Chapter 21: Nuclear Chemistry

21.1 Radioactivity

- **nucleons** – neutron and proton
- all atoms of a given element have the same number of protons, atomic number
- **isotopes** – atoms with the same atomic number but different mass numbers
- three isotopes of uranium: uranium-233, uranium-235, uranium-238
- $^{233}_{92}U$, $^{235}_{92}U$, $^{238}_{92}U$ (superscript is mass number, subscript atomic number)
- radionuclides – nuclei that are radioactive
- radioisotopes – atoms containing radionuclides

21.1.1 Nuclear Equations

- **alpha particles** – helium-4 particles
- **alpha radiation** – stream of alpha particles
- emission of radiation is one way that an unstable nucleus is transformed into a more stable one
- $^{238}_{92}U \rightarrow ^{234}_{90}Th + ^{4}_{2}He$
- superscript = mass number
- subscript = atomic number
- **radioactive decay** – when a nucleus spontaneously decomposes
- sum of the mass numbers is the same on both sides of the equation
- sum of the atomic numbers same on both sides of the equation
- radioactive properties of the nucleus are independent of the state of chemical combination of the atom
- chemical form does not matter when writing nuclear equations

21.1.2 Types of Radioactive Decay

- three most common type of radioactive decay: alpha(α), beta(β), and gamma(γ) radiation

	Types of Radiation		
Property	α	β	γ
Charge	2+	1-	0
Mass	$6.64x10^{-24}$ g	$9.11x10^{-28}$ g	0
Relative penetrating power	1	100	10,000
Nature of radiation	$^{2}_{4}He$ nuclei	electrons	High-energy photons

- **beta particles** – high speed electrons emitted by an unstable nucleus
  - $^{131}_{53}I \rightarrow ^{131}_{54}Xe + ^{0}_{-1}e$
  - beta decay results in increasing the atomic number
  - $^{1}_{0}n \rightarrow ^{1}_{1}p + ^{0}_{-1}e$
- **gamma radiation** – high-energy protons
  - gamma radiation does not change atomic number or mass number or a nucleus
  - almost always accompanies other radioactive emission
  - represents the energy lost when the remaining nucleons reorganize into more stable arrangements

- **positron** – particle that has same mass as an electron but opposite charge
  - represented by $^{0}_{1}e$
- emission of a positron has effect of converting a proton to a neutron → decreasing atomic number of nucleus by 1

        - **electron capture** – the capture by the nucleus of an inner-shell electron from the electron cloud surrounding the nucleus
        - has effect of converting a proton to neutron
    - $^{1}_{1}p + ^{0}_{-1}e \rightarrow ^{1}_{0}n$

Particle	Symbol
Neutron	$^{1}_{0}n$
Proton	$^{1}_{1}H$ or $^{1}_{1}p$
Electron	$^{0}_{-1}e$
Alpha Particle	$^{4}_{2}He$ or $^{4}_{2}\alpha$
Beta Particle	$^{0}_{-1}e$ or $^{0}_{-1}\beta$
Positron	$^{0}_{1}e$

21.2 Patterns of Nuclear Stability

21.2.1 Neutron-to-Proton Ratio

- **strong nuclear force** – a strong force of attraction between a large number of protons in the small volume of the nucleus
- stable nuclei with low atomic numbers up to 20 have nearly equal number of neutrons and protons
- for higher atomic numbers, the number of neutrons are greater than the number of protons
- the neutron-to-proton ratio of stable nuclei increase with increasing atomic number
- **belt of stability** – area where all stable nuclei are found
    - ends at bismuth
    - all nuclei with 84 or more protons are radioactive
    - an even number of protons and neutrons is more stable than an odd number
- determining type of radioactive decay
    - 1) nuclei above the belt of stability
        - high neutron-to-proton ratios
        - move toward belt of stability by emitting a beta particle
        - decreases the number of neutrons and increases the number of protons in a nucleus
    - 2) nuclei below the belt of stability
        - low neutron-to-proton ratios
        - move toward belt of stability by positron emission or electron capture
        - increase number of neutrons and decrease the number of protons
        - positron emission more common with lower nuclear charges
        - electron capture becomes more common with increasing nuclear charge
    - 3) nuclei with atomic numbers ≥ 84
        - alpha emission
        - decreases both number of neutrons and protons by 2

21.2.2 Radioactive Series

- some nuclei cannot game stability by a single emission
- radioactive series or nuclear disintegration series – series of nuclear reactions that begin with an unstable nucleus to a stable one
- three types of radioactive series found in nature
    - uranium-238 to lead-206, uranium-235 to leat-207, and thorium-232 to lead-208

21.2.3 Further Observations

- nuclei with 2, 8, 20, 28, 50, or 82 protons or 2, 8, 20, 28, 50, 82, or 126 neutrons are more stable than with nuclei without these numbers
- numbers called magic numbers
- nuclei with even number of protons and neutrons more stable than with odd number of protons and neutrons
- observations made in terms of the shell model of the nucleus
  - nucleons reside in shells
- magic numbers represent closed shells in nuclei

21.3 Nuclear Transmutations

- **nuclear transmutations** – nuclear reactions caused by the collision of one nucleus with a neutron or by another nucleus
- first conversion of one nucleus into another performed by Ernest Rutherford in 1919
  - converted nitrogen-14 to oxygen-17
- $^{14}_{7}\mathrm{N} + ^{4}_{2}\mathrm{He} \rightarrow ^{17}_{8}\mathrm{O} + ^{1}_{1}\mathrm{H}$
- $^{14}_{7}\mathrm{N}(\alpha, \mathrm{p})^{17}_{8}\mathrm{O}$

