Lesson 8

Alpha Decay
Alpha decay ($\alpha$)

- Decay by the emission of doubly charged helium nuclei $^4\text{He}^{2+}$.
- $^{238}\text{U} \rightarrow ^{234}\text{Th} + ^4\text{He}$
- $\Delta Z = -2$, $\Delta N=-2$, $\Delta A=-4$
- All nuclei with $Z \geq 83$ decay by $\alpha$-decay as do some rare earth nuclei. Alpha decay is also known in the $^{100}\text{Sn}$ region.
Alpha Decay

- The emitted $\alpha$-particles are monoenergetic, ranging in energy from 1.8-11.6 MeV (typically 4-9 MeV).
- They can be stopped by a piece of paper and are thus an internal radiation hazard rather than an external hazard.
- The naturally occurring $\alpha$-emitters form long series of nuclei that decay to one another. Some of these naturally occurring decays series involve isotopes of Rn, a gas.
Typical Alpha Spectra
Important Features of Alpha Decay

• Generally energy of decay increases with increasing Z, but in any case the energy of the emitted $\alpha$-particle is less than the Coulomb barrier for the $\alpha$-nucleus interaction.

• For e-e nuclei, decay leads to gs of daughter. For odd A nuclei, decay is not to the gs but a low-lying excited state.
Energetics of Alpha Decay

- $Q_{\text{alpha}}$
Energetics of Alpha Decay (cont.)

- $Q_{\alpha}$ -- Generally increases with increasing $Z$, but is subject to shell effects.

$Z=82$, $N=126$  

$N=152-154$
\[ Q_\alpha, T_\alpha \]

\[ Q_\alpha = (M_{\text{parent}} - M_{\text{daughter}} - M_{\text{alpha}})c^2 \]

\[ T_\alpha = Q_\alpha \frac{M_{\text{daughter}}}{M_{\text{parent}}} \]

\[ T_{\text{recoil}} = Q_\alpha \frac{M_{\text{alpha}}}{M_{\text{parent}}} \]

Difference between detecting emitted alpha particle and detecting alpha from implanted atom.
Closed decay cycles

Used to measure unknown masses or Q values for beta decay
Understanding natural alpha-decay chains

- In the U natural decay series, see pattern of mixed alpha and beta decays. Why?
Understanding Alpha Decay

• The problem:
Understanding Alpha Decay (cont.)

• The Geiger Nuttall Law

\[ \log(t_{1/2}) = A + \frac{B}{\sqrt{Q_\alpha}} \]
Theory of Alpha Decay

- One of the first successes of quantum mechanics
\[ \lambda = fT \]
\[ f = \frac{v}{2R} = \frac{\sqrt{2(V_0 + Q)/\mu}}{2R} \sim 10^{21}/s \]
\[ T \approx e^{-2G} \]
\[ 2G = \frac{2}{\hbar} \int_{x_1}^{x_2} \left[ 2m(V(x) - E) \right]^{1/2} dx \]
\[ 2G = \frac{2}{\hbar} \int_{R}^{b} \left[ 2\mu \left( \frac{Z_\alpha Z_D e^2}{r} - Q_\alpha \right) \right]^{1/2} dr \]
\[ b = \frac{Z_\alpha Z_D e^2}{Q_\alpha} \]
After some algebra and simplifying for the nuclear case

\[ 2G = 2 \sqrt{\frac{2\mu}{\hbar^2 Q_\alpha}} \left( Z_\alpha Z_D e^2 \right) \left( \frac{\pi}{2} \right) \sim 60 - 120 \]

\[ T \sim 10^{-55} - 10^{-27} \]

Then

\[ t_{1/2} = \frac{\ln 2}{\lambda} = \frac{\ln 2}{fT} = \frac{\ln 2}{\left[ \frac{2(V_0 + Q_\alpha)/\mu}{2R} \right]^{1/2}} e^{-2G} \]

This is called the “one-body” theory of alpha decay
How well does one-body theory work?

Role of “pre-formation factor”
Effect of angular momentum

Selection Rules
Which states of daughter are populated in alpha decay?

- Dominant effect is $Q_\alpha$
- Angular momentum effect

Spin/parity selection rule for $\alpha$ transitions: $I_i^{\pi i} = I_f^{\pi f} + (-)^\ell$

$\ell = 0$ most probable $\alpha$ decay
Higher $\ell$ values hindered significantly because of small $T_\ell$
Estimate range of $\ell$-values from $E_\alpha$ and nuclear radii!
Hindrance Factors

Hindrance Factor = $t_{1/2}(\text{meas})/t_{1/2}(\text{one-body})$
α Decay Patterns

**Data from 251Fm**

<table>
<thead>
<tr>
<th>α Group</th>
<th>α Energy (keV)</th>
<th>Decay Energy (keV)</th>
<th>Excited-State Energy (keV)</th>
<th>α Intensity (%)</th>
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<tr>
<td>α₁</td>
<td>7205 ± 3</td>
<td>7421</td>
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<td>1.5 ± 0.1</td>
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<td>α₄</td>
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<td>7221</td>
<td>202</td>
<td>~ 0.05</td>
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<td>0.26 ± 0.04</td>
</tr>
</tbody>
</table>

From Krane, *Introductory Nuclear Physics*
Proton Decay

- Same theory as alpha decay, except no pre-formation factor for protons
- Where do you expect to see proton decay? \( S_p = 0 \)
Proton Decay (cont.)

- Proton energies are low and transmission factors are small.
Proton Decay (cont.)

- Alpha decay complicates measurements
Heavy Particle Decay

- What about emitting particles other than alphas or protons?