Lecture 34 – Chapter 22, Sections 2-5
Nuclear Reactions

- Type of Nuclear Decay
- Nuclear Decay Kinetics
- Fission Reactions
- Fusion Reactions
Alpha Radiation

- Alpha particles are energetic helium nuclei \( ^4_2\text{He}^{2+} \)
- Very heavy positively charged particles
- Not too dangerous
- Can be stopped by fabric or a couple of sheets of paper

- Mass number of emitter decreases by 4
- Atomic number of emitter decreases by 2
- Occurs to nuclei that are unstable because they are too large (too many total particles)

\[
\begin{align*}
^{222}_{86}\text{Rn} & \rightarrow^{218}_{84}\text{Po} + ^4_2\alpha \\
^{218}_{84}\text{Po} & \rightarrow^{214}_{82}\text{Pb} + ^4_2\alpha
\end{align*}
\]
Belt of Stability

The diagram illustrates the stability of atomic nuclei. The line $N = Z$ marks the line of stability. Above this line, with too many neutrons, the nuclei are unstable and may emit particles such as alpha ($\alpha$) or beta ($\beta$) particles. Below this line, with too many protons, the nuclei may undergo electron capture or positron emission. The specific lines and points represent certain isotopes, such as $^{208}_{82}\text{Pb} (\frac{N}{Z} = 1.54)$ and $^{40}_{20}\text{Ca} (\frac{N}{Z} = 1.00)$, which are highlighted to illustrate the concept of stability and instability in nuclear physics.
Beta Radiation

- Beta particles are electrons ($^0_{-1}\beta^-$)
- Very penetrating
- Beta decay occurs to nuclei that lie above the belt of stability.
  - These nuclei have ‘too many’ neutrons
  - Beta decay converts neutron to proton

\[
_0^1n \rightarrow _1^1p + ^0_{-1}\beta^-
\]

\[
_1^3H \rightarrow _2^3He + ^0_{-1}\beta^-
\]

\[
_{79}^{208}Au \rightarrow _{80}^{208}Hg + ^0_{-1}\beta^-
\]
Belt of Stability

The diagram illustrates the belt of stability for atomic nuclei. Stable nuclei are located on the line $N = Z$. Too many neutrons or too many protons can lead to instability, with the nucleus either emitting particles or undergoing other decay processes. The stability boundary is indicated by the line $N = Z$.

- Too many protons: The nucleus is unstable due to the excess of protons, leading to emission of particles.
- Too many neutrons: The nucleus is also unstable due to the excess of neutrons, leading to similar decay processes.

Different decay modes are represented by arrows and colors:
- **$\beta$** (beta decay) for electrons emitted.
- **$\alpha$** (alpha decay) for helium nuclei emitted.
- **$\beta^+$** (positron emission) for electrons captured.
- **$e^{-}$ capture** for electrons captured.

The example nuclei shown are $^{208}_{82}$Pb ($N/Z = 1.54$) and $^{40}_{20}$Ca ($N/Z = 1.00$).
Positron Radiation

- Positrons are anti-electrons \((^0_{+1} \beta^+)\)
- Very penetrating
- Positron decay occurs to nuclei that lie below the belt of stability.
  - These nuclei have ‘too many’ protons
  - Positron decay converts proton to neutron

\[
^{1}_{1} p \rightarrow ^{1}_{0} n + ^{0}_{1} \beta^+
\]

\[
^{18}_{9} F \rightarrow ^{18}_{8} O + ^{0}_{1} \beta^+
\]

\[
^{144}_{63} Nd \rightarrow ^{144}_{62} Eu + ^{0}_{1} \beta^+
\]
Belt of Stability

\[ \text{Too many neutrons} \]

\[ \text{Belt of stability} \]

\[ \text{Too many protons} \]

\[ \frac{N}{Z} = 1.00 \]

\[ \frac{N}{Z} = 1.54 \]

- Stable
- $\alpha$ emitter
- $\beta$ emitter
- $e^-$ capture and/or positron $\beta^+$ emitter

High $N/Z$ ratio

Low $N/Z$ ratio

Emits $\beta$

Emits $\alpha$

Emits $\beta^+$
More Positron

- Positrons are not usually observed directly
- When a positron and electron run into each other they annihilate
  - Usually there are lots of electrons around, so this happens right away
  - Annihilation destroys both particles (no more mass), but releases loads of energy
  - Energy released as two gamma rays, each of $9.87 \times 10^7$ kJ/mol

