Exam 3

Hour Exam 3: Wednesday, November 29th

- In-class, Quantum Physics and Nuclear Physics
- Twenty multiple-choice questions
- Will cover:Chapters 13, 14, 15 and 16
  Lecture material
- You should bring
  - 1 page notes, written single sided
  - #2 Pencil and a Calculator
  - Review test will be available online

Quantum Mechanics

- Quantization of light
  - Light comes in discrete clumps (photons)
  - Light shows both particle and wave-like properties
  - Photon energy E = hf=hc/λ
  - Evidence for particle properties: the photoelectric effect
- Matter waves
  - Matter shows both particle and wave-like properties

$$\text{deBroglie wavelength} = \frac{\text{Planck's constant}}{\text{momentum}}, \lambda = \frac{h}{p}$$

  - Evidence for wave properties is interference and diffraction

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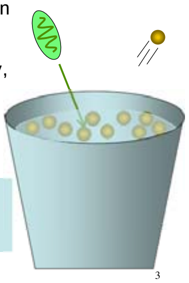
Photoelectric effect summary

- Light is made up of photons, individual 'particles', each with energy: $E = hf = \frac{hc}{\lambda} = \frac{1240 \ eV - nm}{\lambda}$
- **One** photon collides with **one** electron - knocks it out of metal.
- If photon doesn't have enough energy, cannot knock electron out.
- Intensity (= # photons / sec) doesn't change this.



Photon greater than a minimum frequency (less than a maximum wavelength) required to eject electron

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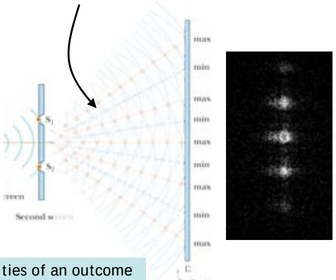
Photon(or electron) interference?

Do an interference experiment again.
But turn down the intensity until only ONE photon at a time is between slits and screen

Only one photon present here



Is there still interference?

Needed the idea of probabilities of an outcome happening to explain the wavelike and particle like results of interference experiments.

Wavelengths of massive objects

- deBroglie wavelength = $\lambda = \frac{h}{p}$
- $p=mv$ for a nonrelativistic ($v<<c$) particle **with mass**.

$$\left.\right\} \lambda = \frac{h}{mv}$$

$$\lambda = \frac{h}{p} = \frac{\boxed{hc}}{\sqrt{2\,\boxed{mc^2}\,\boxed{E_{kinetic}}}}$$

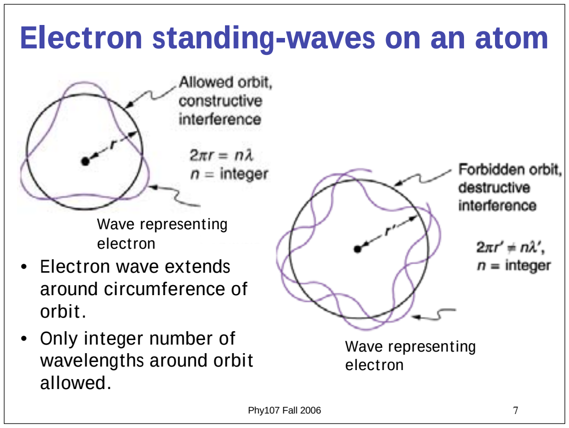
Same constant as before

kinetic energy

rest energy

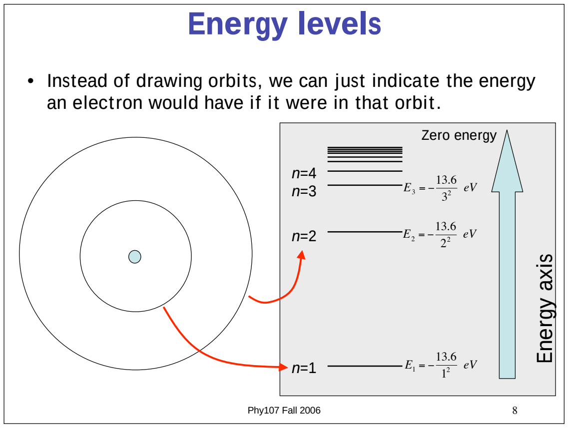
Using Quantum Mechanics

- Quantum states in a hydrogen atom
  - Models of the hydrogen atom
  - Absorption and emission of light (line spectra)
- The wavefunction of a quantum state
  - The ground state and excited states
  - Probabilistic interpretation of the wavefunction.
- Heisenberg uncertainty principle
  - Position and momentum cannot be know simultaneously
  - Consequency of wave properties



