Prof. Dr. Prathap Haridoss
Department of Metallurgical and Materials Engineering
Indian Institute of Technology, Madras

Lecture No. # 38

Superconductivity

Hello, welcome to this thirty eighth class in our course the physics of materials. So, today we are going to look at the phenomenon of superconductivity and try to put to together some of the first of all understand what it is, get a feel for what is this phenomenon, what are its features and then and also try to understand, see if there is a get a feel for the theory that as help try and explain this phenomenon. So, that is what we will do.

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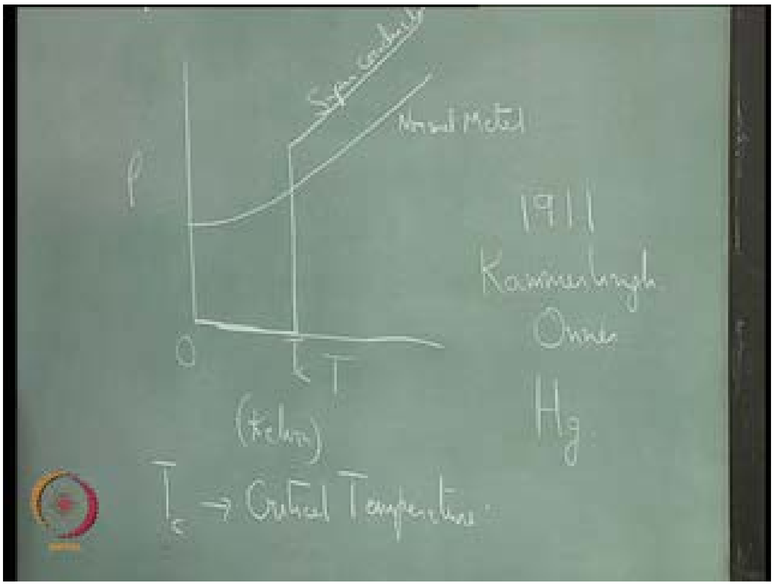

So, the phenomenon is simply called superconductivity. Basically, what it is that if you take the resistivity row, resistivity of materials and plot it as a function of temperature. So, people have done this. We have already seen you know temperature dependence of resistivity of a metals and so on. In general as you raise the temperature resistance goes up. So, as you raise the temperature resistance goes up, this is sort of the trend that you see. Now, for most metals if you keep lowering the temperature.

So, this is going to keep coming down and then eventually it will level off at some value, very close to 0 Kelvin. As you get keep getting closer and closer 0 Kelvin it will reach something like that. So, will assume that this is 0 Kelvin, 0 Kelvin, this is in Kelvin. So, temperature in Kelvin and this is 0 Kelvin. So, as you approach absolute 0 the resistivity of the material keeps decreasing and then it eventually levels off at some value. So, this is what is seen for most metallic systems if you investigated you will find this. Now, it turns out that for some systems what you see is you see the same trend.

Resistance is decreasing with temperature, then at some particular temperature the resistance appropriately drops to virtually 0 and states there all the way as you go down in temperature. So, you see. So, this is a normal metal and material which show you this behavior were you know resistance is decreasing up to some point then abruptly it drops to virtually 0 resistivity and then it is stay's there. This kind of a behavior the materials that display this kind of a behavior or called superconductors. So, these are superconductors. So, and as a and that is mainly because the name as the name suggest once you get pass this temperature once you get below this temperature you can conduct electricity with virtually no resistive losses. So, this is virtually 0. It is more than you know its many many many orders of magnitude, 13 orders of magnitude or even better then what you would ever get there and it virtually drops to 0. So, that is the state at which you find this material.

Superconductivity as a phenomenon was discovered in around the year 19, in the year 1911 and this a credited to Kammerlingh Onnes. So, it was discovered in 1911 and it was discovered in mercury, the metal mercury if you keep lowering its temperature this phenomenon was discovered that once you cross some temperature appropriately it resistance drops to 0. This temperature is called a critical temperature T subscript C, T subscript C is what a it is referred to and it is T subscript C is the critical temperature. So, this is a critical temperature and it represents a temperature that you have to go below for you to get the superconducting stage and if you cross this temperature you get the normal conductivity, materials remains conducting the way you would normally see a metal conduct electricity. So, this is the basic framework within which superconductivity was discovered and as you can see you know if you can if you have a material which has virtually 0 resistance, the technological uses for it our tremendous. So, so that is something and that is the reason why you know since it since the time it was discovered a lot of effects has been spent research researching this class of materials for this type of materials to understand what is superconductivity what is that phenomenon, what are the factors that control it and is it and.

In fact, the dreams has always been that you will get a material that behaves like a superconductor at room temperature that is the dream, but actually as you can see this is something that as it was even as it was discovered, was discovered very close to 0 Kelvin. So, we are talking of just a few degrees past 0 Kelvin that this was discovered, that is not a temperature that is easy to attain. It is very expansive to attain that temperature and maintain the temperature. So, you are actually it is a very difficult process to stay at that temperature and and expensive process. So, therefore, in the form that it was originally discovered, practical usage was going to be difficult except in specialized cases. So, since then it has been seen that you know of the order of various material where then investigated to see if you could see the phenomenon of, observes the phenomenon of superconductivity in them.

