Atomic and Nuclear Physics Summary

KEY IDEAS

- Atoms and subatomic particles sometimes obey laws that are not relevant to larger objects
- Electrons occupy energy levels in atoms.   In order to change energy levels, electrons must absorb or emit photons.
- The energy of a photon is given by $E = hc/\lambda$ where hc= 1240 eV•nm
- Draw an energy level diagram for every atomic physics problem
- Three types of nuclear decay can occur: Alpha, Beta and Gamma
- Charge and momentum are conserved in nuclear decay.
- Mass-energy is conserved in nuclear decay. The conversion between and mass is $E = mc^2$.

EQUATIONS

Energy of a photon	$E = hf = hc/\lambda$
Momentum of a photon	$p = h/\lambda = E/c$
De Broglie wavelength	$\lambda = h/p$
Energy-mass conversion	$E = mc^2$

Atomic and nuclear physics is the bizarre world of the very, very small where objects that have no mass can still have momentum, and where the distinction between waves and particles becomes blurred.

SUBATOMIC PARTICLES

The atom is comprised of a dense nucleus surrounded by a much larger diffuse electron cloud.

Nucleons are similarly sized protons and neutrons. Protons are positively charged particles, neutrons have no charge.

amu = atomic mass unit= u = approx. mass of 1 proton or 1 neutron

Electrons are much smaller, and negatively charged.

When an atom is electrically neutral # p = # e.

When an atom gains or loses electrons it is ionized [becomes an ion].

Cation: atom loses electrons ,   net positive charge

Anion: atom gains electrons, net negative charge.

A photon is a particle of light. Photons have no mass, but can transfer energy to or from electrons. [the photon is the "force carrier particle" for the electrostatic force.]

Summary of particles

Particle	Mass	charge
Proton	1.67×10^{-27} kg = 1 amu	Positive = $+1.6 \times 10^{-19}$C
Neutron	1.67×10^{-27} kg = 1 amu	zero
Electron	9.11×10^{-31} kg = 5.5×10^{-4}amu	Negative = -1.6×10^{-19}C
Photon	0	zero

A neutron actually has slightly more mass than a proton: a neutron can be thought of as a proton and an electron bound together.

The electon-volt , or eV, is a unit of energy that is convenient to use for subatomic particles.

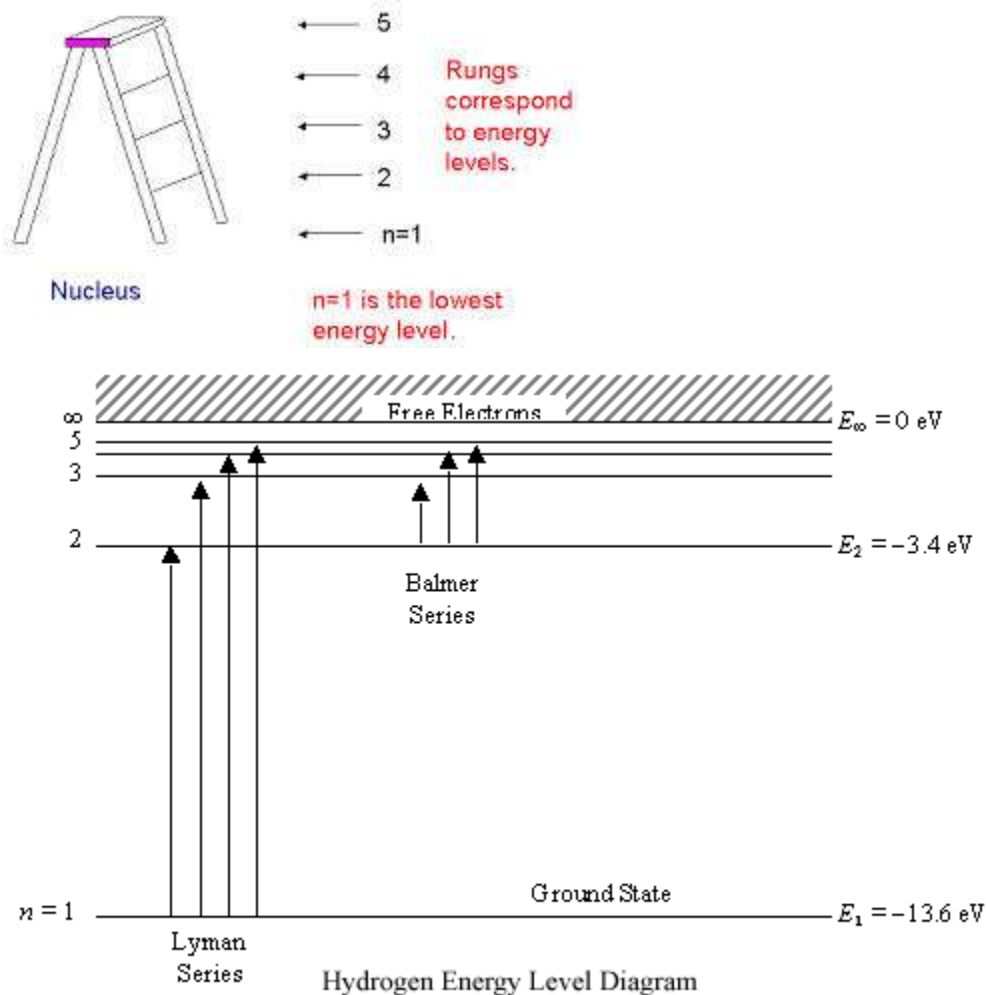One eV is the amount of energy required to change the potential of an electron by one volt.

