Radioactivity and Nuclear Physics

- Radiative decay modes
- Radiative decay rates
- Induced nuclear reactions
- Fission
- Fusion

Facts about the nucleus

- A nucleon is a proton or neutron
- \( Z = \) # of protons—identifies the element—atomic number
- \( N = \) # of neutrons
- \( A = Z+N = \) nucleon number or atomic mass number

Isotopes

- Isotopes—same \( Z \) different \( N \)
- Isotopes have the same chemical properties because \( Z \) is the same
- The number of neutrons affects how tightly the nucleus is bound together so that some isotopes are stable and some are not.

Isotopes: \( ^{17}\text{O} \) and \( ^{18}\text{O} \) and \( ^{19}\text{O} \)

\( N=9 \quad N=10 \quad N=11 \)

Binding Energy

- What holds the nucleus together?
- Strong Force
- What is the Binding Energy of the nucleus?

\[ E_B = (\text{Energy of } Z \text{ protons}) + (\text{Energy of } N \text{ neutrons}) - (\text{Energy of the nucleus}) \]

- Typically we look at the mass energy—mass defect

\[ \Delta m = (\text{mass of } Z \text{ protons and } N \text{ neutrons}) - (\text{mass of the nucleus}) \]

Binding Energy per nucleon

Example: Binding Energy

- Calculate the binding energy of the nucleus \( ^{19}\text{F} \)
- Calculate its mass defect.
- Calculate the binding energy per nucleon.
Radioactivity

- Radioactivity: unstable nuclides are radioactive and can decay by emitting radiation (not just EM radiation).
- Can be spontaneous or induced
- In this process, the element may transmute into another element.
- There are three kinds of radiation:
  - Alpha, $\alpha$
  - Beta, $\beta$
  - Gamma, $\gamma$

Kinds of Radiation

- Alpha, $\alpha$
  - Helium Nucleus $^4\text{He}$
  - Least penetrating radiation
  - Completely blocked by paper
- Beta, $\beta$
  - High energy electrons (or positrons)
  - Can penetrate a hand or thin metal foil
- Gamma, $\gamma$
  - EM radiation
  - Most penetrating

Conservation Laws

1. Total Electric charge is conserved
2. Number of nucleons stays the same
3. Energy is conserved
   - When an unstable nucleus decays, it turns into a more stable nucleus. The difference in the mass is turned into kinetic energy of the byproducts.
   - The total mass of the byproducts must be less than the total mass of the original radioactive nucleus in order for spontaneous decay to occur.
4. Momentum is conserved

Alpha Decay

\[
A_Z P \rightarrow A_{Z-2} D + \frac{4}{2} \alpha
\]

Nucleon #
charge

P = parent; D = daughter

Example: Polonium 210 decays via alpha decay. Identify the daughter nuclide.

Example: If $^{238}\text{U}$ decays by alpha emission
a) What does it decay into?
b) Find the change in mass
c) What is the final kinetic energy of the alpha particle?

Beta Decay

- Beta minus decay
  \[
  A_Z P \rightarrow A_{Z+1} D + e^- + \bar{\nu} \rightarrow p + e^- + \nu
  \]
- Beta plus decay
  \[
  A_Z P \rightarrow A_{Z-1} D + e^+ + \nu \rightarrow n + e^+ + \bar{\nu}
  \]
- Electron Capture (always possible if $\beta^+$ occurs)
  \[
  A_Z P + e^- \rightarrow A_{Z-1} D + \nu \rightarrow n + e^- + \bar{\nu}
  \]

- $\nu$ = neutrino or little neutral one—very small mass

Beta Decay example

- The isotope of nitrogen with a mass number 13 is unstable and decays via beta decay.
- (a) $^{14}\text{N}$ and $^{15}\text{N}$ are stable isotopes of nitrogen. Do you expect $^{13}\text{N}$ to decay via $\beta^+$ or $\beta^-$? Explain.
- (b) Write the decay reaction
- (c) Calculate the maximum KE of the emitted $\beta$ particle.
Gamma Decay

