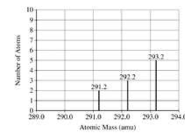
The Nucleus

Nuclear Stability and Radioactive Decay

- **Atomic Number** is the number of protons in the nucleus.
- **Mass Number** is the sum of the protons and neutrons.
- **Nucleons** refer to protons and neutrons.
- **Isotopes** are *atoms* with the same atomic number but a different mass number because of a change in the number of neutrons.

Recent percent abundance

Shown below is a hypothetical mass spectrum for a sample of Lv containing 10 atoms.



Using the information in the graph, determine the average atomic mass of Lv in the sample to four significant figures.

- $\frac{2(291.2) + 3(292.2) + 5(293.2)}{10} = 292.5$

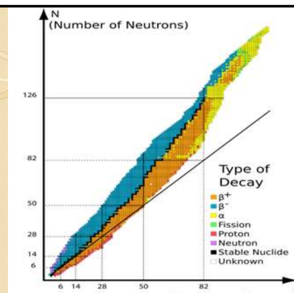
Review

- Nucleotide refers to a specific atom
- Atomic Number (*Z*) – number of protons
- Mass Number (*A*) – sum of protons and neutrons

$${}^{A}_{Z}\mathrm{X}$$

Radioactive decay

- **Radioactive decay** is the process of forming a different nucleus.
- Of the approximately 2000 known nuclides, only 279 are stable with respect to radioactive decay.
- A plot of the positions of the stable nuclei as a function of the number of protons and the number of neutrons reveals a **zone of stability** where the stable nuclides reside.



Important observations

- **All nuclides with 84 or more protons are unstable** with respect to radioactive decay.
- Light nuclides are stable when # of protons equals # of neutrons, that is, when the neutron/proton ratio is 1.
- However for heavier elements, the neutron/proton ratio must be greater than 1. In other words you need more neutrons than protons.

Types of Radioactive Decay

- **Alpha-particle production** is a mode of decay in which an **alpha (α or He nucleus) particle** is produced.
- This is very common for **heavy radioactive nuclides**.

Types of Radioactive Decay

- Alpha production (α):

$${}^{238}_{92}\mathrm{U} \rightarrow {}^{4}_{2}\mathrm{He} + {}^{234}_{90}\mathrm{Th}$$

Showing Alpha Decay

- ~expulsion of 2 p^+ and 2 n^o
- Show the alpha decay of Radon-222.

$$^{222}_{86}Rn \xrightarrow{\alpha\ decay} {}^{218}_{84}Po + {}^{4}_{2}He$$

lose 2 p^+ so the atomic number is now 84

lose 2 p^+ and 2 n^o so the mass number is now 218

element # 84 is Polonium

The particle is also released

alpha particle can also be written as + α

- **Beta-particle production** is a mode of decay in which a **beta (β or electron) particle** is produced.
- This is very common for nuclides above the zone of stability (those nuclides whose **neutron**/proton ratios are too high).

Types of Radioactive Decay

- Beta production (β):

$$^{234}_{90}Th \rightarrow {}^{234}_{91}Pa + {}^{0}_{-1}e$$

Showing Beta Decay

- ~conversion of a neutron to a proton and an electron, and expulsion of the electron.
- The beta decay of Lead-214

$$^{214}_{82}Pb \xrightarrow{\beta\ decay} {}^{214}_{83}Bi + \beta$$

gain 1 p^+ so the atomic number is now 83

lose 1 n^o and gain 1 p^+ so the mass number is the same

element # 83 is Bismuth

The particle is also released

beta particle can also be written as $^{0}_{-1}e$

- **Gamma-particle production** (γ) refers to a high energy photon that accompanies other nuclear decays and particle reactions.

Types of Radioactive Decay

- The following is an alpha decay accompanied with gamma ray production
- Gamma ray production (γ):

$$^{238}_{92}U \rightarrow {}^{4}_{2}He + {}^{234}_{90}Th + 2{}^{0}_{0}\gamma$$

- **Positron production** occurs when a positron, the antiparticle of the electron is produced.
- This occurs for nuclides below the zone of stability (when the neutron/**proton** ratio is too small).

