13 Nuclei

Fastrack Revision

- **Nucleus:** An atom has a nucleus. The nucleus is positively charged. The radius of the nucleus is smaller than the radius of an atom by a factor of 10^4. More than 99.9% mass of the atom is concentrated in the nucleus.
- **Discovery of Neutrons:**
  - Neutrons were discovered by Chadwick in 1932.
  - When beryllium nuclei are bombarded by alpha-particles, highly penetrating radiations are emitted, which consists of neutral particles, each having mass nearly that of a proton. These particles were called neutrons.

$$^{4}_{2}\text{He} + ^{9}_{4}\text{Be} \rightarrow ^{1}_{0}n + ^{12}_{6}\text{C}$$

  - A free neutron decays spontaneously, with a half-life of about 900 s, into a proton, electron and an antineutrino.

$$^{1}_{0}n \rightarrow ^{1}_{1}\text{H} + ^{0}_{-1}e + \bar{\nu}$$

  The composition of a nucleus can be described using following terms and symbols:
  - **Atomic Number:** The number of protons in the nucleus is called the atomic number. It is denoted by Z.
  - **Mass Number:** The total number of protons and neutrons (N) present in a nucleus is called the mass number of the element. It is denoted by A.

    i.e., $A = Z + N$
  - **Number of Protons, Electrons, Nucleons and Neutrons in an Atom:**
    - (i) Number of protons in an atom $= Z$
    - (ii) Number of electrons in an atom $= Z$
    - (iii) Number of nucleons in an atom $= A$
    - (iv) Number of neutrons in an atom $= N = A - Z$
  - **Nuclear Mass:** The total mass of the protons and neutrons present in a nucleus is called the nuclear mass.
- **Nuclide:** A nuclide is a specific nucleus of an atom characterised by its atomic number Z and mass number A. It is represented as, $_{Z}X^{A}$.

  where, X = chemical symbol of the element, Z = atomic number and A = mass number.
- **Isotopes:**
  - The atoms of an element which have the same atomic number but different mass number are called isotopes.
  - Isotopes have similar chemical properties but different physical properties.
- **Isobars:** The atoms having the same mass number but different atomic number are called isobars.
- **Isotones:** The nuclides having the same number of neutrons are called isotones.
- **Isomers:** These are nuclei with same atomic number and same mass number but in different energy states.
- **Atomic Mass Unit:**
  - It is $\frac{1}{12}$th of the actual mass of a carbon (^{12}C) atom.

    It is denoted by amu or just by u.

$$1\text{u} = \frac{\text{mass of one } ^{12}\text{C atom}}{12} = \frac{1.992647 \times 10^{-26}}{12}\text{kg}$$
$$= 1.660565 \times 10^{-27} \text{ kg}$$

  - The energy equivalence of 1 amu = 931 MeV.
- **Density of the Nucleus:** Density of nucleus is the ratio of mass of nucleus and its volume. Density of nucleus is constant and independent of A, for all nuclei and density of nuclear matter is approximately 2.3×10^{17} kg m^{-3} which is very large as compared to ordinary matter, say water which is 10^3 kg m^{-3}.

$$\text{Nuclear density, } \rho = \frac{\text{Nuclear mass}}{\text{Nuclear volume}} = \frac{m}{\frac{4}{3}\pi R^3}$$
$$= 2.3 \times 10^{17} \text{kg m}^{-3}$$

- **Mass-Energy Relation:** Einstein proved that it is necessary to treat mass as another form of energy. According to Einstein, mass is another form of energy and one can convert mass energy into other forms of energy, say kinetic energy and *vice-versa*. He gave the mass-energy equivalence relation as,

$$E = mc^2$$

  where, m is mass and $c = 3 \times 10^8$ ms^{-1} is the velocity of light in vacuum.
- **Nuclear Binding Energy:** When a certain number of neutrons and protons are brought together to form a nucleus of a certain charge and mass, an energy (E_b) will be released in the process. This energy is called the binding energy of the nucleus.
- **Binding Energy per Nucleon:** It is the ratio of binding energy (E_b) of a nucleus to the number of the nucleons (A), in that nucleus.

  i.e., $E_{bn} = \frac{E_b}{A}$

  Binding energy per nucleon as the average energy per nucleon needed to separate a nucleus into its individual nucleons.

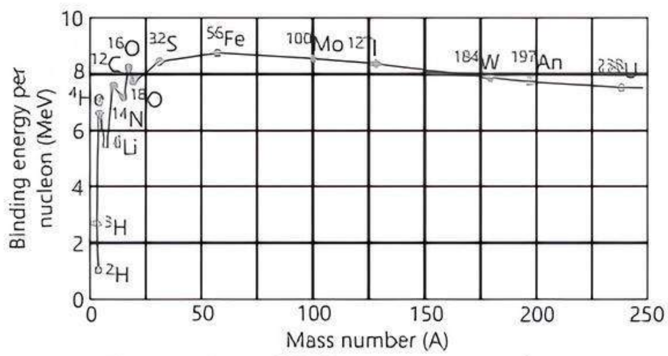


Fig. Variations of binding energy per nucleon with mass number.

Figure shows binding energy per nucleon E_{bn} versus the mass number A for a large number of nuclei. We notice the following main features of the plot:

- The binding energy per nucleon, E_{bn} is practically constant, *i.e.*, practically independent of the atomic number for nuclei of middle mass number ($130 < A < 170$). The curve has a maximum of about 8.75 MeV for $A = 56$ and has a value of 7.6 MeV for $A = 238$.
- E_{bn} is lower for both light nuclei ($A < 30$) and heavy nuclei ($A > 170$).

- **Mass Defect:** The difference between the rest mass of a nucleus and the sum of the rest masses of its constituent nucleon is called its mass defect. It is given by,

$$\Delta M = [Z m_p + (A - Z) m_n)] - M$$

- **Nuclear Forces**
  - These are the strong attractive forces which hold protons and neutrons together in a tiny nucleus.
  - These are short range forces which operate over very short distance of about 2-3 fm of separation between any two nucleons.
  - The nuclear force does not depend on the charge of the nucleon.

- **Nuclear Reaction:** It is a reaction which involves the change of stable nuclei of one element into the nucleus of another element.
- **Nuclear Energy:** Nuclear energy is the energy released during the transformation of nuclei with less total binding energy to nuclei with greater binding energy.
  There are two ways of obtaining energy from nucleus are:
  (i) Nuclear fission
  (ii) Nuclear fusion.
- **Nuclear Fission:** It is the process in which a heavy nucleus when excited gets split into two smaller nuclei of nearly comparable masses.
  For example,

$$^{235}_{92}U + ^{1}_{0}n \rightarrow ^{144}_{56}Ba + ^{89}_{36}Kr + 3^{1}_{0}n + Q$$

The Q-value is equal to the difference of mass of products and reactants multiplied by square of velocity of light.

Energy released per fission of $^{235}_{92}U$ is approximately 200.4 MeV.

- **Nuclear Fusion:** It is the process of fusion of two smaller nuclei into a heavier nucleus with the liberation of large amount of energy.

