Chapter 9: Superconductivity

The Nobel Prize in Physics 1913

"for his investigations on the properties of matter at low temperatures which led, inter alia, to the production of liquid helium"

Heike Kamerlingh Onnes

the Netherlands

Leiden University
Leiden, the Netherlands

b. 1853
d. 1926
Magnetic Properties of Superconductors

Below the critical temperature, $T_c$, it expels all magnetic flux from the interior.

$$B = \mu H (1 + \chi)$$

$B$ = magnetic flux
$H$ = applied field
$\chi$ = magnetic susceptibility

The Meissner Effect

Superconductor
Magnet
Liquid Nitrogen
Foam Container

www.magnet.fsu.edu
- The critical temperature ($T_c$) drops with an increase in magnetic field.
- The minimum value of the field strength required to bring about this change is the critical field strength, $H_c$.

Superconductivity exists only below a critical temperature and below a critical magnetic field strength.

- “Soft superconductors”

### Type I Superconductors

<table>
<thead>
<tr>
<th>Metal</th>
<th>Transition Temperature, $T_c$ (K)</th>
<th>Metal</th>
<th>Transition Temperature, $T_c$ (K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rh</td>
<td>0.00033</td>
<td>Ga</td>
<td>1.1</td>
</tr>
<tr>
<td>Be</td>
<td>0.023</td>
<td>Gd</td>
<td>1.1</td>
</tr>
<tr>
<td>W</td>
<td>0.015</td>
<td>Al</td>
<td>1.2</td>
</tr>
<tr>
<td>Ir</td>
<td>0.1</td>
<td>Pa</td>
<td>1.4</td>
</tr>
<tr>
<td>Lu</td>
<td>0.1</td>
<td>Th</td>
<td>1.4</td>
</tr>
<tr>
<td>Hf</td>
<td>0.1</td>
<td>Re</td>
<td>1.4</td>
</tr>
<tr>
<td>Ru</td>
<td>0.5</td>
<td>Tl</td>
<td>2.39</td>
</tr>
<tr>
<td>Os</td>
<td>0.7</td>
<td>In</td>
<td>3.408</td>
</tr>
<tr>
<td>Mo</td>
<td>0.92</td>
<td>Sn</td>
<td>3.722</td>
</tr>
<tr>
<td>Zr</td>
<td>0.546</td>
<td>Hg</td>
<td>4.153</td>
</tr>
<tr>
<td>Cd</td>
<td>0.56</td>
<td>Ta</td>
<td>4.47</td>
</tr>
<tr>
<td>U</td>
<td>0.2</td>
<td>V</td>
<td>5.38</td>
</tr>
<tr>
<td>Ti</td>
<td>0.39</td>
<td>La</td>
<td>6.00</td>
</tr>
<tr>
<td>Zn</td>
<td>0.85</td>
<td>Pb</td>
<td>1.083</td>
</tr>
</tbody>
</table>
Type II ‘hard’ superconductors have much higher critical fields and carry much higher current densities while remaining in the superconducting state.

<table>
<thead>
<tr>
<th>Compound</th>
<th>Transition Temperature (K)</th>
<th>Critical Field (T)</th>
</tr>
</thead>
<tbody>
<tr>
<td>NbTi</td>
<td>10</td>
<td>15</td>
</tr>
<tr>
<td>PbMoS</td>
<td>14.4</td>
<td>6.0</td>
</tr>
<tr>
<td>V$_3$Ga</td>
<td>14.8</td>
<td>2.1</td>
</tr>
<tr>
<td>NbN</td>
<td>15.7</td>
<td>1.5</td>
</tr>
<tr>
<td>V$_3$Si</td>
<td>16.9</td>
<td>2.35</td>
</tr>
<tr>
<td>Nb$_3$Sn</td>
<td>18.0</td>
<td>24.5</td>
</tr>
<tr>
<td>Nb$_3$Al</td>
<td>18.7</td>
<td>32.4</td>
</tr>
<tr>
<td>Nb$_3$(AlGe)</td>
<td>20.7</td>
<td>44</td>
</tr>
<tr>
<td>Nb$_3$Ge</td>
<td>23.2</td>
<td>38</td>
</tr>
</tbody>
</table>

