From Last Time...

- Solids are large numbers of atoms arranged in a regular crystal structure.
- Each atom has electron quantum states, but interactions shift the energies.
- End result is a broadened “band” of energy levels in a solid.
- Band filling determines electrical properties
  - Partially full bands = metal
  - Bands completely full or empty = insulator / semiconductor
- Substitutional doping of a semiconductor leads to a material useful in electronic devices.

Superconductivity

- Superconductors are materials that have exactly zero electrical resistance.
- But this only occurs at temperatures below a critical temperature, $T_c$
- In most cases this temperature is far below room temperature.

Brief History of Superconductivity

- 1911: Kamerlingh Onnes discovers superconductivity in Hg at $T_c$ = 4.2 K
- 1933: Kamerlingh Onnes wins the Nobel Prize in Physics
- 1941: Weiss and Dresner discover the Meissner Effect
- 1942: Superconductivity is reported in solids at $T_c$ = 35 K
- 1953: Superconductivity is reported in Ni, Cu at $T_c$ = 7.8 K
- 1957: Bardeen, Cooper, and Schrieffer win the Nobel Prize in Physics

Persistent currents

- How zero is zero?
- EXACTLY!
- Can set up a persistent current in a ring.
- The magnitude of the current measured by the magnetic field generated.
- No current decay detected over many years!

Critical current

- If the current is too big, superconductivity is destroyed.
- Maximum current for zero resistance is called the ‘critical’ current.
- For larger currents, the voltage is no longer zero, and power is dissipated.

Superconducting elements

- Many elements are in fact superconducting
- But the critical temperatures are quite low.
Elemental Critical Temperatures

<table>
<thead>
<tr>
<th>Element</th>
<th>Symbol</th>
<th>Tc (K)</th>
<th>Tc (°C)</th>
<th>Tc (°F)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Neon</td>
<td>Ne</td>
<td>10.48</td>
<td>13.5</td>
<td>30.3</td>
</tr>
<tr>
<td>Argon</td>
<td>Ar</td>
<td>15.5</td>
<td>18.4</td>
<td>33.7</td>
</tr>
<tr>
<td>Krypton</td>
<td>Kr</td>
<td>23.84</td>
<td>26°</td>
<td>79°</td>
</tr>
<tr>
<td>Xenon</td>
<td>Xe</td>
<td>29.8</td>
<td>32.9</td>
<td>85°</td>
</tr>
<tr>
<td>Helium</td>
<td>He</td>
<td>4.2</td>
<td>4.2</td>
<td>4.2</td>
</tr>
</tbody>
</table>

Temperature Scales

- All these are near -450° F
- This is because they are near 0° K (Kelvin)
- Kelvin is an absolute temperature scale
- 0 K is the coldest temperature possible
- This is -459.67° F
- This is because temperature describes the average internal kinetic energy of the system.
- The Kelvin scale has the same size degree as the Celsius (°C) scale. But 0 K means no internal kinetic energy.

Reaching low temperature

- Low temperatures obtained with liquid gases.
- To turn a liquid into a gas at fixed temperature requires a certain amount of heat (latent heat)
- So the liquid warms up to its boiling point, then turns into vapor a little at a time.
- A liquid gas will remain at its boiling point.
  - Liquid Oxygen: 90.2 K (-297.4 F)
  - Liquid Nitrogen: 77 K (-320.4 F)
  - Liquid Hydrogen: 20.4 K (-423.2 F)
  - Liquid Helium: 4.2 K (-452.1 F)

Low temperature properties

- Superconductors become superconducting at low temperature
- But also, many mechanical properties change at low temperature.
- Many materials lose their elasticity.
- More subject to fracture.

Meissner effect

- Response to magnetic field
- For small magnetic fields a superconductor will spontaneously expel all magnetic flux.
- Above the critical temperature, this effect is not observed.

Screening currents

- This is really a superposition of magnetic fields.
- The applied field, plus a negative field generated by supercurrents.
- Cancels to give zero total magnetic field inside the superconductor.
- Can be used to shield magnetic fields.
Critical magnetic field

- Magnetic field is screened out by screening current.
- Larger fields require larger screening currents.
- Screening currents cannot be larger than the critical current.
- This says there is a critical magnetic field which can be screened.

Superconductor phase diagram (Type I)

Superconducting vortices

- Above the critical field, magnet field penetrates as quantized flux lines (Type II superconductor).
- Each vortex carries one flux quantum of flux.

Superconducting vortices

Magnetic Levitation

- Permanent magnet above a superconductor

Vortex lines

Higher transition temperatures

<table>
<thead>
<tr>
<th>Table 10-6</th>
<th>( T_c ) and ( J_c ) values for some type I and type II superconductors</th>
<th>( T_c ) (°K)</th>
<th>( J_c ) (at 0 T, 0°C)</th>
<th>( T_c ) (°K)</th>
<th>( J_c ) (at 0 T, 0°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Al</td>
<td>1.175</td>
<td>0.0015</td>
<td>18.1</td>
<td>24.5</td>
<td></td>
</tr>
<tr>
<td>Cu</td>
<td>0.517</td>
<td>0.0001</td>
<td>23.2</td>
<td>24.0</td>
<td></td>
</tr>
<tr>
<td>Hg</td>
<td>0.154</td>
<td>0.0011</td>
<td>30.0</td>
<td>35.0</td>
<td></td>
</tr>
<tr>
<td>Be</td>
<td>3.560</td>
<td>0.0062</td>
<td>16.5</td>
<td>20.6</td>
<td></td>
</tr>
<tr>
<td>Nb</td>
<td>9.25</td>
<td>0.0001</td>
<td>17.1</td>
<td>15.6</td>
<td></td>
</tr>
<tr>
<td>Cs</td>
<td>0.066</td>
<td>0.0070</td>
<td>15.4</td>
<td>6.0</td>
<td></td>
</tr>
<tr>
<td>Pb</td>
<td>7.086</td>
<td>0.0001</td>
<td>40.1</td>
<td>1.7</td>
<td></td>
</tr>
<tr>
<td>Nb</td>
<td>3.722</td>
<td>0.0035</td>
<td>390</td>
<td>10</td>
<td></td>
</tr>
<tr>
<td>Ti</td>
<td>2.38</td>
<td>0.0178</td>
<td>290</td>
<td>7</td>
<td></td>
</tr>
<tr>
<td>Zn</td>
<td>0.85</td>
<td>0.0054</td>
<td>230</td>
<td>7</td>
<td></td>
</tr>
</tbody>
</table>