For example, suppose an electron is near a positively charged particle, such that the electron's potential is 4 V. if you were to push the electron away from the positively charge particle until its potential was 5V, then you would need to use 1 eV of energy.

$$1eV = 1.6X10^{-19} \text{ J}$$

ENERGY LEVELS IN AN ATOM

Recall from chemistry: The electrons in an atom can only have certain, specific amounts of energy. The energy of an electron is *quantized*, not continuous.

http://www.kentchemistry.com/links/AtomicStructure/PlanckQuantized.htm

5

4   Rungs
     correspond
3   to energy
     levels.
2

n=1

Nucleus

n=1 is the lowest
energy level.

∞
5
3

Free Electrons $E_\infty = 0$ eV

2 $E_2 = -3.4$ eV

Balmer
Series

Ground State

$n = 1$ $E_1 = -13.6$ eV

Lyman
Series

Hydrogen Energy Level Diagram

Above is the energy diagram of a hydrogen atom.

 Below is the energy diagram showing a few of the energy levels of a hypothetical atom.

$$E_\infty = 0 \text{ eV}$$

$$E_3 = -6.0 \text{ eV}$$

$$E_2 = -7.0 \text{ eV}$$
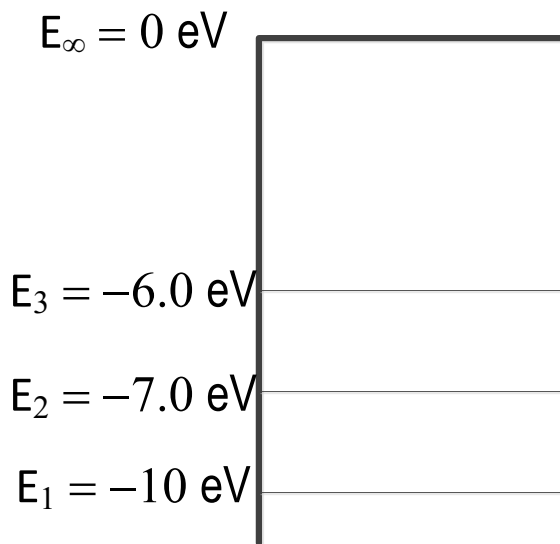
$$E_1 = -10 \text{ eV}$$

E_1 is the **ground state energy** of the atom.   An electron in the ground state is as close as possible to the nucleus. For this atom, when an electron is in the ground state. and when it is completely unexcited, it will have energy E_1 = -10eV.

To increase the energy of the electron – to move the electron to a higher energy level - energy must be transferred to the atom.   This energy transfer is done by a photon. To jump up in energy, an electron absorbs a photon. To drop down in energy , an electron emits a photon.

The energy diagram tells us that that to jump to E_2 from the ground state, an electron must absorb a photon carrying exactly 3 eV – and only 3 eV- of energy. If a photon of energy 2.9 or a photon of 3.1 eV collides with the electron nothing happens.

If the electron in state E_2 then absorbs a 1 eV photon , it will jump to state E3.

Similarly, if a 4.0 eV photon strikes the electron in state E_1, the electron will jump up to state E3.

 An electron in state E_3 will drop to state E_2 if it emits a 1 eV photon,   or will drop to state E_1 if it emits a 4 eV photon.

Finally, if the electron in the ground state absorbs a 10 eV photon the electron will be at E∞ level, and the atom will be ionized.   E∞ is the ionization energy of the atom.

If this atom absorbs a photon of energy greater than the ionization energy,   the excess energy above 10 eV will be converted into kinetic energy as the electron speeds away.

$E_{total} = E_{ionization}$ + Kinetic Energy of electron

$KE = \frac{1}{2} mv^2 =$ $E_{total} - E\infty$

Note: to use this equation, must convert the Kinetic energy from eV into Joules.

$1 \text{ eV} = 1.6 \times 10^{-19} \text{ J}$

The formula that describes the energy of a photon is   **E = hf**,

where h is Planck's constant   **h= 6.63×10^{-34} Joule•sec**

this formula tells up the the energy of a photon is equal to Planck's constant h multiplied by the frequency of the photon.

Recall the formula for wavelength, velocity, and frequency of a wave   **v = λf**

For light, velocity   **c= 3.0×10^8 m/sec**

So   c= λf = λE/h   or   **E = hc/λ = hf**   *Which is the energy of a photon*

This formula tells us

- at high frequencies, photon energy is high and wavelength is small
- and at low frequencies, photon energy is low and wavelength is long.

Note: hc = [6.63×10^{-34} J•sec] [3×10^8 m/sec]

Recall   1 m = 10^9 nm   and 1 eV= 1.6×10^{-19} J

So hc = [6.63×10^{-34} J•sec][3×10^8 m/sec] [10^9 nm]   [1 eV]
                                                                                          [1 m]   [1.6X10-19 J]

Therefore hc = $\underline{1.989 \times 10^{-16}}$ =   **hc = 1240 eV• nm**
1.6×10^{-19}

Use hc = 1240 eV nm   when photon wavelength is measured in nanometers , nm and when photon energy is measured in electron volts, eV.

Problem 1:   What wavelength of light must an electron in the hypothetical atom absorb in order to go from E_1 to E_2?

Colors of photons of visible light [wavelengths in nanometers]
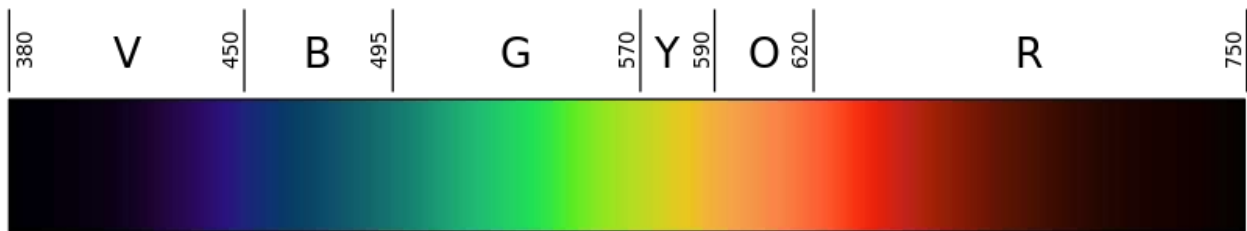
Problem 2: the electron in the hypothetical atom above absorbs 11.0 eV of energy.   What is the kinetic energy of the electron after the atom is ionized?

