From Last Time...
- Molecules
  - Symmetric and anti-symmetric wave functions
  - Lightly higher and lower energy levels
  - More atoms more energy levels
- Conductors, insulators and semiconductors

Today
- Conductors and superconductors

Due Friday: Essay outline
HW9: Chap 15 Conceptual: # 2, 4, 14, 24 Problems: # 2, 4

Energy Levels
- Basic n levels,
- Include l and m_l

Energy Levels in a Metal
Na = [Ne]3s¹
- 3p
  - Partially Full
  - This band not completely occupied
- 3s
  - 1 electron
- 2p
  - 6 electrons
- 2s
  - 2 electrons
- 1s
  - 2 electrons
- Include molecular symmetric and anti-symmetric wavefunctions

n- and p-type semiconductors
- Conduction band
- Valence band
- p-type semiconductor
  - Holes from acceptors
  - Acceptors, one fewer electron
  - n-type semiconductor
  - Donors, one extra electron
  - Electrons from donors

Junctions
- Real usefulness comes from combining n and p-type semiconductors
- Junction develops a 'built-in' electric field at the interface due to charge rearrangement.

Light emitting diode
- Battery causes electrons and holes to flow toward pn interface
- Electrons and holes recombine at interface (electron drops down to lower level)
- Photon carries away released energy.
- Low energy use - one color!
Electrical resistance

- Last time we said that a metal can conduct electricity.
- Electrons can flow through the wire when pushed by a battery.
- But remember that the wire is made of atoms.
- Electrons as waves drift through the atomic lattice.

Life is tough

- In the real world, electrons don’t have it so easy
- Some missing atoms (defects)
- Vibrating atoms!

Electron scatters from these irregularities, $\Rightarrow$ resistance

Resistance

- As electron wave propagates through lattice, it faces resistance
- Resistance:
  - Bumps from vibrating atoms
  - Collisions with impurities
  - Repulsion from other electrons
  - Electrons ‘scatter’ from these atomic vibrations and defects.
- Vibrations are less at low temperature, so resistance decreases.
- More current flows through wire
- Life is tough for electrons, especially on hot days

Temperature-dependent resistance

- Suppose we cool down the wire that carries electrical current to light bulb. The light will
  A. Get brighter
  B. Get dimmer
  C. Stay same

Why does temperature matter?

- Temperature is related to the energy of a macroscopic object.
- The energy usually shows up as energy of random motion.
- There really is a coldest temperature, corresponding to zero motional energy!
- The Kelvin scale has the same size degree as the Celsius (°C) scale. But 0 K means no internal kinetic energy.
- 0 degrees Kelvin (Absolute Zero) is the coldest temperature possible
  - This is -459.67 °F
Temperature scales

- **Kelvin (K):**
  - \( K = C + 273.15 \)
  - \( K = \frac{5}{9} F + 255.37 \)

<table>
<thead>
<tr>
<th>Fahrenheit</th>
<th>Celsius</th>
<th>Kelvin</th>
<th>comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>212</td>
<td>100</td>
<td>373.15</td>
<td>water boils</td>
</tr>
<tr>
<td>32</td>
<td>0</td>
<td>273.15</td>
<td>water freezes</td>
</tr>
<tr>
<td>-300.42</td>
<td>-195.79</td>
<td>77.36</td>
<td>liquid nitrogen</td>
</tr>
<tr>
<td>-452.11</td>
<td>-268.95</td>
<td>4.2</td>
<td>liquid helium</td>
</tr>
<tr>
<td>-459.67</td>
<td>-273.15</td>
<td>0</td>
<td>absolute zero</td>
</tr>
</tbody>
</table>

**Comments:**
- **Absolute zero:** -273.15 K or 0° C or 32° F
- **Liquid helium boils:** 4.2 K or -268.95° C or -452.11° F
- **Liquid nitrogen boils:** 77.36 K or -195.79° C or -300.42° F
- **Water freezes:** 273.15 K or 0° C or 32° F
- **Water boils:** 373.15 K or 100° C or 212° F

**What happens at the lowest temperature?**

- **Kelvin (1824-1907):** electrons freeze and resistance increases
- **Onnes (1853-1926):** Resistance continues drop, finally reaching zero at zero temperature

**Sometimes, something else!**

**Heike Kamerlingh Onnes**
- 1908 - liquefied helium (~4 K = -452°F)
- 1911 investigated low temperature resistance of mercury
- Found resistance dropped abruptly to zero at 4.2 K
- 1913 - Nobel Prize in physics

**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

**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
- In fact, most of them are!

Critical temperatures

If superconductivity is so common, why don’t we have superconducting cars, trains, toothbrushes?

Many superconducting critical temperatures are low.

<table>
<thead>
<tr>
<th>Element</th>
<th>Critical T. (K)</th>
<th>T (°C)</th>
<th>T (°F)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aluminum</td>
<td>1.75</td>
<td>-271</td>
<td>-457</td>
</tr>
<tr>
<td>Mercury</td>
<td>4.15</td>
<td>-269</td>
<td>-452</td>
</tr>
<tr>
<td>Lead</td>
<td>7.2</td>
<td>-266</td>
<td>-447</td>
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<tr>
<td>Tin</td>
<td>3.72</td>
<td>-269</td>
<td>-453</td>
</tr>
<tr>
<td>Niobium</td>
<td>9.25</td>
<td>-264</td>
<td>-443</td>
</tr>
</tbody>
</table>

Higher transition temperatures

- Much higher critical temperature alloys have been discovered
- NbTi 10 K
- Nb₃Sn 19 K
- YBa₂Cu₃O₇ 92 K
- BiSrCaCuO 120 K

High-temperature superconductors

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.

Meissner effect

- Apply uniform magnetic field.
- Superconductor responds with circulating current.
- Produces own magnetic field

Applied field
Field from screening currents
Add these fields together
Addition, field enhanced
Cancellation: field zero
**Question**

A superconductor has a maximum supercurrent it can carry before losing superconductivity. A superconductor expels an applied magnetic field with a circulating supercurrent that generates a canceling magnetic field.

When the applied magnetic field is increased to larger and larger values, the superconductor

A. Continues to expel the field
B. Expels only part of the field
C. Loses superconductivity

**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.
- Above this field, superconductivity is destroyed (screening current exceeds critical current)

**Critical fields**

- It was one of Onnes’ disappointments that even small magnetic fields destroyed superconductivity.
- Superconductivity seemed a fragile effect
  - Only observed at low temperature
  - Destroyed by small magnetic fields.

**A century of superconductivity**

- 1911: Superconductivity discovered at 4K
- 1950: Landau-Ginzburg theory
- 1954: Type II superconductors
- 1957: BCS microscopic theory
- 1962: Josephson effect
- 1986: High temp superconductivity
- 2011

**Discovery!** Some superconductors behave entirely differently in a magnetic field.

These are called type II superconductors.
Multi-electron effect, interactions with lattice vibrations
'Correlated' ground state
Very different from any previous theory.
Add two spin 1/2 particles together to get a spin one particle. No longer fermion - new physics.