Nuclear Physics - Summary - Decays

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This summary is based on the book Chapter 6.1, 8-10 from Krane, Kenneth: Introductory Nuclear Physics.

1 Nuclear Decays

parent radio nucleid $\rightarrow$ spontaneous decay $\rightarrow$ daughter nucleid

Types of decays:

- α decay $\rightarrow$ α particle (^4He) gets ejected or cluster decay (heavier particle gets ejected)
- β decay $\rightarrow$ β particle $(e^-, e^+) + \nu$ gets ejected
- γ decay $\rightarrow$ nuclear energy transition $\rightarrow$ γ gets ejected, this is usually following and α or β decay

Decays follow an **exponential decay law**:

$$\lambda = \frac{dN/dt}{N}$$

where λ is the decay or desintegration constant, N is the number of nuclei at t time, and dN nuclei decay in dt time

$$N(t) = N_0 e^{\lambda t}$$

where N_0 is the number of nuclei at $t = 0$.

$$t_{1/2} = \frac{0.693}{\lambda}$$

is the **half life**, which is the time it takes for half of the initial nuclei to decay

2 α decay

- The Coulomb repulsion ($\sim Z^2$) effect becomes important for heavy nuclei compared to the strong force ($\sim A$).
- energetically the α particle is the best to eject, since it results in the largest energy release for a light particle.
- other nuclei that can be ejected: ^{12}C but these are very rare, they have a much longer half-life compared to the decay trough ^4He

The basic reaction:

$$^A_Z X_N \rightarrow ^{A-4}_{Z-2} X_{N-2} +^4 He$$

The energy release can be calculated from the mass difference:

$$Q = (m_X - m_{X'} - m_\alpha)c^2 = T_{X'} + T_\alpha$$

- The released energy gets distributed as kinetic energy between the daughter and the α particle. The α particle gets most of the energy (98%).
- The small energy for the daughter is effectively a small recoil.
- Q must be > 0 for decays and λ must be not too small.
- from Q we can measure atomic mass for X'
- large Q $\rightarrow$ short half life
- even Z and N $\rightarrow$ short half life
- odd-even and odd-odd nuclei have relatively longer half lives
- adding n^0 to a nucleus increases the half life

2.1 Theory of α decay

- The α particle is already formed inside the nucleus $\rightarrow$ tunneling $\rightarrow$ decay
- potential well + Coulomb potential barrier

The desintegration probability:

$$\lambda = fP$$

where f is the frequency at which the α particle approaches the edge of the potential and P is the tunnelling probability.

This is a simplified model, which is a relatively good approach. However, there are some discrepancies due between calculations and measurements. These are due to:

- the exact wave function
- momentum of the α
- the shape of the nucleus is not symmetrical (heavy nuclei are deformed)

Calculating half lives shows which decays are more likely or less likely to happen.

Proton decay (decay trough ejecting a p^+) for most nuclei energetically forbidden, but can happen for some nuclei with negative proton separation energies.

2.2 Angular momentum and parity

- ^4He spin = 0 (both n and p are paired), only l component.
- parity change: $(-1)^{l_\alpha}$
- parity selection rule → which transition can occur:
  - if initial and final are the same: l_α even
  - if initial and final are not the same: l_α odd
- a given initial state can decay into a number of final states (excited states - rotation and vibration) in the daughter → "fine structure" of α decay
- decays to different E levels:
  - centrifugal force raises the barrier (rotational excitation)
  - excitation energy lowers the barrier
- relative decay probability: decaying into the 0^+ state is the most likely compared to the $2^+, 4^+ or 6^+$ states → the wave function is more different for the later states, it is easier to go from 0^+ to 0^+ because the wave function is very similar.
- parity: $0 \rightarrow 3$ $l_\alpha = 3$ odd → $0^+ \rightarrow 3^-$ possible, $0^+ \rightarrow 3^+$ not possible
- if the initial and final spin are not 0 more combinations are possible
- the angular distribution of the ejected α particles indicates the shape of the nucleus and the angular momentum of the nucleus.

2.3 Applications:

- power source (space crafts, pacemaker)
- cancer treatment
- smoke detectors