PHOTOELECTRIC EFFECT

Physicists observed that when electrons absorb enough energy they are ejected from the atom led to the discovery of the photoelectric effect.

Photoelectric effect: energy in the form of light can cause an atom on the surface of a metal to eject one of its electrons, but only if the frequency of light is above a certain value, called the **cutoff frequency**. The ejected electrons are "photoelectrons"
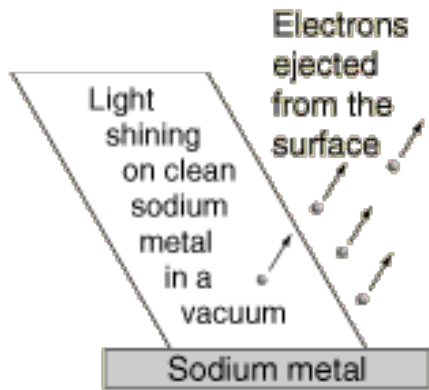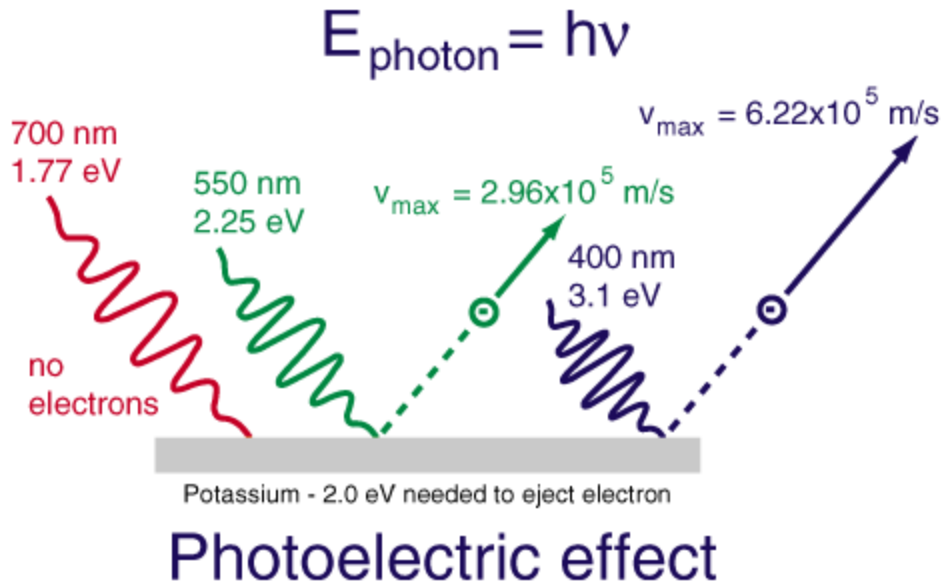
Photoelectric Effect experiments showed these surprising results:

1) The photoelectrons were emitted immediately, with no lag time
2) Increasing the *intensity* of the light increased the NUMBER of photoelectrons, but did NOT increase the maximum kinetic energy of the photoelectrons
3) Red light will NOT cause   photoelectrons to be ejected, no matter how intense the light is.
4) A *weak* [not intense violet light will eject only a few photoelectrons, but the maximum KE of these photoelectrons is greater than the maximum KE of photoelectrons ejected by more intense light at longer wavelengths.

   Conclusions:
   - Energy of photoelectrons is independent of the intensity of the illuminating light.
   - Energy of the ejected electrons is proportional to the frequency of the illuminating light
   - Light behaves like a particle that transmits all of its energy to a specific electron

$$E_{photon} = h\nu$$

700 nm
1.77 eV

no
electrons

550 nm
2.25 eV

$v_{max} = 2.96 \times 10^5$ m/s

$v_{max} = 6.22 \times 10^5$ m/s

400 nm
3.1 eV

Potassium - 2.0 eV needed to eject electron

Photoelectric effect

The **cutoff frequency** is a characteristic of each atom.   The cutoff frequency is the *minimum frequency* of a photon that will cause an electron to be emitted from a specific metal surface

The **work function** is the *minimum energy* of a photon needed to remove an electron from the surface of a solid material in a vacuum.

Problem 3:   A metal surface has a work function of 10 eV. What is the cutoff frequency for this metal?

Momentum of a photon

Since we say a photon can knock an electron away from an atomic nucleus, it is reasonable to discuss the momentum of a photon. Photons *do not* have mass, but the momentum, p, can be found from :

Momentum of a photon   p = h/λ

The momentum of a photon is equal to Planck's constant h divided by the photon's wavelength.

We can rearrange $p = h/\lambda$ using $E = hc/\lambda$ so $p = E/c$ and $E = pc$

deBroglie wavelength

as we have seen, light can behave as a wave and light can behave as a particle.

In the early 20th century, de Broglie proposed that any moving particles that have mass also behave like waves.

The de Broglie wavelength of any object: $\lambda_{deBroglie}$ = **h/p**

For massive particles, such as protons, or baseballs   **p = mv**

for massless particles , such as photons,   **p = h/λ**

why don't we diffract light as we move?