For example, $^{1}_{1}H + ^{1}_{1}H \dashrightarrow ^{2}_{1}H + e^{+} + V + 0.42\,MeV$

- **Critical Size and Critical Mass**
  - The size of the fissionable material for which reproduction factor is unity is called critical size and its mass is called critical mass of the material.
  - The chain reaction in this case remains steady or sustained.
- **Moderator**
  - Any substance which is used to slow down fast moving neutrons to thermal energies is called a moderator.
  - The commonly used moderators are water, heavy water (D_2O) and graphite.

Practice Exercise

Multiple Choice Questions

Q 1. The nuclei of the isotopes of an element all contain the same number of a certain particle. What is this particle?

a. Electron b. Neutron
c. Nucleon d. Proton

Q 2. What is the approximate ratio of volume of a nucleus to the volume of an atom?

a. 10^{-34} b. 10^{-20}
c. 10^{-12} d. 10^{-10}

Q 3. The set which represents the isotope, isobar and isotone respectively is:

a. $(^{2}_{1}H, ^{3}_{1}H)$, $(^{197}_{79}Au, ^{198}_{80}Hg)$ and $(^{3}_{2}He, ^{2}_{1}H)$

b. $(^{3}_{2}He, ^{1}_{1}H)$, $(^{197}_{79}Au, ^{198}_{80}Hg)$ and $(^{1}_{1}H, ^{3}_{1}H)$

c. $(^{3}_{2}He, ^{3}_{1}H)$, $(^{2}_{1}H, ^{3}_{1}H)$ and $(^{197}_{79}Au, ^{198}_{80}Hg)$

d. $(^{2}_{1}H, ^{3}_{1}H)$, $(^{3}_{2}He, ^{3}_{1}H)$ and $(^{197}_{79}Au, ^{198}_{80}Hg)$

Q 4. The atomic mass number is equivalent to which of the following?

a. The number of neutrons in the atom
b. The number of protons in the atom
c. The number of nucleons in the atom
d. The number of α-particles in the atom

Q 5. The mass number of iron nucleus is 56, the nuclear density is:

a. 2.29×10^{16} kg m^{-3} b. 2.29×10^{17} kg m^{-3}
c. 2.29×10^{18} kg m^{-3} d. 2.29×10^{15} kg m^{-3}

Q 6. Two nuclei have their mass numbers in the ratio of 1 : 3. The ratio of their nuclear densities would be:

a. $(3)^{1/3} : 1$ b. 1 : 1 c. 1 : 3 d. 3 : 1

Q 7. The ratio of the nuclear densities of two nuclei having mass numbers 64 and 125 is: *(CBSE 2023)*

a. $\frac{64}{125}$ b. $\frac{4}{5}$ c. $\frac{5}{4}$ d. 1

Q 8. What is the ratio of nuclear radii if the mass numbers of two nuclei are 4 and 32?

a. 1 : 2 b. 1 : 3 c. 1 : 4 d. 1 : 5

Q 9. How much mass has to be converted into energy to produce electric power of 500 MW for one hour?

a. 2×10^{-5} kg b. 1×10^{-5} kg
c. 3×10^{-5} kg d. 4×10^{-5} kg

Q 10. The equivalent energy of 1 g of substance is:

a. 9×10^{13} J b. 6×10^{12} J
c. 3×10^{13} J d. 6×10^{13} J

Q 11. If the binding energy per nucleon of deuterium is 1.115 MeV, its mass defect in atomic mass unit is:

a. 0.0024 b. 0.0012
c. 0.006 d. 0.0048

Q 12. A force between two protons is same as the force between proton and neutron. The nature of the force is:

a. electrical force b. weak nuclear force
c. gravitational force d. strong nuclear force

Q 13. Two nucleons are at a separation of 1 fermi. The net force between them is F_1 if both are neutrons, F_2 if both are protons and F_3 if one is proton and the other is a neutron. Then:

a. $F_1 > F_2 > F_3$ b. $F_1 = F_3 > F_2$
c. $F_2 > F_1 > F_3$ d. $F_1 = F_2 > F_3$

Q 14. Heavy stable nuclei have more neutrons than protons. This is because of the fact that:

(NCERT EXEMPLAR)

a. neutrons are heavier than protons.
b. electrostatic force between protons are repulsive.
c. neutrons decay into protons through beta decay.
d. nuclear forces between neutrons are weaker than that between protons.

Q 15. In reaction:

$_4\text{Be}^9 + {}_2\text{He}^4 \rightarrow {}_6\text{C}^x + {}_0n^1, x =$

a. 16 b. 12 c. 10 d. 14

Q 16. The splitting of a nucleus into smaller nuclei is:

a. half-life b. fusion
c. gamma radiation d. fission

Q 17. In the given reactions, which of the following nuclear fusion reaction is not possible?

a. ${}^{13}_{6}\text{C} + {}^{1}_{1}\text{H} \rightarrow {}^{14}_{6}\text{C} + 4.3\,\text{MeV}$

b. ${}^{12}_{6}\text{C} + {}^{1}_{1}\text{H} \rightarrow {}^{13}_{7}\text{C} + 2\,\text{MeV}$

c. ${}^{14}_{7}\text{N} + {}^{1}_{1}\text{H} \rightarrow {}^{15}_{8}\text{O} + 7.3\,\text{MeV}$

d. ${}^{235}_{92}\text{U} + {}^{1}_{0}n \rightarrow {}^{140}_{54}\text{Xe} + {}^{94}_{38}\text{Sr} + {}^{1}_{0}n + {}^{1}_{0}n + 200\,\text{MeV}$

Q 18. If in a nuclear fusion reaction, mass defect is 0.3%, then energy released in fusion of 1 kg mass is:

a. 27×10^{10} J b. 27×10^{11} J
c. 27×10^{12} J d. 27×10^{13} J

Q 19. In a nuclear fusion reaction, two nuclei, A and B, fuse to produce a nucleus C, releasing an amount of energy ΔE in the process. If the mass defects of the three nuclei are $\Delta M_A, \Delta M_B$ and ΔM_C respectively, then which of the following relations holds? Here, c is the speed of light.

a. $\Delta M_A + \Delta M_B = \Delta M_C - \Delta E/c^2$
b. $\Delta M_A + \Delta M_B = \Delta M_C + \Delta E/c^2$
c. $\Delta M_A - \Delta M_B = \Delta M_C - \Delta E/c^2$
d. $\Delta M_A - \Delta M_B = \Delta M_C + \Delta E/c^2$

Q 20. Which of the following statements about nuclear forces is not true? *(CBSE SQP 2022-23)*

a. The nuclear force between two nucleons falls rapidly to zero as their distance is more than a few femtometres.
b. The nuclear force is much weaker than the Coulomb force.
c. The force is attractive for distances larger than 0.8 fm and repulsive if they are separated by distances less than 0.8 fm.
d. The nuclear force between neutron-neutron, proton-neutron and proton-proton is approximately the same.

Q 21. Light energy emitted by star is due to:

a. breaking of nuclei b. joining of nuclei
c. burning of nuclei d. reflection of solar light

Assertion & Reason Type Questions

Directions (Q.Nos. 22-30): *In the following questions, a statement of Assertion (A) is followed by a statement of Reason (R). Mark the correct choice as:*

a. Both Assertion (A) and Reason (R) are true and Reason (R) is the correct explanation of Assertion (A).
b. Both Assertion (A) and Reason (R) are true but Reason (R) is not the correct explanation of Assertion (A).
c. Assertion (A) is true but Reason (R) is false.
d. Both Assertion (A) and Reason (R) are false.

