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 each type atomic electron state (e.g. 1s) corresponds to a broadened ‘band’ of energy levels in a solid.

• Band filling determines electrical properties
  - Partially full bands = metal
  - Bands completely full or empty = insulator / semiconducotor

• 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 $T_c=4$ K
- 1913 Kamerlingh Onnes the Nobel Prize in Physics
- 1933 Meissner and Ochsenfeld discover the Meissner Effect
- 1941 Superconductivity is reported in Nb nitride at $T_c=16$ K
- 1953 Superconductivity is reported in $V_3Si$ at $T_c=17.5$ K
- 1957 Microscopic BCS theory of superconductivity is developed
- 1962 The Josephson effect is predicted based on the BCS theory
- 1962 Development of first superconducting wire (Westinghouse)
- 1972 Bardeen, Cooper & Schrieffer win the Nobel Prize in Physics
- 1973 Josephson wins the Nobel Prize in Physics
- 1986 Müller and Bednorz (IBM-Zurich) discover High Temperature Superconductivity in La-Ba-Cu-O at $T_c=35$ K!
- 1987 Müller and Bednorz win the Nobel Prize in Physics
- 1987 Superconductivity found in YBCO copper oxide at $T_c=92$ K !!!
- 1988 $T_c$ is pushed to 120K in a ceramic containing Ca and Ti
- 1993 HgBa$_2$Ca$_2$Cu$_3$O$_8$ is found to superconduct at $T_c=133$ K
- ........
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>Aluminium</td>
<td>Al</td>
<td>1.75</td>
<td>-271</td>
<td>-457</td>
</tr>
<tr>
<td>Beryllium</td>
<td>Be</td>
<td>0.03</td>
<td>-273</td>
<td>-460</td>
</tr>
<tr>
<td>Cadmium</td>
<td>Cd</td>
<td>0.52</td>
<td>-273</td>
<td>-459</td>
</tr>
<tr>
<td>Gallium</td>
<td>Ga</td>
<td>1.08</td>
<td>-272</td>
<td>-458</td>
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<tr>
<td>Hafnium</td>
<td>Hf</td>
<td>0.13</td>
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<td>-459</td>
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<tr>
<td>Mercury</td>
<td>Hg</td>
<td>4.15</td>
<td>-269</td>
<td>-452</td>
</tr>
<tr>
<td>Indium</td>
<td>In</td>
<td>3.41</td>
<td>-270</td>
<td>-454</td>
</tr>
<tr>
<td>Iridium</td>
<td>Ir</td>
<td>0.11</td>
<td>-273</td>
<td>-459</td>
</tr>
<tr>
<td>Lanthanum</td>
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<td>-268</td>
<td>-451</td>
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<tr>
<td>Molybdenum</td>
<td>Mo</td>
<td>0.92</td>
<td>-272</td>
<td>-458</td>
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<tr>
<td>Niobium</td>
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<td>-443</td>
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<tr>
<td>Osmium</td>
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<td>-458</td>
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<td>Lead</td>
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<td>-447</td>
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<tr>
<td>Rhenium</td>
<td>Re</td>
<td>1.7</td>
<td>-271</td>
<td>-457</td>
</tr>
<tr>
<td>Ruthenium</td>
<td>Ru</td>
<td>0.49</td>
<td>-273</td>
<td>-459</td>
</tr>
<tr>
<td>Tin</td>
<td>Sn</td>
<td>3.72</td>
<td>-269</td>
<td>-453</td>
</tr>
<tr>
<td>Tantalum</td>
<td>Ta</td>
<td>4.47</td>
<td>-269</td>
<td>-452</td>
</tr>
<tr>
<td>Technetium</td>
<td>Tc</td>
<td>7.8</td>
<td>-265</td>
<td>-446</td>
</tr>
<tr>
<td>Thorium</td>
<td>Th</td>
<td>1.38</td>
<td>-272</td>
<td>-457</td>
</tr>
<tr>
<td>Titanium</td>
<td>Ti</td>
<td>0.4</td>
<td>-273</td>
<td>-459</td>
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<tr>
<td>Tellurium</td>
<td>Tl</td>
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<td>-271</td>
<td>-455</td>
</tr>
<tr>
<td>Vanadium</td>
<td>V</td>
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<td>-450</td>
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<tr>
<td>Tungsten</td>
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</tr>
<tr>
<td>Zinc</td>
<td>Zn</td>
<td>0.85</td>
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<td>-458</td>
</tr>
<tr>
<td>Zirconium</td>
<td>Zr</td>
<td>0.61</td>
<td>-273</td>
<td>-459</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.
Magnetic Levitation

- Permanent magnet above a superconductor

High-temperature superconductor
Vortex lines

Ampere's law: \( \mu_0 J = dB/dx \)

