Chapter 18: Nuclear Chemistry

Problems: 3-4, 7 (a-c, e), 9-12 (a & b only), 13-20, 27-28, 43-46

18.1 NATURAL RADIOACTIVITY

Except for ${}^{1}_{1}\text{H}$, every nuclei contains protons and neutrons.

- Some nuclei are unstable (called "radionuclide")
  - ⇒ they "decay" (break down) by spontaneously emitting particles and/or energy
  - such emissions are called **radioactivity** (or radioactive decay)

18.2 NUCLEAR EQUATIONS

Atomic Notation (or Nuclear Symbol):

- shorthand for keeping track of protons and neutrons in the nucleus

$$\begin{array}{r} \text{\# of protons} + \text{neutrons} = \textbf{mass number} = \textbf{A} \\ \text{\# of protons} = \textbf{atomic number} = \textbf{Z} \end{array} \text{E} = \textbf{element symbol}$$

Examples of common particles: electron: ${}^{0}_{-1}\mathbf{e}^{-}$ proton: ${}^{1}_{1}\mathbf{p}^{+}$ neutron: ${}^{1}_{0}\mathbf{n}$

Different Types of Radioactivity

Alpha (α) emission: a helium nucleus, ${}^{4}_{2}\alpha$ or ${}^{4}_{2}\mathbf{He}$, is emitted

$$^{238}_{92}\mathbf{U} \longrightarrow {}^{4}_{2}\alpha + {}^{234}_{90}\mathbf{Th}$$

Beta (β) emission: a beta particle (or electron), ${}^{0}_{-1}\beta$ or ${}^{0}_{-1}\mathbf{e}$, is emitted

$$^{234}_{90}\mathbf{Th} \longrightarrow {}^{0}_{-1}\beta + {}^{234}_{91}\mathbf{Pa}$$

Gamma (γ) emission: high-energy rays (like X-rays), ${}^{0}_{0}\gamma$, are emitted

$$^{99m}_{43}\mathbf{Tc} \longrightarrow {}^{0}_{0}\gamma + {}^{99}_{43}\mathbf{Tc}$$

nuclide: a specific atom with a given number of protons and neutrons

We use the term **parent-daughter nuclides** to describe a *parent* nuclide decaying to produce a *daughter* nuclide.

Balancing Nuclear Equations

– Differ from general chemical equations in that **mass number** (protons + neutrons) **and atomic numbers are balanced**, not the elements (or atoms) present.

For example: $\underset{\text{parent}}{{}^{238}_{92}\mathbf{U}} \rightarrow {}^{4}_{2}\alpha + \underset{\text{daughter}}{{}^{234}_{90}\mathbf{Th}}$

where the mass numbers are equal to 238, and the atomic numbers are equal to 92.

Ex. 1: Complete the following nuclear equations by identifying the unknown:

a. ${}^{20}_{8}\mathbf{O} \rightarrow {}^{20}_{9}\mathbf{F} + \_\_\_\_\_\_$

b. ${}^{26}_{12}\mathbf{Mg} + {}^{1}_{1}\mathbf{p}^{+} \rightarrow {}^{4}_{2}\alpha + \_\_\_\_\_\_$

c. ${}^{9}_{4}\mathbf{Be} + {}^{4}_{2}\alpha \rightarrow {}^{12}_{6}\mathbf{C} + \_\_\_\_\_\_$

Ex. 2:Write complete nuclear equations for the following processes:

a. Iron-59 decays by beta emission.

b. Ra-226 decays by alpha emission.

c. Cs-118 is produced when a radionuclide decays by beta emission.

18.4 Radioactive Half-Life

Hans Geiger developed an instrument that measures emissions from a radioactive sample as "clicks" (**Geiger counter**)

activity: the number of nuclei that disintegrate in a given amount of time

Half-Life ($t_{1/2}$): the amount of time required for the amount or activity of a radioactive sample to decrease by half

Ex. 1: Rn-222 , a radioactive isotope, is one of the resulting daughter products in the U-238 decay series. The hazards associated with radon involve it being inhaled and thus, decaying in the lungs. The daughter product when Rn-222 decays is Po-218.

a. If 128 mg of Rn-222 ($t_{1/2}$=4 days) is inhaled but not exhaled or otherwise eliminated, what mass of it remains in the lungs after 12 days.

b. If 276 mg of Po-218 ($t_{1/2}$=3.1 minutes) formed in the lungs from the decay of Rn-222 inhaled in part a, what mass of it remains in the lungs after 9.3 minutes?

c. If 32.0 mg of Pb-214 ($t_{1/2}$=27 minutes) formed in the lungs from the decay of Po-218 inhaled in part b, what mass of it remains in the lungs after 54 minutes?

