

# Nuclear Physics

$E = mc^2$  → Mass and Energy are two different manifestations of the same thing.

$E$ : energy created out of mass

$m$ : mass  $c$ : speed of light in vacuum ( $3.0 \times 10^8 \text{ ms}^{-1}$ )

Radioactive Decay:  $U \rightarrow \beta + Y + \text{energy}$

Nuclear Fusion:  $X + Y \rightarrow Z + \text{energy}$

Nuclear Fission:  $X + n \rightarrow Y + Z + \text{energy}$

Nuclear Synthesis:  $6p + 6n \rightarrow {}_6^{12}\text{C} + \text{energy}$

can be calculated using  $E = mc^2$

## Mass Defect

- The difference in mass of reactants and products at the end of a nuclear reaction.
- During stable reactions, mass of product is LESS THAN the mass of reactants. This is due to some of the mass being converted to energy.

	mass/u
proton	1.00728
neutron	1.00867
tritium ( ${}^3_1\text{H}$ ) nucleus	3.01551
polonium ( ${}^{210}_{84}\text{Po}$ ) nucleus	209.93722

$$1 \text{ u} = 1.66 \times 10^{-27} \text{ kg}$$

## Nuclear Synthesis of Tritium



$$\text{mass defect} = (1p + 2n) - ({}^3_1\text{H})$$

$$\Delta m = (1.00728 + 2(1.00867)) - (3.01551)$$

$$\Delta m = 0.00911 \text{ u}$$

$$\Delta m = 0.00911 \times 1.66 \times 10^{-27}$$

$$\Delta m = 1.51 \times 10^{-29} \text{ kg}$$

## Binding Energy

It is the amount of energy needed to separate the nucleons of a nucleus apart, to infinity.

It is calculated using  $E = mc^2$

$E = mc^2$   
Binding energy ← mass defect

finding binding energy of tritium

$$E = mc^2$$

$$E = (1.51 \times 10^{-29})(3 \times 10^8)^2$$

$$E = 1.359 \times 10^{-12} \text{ J}$$

mass defect of Polonium

$$\Delta m = (84p + 126n) - (P_0)$$

$$\Delta m = 1.76672 \text{ u}$$

Binding energy

$$E = mc^2$$

$$= (1.76672 \times 1.66 \times 10^{-27})(3 \times 10^8)^2$$

$$E = 2.639 \times 10^{-10} \text{ J}$$

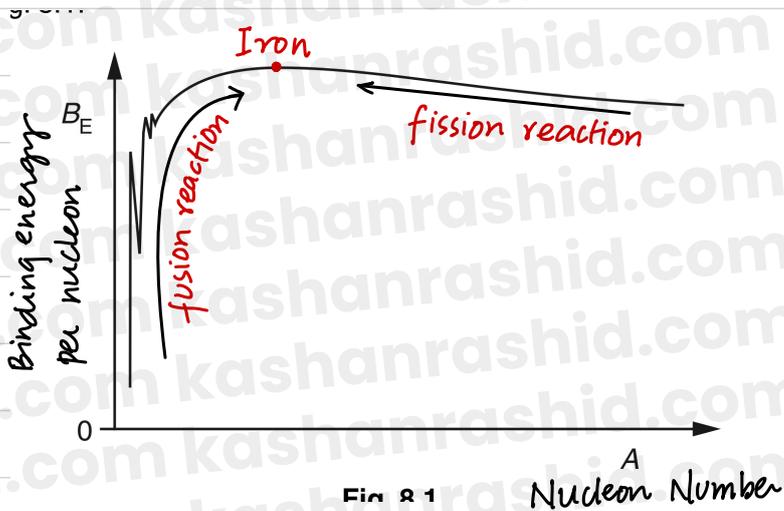
Binding Energy per nucleon =  $\frac{\text{Binding energy}}{\text{no. of nucleons}}$

\* It gives the idea about stability of nucleus! More BE per nucleon means more stable nucleus.

$$\text{Tritium: BE per nucleon} = \frac{1.359 \times 10^{-12}}{3} = 4.53 \times 10^{-13} \text{ J}$$

$$\text{Polonium: BE per nucleon} = \frac{2.639 \times 10^{-10}}{210} = 1.26 \times 10^{-12} \text{ J}$$

more BE per nucleon hence more stable.



- Iron has the most stable nucleus!
- Element with nucleon number less than Iron prefer fusion reaction whereas elements with nucleon number above Iron prefer fission reaction.

- 8 (a) State what is meant by the *binding energy* of a nucleus.

Amount of energy needed to separate the nucleons of a nucleus apart till infinity.