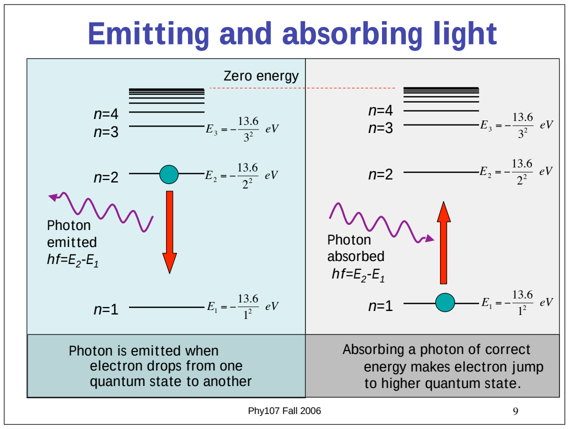
Electron standing-waves on an atom

- Electron wave extends around circumference of orbit.
- Only integer number of wavelengths around orbit allowed.



Energy levels

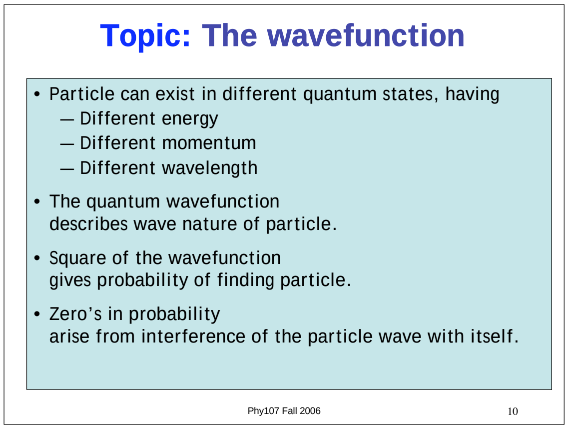
- Instead of drawing orbits, we can just indicate the energy an electron would have if it were in that orbit.



Emitting and absorbing light

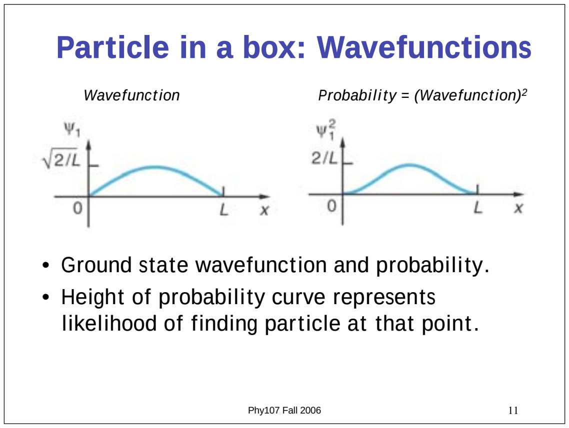
Photon is emitted when electron drops from one quantum state to another

Absorbing a photon of correct energy makes electron jump to higher quantum state.



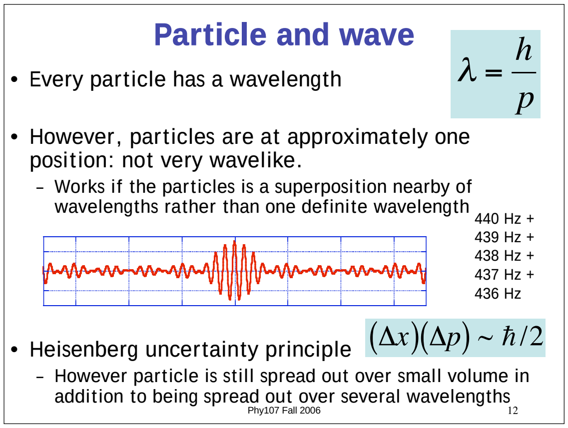
Topic: The wavefunction

- Particle can exist in different quantum states, having
  - Different energy
  - Different momentum
  - Different wavelength
- The quantum wavefunction describes wave nature of particle.
- Square of the wavefunction gives probability of finding particle.
- Zero's in probability arise from interference of the particle wave with itself.



