

Nuclear Physics

NUCLEAR PHYSICS

Nuclei are protons (p^+) and neutrons (n^0) held together by Strong Nuclear Force

$$\left. \begin{aligned} m_p &= 1.673 \times 10^{-27} \text{ kg}, m_p c^2 = 938.3 \text{ MeV} \\ m_n &= 1.675 \times 10^{-27} \text{ kg}, m_n c^2 = 939.6 \text{ MeV} \\ m_e &= 9.11 \times 10^{-31} \text{ kg}, m_e c^2 = 0.511 \text{ MeV} \end{aligned} \right\} m_p \approx m_n$$

Mass of the nucleus is

$$m_{\text{nucleus}} = Zm_p + Nm_n - \frac{B}{c^2} \approx Am_p$$

where

Z = Atomic number = number of protons: determines element

N = Neutron number: determines isotope

A = Z + N = Mass number: determines isobar

B = binding energy of nucleus (energy required to pull nucleus apart)

Nuclear symbols ${}^A_Z X_N$ e.g. ${}^1_1 H_0$, ${}^{238}_{92} U_{146}$

Nuclei mostly spherical with constant densities (nucleons don't compress) $R_{\text{nucleus}} = R_0 A^{1/3}$

Strong Nuclear Force

Acts on all nucleons

Acts within 2 fm (within nucleus, 1 fm = 10^{-15} m)

Coulomb repulsion among protons

100 times weaker than Strong force

significant only in heavy nuclei

raises energy well for p^+

Nature prefers

Tops of p^+ and n^0 wells even

Even numbers of p^+ and n^0

Binding Energy from atomic masses

$$B = (Zm_p + Nm_n - m_{\text{atom}})c^2$$

Nucleon separation energies

$$S_n(Z, N) = B(Z, N) - B_n(Z, N - 1)$$

$$S_p(Z, N) = B(Z, N) - B_n(Z - 1, N)$$

Binding Energy per nucleon

Peaks at iron ... ${}^{56}_{26} Fe_{30}$

Lighter nuclei:

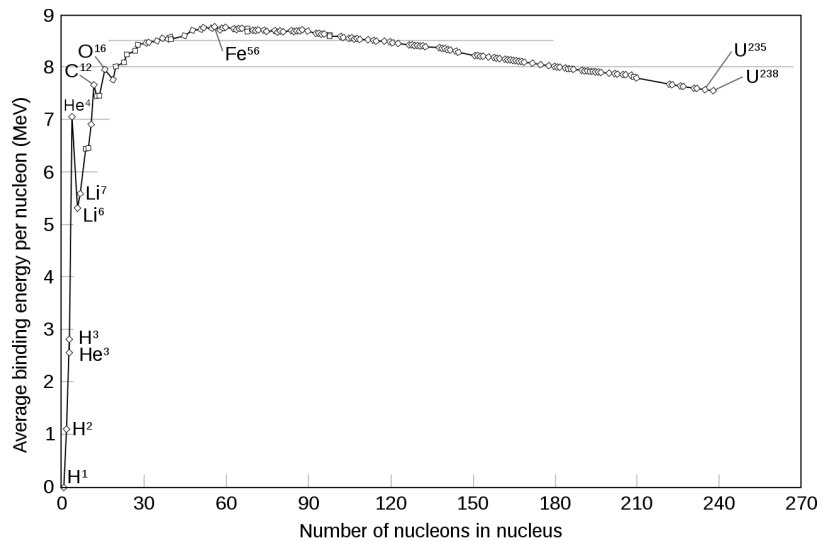
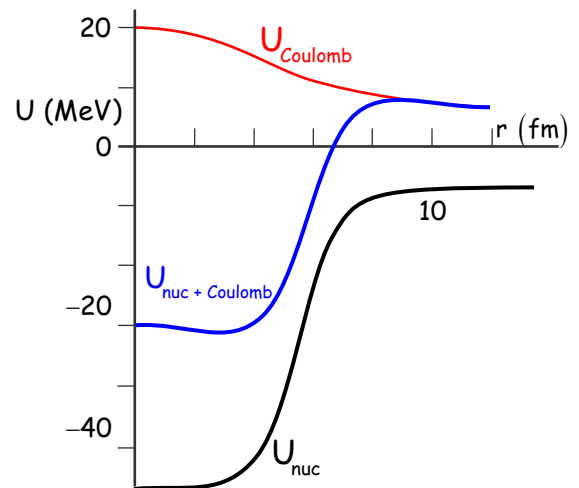
Fusion yields energy

Power source for stars

Heavier nuclei:

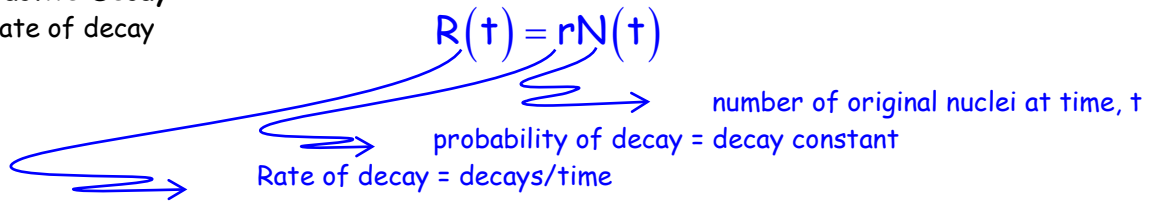
Fission yields energy

Nuclear power plants



Radioactive Decay

Rate of decay



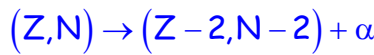
Number of nuclei remaining from N_0 after a time, t $N(t) = N_0 e^{-rt}$

Half Life $t_{1/2} = \frac{\ln(2)}{r}$

Types of decay

α -Decay:

Requires quantum tunneling as α particles form near surfaces of heavy nuclei



β -Decay:

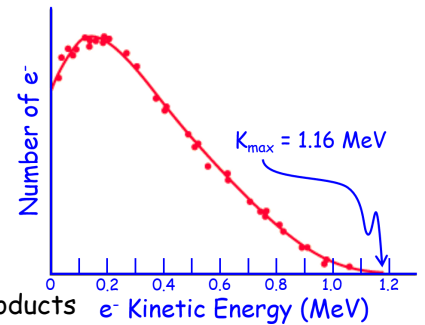
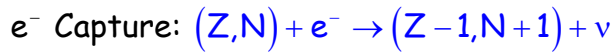
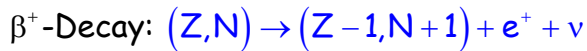
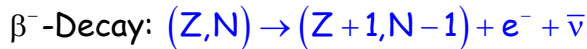
Governed by the weak nuclear force (acts within 10^{-17} m ... within nucleons)

Weak force ejects positrons from protons, or electrons from neutrons

Range of ejected electron energies led to discovery of neutrino

Positrons then annihilate electrons to release more energy

Three types



Mass defect and possibility of decay

Mass defect = difference between parent, daughters and products

$$K = \Delta Mc^2 = \left\{ m_{\text{nucleus}}(Z, N) - [m_{\text{daughter}} + m_{\text{product}}] \right\} c^2$$

That lost mass is converted to energy by $E = mc^2$

$$\left. \begin{aligned} K_{\alpha} &= \Delta Mc^2 = \left\{ m_{\text{atom}}(Z, N) - [m_{\text{atom}}(Z - 2, N - 2) + m_{\text{He}}] \right\} c^2 \\ K_{\beta^+} &= \Delta Mc^2 = \left\{ m_{\text{atom}}(Z, N) - [m_{\text{atom}}(Z - 1, N + 1) + 2m_e] \right\} c^2 \\ K_{\beta^-} &= \Delta Mc^2 = \left\{ m_{\text{atom}}(Z, N) - m_{\text{atom}}(Z + 1, N - 1) \right\} c^2 \\ K_{\text{EC}} &= \Delta Mc^2 = \left\{ [m_{\text{atom}}(Z, N) + m_e] - m_{\text{atom}}(Z + 1, N - 1) \right\} c^2 \end{aligned} \right\} 1 \text{ u} = 931.5 \frac{\text{MeV}}{c^2}$$

Nuclear Fission and Fusion

Fission is the breaking of large nuclei into smaller nuclei

Produces energy for nuclei heavier than iron

Fusion is the combining of light nuclei into larger nuclei

Produces energy for nuclei lighter than iron

Nuclear fission

Large nuclei form lobes that Coulomb repel

α -decay Requires quantum tunneling

Potential peaks where U_{Strong} meets U_{Coulomb}

Fragment must tunnel past barrier

Natural Radioactive Series

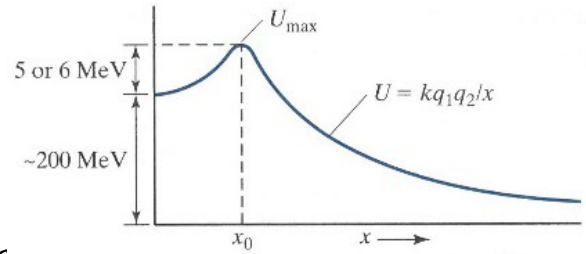
α -decay is fission that occurs naturally

Daughter nuclei can also decay via α , β , or EC so decays continue to stable nuclei

Nuclear power plants and bombs

Utilize ^{235}U and fission triggered by slow neutrons fired at nuclei

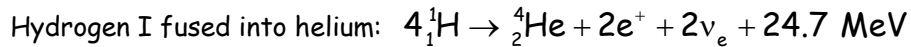
provide fragments energy to overcome barrier



Nuclear fusion

Requires high densities and temperatures of light elements

Fusion in stars



2 MeV released by annihilation of e^- by e^+

7 g of each kg of H fused is released as energy

Elements up to iron fused in living stars

Iron core can not fuse, causing stars to explode in supernovae

Elements heavier than iron created in supernova explosions

Also produced in events such as magnetar flares and neutron star mergers