Because : our wavelength is extremely small.
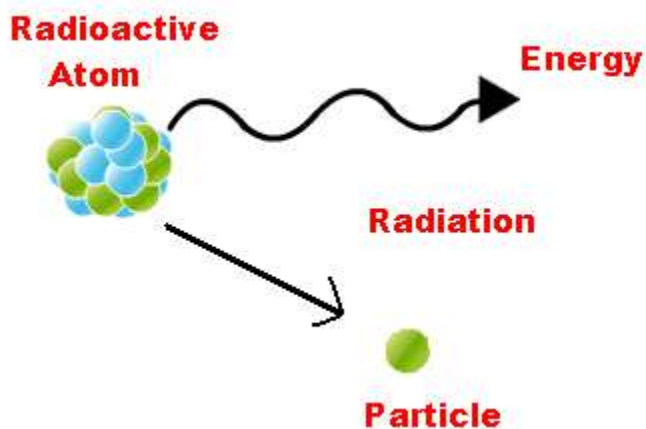
For example, a 60 kg person walking at 2 m/sec

$\lambda_{deBroglie}$ = $\dfrac{h}{P}$ = $\dfrac{h}{mv}$ $\dfrac{6.36 \times 10^{-34}}{[60][2]}$ = $\dfrac{5.3 \times 10^{-36}}{kg \; [m/sec]}$ J-sec

$\lambda_{deBroglie}$ =   = $\dfrac{5.3 \times 10^{-36} \; N \text{-m-sec}}{kg \; [m/sec]}$ = $\dfrac{5.3 \times 10^{-34} \; kg \bullet m \bullet m^{\cdot} sec/sec^2}{kg \; m/sec}$

$\lambda_{deBroglie}$ = $\dfrac{5.3 \times 10^{-34} \; kg \bullet m \bullet m^{\cdot} \cancel{sec}/\cancel{sec}^{\cdot} \cancel{sec}}{\cancel{kg \; m/sec}}$ = 5.31×10^{-34} m

THREE TYPES OF   OR NUCLEAR DECAY PROCESSES

Nuclear decay is also known as radioactive decay.

During ordinary chemical reactions,   the nucleus is unchanged. The valence electrons are gained, lost or shared.   During ionic bonding,   cations and anions are attracted to each other.   In covalent compounds, valence electrons are shared.

During ordinary reactions, mass is conserved

Atomic number , Z, is the number of protons in a nucleus. The number of protons identifies an atom.

Mass number, A, is the number of protons plus neutrons in a nucleus

Isotopes have the same atomic number but different mass number.

Isotopes are written using the element name and the mass number.   For example, three isotopes of carbon are Carbon-12 , Carbon-13, Carbon-14

Atomic mass is the weighted average of the isotopes of an atom

A nucleus is usually represented by $^A_Z Symbol$.

The symbol and atomic number Z for each element is found in the periodic table.

Problem 4: What do ^5_2He and ^4_2He mean?

There are three forms of nuclear decay:

Alpha decay , Beta Decay and Gamma Decay.

Atoms with many more neutrons than protons are highly unstable.

Unstable nuclei will emit particles until they reach a stable state.   Any element that has more protons than lead tends to be unstable.

During nuclear decay,   the unstable parent radionuclide   changes into a *different element because the number of protons is changed.*

 During nuclear reactions, mass and charge are conserved.

The emission of alpha particles from parent nuclei to form new daughter nuclei is called as **alpha decay**.

Alpha rays are comprised of   alpha particles emitted from unstable nuclei. An alpha particle is a fairly massive particle   that contains 2protons and 2 neutrons, and it has charge +2. [there are no electrons to balance the charge]

After alpha decay, daughter nucleus will have 2 fewer protons and 2 fewer neutrons than the parent nucleus.   Atomic number will decrease by 2 and mass number will decrease by 4

Large, unstable nucleus   ---▶   Smaller, more stable nucleus   +   Alpha Particle
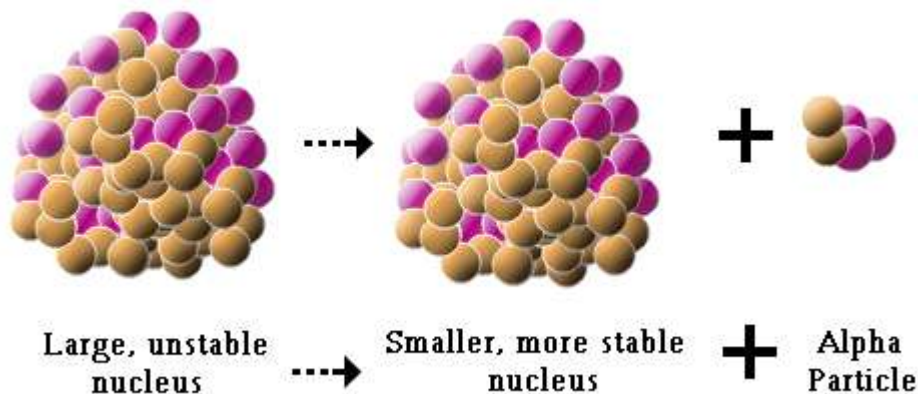
An alpha particle $^4_2\alpha$ is a Helium nucleus : $^4_2\alpha = {}^4_2He^{2+}$

Alpha particles travel at a very high speed: 1.5×10^7 m/sec but travel only a short range.   Alpha particles are very dangerous to living cells, particularly if ingested.

Problem 5:   Uranium-238 undergoes alpha decay.   Give the atomic number and mass number of the nucleus produced.   Write the correct symbol for the daughter nucleus.
Problem 6: write equation for alpha decay of Plutonium-240

Problem 7: what is the parent radionuclide that produces Rutherfordium-259 after alpha decay?

Problem 8: write equation for alpha decay of Thorium-234.

During Beta Decay, a radioactive **nucleus** emits either a **positron [β⁺decay]** or emits an **electron [β⁻decay]**

Beta rays are composed of fast moving positrons or electrons. The velocity of beta particles is about 2×10^7 m/sec

Beta rays [or cathode rays] were first recognized by JJ Thompson.

