Explanations

1. Radius of nucleus, $R = R_0 A^{1/3}$

where, R = radius of nucleus,

A = mass number

and $R_0 = 1.2 \text{ fm} = 1.2 \times 10^{-15}\text{m}$ is the range of nuclear size or nuclear unit radius. **(1)**

2. (i) Nuclides of an element having same atomic number but different mass number called isotopes while isobars are the nuclides with same mass number but different atomic number. **(1)**

(ii) No, the difference in mass number may be due to different atomic number, so these can't be necessarily isotopes of same element. For isotopes, their atomic number must be same. **(1)**

3. The size of the nucleus is experimentally determined using Rutherford's α-scattering experiment and the distance of closest approach and impact parameter.

The relation between radius and mass number of nucleus is $R = R_0 A^{1/3}$

where, $R_0 = 1.2$ fm

A = mass number

and R = radius of nucleus **(1)**

$$\text{Nuclear density, } \rho = \frac{\text{Mass of nucleus}}{\text{Volume of nucleus}}$$

$$= \frac{mA}{\frac{4}{3}\pi (R_0 A^{1/3})^3}$$

where, m = mass of each nucleon

$$\rho = \frac{mA}{\frac{4}{3}\pi R_0^3 A}$$

$$\Rightarrow \qquad \rho = \frac{m}{\frac{4}{3}\pi R_0^3}$$

From the above formula, it is clear that ρ does not depend on the mass number. **(1)**

Explanations

1. According to question,

$$4\,{}_{Z}X^{A} \longrightarrow {}_{Z'}Y^{A'} + Q$$

(Parent nuclei) (Daughter nucleus)

As the daughter nucleus is a heavier nucleus as compared to parent nuclei, which are more stable than lighter nuclei, hence daughter nucleus has more binding energy per nucleon than parent nuclei. **(1)**

2. According to question,

$${}_{1}^{2}\text{H} + {}_{1}^{2}\text{H} \longrightarrow {}_{2}^{3}\text{He} + {}_{0}n^{1}$$

Energy released in fusion = Binding energy of ${}_{2}^{3}\text{He}$ $-\,2\times$ Binding energy of ${}_{1}^{2}\text{H}$

$$= 7.73 - 2\times 2.23 = 3.27\text{ MeV}$$ **(1)**

3. According to question,

$$P \longrightarrow Q + Q$$

BE/A of element $P = 7.6$ MeV (given)

So, BE of $P = 7.6\times 240$ MeV [$A = 240$]

BE/A of element $Q = 8.5$ MeV (given)

So, BE of $Q = 8.5\times 120$ MeV

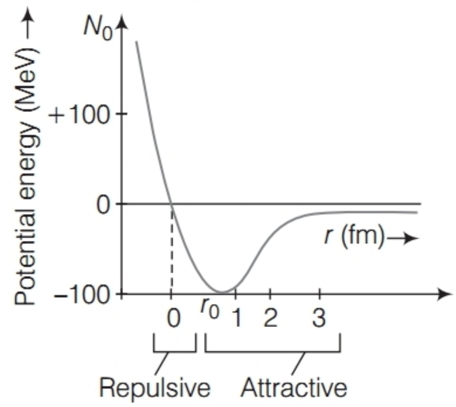
Now, energy released = $2\times$(BE of Q) $-$ BE of P

$$= 8.5\times 120\times 2 - 7.6\times 240$$

$$\Rightarrow = (2040 - 1824)\text{ MeV}$$

$$= 216\text{ MeV}$$ **(1)**

4. Plot of potential energy of a pair of nucleons as a function of their separation is given in the figure.



(1)

5. Two characteristics of nuclear force are given as below

(i) These are short range forces.