Q 22. Assertion(A): The nucleus ${}^{7}_{3}X$ is more stable than the nucleus ${}^{4}_{3}Y$.

Reason (R): ${}^{7}_{3}X$ contains more number of protons.

(CBSE 2023)

Q 23. Assertion (A): The whole mass of the atom is concentrated in the nucleus.

Reason (R): The mass of a nucleus can be either less than or more than the sum of the masses of nucleons present in it.

Q 24. Assertion (A): Forces acting between proton-proton (f_{pp}), proton-neutron (f_{pn}) and neutron-neutron (f_{nn}) are such that $f_{pp} < f_{pn} = f_{nn}$.

Reason (R): Electrostatic force of repulsion between two protons reduces net nuclear forces between them.

Q 25. Assertion (A): Nuclear force between neutron-neutron, proton-neutron and proton-proton is approximately the same.

Reason (R): The nuclear force does not depend on the electric charge.

Q 26. Assertion (A): Neutrons penetrate matter more readily as compared to protons.

Reason (R): Neutrons are slightly more massive than protons.

Q 27. Assertion (A): Fusion of hydrogen nuclei into helium nuclei is the source of energy of all stars.

Reason (R): In fusion, heavier nuclei split to form lighter nuclei.

Q 28. Assertion (A): There occurs a chain reaction when uranium is bombarded with slow neutrons.
Reason (R): When uranium is bombarded with slow neutrons, more neutrons are produced.

Q 29. Assertion (A): Thermonuclear fusion reactions may become the source of unlimited power for the mankind.
Reason (R): A single fusion event involving isotopes of hydrogen produces more energy than energy from nuclear fission of a single uranium.

Q 30. Assertion (A): Cadmium rods used in a nuclear reactor, control the rate of fission.
Reason (R): Cadmium rod speed up the slow neutrons.

Fill in the Blanks Type Questions

Q 31. Two nuclei have mass numbers in the ratio 27 : 125. Then the ratio of their radii is ....

Q 32. The rest mass of a nucleus is .... than sum of the rest masses of its constituent nucleons.

Q 33. One atomic mass unit is defined as .... of mass of an atom of $_6C^{12}$.

Q 34. The energy which is responsible for binding the .... together in a nucleus is called the binding energy.

Q 35. The .... holds the nucleons together inside a nucleus.

Q 36. Heavy water is a .... which slows down fast moving neutrons to thermal velocities so that they can cause fission of $^{235}_{92}U$ nuclei.

Q 37. Nuclear reactor uses .... for peaceful purpose.

Q 38. The process responsible for energy production in the Sun is ....

Answers

1. (d) Proton
2. (c) 10^{-12}
3. (d) (^2_1H, ^3_1H), (^3_2He, ^3_1H) and ($^{197}_{79}Au$, $^{198}_{80}Hg$)

Nuclides with same atomic number Z but different mass number A are known as isotopes.

Nuclides with same mass number A but different atomic number Z are known as isobars.

Nuclides with same neutron number $N = (A - Z)$ but different atomic number Z are known as isotopes.

^2_1H and ^3_1H are isotopes.

^3_2He and ^3_1H are isobars.

$^{197}_{79}Au$ and $^{198}_{80}Hg$ are isotopes.

4. (c) The number of nucleons in the atom
5. (b) 2.29×10^{17} kg m^{-3}

Nuclear density is independent of mass number.

6. (b) 1 : 1

Given, $A_1 : A_2 = 1 : 3$

Their radii will be in the ratio $R_0A_1^{1/3} : R_0A_2^{1/3} = (1:3)^{1/3}$

$$\because \text{Density, } \rho = \frac{A}{\frac{4}{3}\pi R^3}$$

$$\therefore \rho_{A_1} : \rho_{A_2} = \frac{1}{\frac{4}{3}\pi R_0^3 \cdot 1^3} : \frac{3}{\frac{4}{3}\pi R_0^3 (3^{1/3})^3} = 1:1$$

Their nuclear densities will be the same.

7. (d) 1

Given, $A_1 = 64$ and $A_2 = 125$

The density of nuclei is given by

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

As the nuclear density is independent of the mass number so the ratio of nuclear densities of two given nuclei are 1 : 1, *i.e.*, 1.

8. (a) 1 : 2

Nuclear radius, $R = R_0 A^{1/3}$

$$\therefore \frac{R_1}{R_2} = \left(\frac{A_1}{A_2}\right)^{1/3}$$

$$= \left(\frac{4}{32}\right)^{1/3} = \left(\frac{1}{8}\right)^{1/3} = \frac{1}{2} = 1:2$$

9. (a) 2×10^{-5} kg

Given, $P = 500$ MW $= 5 \times 10^8$ W, $t = 1$ h $= 3600$ s

Energy produced, $E = P \times t$

$$= 5 \times 10^8 \times 3600 = 18 \times 10^{11} \text{ J}$$

As $E = \Delta mc^2$

$$\therefore \Delta m = \frac{E}{c^2} = \frac{18 \times 10^{11}}{(3 \times 10^8)^2} = \frac{18 \times 10^{11}}{9 \times 10^{16}} = 2 \times 10^{-5} \text{ kg}$$

10. (a) 9×10^{13} J

Using, $E = mc^2$

Given, $m = 1$ g $= 1 \times 10^{-3}$ kg, $c = 3 \times 10^8$ ms^{-1}

$$\therefore E = 10^{-3} \times 9 \times 10^{16} = 9 \times 10^{13} \text{ J}$$

11. (a) 0.0024

As we know, binding energy per nucleon,

$$E_{bn} = \frac{E_b}{A}$$

For deuterium, $A = 2$

Given, $E_{bn} = 1.115$ MeV

$$\therefore 1.115 = \frac{E_b}{2}$$

$$E_b = 2 \times 1.115 = 2.23 \text{ MeV}$$

$$\because E_b = \Delta mc^2$$

Mass defect,

$$\Delta m = \frac{2.23}{931.5} \quad [\because 1 \text{ amu} = 931.5 \text{ MeV}/c^2]$$

$$= 0.0024 \text{ amu}$$

12. (d) strong nuclear force

13. (b) $F_1 = F_3 > F_2$

14. (b) electrostatic force between protons are repulsive

15. (b) 12

$\because \quad 9 + 4 = x + 1$

$\Rightarrow \quad x = 13 - 1 = 12$

16. (d) fission

17. (a) ${}^{13}_{6}C + {}^{1}_{1}H \rightarrow {}^{14}_{6}C + 4.3\,MeV$

During nuclear fusion, two or more light nuclei combine to form a heavier and more stable nucleus. As ${}^{14}_{6}C$ is radioactive, so (a) is not possible.

18. (d) 27×10^{13} J

Given, $\Delta m = 0.3\%$ of 1 kg

$$= \frac{0.3}{100}\,kg = 3 \times 10^{-3}\,kg$$

$\therefore \quad E = \Delta mc^2 = 3 \times 10^{-3} \times (3 \times 10^8)^2 = 27 \times 10^{13}$ J

19. (a) $\Delta M_A + \Delta M_B = \Delta M_C - \Delta E/c^2$

20. (b) The nuclear force is much weaker than the Coulomb force.

The nuclear force is much stronger than the Coulomb force acting between charges or the gravitational forces between masses.

21. (b) joining of nuclei

Light energy emitted by stars is due to fusion of light nuclei.