A positron is a positively charged particle that has the same mass as an electron. A positron is also known as an antielectron. It it the antimatter version of the electron.
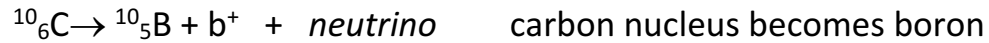
During **β⁺decay** , a proton turns into a neutron and emits a positron **β+** , which has charge +e. In decay equations, a positron is written as $^0_1\beta$

$$^1_1p \rightarrow {}^1_0n + {}^0_1\beta + \nu$$

The symbol ν [pronounced "nu"]   stands for   a neutrino. A neutrino is a very small neutral particle emitted from the nucleus   to maintain conservation of mass

 daughter nucleus: The atomic number decreased by 1, the mass number remains constant
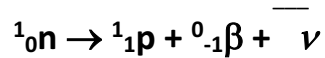
Example: β+ decay of Carbon-10:

$$^{10}_6C \rightarrow {}^{10}_5B + b^+ + neutrino \qquad \text{carbon nucleus becomes boron}$$

Total mass before = 10   total mass after = 10

Total charge before = 6   total charge after = 5+1 = 6

During β^-**decay ,** a neutron turns into a proton and emits an electron, e-.   In decay equations, the electron is represented by : $^0_{-1}\beta$

$$^1_0n \rightarrow {}^1_1p + {}^0_{-1}\beta + \overline{\nu}$$

The symbol $\overline{\nu}$ *stands for antineutrino. An antineutrino is a small neutral particle emitted from the nucleus to maintain conservation of mass.*

Daughter nucleus: The atomic number increased by 1, the mass number remains constant
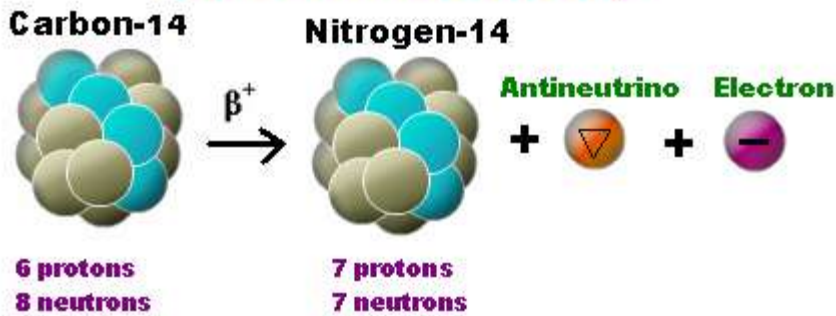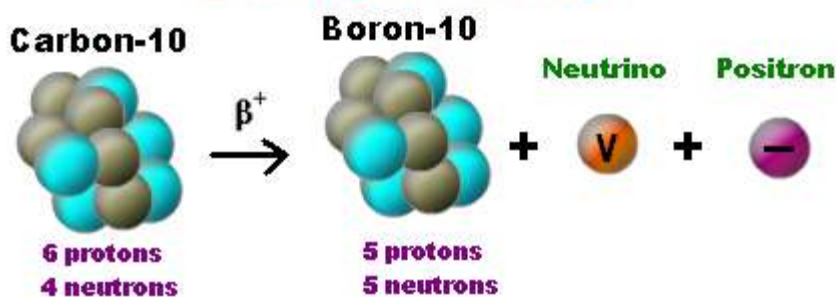
Example: β- decay of Carbon-14

$$^{14}_6C \rightarrow {}^{14}_7N + \textbf{e-} + antineutrino \qquad \text{carbon nucleus becomes nitrogen}$$

Mass number before = 14   mass number after = 14

Total charge before = 6,   total   charge after = 7 -1 = 6

Beta-minus Decay

Carbon-14 → Nitrogen-14 + Antineutrino + Electron

6 protons
8 neutrons

7 protons
7 neutrons

Beta-plus Decay

Carbon-10 → Boron-10 + Neutrino + Positron

6 protons
4 neutrons

5 protons
5 neutrons

During beta decay a neutrino or antineutrino must also be emitted to carry off some extra energy. This does not affect the products of the decay, just the KE of the products.

Problem 9:   write equation for beta decay of Hydrogen -3 to Helium-3

Problem 10: write equation for beta- decay of thorium-234.

Problem 11: write equation for beta+ decay of Barium-7 to Lithium-7

Problem 12: write equation for beta decay of Fluorine-18 to Oxygen-18.

Gamma decay

- Gamma radiation is made of high energy   photons which have no mass and no charge.
- Gamma particles are light so they travel at the speed of light: 3×10^8 m/sec

- Gamma rays originate due to the change in structure and energy levels of the atomic nucleus because of alpha or beta emission, so gamma decay is secondary effect of atomic disintegration.
- Since gamma rays are neutral and mass less; there is no change in atomic number and mass number in daughter nuclei compare to parent nuclei.

