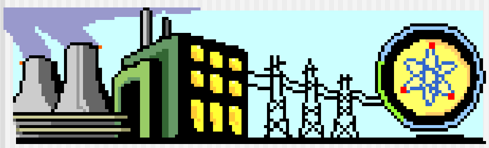
Chapter 22

Nuclear Chemistry

GCC CHM 152



Nuclear Chemistry

- Nuclear (**<u>NOT</u>** Nucular) chemistry involves changes in the nuclear composition (protons and neutrons) of radioactive atoms.
- Applications of nuclear chemistry:
  - **medical diagnosis and treatment**
  - **C-14 dating**
  - **nuclear power plants**
  - **create new elements**

Chemical Reactions

- **Bonds break/form via electrons**
- **Same number and type of atoms both sides of rxn (conservation of mass)**
- **Different isotopes of an element undergo same chemical reactions**
- **$\Delta H \approx$ -1 - 1000 kJ**
- **Rates affected by temperature, pressure, concentration, catalyst**

Nuclear Reactions

- Change one element into another via reactions in the nucleus
- Balance atomic # and mass # instead of atoms
- Nuclear reactions involve a specific isotope of an element; Different isotopes may undergo different nuclear reactions or may not decay at all.
- ΔH can be -10^{10} kJ (energy change is much larger).
- Rates only affected by changing concentrations

Atomic notation for Isotopes

- Recall notations used for isotopes: ${}^{A}_{Z}X$
  - A = mass number = # neutrons + # protons
  - Z = atomic number = # protons

  ${}^{12}_{6}C$ ${}^{13}_{6}C$ ${}^{14}_{6}C$

  - Three isotopes of carbon. What's different?
- Protons and neutrons are collectively called **nucleons**. The nucleus of a specific isotope is called a **nuclide**.

22.1 Nuclear Reactions

- **Radioactive decay/emission**: an unstable atom emits a particle or energy. Radiation arises from nuclear reactions:

  parent nuclide → daughter nuclide + radiation

  <u>Parent nuclide</u> undergoes decay.

  <u>Daughter nuclide</u> is formed by the decay.

Radioactivity

- Many nuclides are radioactive (they spontaneously emit radiation).
- Rutherford studied nuclear reactions and discovered three types of radiation: alpha (α), beta (β), and gamma (γ).
- Alpha radiation emits an alpha particle, beta radiation emits a beta particle, and gamma radiation emits gamma rays.

Nuclear Particles

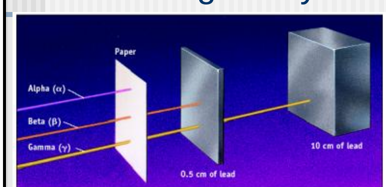
- Alpha particle: $\alpha = {}^{4}_{2}He^{2+}$; written as α or ${}^{4}_{2}He$
- Beta particle (an e^-): β or ${}^{0}_{-1}e$
- Gamma ray: γ = high energy wave = ${}^{0}_{0}\gamma$
- Positron particle (positive e^-): β^+ or ${}^{0}_{+1}e$
- Neutron: $n^0 = {}^{1}_{0}n$
- Proton: $p^+ = {}^{1}_{1}p$

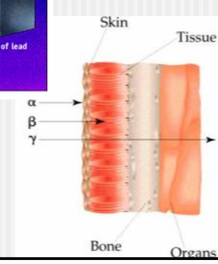
Nuclear Reactions Table 22.1

TABLE 22.1 A Summary of Radioactive Decay Processes

Process	Symbol	Change in Atomic Number	Change in Mass Number	Change in Neutron Number
α emission	${}^{4}_{2}He$ or α	−2	−4	−2
β emission	${}^{0}_{-1}e$ or β^-	+1	0	−1
γ emission	${}^{0}_{0}\gamma$ or γ	0	0	0
Positron emission	${}^{0}_{1}e$ or β^+	−1	0	+1
Electron capture	E. C.	−1	0	+1