A Type-II superconductor is characterized by a gradual transition from the superconducting to the normal state within an increasing magnetic field,
BCS Theory of Superconductivity

- electron-phonon interactions
- energy of the pairing interaction is quite weak, of the order of $10^{-3}$ eV, and thermal energy can easily break the e⁻ pairs up.
The Nobel Prize in Physics 2003

"for pioneering contributions to the theory of superconductors and superfluids"

Alexei A. Abrikosov
- 1/3 of the prize
- USA and Russia
- Argonne National Laboratory
- Argonne, IL, USA
- b. 1928

Vitaly L. Ginzburg
- 1/3 of the prize
- Russia
- P.N. Lebedev Physical Institute
- Moscow, Russia
- b. 1916

Anthony C. Leggett
- 1/3 of the prize
- United Kingdom and USA
- University of Illinois Urbana, IL, USA
- b. 1938

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High $T_c$ Superconductivity

MILESTONES IN SUPERCONDUCTIVITY

**Mercury** $(Hg)$ 4 K (1911) – Onnes discovers superconductivity while experimenting with mercury. He soon makes the same discovery with lead (Pb) and tin (Sn).

**Nickel** $(Ni)$ 10 K (1930)

**Nioium-Nitride** 18 K (1941) – Researchers switch from single elements to alloys and are able to raise superconducting temperatures.

**Vanadium3-Silicon** $(V_3Si)$ 17.6 K (1963)

**Nioium-Germanium** $(Nb_3Ge)$ 23.2 K (1971)

**LBCO** 30 K (1986) – IBM researchers Alex Müller and Georg Bednorz create the first cuprate superconductor using a lanthanum-barium-copper oxide. It’s critical temperature defies the BCS theory, and cuprates come to dominate superconductor research.

**YBCO** 92.0 K (1987) – First material to superconduct at temperatures warmer than liquid nitrogen. Discovered when University of Alabama-Huntsville researchers substitute Yttrium for Lanthanum in the Müller & Bednorz molecule.

**Tl$_2$Ba$_2$Ca$_2$Cu$_3$O$_{10}$** (TBCO) 127.0 K (1988)

**HgBa$_2$Ca$_2$Cu$_3$O$_{8+}$** 133 K (1993) – Swiss researchers produce a cuprate using mercury and bismuth which is still the highest temperature superconductor in ambient-pressure.

**Hg$_{0.8}$Tl$_{0.2}$Ca$_2$Cu$_3$O$_{8+}$** 147.0 K (1993) – by inducing extreme pressure researchers at the University of Houston are able to bring critical temperatures even higher.

http://www.magnet.fsu.edu/education/tutorials/magnetacademy/superconductivity101/page6.html
La$_{2-x}$Ba$_x$CuO$_4$

If $x > 0$, average oxidation state Cu is $>2+$

Positive holes formed in the valence band, p-type

$T_c = 35$ K

YBa$_2$Cu$_3$O$_{7-d}$

Related to the Perovskite structure type.

SrTiO$_3$

High $T_c$ Superconductivity

$T_c = 93$ K
Sr$_2$RuO$_4$ is related to the La$_2$CuO$_4$ structure.

Metallic, $T_c = 1.5$ K
- Conventional superconductors are diamagnetic

Triplet state, four 4d electrons in $t_{2g}$ band

LaFeAsO (F-doped) $T_c = 26$ K

SmFeAsO$_{1-x}$F$_x$ under pressure, $T_c = 55$ K

Layered structure
Superconducting elements of the wire found in NMR spectrometers are made of Nb₃Sn or (NbTaTi)₃Sn embedded in Cu.

Figure 17.27 The manufacture of composite superconductor wires: (a) Niobium wire is surrounded with copper during forming. (b) Tin is plated onto Nb-Cu composite wire. (c) Tin diffuses to niobium to produce the Nb₃Sn-Cu composite.

Other Applications of Superconductors

- NMR SQUID Magnetometer
- Maglev Train
- Power-transmission cable

http://chem4823.usask.ca/nmr/magnet.html
http://www.nanomagnetics.org/instrumentation_and_characterization/squid_magnetometers.php
http://www.magnet.fsu.edu/education/tutorials/magnetacademy/superconductivity101/maglev.html
http://spectrum.ieee.org/energy/the-smarter-grid/superconductors-enter-commercial-utility-service