Example of gamma radiation: $^{238}_{92}U \rightarrow\ ^{238}_{92}U + \gamma$

Decay series or Decay chain: after a nucleus decays , the daughter nucleus produced may still be unstable. In that case, the nucleus undergoes more decays until it reaches a stable form.   This is known as a decay series . The time for the nucleus to decay in each step can vary greatly from milliseconds to thousands of years.
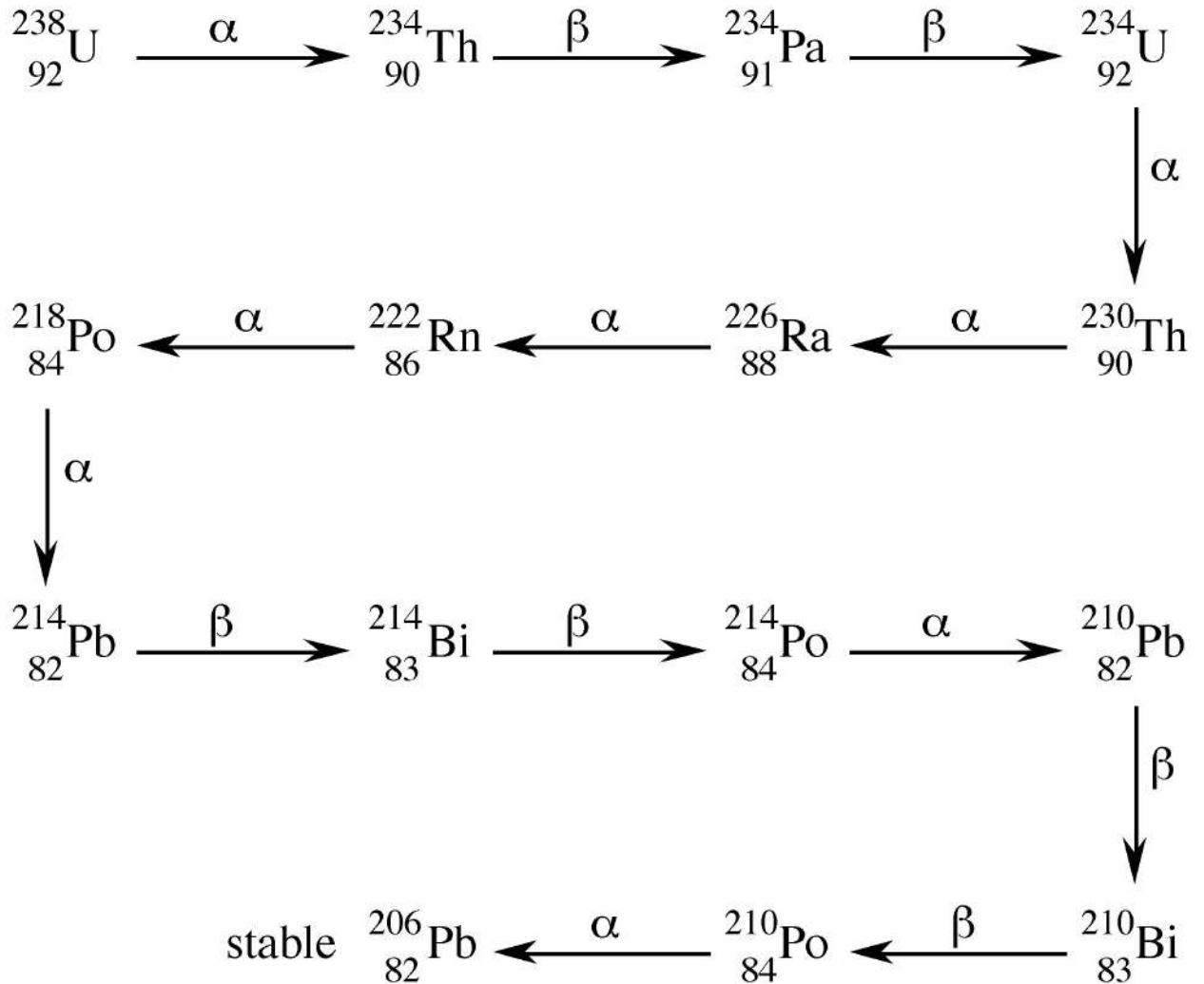
The **half-life** of a radioactive isotope is the amount of time for ½ of a sample to decay.
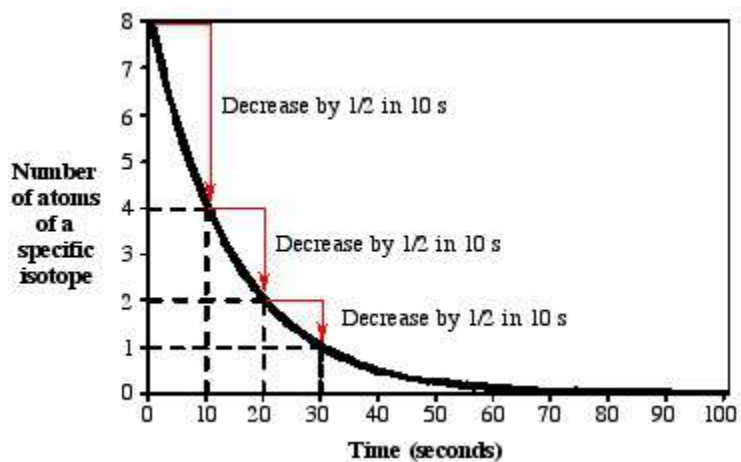
Isotope	Half life
Ceriuium-142	5×10^{15} years
Radium-226	1590 years
Radon-222	3.82 days
Polonium-216	0.16 s

TABLE 3: Half life values for selected isotopes.

Uranium-238 decays into [stable] Lead-206 in a 14 step process:

$$^{238}_{92}U \xrightarrow{\alpha} {}^{234}_{90}Th \xrightarrow{\beta} {}^{234}_{91}Pa \xrightarrow{\beta} {}^{234}_{92}U$$

$$\Big\downarrow \alpha$$

$$^{218}_{84}Po \xleftarrow{\alpha} {}^{222}_{86}Rn \xleftarrow{\alpha} {}^{226}_{88}Ra \xleftarrow{\alpha} {}^{230}_{90}Th$$

$$\Big\downarrow \alpha$$

$$^{214}_{82}Pb \xrightarrow{\beta} {}^{214}_{83}Bi \xrightarrow{\beta} {}^{214}_{84}Po \xrightarrow{\alpha} {}^{210}_{82}Pb$$

$$\Big\downarrow \beta$$

$$\text{stable } {}^{206}_{82}Pb \xleftarrow{\alpha} {}^{210}_{84}Po \xleftarrow{\beta} {}^{210}_{83}Bi$$

Problem 13: write the decay equations for decay series thorium-226 into astatine-214.

