From Last Time…

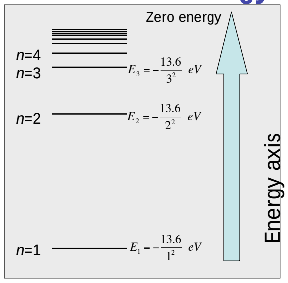
- Molecules
  - Symmetric and anti-symmetric wave functions
  - Lightly higher and lower energy levels
  - More atoms more energy levels
- Conductors, insulators and semiconductors

Today

- Conductors and superconductors

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

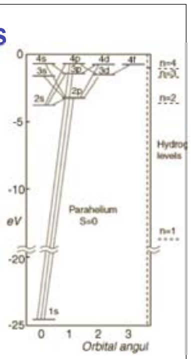
Energy Levels



$$E_3 = -\frac{13.6}{3^2}\ eV$$

$$E_2 = -\frac{13.6}{2^2}\ eV$$

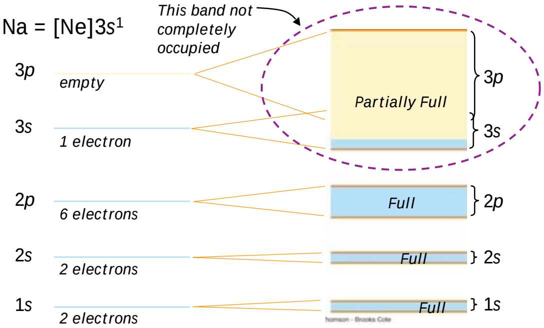
$$E_1 = -\frac{13.6}{1^2}\ eV$$



- Basic n levels,
- include l and m_l

Energy Levels in a Metal

Na = $[Ne]3s^1$



- Include molecular symmetric and anti-symmetric wavefuctions

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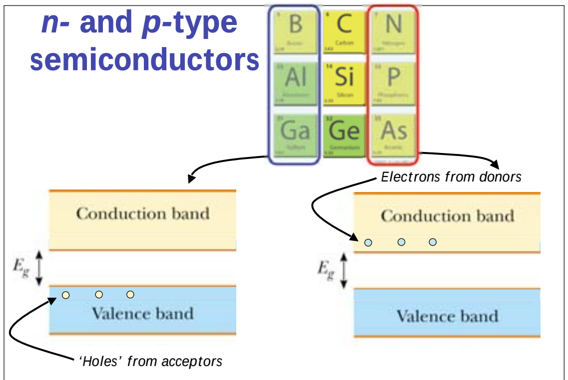
n- and *p*-type semiconductors

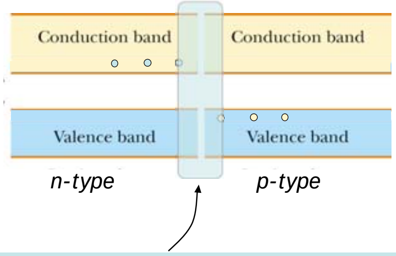


p-type semiconductor
Acceptors, one fewer electron

n-type semiconductor
Donors, one extra electron

Junctions

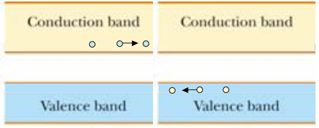
- Real usefulness comes from combining *n* and *p*-type semiconductors



Junction develops a 'built-in' electric field at the interface due to charge rearrangement.

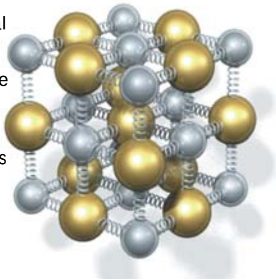
Light emitting diode

- 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.



