

MIE407 Nuclear Reactor Theory & Design

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Nuclear Stability:

- Stability of nucleus is the result of the balance between the strong nuclear force and the electromagnetic force.
- Range of the strong nuclear force is about 1 fm (femtometre, 10^{-13} cm)
- The strong nuclear force acts equally between protons and neutrons, but neutrons also reduce repulsions between protons by pushing them further apart from each other.
- Fermi approx: $r = R_0 A^{1/3}$ where $R_0 = 1.2$ fm
- The strong nuclear force is repulsive at very small distances, which contributes to the incompressibility of the nucleus.
- The strong nuclear force is insignificant at larger than around 4 proton diameters.

Nuclear Binding Energy:

- The binding energy of a nucleus can be found by calculating the mass defect of the nucleus compared to the mass of the unbound nucleons.

$$E_B = [Zm_p + (A - Z)m_n - m]c^2 \equiv \Delta M \times c^2 \quad (1)$$

- The binding energy is usually expressed as the average binding energy per nucleon $\varepsilon = E_B/A$.
- $1 \text{ u} = 931.5 \text{ MeV}/c^2$

Compound nucleus decay modes:

- Neutron capture (n, γ): Nucleus decays to a lower energy state by emitting some gamma rays. $n + {}^A_Z X \rightarrow {}^{A+1}_Z X^* \rightarrow {}^{A+1}_Z X + \gamma$
- Elastic scattering (n, n'): Neutron is re-emitted after leaving the nucleus in the ground state.
- Inelastic scattering ($n, n'\gamma$): Neutron (usually high energy) is re-emitted at a lower energy, leaving the nucleus in an excited state. Then, the nucleus emits some gamma rays to return to the ground state.
- Fission (n, f): Nucleus splits into two fragments with approx. 2 : 3 mass ratio.
- Particle emission (n, α), (n, p), (n, kn): A particle other than a neutron, or multiple neutrons are emitted. Only occurs with very high energy neutrons. Hence, only a small number of ($n, 2n$) reactions occur in nuclear reactors.

Nuclear Fission

- When a thermal neutron (≤ 1 eV) is absorbed by a U-235 nucleus, it forms a compound nucleus that fissions with $\approx 84\%$ probability.
- Fission is a threshold reaction. In cases for U-235, the threshold energy is lower than the energy gained by binding the extra neutron. Hence, fissions may occur by neutrons with any energy. However, for U-238, the threshold energy is about 1 MeV greater than the energy gained by binding the extra neutron. Hence, fissions only occur by neutrons with kinetic energy greater than 1 MeV, which rarely occurs in even a fast reactor.
- Under thermal conditions (0.0253 eV or 2200 m/s) the distribution of fission products is a strong bimodal distribution (Peaks at $A = 96, 135$).
- Most neutrons (prompt neutrons) emitted in fission are released at the instant of fission.
- A small number of fission fragments also emit neutrons (delayed neutrons). These compose of $< 1\%$ of the total neutrons, but they are significant in the transient behavior of the reactor.
- Delayed neutrons result from high nuclear excitation of the daughter (when the excess energy exceed the nuclear binding energy of the neutron)
- Between 0 to 7 prompt neutrons may be emitted by fission, on average around 2.4. This is very important.
- The fission neutron spectrum is approximately $\chi(E) = 0.484 \sinh(\sqrt{2E}) e^{-E} \text{MeV}^{-1}$. Integrate this over a interval of E to obtain the probability of energy in that interval. (Average 2 MeV)
- Delayed neutrons are much lower energy (400 keV)