22. (c) In nucleus ${}^{7}_{3}X$:

Number of protons (p) = 3

Number of neutrons (n) = 7 − 3 = 4

In nucleus ${}^{4}_{3}Y$:

Number of protons (p) = 3

Number of neutrons (n) = 4 − 3 = 1

Thus, for the same charge number Z, the nucleus with more neutrons is more stable. Therefore, ${}^{7}_{3}X$ is more stable.

23. (c) The mass of a nucleus is always less than the sum of the masses of the nucleons present in it. When nucleons combine to form a nucleus, some energy is liberated, and this is the binding energy of the nucleus. The mass of the nucleus cannot be more than the total mass of the nucleons because then stable nucleus cannot be formed.

24. (d) The electrostatic force of repulsion between proton-proton decreases the nuclear force between them.

25. (a) Both Assertion (A) and Reason (R) are true and Reason (R) is the correct explanation of Assertion (A).

26. (b) Neutron is about 0.1 more massive than protons. But the unique thing about the neutron is that while it is heavy, it has no charge (it is neutral). This lack of charge gives it the ability to penetrate matter without interacting as quickly as the beta particles or alpha particles.

27. (c) In fusion, lighter nuclei combine to form a heavier nucleus. Fusion of hydrogen nuclei into helium nuclei is the source of energy of all stars including our Sun.

28. (a) When uranium is bombarded by slow neutrons, the reaction is represented as

$${}^{235}_{92}U + {}^{1}_{0}n \rightarrow {}^{144}_{56}Ba + {}^{89}_{36}Kr + 3{}^{1}_{0}n + \text{Energy}$$

As more neutrons are produced, there are additional neutrons strike on other uranium nuclei to produce even more neutrons. Thus, a chain reaction is established.

29. (c) When fusion is achieved by raising the temperature of the system so that particles have enough kinetic energy to overcome the coulomb repulsive behaviour, it is called thermonuclear fusion. It is clean source of energy but energy released in one fusion is much less than a single uranium fission.

30. (c) Cadmium rods are used in a nuclear reactor to control the rate of fission. The cadmium rods do not slow down or speed up the neutrons produced in a fission reaction of ${}^{235}U$. Instead they absorb the neutrons thereby regulating the power level of the reactor.

31. 3 : 5

As we know, $R = R_0 A^{1/3}$

$$\frac{R_1}{R_2} = \frac{R_0(27)^{1/3}}{R_0(125)^{1/3}}$$

$$\frac{R_1}{R_2} = \frac{3}{5}$$

Hence, $R_1 : R_2 = 3 : 5$

32. less

33. (1/12th)

34. nucleons

35. strong nuclear force

36. moderator

37. nuclear energy

38. nuclear fusion

Case Study Based Questions

Case Study 1

The nucleus of an atom consists of a tightly packed arrangement of protons and neutrons. These are the two heavy particles in an atom and hence 99.9% of the mass is concentrated in the nucleus. Of the two, the protons possess a net positive charge and hence the nucleus of an atom is positively charged on the whole and the negatively charged electrons revolve around the central nucleus. Since, the mass concentration at the nucleus of an atom is immense the nuclear forces holding the protons and the neutrons together are also large.

Read the given passage carefully and give the answer of the following questions:

Q 1. The nuclide ${}^{238}_{92}U$ has all the following except:

a. 92 b. 146

c. 238 d. 0

Q 2. The density of a nucleus is of the order of:

a. 10^{15} kg m^{-3} b. 10^{18} kg m^{-3}
c. 10^{17} kg m^{-3} d. 10^{16} kg m^{-3}

Q 3. Nuclear force is:

a. strong, short range and charge independent force
b. charge independent, attractive and long range force
c. strong, charge dependent and short range attractive force
d. long range, charge dependent and attractive force

Q 4. The mass number of a nucleus is M and its atomic number is Z. The number of neutrons in the nucleus is:

a. $M - Z$ b. M
c. Z d. $M + Z$

Answers

1. (d) 0

The nuclide $^{238}_{92}U$ has number of protons 92, number of neutrons 146 (238 − 92) and number of nucleons 238 (146 + 92). Hence, nuclide $^{238}_{92}U$ has all *i.e.*, 92, 146 and 238 except 0.

2. (c) 10^{17} kg m^{-3}
3. (a) strong, short range and charge independent force
4. (a) $M - Z$

Case Study 2

Apsara is the oldest of India's research reactors. The reactor was designed by the Bhabha Atomic Research Centre (BARC) and built with assistance from the United Kingdom. A nuclear reactor, formerly known as an atomic pile, is a device used to initiate and control a self-sustained nuclear chain reaction. Nuclear reactors are used at nuclear power plants for electricity generation and in nuclear marine propulsion. Heat from nuclear fission is passed to a working fluid (water or gas), which in turn runs through steam turbines.

Read the given passage carefully and give the answer of the following questions:

Q 1. The splitting of a nucleus into smaller nuclei is:

a. fusion b. fission
c. half-life d. gamma radiation

Q 2. Name the moderator used in the nuclear reactor.

a. Plutonium b. Thorium
c. Graphite d. Beryllium

Q 3. Which isotope of uranium (U) has the capacity to sustain the chain reaction?

a. U-230 b. U-235 c. U-245 d. U-225

Q 4. What is the beneficial aspect of nuclear fission?

a. The ability to absorb energy
b. The ability to produce more energy than nuclear fusion
c. The ability to release tremendous amount of energy
d. There are no beneficial aspects of nuclear fission

Answers

1. (b) fission 2. (c) Graphite
3. (b) U-235
4. (c) The ability to release tremendous amount of energy.

Case Study 3

Neutrons and protons are identical particle in the sense that their masses are nearly the same and the force, called nuclear force, does into distinguish them. Nuclear force is the strongest force. Stability of nucleus is determined by the neutron-proton ratio or mass defect or packing fraction. Shape of nucleus is calculated by quadrupole moment and spin of nucleus depends on even or odd mass number. Volume of nucleus depends on the mass number. Whole mass of the atom (nearly 99%) is centered at the nucleus.

Read the given passage carefully and give the answer of the following questions:

Q 1. What is the range of nuclear force?

Q 2. A force between two protons is same as the force between proton and neutron. What is the nature of the force?

Q 3. Two protons are kept at a separation of 40 Å. If F_n is the nuclear force and F_e is the electrostatic force between them, then what is the relation between F_n and F_e?

Q 4. All the nucleons in an atom are held by which forces?

Answers

1. The nuclear force is of short range and the range of nuclear force is the order of 1.4×10^{-15} m.
2. The nature of the force is strong nuclear force.
3. Nuclear force is much stronger than the electrostatic force inside the nucleus *i.e.*, at distances of the order of fermi. At 40 Å, nuclear force is ineffective and only electrostatic force of repulsion is present. This is very high at this distance because nuclear force is not acting now and the gravitational force is very feeble. Thus, $F_{nuclear} << F_{electrostatic}$ in this case.
4. All the nucleons in an atom are held by nuclear forces.

