CHAPTER 23 NUCLEAR CHEMISTRY

23.1 THE NATURE OF NUCLEAR REACTIONS

radioactivity - the spontaneous decay of an unstable nucleus with accompanying emission of radiation.

nuclide - atom with a specific number of protons and neutrons in its nucleus.

$\Rightarrow$ There are 271 stable nuclides in nature, others are radioactive

radionuclide - unstable isotope that undergoes nuclear decay

$\Rightarrow$ All isotopes of elements with $\geq$ 84 protons are radioactive; specific isotopes of lighter elements are also radioactive. (E.g. $^{3}_{1}H$)

\# nucleons = # protons + # neutrons

Nuclear reactions differ from ordinary chemical reactions

- Atomic numbers of nuclei may change (elements are converted to other elements or an element can be converted to an isotope of that element).
- Protons, neutrons, electrons and other elementary particles may be involved in a nuclear reaction.
- Reactions occur between particles in the nucleus.
- Matter is converted to energy & huge amounts of energy are released.
- Nuclear reactions involve a specific isotope of an element; different isotopes of an element may undergo different nuclear reactions.

Types of Radioactive Decay:

1) alpha, α, emission

α particles - high energy and low speed + charged particles; $^{4}_{2}He$ (helium-4)

E.g. emission of an α particle: $^{238}_{92}U \rightarrow ^{234}_{90}Th + ^{4}_{2}He$

2) beta, β, emission

β particles – high energy and high speed – charged electrons: $^{0}_{-1}e$

E.g. emission of a β particle: $^{234}_{90}Th \rightarrow ^{234}_{91}Pa + ^{0}_{-1}e$

- During β decay, a neutron is converted into a proton: $^{1}_{0}n \rightarrow ^{1}_{1}p + ^{0}_{-1}e$

3) gamma, γ, emission; gamma emission accompanies other types of decay

γ particles - high energy photons, very penetrating: $^{0}_{0}\gamma$

4) positron, $^{0}_{1}e$, emission - same mass, but opposite charge of electron

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

5) Electron capture - β particle is captured instead of emitted

$^{82}_{37}Rb + ^{0}_{-1}e \rightarrow ^{82}_{36}Kr$

23.2 NUCLEAR STABILITY

Nuclear Stability

- Nuclei containing 2, 8, 20, 50, 82, or 126 protons or neutrons are generally more stable than nuclei that do not possess these "magic" numbers.
- As the atomic number increases, more neutrons are needed to help bind the nucleus together, so there is a high neutron:proton ratio.
- Nuclei of elements with > 83 protons are unstable due to the large # of nucleons present in the tiny nucleus; by undergoing radioactive decay unstable nuclei can form more stable nuclei.
- Nuclei with both even numbers of both protons & neutrons are generally more stable than those with odd numbers:

# protons	# neutrons	# stable nuclei
even	even	164
even	odd	53
odd	even	50
odd	odd	4

23.3 NATURAL RADIOACTIVITY

Radioactive Decay Series

Many heavy elements undergo several sequential emissions before forming a more stable nuclei:

$$^{238}_{92}U \rightarrow\ ^{234}_{90}Th +\ ^{4}_{2}He \rightarrow\ ^{234}_{91}Pa +\ ^{0}_{-1}e \rightarrow\ ^{234}_{92}U +\ ^{0}_{-1}e \rightarrow\rightarrow\rightarrow\ ^{206}_{82}Pb +\ ^{4}_{2}He$$

Kinetics of Radioactive Decay

- Different isotopes decay at different rates; rates vary from ms to days to years.
- Radioactive decay is a first order rate process; all radioactive substances have a characteristic half-life:

$kt_{1/2} = 0.693$ — $t_{1/2}$ = half-life; k = rate constant

$\ln \frac{A_t}{A_0} = -kt$ — A_0 = initial activity or amount; A_t = activity after a certain time

$\frac{A_t}{A_0}$ = fraction of material remaining after time t

23.4 NUCLEAR TRANSMUTATION

Transmutation - Change of one element to another as a result of bombardment by high-energy particles (e.g. neutrons, electrons, and other nuclei).

- Rutherford prepared 1st synthetic nuclide, ^{17}O, in 1919; Irene Curie prepared 1st radioactive nuclide, ^{30}P, in 1934.
- All trans-Uranium elements (Z > 92) are both synthetic (man-made) and radioactive.

Nuclear transmutations can show α–, β–, and γ-emissions as well as production of protons, neutrons, and other isotopes:

E.g. $^{27}_{13}Al +\ ^{4}_{2}He \rightarrow\ ^{30}_{15}P +\ ^{1}_{0}n$

23.5 NUCLEAR FISSION

Fission - A nuclear reaction that releases energy as a result of splitting of large nuclei into smaller ones.

Nuclear Power plants use fission to split U-235 to produce energy:

1. U-235 is bombarded with slow neutrons - this produces smaller nuclei as well as more neutrons and energy.
2. A chain reaction results because each neutron produced can cause fission of another U-235 nucleus.

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

Critical mass - minimum mass required to sustain a chain reaction.

Control rods are made of B or Cd; these rods absorb neutrons so the process doesn't accelerate too rapidly. Rods are raised/lowered to control the speed of the process.

Fuel rods are made of U-235. ^{238}U is the most abundant U isotope but is not fissionable so uranium must be enriched to increase the amount of ^{235}U.

Moderator - slows down the neutrons. Water or other liquid coolant surround rods. The water serves to 1) slow down neutrons so they can collide with U-235; 2) transfer heat to steam generator.

Primary problems with nuclear power plants:

1) safety (Chernobyl and Three Mile Island had cooling system failures that led to reactor meltdowns. Chernobyl also did not have containment building around reactor.)
2) nuclear waste - some products will remain radioactive for thousands of years.

23.6 NUCLEAR FUSION

Fusion - A nuclear reaction that releases energy as a result of the union of smaller nuclei to form larger ones.

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

- Fusion generates even more energy than fission and creates little radioactive waste, so it would provide a wonderful source of energy.
- ...but, fusion requires very high temps (tens of millions of degrees Celsius) in order for nuclei to overcome strong repulsive forces – magnetic fusion reactors are being designed and tested.

23.7 APPLICATIONS OF RADIOACTIVE ISOTOPES

- Nuclear power plants
- Medical diagnosis and treatment e.g. PET scan monitors glucose metabolism in brain using C-11 isotope; I-131 measures activity of thyroid
- Carbon dating (measure amount of C-14 remaining in a sample)
- Synthesis of new elements
- Irradiation of food - preserves food & destroys parasites
- Nuclear Weapons (Atomic bombs and H bombs)