21.1 Radioactivity

• When nuclei change spontaneously, emitting energy, they are said to be **radioactive**.

• **Nuclear chemistry** is the study of nuclear reactions and their uses.

• **Nucleons** are particles in the nucleus:
  • \( p^+ \): proton
  • \( n^0 \): neutron

• Atomic number is the number of \( p^+ \).

• Mass number is the number of \( p^+ + n^0 \).

• The mass number is the total number of nucleons in the nucleus.

• **Isotopes** have the same number of \( p^+ \) but different numbers of \( n^0 \).
  • Different isotopes of the same element are distinguished by their mass numbers.
  • Different isotopes have different natural abundances.

• A **radionuclide** is a radioactive nucleus.

• Atoms containing these nuclei are called **radioisotopes**.

**Nuclear Equations**

• Most nuclei are stable.

• Radionuclides are unstable and spontaneously emit particles and/or electromagnetic radiation.

• Example: Uranium-238 is radioactive.

• It emits **alpha (α) particles**.
  • These are helium-4 particles.

• When a nucleus spontaneously decomposes in this manner, we say it has decayed (**radioactive decay**).

• In nuclear equations, the total number of nucleons is conserved.

• We can represent the uranium-238 decay by the following nuclear equation:

\[
^{238}_{92}U \rightarrow ^{234}_{90}Th + ^{4}_{2}He
\]

• The total number of protons and neutrons before a nuclear reaction must be the same as the total number of nucleons after the reaction.

**Types of Radioactive Decay**

• There are three types of radiation which we will consider:

  • \( \alpha \)-Radiation is the loss of \( ^{4}_{2}He \) (alpha particles) from the nucleus.
  • \( \beta \)-Radiation is the loss of \( ^{0}_{-1}e \) (an electron) from the nucleus. These high-speed e- are called beta particles.
  • \( \gamma \)-Radiation is the loss of gamma rays (high-energy photons) from the nucleus.

• Nucleons can undergo two other types of decay:

  • **positron emission**
    • A positron is a particle with the same mass as an electron but with the opposite sign.
  • **electron capture**
    • The nucleus captures an electron from the electron cloud surrounding the nucleus.

• Representations:

  • In nuclear chemistry, to ensure the conservation of nucleons we write all particles with their atomic and mass numbers: \( ^{4}_{2}He \) and \( ^{4}_{2} \) represent \( \alpha \)-radiation.

• Nucleons can undergo decay:

  • \( (\beta^- \text{emission}) \quad ^{1}_{0}n \rightarrow ^{1}_{+1}p + ^{0}_{0}e \)
  • \( \text{(positron annihilation) } \quad ^{0}_{-1}e + ^{0}_{0}e \rightarrow ^{0}_{0} \gamma \)
  • \( \text{(positron or } \beta^+ \text{-emission) } \quad ^{1}_{+1}p \rightarrow ^{1}_{0}n + ^{0}_{0}e \)
  • \( \text{(electron capture) } \quad ^{1}_{-1}p + ^{0}_{0}e \rightarrow ^{0}_{1}n \)
21.2 Patterns of Nuclear Stability

Neutron-to-Proton Ratio

- The proton has high mass and high charge.
- Therefore, the proton-proton repulsion is large.
- In the nucleus the protons are very close to each other.
- The cohesive forces in the nucleus are called strong nuclear forces.
  - Neutrons are involved with the strong nuclear force.
- As more protons are added (the nucleus gets heavier) the proton-proton repulsion gets larger.
  - Therefore, the heavier the nucleus, the more are neutrons required for stability.
- The belt of stability is the portion of a graph of (number of protons) vs. (number of neutrons) that contains all stable nuclei.
  - All nuclei with 84 or more protons are radioactive.
  - Nuclei above the belt of stability undergo \( \beta^- \)-emission.
    - An \( _{\text{e}}^0 \) is lost; the number of neutrons decreases and the number of protons increases.
  - Nuclei below the belt of stability undergo \( \beta^+ \)-emission or electron capture.
    - This results in the number of neutrons increasing and the number of protons decreasing.
  - Nuclei with atomic numbers greater than 83 usually undergo \( \alpha \)-emission.
    - The number of protons and neutrons decreases (in steps of 2).

Radioactive Series

- A nucleus usually undergoes more than one transition on its path to stability.
- The series of nuclear reactions on this path comprise the radioactive series, or the nuclear disintegration series.