Case Study 4

When subatomic particles undergo reactions, energy is conserved, but mass is not necessarily conserved. However, a particle's mass contributes to its total energy, in accordance with Einstein's famous equation, $E = mc^2$. In this equation, E denotes the energy carried by a particle because of its mass. The particle can also have additional energy due to its motion and its interactions with other particles. Consider a neutron at rest and well separated from other particles. It decays into a proton, an electron and an undetected third particle as given here:

$$\text{Neutron} \rightarrow \text{Proton} + \text{Electron} + ?$$

The given table summarizes some data from a single neutron decay, Electron volt is a unit of energy. Column 2 shows the rest mass of the particle times the speed of light squared.

Particle	Mass × c^2 (MeV)	Kinetic energy (MeV)
Neutron	940.97	0.00
Proton	939.67	0.01
Electron	0.51	0.39

Read the given passage carefully and give the answer of the following questions:

Q 1. From the given table, which properties of the undetected third particle can be calculate?

Q 2. Assuming the table contains no major errors, what can we conclude about the (mass × c^2) of the undetected third particle?

Q 3. Could this reaction occur?

$$\text{Proton} \rightarrow \text{Neutron} + \text{Other particles}$$

Q 4. How much mass has to be converted into energy to produced electric power of 500 MW for one hour?

Answers

1. As just shown, energy conservation allows us to calculate the third particle's total energy. But we do not know what percentage of that total energy is mass energy.
2. According to the given information, subatomic reactions do not conserve mass. So, we cannot find the third particle's mass by setting
$$m_{neutron} = m_{proton} + m_{electron} + m_{third\ particle}$$
The neutron has energy 940.97 MeV. The proton has energy 939.67 MeV + 0.01 MeV = 939.68 MeV. The electron has energy 0.51 MeV + 0.39 MeV = 0.90 MeV. Therefore, the third particle has energy
$$E_{third\ particle} = E_{neutron} - E_{proton} - E_{electron}$$
$$= 940.97 - 939.67 - 0.90 = 0.40 \text{ MeV}$$
We just found the third particle's total energy, the sum of its mass energy and kinetic energy. Without more information, we cannot figure out how much of that energy is mass energy.
3. Yes, but only if the proton has potential energy (due to interactions with other particles).
4. Given, $P = 500$ MW $= 5 \times 10^8$ W, $t = 1$ h $= 3600$ s
Energy produced,
$$E = P \times t = 5 \times 10^8 \times 3600 = 18 \times 10^{11} \text{ J}$$
As $\quad E = \Delta mc^2$
$$\therefore \quad \Delta m = \frac{E}{c^2} = \frac{18 \times 10^{11}}{(3 \times 10^8)^2} = \frac{18 \times 10^{11}}{9 \times 10^{16}} = 2 \times 10^{-5} \text{ kg}$$

Case Study 5

In the year 1939, German scientist Otto Hahn and Strassmann discovered that when an uranium isotope was bombarded with a neutron, it breaks into two intermediate mass fragments. It was observed that, the sum of the masses of new fragments formed were less than the mass of the original nuclei. This difference in the mass appeared as the energy released in the process. Thus, the phenomenon of splitting of a heavy nucleus (usually $A > 230$) into two or more lighter nuclei by the bombardment of proton, neutron, α-particle, etc. with liberation of energy is called nuclear fission.

$${}^{235}_{92}\text{U} + {}^{1}_{0}n \rightarrow \underset{\text{Unstable nucleus}}{{}^{236}_{92}\text{U}} \rightarrow {}^{144}_{56}\text{Ba} + {}^{89}_{36}\text{Kr} + 3\,{}^{1}_{0}n + Q$$

Read the given passage carefully and give the answer of the following questions:

Q 1. Nuclear fission can be explained on which basis?

Q 2. Which of the following is/are fission reaction(s)?

(i) ${}^{1}_{0}n + {}^{235}_{92}\text{U} \rightarrow {}^{236}_{92}\text{U} \rightarrow {}^{133}_{51}\text{Sb} + {}^{99}_{41}\text{Nb} + 4\,{}^{1}_{0}n$

(ii) ${}^{1}_{0}n + {}^{235}_{92}\text{U} \rightarrow {}^{140}_{54}\text{Xe} + {}^{94}_{38}\text{Sr} + 2\,{}^{1}_{0}n$

(iii) ${}^{2}_{1}\text{H} + {}^{2}_{1}\text{H} \rightarrow {}^{6}_{2}\text{He} + {}^{1}_{0}n$

Q 3. What is the energy of a neutron released per fission of a uranium atom?

Q 4. In any fission process, what is the ratio of mass of daughter nucleus to mass of parent nucleus?

Answers

1. Nuclear fission can be explained on the basis of liquid drop model.
2. Reactions I and II represent fission of uranium isotope ${}^{235}_{92}\text{U}$ when bombarded with neutrons that breaks it into two intermediate mass nuclear fragments. However, reaction III represents two deuterons fuses together to form the light isotope of helium.
3. The energy of the neutron released per fission of the uranium atom is 2 MeV.
4. In fission process, when a parent nucleus breaks into daughter products, then some mass is lost in the form of energy. Thus,
Mass of fission products < Mass of parent nucleus.
$$\Rightarrow \frac{\text{Mass of fission products}}{\text{Mass of parent nucleus}} < 1$$

Very Short Answer Type Questions

Q 1. Write the relation between mass number and radius of a nucleus.

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

where, R = radius of nucleus, A = mass number and R_0 is constant = 1.2 fm = 1.2×10^{-15} m.

Q 2. What is the nuclear radius of ^{125}Fe, if that of ^{27}Al is 3.6 fermi?

Sol. $R \propto A^{1/3} \Rightarrow \frac{R_1}{R_2} = \left(\frac{A_1}{A_2}\right)^{1/3} = \left(\frac{125}{27}\right)^{1/3} = \frac{5}{3}$

$\Rightarrow \quad R_1 = R_2 \times \frac{5}{3} = 3.6 \times \frac{5}{3} = 6$ fermi

Q 3. Compare the radii of two nuclei with mass numbers 1 and 27 respectively.

Sol. $R \propto A^{1/3} \Rightarrow \frac{R_1}{R_2} = \left(\frac{A_1}{A_2}\right)^{1/3} = \left(\frac{1}{27}\right)^{1/3} = \frac{1}{3}$

Q 4. The nuclear radius of $^{27}_{13}Al$ is 3.6 fermi. Find the nuclear radius of $^{64}_{29}Cu$. *(CBSE 2020)*

Sol. We know that, $R = R_0 A^{1/3}$

So, $\frac{R_{Cu}}{R_{Al}} = \frac{A_{Cu}^{1/3}}{A_{Al}^{1/3}} = \frac{(64)^{1/3}}{(27)^{1/3}} = \frac{4}{3}$

$R_{Cu} = \frac{4}{3} R_{Al}$

But $R_{Al} = 3.6$ fermi

So, $R_{Cu} = \frac{4}{3} \times 3.6 = 4.8$ fermi.

TiP

The size of nucleus will increase with the increase of mass number.

Q 5. Calculate the radius of the nucleus of an iron atom. Given, $A = 56$, $R_0 = 1.2 \times 10^{-15}$ m.

Sol. Radius, $R = R_0 A^{1/3}$, where A is mass number

$= (1.2 \times 10^{-15} \text{ m}) \times (56)^{1/3}$

$= (1.2 \times 10^{-15} \text{ m}) \times 3.826 \approx 4.6 \times 10^{-15} \text{ m} = 4.6$ F

Q 6. Obtain approximately the ratio of nuclear radii of the gold isotope $^{197}_{79}Au$ and the silver isotope $^{107}_{47}Ag$. What is the ratio of their nuclear densities?