Penetrating Ability of Particles





Alpha Emission

- alpha = ${}^{4}_{2}He^{2+}$ or ${}^{4}_{2}He$ or ${}^{4}_{2}\alpha$
- least penetrating- stopped by aluminum foil (> 10^{-3} cm), paper, skin
- most massive particles but least harmful
- Heavy radioactive isotopes (radioisotopes) tend to emit alpha particles:

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

- Note:the mass # = # nucleons and the atomic # = # protons are the same on both sides

Example Alpha Emission Rxns

- Daughter: mass # ↓ by 4, atomic # ↓ by 2
- Predict products:

${}^{226}_{88}Ra \rightarrow$

${}^{232}_{90}Th \rightarrow$

Beta Emission, Positron Emission

- β = electron: ${}^{0}_{-1}\beta^{-}$ or ${}^{0}_{-1}e$
- β^{+} = positron = positive electron: ${}^{0}_{1}\beta^{+}$ or ${}^{0}_{1}e$
- electrons and positrons are high energy particles ejected from the nucleus during the reaction
- more penetrating - stopped by 0.05 - 0.1 cm of Al
- E.g. ${}^{234}_{90}Th \rightarrow {}^{234}_{91}Pa + {}^{0}_{-1}e$
- β emission: a neutron is converted into a proton so the # of protons increases by 1 for the daughter.
- positron emission: a proton is converted to a neutron so the # of protons decreases by 1.

Beta Emission, Positron Emission

- Beta: mass # stays same, atomic # ↑ by 1
- Positron: mass # stays same, atomic # ↓ by 1
- Predict products:
  - Beta emission: ${}^{239}U \rightarrow$
  - Positron emission: ${}^{40}K \rightarrow$

Group Quiz # 22

- Beta emission: ${}^{131}I \rightarrow$
- Positron emission: ${}^{207}Po \rightarrow$

Gamma Radiation (Emission)

- γ = high energy radiation with no mass or charge
- Most penetrating radiation - stopped by 5 - 11 cm of aluminum or thick layer of concrete or lead
- Often accompanies alpha or beta decay reactions
- metastable (*m* after mass number) = Highly energetic/unstable nuclide that emits γ rays

$${}^{11m}_{5}B \rightarrow {}^{11}_{5}B + {}^{0}_{0}\gamma$$

Electron Capture

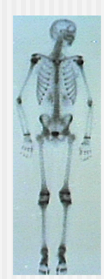
- Electron capture is the opposite of beta emission. A nucleus captures an inner-shell electron, converting a p^{+} to a n^{o}:

$${}^{197}_{80}Hg + {}^{0}_{-1}e \rightarrow {}^{197}_{79}Au$$

- Worked example 22.1, Problems 22.1, 22.2

Nuclear Reactions

- Write balanced equations for:
  1. Alpha emission from curium-242
  2. Beta emission from magnesium-28
  3. Positron emission from xenon-118
  4. Electron capture by polonium-204
- What particle is produced by decay of thorium-214 to radium-210?
- A radioisotope decays to give an alpha particle and Rn-222. Identify the radioisotope.



1^{st} order Decay of a Radionuclide

- half-life, $t_{1/2}$, is the time required for the number of radioactive nuclei in a sample to drop to half its initial value.
- Figure 22.2
- $t_{1/2}$ is constant

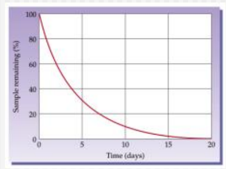


Table 22.2: Half-lives of some radioisotopes

TABLE 22.2 Half-lives of Some Useful Radioisotopes

Radioisotope	Symbol	Radiation	Half-life	Use
Tritium	${}^{3}_{1}H$	β^-	12.33 years	Biochemical tracer
Carbon-14	${}^{14}_{6}C$	β^-	5730 years	Archaeological dating
Phosphorus-32	${}^{32}_{15}P$	β^-	14.26 days	Leukemia therapy
Potassium-40	${}^{40}_{19}K$	β^-	1.28×10^9 years	Geological dating
Cobalt-60	${}^{60}_{27}Co$	β^-, γ	5.27 years	Cancer therapy
Technetium-99m*	${}^{99m}_{43}Tc$	γ	6.01 hours	Brain scans
Iodine-123	${}^{123}_{53}I$	γ	13.27 hours	Thyroid therapy
Uranium-235	${}^{235}_{92}U$	α, γ	7.04×10^8 years	Nuclear reactors

*The *m* in technetium-99*m* stands for *metastable,* meaning that it undergoes gamma emission but does not change its mass number or atomic number.