Further Observations

- Magic numbers are 2, 8, 20, 28, 50, or 82 protons or 2, 8, 20, 28, 50, 82, or 126 neutrons.
  - Nuclei with a “magic number” of nucleons are more stable than nuclei without the magic number of nucleons.
    - The magic numbers correspond to filled, closed-shell nucleon configurations.
  - Nuclei with even numbers of protons and neutrons are more stable than nuclei with any odd numbers of nucleons.
    - The shell model of the nucleus rationalizes these observations.
      - The shell model of the nucleus is similar to the shell model for the atom.
        - Pairs of protons and neutrons in the nucleus are analogous to pairs of electrons in the atom.

21.3 Nuclear Transmutations

Nuclear transmutations are nuclear reactions resulting from the collisions between nuclei or between a nucleus and a neutron.

Using Charged Particles

- For example, nuclear transmutations can occur using high-velocity \( \alpha \)-particles:
  \[
  ^{14}\text{N} + ^{4}\alpha \rightarrow ^{17}\text{O} + ^{1}\text{H}
  \]
- In short-hand notation the preceding reaction is written as \(^{14}\text{N}(\alpha,p)^{17}\text{O}\).

Accelerating Charged Particles

- To overcome electrostatic forces, charged particles need to be accelerated before they react.
  - Particle accelerators (atom smashers, cyclotrons, synchrotrons) are used to accelerate particles using strong magnetic and electrostatic fields.
  - A cyclotron consists of D-shaped electrodes (dees) with a large circular magnet above and below the chamber.
  - Particles enter the vacuum chamber and are accelerated as the dees are alternately made positive and negative.
    - The magnets above and below the dees keep the particles moving in a spiral path.
  - When the particles are moving at a sufficient velocity they are allowed to escape and strike the target.
  - The circumference of the ring at the Fermi National Accelerator Laboratory in Chicago is 6.3 km.
Using Neutrons
• Most synthetic isotopes used in medicine and research are made using neutrons as projectiles.
• An example is the preparation of cobalt-60 for use in cancer radiation therapy.

Transuranium Elements
• Transuranium elements follow uranium in the periodic table.

21.4 Rates of Radioactive Decay
• Radioactive decay is a first-order process.
• Each isotope has a characteristic half-life.
  • Half-lives are not affected by temperature, pressure or chemical composition.
  • Natural radioisotopes tend to have longer half-lives than synthetic radioisotopes.
  • Half-lives range from fractions of a second to millions of years.
  • Naturally occurring radioisotopes can be used to determine the age of a sample.
    • This process is radioactive dating.

Dating
• Carbon-14 (\(^{14}\text{C}\)) is used to determine the ages of organic compounds because half-lives are constant.
• For \(^{14}\text{C}\) to be detected, the object must be less than 50,000 years old.
  • We assume that the ratio of \(^{12}\text{C}\) to \(^{14}\text{C}\) has been constant over time.
  • The half-life of \(^{14}\text{C}\) is 5,715 years.
  • \(^{14}\text{C}\) undergoes decay to \(^{14}\text{N}\) via β-decay:

\[
^{14}\text{C} \rightarrow ^{14}\text{N} + ^{6}\text{He}
\]

• Other dating methods are also used.
  • Uranium-lead dating has been used to estimate the age of the Earth at approximately 4.0 billion years.

Calculations Based on Half-life
• Radioactive decay is a first-order process:

\[
\text{Rate} = kN
\]

• If the activity of a sample at time = \(t\) is \(N_t\), and the activity at time = 0 is \(N_0\), then:

\[
\ln \frac{N_t}{N_0} = -kt
\]

• The half-life of the sample is given by:

\[
\frac{t_{\frac{1}{2}}}{k} = \frac{0.693}{k}
\]

• In radioactive decay the constant, \(k\), is called the decay constant.
• The rate of decay is called activity (disintegrations per unit time).

• There are several units used to express activity or radioactivity.
  • The becquerel (Bq) is the SI unit of radioactivity.
  • 1 Bq = 1 disintegration per second (dps).
  • The Curie (Ci) is an older, but still very widely used, unit of activity.
    • 1 Ci = 3.7 \times 10^{10} disintegrations per second

21.5 Detection of Radioactivity
• Matter is ionized by radiation.
• A Geiger counter determines the amount of ionization by detecting an electric current.
  • A thin window is penetrated by the radiation and causes the ionization of Ar gas.
    • The ionized gas carries a charge, so current is produced.
    • The current pulse generated when the radiation enters is amplified and counted.
• Other methods are also used to detect radioactivity.
• One common method employs an instrument called a scintillation counter.
  • A substance called a phosphor is allowed to interact with radiation.
    • Light is produced when radiation strikes a suitable phosphor.
    • This light is detected and used to quantify the amount of radiation.
Radiotracers
• Photosynthesis has been studied using $^{14}$C:

\[ 6^{14}\text{CO}_2 + 6\text{H}_2\text{O} \xrightarrow{\text{sunlight}} 14^{\text{C}}\text{H}_2\text{O}_6 + 6\text{O}_2 \]

• The carbon dioxide is said to be $^{14}$C labeled.
• The presence of $^{14}$C in the intermediates or products of photosynthesis can be determined.
  • $^{14}$C is detected as it moves from carbon dioxide to ultimately become incorporated into glucose.
  • Thus the path of the carbon atoms may be traced.
• Radiotracers are used to follow an element through a chemical reaction.