Sol. Since, $R = R_0 A^{1/3}$, where R_0 is a constant and A is mass number.

$\therefore \quad \frac{R(Au^{197})}{R(Ag^{107})} = \left(\frac{197}{107}\right)^{1/3} = (1.841)^{1/3} = 1.225$

The nuclear density is independent of mass number. Hence, the density ratio is 1.

Q 7. Calculate the total mass in kg of fundamental particles present in ^7_3Li nucleus. Mass of proton is 1.6725×10^{-27} kg and mass of neutron is 1.6748×10^{-27} kg.

Sol. ^7_3Li nucleus has 3 protons and 4 neutrons.

Mass of 3 protons $= 3 \times 1.6725 \times 10^{-27}$
$= 5.0175 \times 10^{-27}$ kg

Mass of 4 neutrons $= 4 \times 1.6748 \times 10^{-27}$
$= 6.6992 \times 10^{-27}$ kg.

$\therefore$ Total mass $= (5.0175 + 6.6992) \times 10^{-27}$
$= 11.7167 \times 10^{-27}$ kg.

Q 8. Show that nuclear density in a given nucleus is independent of mass number A. *(CBSE 2016)*

Sol. Nuclear density, $\rho = \frac{M}{V} = \frac{A}{\frac{4}{3}\pi r^3} = \frac{A}{\frac{4}{3}\pi (R_0 A^{1/3})^3} = \frac{3}{4\pi R_0^3}$

Q 9. Two nuclei have mass numbers in the ratio 1 : 2. What is the ratio of their nuclear densities?

Ans. 1 : 1 as nuclear density does not depend on mass number.

Q 10. Define the term mass defect.

Ans. The difference between the rest mass of a nucleus and the sum of the rest masses of its constituent nucleon is called its mass defect. It is given by,

$\Delta M = [Zm_p + (A - Z)m_n] - M$

Q 11. What are nuclear forces?

Ans. Very short range, strong attractive forces, which firmly hold the nucleons together inside a nucleus, are called nuclear forces.

Q 12. State any two characteristic properties of nuclear forces. *(CBSE 2015, 17)*

Ans. Properties of Nuclear Forces:

(i) Very short range, strong attractive forces.
(ii) Does not depend on the charge of the nucleon.
(iii) Non-central forces.
(iv) Do not obey inverse square law.

Q 13. Calculate the energy in fusion reaction:
$^2_1H + ^2_1H \longrightarrow ^3_2He + n$, where BE of ^2_1H = 2.23 MeV and of ^3_2He = 7.73 MeV. *(CBSE 2016)*

Sol. According to the question,

$$^2_1H + ^2_1H \longrightarrow ^3_2He + {}_0n^1$$

Energy of fusion = Binding energy of ^3_2He
$- 2 \times$ Binding energy of ^2_1H
$= 7.73 - 2 \times 2.23 = 3.27$ MeV.

Q 14. Four nuclei of an element undergo fusion to form a heavier nucleus, with release of energy. Which of the two, the parent or the daughter nucleus, would have higher binding energy per nucleon? *(CBSE 2018)*

Ans. According to the question,

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

(Parent nuclei) (Daughter nuclei)

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.

Q 15. Fission of U-235 nucleus releases 200 MeV of energy. Calculate the fission rate (*i.e.,* number of fissions per second) in order to produce a power of 320 MW.

Sol. Power received from the reactor is

$P = 320 \text{ MW} = 320 \times 10^6 \text{ W} = 320 \times 10^6 \text{ Js}^{-1}$.

Energy released per fission = 200 MeV

$= 200 \times 10^6 \times 1.6 \times 10^{-19}$ J

$= 320 \times 10^{-13}$ J

Number of fission per second $= \dfrac{320 \times 10^6}{320 \times 10^{-13}} = 10^{-19} \text{s}^{-1}$

Short Answer Type-I Questions

Q 1. How much energy will be created if 1.0 g of matter is destroyed completely? How much kilowatt-hour energy will be obtained by it?

Sol. According to Einstein's energy-mass relation, the energy liberated is $\Delta E = (\Delta m)c^2$.

Here, mass loss $\Delta m = 1.0 \text{ g} = 1.0 \times 10^{-3}$ kg

and speed of light $c = 3.0 \times 10^8 \text{ ms}^{-1}$.

$\therefore \Delta E = (1.0 \times 10^{-3} \text{ kg}) \times (3.0 \times 10^8 \text{ ms}^{-1})^2$

$= 9.0 \times 10^{13}$ J (or Ws)

$= \dfrac{9.0 \times 10^{13} \text{ Ws}}{(60 \times 60) \text{ s/h}} = 2.5 \times 10^{10} \text{Wh} = 2.5 \times 10^7$ kWh.

Q 2. A neutron is absorbed by a $^6_3$Li nucleus with subsequent emission of an α-particle. Write the corresponding nuclear reaction and calculate the energy released in the reaction.

Given: $m(^4_2\text{He}) = 4.002603$ u, $m(^1_0 n) = 1.008665$ u, $m(^6_3\text{Li}) = 6.015126$ u, $m(^3_1\text{H}) = 3.016049$ u and $1 \text{ u} \times c^2 = 931.5$ MeV.

Sol. The nuclear reaction is

$^6_3\text{Li} + ^1_0 n \longrightarrow ^3_1\text{H} + ^4_2\text{He}$ (α-particle)

Mass of $^6_3\text{Li} + ^1_0 n$

$= 6.015126 \text{ u} + 1.008665 \text{ u} = 7.023791 \text{ u}$

Mass of $^1_3\text{H} + ^4_2\text{He} = 3.016049 + 4.002603$

$= 7.018652$ u

$\therefore$ Mass loss,

$\Delta m = 7.023791 - 7.018652 = 0.005139$ u

Its energy equivalent is

$\Delta E = (\Delta m) \times c^2 = (0.005139 \text{ u}) \times c^2$

Now, $1 \text{ u} \times c^2 = 931.5$ MeV

$\therefore \Delta E \approx 0.005139 \times 931.5 \approx 4.787$ MeV

TiP

Practice more questions to better understand this topic.

Q 3. Draw a graph showing the variation of binding energy per nucleon as a function of mass number *A*. The binding energy per nucleon for heavy nuclei ($A > 170$) decreases with the increase in mass number. Explain. *(CBSE 2023)*

Ans. Graph of Variations of Binding Energy per Nucleon:

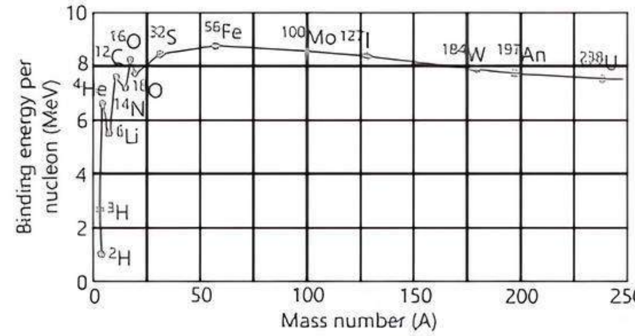


Figure shows binding energy per nucleon E_{bn} versus the mass number *A* for a large number of nuclei. We notice the following main features of the plot:

(i) The binding energy per nucleon, E_{bn} is practically constant, *i.e.,* practically independent of the atomic number for nuclei of middle mass number (130 < A < 170). The curve has a maximum of about 8.75 MeV for A = 56 and has a value of 7.6 MeV for A = 238.

