

# 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):

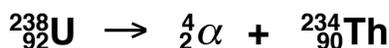
- shorthand for keeping track of protons and neutrons in the nucleus

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

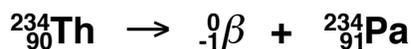
Examples of common particles: electron:  ${}^0_{-1}\text{e}^-$     proton:  ${}^1_1\text{p}^+$     neutron:  ${}^1_0\text{n}$

### Different Types of Radioactivity

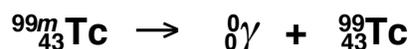
**Alpha ( $\alpha$ ) emission:** a helium nucleus,  ${}^4_2\alpha$  or  ${}^4_2\text{He}$ , is emitted



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



**Gamma ( $\gamma$ ) emission:** high-energy rays (like X-rays),  ${}^0_0\gamma$ , are emitted



**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.



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:

- $^{20}_8\text{O} \rightarrow ^{20}_9\text{F} + \underline{\hspace{2cm}}$
- $^{26}_{12}\text{Mg} + ^1_1\text{p}^+ \rightarrow \frac{4}{2}\alpha + \underline{\hspace{2cm}}$
- $^9_4\text{Be} + \frac{4}{2}\alpha \rightarrow ^{12}_6\text{C} + \underline{\hspace{2cm}}$

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

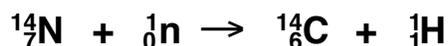
- Iron-59 decays by beta emission.
- Ra-226 decays by alpha emission.
- Cs-118 is produced when a radionuclide decays by beta emission.



## 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:



- 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:



- 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  $4.5 \times 10^9$  years:



- 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  $4.5 \times 10^9$  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
    - $\gamma$ -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 ( $^{131}\text{I}$  or  $^{123}\text{I}$ ). 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 ( $\text{C}_6\text{H}_{12}\text{O}_6$ ) 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  $\beta$ -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 occurring isotopes,  $^{235}_{92}\text{U}$  and  $^{239}_{94}\text{Pu}$ , 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  $^{235}_{92}\text{U}$ :
    - A representative reaction is



- 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  $^{235}_{92}\text{U}$  present, so the neutrons produced can collide with them to cause more fission reactions

### Fission Energy

- The energy released is or  $8.4 \times 10^7$  kJ/g of  $^{235}_{92}\text{U}$ , which is about equal to the explosion of 30 metric tons ( $3 \times 10^4$  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:  $\text{UO}_2$  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

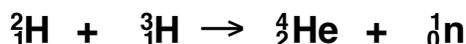
- The energy available from such fusion reactions is considerably greater than that given off by fission reactions.
- This is the type of reaction that provides the Sun its energy.

### **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:



- 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.