(ii) These are strongest force of attractive nature upto certain distance. **(1)**

6. Energy released = $\Delta m\times 931$ MeV

$$\Delta m = 4\,m\,({}_{1}^{1}\text{H}) - m\,({}_{2}^{4}\text{He})$$

Energy released

$Q = \{4m({}_{1}^{1}\text{H}) - m\,({}_{2}^{4}\text{He})\}\times 931]$ MeV

$$= [4\times 1.007825 - 4.002603]\times 931\text{ MeV}$$

$$= 26.72\text{ MeV}$$ **(1)**

7. Energy released per fission

$$= (\text{Initial mass} - \text{final mass})\times c^2$$

$$= (110 + 130)\times 8.5\text{ MeV} - 240\times 7.6\text{ MeV}$$

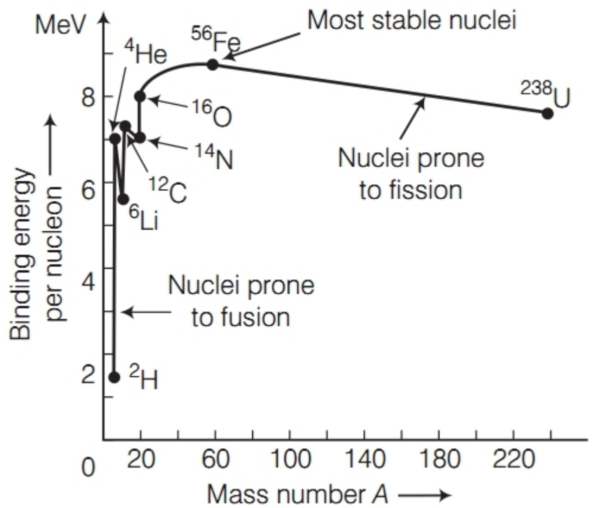
$$= 240\times(8.5 - 7.6)\text{ MeV}$$

$$= 240\times 0.9 = 216\text{ MeV}$$ **(1)**

8. The sum of masses of nuclei of product element is less than the sum of masses of reactants and hence, loss of mass takes place during the reaction. This difference of mass of product elements and reactant gets converted into energy and liberated in the form of heat.

Here, the sum of masses of $_{10}Ne^{20}$ and $_2He^4$ is less than the sum of two $_6C^{12}$ and conversion of this mass defect is used to produce energy. **(1)**

9. The binding energy per nucleon curve is shown as below



Binding energy per nucleon as a function of mass number A

The binding energy per nucleon in the range of $30 < A < 170$ has average binding energy per nucleon = 8.5 MeV. The higher value of binding energy per nucleon is due to stability of these nucleons. Neutron-proton ratio is higher in this range of mass number which leads to stability of the nuclei. **(1)**

10. Let t be the time.

According to the Avogadro number concept, number of atoms in 2 g of deuterium

$$= 6.023 \times 10^{23}$$

and number of atoms in 2 kg of deuterium

$$= \frac{6.023 \times 10^{23} \times 2 \times 10^3}{2}$$

$$= 6.023 \times 10^{26} \text{ nuclei}$$

Energy released during fusion of two deuteriums

$$= 3.27 \text{ MeV}$$

$\therefore$ Energy released per deuterium = 1.635 MeV

Energy released in fusion of 6.023×10^{26} deuterium atoms

$$= 1.635 \times 6.023 \times 10^{26}$$

$$= 9.848 \times 10^{26} \text{ MeV}$$

$$= 9.848 \times 10^{26} \times 1.6 \times 10^{-13}$$

$$= 15.75 \times 10^{13} \text{ J}$$

Energy used by bulb in 1s = 800 J $\quad (\because W = J/s)$

As, 800 J of energy used in time = 1 s.

So, 15.75×10^{13} J of energy used in time

$$= \frac{1 \times 15.75 \times 10^{13}}{800}$$

$$= 1.969 \times 10^{11} \text{ s}$$

$$[\because 1 \text{ yr} = 60 \times 24 \times 60 \times 365 \text{ s}]$$

$$= \frac{1.969 \times 10^{11}}{60 \times 24 \times 60 \times 365} \text{ yr}$$

$$= 6.243 \times 10^3 \text{ yr}$$

Thus, the bulb glows for 6.243×10^3 yr.

11. (i) Refer to Sol. 4 on page 394.