- Gamma decay does not change the element.
- Gamma radiation is high energy photons
- A gamma-ray is emitted when a nucleus in an excited state transitions to a lower energy state (similar to the way electrons have energy levels in atoms, nucleons have energy levels in the nucleus)

\[ \frac{A}{Z} P^* \rightarrow \frac{A}{Z} P + \gamma \]

*indicates excited state

Biological Effects of Radiation

- Effect depends on
  - Kind of radiation
  - Duration of exposure
  - How much is adsorbed
  - Kind of tissue exposed
- Problem is the energy of the radiation can ionize an atom or molecule which makes them chemically active and interferes with normal cell operation.
- Average dose of radiation humans are exposed to each year = 0.3 rem
  - 0.2 rem inhaled from radon
  - 0.07 rem from food/water due to soil and building materials
  - 0.03 rem from cosmic radiation

Penetration of Radiation

**Alpha**
- Range in human tissue 0.03-0.33 mm (can be stopped by paper)
- Can't penetrate the skin, so outside of the body they aren't dangerous
- Inside of the body, they are the most dangerous because they can ionize large numbers of molecules. They lose their energy through a large number of collisions with molecules.
- Alpha emitters present in food can deliver significant radiation to the digestive track and other body tissue

**Beta, β** (electron)
- Range in human tissue is a few cm
- They can ionize molecules, and as they are slowed down, they emit X-rays. They lose their energy as they collide with molecules.
- More dangerous inside the human body than outside (but not as dramatic a difference as α)

**Gamma, γ** (EM radiation)
- They can lose all of their energy in a single interaction.
- For photons of a given energy, their average penetration depth can be calculated using quantum mechanics.
- Gamma irradiated milk

Stability Curve

Penetration of Radiation

Radioactive Decay rates

- When a radioactive nucleus will decide to decay can only be determined by probability.

\[ \Delta N = -N\lambda\Delta t \]

The number of decays, \( \Delta N \), the number of particles, \( N \), multiplied by the decay rate, \( \lambda \), multiplied by the time interval, \( \Delta t \).

The minus sign indicates that the number of nuclei is decreasing
### Radioactive Decay rates

- **Units**
  - 1 becquerel (Bq) = 1 decay/s
  - 1 curie (Ci) = 3.7x10^10 Bq

Activity = \( R = \frac{\text{number of decays}}{\text{unit time}} = -\frac{\Delta N}{\Delta t} = \lambda t \)

\[ N(t) = N_0 e^{-t/\tau} \text{ where } \tau = \frac{1}{\lambda} \]

- \( \tau \) = mean lifetime

\( N(t) \) is the remaining number of nuclei after a time, \( t \), has elapsed when you started with \( N_0 \) nuclei at \( t=0 \).

### Decay Rate Example

- **Example 29.8**
  - Radioactive Decay of Nitrogen-13
  - The half-life of \(^{13}\text{N}\) is 10.0 minutes.
  - (a) If a sample contains \( 3.20 \times 10^{12} \) \(^{13}\text{N}\) atoms at \( t=0 \), how many nuclei are present 40.0 minutes later?
  - (b) What is the activity at \( t=0 \) and at \( t=40 \) minutes?
  - (c) What is the probability that any one nucleus decays during a one-second time interval?

### Radioactive Decay rates

- Since the decay rate is proportional to the number of nuclei, the decay rate also changes exponentially

\[ R(t) = R_0 e^{-t/\tau} \text{ where } \tau = \frac{1}{\lambda} \]

- We can also talk about half life, \( t_{1/2} \)

\[ t_{1/2} = \frac{\ln 2}{\lambda} = 0.693 \tau \]

\[ N(t) = N_0 (2^{-t/T_{1/2}}) = N_0 \left( \frac{1}{2} \right)^{t/T_{1/2}} \]