Particle in a box: Wavefunctions

- Ground state wavefunction and probability.
- Height of probability curve represents likelihood of finding particle at that point.



Particle and wave

$$\lambda = \frac{h}{p}$$

- Every particle has a wavelength
- However, particles are at approximately one position: not very wavelike.
  - Works if the particles is a superposition nearby of wavelengths rather than one definite wavelength

- Heisenberg uncertainty principle $(\Delta x)(\Delta p) \sim \hbar/2$
  - However particle is still spread out over small volume in addition to being spread out over several wavelengths

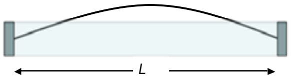
Uncertainty in Quantum Mechanics

Position uncertainty = L

(Since λ=2L)

Momentum ranges from $-\frac{h}{\lambda}$ *to* $+\frac{h}{\lambda}$: range $= 2\frac{h}{\lambda} = \frac{h}{L}$

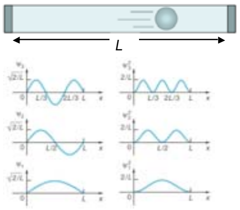
$\lambda = 2L$
One half-
wavelength

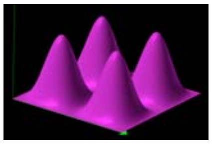


Reducing the box size reduces position uncertainty, but the momentum uncertainty goes up!

The product is constant:
(Δx) • (Δp) is always greater than (h / 4π)

Particle in a box or a sphere





- Simple in 1D(or 2,3D) box
  - Fit n half wavelengths in the box
- More complex in the hydrogen atom
  - Box, the force that keeps the electron near the nucleus, is the coulomb force
  - Coulomb force is spherically symmetric - the same in any direction
  - Still 3 quantum numbers

Hydrogen Quantum Numbers

- Quantum numbers, n, l, m_l
- n: how charge is distributed radially around the nucleus. Average radial distance.
  - This determines the energy
- l: how spherical the charge distribution
  - l = 0, spherical, l = 1 less spherical…
- m_l: rotation of the charge around the z axis
  - Rotation clockwise or counterclockwise and how fast
- Small energy differences for l and m_l states

$n=1,\ \ell=0,\ m_l=0$

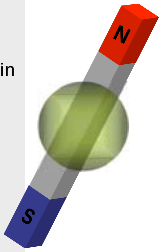
$n=2,\ \ell=1,\ m_l=\pm1$

Additional Lecture Material

- Spin
  - An additional quantum property of a particle
- Indistinguishability and symmetry
  - Fermions and Bosons
  - Pauli exclusion principle
- Physics of solids
  - Energy bands in a solid
  - Metals, insulators, and semiconductors
  - Superconductors

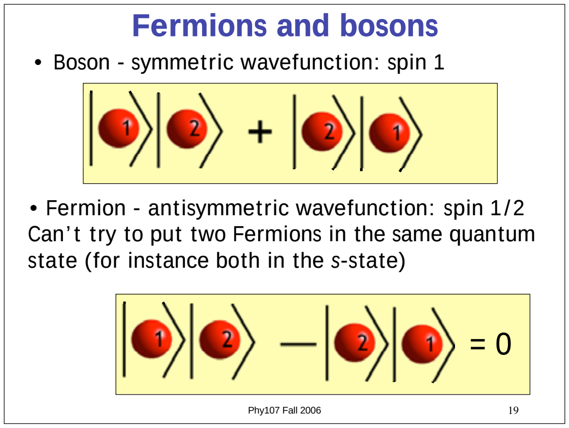
Topic: spin

- Free electron, by itself in space, not only has a charge, but also acts like a bar magnet with a N and S pole.
- Since electron has charge, could explain this if the electron is spinning.
- Then resulting current loops would produce magnetic field just like a bar magnet.
- But…
  - Electron in NOT spinning.
  - As far as we know, electron is a point particle.