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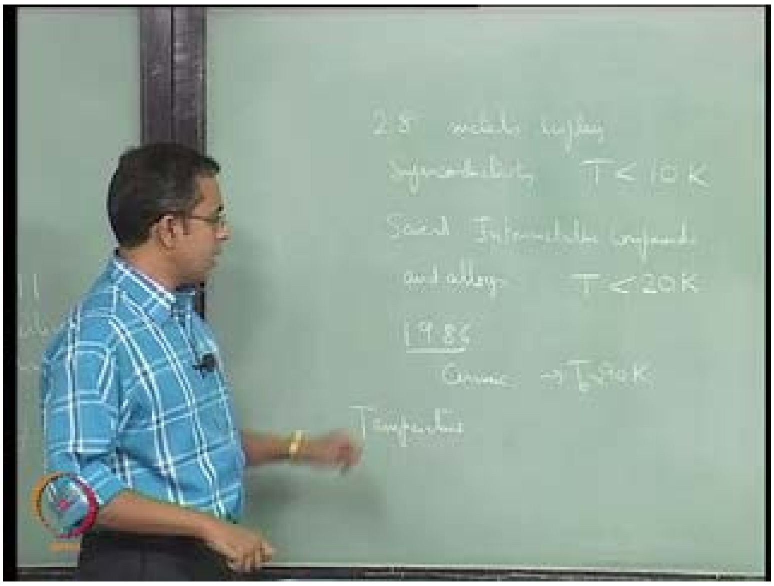

And it turns out that something like 28 metals display superconductivity and usually this is occurring at temperatures less than about 10 Kelvin. So, all of these metals in there elemental state or showing you superconductivity at temperatures less than 10 Kelvin. So, that is what you see then there are several inter-metallic’s, inter-metallic compounds and alloys that show superconductivity in the temperature range in temperature less than about 20 Kelvin. So, temperature less than 20 Kelvin is sort of what you are looking at for most of these systems. So, this is very. So, this is all you know minus 250 degree C that is what you are looking at or even less minus 253 degree C and lower. So, that is not something that easily attained you need, typically you would you would be using something likely helium to get to those kinds of temperatures. So, this was seen and so, you can see that you know since it discovery more and more materials have been discovered which show use this phenomenon of superconductivity and more recently in the year 1986 a new class of materials were discovered which were actually ceramic type of materials which by the way incidentally at room temperature are going to be insulators. So, they are ceramics.

So, at room temperatures they are insulators, but if lower there temperature they go the opposite way they become they do not just become conductors they become superconductors and in fact, so, ceramic type of materials were discovered lanthanum barium copper oxide, atrium barium copper oxide and so on which were which basically had of the order of say, of the order of say 90 Kelvin as the temperature T subs C. So, this is the kind of temperature you are you can start C and you when start looking at these kinds of temperatures they are materials which can be, which can then be cooled to this temperatures you using say liquid nitrogen which is much easier to handle. So, that is the basic idea that. So, when you get to the 90 Kelvin, 100 Kelvin ranges you can start reaching their temperature with liquid nitrogen. So, but of course, these is ceramic materials. So, they are very difficult to process.

So, if you want to make something technological out of it were you want long wires and so on. This is going to be very brittle. So, it is not a very convenient think to work with. So, experimentally this is what is been done and so experimentally lot of people have worked with the these materials to worked with the variety of investigated variety of materials to see if they are superconducting, they have try to come up with new configurations of materials which may be superconducting. Some of these discovery have been accidental, some of them have been very well planed in systematically encountered and so on. And so this is the state of affairs. Additionally people also investigated the various features associated with the material that is showing you superconducting behavior.

So, what was seen is of course, as you can see right here temperature was and had a very important row to play. In other words you, if you cross the certain temperature you broke down the superconducting stage stage right states. So, you have superconducting state you raise the temperature you cross some temperature threshold you break down the superconducting state and so therefore, raising temperature is in some way opposing the superconducting state. So, in the same form when they looked at all the parameters that that would impact the superconducting state they found the following. If you if you stake a superconductor and you send current through it, you send correct current through it you keep increasing the amount of current you send in it. So, then effectively we would quantify that using by saying the by looking at the current density that you are sending through the material. So, you can keep raising the current density that goes through the material and what is found is that once you crosses certain current density again the superconducting state breaks down. So, it remain superconducting till you reach a certain current density then breaks down.

Also, similarly you can take this superconductor and place it in the presence of an externally applied magnetic field and in the presence of an externally applied magnetic field it will largely it will continue to remain superconducting, you keep increasing the field. So, we will we spoke of magnetic fields we basically had a set that that is the up externally applied field is a field that we would designate as h. So, you can increase H. So, So, amperes per meters. So, you keep increasing H then you will reach a certain value of magnetic field imposed on that material when suddenly the superconductivity breaks down. So, so there are 3 things that can break down the superconducting state high temperature, high current density and high magnetic field.

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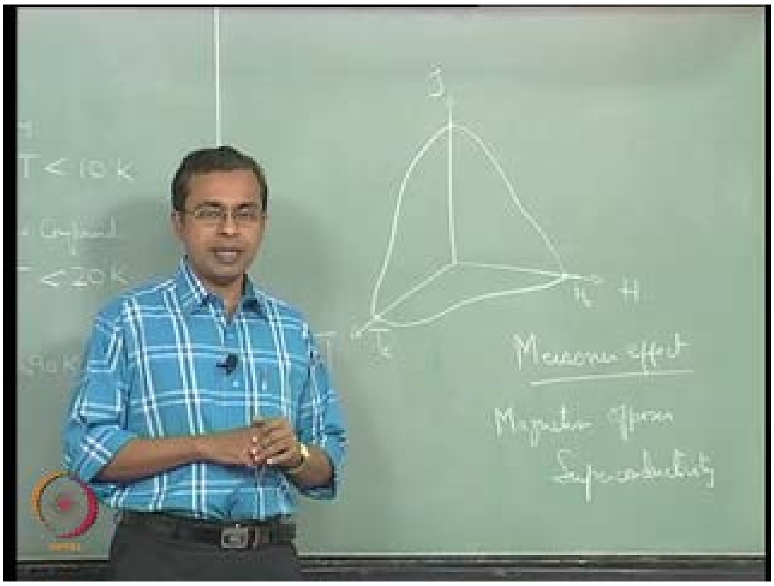