Thorium-226 undergoes alpha decay to form daughter A

DaughterA undergoes beta- decay to daughter B

Daughter B undergoes alpha decay to daughter C

Daughter C undergoes alpha decay to Astatine-214.

Sometimes a decay chain is written just showing the products and not the decay particles.

Ernest Rutherford   found three distinct forms of radiation, and originally divided them up based on their ability to pass through certain materials and by their deflection in magnetic fields...

Alpha (α): could barely pass through a single sheet of paper. Deflected as a positive particle in a magnetic field.

Beta- (β-): can pass through about 3mm of aluminum. Deflected as a negative particle in a magnetic field. *

Gamma (γ): can pass through several centimetres of LEAD! Not deflected in a magnetic field.
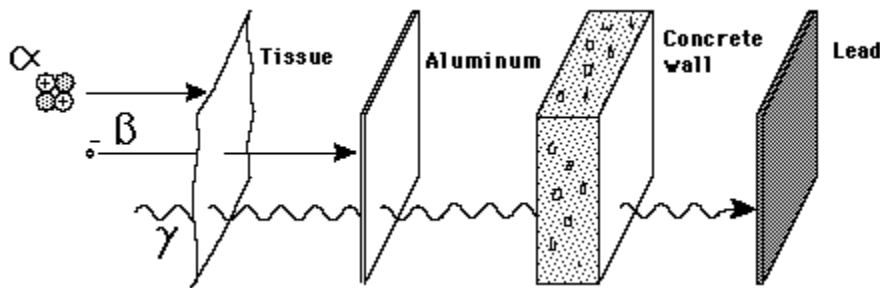
Conservation of momentum
Suppose the parent nuclei at rest before emitting alpha, beta or gamma particles.   When the nuclei decay and produce high speed alpha, beta and or gamma particles   the daughter nuclei will recoil and travel off in opposite directions so that the conservation of momentum is obeyed.

Conservation of energy

Suppose the parent nuclie are at rest before nuclear decay, then no kinetic energy existed. After the decay, both the daughter nuclei and the emitted particles have considerable amounts of kinetic energy.

Where did all this energy come from?   It comes from mass.

The total mass present before decay is very slightly greater than the mass present after the decay. This very slight difference is called the **mass defect**, and is labeled as Δm. This mass is converted into pure kinetic energy.

Define 1 mega electron volt = 1 MeV = 10^6 eV

If one amu is converted into energy   1 amu = 1 u = 931.5 MeV = 931.5 X10^6 eV

Three things need to be known in order to calculate the mass defect:

- the actual mass of the nucleus,
- the composition of the nucleus (number of protons and of neutrons),
- the masses of a proton and of a neutron.

To calculate the mass defect:

- add up the masses of each proton and of each neutron that make up the nucleus,
- subtract the actual mass of the nucleus from the combined mass of the components to obtain the mass defect.

    Example: the total mass of a Carbon-12 atom is slightly less than the sum of 6 protons plus 6neutrons .   The "missing" mass has been transformed into the binding energy that holds nucleons together.

    Note: we also add the mass of the electrons .

    Mass of 1 e- is approximately 1/1836 the mass of 1amu

Particle	Mass (kg)	Mass (u)	Mass (Mev/c²)
1 atomic mass unit	1.660540 x 10^{-27} kg	1.000 u	931.5 MeV/c²
neutron	1.674929 x 10^{-27} kg	1.008664 u	939.57 MeV/c²
proton	1.672623 x 10^{-27} kg	1.007276 u	938.28 MeV/c²
electron	9.109390 x 10^{-31} kg	0.00054858 u	0.511 MeV/c²

mass of 6 p = 6 [1.007276 u] = 6.043656 u

mass of 6 p=6[1.008664 u]=6.051984 u

mass of 6e = 6[0.00054858 u]   =.0032915 u

mass of 6p + 6n + 6e = 12. 09893 u

Mass of C-12 = 12 u

Mass defect of C-12 = 0.09893u

Binding energy = .09893 u X 931.5 MeV/u =92.15 MeV

http://physics.bu.edu/~duffy/sc546_notes10/mass_defect.html

A CHAIN REACTION

A chain reaction refers to a process in which neutrons released in fission produce an additional fission in at least one further nucleus.

This nucleus in turn produces neutrons, and the process repeats. The process may be controlled (nuclear power) or uncontrolled (nuclear weapons).

If each neutron releases two more neutrons, then the number of fissions doubles each generation. In that case, in 10 generations there are 1,024 fissions and in 80 generations about 6×10^{23} (a mole) fissions.