Topic: Indistinguishability & symmetry

- Several important conceptual aspects of quantum mechanics
- Indistinguishability
  - particles are absolutely identical
  - Leads to Pauli exclusion principle (one Fermion / quantum state).
- Symmetry
  - Characterizes the wavefunctions
  - Leads to different energy levels.



Fermions and bosons

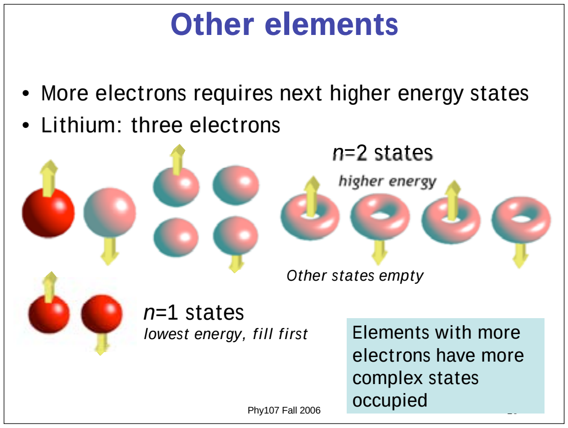
- Boson - symmetric wavefunction: spin 1

$|1\rangle|2\rangle + |2\rangle|1\rangle$

- Fermion - antisymmetric wavefunction: spin 1/2

Can't try to put two Fermions in the same quantum state (for instance both in the *s*-state)

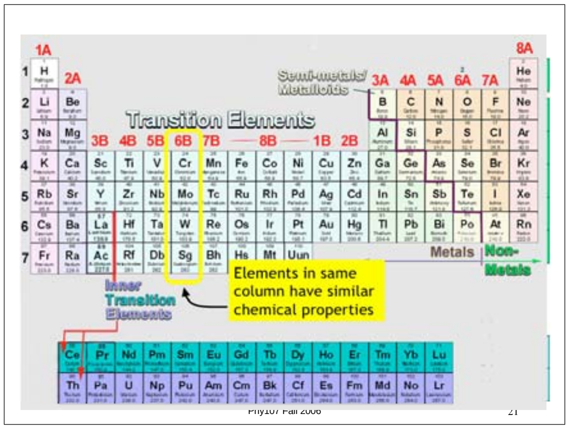
$|1\rangle|2\rangle - |2\rangle|1\rangle = 0$



