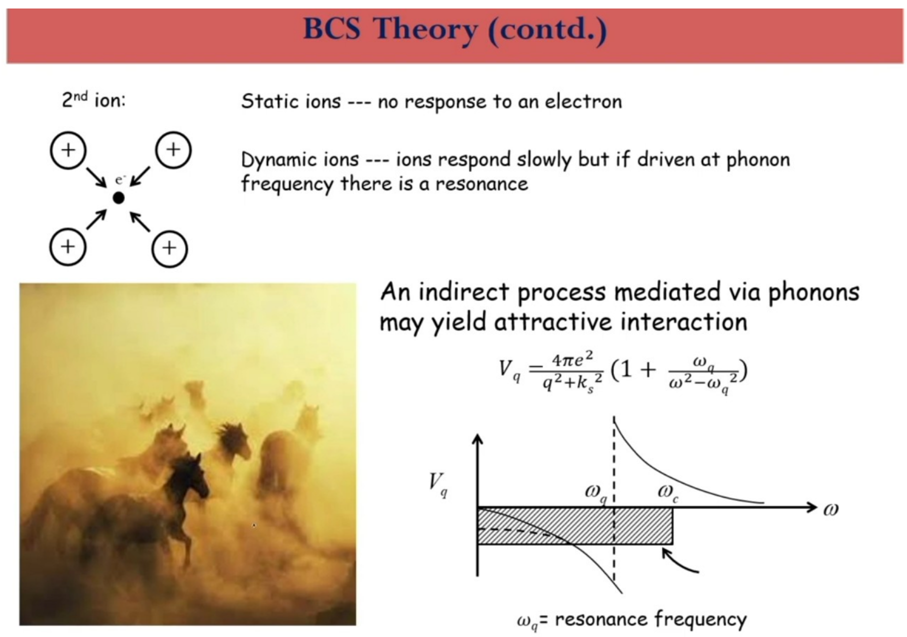
So Schiffer, one of the recipients of the Nobel Prize for the discovery of BCS theory, actually visualized this as a dancing room scenario. So you see that the pairs are dancing. This has been taken from the Internet. So these pairs are dancing, and they are dancing in a manner that they are completely oblivious of each other. So they keep dancing and not knowing the presence of another pair in the room.

So that's a dancing room scenario. And these pairs are like the Cooper pairs. So the Cooper pairs, when they conduct supercurrent, they do not undergo any collision with other Cooper pairs. And that's why it's a dissipationless current. Just a little bit of BCS theory, so it is because of electron-phonon interaction and which Frohlich and Pines and Bardin, they have discussed in or rather discovered it in 1950s.



And if you take these electron-electron interaction via a bare Coulomb term, which is, this is the Coulomb term in K-space, That does not give rise to any attractive interaction. But if you add screening by electrons due to ions, we will show you a picture of that. You get some Vq which becomes in the momentum space is like 4 pi square by q square plus K square. Well, lambda is 1 over Ks, and q is, you know, the running sort of the total momentum of the two pairs.

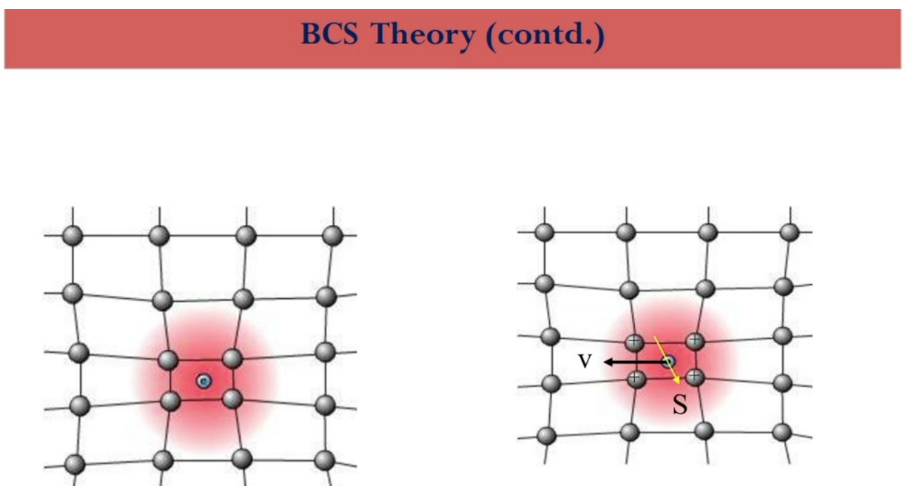
And so this is, you know, kind of important in this discussion, in the initial discussion. We are still in the repulsive regime. There is no superconductivity here. And if you consider an indirect process mediated by phonons, so that's between the electrons, I do not go into details. Once again, I refer to this course on superconductivity where I discuss the origin of this attractive interaction.