Resistance question

Suppose we have a perfect crystal of metal in which we produce an electric current. The electrons in the metal

A. Collide with the atoms, causing electrical resistance

B. Twist between atoms, causing electrical resistance

C. Propagate through the crystal without any electrical resistance

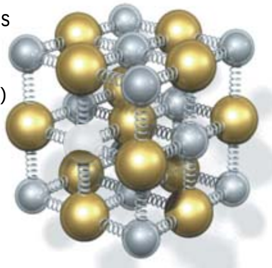
If all atoms are perfectly in place, the electron moves though the without any resistance!

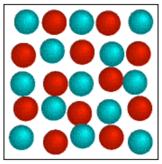
Life is tough

- In the real world, electrons don't have it so easy

Some missing atoms (defects)

Vibrating atoms!





Electron scatters from these irregularities, -> resistance

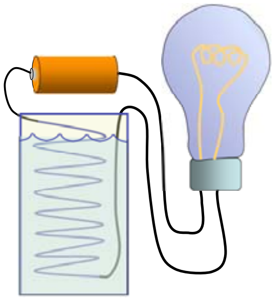
Temperature-dependent resistance

Suppose we cool down the wire that carries electrical current to light bulb. The light will

A. Get brighter

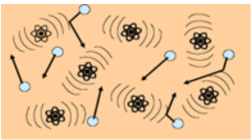
B. Get dimmer

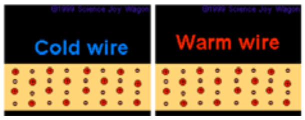
C. Stay same



Resistance

- As elecron 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, <u>especially on hot days</u>





http://regentsprep.org/Regents/physics/phys03/bresist/default.htm

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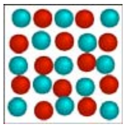
Why does temperature matter?

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

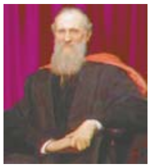


Temperature scales

- Kelvin (K):
  - **K = C + 273.15**
  - **K = 5/9 F + 255.37**

Fahrenheit	Celsius	Kelvin	comments
212	100	373.15	water boils
32	0	273.15	water freezes
-300.42	-195.79	77.36	liquid nitrogen boils
-452.11	-268.95	4.2	liquid helium boils
-459.67	-273.15	0	absolute zero

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

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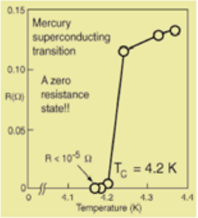
Sometimes, something else!

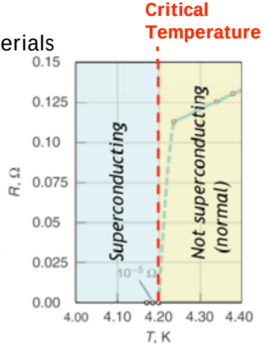
Heike Kamerlingh Onnes

- 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

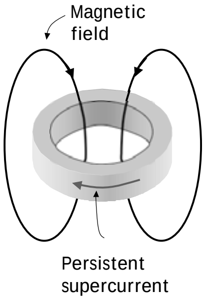
- Superconductors are materials that have exactly zero electrical resistance.
- But this only occurs at temperatures below a critical temperature, T_c
- In most cases this temperature is far below room temperature.



Hg (*mercury*)

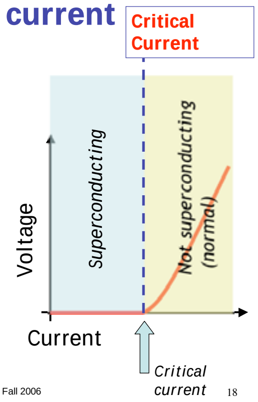
Persistent currents

- 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!



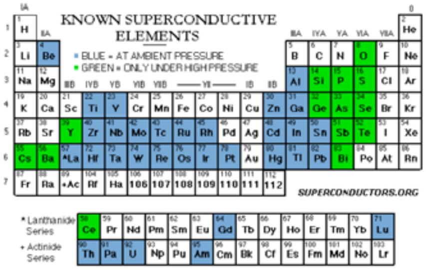
Critical current

- 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
- 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.