(ii) Energy released in the process,

$$Q = \Delta m \times 931 \text{ MeV}$$

$$= [m\,(^{56}_{26}\text{Fe}) - 2m\,(^{28}_{13}\text{Al})] \times \text{MeV}$$

$$= (55.93494 - 2 \times 27.9819) \times 931 \text{MeV}$$

$$= -0.02886 \times 931 \text{ MeV} = -26.89 \text{ MeV}$$

Since, energy is absorbed. Hence, fission is energetically not possible. **(1½)**

12. (i) Refer to Sol. 5 on page 394. **(1½)**

(ii) Refer to Sol. 4 on page 394. **(1½)**

13. (i) Refer to Sol. 4 on page 394. **(1½)**

(ii) As in a nuclear process the number of electrons and protons remains the same on both side of reaction, hence

Atomic mass, $1 + 235 = a + 94 + 2(1)$

$\Rightarrow \quad a = 140$

and atomic number,

$$0 + 92 = 54 + b + 2(0)$$

$\Rightarrow \quad b = 38$ **(1½)**

14. (i) **Characteristics properties of nuclear force**

(a) Nuclear forces act between a pair of neutrons, a pair of protons and also between a neutron-proton pair, with the same strength. This, shows that nuclear forces are independent of charge.

(b) The nuclear forces are dependent on spin or angular momentum of nuclei.

(c) Nuclear forces are non-central forces. This shows that the distribution of nucleons in a nucleus is not spherically symmetric. **(1)**

(ii) For graph, Refer to Sol. 4 on page 394. **(1)**

From the plot, it is concluded that

(a) The potential energy is minimum at a distance $r_0 (\approx 0.8 \text{ fm})$ which means that the force is attractive for distances larger than 0.8 fm and repulsive for the distance less than 0.8 fm between the nucleons.

(b) Nuclear forces are negligible, when the distances between the nucleons is more than 10 fm. **(1)**

15. Nuclear fission is the phenomenon of splitting of a heavy nucleus (usually $A > 230$) into two or more lighter nuclei.

$$U_{92}^{235} + n_0^1 \longrightarrow Ba_{56}^{141} + Kr_{36}^{92} + 3n_0^1 + Q$$

In this case, the energy released per fission of U_{92}^{235} is 200.4 MeV. **(1)**

Nuclear fusion is the phenomenon of joining two or more lighter nuclei to form a single heavy nucleus. The mass of the product nucleus is slightly less than the sum of the masses of the lighter nuclei fusing together. This difference in the masses results in the release of tremendous amount of energy. **(1)**

e.g. $_1^1H + _1^1H \longrightarrow _1^2He + e^+ + \nu + 0.42\text{MeV}$

$$_1^2H + _1^2H \longrightarrow _1^3He + n + 3.27\text{MeV}$$

$$_1^2H + _1^2H \longrightarrow _1H^3 + _1^1H + 4.03\text{MeV}$$

According to the question,

$$_1^2H + _1^3H \longrightarrow _2^4He + n\text{MeV}$$

$$\Delta m = (2.014102 + 3.016049) - (4.002603 + 1.008665)$$

$$= 0.018883\,u$$

Energy released, $Q = 0.018883 \times 931.5 \dfrac{\text{MeV}}{c^2}$

$$= 17.589 \text{ MeV}$$ **(1)**

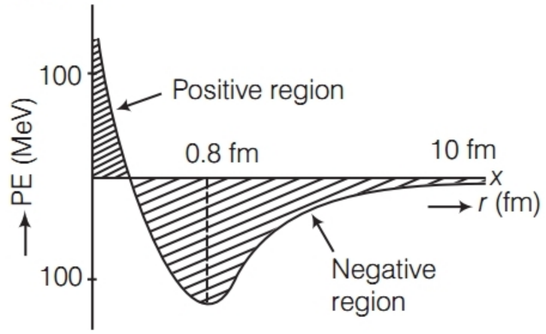
16. (i) $BE = [Zm_p + (A - Z)m_n - _Z^AM] \times c^2$

where, Z = atomic number, A = mass number, M = mass of nucleus, m_p is the mass of proton and m_n = the mass of neutron. **(1½)**