So, these are 3 things that can break down the superconducting state. So, In fact, what we normally do I mean you can just plot it like this. So, this is temperature axis, this is the magnetic field axis applied magnetic field and then the current density j. So, if you if you have no current flowing through it or a virtually no current flowing through it and the no field applied you find that as you raise the temperature you cross this T subs T subscript C or in the parlance of people who this material they will just say T subs C. So, to speak. So, once you cross the critical temperature the material stops being superconducting. Similarly, if you keep it even at very close to 0 Kelvin and you keep raising the field that you have applied at some particular field H subscript C the material stops being superconducting.

Similarly, with no applied field and very low temperature if you raise the current density at some particular current will cross some current density and you looses superconducting behavior right. So, what is actually seen is you have a range of combination of all these. So, within this, from the origin till you reach there is some surface that you can think of which consists of a current density values, the field values and the temperature values. Within that surface as you go below that surface towards the origin you have a range of combination of conditions under which the material continues to remain superconducting. So, that is. So, this is a very fundamental piece of information that you can obtain for a superconductor. This kind of a behavior and originally this was obtained. So, once. So, trying to understand superconductivity would require as to coming up with theories which would then help explain what is happening on the other side of the boundary, what is happening this side of the boundary.

So, that is the basic thing that people working in this area have to tried to explain. Now, what is seen. In fact, with respect to the magnetic field with respect to the magnetic field what was seen is that when you take a superconductor and you apply a magnetic field around you place it in the presence of a magnetic field. It is seen that the superconductor completely excludes that magnetic field it does not pre permit the magnetic field lines to enter it. So, it prevents it excludes a magnetic field. So, and that phenomenon is known as the Meissner effect. The Meissner effect refers to the fact that a superconductor opposes a magnetic field. So, which is not the case actually with the normal conductor, a superconductor opposes a magnetic field.

Now, this is very this is considered a very important effect that was discovered about superconductors because it clearly says the fact this Meissner effect exists for a superconductor indicates that a superconductors is not simply an exceptionally good conductor. In other words if you take very good conductor, the theories for a conductor or such that if you take the very good conductor and hypothetically you find ways in which you can reduces its resistance, it will still not display the Meissner effect. The Meissner effect is such that it is it somewhat different. It is it is ensuring that no matter when or how the magnetic field is applied the material will excludes that magnetic field. So, in other words something. So, it say it tells us 2 things. First is that the material that is showing you superconductivity is doing so using a mechanism that is not the same as the normal conductor.

So, that is why it is not simply a very good normal conductor because characteristically it is doing things that are different from a normal conductor and importantly that magnetism opposes superconductivity. Magnetism opposes superconductivity. So, something about what magnetism requires of a material is opposed to what is superconductivity requires of the material. So, this is a very important idea to identify and grasp of the superconductors. So, something that magnetism requires of the material is opposed by what superconductivity requires of the material or vice-versa, something that superconductivity requires to sustain itself is being opposed by what the magnetism requires of it. We will also note that having stated this if you actually look at this kind of materials for example, I said you know ceramic materials, certain ceramic materials have show you superconductivity at relatively high temperatures. They are in fact, called high temperatures superconductors and that is a little bit misleading because normally in the conventional sense when you talk of high temperature you are talking of 1000 degree C to 2000 degree C and so on. This is not at all in that scale.

This so called high temperatures superconductor is not even at room temperature, it is at much lower them room temperature. In fact, it is of the order of you know minus 200 degree C is where it is a superconducting or of or of that minus 190 degree C lets say, minus 190 degree C is where it is a superconducting. It is only a high temperature superconductor relative to the fact that the original superconductors where discovered at showing superconductivity even low at much lower temperatures than that. So, were you are talking of in Kelvin scale were you are talking of you know about 100 Kelvin temperature for high temperature superconductor, the original superconductors which are low temperature superconductors where less than 10 Kelvin. So, in that relative sense it is a high temperature superconductor. It is not even at room temperature. So, so we definitely need some amount of cooling as of today, the materials in which superconductivity has been discovered are such that you definitely need some cooling to have this superconducting state.

So, anyway. So, you have this theory that I mean this indication that magnetism opposes superconductivity. So, that is a very important piece of information. So, so attempts were made to try and see if there is a manner in which you can explain what is going on in the material and see if you can understand why or how the material is beginning to show a superconducting state.