Critical current

 Flux quanta

**FLUX PINNING**
prevents flux penetration

S
MAGNET

N

HTS
Higher transition temperatures

**Table 10-6** $T_c$ and $B_c$ values for some type I and type II superconductors

<table>
<thead>
<tr>
<th>Type I element</th>
<th>$T_c$ (K)</th>
<th>$B_c$ (at 0 K, $T$)</th>
<th>Type II compound</th>
<th>$T_c$ (K)</th>
<th>$B_{c2}$ (at 0 K, $T$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Al</td>
<td>1.175</td>
<td>0.0105</td>
<td>Nb$_3$Sn</td>
<td>18.1</td>
<td>24.5</td>
</tr>
<tr>
<td>Cd</td>
<td>0.517</td>
<td>0.0028</td>
<td>Nb$_3$Ge</td>
<td>23.2</td>
<td>34.0</td>
</tr>
<tr>
<td>Hg</td>
<td>4.154</td>
<td>0.0411</td>
<td>NbN</td>
<td>16.0</td>
<td>15.3</td>
</tr>
<tr>
<td>In</td>
<td>3.408</td>
<td>0.0282</td>
<td>V$_3$Ga</td>
<td>16.5</td>
<td>35.0</td>
</tr>
<tr>
<td>Nb</td>
<td>9.25</td>
<td>0.2060</td>
<td>V$_3$Si</td>
<td>17.1</td>
<td>15.6</td>
</tr>
<tr>
<td>Os</td>
<td>0.66</td>
<td>0.0070</td>
<td>PbMoS</td>
<td>14.4</td>
<td>6.0</td>
</tr>
<tr>
<td>Pb</td>
<td>7.196</td>
<td>0.0803</td>
<td>CNb</td>
<td>8.0</td>
<td>1.7</td>
</tr>
<tr>
<td>Sn</td>
<td>3.722</td>
<td>0.0305</td>
<td>MgB$_2$</td>
<td>39.0</td>
<td>16</td>
</tr>
<tr>
<td>Tl</td>
<td>2.38</td>
<td>0.0178</td>
<td>Rb$<em>3$C$</em>{60}$</td>
<td>29.0</td>
<td>?</td>
</tr>
<tr>
<td>Zn</td>
<td>0.85</td>
<td>0.0054</td>
<td>Cs$<em>2$RbC$</em>{60}$</td>
<td>33.0</td>
<td>?</td>
</tr>
</tbody>
</table>
Superconducting Train

- At the base of Mount Fuji, close to Tokyo, 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 propells 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>
</tr>
</thead>
<tbody>
<tr>
<td>850T</td>
<td>the strongest Destructive Pulsed magnet</td>
</tr>
<tr>
<td>60T</td>
<td>60 T long Pulse magnet</td>
</tr>
<tr>
<td>33T</td>
<td>33T continuous field magnet</td>
</tr>
<tr>
<td>2T</td>
<td>MRI machine</td>
</tr>
<tr>
<td>4x10^-1T</td>
<td>Stereo Speaker Magnets</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Field Size</th>
<th>Example</th>
</tr>
</thead>
<tbody>
<tr>
<td>4x10^-1T</td>
<td>Ice cube</td>
</tr>
<tr>
<td>3x10^-1T</td>
<td>Household refrigerator magnet</td>
</tr>
<tr>
<td>10^-2 T</td>
<td>Surface of Sun</td>
</tr>
<tr>
<td>10^-4 T</td>
<td>Near Household Wiring</td>
</tr>
<tr>
<td>3 x 10^-5 T</td>
<td>Surface of Earth</td>
</tr>
<tr>
<td>3 x 10^-10T</td>
<td>Produced by Human Body</td>
</tr>
</tbody>
</table>
Magnets for MRI

- **Magnetic Resonance Imaging** typically done at 1.5 T
- Superconducting magnet to provides 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.

Wavefunction quantization around this loop
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.

Superconductor 2

Weak link, or tunnel barrier
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

- Earth's field
- Power lines
- Automobile at 50 meters
- Screwdriver at 5 meters
- Chip transistor at 2 meters

- Microtesla
- Nanotesla
- Picotesla
- Femtotesla

- Lung particles
- Human heart
- Skeletal muscles
- Fetal heart
- Human eye
- Human brain (alpha waves)
- Human brain (evoked response)
- SQUID system noise level

Wed. Oct 19
Phy107 Lecture 30
Biomagnetic SQUID array

Los Alamos: 155 squid sensors
Bio-Magnetic Data

- Spatially localized information about electrical current flow in brain.
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>LaBaCuO</td>
<td>30</td>
</tr>
<tr>
<td>La$_2$CuO$_4$</td>
<td>40</td>
</tr>
<tr>
<td>YBa$_2$Cu$_3$O$_7$</td>
<td>92</td>
</tr>
<tr>
<td>DyBa$_2$Cu$_3$O$_7$</td>
<td>92.5</td>
</tr>
<tr>
<td>C$_{60}$(CHBr$_3$)</td>
<td>117</td>
</tr>
<tr>
<td>BiSrCaCuO</td>
<td>120</td>
</tr>
<tr>
<td>TlBaCaCuO</td>
<td>125</td>
</tr>
</tbody>
</table>
Another new material

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