Energy Released From Each Fission

165 MeV ~ kinetic energy of fission products
   7 MeV ~ gamma rays
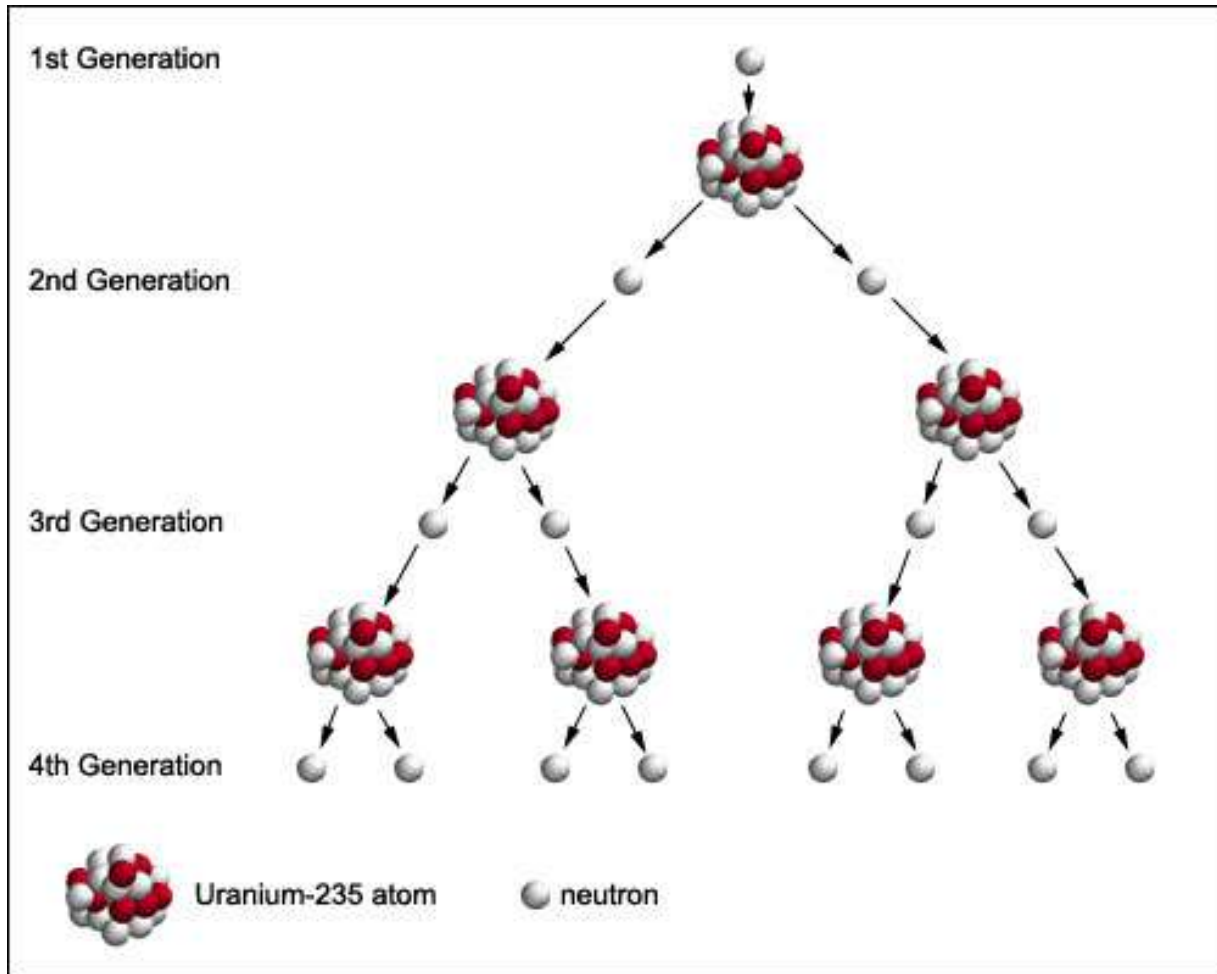   6 MeV ~ kinetic energy of the neutrons
   7 MeV ~ energy from fission products
   6 MeV ~ gamma rays from fission products
   9 MeV ~ anti-neutrinos from fission products

200 MeV

1 MeV (million electron volts) = 1.609 x 10 $^{-13}$ joules

Problem 14: Determine how much energy is released when Uranium-238 decays into Thorium-234. Total mass of Uranium-238 is 238.0508 u. the total mass of Thoruium-234 is 234.0436 amu. The total mass of an alpha particle is 4.0026 U.

Problem 15: write equation for beta- decay of calcium-46.

Problem 16: list these types of electromagnetic radiation in order from least to greateset energy per photon

Yellow, Ultraviolet, infared, green, red,violet, blue, orange,

Problem 17: In a chain reaction,   a particle produced from the nuclear reaction of one isotope is used to initiate a nuclear reaction in another isotope.

 in a nuclear reactor , a high energy neutron strikes a uranium isotope which fissions [splits the nucleus] into krypton and barium and three high energy neutrons.

$$n + \,^{235}_{92}U \rightarrow \,^{141}_{56}Ba + \,^{A}_{Z}Kr + 3n$$
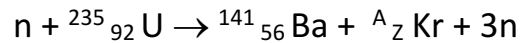
a) What are the values for A and Z in this reaction?

b) How much mass is converted into the kinetic energy of the resulting nuclei

Problem 18: Oxygen-15 decayse via β+emission. What is the resulting daughter nucleus?

Problem 19: A hypothetical atom has two energy levels as shown below.

$$E_\infty = 0 \text{ eV}$$

$$E_2 = -1.2 \text{ eV}$$

$$E_1 = -3.3 \text{ eV}$$
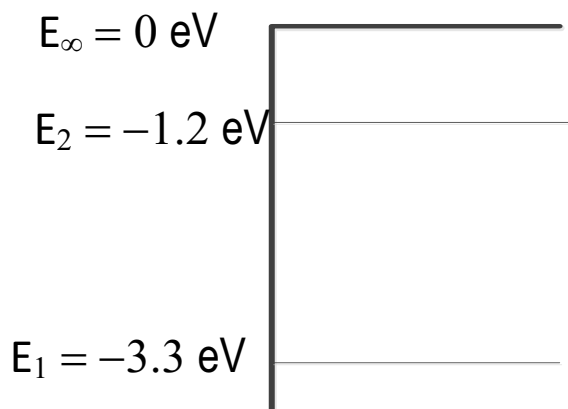
a) What wavelengths of electromagnetic radiation can be absorbed by this atom? Indicate if any of these wavelengths are visible light.
b) Now, monochromatic 180-nm ultraviolet radiation is incident on the atom, ejecting an electron from the ground state.   What wil be
   i.   The ejected electron's kinetic energy

   ii.   The ejected electron's speed

   iii.   The incident photon's speed

c) The 180-nm radiation ejected an electron that was initially in the -1.2 eV state.

    i.   How would the speed of the ejected electron compare to the ejected electron in part b?

    ii.   How would the speed of the incident photon compare to the incident photon in part b?