So, what happens is that one electron when it passes through the lattice, it sort of looks like these horses running in dusty fields. So, you do not see the horses, but you see some kind of ball of dust kind of moving ahead or moving farther. So, this electron, one electron going through the lattice picks up a lot of positive charge just like this dust. And another electron seeing this, you know, ball of positive charge gets attracted towards it. And that gives rise to a potential which gives us this 1 plus omega q by omega squared minus q omega q squared.

Well, omega is the, you know, the total energy of the two electrons and omega q is the energy of the phonon. And there, you know, if you have omega squared to be less than omega q squared, this term can be negative. And it somehow, if it becomes, you know, greater than 1, there's a negative term in magnitude over sort of shoots these plus 1. Then you'll have a negative sign, effective negative sign arising in this equation. And that will give rise to superconductivity.

schematic picture is shown, you have in this kind of region, we have this superconductivity, you know, in the VQ versus omega region. So, if you really think about it, it is like, you know, a sort of a region formed where there is a small attractive region region which is formed here and this is V as a function of omega and these attractive region will give rise to the superconductivity and that will of course be possible as the temperature is low. So this is a schematic representation of what I said is that the first electron actually polarizes the lattice. So the red dish region that you see is actually like a positive charge.

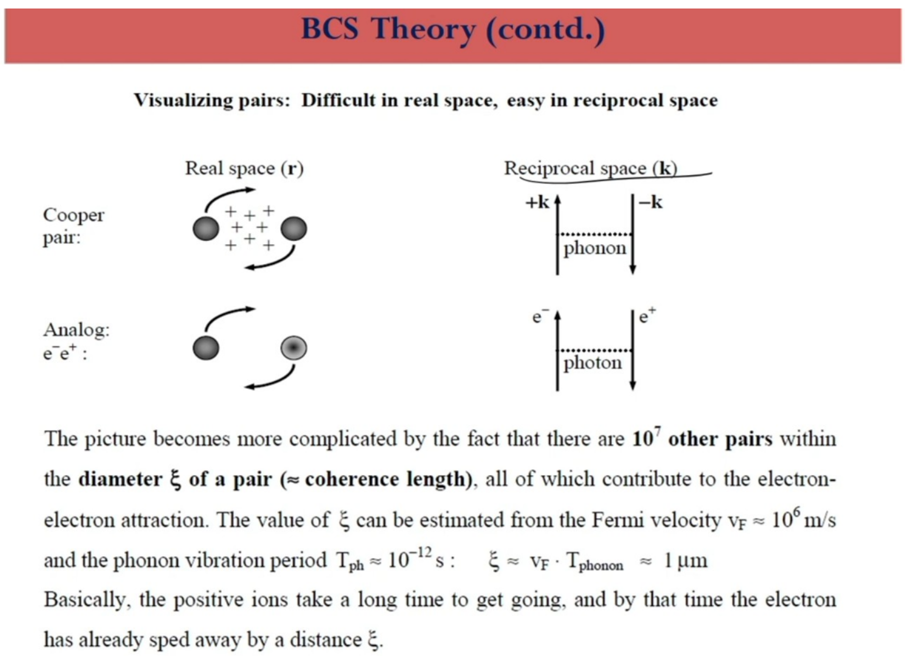


First electron polarizes the lattice

Second electron is attracted to the concentration of positive charges left behind by the first electron