Types of Radioactive Decay

- Positron production:

$$^{22}_{11}Na \rightarrow {}^{0}_{1}e + {}^{22}_{10}Ne$$

Showing positron production

- Positron production- a proton converts into a neutron and a positron, a particle with the same mass of an electron but opposite charge.
- The positron production from sodium-22

$$^{22}_{11}Na \longrightarrow {}^{22}_{10}Ne + {}^{0}_{1}e$$

lose 1 p^+ so the atomic number is now 10

gain 1 n^o and lose 1 p^+ so the mass number is the same

element # 10 is Neon

The particle is also released

Note that is it positive 1 not negative 1 like in beta

- Electron capture occurs when a nuclide captures an inner energy level electron.
-

Electron capture

- Electron capture occurs when a nuclide captures an inner energy level electron.

$$^{201}_{80}\text{Hg} + {}^{0}_{-1}\text{e} \rightarrow {}^{201}_{79}\text{Au} + {}^{0}_{0}\gamma$$

Inner-orbital electron

Electron Capture

- ~An inner orbital electron is captured by the nucleus converting a proton into a neutron
- Electron capture of Aluminum-26

$$^{26}_{13}\text{Al} + {}^{0}_{-1}\text{e} \longrightarrow {}^{26}_{12}\text{Mg}$$

lose 1 p^+ so the atomic number is now 12

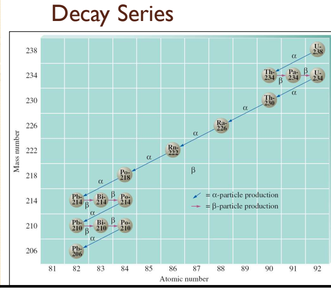
gain 1 n° and lose one 1 p^+ so the mass number is the same

element # 12 is Magnesium

Decay Series

- Often a radioactive nucleus cannot reach a stable state through a single decay process and must occur in several steps until a stable nuclide is produced.

Decay Series



Types of radiation

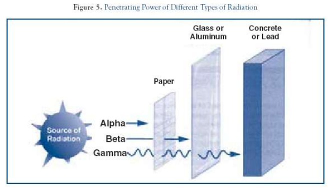
- (alpha) α radiation- 2 protons and 2 neutrons (helium nucleus) are released by the atom
- α particle-2 p^+ 2 n°
- (beta) β radiation 1 neutron breaks into a proton and an electron, the electron is released
- β particle- an electron
- (gamma) γ radiation – An energetic atom releases energy as a photon (gamma ray).
- There is no particle, just a light pulse.

Stopping radiation

type of radiation	How to stop it	Danger Level
α radiation	a sheet of paper, or skin	Most damaging
β radiation	a sheet of aluminum foil	Damaging
γ radiation	several cm of lead	Still damaging

diagram

Figure 5. Penetrating Power of Different Types of Radiation



Most Dangerous

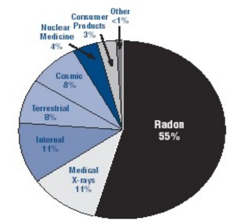
- α particles are the most dangerous if they are not stopped.
- They are exceptionally large compared to the other particles
- It is like a cannon ball ripping through a cell. If hit, a cell will most likely die.
- Because of their size they damage the first thing they hit (they aren't likely to squeeze through gaps)

Continuing

- If it hits something nonliving (dead cells or molecules), it will damage the nonliving structure. However, it was already dead.
- β particles are much smaller and more likely to squeeze through gaps, penetrating much deeper before hitting and damaging something.
- Once the radiation is stopped, it is no longer dangerous. It is only dangerous when it is moving at a high velocity.

Where does radiation come from

- only about 18% of the radiation that hits the average person comes from manmade sources.
- The majority of that comes from X-rays or related procedures.
- The rest are naturally occurring on the Earth.
- Mainly Radon gas (naturally occurring)



Source: National Council on Radiation Protection and Measurements

The Kinetics of Radioactive Decay

- The Rate of Radioactive Decay.
- Radioactive decay is a FIRST ORDER process
- $\ln (N_o / N_t) = k t$
- Where N_o is the number of nuclides at t = 0, N_t represents the number of remaining nuclides at time t, and *k* is the decay constant
- This is the same as integrated first order rate law.
- $\ln [A]_t - \ln[A]_o = - k t$

Half life

- **Half-life ($t_{1/2}$)** of a radioactive sample is defined as the time required for the number of nuclides to reach *half* the original value.
- $t_{1/2} = \ln 2 / k$ for a first-order process.
- Or
- $t_{1/2} = .693 / k$

Kinetics of Nuclear Decay

- Technetium-99m is used to form pictures of internal organs in the body and is often used to assess heart damage. The m for this nuclide indicates an excited nuclear state that decays to the ground state by gamma emission. The rate constant for decay of Tc-99m is known to be 1.16 x10^{-1} h^{-1}, What is the half-life of this nuclide?

answer

- $t_{1/2} = .693 / k$
- $t_{1/2} = .693/.161\ hr^{-1}$
- $t_{1/2} = 4.3$ hr

Kinetics of Nuclear Decay II

- The half-life of molybdenum-99 is 67.0 h. How much of a 1.000-mg of Mo-99 is left after 335 h?

answer

- $t_{1/2} = .693 / k$
- 67 hr = .693 / k
- k = .010 h^{-1}
- $\ln [A]_t - \ln[A]_o = - k t$
- $\ln [A]_t - \ln[1.00\ mg]_o = - 0.010\ (335)$
- [A] = .0313 mg

Radio-dating

- The age of old materials may be dated by radioactive isotopes present.
- To do this you need a radioactive isotope present with a known half life, and a way to compare the amount present, to the amount that was present at some date in the past.