(ii) E_{bn} is lower for both light nuclei ($A < 30$) and heavy nuclei ($A > 170$).

Thus, the decrease of the binding energy per nucleon for nuclei with high mass number is due to increased coulomb repulsion between protons inside the nucleus.

Q 4. Find the energy equivalent of one atomic mass unit, first in Joules and then in MeV. Using this, express the mass defect of $^{16}_8$O in MeV/c^2.

Sol. $1 \text{ u} = 1.6605 \times 10^{-27}$ kg

To convert it into energy units, we multiply it by c^2 and find that energy equivalent

$= 1.6605 \times 10^{-27} \times (2.9979 \times 10^8) \text{kg m}^2/\text{s}^2$

$\approx 1.4924 \times 10^{-10}$ J

$= \dfrac{1.4924 \times 10^{-10}}{1.602 \times 10^{-19}}$ eV

$= 0.9315 \times 10^9 \text{ eV} = 931.5$ MeV

or $1 \text{ u} \approx 931.5 \text{ MeV}/c^2$

For $^{16}_8$O, $\Delta M = 0.13691 \text{ u} = 0.13691 \times 931.5 \text{ MeV}/c^2$

$\approx 127.5 \text{ MeV}/c^2$

Thus, the energy needed to separate $^{16}_8$O into its constituents is 127.5 MeV/c^2.

Q 5. Complete the following nuclear reactions:

(i) $^{10}_5\text{B} + ^1_0 n \longrightarrow ^4_2\text{He} + \ldots\ldots$

(ii) $^{94}_{42}\text{Mo} + ^2_1\text{H} \longrightarrow ^{95}_{43}\text{Te} + \ldots\ldots$ *(CBSE 2015)*

Ans. (i) $^{10}_5\text{B} + ^1_0 n \longrightarrow ^4_2\text{He} + ^7_3\text{Li}$

$\because$ $10 + 1 = 4 + A$

$\Rightarrow$ $A = 11 - 4 = 7$

and $5 + 0 = 2 + Z$

$\Rightarrow$ $Z = 5 - 2 = 3$

$\therefore$ $A = 7, Z = 3$

(ii) $^{94}_{42}\text{Mo} + ^2_1\text{H} \longrightarrow ^{95}_{43}\text{Te} + ^1_0 n$

$\because$ $94 + 2 = 95 + A$

$\Rightarrow \qquad A = 96 - 95 = 1$

and $\qquad 42 + 1 = 43 + Z$

$Z = 43 - 43 = 0$

Q 6. Calculate for how many years the fusion of 2.0 kg deuterium will keep 800 W electric lamp glowing? Take the fusion reaction as

$$^{2}_{1}\text{H} + ^{2}_{1}\text{H} \rightarrow ^{3}_{2}\text{He} \rightarrow ^{1}_{0}n + 3.27 \text{ MeV}$$ *(CBSE 2020)*

Sol. The given fusion reaction is:

$$^{2}_{1}\text{H} + ^{2}_{1}\text{H} \rightarrow ^{3}_{2}\text{He} \rightarrow ^{1}_{0}n + 3.27 \text{ MeV}$$

Amount of deuterium, $m = 2$ kg

1 mole, *i.e.*, 2 g of deuterium contains 6.023×10^{23} atoms.

So, 2.0 kg of deuterium contains

$$= \frac{6.023 \times 10^{23}}{2} \times 2000 = 6.023 \times 10^{26} \text{ atoms}.$$

Two atoms of deuterium fuse to release 3.27 MeV energy.

So, total energy released $= \frac{3.27}{2} \times 6.023 \times 10^{26}$ MeV

$$= \frac{3.27}{2} \times 6.023 \times 10^{26} \times 10^{6} \times 1.6 \times 10^{-19} \text{ J}$$

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

Power of the electric lamp, $P = 800$ W $= 800$ J/s

Hence, the energy consumed by the lamp per second $= 800$ J

So, the third lamp will glow for

$$= \frac{15.75 \times 10^{13}}{800} \text{ s} = 0.0197 \times 10^{13} \text{ s}$$

$$= \frac{0.0197 \times 10^{13}}{60 \times 60 \times 24 \times 365} = 6246.8 \text{ years}$$

TiP

The calculation part in the numerical should be done carefully.

Short Answer Type-II Questions

Q 1. Calculate the binding energy of an alpha particle in MeV. Given:

Mass of a proton = 1.007825 u

Mass of a neutron = 1.008665 u

Mass of He nucleus = 4.002800 u

1u = 931 MeV/c^2. *(CBSE 2023)*

Sol. $\because \Delta m$ = Mass of α-particle – Mass of total number of proton and neutron

$$= 4.002800 - 2 \times (1.007825 + 1.008665)$$

$$= 4.002800 - 4.03298 = -0.0301 \text{ u}$$

$\therefore$ Binding energy $= \Delta mc^2$

$$= 0.0301 \times 931 \text{ MeV}$$

$$= 28.09 \text{ MeV}$$

Q 2. A given coin has a mass of 3.0 g. Calculate the nuclear energy that would be required to separate all the neutrons and protons from each other. For simplicity assume that the coin is entirely made of $^{63}_{29}$Cu atoms (of mass 62.92960 u). *(CBSE SQP 2023-24)*

Sol. Number of atoms in a 3 g coin

$$= \frac{6.023 \times 10^{23} \times 3}{63} = 2.868 \times 10^{22}$$

Each copper atom has 29 protons and 34 neutrons.

Thus, the mass defect of each atom is

$29 \times 1.00783 + 34 \times 1.00867 - 62.92960 = 0.59225$ u

Total mass defect of all atoms

$= 0.59225 \text{ u} \times 2.868 \times 10^{22} = 1.6985 \times 10^{22}$ u

Thus, the nuclear energy required

$= 1.6985 \times 10^{22} \times 931 \text{ MeV} = 1.58 \times 10^{25}$ MeV

Q 3. Draw the graph showing the variation of binding energy per nucleon with mass number. Write two inferences which can be drawn from this graph. *(CBSE SQP 2023-24)*

Ans. Graph of Variations of Binding Energy per Nucleon:

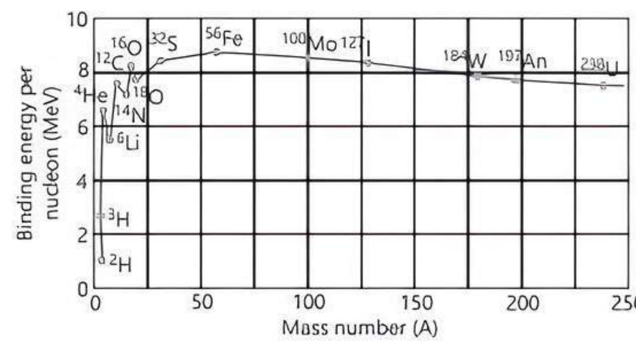


Figure shows binding energy per nucleon E_{bn} versus the mass number A for a large number of nuclei. We notice the following main features of the plot:

(i) The binding energy per nucleon, E_{bn} is practically constant, *i.e.*, practically independent of the atomic number for nuclei of middle mass number ($130 < A < 170$). The curve has a maximum of about 8.75 MeV for A = 56 and has a value of 7.6 MeV for A = 238.

