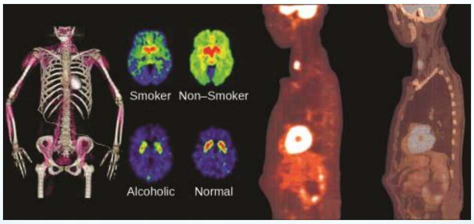
Chapter 21

Nuclear Chemistry



Nuclear chemistry provides the basis for many useful diagnostic and therapeutic methods in medicine, such as these positron emission tomography (PET) scans. The PET/computed tomography scan on the left shows muscle activity. The brain scans in the center show chemical differences in dopamine signaling in the brains of addicts and nonaddicts. The images on the right show an oncological application of PET scans to identify lymph node metastasis.

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Nuclear Chemistry

- Nuclear chemistry involves changes in the nucleus (protons and neutrons) of radioactive atoms.
- Applications of nuclear chemistry:
  - **medical diagnosis and treatment**
  - **C-14 dating**
  - **nuclear power plants**
  - **create new elements**

Nuclear Reactions

Spontaneous emission of particles or electromagnetic radiation is known as ***radioactivity***.

All elements with $Z > 83$ are radioactive. specific isotopes of lighter elements are also radioactive.

Key Differences from Chemical Reactions:

- Balance atomic # and mass # instead of atoms
- Nuclear reactions involve a specific isotope of an element; Different isotopes may undergo different nuclear reactions or not decay at all.
- ΔH is much larger (about 10^{10} kJ)!
- Reaction rates are only affected by concentration.

Atomic notation for Isotopes

Recall atomic notation: $^{A}_{Z}X$

- A = mass # = # neutrons + # protons
- Z = atomic # = # protons
- #neutrons for element may vary giving rise to different isotopes
  - an isotope is also referred to as a nuclide

Example: C has 3 different nuclides:

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

Types of Nuclear Processes

- **Radioactive decay/emission**: an unstable atom emits a particle or energy.
  - parent nuclide → daughter nuclide + radiation
  - **Parent nuclide** undergoes decay.
  - **Daughter nuclide** is formed by the decay.
- **Transmutation**: atoms are bombarded by high energy particles to create elements/isotopes.

$$^{14}_{7}N + ^{4}_{2}He \rightarrow ^{17}_{8}O + ^{1}_{1}H$$

$$^{238}_{92}U + ^{4}_{2}He \rightarrow ^{239}_{94}Pu + 3\,^{1}_{0}n$$

Nuclear Particles

- Alpha particle: α = ${}^4_2He^{2+}$, written as α or ${}^4_2He$
- 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 = ${}^1_0n$
- Proton: p^+ = ${}^1_1p$

Alpha Decay: ${}^4{}_2$He is product

- α = ${}^4{}_2$He or ${}^4{}_2\alpha$
- most massive particle but least harmful since its least penetrating – stopped by paper, skin
- Heavy radioactive isotopes tend to emit α particles: ${}^{238}_{92}U \rightarrow {}^{234}_{90}Th + {}^4_2He$

Note: mass # = # n + # p and atomic # = # p are the same on both sides

Alpha Decay Reactions

- Daughter: mass # ↓ by 4, atomic # ↓ by 2
- Write alpha decay rxns for the following:

${}^{226}{}_{88}Ra \rightarrow {}^4_2He + {}^{222}_{86}Rn$

${}^{232}{}_{90}Th \rightarrow {}^4_2He + {}^{228}_{88}Ra$

${}^4_2He$ can be written as ${}^4_2\alpha$

Beta Emission: ${}^0{}_{-1}\beta$ is product

- β = electron: ${}^0{}_{-1}\beta$ or ${}^0{}_{-1}e$
- more penetrating - stopped by 0.05 - 0.1 cm of Al
- β emission: A high energy ${}^0{}_{-1}e$ is ejected from the nucleus & a neutron is converted into a proton.
- daughter: mass # is same, atomic # ↑ by 1
- E.g. ${}^{234}{}_{90}Th \rightarrow {}^{234}{}_{91}Pa + {}^0{}_{-1}e$

Predict products for this Beta decay rxn:

- ${}^{239}_{92}U \rightarrow {}^0_{-1}e + {}^{239}_{93}Np$

Positron Emission

- β^+ = positron = positive electron: ${}^0{}_1\beta^+$ or ${}^0{}_1e$
- ${}^0{}_1e$ is ejected from the nucleus & a p^+ is converted to a n. Thus, mass # is same, atomic # ↓ by 1

${}^{40}_{19}K \rightarrow {}^0_{+1}e + {}^{40}_{18}Ar$

Electron Capture

- Electron capture is the opposite of β emission. A nucleus captures an electron, converting a p^+ to a n.

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

Gamma Radiation: ${}^0{}_0\gamma$ is product

- 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
- The release of gamma particles does not change the mass # or atomic #.

Nuclear Reactions

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

Nuclear decay is 1st order process

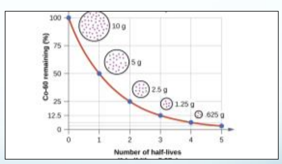
$$\ln\left(\frac{A_t}{A_0}\right) = -kt$$

- A = number of radioactive nuclei present (symbol N used for A for nuclear problems)
- $A = 1/2\ A_o$ at $t = t_{1/2}$: $k = \dfrac{\ln 2}{t_{\frac{1}{2}}} = \dfrac{0.693}{t_{\frac{1}{2}}}$

$$\ln\left(\frac{A_t}{A_0}\right) = -0.693\left(\frac{t}{t_{1/2}}\right)$$

1st 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.
- $t_{1/2}$ is constant for a given radioisotope



- Half-lives can vary from milliseconds to millions of years!