For  
Examiner's  
Use

[2]

- (b) Show that the energy equivalence of 1.0u is 930MeV.

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

$$E = mc^2$$

$$E = (1 \times 1.66 \times 10^{-27})(3 \times 10^8)^2$$

$$E = 1.494 \times 10^{-10} \text{ J}$$

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

$$1.494 \times 10^{-10} \text{ J} = x$$

$$x = 933750000 \text{ eV}$$

$$933.75 \times 10^6 \text{ eV}$$

$$934 \text{ MeV (3sf)}$$

$$930 \text{ MeV (2sf)}$$

[3]

- (c) Data for the masses of some particles and nuclei are given in Fig. 8.1.

	mass/u
proton	1.0073
neutron	1.0087
deuterium ( ${}^2_1\text{H}$ )	2.0141
zirconium ( ${}^{97}_{40}\text{Zr}$ )	97.0980

Fig. 8.1

Use data from Fig. 8.1 and information from (b) to determine, in MeV,

- (i) the binding energy of deuterium,

$$\begin{aligned} \text{mass defect} &= (1p + 1n) - ({}^2_1\text{H}) \\ &= (1.0073 + 1.0087) - (2.0141) \\ &= 1.9 \times 10^{-3} \text{ u} \end{aligned}$$

$$\begin{aligned} \text{Binding energy} &= 1.9 \times 10^{-3} \times 930 \\ &= 1.767 \text{ MeV} \end{aligned}$$

binding energy = 1.8 MeV [2]

(ii) the binding energy **per nucleon** of zirconium.

$$\bullet \text{ mass defect} = (40p + 57n) - (Zr)$$

$$\Delta m = 40(1.0073) + 57(1.0087) - 97.0980$$

$$\Delta m = 0.6899 \text{ u}$$

$$\bullet \text{ Binding energy} = 0.6899 \times 930 = 641.6 \text{ MeV}$$

$$\bullet \text{ BE per nucleon} = \frac{641.6}{97} = 6.614 \text{ MeV}$$

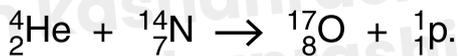
binding energy per nucleon = ..... 6.6 ..... MeV [3]

For  
Examiner's  
Use

## Nuclear Fusion Reaction

"A nuclear reaction in which two small nuclei combine to form a larger more stable nucleus, releasing energy."

→ Products have more BE per nucleon than reactants



## Nuclear Fission Reaction

"A nuclear reaction in which a larger nucleus breaks into smaller more stable nuclei by inserting a slow moving neutron in the nucleus."

→ Products have more BE per nucleon than reactants



for finding  $x$

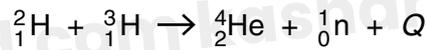
$$235 + 1 = 95 + 139 + x(1) + 7(0)$$

$$x = 2$$

## Quantities conserved during a nuclear reaction

1. Proton number
2. Mass number / Nucleon number
3. Charge
4. Momentum
5. Mass-Energy

- 8 The controlled reaction between deuterium ( ${}^2_1\text{H}$ ) and tritium ( ${}^3_1\text{H}$ ) has involved ongoing research for many years. The reaction may be summarised as



where  $Q = 17.7\text{MeV}$ .

Binding energies per nucleon are shown in Fig. 8.1.

	binding energy per nucleon / MeV
${}^2_1\text{H}$	1.12
${}^1_0\text{n}$	—
${}^4_2\text{He}$	7.07

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

Fig. 8.1

- (a) Suggest why binding energy per nucleon for the neutron is not quoted.

Neutron is one individual particle not joined with anything else. [1]

- (b) Calculate the mass defect, in kg, of a helium  ${}^4_2\text{He}$  nucleus.

$$\begin{aligned} BE &= 7.07 \times 4 \\ &= 28.28 \text{ MeV} \end{aligned} \quad E = mc^2$$

$$(28.28 \times 10^6 \times 1.6 \times 10^{-19}) = m(3 \times 10^8)^2$$

$$m = 5.03 \times 10^{-29} \text{ kg}$$

mass defect =  $5.0 \times 10^{-29}$  kg [3]

- (c) (i) State the name of the type of reaction illustrated by this nuclear equation.