(ii) Refer to Sol. 9 on page 395. **(1½)**

17. In a nuclear reaction, the sum of the masses of the target nucleus ($_1^2H$) and the bombarding particle ($_1^2H$) may be greater than the product nucleus ($_2^3He$) and the outgoing neutron $_0^1n$. So, from the law of conservation of mass-energy some energy (3.27 MeV) is evolved due to mass defect in the nuclear reaction. This energy is called Q-value of the nuclear reaction. **(3)**

18. Plot between the potential energy of a pair of nucleons as a function of their separation, is shown below **(1)**



(i) For distance less than 0.8 fm, negative potential energy decreases to zero and then becomes positive. **(1)**

(ii) For distance larger than 0.8 fm, negative potential energy goes on decreasing. **(1)**

19. (i) The binding energy per nucleon for nucleus of range, $30 < A < 170$ is close to its maximum value. So, the nucleus belongs to this region is highly stable and does not show radioactivity. **(1)**

(ii) Binding energy per nucleon is smaller for heavier nuclei than the middle ones, i.e. heavier nuclei are less stable. When a heavier nucleus such as nucleus of mass number 240 splits into lighter nuclei (mass number 120), the BE/nucleon changes from about 7.6 MeV to 8.4 MeV. Greater BE of the product nuclei result in the liberation of energy. **(2)**

20. (i) Refer to Sol. 17 on page 396. **(1)**

(ii) Density of nuclear matter is the ratio of mass of the nucleus and its volume.

Density of the nuclear matter

$$= \frac{\text{Mass of nucleus}}{\text{Volume of nucleus}} \quad \ldots\text{(i)}$$

If m is average mass of a nucleon and R is the nuclear radius, then mass of nucleus $= mA$, where, A is the mass number of the element.

Volume of the nucleus $= \dfrac{4}{3}\pi R^3$

$$= \frac{4}{3}(\pi R_0 A^{1/3})^3 = \frac{4}{3}\pi R_0^3 A$$

But put the value in Eq. (i).

Thus, density of nucleus $= \dfrac{mA}{\frac{4}{3}\pi R_0^3 A}$

$$= \frac{3m}{4\pi R_0^3}$$

where, m = mass of one nucleon

A = mass **(1)**

As, m and R_0 are constants, therefore density of the nuclear matter is the same for all elements. Now, using $m = 1.66 \times 10^{-27}$kg.

$$= \frac{3 \times 1.66 \times 10^{-27}}{4\pi R_0^3}$$

Using $R_0 = 1.1 \times 10^{-15}$ m

and density $= 2.97 \times 10^{17}$kg m^{-3}

which shows that the density is independent of mass number A. **(1)**

21. (i) The saturation effect of nuclear force explains the constancy of BE/A over wide range of mass number, 170> A > 30. Saturation effect implies that nucleon interacts only with its neighbouring nucleons and does not interact with nucleons which are not in direct contact with it. **(1½)**

(ii) Refer to Sol. 20 (ii) on page 396. **(1½)**

22. **For graph** Refer to Sol. 4 on page 394. **(1)**

Net interactive force is zero when potential energy is minimum, i.e. nearly, $r_0 = 1$ fm (in graph).

(i) The nuclear force is attractive when separation between the nuclei is greater than $r_0 > 1$ fm. **(1)**

(ii) Repulsive when $r_0 < 1$ fm. **(1)**

23. Refer to Sol. 9 on page 395. **(1)**

Explanation of Release of Energy in Nuclear Fission and Fusion The curve reveals that binding energy per nucleon is smaller for heavier nuclei than the middle level nuclei. This shows that heavier nuclei are less stable than middle level nuclei. In nuclear fission, binding energy per nucleon of reactants (heavier nuclei) changes from nearly 7.6 MeV to 8.4 MeV (for nuclei of middle level mass).

Higher value of the binding energy of the nuclear product results in the liberation of energy during the phenomena of nuclear fission.