Another electron is attracted towards this concentration of the positive charge left behind by the first electron. You could ask this question that why doesn't the first electron see the cloud due to the second electron? Now this cloud is basically a quasi-particle, which is like a dressed particle, like that dusty horse, and that has much smaller velocity. So if this positive charge has to see another positive charge, the time scale is much larger for that to happen, because these are slowly moving objects, because these are just polarization, you know, created by the electron. So in real space, we have these two electrons forming a pair which is analogous to this electron positron pair in nuclear physics or high energy physics.

So but in it's easier to visualize in real space or other reciprocal space. where there are these plus K and minus K mediated by phonons, they form a bound pair, and in the positron-electron-positron pair, that's by an electromagnetic radiation or a photon. So the picture, of course, become very complicated because you have several others, billion, 10 billion and so on. Other pairs within a diameter, which is xi, called as a coherence length, that is basically the extent of the wave function of this pair, of this Cooper pair. And all of these, all of these 10 to the power 7 pairs will contribute to the electron-electron interaction.



And the value of psi, which we can estimate from this Fermi velocity, etc., to be equal to about 1 micrometer. Because, you know, the positive ions take a long time to get going since these are massive objects. By the time the electron has already sped away by a distance which is beyond that coherence length. So, that is why, you know, this hand-waving, of course, is a way of explaining how the pairs are formed, which finally gives rise to superconductivity. These are some of the, you know, facts there.

So these are momentum plus K and minus K of the two electrons. The total momentum is zero. They both are spin half. For one of them, the MS value is plus half and minus half, which means the electron of up electron and down electron forming a pair. And this, by definition, you know, is singlet pairing.

BCS Theory (contd.)

Quantum numbers of electron pairs

Quantum number	e^-_1	e^-_2	pair	
Momentum: **p=ħk**	**+k**	**−k**	**0**	
Spin: s	½	½	0	"singlet" pairing (s=0)
m_s	+½	−½	0	
Orbital angular momentum l			0	"s-wave" pairing (l=2 "d-wave" in HiTc)

$\omega_q \sim \sqrt{\frac{K}{M}}$ vibrational or phonon frequency

T_c should scale also as $1/\sqrt{M} \Rightarrow$ Isotope effect

$$T_c \cong \Omega_{Debye}\, e^{-1/NV}$$

Ω_{Debye} is the characteristic phonon (lattice vibration) frequency

N is the electronic density of states at the Fermi Energy

V is the attractive electron-electron interaction

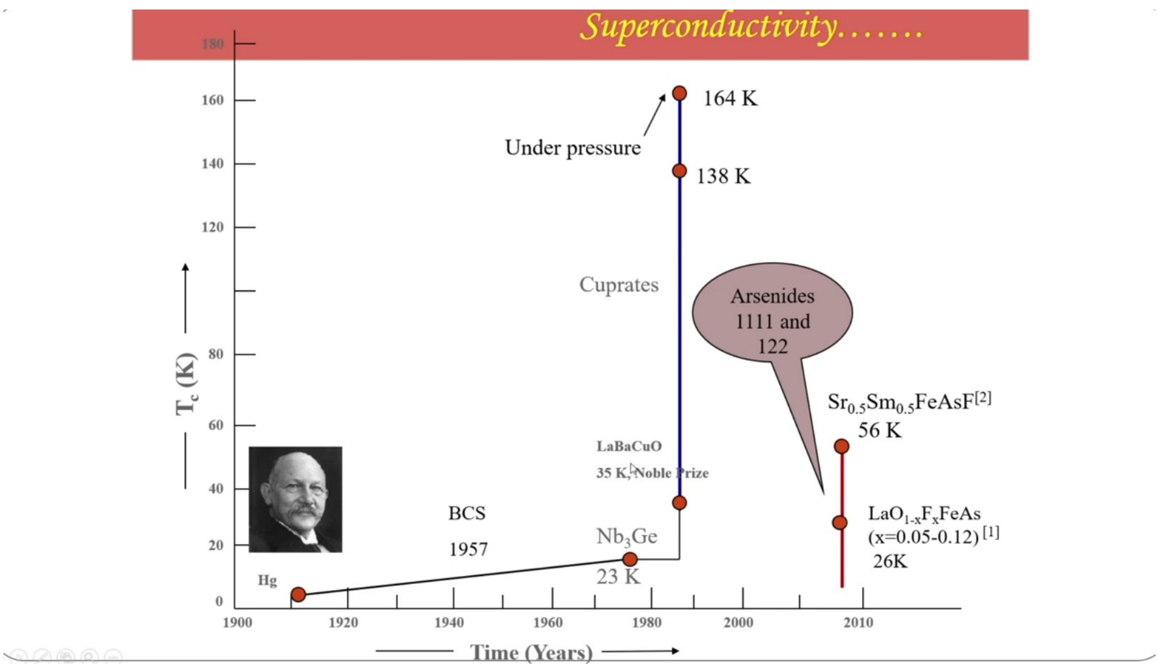
Variational Theory Is needed.