21.6 Energy Changes in Nuclear Reactions
• Einstein showed that mass and energy are proportional:

\[ E = mc^2 \]

• If a system loses mass, it loses energy (exothermic).
• If a system gains mass, it gains energy (endothermic).
• Since $c^2$ is a large number, small changes in mass cause large changes in energy.
• Mass and energy changes in nuclear reactions are much greater than in chemical reactions.
• Consider:

\[ ^{238}\text{U} \rightarrow ^{234}\text{Th} + ^4\text{He} \]

• For 1 mol of Uranium-238, the masses are:

\[ 238.0003 \text{ g} \rightarrow 233.9942 \text{ g} + 4.0015 \text{ g} \]

• The change in mass during the reaction is:

\[ 233.9942 \text{ g} + 4.0015 \text{ g} - 238.0003 \text{ g} = -0.0046 \text{ g} \]

• The process is exothermic because the system has lost mass.
• To calculate the energy change per mole of Uranium-238, plug mass change and speed of light (3.0x10^8 m/s) into $E=mc^2$ equation!

Nuclear Binding Energies
• The mass of a nucleus is less than the mass of its nucleons.
  • Mass defect is the difference in mass between the nucleus and the masses of its nucleons.
  • Nuclear binding energy is the energy required to separate a nucleus into its nucleons.
  • Since $E = mc^2$, the binding energy is related to the mass defect.
• The larger the binding energy, the more likely a nucleus is to decompose.
• Heavy nuclei gain stability by splitting into smaller nuclei.
  • They give off energy if fragmented into two mid-sized nuclei.
  • This reaction is called fission.
• Very light nuclei are combined or fused together to form more massive nuclei.
  • Energy is released from this nuclear fusion.

\[ \Delta E = \Delta\left(mc^2\right) = c^2 \left(\Delta m\right) \]

\[ \Delta E = \left(2.9979 \times 10^8 \text{ m/s}\right) \left(-0.0046 \text{ g}\right) \left(\frac{1 \text{ kg}}{1000 \text{ g}}\right) \]

21.7 Nuclear Fission

\[ \Delta E = -4.1 \times 10^{11} \text{ kg m}^2/\text{s}^2 = -4.1 \times 10^{11} \text{ J} \]

• Splitting of heavy nuclei is exothermic for large mass numbers.
Consider a neutron bombarding a $^{235}\text{U}$ nucleus.

- The heavy $^{235}\text{U}$ nucleus can split in several different ways such as:
  \[ _1\text{n} + ^{235}_9\text{U} \rightarrow ^{142}_{56}\text{Ba} + ^{91}_{36}\text{Kr} + 3^1_0\text{n} \]
- For every $^{235}\text{U}$ fission an average of 2.4 neutrons are produced.
  - Each neutron produced can cause the fission of another $^{235}\text{U}$ nucleus.
  - The number of fissions and the resulting energy increase rapidly.
- Reactions that multiply this way are called chain reactions.

Without controls, an explosion results.

- Consider the fission of a nucleus which results in the production of neutrons.
- Each neutron can cause another fission.
- Eventually, a chain reaction forms.
  - A minimum mass of fissionable material is required for a chain reaction (or neutrons will escape before they can cause another fission).
    - This is called a critical mass.
  - When enough material is present for a chain reaction, we have a critical mass.
  - If the mass is lower than the critical mass (subcritical mass) the neutrons escape and a chain reaction does not occur.
    - At the critical mass one neutron from each fission is effective in causing another fission.
    - Any mass over the critical mass is called supercritical mass.
    - Critical mass for $^{235}\text{U}$ is about 1 kg.

### Nuclear Reactors

- Use fission as a power source.
- Use a subcritical mass of $^{235}\text{U}$ ($^{238}\text{U}$ is enriched with about 3% $^{235}\text{U}$).
- Enriched $^{235}\text{UO}_2$ pellets are encased in Zr or stainless steel rods.
- Control rods are composed of Cd or B, which absorb neutrons.
  - They help to regulate the flux of neutrons.
- Moderators are inserted to slow down the neutrons to make them more easily captured.
- Heat produced in the reactor core is removed by a cooling fluid and carried to a steam generator.
- The steam is used to drive an electric generator.
- Storage of radioactive wastes from such reactions is not a simple problem.
- The potential for environmental contamination by long-lived isotopes is a serious consideration.