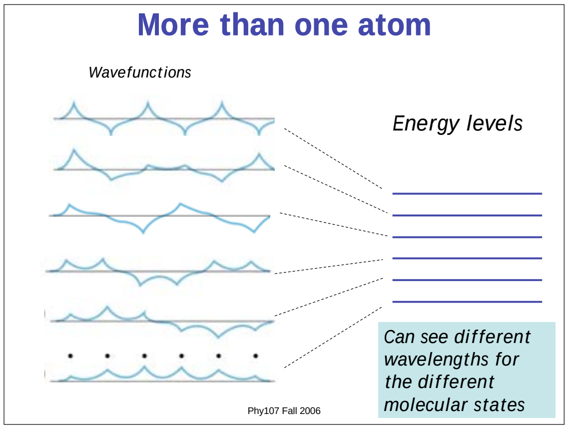
Other elements

- More electrons requires next higher energy states
- Lithium: three electrons

Elements with more electrons have more complex states occupied

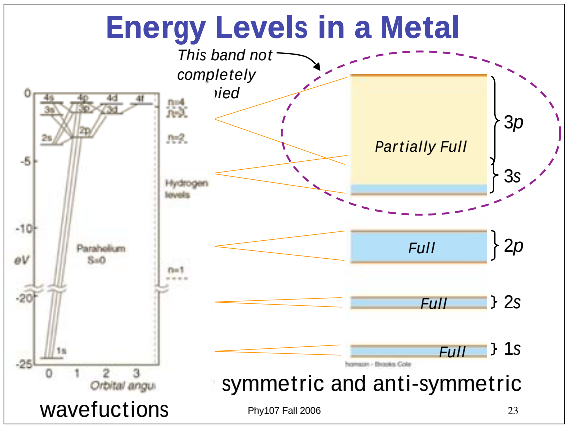


Elements in same column have similar chemical properties



More than one atom

Can see different wavelengths for the different molecular states

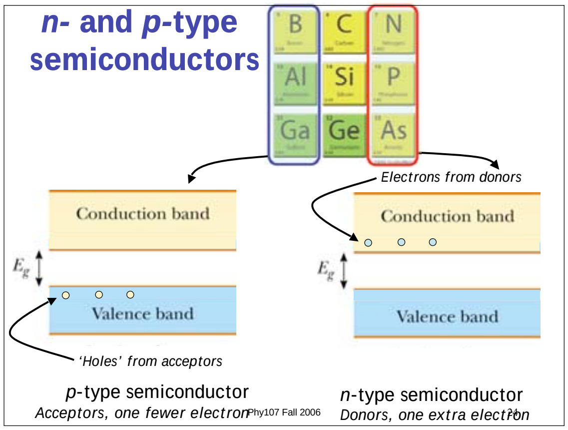


Energy Levels in a Metal

This band not completely [illegible]*ied*

wavefuctions

symmetric and anti-symmetric



n- and *p*-type semiconductors

Electrons from donors

'Holes' from acceptors

p-type semiconductor

Acceptors, one fewer electron

n-type semiconductor

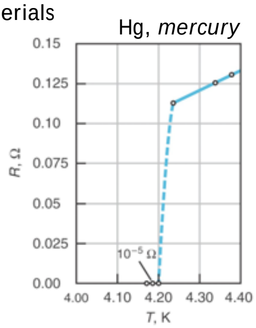
Donors, one extra electron

Topic: Superconductivity

- Superconductor = zero-resistance material
  - Usually some resistance: impurities, vibrations
- Many elements are superconducting
  - Critical temperature
  - Critical current
  - Critical magnetic field
  - no superconductivity outside of critical ranges
- Superconductor types
  - Type I - superconductivity at low temperature only
  - High T superconductors
  - Type II - superconductivity in high magnetic fields
- Meissner effect = exclusion of magnetic field

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.

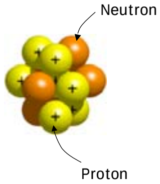


Nucleus and radioactivity

- Structure of the nucleus
  - Nucleus has small size, large energy scale
  - Strong force holds nucleus together
  - Isotope: different neutron #, same proton #
  - Nuclear binding energy different for different nuclei
- Radioactive decay
  - 'Unstable' nuclei decay by emitting radiation
  - Alpha, beta, gamma decay
- Decay half-life and carbon-dating
  - Decay is a random process
  - Half-life characterizes decay rate

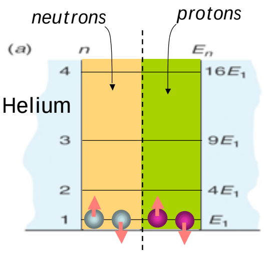
Size & structure of nucleus

- Nucleus consists of protons and neutrons densely combined in a small space (~10^{-14} m)
  - Protons have a positive electrical charge
  - Neutrons have zero electrical charge (are neutral)
- Spacing between these **nucleons** is ~ 10^{-15} m
- Size of electron orbit is 5×10^{-11} m
- Nucleus is 5,000 times smaller than the atom!
- Strong force to hold them together



Populating nucleon states

- Quantum states for nucleons in the nucleus
  - Similar to the hydrogen atom:
    one electron in each quantum state.
  - Two states at each energy (spin up & spin down)

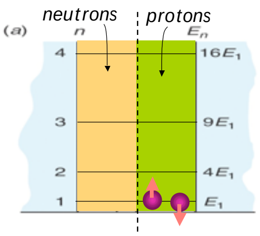


This is ^{4}He, with
2 neutrons and
2 protons
in the nucleus

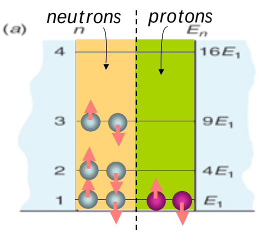
In the lowest
possible energy state

Other(less stable) helium isotopes

Too few neutrons, ->
protons too close together.
High Coulomb repulsion energy



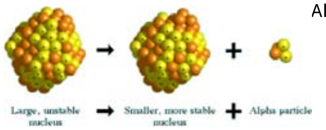
Too many neutrons, requires
higher energy states.