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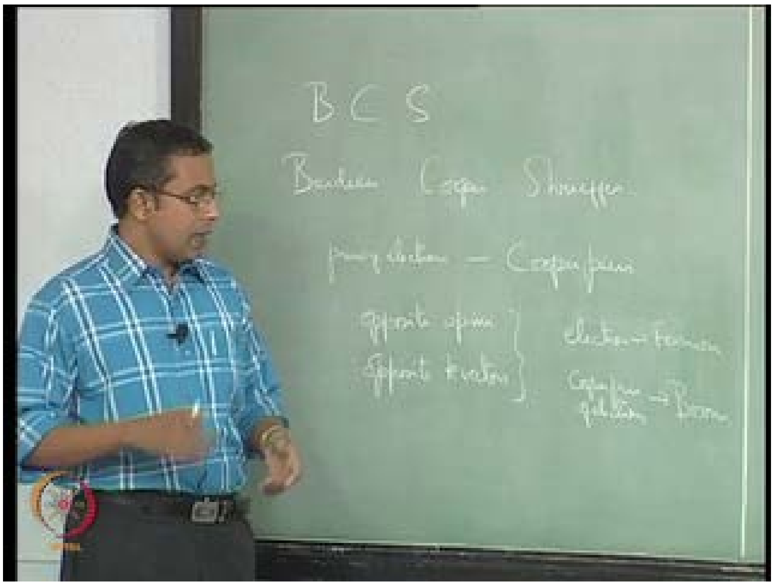

So, the most successful attempt is what is now the accepted theory for superconductivity and that is attributed to three people BCS, this is Bardeen, Cooper and Schrieffer. Bardeen, Cooper and Schrieffer, they came up with a theory that help explain a superconductivity still it only explain superconductivity for the original set of materials where you know the temperature the critical temperature was of the order of a few Kelvin. So, this theory for example, is unable to explain how a material at say 90 Kelvin or 100 Kelvin or there about can show you superconductivity. So, therefore, this even at this stage even though this is successfully explain low temperature superconductivity, there is no there is still no accepted theory that explain high temperature superconductivity convincingly. So, that is the that is the state it is in and the way they explained it is that they said in terms of a theory, they theorized that there were pairs of electrons, that sort of operated in a coordinated way and these pairs of electrons were attributes this idea was attributed to Coopers. So, they are called Cooper pairs and it requires the electrons to have opposites spins and opposite k vectors. So, the pairs of electrons would have opposite spins and opposite k vectors and as a result of opposites spins it would as a result of this combination it would appear as though the net k vector was 0 and the net spin was 0. So, suddenly form from electron which is a half spin half integer spin particle, we are having some kind of a composite particle. You can image it in as a some kind of a composite particle which is operating as this pair where the taken together, their net spin is now an integer spin.

So, what was the half integer spin suddenly becomes an integer spin. So, what was half becomes 0, plus or minus half become 0. The important thing about this is that when you go from half to 0 the qualitative difference the specific difference that comes in is that when it is a half spin particle it follows the Fermi Dirac statistics which is what we have discussed in great detail early on. And for a particle to qualify as a Fermion. So, that it follows this Fermi Dirac statistics the requirement is that the the spin should be a half integer spin which is what is true is for an electron, but when you take a pair of electrons especially a pair of this sort where this spins are opposed to each other and the net spin for that then looks like a 0 spin, it was suddenly become an integer spin particle. So, it or it behaves like an integer spin particle, if they are really coordinated, if they really have linked up with each other in some fundamental sense. So, then it behaves like an integer spin particle at which point the statistical behavior of the set of particles changes.

So, that from being up Fermion, the Cooper pair. So, and is an individual electron is a Fermion and it follows Fermi Dirac statistics, but Copper pair of electrons which now has an integers spin behaves like set of particles which are called bosons. In the next class we will look in great detail about bosons which is and they are a set of particles just the way Fermions or particles which follow Fermi Dirac statistics and therefore, I mean they are the people Fermi Enrico Fermi and Paul Dirac are credited with that with that distribution and the use of that distribution. So, to speak the Cooper, I mean sorry the bosons are credited to Sathiyendra Nath Bose and Einstein, together they proposed it and so, that is and they are and in honor of Sathiyendra Nath Bose the name Boson is given.

In fact, he was the one who originally proposed it there was some relectunce to accept it. Einstein supported him and actually showed that there was something more fundamental that could be set about those particles and so they become Bosons and that only then they got accepted. So, electrons behave like Fermions, the Cooper pair of electrons behaves like Bosons because the suddenly what was half integer spin has become an integer spin and Bosons or particles which require integer spin. As I mentioned in the last class what we think of as light photons or bosons I mean they they have all the characteristics required to be a Boson, the lattice waves in, the waves in a lattice which are called phonons they are also Bosons. So, so we suddenly see that you have number of particles that we are we are. In fact, photons certainly we have been used to before and they are bosons and there are 2 other things that we have just discussed which are bosons.

Now, the interesting thing is and that is why we will actually look at Bose Einstein statistics in greater detail in the next class. There are two things that are interesting, this Cooper pair of electrons actually in terms of a distance it is not that they are very close that is the very interesting thing about this cooper pair. This cooper pair can actually be a pair of electrons which can be relatively far apart, but they interact through the lattice with each other and therefore, maintain they are state the actually what happens is there is a certain energy associated or certain decrease in energy associated with the formation of the Cooper pair and once that pair is formed they actually maintain that state, they maintain that state and you have to provide enough energy to break that states, you have to break that cooper pair before they start behaving like electrons before. So, this sort of condense into this state. They condense into this state of where in they are in this paired state and because they are paired with each other they sort of in this condensed state they avoid the interactions with the lattice or they are somewhat impervious to the interaction with the rest of the with I am I am sorry with impervious to the scattering events that normally the electrons are prone to. They tend to be relatively far. So, if you actually see you know atomic distances or of the order of angstroms, this could of the order of several nano meters, several nano meters apart this electrons could be and they would still continue in a coordinated way and therefore, in a certain length scale you may actually have several Cooper pairs which are sort of within that length scale. So, confined to the same length scale. So, Cooper pairs are of that sort and interestingly they themselves are Bosons, on top of it they interact with each other the fact that they are you know it is and it is a long range phenomenon so to speak. They are interacting through in this long range using lattice vibrations.

