Superconductors

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Superconductivity

Some metals and compounds have an electrical resistance

$$R \to 0 \text{ for } T < T_c$$

where T_c is a (low) *critical temperature.*

The mechanism for pure metals is well explained by the BCS theory of paired electrons at low T.

Since 1986 a number of mixed metallic oxides have exhibited superconductivity at as high as $T = 150$ K. There is no currently accepted theory to explain all of these in detail.

Meissner effect

Superconductors are perfect *paramagnets.* They expel magnetic fields when they reach the critical T.

Everywhere inside a perfect conductor, $\vec{\mathbf{E}} = 0$. From Faraday's law:

$$\oint \vec{\mathbf{E}} \cdot d\vec{\mathbf{s}} = -\frac{d\Phi_B}{dt}$$

we see that $d\Phi_B/dt = 0$, so the magnetic flux inside cannot change.

Experimentally, not only is $\vec{\mathbf{B}}$ constant, but $\vec{\mathbf{B}} = 0$. If a superconductor is cooled below T_c in the presence of a weak $\vec{\mathbf{B}}$, the field is ejected.

If the field strength is above some B_c, superconductivity is destroyed.

BCS superconductivity in metals

As a metal lattice cools, an electron can distort the lattice of ions slightly toward it. This makes a positive charge density around it, which will attract another electron.

The electrons form pairs of opposite spins. These act as **bosons** and now obey BE statistics— they can go into the same lowest energy state. These are *Cooper pairs*.

The binding energy of the pair is on the order of 0.001 eV, and so the kT of the lattice must be small before the pairs dominate conduction.

Cooper pair conduction

The entire collection of Cooper pairs is described by a *single* wavefunction.

Above the ground state is a gap of the pair binding E. A collision with the lattice would transfer energy to the lattice and lower the pair energy. But—they are already in the lowest state. They cannot gain energy from the lattice either because of the E gap.

So lattice-electron collisions are forbidden—there is no resistance to the Cooper pairs.

BCS theory also explains why a large $\vec{\mathbf{B}}$ destroys superconductivity: the pair have opposite spins, and so opposite magnetic moments. A $B > B_c$ will raise the energy of one of the electrons and lower that of the other, when the energy gap between them is greater than their binding E, the pair is disrupted.

High T_c superconductivity

BCS predicts an upper limit $T_c \approx 30$ K for metal lattices, and this is about right from experiment.

However, metal oxide ceramics such as $YBa_2Cu_3O_7$ and others show superconductivity at much higher T_c. The mechanism(s) are not understood.

These could have great economic value—but generally are brittle and have low B_c.