Radioactivity

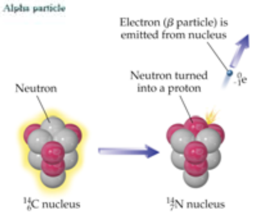
- Most stable nuclei have about same number of protons as neutrons.
- If the energy gets too high, nucleus will spontaneously try to change to lower energy configuration.
  - Too many neutrons or protons
  - To large
  - Nucleons in a excited energy state
- These nuclear are unstable, and are said to decay.
- They are called radioactive nuclei.

Alpha and beta decay



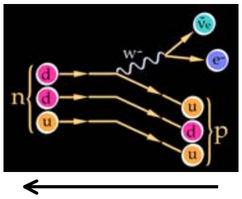
Alpha decay: chunk of nucleus ejected

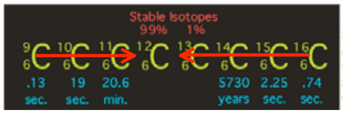
Beta decay:
electron emitted
neutron changes to proton



What is going on?

- ^{14}C has more neutrons than the most stable form ^{12}C.
  - So it decays by electron emission, changing neutron into a proton.
- Other isotopes of carbon have fewer neutrons
  - Decays by emitting **positron**, changing proton into neutron.



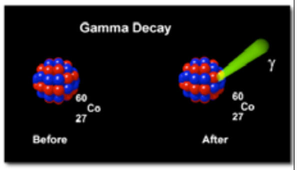


Gamma decay

- Alpha and beta decay can bothleave the nucleus in excited state
  - Just like a hydrogen atom can be in an excited state
  - Hydrogen emits photon as it drops to lower state.

Nucleus also emits photon as it drops to ground state
This is gamma radiation

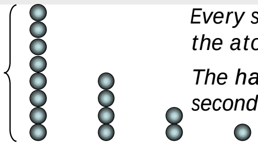
But energies much larger, so **extremely** high energy photons.



Topic: Radioactive half-life

- Example of random decay.
- Start with 8 identical radioactive nuclei
- Suppose probability of decaying in one second is 50%.

Undecayed nuclei



Every second, half the atoms decay

The half-life is one second

t=0 *t*=1 sec *t*=2 sec *t*=3 sec

Carbon Dating

- ^{14}C has a half-life of ~6,000 years, continually decaying back into ^{14}N.
- Steady-state achieved in atmosphere: decay vs. creation from collisions with cosmic rays. ^{14}C:^{12}C ratio of 1:1 trillion (1 part in 10^{12})

As long as biological material alive, atmospheric carbon mix ingested (as CO_2), ratio stays fixed.

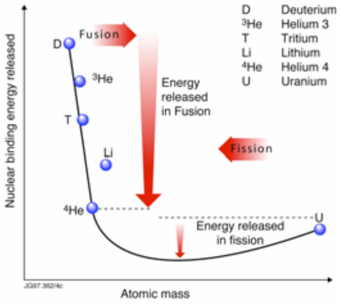
After death, no exchange with atmosphere. Ratio starts to change as ^{14}C decays

Fission & fusion

- The fission process
  - Some heavy nuclei split apart after absorbing a neutron.
  - Energy is released according to binding energy
- The fusion process
  - Light nuclei can fuse together under high temperature, pressure
  - Energy is released: binding energy differences
- Fission and fusion weapons
- Fission and fusion reactors

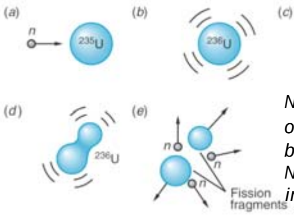
Differences between nuclei

- Schematic view of previous diagram
- ^{56}Fe is most stable
- Move toward lower energies by fission or fusion.
- Energy released related to difference in binding energy.