So, therefore, they are Bosons and the use phonons to interact with each other which are also Bosons. So, you actually have two sets of bosons existing there which are interacting with each other. The particles themselves to the together or represent Boson kind of behavior and they are interacting with each other they are sustaining themselves by interacting with each other using phonons which are also Bosons. So, you see for a multiple in a multiple sense you get this Bosons phenomenon here and that is the reason why we will look at it in little greater detail in the next class and also one of the characteristics of the Bosons is that at very low temperatures they form something called the Bose Einstein, Bose Einstein condensate. So, these are also some forms of condensate these are also or essentially condensing into a condensate there and so in the next class we will look at the Bose Einstein statistics and we will also look at the Bose Einstein condensate. So, Cooper pairs are for. So, the theory says that there are cooper pairs of electrons which have opposite spin, opposite k vectors.

So, they behave as though they have no net spins and no net k vector and they are Bosons, they avoid lot of the scattering events in the in the material and they are able to they have certain distance associated with them and so they are able to travel long through the system and as you raise the temperature, if you provide enough energy you break down this pair and that is when the superconducting state suddenly fails, but importantly the all these ideas trace themselves back to the Meissner effect.

The Meisssner effect and that is the reason why we say that the Meissner effect is such an important effect in trying to understand superconductivity. See, the Meissner effect basically says that the discovery of the Meissner effect convey to the idea that magnetism is in some fundamental sense opposed to superconductivity. So, what is it that magnetism requires of the material. Magnetism requires that you know the electrons align themselves in certain way so that the magnetic field moments of the electrons align themselves. So, therefore, the spins of the electrons have would have to align themselves right. So, you have randomly oriented spins, you suddenly want them all oriented in 1 direction. So, that you get the magnetic momentum in that direction.

So, when you say that the alignment of electrons is what magnetism brings to the material or a tries to enforce on the material, the fact that that alignment is causing is disturbing superconductivity. The fact that the alignment is disturbing superconductivity suggests that the superconductivity state requires the opposite. So, that is the very important thing is to repeat it the magnetism will require spins of electrons to align themselves. So, that you get the magnetic moment in 1 particular direction. So, if you say that magnetism is somehow interfering with superconductivity and that if you raise them magnetic field strength you break down superconductivity. It conveys the idea that the aligning of spins is something that is not desired in the superconducting state which means which also which can be taken 1 step forward to say that perhaps deliberately aligning then in the opposite way is what superconductivity requires and that is what is a captured in this Cooper pair.

The fact that this Cooper pair takes an electrons of opposite spins. So, that is how this and that is why the Missner effect is not simply some interesting experiment that interesting, but an asides of. So, to speak of superconductivity, but it is very fundamental aspect of superconductivity and in it is in that sense that it captures this basic idea of superconductivity and tells you that it is something that it is different from a normal conductor.

In on normal conductor we are not talking of pairing up of electrons of opposites spins and so on. So, the electrons are all independently running around. So, this entire process is not required for normal conduction process. So, only for a superconducting state it seems to require all of this additional information. So, they have received a noble price for this, for their theory on the of a superconductivity, I believe it is on 1972 Noble prize that they got for they work to explain superconductivity. We just a discussed that you know magnetism is opposed to superconductivity and vice-versa and that they actually and therefore, as you raise the magnetic field eventually the superconducting state breaks down.

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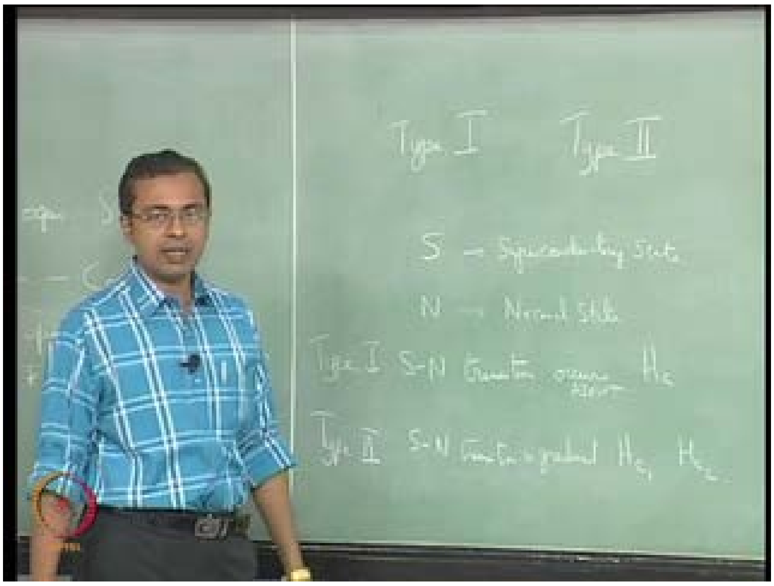

In this context there are actually 2 types of superconductors. They are simply called type 1 superconductor and type 2 superconductors. So, there is a type 1 superconductor and a type 2 superconductor. The difference is simply this, in a type 1 superconductor what we just described is how the system behaves. That is you raise the magnetic field that the superconductor is experiencing, when you cross some threshold the superconducting state suddenly fails. So, in fact, they we use the terminology S state and N state. So, this is the superconducting state and the N state is the normal state. So, in a type 1 superconductor when it is in the superconducting state when you are below that critical field, when you are below the critical field H, some critical field, it is entirely the entire material, the entire material is in the superconducting state.

