

## PHYSICS

Nuclide Abbreviation:  ${}^A_Z X$

where X: chemical element symbol,  
 Z: *atomic number* (the number of protons),  
 N: *neutron number* (the number of neutrons), and  
 A=N+Z: *atomic mass number* (the number of *nucleons*).

### Definitions and Distinctions

- *atomic mass number* (A) [integer number] vs. *atomic weight* or *atomic mass* (M) [real value]:  $M \cong A$
- *isotope*: nuclides with equal number of protons, but different numbers of neutrons
- *isotone*: nuclides with equal number of neutrons, but different number of protons
- *isobars*: nuclides with same total number of protons and neutrons, different combinations of Z & N
- *element* (particular Z, any N) vs. *nuclide* (any Z and N) vs. *isotope* (same Z, different N)
- an *atom* is composed of the *nucleus* (protons and neutrons) and the orbiting electrons

### Binding Energy/Mass Defect

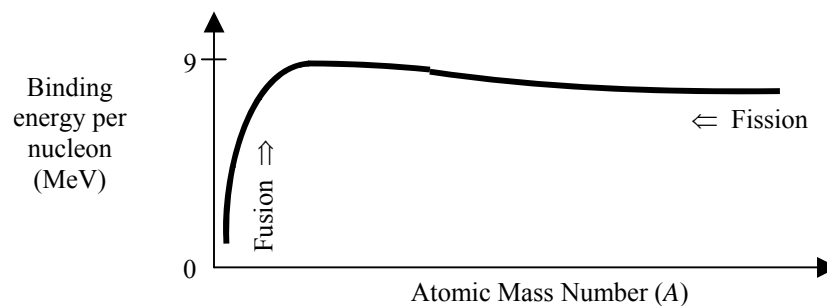
If the masses of the individual neutrons ( $m_n$ ) and protons ( $m_p$ ) making up the nucleus are added, the total will exceed the experimentally determined mass ( $m_X$ ) for that nucleus; this difference in mass is called the *mass defect* ( $\Delta m$ )

$$\begin{aligned} \Delta m &= [Z m_p + N m_n] - m_X \\ &= [Z(m_p + m_e) + N m_n] - [m_X + Z m_e] \\ &= Z M_{H-1} + N m_n - M_X \end{aligned} \quad (1)$$

where  $m_X$  is the mass of the nucleus,  $M_X$  is the mass of the neutral atom, and  $M_{H-1}$  is the mass of the neutral hydrogen atom,  ${}^1\text{H}$ . The latter expression given in Equation (1) is the most convenient since the mass of the nucleus is rarely tabulated but the mass of the neutral atom can easily be obtained from a reference textbook. The *binding energy* is the energy required to break the nucleus into its constituent nucleons

$$BE = \Delta m c^2 \quad (2)$$

Releasing the binding energy is the key to energy production using both nuclear *fusion* and *fission*. Fusion and fission both increase the binding energy per nucleon, as shown below.



*Example:* Find the equivalent (binding) energy for 1 amu.

From standard reference tables: 1 amu =  $1/N_{Av} = 1.6605 \times 10^{-27}$  kg; and 1 eV =  $1.6022 \times 10^{-19}$  J

$$E = m c^2 = \frac{(1.6605 \times 10^{-27} \text{ kg})(2.998 \times 10^8 \text{ m/s})^2}{(1.6022 \times 10^{-13} \text{ J/MeV})} = 931.5 \text{ MeV} \quad (3)$$

## Fuels

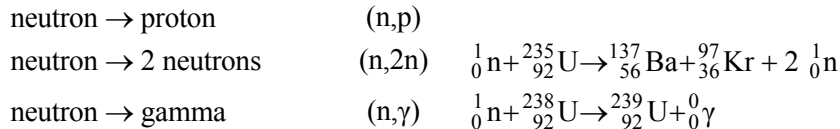
Fissile nuclides (fission with thermal or fast neutrons):  $^{233}\text{U}$ ,  $^{235}\text{U}$ ,  $^{239}\text{Pu}$ ,  $^{241}\text{Pu}$   
 Fissionable nuclides (fission with fast neutrons):  $^{232}\text{Th}$ ,  $^{238}\text{U}$ ,  $^{240}\text{Pu}$ ,  $^{242}\text{Pu}$   
 Fusion nuclides: Deuterium (D or  $^2\text{H}$ ), Tritium (T or  $^3\text{H}$ ),  $^3\text{He}$

## Basic Nuclear Reaction Equation



The nuclear reaction equation  $[a + b \rightarrow c + d]$  is sometimes abbreviated as  $a(b,c)d$ .

Example reaction categories include



All reactions obey four fundamental governing laws

- conservation of nucleons:  $A_1 + A_2 = A_3 + A_4$
- conservation of charge:  $Z_1 + Z_2 = Z_3 + Z_4$
- conservation of momentum:  $p_a + p_b = p_c + p_d$
- conservation of total energy (including rest mass and kinetic):

$$KE_a + KE_b + M_a c^2 + M_b c^2 = KE_c + KE_d + M_c c^2 + M_d c^2 \quad (5)$$

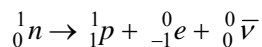
## Reaction $Q$ Value

Application of the conservation of energy gives the  $Q$  value of the reaction. This  $Q$  represents the change in rest mass energies (or equivalently the change in kinetic energies) of the particles:

$$Q = \left[ \sum_{\text{react}} m - \sum_{\text{prod}} m \right] c^2 = \left[ \sum_{\text{prod}} E_K - \sum_{\text{react}} E_K \right] = \left[ \sum_{\text{prod}} BE - \sum_{\text{react}} BE \right] \quad (6)$$

For  $Q > 0$ , the reaction is exothermic; for  $Q < 0$ , reaction is endothermic. From Equation (6), we see that the binding energy ( $BE$ ) release goes to the kinetic energy of the reaction products. For comparison fission reactions have a  $Q$  around 200 MeV, and each fusion reaction releases roughly 10 MeV.

*Example:* A free neutron decays with a half-life of about 10.3 minutes. The decay reaction produces a proton, an electron and an antineutrino ( $\bar{\nu}$ ) via



Neglecting the antineutrino in the reaction, determine the total kinetic energy (MeV) imparted to the two products (the proton and electron).

*Solution:*

If the neutron is initially at rest, the reaction  $Q$  value is equal to the total kinetic energy received by the decay products:

$$\begin{aligned} Q &= [m_n - (m_p + m_e)]c^2 \\ &= [1.0086649158 - (1.0072764669 + 0.0005485799) \text{ amu}] (931.5 \text{ MeV/amu}) \\ &= 0.7823 \text{ MeV} \end{aligned}$$