Nuclear Fission: Neutron Capture

- Fission: heavy nucleus breaks apart into pieces.
- Not spontaneous, induced by capture of a neutron
- When neutron is captured, ^{235}U becomes ^{236}U
  - Only neutron # changes, same number of protons.



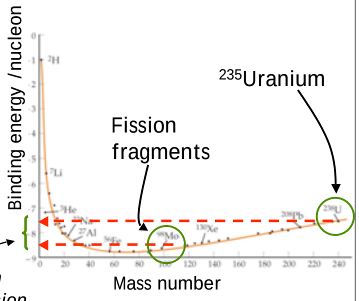
Nucleus distorts and oscillate, eventually breaking apart (fissioning)
Neutrons can cause more interactions(chain reaction)

How much energy?

Binding energy/nucleon ~1 MeV less for fission fragments than for original nucleus

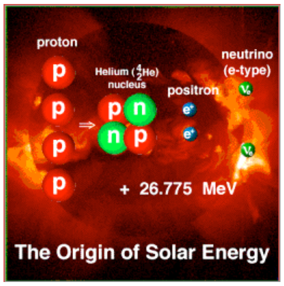
This difference appears as energy.

Energy/nucleon released by fission



Nuclear Fusion

- Fusing together light nuclei releases energy
- Energy of 6.7MeV per nucleon.
- Remember U^{235} fission release 1MeV per nucleon
- Hard to reproduce the conditions of the sun. Use different process in fusion experiments



Terrestrial fusion reactions

- Difficult to push 4 positive protons together

- Deuterium = nucleus of (1 proton & 1 neutron)
- Tritium = nucleus of (1 proton & 2 neutrons)
- Two basic fusion reactions:
  - deuterium + deuterium -> ^{3}He + n
  - deuterium + tritium -> ^{4}He + n

Energy is released as result of fusion:

D + T -> ^{4}He (3.5 MeV) + n (14.1 MeV)

Energy determined by mass difference

Photoelectric effect question

A scientist is trying to eject electrons from a metal by shining a light on it, but none are coming out. To eject electrons, she should change the light by…

A. decreasing the frequency
[✓ B. increasing the frequency]
C. increasing the intensity
D. increasing the wavelength

Minimum frequency
(maximum wavelength)
required to eject electron

Matter wave question

A neutron has almost 2000 times the rest mass of an electron. Suppose they both have 1 ev of energy. How do their wavelengths compare?

A. both same

[✓ B. neutron wavelength < electron wavelength]

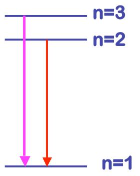
C. neutron wavelength > electron wavelength

Wavelength depends on **momentum**, as h/p.
Same momentum -> same wavelength.
Momentum = $\sqrt{2mE}$, depends on energy **AND** mass

Spectral Question

Compare the wavelength of a photon produced from a transition from n=3 to n=1 with that of a photon produced from a transition n=2 to n=1.

[✓ A. $\lambda_{31} < \lambda_{21}$]
B. $\lambda_{31} = \lambda_{21}$
C. $\lambda_{31} > \lambda_{21}$

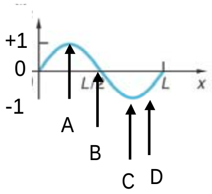


$E_{31} > E_{21}$ so $\lambda_{31} < \lambda_{21}$

Wavefunction question

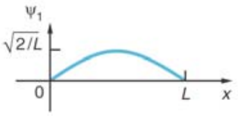
For this wavefunction, at what point is the probability of finding the particle the smallest?

A. A
[✓ B. B]
C. C
D. D



Question

The lowest energy state for a particle in a box looks like this. How many electrons can have a wavefunction that looks like this?



A. 0
B. 1
[✓ C. 2]
D. Any number

Radioactive decay question

^{14}C has 6 protons and 8 neutrons in its nucleus, and 6 electrons orbiting around the nucleus. It decays by emitting an electron from the nucleus. After the decay, it becomes

A. ^{12}C
B. ^{13}C
C. ^{14}B
[✓ D. ^{14}N]

B is the element with 5 electrons
C is the element with 6 electrons
N is the element with 7 electrons