Nuclear Kinetics Calcs

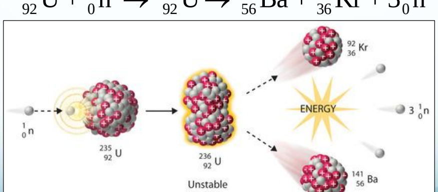
Use 1st order IRL and half-life relationships!

- If you ingest a sample containing I-131, how much time is required for a 75.0 mg sample to decay to 12.5 mg? The half-life for I-131 is 8.05 days.
- The half-life of Au-98 is 2.7 days. If you begin with 5.6 mg of this gold isotope, what mass remains after 9.5 days?

Nuclear Fission

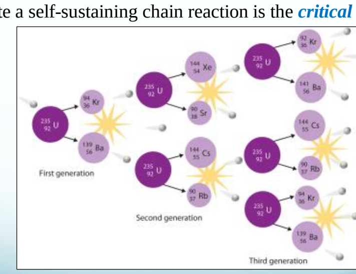
Nuclear fission: heavy nuclei (mass number > 200) are bombarded by neutrons to form smaller nuclei and one or more neutrons. Used in nuclear power plants.

$$^{235}_{92}\text{U} + ^{1}_{0}\text{n} \rightarrow ^{236}_{92}\text{U} \rightarrow ^{141}_{56}\text{Ba} + ^{92}_{36}\text{Kr} + 3^{1}_{0}\text{n}$$

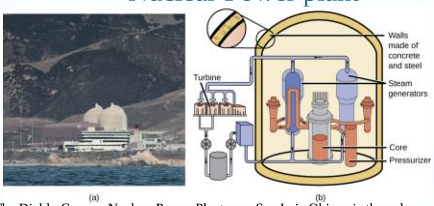


Nuclear Fission

^{235}U is capable of a self-sustaining sequence of nuclear fission known as a ***nuclear chain reaction***. The minimum mass of material required to generate a self-sustaining chain reaction is the ***critical mass***.



Nuclear Power plant



(a)The Diablo Canyon Nuclear Power Plant near San Luis Obispo is the only nuclear power plant currently in operation in California. The domes are the containment structures for the nuclear reactors, and the brown building houses the turbine where electricity is generated. Ocean water is used for cooling. (b) The Diablo Canyon uses a pressurized water reactor, one of a few different fission reactor designs in use around the world, to produce electricity. Energy from the nuclear fission reactions in the core heats water in a closed, pressurized system. Heat from this system produces steam that drives a turbine, which in turn produces electricity. (credit a: modification of work by "Mike" Michael L. Baird; credit b: modification of work by the Nuclear Regulatory Commission)

Nuclear Energy

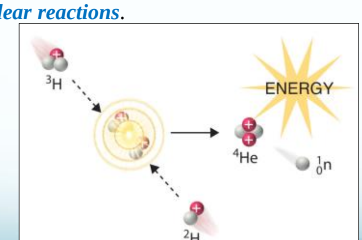
- 17% of world's energy comes from nuclear plants.
- Currently there are more than 110 nuclear power plants in the U.S.; about 435 worldwide.
- B or Cd control rods are lowered and raised to "control" the rate of the fission reaction.
- Energy produced is used to heat water and drive steam turbines.
- Storage of used rods is a major challenge.
- Natural disasters, terrorist acts, operator errors, etc. can lead to huge release of radioactive energy.

Well-Known Incidents

- **Three-Mile Island** (Pennsylvania, 1979): Caused by mechanical failures; small radiation leak (not linked to a cancer fatality, no observable long term health effects).
- **Chernobyl** (Ukraine, 1986): No containment, 31 deaths attributed to accident, radiation leak caused health issues (50,000 excess cancer cases).
- **Fukushima, Japan** (March 2011): Not **caused by** earthquake – low-lying generators flooded from tsunami; seawater to cool down reactors used too late. Single-replacement reaction produced hydrogen gas causing several chemical explosions. Radioactivity release about 1/10 of Chernobyl.

Nuclear Fusion

Nuclear fusion is the process of combining small nuclei into larger ones (up to ^{59}Fe). Because fusion reactions take place at very high temperatures, they are often called ***thermonuclear reactions***.



Nuclear Fusion

ITER: France – building the Tokamak, a device that uses magnetic fields to contain and control hot plasma needed for fusion. ${}^{2}_{1}D + {}^{3}_{1}T \rightarrow {}^{4}_{2}He + {}^{1}_{0}n + 17.6\ MeV$

Due to the high temperature requirements, containment is an issue.

https://en.wikipedia.org/wiki/Tokamak_Fusion_Test_Reactor

Medical Uses of Radioactive Isotopes

- **Prostate Cancer: yttrium-90**
- **Bones: calcium-47 (also phosphorus)**
- **Positron-emission tomography (PET scans): carbon-11**
- **Leukemia: actinium-225**
- **Spleens: iron-59**
- **Arteries: rhenium-188**
- **Arthritis: erbium-169**
- **Liver: cobalt**
- **Thyroid: iodine**
- **Technetium-99: tumors and imaging brain, lungs, liver, skeleton, and blood**