7.3 Nuclear Reactions, fission + fusion

Artificial transmutation

- the name given to the process of transmutation when it is conducted artificially, such as in a laboratory.

Example The transmutation of O^{18} into F^{18}

Fluorine-18 is a short-lived radioisotope used as a tracer in medicine (i.e. PET -> positron emission tomography)

$$O_8^{18} + H_1^1 \longrightarrow F_9^{18} + n_0^1$$

radioisotope => radioactive isotope → emits radiation during decay to become more stable

↳ used in medical diagnosis, treatment + research.

Conservation Laws in nuclear reactions

→ Charge - the total proton number (or atomic number) Z must be the same on both sides of the reaction.

→ number of nucleons - the number of nucleons (or mass number) A must be the same on both sides of the reaction.

Examples

Radioactive decay of radium-224: $Ra_{88}^{226} \rightarrow Rn_{86}^{222} + ?\ (He_2^4)$

Thorium-234 is a beta emitter and decays into the element protactinium:

$Th_{90}^{234} \rightarrow ? + ? + ?$

$Pa_{91}^{234} \quad e_{-1}^{0} \quad \bar{\nu}$

You may get questions combining TOPIC 2 (Mechanics) and TOPIC 7. Recall:

Kinetic energy $E_K = \frac{1}{2}mv^2$

momentum $p = mv$

$p = \sqrt{2mE_K}$

data booklet $\rightarrow \left(E_K = \frac{p^2}{2m} \right)$

Unified atomic mass unit:

One unified atomic mass unit (u) is defined as one-twelfth of the mass of a single neutral atom of the isotope carbon-12 at rest* and in its ground state*.

$$1\,u = \frac{1}{12}\,\text{mass}_{\text{of}}\,C^{12}\,\text{atom}$$

* must be at rest because the mass of a body depends on the speed of the observer.

* mass is related to energy

Carbon-12 has 12 nucleons within its nucleus (6p + 6n)

The mass of C^{12} atom = $12u$ (exactly)

mass of O^{16} atom $\approx 16u$ (approximately)

Mg^{24} atom $\approx 24u$ (approx)

H_2O molecule $\approx 18u$ (approx)

Recall from TOPIC 3:

molar mass -> its molecular mass expressed in grams.

Avogadro's constant (N_A) = $6.02\times10^{23}\,mol^{-1}$

So there are N_A atoms in 12g of C^{12}
16g of O^{16}

and N_A molecules in 18g of H_2O.
32g of O_2

Unified atomic mass unit and the kilogram:

1 mole of C^{12} has a mass of 12g

1 atom of C^{12} has a mass of $\frac{12g}{6.02\times10^{23}} = 1.99\times10^{-26}kg$

$$1u = \frac{1}{12}(1.99\times10^{-26}kg)$$

$$1u = 1.66\times10^{-27}kg$$

(Data booklet $1u = 1.661\times10^{-27}kg$

Relation between the unified atomic mass unit and the energy unit MeV

Recall: $E = mc^2$ (mass & energy equivalence)

$1u = 1.661 \times 10^{-27}\ kg$

$= 1.661 \times 10^{-27}\ kg\ (3.0 \times 10^{8}\ m/s)^2$

$= 1.495 \times 10^{-10}\ J$ $\div 1.6 \times 10^{-19}\ J\ eV^{-1}$

$= 9.31 \times 10^{8}\ eV$

$= 931\ MeV$

The units $MeV\ c^{-2}$ and $GeV\ c^{-2}$ for mass:

$E = mc^2$

$m = \frac{E}{c^2}$ ← $\frac{MeV}{c^2}$ or $MeV\ c^{-2}$ common units for particle mass

units: → $\frac{J}{m^2/s^2}$

$\frac{kg\ m^2/s^2}{m^2/s^2}$

Example

Determine the energy equivalent to the mass of an alpha particle in units of $GeV\ c^{-2}$. ($m_\alpha = 6.67 \times 10^{-27}\ kg$)

$E = mc^2$

$E = (6.67 \times 10^{-27}\ kg)(3.00 \times 10^{8}\ ms^{-1})^2$

$E = 6.003 \times 10^{-10}\ J \left(\frac{1\ eV}{1.6 \times 10^{-19}\ J}\right)$

$E = 3.75 \times 10^{9}\ eV$

$E = 3.75\ GeV\ c^{-2}$

Example

Determine the energy equivalent to the mass of an electron. Give your answer in $MeV\ c^{-2}$. ($m_e = 9.11 \times 10^{-31}\ kg$)

($0.511\ MeV\ c^{-2}$)