![Diagram](image-url)
Electron Capture

• Absorption of electron by the nucleus
• Electron removed from 1s orbital – leaves a ‘hole’
• This hole is filled by an outer electron falling down
  – Electron releases energy as an X-ray photon
• Like positron decay, electron capture occurs to nuclei that lie below the belt of stability.
  – Electron capture converts proton to neutron

\[
^{26}_{13}Al + ^0_{-1}e \rightarrow ^{26}_{12}Mg^* \\
^{26}_{12}Mg^* \rightarrow ^{26}_{12}Mg + h\nu_{X-ray}
\]
Belt of Stability

The diagram illustrates the belt of stability for nuclear stability. The stability of a nucleus is determined by the number of protons (Z) and neutrons (N). The lines on the graph represent the number of neutrons (N) versus the number of protons (Z). Stable nuclei lie within the belt, which is the region where the number of neutrons is approximately equal to the number of protons (N/Z ≈ 1). Outside the belt, nuclei are either too neutron-rich (Too many neutrons) or too proton-rich (Too many protons), leading to instability and radioactive decay. Examples include 

- **Too many neutrons**: 
  - $^{208}_{82}$Pb (N/Z = 1.54) is neutron-rich and emits beta ($\beta$) decay.
  - $^{40}_{20}$Ca (N/Z = 1.00) is near the stability line.

- **Too many protons**: 
  - Emits alpha ($\alpha$) decay.
  - Emits beta ($\beta^+$) decay.
  - Emits electron capture and/or positron ($\beta^+$) decay.

The diagram also includes symbols for stable nuclei, alpha emitters, beta emitters, and electron capture/positron emitters.
Gamma Radiation

- Electromagnetic photons of **very** high energy
- Very penetrating → can pass through the human body
- Require thick layers of lead or concrete to be stopped
- Emitted from nuclei that have excess energy
  - Usually from products of other nuclear decay

\[ ^{226}_{88}Ra \rightarrow ^{222m}_{86}Rn + ^4_2\alpha \]
\[ ^{222m}_{86}Rn \rightarrow ^{222}_{86}Rn + \gamma \]
\[ ^{222}_{86}Rn \rightarrow ^{218m}_{84}Po + ^4_2\alpha \]
\[ ^{218m}_{84}Po \rightarrow ^{218}_{84}Po + \gamma \]

Sometimes metastable (m) is denoted with a * meaning just ‘excited’
Identify the Product

\[ ^{214}_{84}Po \rightarrow ? + \alpha \]

<table>
<thead>
<tr>
<th>Percentage</th>
<th>Option</th>
</tr>
</thead>
<tbody>
<tr>
<td>20%</td>
<td>1. Polonium-210</td>
</tr>
<tr>
<td>20%</td>
<td>2. Lead-212</td>
</tr>
<tr>
<td>20%</td>
<td>3. Lead-210</td>
</tr>
<tr>
<td>20%</td>
<td>4. Mercury-212</td>
</tr>
<tr>
<td>20%</td>
<td>5. Mercury-210</td>
</tr>
</tbody>
</table>
Identify the product

\[ ^{210}_{82}Pb \rightarrow ^{210}_{83}Bi + ? \]

- 20% 1. Alpha particle
- 20% 2. Beta particle
- 20% 3. Positron
- 20% 4. Gamma Ray
- 20% 5. X-Ray
If $^{14}\text{O}$ undergoes electron capture, what is the product?

<p>| | | | | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>20%</td>
<td>1.</td>
<td>Fluorine-13</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>20%</td>
<td>2.</td>
<td>Fluorine-14</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>20%</td>
<td>3.</td>
<td>Nitrogen-13</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>20%</td>
<td>4.</td>
<td>Nitrogen-14</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>20%</td>
<td>5.</td>
<td>Oxygen-13</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Rates of Decay

- Recall from Chapt 15 that nuclear decay is unimolecular
  - First Order
  - Rate = $k \times \text{concentration}$ (or often # of nuclei)

\[
c = c_0 e^{-kt}
\]

\[
\ln \left( \frac{c_0}{c} \right) = kt
\]