21.3.1 Using Charged Particles

- **particle accelerators** – used to accelerate particles at very high speeds
  - cyclotron, and synchrotron

21.3.2 Using Neutrons

- neutrons do not need to be accelerated

21.3.4 Transuranium Elements

- **transuranium elements** – elements with atomic numbers above 92 that are produced by artificial transmutations

21.4 Rates of Radioactive Decay

- radioactive decay is a first-order process
  - has characteristic of half life, which is the time required for half of any given quantity of a substance to react
  - half-life unaffected by external conditions

21.4.1 Dating

- radiocarbon dating assumes that the ratio of carbon-14 to carbon-12 in the atmosphere has been constant for at least 50,000 years
- age of rocks can be determined by ratio of uranium-238 to lead-206

21.4.2 Calculations Based on Half-life

- rate = kN
- k = decay constant, N = nuclei
- $\ln \frac{N_t}{N_o} = -kt$
- t = time interval of decay, k = decay constant, N_0 = initial number of nuclei at time zero, N_t = number remaining after time interval
- $k = \frac{0.693}{t_{\frac{1}{2}}}$

21.5 Detection of Radioactivity

- **Geiger counter** – device used to measure and detect radioactivity
- Based on ionization of matter caused by radiation

- **Phosphors** – substances that give off light when exposed to radiation
- **Scintillation counter** – used to detect and measure radiation based on tiny flashes of light produced when radiation strikes a suitable phosphor

21.5.1 Radiotracers

- radioisotopes can be used to follow an element through its chemical reactions
- isotopes of same element have same properties
- **radiotracer** – radioisotopes used to trace an element

21.6 Energy changes in Nuclear Reactions

- $E = mc^2$
- E = energy, m = mass, c = speed of light
- If system loses mass, it loses energy (exothermic)
- If system gains mass, it gains energy (endothermic)

21.6.1 Nuclear Binding Energies

- masses of nuclei always less than masses of individual nucleons
- **mass defect** – mass difference between a nucleus and its constituent nucleons
- energy is needed to break nucleus into separated protons and neutrons, addition of energy must also have an increase in mass
- nuclear binding energy – energy required to separate a nucleus into its individual nucleons
  - the larger to nuclear binding energy the more stable the nucleus toward decomposition
- **fission** – energy produced when heavy nuclei split
- **fusion** – energy produced when light nuclei fuse

21.7 Nuclear Fission

- fission and fusion both exothermic
- chain reaction – reaction in which the neutrons produced in one fission cause further fission reactions
- in order for a fission chain reaction to occur, the sample of fissionable material must have a certain minimum mass
- **critical mass** – amount of fissionable material large enough to maintain the chain reaction with a constant rate of fission
- **supercritical mass** – mass in excess of a critical mass

21.7.1 Nuclear Reactors

- nuclear reactors the fission is controlled to generate a constant power
- reactor core consists of fissionable fuel, control rods, a moderator, and cooling fluid
- fission products are extremely radioactive and are thus hard to store
- about 20 half-lives needed for products to react acceptable levels for biological exposure

21.8 Nuclear Fusion

- fusion is appealing because of availability of light isotopes and fusion products are not radioactive
- high energies needed to overcome attraction of nuclei
- **thermonuclear reactions** – fusion reactions
- lowest temperature required is about 40,000,000 K

21.9 Biological Effects of Radiation

- when matter absorbs radiation, the energy of the radiation can cause either excitation or ionization
- ionization radiation more harmful than nonionization radiation
- most of energy of radiation absorbed by water molecules

- **free radical** – a substance with one ore more unpaired electrons
    - can attack other biomolecules to produce more free radicals
- gamma rays most dangerous
- tissues that take most damage are the ones that reproduce at a rapid rate
    - bone marrow, blood forming tissues, lymph nodes

21.9.1 Radiation Doses

- becquerel (Bq) – SI unit for activity of the radiation source; rate at which nuclear disintegrations are occurring
- 1 (Bq) = 1 nuclear disintegration/s
- curie (Ci) = 3.7×10^{10} disintegrations/s = rate of decay of 1g of radium
- two units used to measure amount of exposure to radiation: gray (Gy) and rad
- gray – SI unit of absorbed dose = absorption of 1 J of energy per kilogram of tissue
- rad (radiation absorbed dose) – absorption of 1×10^{-2} J of energy per kilogram of tissue
- 1 Gy = 100 rads
- relative biological effectiveness – RBE
    - 1 for gamma and beta radiation, 10 for alpha radiation
    - exact value varies with dose rate, total dose, and type of tissue affected
    - rem (roentgen equivalent for man) – product of the radiation dose in rads and the RBE of the radiation gibes the effective dosage
        - rem is unit of radiation damage that is usually used in medicine
        - number of rems = (number of rads)(RBE)
- Sievert (Sv) – SI unit for dosage
    - 1 Sv = 100 rem
    - annual exposure = 360mrem

21.9.2 Radon

- radon exposure estimated to account for more than half annual exposure
- half-life of radon is 3.82 days
- decays into radioisotope polonium
- atoms of polonium can be trapped in lungs giving out alpha radiation causing lung cancer
- recommended levels of radon-222 in homes is to be less than 4 pCi per liter of air