Superconducting Train

- At the base of Mount Fuji, close to Tokyo, a 18 km long track of the new testing line was constructed for testing components, functionality and principles of the levitating train.
- Electric current passing through the copper coils on the ground produce alternating magnetic field that attracts the superconducting magnets of the train and propels the train forward.
Superconducting Magnets

- Solenoid as in conventional electromagnet.
- But once current is injected, power supply turned off, current and magnetic field stays forever... ...as long as $T < T_c$

Magnetic Field Ranges

<table>
<thead>
<tr>
<th>Field Size</th>
<th>Example</th>
<th>Field Size</th>
<th>Example</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.5 T</td>
<td>900 MHz NMR (UW Chemistry)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>21.7 T</td>
<td>900 MHz NMR (UW Chemistry)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Magnets for MRI

- Magnetic Resonance Imaging typically done at 1.5 T
- Superconducting magnet to provide static magnetic field
- Spatial resolution of positions of tracer atomic nuclei.

900 MHz NMR (UW Chemistry)

21.7 T field

Higher-frequency NMR

- 1 GHz NMR (Nuclear Magnetic Resonance)
- 23.5 T
- Higher frequency gives higher resolution, more information about chemical bonding, etc.

Large scale applications

- Superconducting magnet
- Plasma confinement torus
- Proposed ITER fusion test reactor
**Superconducting wire**
- Multifilamentary wire
- Induce strong pinning by incorporation of defects.
- Strong pinning leads to zero dissipation even with vortex penetration.

**Lorentz microscopy of vortices**
- Magnetic flux from vortices can be imaged in a specialized electron microscope.
- Vortex pinning to increase the critical current.

**Quantum mechanics again**
- Vortex flux is quantized for the same reason atomic orbitals are quantized.
- Superconducting state is a macroscopic quantum state very analogous to a giant atom.
- On a path surrounding the vortex, the superconducting wavefunction must have an integer number of wavelengths.

**Flux quantization**
- In fact, any closed loop in a superconductor contains an integer number of flux quanta.
- Including a superconducting ring.

**Flux quantization in a loop**
- Flux passing through center of ring can only be integer multiples of the flux quantum.
- Arises from quantization condition on macroscopic superconducting wavefunction.

**Josephson effect**
- Another macroscopic quantum effect.
- Arises from 'phase coherence' of wavefunction across macroscopic distances.
- Special electrical properties across interface between two superconductors.

**Wavefunction quantization around this loop**
- Uniform flux out here
- Persistent supercurrent
**SQUID**

- Superconducting Quantum Interference Device
- Can think of as optical interference along two paths
- Phase difference controlled by magnetic flux
- Sensitive measure of tiny magnetic fields

**Small magnetic fields**

- Critical current
- Flux thru ring

**Biomagnetic SQUID array**

- Los Alamos: 155 squid sensors

**Bio-Magnetic Data**

- Spatially localized information about electrical current flow in brain.

**Microscopic theory of superconductivity**

- Bardeen, Cooper, Schrieffer
- BCS theory (1957) - Nobel Prize in Physics 1972

- Multi-electron effect, interactions with lattice vibrations
- ‘Correlated’ ground state
- Very different from any previous theory.

**High temperature superconductors**

- Copper and oxygen based materials.
- Very different from low-temperature superconductors.
- Discovered - 20 years ago.
- No theoretical consensus.
- Much more difficult problems than Low-temp. materials.

**Table 10-8: Critical temperatures of some high $T_c$ superconductors**

<table>
<thead>
<tr>
<th>Material</th>
<th>$T_c$, K</th>
</tr>
</thead>
<tbody>
<tr>
<td>La$_2$CuO$_4$</td>
<td>30</td>
</tr>
<tr>
<td>Li$_2$CuO$_2$</td>
<td>40</td>
</tr>
<tr>
<td>YBa$_2$Cu$_3$O$_y$</td>
<td>92</td>
</tr>
<tr>
<td>D$_4$Ba$_2$Cu$_3$O$_x$</td>
<td>92.5</td>
</tr>
<tr>
<td>Cu$_2$(OH)$_2$Cl$_2$</td>
<td>117</td>
</tr>
<tr>
<td>Bi$_2$Sr$_2$CaCu$_2$O$_x$</td>
<td>125</td>
</tr>
<tr>
<td>Tl$_2$Ba$_2$Ca$_2$Cu$_3$O$_x$</td>
<td>125</td>
</tr>
</tbody>
</table>
Another new material

- Magnesium diboride
- MgB$_2$, $T_c=39$K
- Discovered ~ 3 years ago.
- Microscopic theory understood, but novel in that it has two independent electron bands.
- Like two superconductors in the same spatial location.