Chapter 1: Radioactivity
Radioactivity

- **Radioactivity** is defined as the spontaneous nuclear transformation that results in the formation of new elements.

- **Radioactivity and radioactive properties of nuclides** are determined by nuclear considerations and independent of the chemical and physical states of the radioisotope.

- The probability of radioactive transformation depends primarily on two factors:
  - **Nuclear stability** as related to the neutron-to-proton ratio.
  - **The mass-energy relationship** among the parent nucleus, daughter nucleus, and the emitted particles.
The Origin of Nuclear Radiation and a Few Related Concepts

- Nuclear force and Coulomb barrier.
- Nuclear binding energy and nuclear stability.
- Nuclear transformation as a way to achieve greater nuclear stability and associated energy release.
Nuclear Forces

Within the incredibly small nuclear size (~ $10^{-15}$m), the two strongest forces in nature, Coulomb force and strong nuclear force, are pitted against each other. When the balance is broken, the resultant radioactivity yields particles of enormous energy.

Coulomb potential

$$V_C = \frac{1}{4\pi\varepsilon_0} \frac{q_1 \cdot q_2}{r},$$

where $\varepsilon_0$ is the electrical permittivity

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Potential Energy of Nucleus

- Nucleons are bounded together in nucleus by the strong force, which has a short range of $\sim 10^{-15}$m.
- The strong force is powerful enough to overcome the Coulomb repulsion between the positively charged protons.

Coulomb potential

$$V_c = \frac{1}{4\pi\varepsilon_0} \frac{q_1 \cdot q_2}{r},$$

where $\varepsilon_0$ is the electrical permittivity.
Coulomb Barrier

Example

Estimate the minimum energy that a proton would have to have in order to react with the nucleus of a stationary Cl atom.

In terms of Fig. 3.1(a), the proton would have to have enough energy to overcome the repulsive Coulomb barrier in a head-on collision. This would allow it to just reach the target nucleus.
Coulomb Barrier

We can use the following equation to estimate the radiuses of the Cl nucleus and the proton,

\[ R \approx 1.3A^{1/3} \times 10^{-15} m \]

With \( A=1 \) and \( A=35 \) for the proton and the Cl nucleus, we have

\[ r_p = 1.3 \times 1^{1/3} \times 10^{-15} = 1.3 \times 10^{-15} m, \]
\[ r_{Cl} = 1.3 \times 35^{1/3} \times 10^{-15} = 4.3 \times 10^{-15} m. \]

The proton has unit positive charge, \( e = 1.60 \times 10^{-19} \) C, and the chlorine (\( Z = 17 \)) nucleus has a charge \( 17e \). The potential energy of the two charges separated by the distance \( r_p + r_{Cl} = 5.6 \times 10^{-15} m \) is therefore

\[ PE = \frac{8.99 \times 10^9 \times 17 \times (1.60 \times 10^{-19})^2}{5.6 \times 10^{-15}} = 7.0 \times 10^{-13} J = 4.4 \text{ MeV}. \]

\[ V_c = \frac{1}{4\pi\epsilon_0} \frac{q_1 \cdot q_2}{r}, \]

where \( \epsilon_0 \) is the electrical permitivity.
A Simple Nuclear Reaction

we now consider one of the simplest nuclear reactions, the absorption of a thermal neutron by a hydrogen atom, accompanied by emission of a gamma ray. This reaction, which is very important for understanding the thermal-neutron dose to the body, can be represented by writing

\[ ^{1}_0 n + ^{1}_1 H \rightarrow ^{2}_1 H + ^{0}_0 \gamma, \]

For example, thermal neutron capture by hydrogen nucleus.
Mass Defect and Nuclear Binding Energy

We now consider one of the simplest nuclear reactions, the absorption of a thermal neutron by a hydrogen atom, accompanied by emission of a gamma ray. This reaction, which is very important for understanding the thermal-neutron dose to the body, can be represented by writing

\[ {^1_0}n + {^1_1}H \rightarrow {^2_1}H + {^0_0}\gamma, \]  

(3.7)

the photon having zero charge and mass. The reaction can also be designated \(^{1}_1\text{H}(n,\gamma)^{2}_1\text{H}.\)

In this case, the energy transition due to the mass defect is

\[ Q = 8.0714 + 7.2890 - 13.1359 = 2.2245 \text{ MeV}. \]
Nuclear Binding Energy

\[ \frac{1}{0}n + \frac{1}{1}H \rightarrow \frac{2}{1}H + \frac{0}{0}\gamma, \]

In this case, the binding energy for the deuterium nucleus is given by

\[ Q = 8.0714 + 7.2890 - 13.1359 = 2.2245 \text{ MeV}. \]
Nuclear Binding Energy

• Nuclei are made up of protons and neutron, but the mass of a nucleus is always less than the sum of the individual masses of the protons and neutrons which constitute it.