### 21.8 Nuclear Fusion

- Light nuclei can fuse to form heavier nuclei.
- Most reactions in the Sun are fusion reactions.
- Fusion products are not usually radioactive, so fusion is a good energy source.
- Also, the hydrogen required for the reaction can easily be supplied by seawater.
  - However, high energies are required to overcome repulsion between nuclei before the reaction can occur.
  - High energies are achieved by high temperatures, the reactions are known as thermonuclear reactions.

- Fusion of tritium and deuterium requires a temperature of about 40,000,000 K:
  \[ _1^3\text{H} + _1^1\text{H} \rightarrow _2^4\text{He} + _0^1\text{n} \]
  - These temperatures can be achieved in a nuclear bomb, or a tokamak.
  - A tokamak is a magnetic bottle; strong magnetic fields contain a high-temperature plasma, so the plasma does not come into contact with the walls. (No known material can survive the temperatures required for fusion.)
  - To date, temperatures of about 3,000,000 K have been achieved in a tokamak.

### 21.9 Biological Effects of Radiation

- Ionizing radiation involves ionization that occurs when radiation removes an electron from an atom or molecule.
  - This is generally more harmful to biological systems than nonionizing radiation.
Radiation absorbed by tissue causes excitation (nonionizing radiation) or ionization (ionizing radiation).

Most ionizing radiation interacts with water in tissues to form $\text{H}_2\text{O}^+$.

- The $\text{H}_2\text{O}^+$ ions react with water to produce $\text{H}_3\text{O}^+$ and OH.
- OH has one unpaired electron.
  - It is called the hydroxy radical.
  - This is an example of a free radical, a substance with unpaired electrons.
  - Free radicals generally undergo chain reactions.
  - They are capable of causing substantial damage in biological tissues.

The penetrating power of radiation is a function of the mass of the radiation.

- Therefore, $\gamma$-radiation (zero mass) penetrates much further than $\beta$-radiation, which penetrates much further than $\alpha$-radiation.

**Radiation Doses**

- Absorbed radiation is measured in:
  - Gray: 1 Gy is the SI unit for absorption of 1 J of energy per kg of tissue.
  - Rad is the radiation absorbed dose.
    - One rad is the absorption of $10^{-2}$ J of radiation per kg of tissue.
    - One gray is equivalent to 100 rads.
  - Because not all forms of radiation have the same effect, we correct for the differences using the RBE (relative biological effectiveness).
    - The RBE is about 1 for $\beta$- and $\gamma$-radiation and 10 for $\alpha$-radiation.
    - A rem (roentgen equivalent for man) = (rads) x (RBE).
    - The SI unit for effective dosage is the Sievert (1 Sv = 1 Gy = 100 rem).

**Radon**

- The nucleus is $^{222}_{86}\text{Rn}$ which is a decay product of $^{238}_{92}\text{U}$.
- Radon exposure accounts for more than half of the 360 mrem annual exposure to ionizing radiation.
- Rn is a noble gas; it is extremely stable.
  - Therefore, it is inhaled and exhaled without any chemical reactions occurring.
  - The half-life of radon-222 is 3.82 days.
  - It decays as follows:
    $$^{222}_{86}\text{Rn} \rightarrow ^{218}_{84}\text{Po} + ^{4}_{2}\text{He}$$

- The $\alpha$-particles produced have a high RBE.
  - Therefore, inhaled Rn is thought to be a cause of lung cancer.

- The situation is complicated because $^{218}_{84}\text{Po}$ has a short half-life (3.11 min) also:
  $$^{218}_{84}\text{Po} \rightarrow ^{214}_{82}\text{Pb} + ^{4}_{2}\text{He}$$

- The Polonium-218 gets trapped in the lungs where it continually produces $\alpha$-particles.
- The EPA recommends Radon-222 levels in homes be kept below 4 pCi per liter of air.
- Radon testing kits are readily available in many areas of the country.

**AP Chemistry Spring Break Homework**

1. Read Chapter 21 & complete
   - pg 931 #1, 4, 6, 9, 11, 13, 25, 27, 33, 35, 49, 55

2. Take the AP Practice exam
   a. In the allotted time period with the appropriate resources, answer the questions on a separate paper. Do not write on the practice exam.
   b. For the multiple choice questions, make a note of how many choices you eliminated before you guess at an answer.
   c. Go back and find some of the answers that you were unsure of and record them in a different color.

3. Study for cumulative exams. (Ex. Solubility rules & ion formulas)