18.5 Radionuclide Applications

Radiocarbon Dating; Age of *Organic* Material

- Carbon-14 is used to date organic materials.
  - Carbon-14 is produced by neutron capture in the upper atmosphere:

$$^{14}_{7}\mathrm{N} + {}^{1}_{0}\mathrm{n} \rightarrow {}^{14}_{6}\mathrm{C} + {}^{1}_{1}\mathrm{H}$$

  - We assume the ratio of carbon-14 and carbon-12 in the atmosphere has been constant for about 50,000 years.
  - Because living plants and animals have a constant intake of carbon compounds, they are able to maintain a ratio of carbon-14 to carbon-12 that is identical with the atmosphere.
  - Once the organism dies, it no longer ingests carbon compounds, and the carbon-14 content decreases because of its radioactive decay:

$$^{14}_{6}\mathrm{C} \rightarrow {}^{14}_{7}\mathrm{N} + {}^{0}_{-1}\beta \qquad t_{1/2} = 5730 \text{ years}$$

  - Radiocarbon dating cannot be used to date objects older than 50,000 years because the radioactivity is too low to be measured accurately.
  - Used to date linen wrapped around the Dead Sea Scrolls, which were found to be about 2000 years old

Uranium-Lead Dating; Age of Rocks

- The half-life for uranium-238 to decay to lead-206 is 4.5×10^9 years:

$$^{238}_{92}\mathrm{U} \rightarrow {}^{206}_{82}\mathrm{Pb} + 8\,{}^{4}_{2}\alpha + {}^{0}_{-1}\mathrm{e}$$

- By analyzing rocks to determine the ratio of U-238 to Pb-206 present, one can determine the "age" of the rocks—i.e. the amount of time since the rock solidified.
  - For example, assuming the rock originally has no Pb-206 present, the Pb-206 could only have come from the U-238 decay, and equal amounts of both means half the U-238 has decayed to Pb-206.
    ⇒ The rock is 4.5×10^9 years old (equal to U-238's half life).
  - Used to estimate age of Earth and lunar rock samples brought back from the *Apollo* missions

Medical Applications:

- Radiation can break chemical bonds
  ⇒ radiation can destroy healthy and unhealthy tissue!
- Some radioactive isotopes are used in cancer therapy
  - Cobalt-60 is often used
    - γ-rays from this source are focused at small areas where cancer is suspected
    - Thyroid cancer patients drink a solution of NaI containing radioactive iodide ions (^{131}I or ^{123}I). The iodine moves preferentially through the thyroid gland, where the radiation can (depending on the dosage) either image or destroy overactive thyroid cells.
  - More often, radioactive nuclei (called "radiotracers") are used for diagnosis
    - Positron emission tomography (PET) is a technique used to study brain disorders. A patient is given glucose ($C_6H_{12}O_6$) containing carbon-11, a positron emitter. The brain is then scanned to detect positron emission, and differences in glucose uptake and metabolism can be traced.
    - Sodium-24 (a β-emitter) injected into the bloodstream can be monitored to trace the flow of blood and detect possible constrictions or obstructions.
    - Isotopes of technetium are valuable as diagnostic tools. Patients drink or are injected with solution containing Tc-99m, which helps doctors imaging of organs like the heart, liver, or lungs.

Agricultural Applications:

- Controlling insects without using pesticides
- Cobalt-60 emits gamma rays that sterilize male insects and reduce insect population.
- Gamma irradiation of processed food also destroys microorganisms.
  - Cobalt-60 irradiation destroys parasites in pork (trichinosis) and chicken (salmonella).
  - Gamma irradiation also increases shelf life without using preservatives.

18.6 Artificial Radioactivity

Nuclei can also be induced to decay as a result of bombardment by high energy particles (e.g. neutrons, electrons, and other nuclei)

- These kinds of nuclear changes are called **nuclear transmutation**.

This means we can cause nuclear reactions to occur!