Nuclear Fusion reaction [1]

- (ii) Determine the binding energy per nucleon, in MeV, of tritium ( ${}^3_1\text{H}$ ).

$$\begin{aligned} BE_H + BE_T &= BE_{He} - Q \\ (1.12 \times 2) + BE_T &= (7.07 \times 4) - 17.7 \end{aligned}$$

$$BE_T = 8.34 \text{ MeV} \rightarrow BE_T \text{ per nucleon} = \frac{8.34}{3} = 2.78 \text{ MeV}$$

$$E_{\text{prod}} - E_{\text{react}} = Q \rightarrow \text{energy released during reaction}$$

binding energy per nucleon = ..... MeV [3]

For  
Examiner's  
Use

"It is the probability of a nucleus to decay per unit time."

decay constant =  $\frac{\text{probability}}{\text{time}}$   $\longrightarrow$  probability =  $\frac{\text{possible outcomes}}{\text{total outcomes}}$

$\lambda = \frac{\Delta N}{N \times \Delta t}$   $\longrightarrow$   $\lambda = \frac{A}{N}$

time  $\longrightarrow$  time taken  $\Delta t$

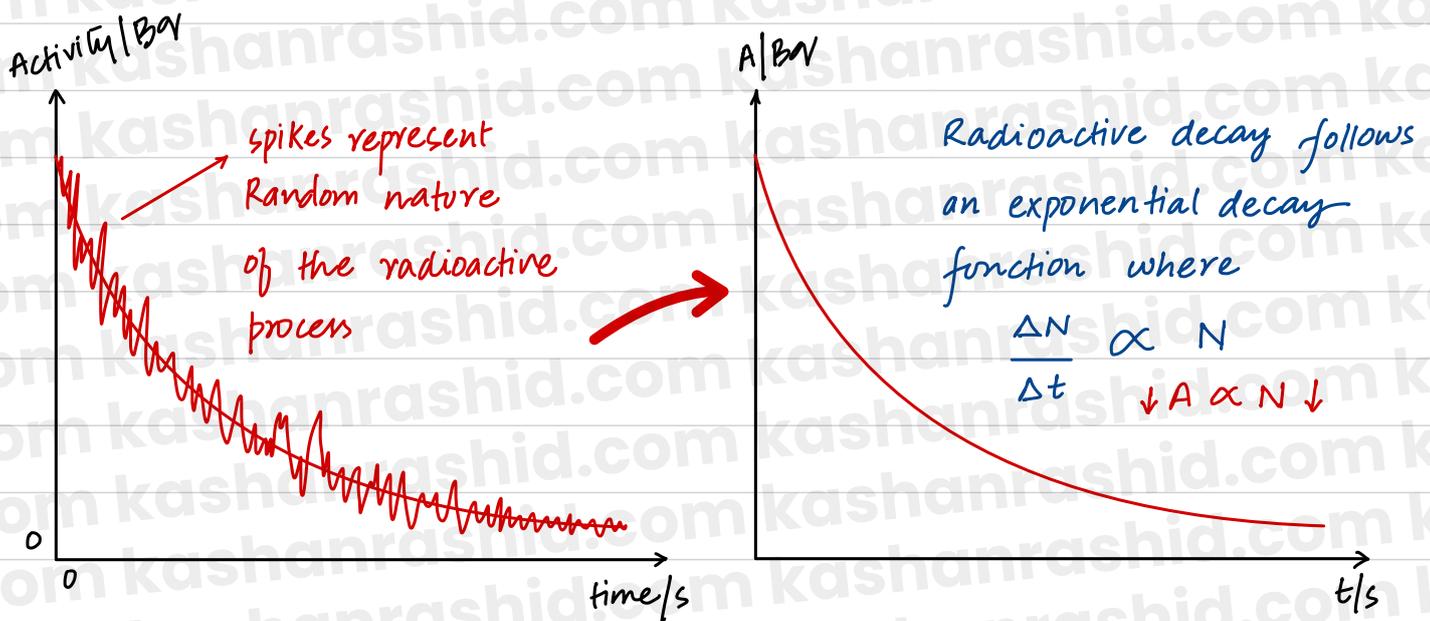
$\Delta N$   $\longrightarrow$   $N$

or  $A = \lambda N$

activity  $\downarrow$   $\downarrow$   $\downarrow$  no. of undecayed nuclei

decay constant  
(SI Unit:  $s^{-1}$ )

Variation of Activity, Count rate or No. of nuclei w.r.t time



Whenever the rate of change of a quantity is proportional to the quantity itself, it follows an exponential function.

General form:  $y = y_0 e^{-kx}$  where  $k$ : constant

$$A = A_0 e^{-\lambda t}$$

$$N = N_0 e^{-\lambda t}$$

$$R = R_0 e^{-\lambda t}$$

$A_0$ : initial activity

$t$ : time

$A$ : final Activity

$N_0$ : initial nuclei

$t$ : time

$N$ : final nuclei

$R_0$ : initial count rate

$t$ : time

$R$ : final count rate

$\lambda$ : decay constant