So, there is a no, so it is only in 1 state is entirely in superconducting state and when you when you when the superconductivity breaks down it does so, kind of abruptly and then everything becomes the normal state, the entire material becomes normal state and so, the S N transition occurs at the critical field that you have applied H subs C, critical magnetic field. At the moment we are not talking of the electric field of the temperature. So, it occurs at this temperature. In a type 2 semiconductor the S N transition is not abrupt. So, that is a significant difference, this S N transition is not abrupt. So, you have the S state the superconducting state and the N state which is the normal state, but in between there is a mixed state. So, in which what is happening is, there are regions in the material which are superconducting and regions in the material which are normal conductors.

So, there is a mix of superconducting state material within the system and normal conducting state within the within the system and then as you keep increasing the field slowly the normal conducting state becomes more and more and more and eventually it completely becomes the normal conductor. You lose complete superconductivity in the material. So, that is how you have it. So, for a type 2. So, this is type 1, for type 2 you have. So, S N transition is gradual. So, the here it occurs abruptly, S N transition is gradual and so, you actually have H C subscript C subscript 1 and A H subscript subscript 2. So, you have you have to cross H subs C before the normal states begins to appear in the system and then if you continue you will have to cross H sub subscript C subscript 2 H C 2 H C 1 you will cross then its starts getting make into the mix state between H C 1 and H C 2 it remains in the mix state.

If you go past H C 2 it becomes a normal conductor. So, so this is how it is occurring, it is gradual. The advantage though is in some usage the type 2 semiconductor becomes preferable because you can handle much higher fields. So, that is that is the reason why sometimes type 2 semiconductors may become preferred. So, so in that sense there is some variation in the even within the superconductors you have this variation in a in the type of superconductivity that may be present within the material and therefore, you have different classes of materials which are rather type 1 or type 2. So, if it is a type 1 you will only have a H C whereas, if it is a type 2 you will have a H C 1 and a H C 2. So, that is the difference between.

Now, in terms of relating to what we have learnt what we have to understand is that we are looking at see one of the problem with this which is how the hole B C S theory actually was considered a very significant contribution. One of the problem with this the situation is that the temperature at which this when the original set of superconductors where discovered the fact that state of matter or particular state that it was existing in superconducting state broke down at in the order of 5 to 10 Kelvin, that is a temperature range at which it broke down that meant the energy difference that it; obviously, it means that there are some state that is existing in the material which is a lower energy state. So, that is why it is getting into that lower energy state as you are cooling the system there is some lower energy state this system is able to attain, its able to get into that lower energy state and it stays there and as you raise the temperature you are adding more and more energy to the system.

When you put in just the amount of energy difference between that lowest energy state and the next state it breaks down this lower energy state and you will start getting the normal system normal material. Now, the fact that it is in the 10 Kelvin range or less ah implies that the energy required for breaking down that state is very very very small relatively speaking. So, that was the problem because if you look at our systems when you when you say that you know the electrons participating in conduction and so on are all setting near the Fermi surface and that is what is really doing all this work. The Fermi surface relatively speaking is a relatively large amount of energy. So, you have to find ways in which electrons setting at the Fermi surface can attain a state which is a very where the difference in their energy levels from their original state and this state is a very small energy level and that is where this Cooper pair concept really helped address a lot of those issues in trying to explain something where the energy related the relative amounts of energy that people had to account for where very small.

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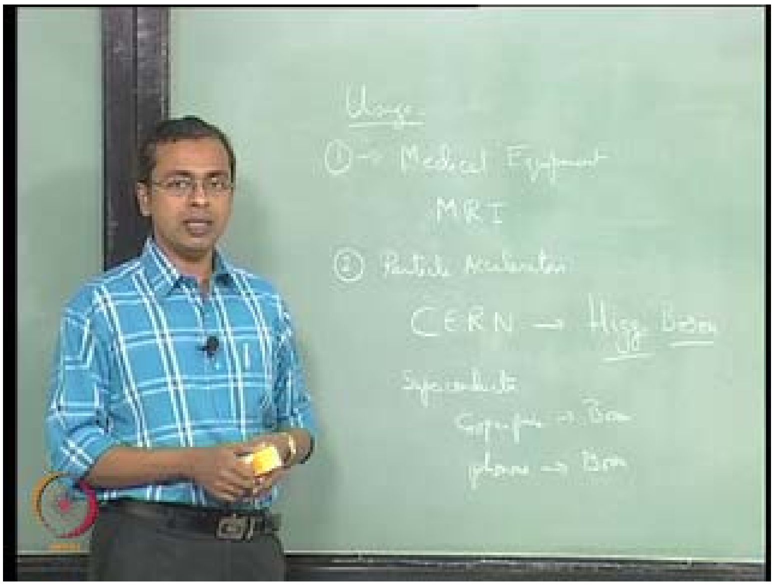

So, that is why this is important. Now, in terms of usage it is superconductors have not really in the have not really penetrated normal day to common day today usage and mainly because of the cost of cost involved in making the material, cost involved in a and especially even the so called the high temperature superconductors are still at relatively low temperature operation. So, therefore, in terms of operating the superconductors it is not an easy thing and on top of it these are and therefore, to if it is a ceramic material also it is a brittle materials. So, these are all the issues that are involved in its usage. Therefore, it is not really penetrated the more common places where you are you may expect a very good conductor to exist. However, there are lot of specialized uses for which superconductors are necessary and have therefore, found a lot of utility.