18.7 Nuclear Fission

Nuclear Binding Energy

- energy required to break up a nucleus into its component nucleons
- The most stable nuclei have mass numbers of about 40-80
  - ⇒ Heavier nuclei (those with mass numbers > 80) can split into smaller, more stable nuclei: **nuclear fission**
  - ⇒ Smaller nuclei (those with mass numbers < 40) combine with other smaller nuclei to form more stable nuclei: **nuclear fusion**

Nuclear Fission: A heavy nucleus (mass number > 200) divides to form smaller, more stable nuclei, resulting in the release of large amounts of energy

The Fission Process

- Many isotopes of heavy elements undergo fission if bombarded by high-energy neutrons.
- Two naturally occuring isotopes, $^{235}_{92}\mathrm{U}$ and $^{239}_{94}\mathrm{Pu}$, have practical applications.
  - They undergo fission when hit with even low energy neutrons moving at about the same speed as air molecules at room temperature.
  - Let's focus on $^{235}_{92}\mathrm{U}$:
    - A representative reaction is

$$^{235}_{92}\mathrm{U} + {}^{1}_{0}\mathrm{n} \rightarrow {}^{90}_{38}\mathrm{Sr} + {}^{143}_{54}\mathrm{Xe} + 3\,{}^{1}_{0}\mathrm{n}$$

  - Note that additional neutrons are also produced
  - ⇒ The neutrons generated can induce fission in other nuclei, which turn produces more neutrons, and so on.
    - ⇒ **nuclear chain reaction:** self-sustaining sequence of nuclear reactions
  - Nuclear chain reaction's also require a **critical mass**, the minimum amount of fissionable material needed to generate a self-sustaining chain reaction.
  - i.e. there must be enough $^{235}_{92}\mathrm{U}$ present, so the neutrons produced can collide with them to cause more fission reactions

Fission Energy

- The energy released is or 8.4×10^{7} kJ/g of $^{235}_{92}\mathrm{U}$, which is about equal to the explosion of 30 metric tons (3×10^{4} kg) of TNT!

Nuclear Reactors

- Entire reactor is contained in a concrete building to shield personnel and nearby residents from radiation.
- Fuel rods alternate with control rods in a containment chamber.
  - fuel rods: UO_2 pellets in a zirconium alloy tube, where the uranium is "enriched" to contain 3% U-235, the fissionable material.
    - Only about 0.7% of naturally occurring uranium is U-235 while 99.3% is U-238, so a sample must be "enriched" to increase the amount of U-235 present.
  - control rods: cadmium or boron rods that capture neutrons and serve to control the number of neutrons, and thus, the nuclear fission reactions.
- Water is passed through the reactor to absorb the heat given off by fission and to moderate (or slow down) the neutrons produced.
- The heated water heats more water to steam, which drives a turbogenerator that produces electrical energy.
- Cooling water (usually a river) is also used to cool the steam for reuse.

Nuclear Waste

- Each year, on average, one-fourth of the intensely radioactive fuel rods used in nuclear reactors must be replaced.
- In 1982, the Nuclear Waste Policy Act established a timetable for choosing and preparing sites for underground disposal of radioactive materials.
- Potential problems:
  - It's estimated that 20 half-lives are required for the radioactivity to reach acceptable levels for biological exposure.
    - Since Sr-90's half-life is 28.8 years, the wastes must be stored for at least 600 years.
    - If Pu-239 is being stored, the storage must last much longer since Pu-239 's half-life is 24,000 years.
- There must be assurances that the containers do not crack, allowing radioactivity to find its way into underground water supplies.

18.8 Nuclear Fusion

Nuclear Fusion : Lighter nuclei combine to form more stable nuclei

- The energy available from such fusion reactions is considerably greater than that given off by fission reactions.
- This is the type of reaction that provides the Sun its energy.

Advantages of Nuclear Fusion:

- Produces more energy per gram of materials
- Light isotopes needed for fusion reactions are more abundant than heavy isotopes needed for fission reactions.
- Fusion products are not radioactive.

Disadvantages of Nuclear Fusion:

- High energies are required to overcome repulsion between nuclei.
  - For example, a temperature of 40 million Kelvin is required for the following fusion reaction:

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

  - Such high temperatures have been achieved by using an atomic bomb to initiate the fusion process, but this approach can't be used for controlled power generation.
  - In addition, no known structural material can withstand the enormous temperatures necessary for fusion on the scale needed for power generation.