Class 38: Superconductivity

In this class we look at the phenomenon of superconductivity. It is being discussed as a separate topic, because superconductivity is significantly different from ‘exceptionally good’ normal conductivity in the sense that the behavior of electrons in superconductors is very different from that in normal conductors, as will be explained later in this class.

In general, in normal metallic conductors, as the temperature is lowered, the resistivity of the metal decreases and levels off at some finite value at zero Kelvin. In a few materials it was discovered that on lowering the temperature, up to a point the behavior was similar in that the resistivity kept gradually decreasing, but then on crossing a specific value of temperature, the conductivity abruptly dropped to virtually zero. These materials, where the resistivity abruptly drops to zero when the temperature goes below a critical value, are called superconductors. Schematically the difference in behavior of superconductors and normal conductors, with respect to variation in temperature, is shown in Figure 38.1 below:

![Graph showing the difference in behavior of superconductors and normal conductors](image)

**Figure 38.1**: Difference in behavior of superconductors and normal conductors, with respect to variation in temperature
The phenomenon of superconductivity was discovered in 1911 by H. Kammerlingh Onnes in Hg. To date superconductivity has been demonstrated only at temperatures significantly below 0 °C, in fact at least temperatures close to -180 °C continue to be required to demonstrate superconductivity. Superconductors can broadly be classified into ‘high temperature superconductors’ and ‘low temperature superconductors’, however the phrase “High Temperature Superconductor”, is strictly a relative term, the “high temperature” of -180 °C is only in relation to the low temperature of nearly -270 °C that is required to demonstrate superconductivity in certain other materials.

Several metals, alloys and intermetallic compounds show superconductivity at or below 10 K. This is a temperature that is typically attained using liquid He. In 1986, materials were discovered that showed superconductivity at temperatures that were around -180 °C, temperatures that could be attained using liquid N₂. It is interesting to note that these high temperature superconductors are actually ceramic materials and are very poor conductors of electricity at room temperature.

Investigations into the phenomenon of superconductivity showed that superconductors responded to the conditions they were subject to in interesting ways. It was found that when the current passing through the superconductor was increased, above a certain critical current density, designated as $J_c$, superconductivity ceased to exist. Similarly when an external magnetic field was imposed on the superconductor, above a critical value of the external field, designated as $H_c$, superconductivity ceased to exist. As already pointed out, above a critical temperature, superconductivity ceased as well, and this critical temperature is designated as $T_c$. Combined action of more than one of these influences, resulted in a breakdown of the superconductivity state even more easily. The schematic in Figure 38.2 below summarizes the response of a superconductor to the current density flowing through it, the temperature it is subject to, and the magnetic field it is placed in. The material stays a superconductor for all conditions between the origin of the plot and the surface defined in the figure.
Superconductors were observed to exclude magnetic fields, an effect called the Meissner effect, after the person who discovered it. This turned out to be a very important observation since this behavior was different from that of a regular metallic conductor. The Meissner effect indicated that superconductivity could not be merely thought of as better or improved conductivity – a new mechanism had to be proposed. The Meissner effect indicated that magnetism of materials opposed what superconductivity required of materials.

The theory that explained low temperature superconductivity is credited to Bardeen, Cooper and Schrieffer, and is hence called the BCS theory. They theorized that the electrons in superconductors operate in pairs, called Cooper pairs, which have opposite spin and opposite $k$ vectors. As a result, the pair of particles operate as though they have zero spin and have no net...
wave vector. Particles that have integer spins belong to the class of particles called Bosons, just as photons and phonons that we discussed in the previous class. In the case of superconductors, electrons, which are normally Fermions, pair up and behave like Bosons. In view of the zero wave vector of the Cooper pairs, they do not suffer from the typical scattering effects that normal electrons experience.

Cooper pairs can have a significant distance between them, of the order of several nm, and still maintain the interaction between them. This is accomplished using lattice waves, or phonons. In other words, in this situation, one boson (a cooper pair), uses another boson (a phonon), to sustain itself. The formation of a Cooper pair results in a small decrease in energy, and at least this small amount of energy must be provided to breakdown the superconducting state.

These ideas of how the Cooper pairs enable superconductivity, directly address the implications of Meissner effect which showed that magnetism opposes superconductivity. Since magnetism requires spins of electrons to align with each other, the Cooper pairs having opposite spins explain the conflict with magnetism.

Based on the interaction with magnetism, superconductors are classified into two types, called Type-I and Type-II superconductors.

Type-I superconductors completely exclude any applied magnetic fields in the superconducting state called the S-state, and abruptly become normal conductors, or attain the normal N-state, above $H_c$. In the N-state, the magnetic field completely penetrates the sample. These superconductors are usually the low temperature superconductors.

Type-II superconductors completely exclude the magnetic field up to an applied field $H_{c1}$, at which point the material develops two regions within it – regions that remain superconducting, and others that are normal. In other words, the S-state and the N-state coexist. Above a higher level of applied magnetic field $H_{c2}$ the material becomes entirely normal. This type of superconductor can usually handle much higher magnetic fields compared to Type-I superconductors.

It is relevant to note that it takes only 5-10 K of thermal energy to breakdown the low temperature superconducting state. The stability of the Cooper pairs is consistent with this energy. Therefore the BCS theory is unable to explain high temperature superconductivity – since the Cooper pairs are not believed to be capable of surviving at those high temperatures.

Superconductors face challenges in commercialization. They require low temperatures to operate, which is expensive to generate and sustain. Further, the high temperature superconductors are ceramic materials which are not easy to process, and can be brittle. Even with these challenges there are special applications where superconductors have made their mark. These include:

1) Magnetic Resonance Imaging (MRI) scans, which are increasingly commonly used in the medical field.
2) Superconducting electro magnets in particle accelerators. In particle accelerators, such as the one in CERN, very powerful magnets are required to accelerate particle beams. This is accomplished using electromagnets with high amounts of current running through the coils. With normal conductors, the heat generated would be so high that the conductors would likely melt after a short duration of operation. By using superconductors it is possible to sustain high currents, and hence very strong magnetic fields, without the associated heat.

Interestingly, one of the primary purposes of the particle accelerator at CERN is to look for a particle called the Higgs boson. This is therefore an instance where two bosons, phonons and cooper pairs, are used to look for a third boson, the Higgs boson.

In summary, we have seen the basic features associated with superconductivity. The dream is to have a room temperature superconductor – something that may or may not happen. The BCS theory has not been able to explain the high temperature superconductivity, therefore it is likely that a more fundamental theory may appear that augments or replaces the BCS theory.

In view of our repeated encounters with bosons, in the next class we will look at the Bose-Einstein statistics, which describes the statistical behavior of Bosons, and also look at a very unique prediction based on these statistics.