Element	Critical T. (K)	(˚C)	(˚F)
Aluminum	1.75	-271	-457
Mercury	4.15	-269	-452
Lead	7.2	-266	-447
Tin	3.72	-269	-453
Niobium	9.25	-264	-443

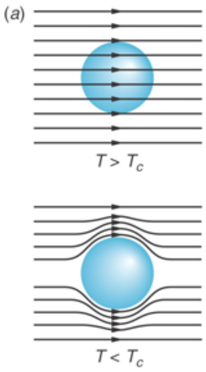
Higher transition temperatures

- Much higher critical temperature alloys have been discovered

NbTi	10 K	
Nb_3Sn	19 K	
$YBa_2Cu_3O_{7,}$	92 K	High-temperature superconductors
BiSrCaCuO,	120 K	

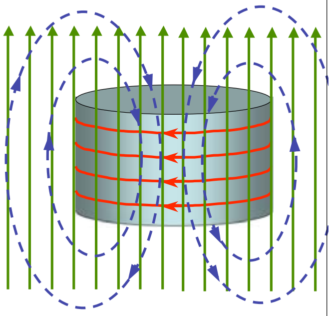
Meissner effect

- 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

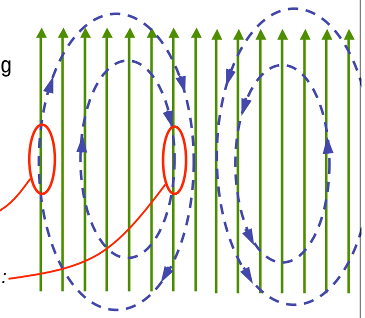
- Apply uniform magnetic field.
- Superconductor responds with circulating current.
- Produces own magnetic field



Applied field

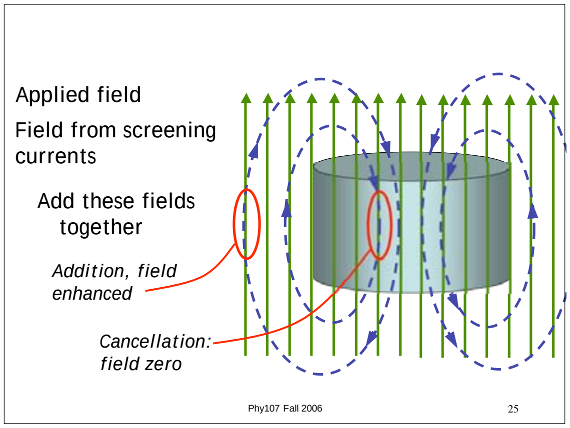
Field from screening currents

Add these fields together



Addition, field enhanced

Cancellation: field zero



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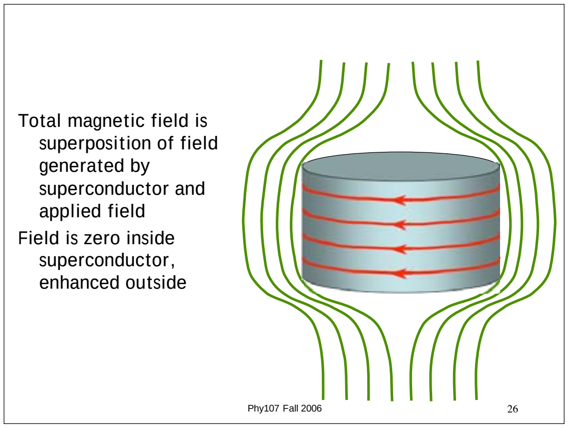


Total magnetic field is superposition of field generated by superconductor and applied field

Field is zero inside superconductor, enhanced outside

Question

A superconductor has a maximum supercurrent it can carry before losing superconductivity.