So the orbital momentum, or angular momentum, is 0, and of course, this vibration frequency or this omega Q is the square root of K over M. We have seen how this K over M, where K is the force constant, which is a model for a solid where each atom or ion is connected to another atom or ion by a spring. So that is the energy or the frequency associated with this. So, we have talked about this isotope effect where Tc is actually proportional to the Debye frequency, and the Debye frequency, you know, is a characteristic phonon frequency and so on. So, there is an involvement of phonons in

There, and we have also said that, you know, so this Tc actually goes as m to the power minus alpha, where m is the isotope mass. So, if you take two isotopes, which differ by a small amount, the masses differ by a small amount. If you calculate the Tc, Tc goes as m to the power minus alpha, and for these superconductors, alpha equals half. So, alpha being half means it is 1 by root over m, and this is also the dependence of the angular frequencies on the ionic masses, as you can see there. It is 1 by root over m. So, the phonons must be playing an important role, which is what Cooper had understood.

To tell you a bit about the discovery of superconductivity, it started in 1908 at about 4.2 Kelvin. Then it was 1977, etc. It was about 23 Kelvin. In 1986, there was a sudden surge. And it went up to 164, even 170, close to 170 Kelvin under pressure.

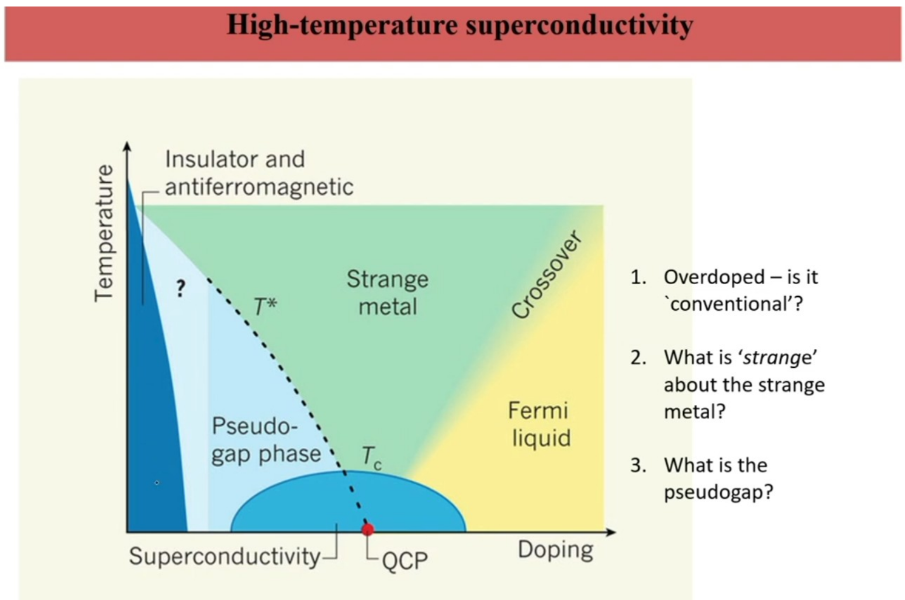
So, there the cuprates, etc., they lie. And then, of course, you know, from 2008 onwards, there were some other superconductors that were discovered, which had, of course, lower TCs, not so low—it's about 60 Kelvin most. For these strontium, samarium, iron, arsenide superconductors, so to say. And this is how, you know, as time progressed, more and more superconductors were discovered. And these also got a Nobel Prize for this lanthanum barium copper oxide or lanthanum strontium copper oxide.