Nuclear decay is 1^{st} order process

$$\ln\left(\frac{N_t}{N_0}\right) = -kt$$

- N = number of atoms of a nuclide (same as A)
- N = 1/2 N_o at t = $t_{1/2}$: $k = \frac{\ln 2}{t_{\frac{1}{2}}} = \frac{0.693}{t_{\frac{1}{2}}}$

$$\ln\left(\frac{N_t}{N_0}\right) = -0.693\left(\frac{t}{t_{1/2}}\right)$$

Nuclear Kinetics Calcs

$$\ln\left(\frac{N_t}{N_0}\right) = -0.693\left(\frac{t}{t_{1/2}}\right)$$

- If you ingest a sample containing Iodine-131, how much time is required for the isotope to fall to 5.0 % of its original activity? The half-life for I-131 is 8.05 days.
- The half-life of 98Au is 2.7 days. If you begin with 5.6 mg of this gold isotope, what mass remains after 9.5 days?

Ex. Calc. Fraction remaining

- Gold-128 undergoes beta decay to give mercury-128 with a half-life of 2.7 days. What fraction of gold-128 is left after 14 days?

$$\ln\left(\frac{N_t}{N_0}\right) = -0.693\left(\frac{14 \text{ days}}{2.7 \text{ days}}\right) = -3.59$$

$$\left(\frac{N_t}{N_0}\right) = e^{-3.59} = 0.0276$$

Fraction remaining = 0.0276
Percentage remaining = 2.76%

Group Quiz #23

- Plutonium-239 decays by alpha emission and has a half-life of 2.4062×10^4 yr.
  - 1) Write the balanced decay reaction.
  - 2) What percentage of a ${}^{239}Pu$ sample remains after 1000 years?
- Phosphorus-32 (used in leukemia therapy) has a half-life of 14.26 days. What percent of a sample remains after 35.0 days?

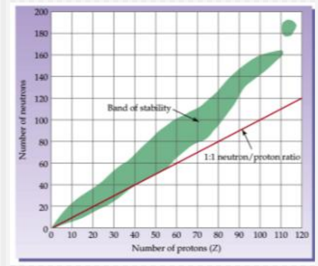
22.4 Nuclear Stability

- **Stable isotopes** refer to isotopes whose half-lives can be measured.
- **Unstable isotopes** decay too fast to be measured.
- Every element up to Bi (except Tc) has 1 or more stable isotopes. Elements > Bi are all radioactive.
- The heavier elements (93 and higher) are synthetic and radioactive. Elements with molar mass in parentheses on the periodic table are radioactive. Why is their molar mass not very precise?
- The "Band of Stability" plots the stable atoms
  - Neutron/proton ratio helps predict stability.

Spontaneous Decay

Band of stability (and the higher "island of stability")

- For Z = 1-20, N = Z (N/Z = 1)
- For Z > 20, N > Z (N/Z $\leq$ 1.6)



Nuclear Stability Patterns

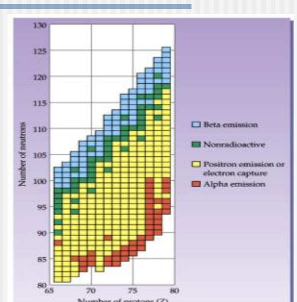
1. Nuclei containing 2, 8, 20, 28, 50, 82, or 126 protons or neutrons are generally more stable than nuclei that do not possess these "magic" numbers.
2. As Z ↑, more neutrons are needed to help bind the nucleus together, so there is a high neutron:proton ratio.
3. Nuclei of elements with > 83 protons are unstable due to the large # of nucleons.
4. Nuclei with both even numbers of protons and neutrons are generally more stable than those with odd #'s.