The first 1 is of course, is a is in the medical devices or medical equipment. So, for example, you are MRI scans, magnetic resonance imaging scans are places where superconductors are used. So, MRI scans use superconductors. The reason being for on MRI scan to work they need a very high intense magnetic field, to have a very intense magnetic field you have to if you are using an electromagnet to generate that intense magnetic field you have to flow very high current through those electromagnets. So, you have flow extremely high current through those electromagnets to get the kinds of fields necessary for you to do MRI imaging.

Now, if you use a normal conductor, no matter how low its resistivity if you use a normal conductor when you flow higher and higher amount of current then it is going to generate a lot of heat. In fact, most normal conductors if you use the kind of currents that in MRI scan might used you are actually going to sort of you are very likely to even melt the material that is the amount of heat that you will generate by sending forcing that amount of current through those wires you will have to put a lot of voltage to send that kinds of current through those wires. So, therefore, normal conductors are not convenient or simply not capable of doing this job of an MRI of doing the job that is required of them to create the magnetic fields in the electromagnets in an MRI equipment. Superconductors are able to do that so, but and this is also specialized equipment. So, the you can afford to have equipment of this sort using expansive material, there are I mean in a at least in a relative sense and therefore, this is actually becomes successful you find MRI scans quite commonly available in a in various hospitals and so on. So, this is 1 place where you use a such superconductors.

There is an another place where you use it again for mainly from the perspective more than it mainly to take enough current. So, that you can generate a magnetic field. So, that is that is the general place where you are using it. It is not simply to carry high currents, it is not simply just to carry high current between point a and point b. It is more that by carrying this current in the form of a coil or some such thing you can create very high magnetic fields. So, that is the basic reason place where this is use. So, this is actually used in particle accelerators. Particle accelerators where you need intense magnetic fields use superconductors.

In fact, very major part of their engineering and so on is to have coils made out of superconductors. So, that they can get the magnetic fields that they desire. So, In fact, in at the time of recording this lecture if you see, if you know the at C E R N they are working with a particle accelerator, is specifically looking for they will basically the accelerate the particles and they smash them together and so, that they can look at the debri of that collision and see if they can understand what are the more fundamental constituents of those particles. So, there they are working and a particular particle which is called the Higgs Bosons.

So, they are looking for a particular particle which is a which theory has predicted or theory claims it might exist called the Higgs Bosons and the only way they can find out whether or not such a particle exist is to do this accelerator test where I mean this test where particles with which have been accelerated in very significant sense are smash together and then the debri they look for the what is the constituents. Their expectation is that if you have high enough energy you will get this you are likely to see this boson. And so, it is interesting to see here that this particle which they are searching for is a Boson.

So, it means it meets all the requirements to be Bose Einstein particle Boson and to do that you are using Cooper pairs which. So, it to look for it you are using a superconductor where the Cooper pair of electrons operates like a Boson and it uses phonons to interact with each other which is also a Boson. So, at some fundamental level you are using 2 bosons to search for a third Boson, if you want to look at it that way of course, it is not it is not as simply stated it is not as simple as I have stated it, but that is the basic idea in the in the system that you have you are using 2 bosons to search for a third boson. So, so basically and.

So, I think you can see here that it is in the context that we will actually look more carefully at what a Bose Einstein material is what are these Bosons and what is what can be set about them in a greater detail in our next class. So, so this is another area where superconductor is used. So, it is used in medical equipment and it is used in particle accelerators in both of these cases as I mentioned, it is not simply the fact that it can hold high current or it that it can carry high current between point a and point b, it is because that ah you actually have to you can generate very high magnetic fields with them.

Still cooling is a very big issue here. So, from a technological perspective when you look at superconductors cooling still remains a major issue and it is also it is it is something that you have to control in a very careful way. So, for example, in the particle accelerators when you are saying that you know when you say you are going to operate your system at say 2 Kelvin. So, 2 Kelvin is something that is very close to absolute 0. 2 Kelvin, that is actually a very is a big technological challenge you have a massive piece of equipment. A very significant fraction of it has to sit at 2 Kelvin. It is a big challenge because even if something goes wrong you cannot cycle from 2 Kelvin to room temperature and back to 2 Kelvin quickly. It may take several weeks for you to very gradually raise the temperature of the system which ever is the affected system to room temperature.

So, that you can attend to it and then very very gradually lower the temperature. So, just attaining the temperature and you know coming back from the temperature to room temperature or going back to the temperature is a very has to be a very gradual process otherwise you will create a thermal shock.

So, this is has this has to be done very very carefully. So, there are lot of in addition to the fact that it is at low temperature simply reaching the temperature and maintaining that temperature is something that has to be done in a very control way. So, therefore, even in that sense there is a technological challenge in using, in working with superconducting materials and as I mentioned and. So, it has already percolated into certain types of activities and those are at least 2 examples are out here, but it has still got some base to go before you can expect to, before you can consider a possibility that it might pervade all normal usage of materials.

As a technological accomplishment or a dream it suddenly a very good thing to aim for that you could have a material that is perhaps superconducting at much higher temperature and possibly even at room temperature, but we do not know if there is a theoretical limit to the superconductor, we do not know if you mean that there is a fundamental reason why you may never have a superconductor room temperature, those things are not really known and in that sense. In fact, even the as I mentioned you know the Bardeen BCS theory the Bardeen Schrieffer Coopers theory, it is still is something that only explains the low temperature superconductivity. In fact, based on this process that they have explained they expect that the superconducting state has to break down around 10 Kelvin also or some low temperature of that order. So, so if something is showing you superconductivity at 100 Kelvin it is fundamentally not using this, I mean it is fundamentally not going on the bases of what this theories suggested.