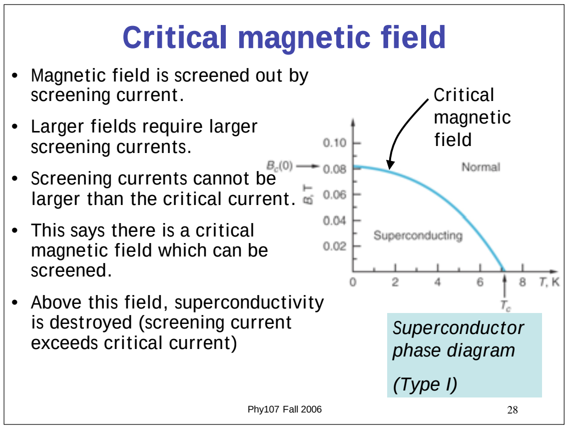
A superconductor expels an applied magnetic field with a circulating supercurrent that generates a canceling magnetic field.

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 magnetic field

Superconductor phase diagram

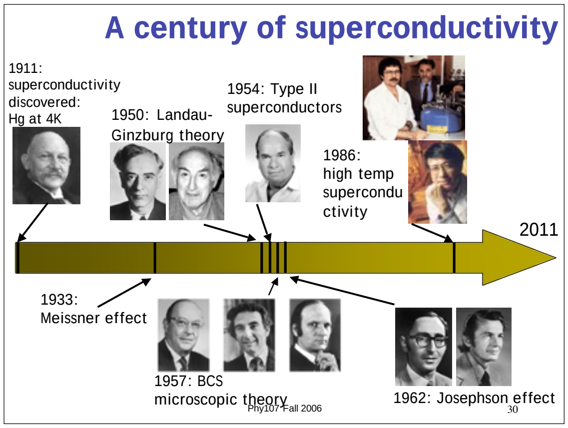
(Type I)

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.

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

These are called type II superconductors



A century of superconductivity

1911: superconductivity discovered: Hg at 4K

1950: Landau-Ginzburg theory

1954: Type II superconductors

1986: high temp superconductivity

2011

1933: Meissner effect

1957: BCS microscopic theory

1962: Josephson effect

Microscopic theory of superconductivity

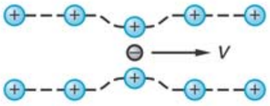
BCS theory (1957) - Nobel Prize in Physics 1972

Multi-electron effect, interactions with lattice vibrations

'Correlated' ground state

Very different from any previous theory.

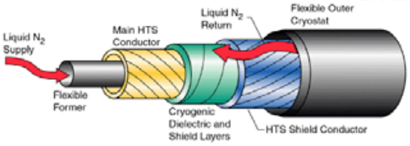
Add two spin 1/2 particles together to get a spin one particle. No longer fermion - new physics



Superconducting power cables

- 2001: Detroit, MI
  - Detroit Edison,Frisbie Substation
  - three 400-foot HTS cables
  - 100 million watts of power
  - Uses high-temperature superconductors
  - Discovered 1986, work at temperature of liquid notrogen

Figure 1.
Superconducting cable being pulled in underground circuit.



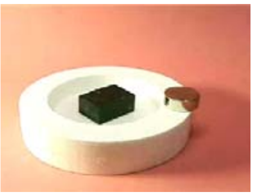
http://www.ornl.gov/sci/fed/applied/htspa/cable.htm

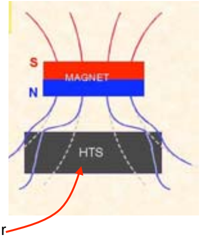
Superconducting Magnets

- 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 Levitation





High-temperature superconductor

- Permanent magnet above a superconductor

Superconducting Train

430 km/h = 267.2 mph

Copper coils

Superconducting coil

- At base of Mount Fuji, close to Tokyo,
- 18 km long test track constructed

Tevatron

- 1983
- Radius = 6.3 km
- 1000 superconducting magnets (Nb_3Ti wires)
- Protons + Antiprotons
- Energy = 1000 GeV (=1 TeV)
- v ~ 200 mph slower than speed of light