That fetched another Nobel Prize for the discovery of the cuprate superconductors. This is a picture of Kemmerling-Owens, which we have seen. So these are some of the TCs recorded and some of the discoveries that you see there. These are Bednorz and Müller in 1986, which was one of the most studied materials. And then there were many other discoveries.

These are also of the same type, which are copper oxide is one of the main things. And they went up to 134, 164, and all that. Some of these materials are also hazardous, which is why not much active research has taken place. So, just one or two slides on these high TC superconductors and these are, there is still no theory and because the normal state, the starting point is not known. Pairing is not phonon mediated because phonon mediated would not have given rise to such large TC.

There are a lot of experimental data that contradict each other. The coherence length is too short. The presence of a pseudogap—I'll tell you just in a while. There are no controlled expansion parameters. So perturbation theory is not allowed.



Many other things. There's a very strange phase diagram where there's an insulator, antiferromagnetic insulator at low doping. This temperature versus doping. This doping is, you know, it's usually a strontium doping or barium doping. And there is a pseudo gap phase here, which means that there's a gap, a spectral gap in the metallic phase.

This is a strange metal, which means that the Fermi liquid theory is not obeyed. In the over doping region, it's more clear that it's it behaves like more like, you know, BCS superconductors. So, all these put together have made these studies interesting for a very long time. However, there were no real consensus about these or microscopic theory about this superconductivity. Many things are known experimentally, but they could not reconcile all of them together.

High-temperature superconductivity

Q. What are most unconventional about high T_c superconductors?

Ans. (1) Superconductivity by doping a Mott insulator (see the vicinity in the phase diagram).

(2) A non s-wave pairing mechanism – gapless regions along the Fermi surface.

(3) Short ranged pairing correlations in the normal phase (Pseudogap).

(4) Consists of CuO2 planes where the electron-electron correlations are very high.

(5) Tc depends crucially on the doping concentration, number of CuO2 planes.

(6) Violation of Landau Fermi liquid theory.

Like the success that BCS enjoyed, BCS theory enjoyed could not be possible for this. And there are, you know, these unconventionality, they lie in this, that superconductivity is by doping a Mott insulator. The superconducting dome and the Mott insulating phase, they are too close to each other. They are not L equal to zero pairing. There are gapless regions from the angular resolve photoemission studies.