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

\[
\ln \left( \frac{N_0}{N} \right) = \frac{t \ln 2}{t_{\frac{1}{2}}}
\]
Some Everyday Decay

- Bananas
  - Typical banana contains about 400 mg of K
  - Generates about 12 decays per second
  - $^{40}\text{K}$ half-life is 1,260,000,000 years
  - Average adult male contains 140 g of K (4,400 decays per second)

- Fiesta ware
  - Any old pottery with a deep orange/red color contains uranium oxide
  - The Fiesta Ware collection (1936-1943) is particularly famous

- Luminescent dials
  - Old (early 1900’s) glow-in-the-dark dials contain radium paint
  - Mostly replaced now by tritium
Induced Nuclear Reactions

• Reactions in which a nuclear projectile collides and reacts with another nucleus

• Neutron-Capture Reactions – usually exothermic, the produced nuclide usually decays by proton or γ emission.

\[
{^{14}_7 N + ^1_0 n \rightarrow ^{15m}_7 N \rightarrow ^{14}_6 C + ^1_1 p}
\]

\[
{^{14}_7 N + ^1_0 n \rightarrow ^{15m}_7 N \rightarrow ^{12}_6 C + ^3_1 H}
\]

• Binuclear reactions – collision of two nuclei at very high energy.

\[
{^{14}_7 N + ^4_2 \alpha \rightarrow ^{18m}_9 F \rightarrow ^{17}_8 O + ^1_1 p}
\]
Making Synthetic Elements

- Elements Z=43, 61, 85 and Z > 92 are not naturally occurring on Earth.
- They can be made from nuclear reactions.
- **Cyclotron** – a positive particle accelerator used to fabricate some of the “unnatural” elements.
  - Doesn’t work well for heavy particles
- **Linear accelerator** – a heavy-ion accelerator.
- Accelerators mainly used to study what happens during nuclear reactions.
Nuclear Fission

- Fission splits a nucleus into two fragments, which are themselves usually unstable.
- The reaction also releases neutrons and loads of energy.

\[
\frac{235}{92} U + \frac{1}{0} n \rightarrow \frac{138}{54} Xe + \frac{95}{38} Sr + 3\frac{1}{0} n
\]

The total energy released could be determined by the same kind of mass difference calculation we used earlier.
Nuclear Fission

- **Critical Mass** – the amount of material that is just large enough to recapture one neutron for every fission reaction, thus causing another fission, which causes another, which…
  - Thus, fission becomes **self-sustaining**.

Reaction growing exponentially = bomb
Nuclear Reactors

- If number of neutrons absorbed can be carefully controlled, then the rate of reaction can be kept constant
  - Constant release of energy = useful
- The rate of fission is controlled by adjusting the number of recaptured neutrons with $^{112}\text{Cd}$
- Moderator (water or graphite) slows neutrons – smaller mass needed to become critical
Nuclear Fusion

- Fusion is easiest for lightest nuclides (smallest charge)
- Generates a small amount of radioactive by-products
- Fusion can be induced from a particle accelerator
  - Small scale does not release useful amounts of energy
- Fusion begins when *temperature* is high enough to overcome Coulombic repulsion
  - Not dependent on mass of reactants (*i.e.* no critical mass)
- So, just get some H hot $\rightarrow$ fusion! Easy!
  - Critical temperature is $10^7$ K
- The whole trick is to contain the fusion reaction
  \[
  \frac{2}{1} H + \frac{3}{1} H \rightarrow \frac{5}{2}^m He \rightarrow \frac{4}{2} He + \frac{1}{0} n
  \]
  \[
  \frac{6}{3} Li + \frac{1}{0} n \rightarrow \frac{7}{3}^m Li \rightarrow \frac{4}{2} He + \frac{3}{1} H
  \]
- Fusion not contained == bomb
- Fusion bomb can be BIG because of lack of critical mass
Tokamak

- One solution is a toroid of magnets – a tokamak reactor
- Heat provided by electrical resistance, neutron beams and RF
Inertial Fusion

- Second possibility is to confine the plasma with the same beams that supply heat (laser or particle)
- Momentum of incoming beams holds fuel in place
Today

• Review

Wednesday

• Finish CAPA #20
• Why not keep reviewing?