Applications of Radioactivity

- Carbon-14 Dating is the most commonly used dating processes for samples 10,000-years old or less. Dating with C-14 produces errors of up to 3,000 years for 20,000- to 30,000-year old samples.
- The half-life of C-14 is 5730 years.

Carbon dating

- Radiation on this planet causes radioactive isotopes to form.
- A known percentage of the carbon dioxide in the air contains the radioactive C-14 isotope.
- This carbon dioxide is used to "build" all living things (plants use it for food, animals eat the plants etc.) while they are alive. Once the organism dies it stops taking in new C-14.
- The C-14 left begins to decay at a known rate.

Finding an age

- The amount of C-14 in an object is measured, and is compared to the amount that is known to be in all living things, which is assumed to be there when it died.
- Using the half lives to determine how much time has passed since it died.

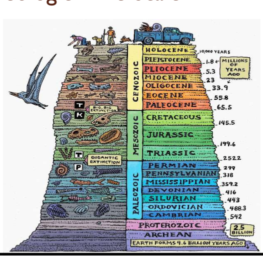
Potassium-40 dating

- Rocks (never living) can also be dated if they have other certain isotopes.
- K-40 decays into Ar-40.
- When a rock is formed we can assume all gases would escape, so all argon in a rock should be the product of K-40 decay.
- measure the K-40 and compare it to the Ar-40 and you can determine its age.

Uranium-238 dating

- U-238 decays into Pb-206. Pb-206 is extremely rare.
- If you have a rock with U-238 and Pb-206 present, the assumption is the Pb-206 came from the decay of U-238.
- Scientists have come up with the **4.6 billion year age of the planet** using these methods.

Geologic Time Scale



C-14 Dating problem

- The remnants of an ancient fire cave in Africa showed a C-14 decay rate of 3.1 counts per minute per gram of carbon.
- Assuming that the decay rate of C-14 in freshly cut wood (corrected for changes in the C-14 content of the atmosphere) is 13.6 counts per minute per gram, calculate the age of the remnants. The half-life of C-14 is 5730 years.

answer

- $t_{1/2}$ = .693 / k
- 5730= .693 / k
- k = 1.20 x10^{-4} $years^{-1}$
- ln $[3.1]_t$ – ln$[13.6]_o$ = - 1.20 x10^{-4} $years^{-1}$ t
- t =12,000 years

Mass Defect and Binding Energy

- The law of conservation of mass appears to be violated in nuclear decay. Some mass was missing (mass defect, Δ m).
- Einstein theorized that the missing mass was converted to energy (binding energy, ΔE).
- $\Delta E = \Delta m c^2$
- c = speed of light = 3.0×10^8 m/s

Nuclear Fission

- Fission is the splitting of a heavy nucleus into two nuclei with smaller mass numbers.
- The process is exothermic.
- A self-sustaining fission process is called a *chain reaction*. If less than one neutron causes another fission event, the process dies out and the reaction is said to be *subcritical*. If exactly one neutron causes another fission event, the process sustains itself and the reaction is said to be *critical*.

Critical mass

- To achieve a critical state, a minimum mass of fissionable material is required called the *critical mass*.
- If more than one neutron causes another fission event, the process rapidly escalates and the heat buildup causes a violent explosions and is said to be *supercritical*.

Nuclear Fission

- Fission – Splitting a heavy nucleus into two nuclei with smaller mass numbers.

$$^{1}_{0}n + ^{235}_{92}U \rightarrow ^{142}_{56}Ba + ^{91}_{36}Kr + 3\,^{1}_{0}n$$

49

Fission

- Nuclear fission is the process by which all functioning nuclear power plants or nuclear powered submarines work.
- It is also the process used in an atom bomb.

Nuclear Fusion

- Fusion is the combining of two light nuclei to form a more stable nucleus.
- The process releases more energy per gram than fission.
- It also creates no radioactive waste.
- This occurs in stars.
- It has been used in a hydrogen bomb

Nuclear Fusion

- Fusion – Combining two light nuclei to form a heavier, more stable nucleus.

$$^{3}_{2}He + ^{1}_{1}H \rightarrow ^{4}_{2}He + ^{0}_{1}e$$

Fusion

- Because of the high temperatures, current energy production is not possible.
- There is no plant yet that can control a self sustaining fusion reaction.
- There are prototypes being worked on, and many believe the future of energy is in this field.