• This difference is a measure of the nuclear binding energy, which holds the nucleus together. The binding energy can be calculated from the Einstein relationship:

\[ \text{Nuclear binding energy} = \Delta m \cdot c^2 \]
Average Binding Energy Per Nucleon

What can we find from this graph?
- What are the more stable elements?
- What are the spikes on the left-hand side telling us?
- If we look at nuclear reactions from the viewpoint of energy production, can you give a few examples for producing energy through nuclear reactions?
- Which one(s) are more efficient in producing energy (say energy/kg fuel)?
Nuclear Binding Energy

• Binding energy is always positive.

• The average binding energy per nucleon peaks for $A = 40$ to 120, with a maximum of $\sim 8.5\text{MeV}$.

• It then drops off for either higher or lower $A$.

• There are a few nuclei, $^4\text{He}$, $^{12}\text{C}$ and $^{16}\text{O}$ at the lower mass number end that have binding energies (per nucleon) well above that for adjacent nuclei.

• In fact, these nuclei are all “multiples” of the alpha particle.

• And ...
Fission Reactions

• A fission reaction splits up a large nucleus into smaller pieces.
• A fission reaction typically happens when a neutron hits a nucleus with enough energy to make the nucleus unstable.

\[
\text{n} + \text{U}^{235} \rightarrow \text{Mo}^{99} + \text{Sn}^{135} + 2\text{n} + \text{energy}
\]
Average Binding Energy Per Nucleon Comparing Fusion and Fission Reactions

FUSION
- Fast particles: deuterium (m=2), tritium (m=3)
- Conversion to energy per kg fuel: 676 units

FISSION
- Slow neutron: 235 U
- Conversion to energy per kg fuel: 176 units

1 UNIT = energy use of one U.S. citizen in 1 year.

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Binding Energy of Atoms

The loss of mass that accompanies the binding of particles is not a specifically nuclear phenomenon. The mass of the hydrogen atom is smaller than the sum of the proton and electron masses by $1.46 \times 10^{-8}$ AMU. This is equivalent to an energy $1.46 \times 10^{-8} \text{ AMU} \times 931 \text{ MeV/AMU}^{-1} = 1.36 \times 10^{-5} \text{ MeV} = 13.6 \text{ eV}$, the binding energy of the H atom.

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The nuclides are the possible nuclei of atoms. Z determines the chemistry, because the neutral atom with the nuclide as its nucleus has Z electrons.

Chart of the Nuclides

Be\textsuperscript{11}
\- 11.5, 9.4
\γ 2.1
Nuclear Stability and the Origin of Radioactivity

Secondary radiations, e.g., gamma-rays, X-rays, alpha-particles, and electrons

**Alpha decay**
Parent \((Z, N) \rightarrow \text{Daughter} (Z-2, N-2)
\[ ^{210}_{84}Po \rightarrow ^{206}_{82}Pb + ^{4}_{2}He \]

**Beta decay:**
Parent \((Z, N) \rightarrow \text{Daughter} (Z+1, N-1)
\[ ^{A}_{Z}X \rightarrow ^{A}_{Z+1}X + e^- + \bar{\nu} \]
\[ ^{137}_{55}Cs \rightarrow ^{137}_{56}Ba + ^{0}_{-1}\beta + ^{0}_{0}\bar{\nu} \]

**Positron decay:**
Parent \((Z, N) \rightarrow \text{Daughter} (Z-1, N+1)
\[ ^{A}_{Z}X \rightarrow ^{A}_{Z-1}X + e^+ + \nu \]
\[ ^{22}_{11}Na \rightarrow ^{22}_{10}Ne + ^{0}_{+1}\beta + \nu \]

**Electron capture:**
Parent \((Z, N) \rightarrow \text{Daughter} (Z, N-1)
\[ ^{A}_{Z}X + e^- \rightarrow ^{A}_{Z-1}Y + \nu \]