264 nonradioactive Nuclei

# protons	# neutrons	# stable nuclei
Even	Even	156
Even	Odd	53
Odd	Even	51
Odd	Odd	4

Spontaneous Nuclear Decay

- Figure 22.5
- Nuclei with higher neutron/proton ratios tend to emit beta particles.
- Nuclei with lower neutron/proton ratios tend to favor positron emission, electron capture, or alpha emission.



Types of Decay Processes

- If Z > 83, α emission gets rid of excess mass, with a slight increase in N/Z.
- If N/Z is too high, β emission converts a neutron to a proton plus an electron, decreasing N/Z.
- If N/Z is too low, β+ emission converts a proton to a neutron and a positron; OR electron capture results in a proton capturing an inner electron and becoming a neutron, increasing N/Z.

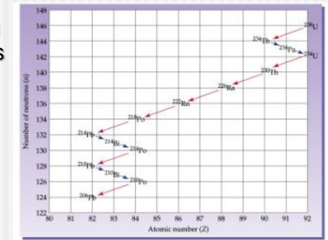
Predict if stable or unstable

- Identify whether each nuclide will most likely be stable or unstable. Stable N/Z < 1.25 (elements 1-20) and even Z & even N.

^{13}B	^{14}C
^{17}O	^{28}Si
^{40}K	^{48}Ca
^{3}H	^{30}P

Figure 22.6 Uranium Series

Some nuclei undergo a series of disintegrations called a *decay series*, before they form a nonradioactive species

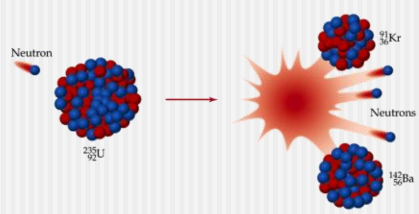


Nuclear Fission and Fusion

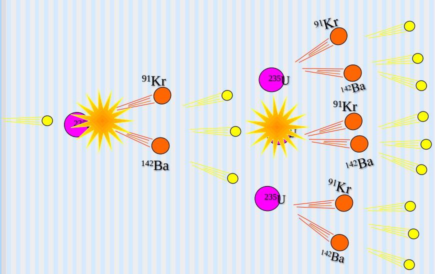
- **Nuclear fission**: nuclei of heavier isotopes are split to form lighter, more stable ones after bombardment by a neutron.
  - This often results in a chain reaction.
- **Nuclear fusion**: nuclei of atoms are joined together or fused. This requires very hot conditions (i.e., the sun).
  - The hydrogen bomb works by fusion. An atomic bomb is used to provide the heat needed.

Chain Reaction

- One step in a chain reaction produces more neutrons than it consumes. Each step gets faster.
- **Critical mass** is the mass required for the chain reaction to become self-sustaining.

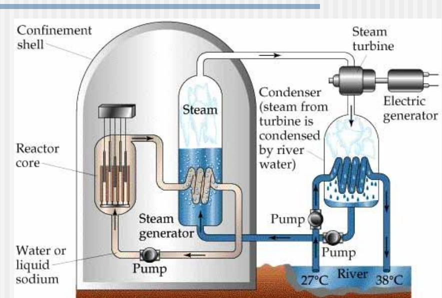


CHAIN REACTION



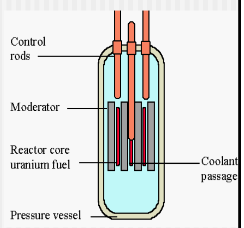
Nuclear Reactor uses Fission

- Figure 22.9



Reactor core

- We use B or Cd control rods to “control” the rate of the fission reaction. They can be raised and lowered as needed.
- Energy produced is used to heat water and drive steam turbines



Nuclear Reactor

- Storage of fission products is a major challenge.
- Chernobyl (1986) used no containment, so the radiation leak was worse than from Three Mile Island (1979).
- Currently there are more than 110 nuclear power plants in the U.S.; about 435 worldwide.
- 17% of the world’s energy comes from nuclear sources.