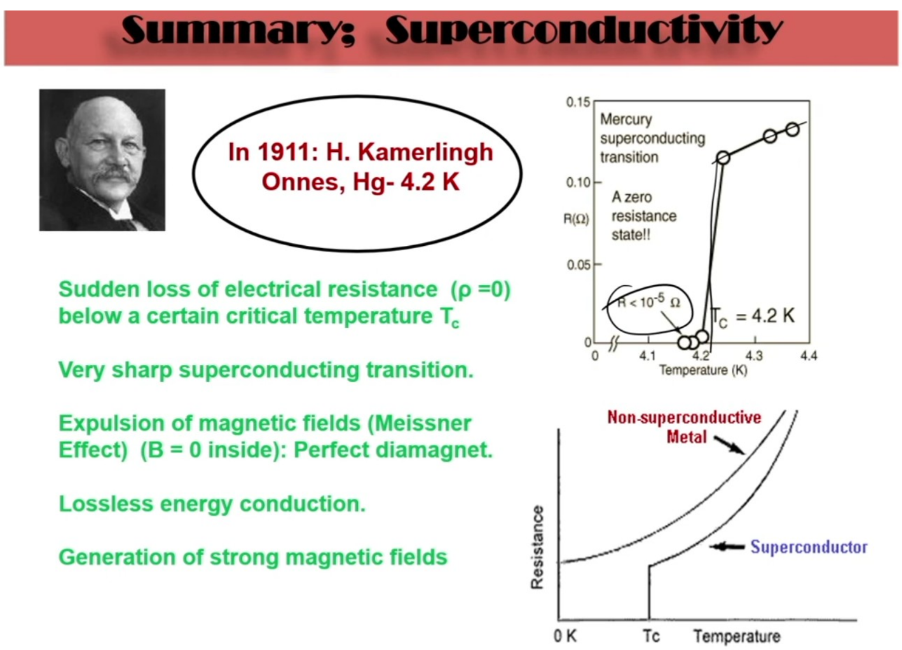
There are gapless regions in the Fermi surface. There is a pseudogap in the normal phase, copper oxide planes where the electron correlations are high. TC depends on doping concentration and also on the number of copper oxide planes. It sort of has a violation or shows a violation with Landau's Fermi liquid theory. So the developments for the last two decades are superconductivity in graphene at magic angles, ruthenates, iron-based superconductors, topological superconductors, arsenides, nickelate superconductors.

There are non-cytrosymmetric superconductors such as BIPD, etc., granular superconductors, and so on. The infrared, the experiments that can detect superconductivity or the superconducting energy gap or the TC are the infrared emission, ultrasound attenuation, tunneling experiments that is making a junction and put a bias and then measure the current. And photo emission spectroscopy, NMR, nuclear magnetic resonance to probe short pairs, XRD to look at the crystal structures of these. So just a summary of this. So Kamerlingh in 1911.

Experiments.........

- Infrared Absorption (measurement of energy gap)
- Ultrasound attenuation (measurement of energy gap)
- Tunneling (measurement of DOS)
- Photoemission (*k*-dependence of gap)
- NMR (Probing of short range pairs)
- XRD (crystal structure)

He discovered superconductivity at very low temperatures. So this is the plot that we had not shown earlier, but we're showing it now. So there is a very sharp drop in Tc at around 4 Kelvin. It's a zero-resistance state where the resistance is less than 10 to the power of minus 10. So, a superconductor and a good conductor will show behavior like this as a function of temperature.



So, the resistivity will or the resistance will sharply drop at some finite Tc, whereas it will smoothly, you know, vary and go to a finite value at T equal to 0. So, sudden loss of electrical resistance below certain critical temperature, sharp superconducting transition, expulsion of magnetic field. which are Meissner effect and perfect diamagnet, lossless energy conduction and generation of strong, very strong magnetic fields. These are some of the applications of superconductors. These are maglev trains, which were proposed to achieve or it has achieved, a test vehicle has achieved a speed of 343 miles per hour, which is 552 kilometers per hour on April 14, 1999.

And these rails that you see below are superconducting rails. And this whole thing actually floats. It doesn't have any wheels. And that is due to the Meissner effect. And then there are other applications in power cables, in this weight reduction of wind turbines and so on.

And many of these are in the medical industry also. These are superconducting magnets. giving rise to very large and uniform magnetic field to probe non-healthy body. So these are medical applications and so the superconductivity study of superconductivity does not end here neither it is complete in any form but I propose that you have a look at various literature And also, if you feel the need, you can look at this course on brief theory of superconductivity.

The course discusses at least the BCS theory in quite a bit of detail, and it will benefit you. We could only give a bird's-eye view of magnetism and superconductivity. So that finishes the module of solid state physics where we have talked about phonons, the crystal lattice, phonons, phonon specific heat, electrons, magnetism and superconductivity now. We will stop here. Thank you.

Thank you.