So, there is still hopes to understand superconductivity in the sense that there may be something much more fundamental which explain superconductivity which may either augment to the BCS theory or may even replace the BCS theory,

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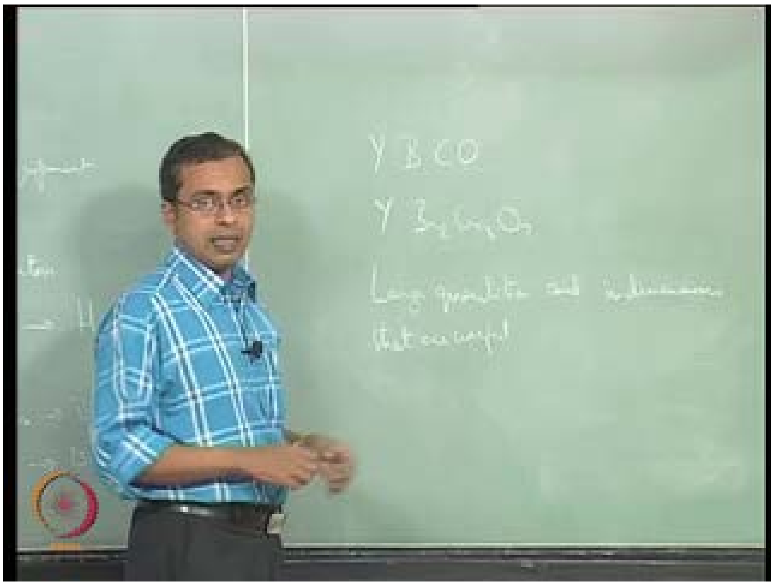

But in principles BCS theory is the fundamental theory that explains superconductivity. In terms of technological challenges as I mentioned you know yttrium barium copper oxide. We will they. In fact, they will say YBCO is how it is typically mentioned. It, but it is actually yttrium barium copper and oxide. So, this is 3 7 is what I remember. So, this is yttrium barium copper oxide. So, these are the kinds of ceramic materials with which you can get superconductivity at higher temperatures and in this case what is what is complicated about this kind of material is you have to get a particular phase, which may have a particular crystal structure and so on.

So, to get these materials in large quantities and in dimensions that are useful. Meaning in the form of a wire or in the form of a tape. So, in the form of a wire or in the form of a tape to either get it in large quantities or in dimensions that are useful and if it is a wire or a tape you want it to be a continues wire or a tape, it does not help you know if ever. So, often you have to make a joint and perhaps the joint is made out of some other material that that does not work, you will have to have something continues. So, only then you can have it working. So, the challenges to make it in large quantities and in dimensions that are useful, this is not an easy challenge because it is a ceramic material you cannot just form of block of it and then start post processing it to get this material. You have to sort of make it in the shape that you wish.

So, that is how it is. So, this is a challenge and so, a lot of people work on this. So, but at the same time as I mentioned you know already specific usages has already occurred and people are using it. So, to summarize what we see is that today we have looked at the concept of superconductivity.

We have looked at several of the key aspects associated with it for example, the fact that it has a critical temperature T subs C, it has the critical current density J sub C. So, where if you cross that current density you will break down the superconducting state and it has a critical field associated with it, where if you cross that particular field the superconducting state will break down. For every given superconducting material you can create the you can identify these 3 parameters the H subs C, the J subs C and the T subs C and that will then give you the envelope within which you have to operate to keep it in the superconducting state. So, this is the fundamental aspect of a superconductor.

As I mentioned the of the three the temperature and the current more than the temperature and current it is the effect of the magnetic field on the superconducting behavior that that formed the bases of trying to come up with theory for understanding superconductivity. The effect of the magnetic field on the superconductor was something that had been explored in great detail by Meissner and hence it was called the Meissner effect and so, the first successful theory in explaining superconductivity really focused on taking advantage of the Meissner effect to explain the superconducting behavior.

That first successful theory as we saw was the BCS theory of the Bardeen Schrieffer Cooper theory. However, I have also indicated you that you know it is not something that explains all of superconductivity as we know it today. There is still aspects of superconductivity that that are not explain and in terms of utility already several specific utility of superconductivity is already there. It is already there as a commercial device, there are many places that you can actually utilize superconductivity, it is there. It is there both as a commercial device that common people can use in the form of these MRI equipment and it is also still there in a highly sophisticated equipment such as the particle accelerators which or the few particle accelerators that you see around the world which are which are by themselves very complex engineering equipment.

And in principle the in a fundamental sense the superconducting theory requires the use of Bosons both in the form of Cooper pairs which are Bosons and in terms of the phonons that are used for the Cooper pairs to sort of communicate with each other and it is that coordinated moments of those two electrons that enables them to avoid getting scattered by all the other phenomena that exist, the normal scattering phenomena that electrons face.

So, this is the layout of the basic ideas of superconductivity. So, with this we will halt today. We will in the next class as I mentioned we will look exclusively since we have encountered Bosons now in 3 different levels and a few different levels. In fact, in the form of photons, phonons and also the cooper pair's. 3 levels we have looked at Bosons and I also mentioned that they are using to search for the Higgs Boson. We will look more carefully at the Bose Einstein statistics because it seems to impact the way some of the material behavior happens. So, next class we will look at Bose Einstein statistics in great detail plus also some peculiarities of the Bose Einstein statistics. Sudden, special prediction that it makes and what is happened with respect to those predictions. So, this is this will be the main idea that we will explore in our next class.

So, with this we will halt for today and we will take it up in our next class. Thank you.

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