Nuclear Fusion

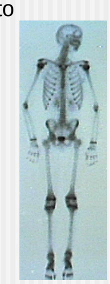
- **Nuclear Fusion** is the formation of heavier nuclei by the joining of lighter ones.
- Fusion products are generally not radioactive.
- Smaller atoms are fused together into one larger atom: $^{1}_{1}H + ^{2}_{1}H \rightarrow ^{3}_{2}He$ (i.e., in the sun)
- Called thermonuclear because they require extremely high temperatures.
- Positive side: H is cheap, plentiful; He is waste which isn’t toxic
- Negative side: Still have trouble controlling the reactions.

Atomic vs Hydrogen Bombs

- Atomic weapons utilize the splitting of atoms (^{235}U) and are detonated through fission and its resulting chain reaction. Hiroshima = 13 ktons
- Hydrogen bombs are detonated through fusion. They are 1000 times more explosive than atomic bombs. Energy is released because of overall loss of mass. **Typical = 10 megatons!**
- Great site - summary of nuclear weapons: http://library.thinkquest.org/3471/abomb.html

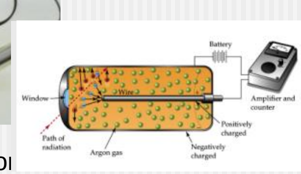
Nuclear Transmutation

- **Transmutation**: atoms are bombarded by high energy particles, this method is used to create new elements.
  $^{14}_{7}N + ^{4}_{2}He \rightarrow ^{17}_{8}O + ^{1}_{1}H$
- Preparation of Tc for medical imaging:
  $^{97}_{42}Mo + ^{2}_{1}H \rightarrow ^{97}_{43}Tc + 2^{1}_{0}n$
- Synthesis of transuranium elements:
  $^{238}_{92}U + ^{4}_{2}He \rightarrow ^{239}_{94}Pu + 3^{1}_{0}n$
  $^{238}_{92}U + ^{12}_{6}C \rightarrow ^{246}_{98}Cf + 4^{1}_{0}n$
  $^{238}_{92}U + ^{14}_{7}N \rightarrow ^{247}_{99}Es + 5^{1}_{0}n$



Detection of Radioactive Decay

Geiger Counter



- Geiger or scintillation
  - NaI fluoresces (light flashes) when irradiated; counts nuclear disintegrations
- activity = number of nuclei disintegrating per unit time; units = Curie (Ci)

Measuring Radioactivity

- activity = number of nuclei disintegrating per unit time
- units = Curie (Ci)
- 1 Ci = 3.7×10^{10} disintegrations/sec = amount for 1 g of ^{226}Ra

Pierre and Marie Curie

22.10 Archeological Dating

- ^{14}C is produced in upper atmosphere and diffuses into lower atmosphere where it is taken up by plants and animals.
- ^{14}C is incorporated into living systems, but undergoes radioactive beta decay with a half-life of 5730 years:
  $^{14}_{6}C \rightarrow {}^{14}_{7}N + {}^{0}_{-1}e^{-}$
- The ratio of ^{14}C to ^{12}C in living organisms is the same as in the atmosphere. When the plant or animal dies, the ratio decreases and an age can be determined.

Archeological Dating

- Living tissue has 15.3 disintegrations per minute per gram of Carbon.
- The Shroud of Turin (thought to be the burial shroud of Christ) was measured to have 14.2 disintegrations per minute per g C. How old is it? ($t_{1/2}$ ^{14}C = 5,730 yrs)
- $\ln (N/N_o) = (-\ln 2)(t / t_{1/2})$
- t = 617 years old

- Problem 22.17

Applications of Isotopes

- Medical diagnoses
  - ^{99}Tc for tumors in spleen, liver, brain, thyroid
    - tracer put into a metabolite that concentrates in cancerous cells
  - ^{131}I or ^{123}I in thyroid
- Cancer therapy -- destroy cells with γ rays
  - ^{131}I for thyroid cancers
  - ^{198}Au for lung cancer
  - ^{32}P for eye tumors

PET scans

- Use radiotracers to measure amounts absorbed by the body to determine structure and function of organs and tissues.