In nuclear fusion, binding energy per nucleon of lighter nuclei into heavier one changes from low value of binding energy per nucleon to high value and release of energy takes place in fusion e.g. two $_1H^2$ (Binding energy per nucleon

$\simeq$ 1.5 MeV/nucleon) combine to form $_2He^4$

(Binding energy per nucleon $\simeq$ 7 MeV/nucleon) and therefore the energy is liberated during nuclear fusion. **(2)**

24. (i) **Nuclear Fission** The phenomenon of splitting of heavy nuclei (mass number > 120) into smaller nuclei of nearly equal masses is known as nuclear fission.

In nuclear fission, the sum of the masses of the product is less than the sum of masses of the reactants. This difference of mass gets converted into energy $E = mc^2$ and hence sample amount of energy is released in a nuclear fission.

e.g. $^{235}_{92}U + ^1_0n \rightarrow ^{141}_{56}Ba + ^{92}_{36}Kr + 3\,^1_0n + Q$ **(1/2)**

Masses of reactant

= 235.0439 amu + 1.0087 amu

= 236.0526 amu

Masses of product

= 140.9139 + 91.8973 + 3.0261

= 235.8373 amu

Mass defect Z = 236.0526 − 235.8373

= 0.2153 amu

$\because$ 1 amu ≡ 931 MeV

$\Rightarrow$ Energy released = 0.2153 × 931

= 200 MeV nearly

Thus, energy is liberated in nuclear fission if $^{235}_{92}U$. **(1)**

(ii) **Nuclear Fusion** The phenomenon of conversion of two lighter nuclei into a single heavy nucleus is called nuclear fusion. **(1/2)**

Since, the mass of the heavier product nucleus is less than the sum of masses of reactant nuclei and therefore certain mass defect occurs which converts into energy as per Einstein's mass-energy relation. Thus, energy is released during nuclear fusion.

e.g.

$$_1H^1 + _1H^1 \longrightarrow _1H^2 + e^+ + \nu + 0.42\text{ MeV}$$

Also,

$$_1H^2 + _1H^2 \longrightarrow _1H^3 + _1H^1 + 4.03\text{ MeV}$$ **(1)**

25. (i) **For plot of binding energy per nucleon as the function of mass number A** **(1)**

Refer to Sol. 9 on page 395.

Following are the two conclusions that can be drawn regarding the nature of the nuclear force.

(a) The force is attractive and strong enough to produce a binding energy of few MeV per nucleon. **(1/2)**

(b) The consistency of the binding energy in the range of 30<A<170 is a consequence of the fact that the nuclear force is short range force. **(1/2)**

(ii) **Nuclear Fission** A very heavy nucleus (say A = 240) has lower binding energy per nucleon as compared to the nucleus with A = 120. Thus, if the heavier nucleus breaks into the lighter nucleus with high binding energy per nucleon, nucleons are tightly bound. This implies that energy will be released in the process which justifies the energy released in fission reaction. **(1)**

Nuclear Fusion When two light nuclei (A<10) are combined to form a heavier nuclei, the binding energy of the fused heavier nuclei is more that the binding energy per nucleon of the lighter nuclei. Thus, the final system is more tightly bound than the initial system. Again the energy will be released in fusion reaction. **(1)**

(iii) The basic nuclear process of neutron undergoing β-decay is given as below

$$n \rightarrow p + e^{-} + \bar{\nu}$$

Neutrinos interact very weakly with matter, so they have a very high penetrating power. That's why the detection of neutrinos is found very difficult. **(1)**

26. The Q-value of a nuclear process refers the energy release in the nuclear process which can be determined using Einstein's mass-energy relation, $E = mc^2$. The Q-value is equal to the difference of mass of products and reactant nuclei multiplied by square of velocity of light.

$$Q = [m_x - m_\pi - m_{He}]\, c^2$$ **(2)**

The nuclear process does not proceed spontaneously when Q-value of a process is negative or sum of masses of product is greater than sum of masses of reactant. **(1)**

For further part Refer to Sol. 8 on pages 394 and 395. **(2)**