(ii) E_{bn} is lower for both light nuclei ($A < 30$) and heavy nuclei ($A > 170$).

We can draw some inferences from these two observations:

(i) The force is attractive and sufficiently strong to produce a binding energy of a few MeV per nucleon.

(ii) The constancy of the binding energy in the range $30 < A < 170$ is a consequence of the fact that the nuclear force is short ranged.

Q 4. (i) Draw a graph showing the variation of potential energy of a pair of nucleons as a function of their separation.

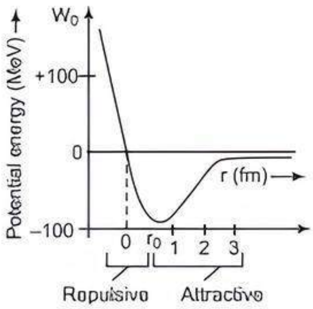
Mark the regions, where the nuclear force is (a) attractive and (b) repulsive.

(ii) In the nuclear reaction,

$$n + ^{235}_{92}\text{U} \longrightarrow ^{a}_{54}\text{Xe} + ^{94}_{b}\text{Sr} + 2n$$

Determine the value of a and b. *(CBSE 2018)*

Ans. (i) Graph of potential energy of a pair of nucleons as a function of their separation is given in the figure.



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

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

$\Rightarrow \quad a = 140$

and atomic number,

$0 + 92 = 54 + b + 2(0) \quad \Rightarrow \quad b = 38$

Q 5. (i) Prove that the nuclear density is same for all nuclei.

(ii) Draw a plot of potential energy of a pair of nucleons as a function of their separation. Draw two inferences from this plot. *(CBSE 2023)*

Ans. (i) As we know that, the density of nuclear matter is the ratio of of nucleus and its volume. *i.e.*,

$$\text{Density} = \frac{\text{Mass}}{\text{Volume}}$$

Let m be the average mass of a nucleon and R be the nuclear radius. Mass of the radius $= mA$

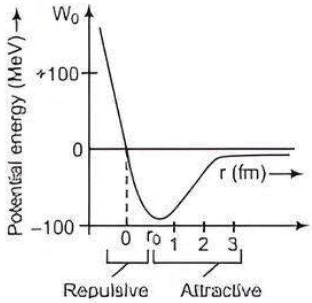
where, A = mass number of element.

$$\text{Volume of nucleus} = \frac{4}{3}\pi r^3 = \frac{4}{3}\pi\left(R_0 A^{1/3}\right)^3$$
$$= \frac{4}{3}\pi R_0^3 A$$

$$\therefore \text{Nuclear density } (\rho) = \frac{mA}{\frac{4}{3}\pi R_0^3 \cdot A} = \frac{m}{\frac{4}{3}\pi R_0^3}$$
$$= \frac{3m}{4\pi R_0^3}$$

As, m and R_0 are constants; density ρ of nuclear matter is the same for all elements.

(ii) Graph of potential energy of a pair of nucleons as a function of their separation is given in the figure.



Inferences from above plot:

(i) The nuclear forces between two nucleons falls rapidly to zero as their distance is more than a few femtometers.

(ii) For a separation greater than r_0, the force is attractive and separations less than r_0, force is repulsive.

Q 6. How long an electric lamp of 100 W can be kept glowing by fusion of 2.0 kg of deuterium? The fusion reaction can be taken as:

$$^2_1\text{H} + {}^2_1\text{H} \rightarrow {}^3_2\text{He} + n + 3.2 \text{ MeV}$$

(NCERT EXERCISE, CBSE SQP 2022 Term-2)

Sol. Number of deuterium atoms in 2.0 kg $= 6.02 \times 10^{26}$

$$\text{Number of reactions} = \frac{6.02 \times 10^{26}}{2} = 3.01 \times 10^{26}$$

Energy released in one reaction = 3.2 MeV

Total energy released,

$$E = 3.01 \times 10^{26} \times 3.2 \text{ MeV} = 9.632 \times 10^{26} \text{ MeV}$$
$$= 9.632 \times 10^{26} \times 1.6 \times 10^{-13} \text{ J}$$
$$= 15.4 \times 10^{13} \text{ J}$$

If t second is the required time during which the bulb glows, then

$E = Pt$ gives

$$t = \frac{E}{P} = \frac{15.4 \times 10^{13}}{100} = 15.4 \times 10^{11} \text{ s}$$
$$= \frac{15.4 \times 10^{11}}{3.15 \times 10^7} \text{ years} = 4.9 \times 10^4 \text{ years.}$$

COMMON ERR(!)R

Students often do silly mistakes in calculations.

Long Answer Type Questions

Q 1. (i) Explain the process of nuclear fission due to bombardment by neutrons or uranium nuclei.

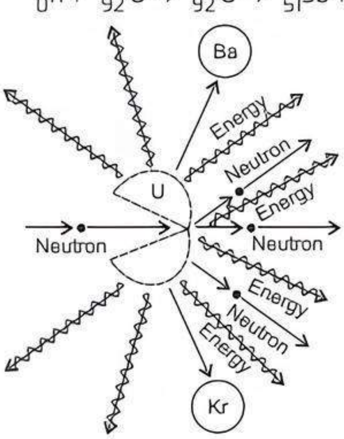
(ii) A nuclear reactor using U^{235} is to generate 10000 MW of electric power. The efficiency of conversion of thermal energy into electric energy in the reactor is 25%. How much amount of U^{235} will be consumed in the reactor per year? The thermal energy released per fission of U^{235} is 200 MeV. The Avogadro's number is 6.023×10^{23} mol^{-1}. (1 MeV $= 1.60 \times 10^{-13}$ J)

Ans. (i) **Nuclear Fission:** A most important neutron-induced nuclear reaction is nuclear fission. An example of nuclear fission is when a uranium isotope $^{235}_{92}\text{U}$ bombarded with a neutron breaks into two intermediate mass nuclear fragments.

$$^1_0n + {}^{235}_{92}\text{U} \rightarrow {}^{236}_{92}\text{U} \rightarrow {}^{144}_{56}\text{Ba} + {}^{89}_{36}\text{Kr} + 3\,{}^1_0n$$

The same reaction can produce other pairs of intermediate mass fragments.

$$^1_0n + {}^{235}_{92}\text{U} \rightarrow {}^{236}_{92}\text{U} \rightarrow {}^{133}_{51}\text{Sb} + {}^{99}_{41}\text{Nb} + 4\,{}^1_0n$$



Or as another example,

$${}^1_0n + {}^{235}_{92}U \rightarrow {}^{140}_{54}Xe + {}^{94}_{38}Sr + 2{}^1_0n$$

The fragment products are radioactive nuclei; they emit β particles in succession to achieve stable end products.

The energy released (the Q value) in the fission reaction of nuclei like uranium (U) is of the order of 200 MeV per fissioning nucleus. This is estimated as follows:

Let us take nucleus with $A = 240$ breaking into two fragments each of $A = 120$. Then

E_{bn} for $A = 240$ nucleus is about 7.6 MeV,

E_{bn} for the two $A \simeq 120$ fragment nuclei is about 8.5 MeV.

□ Gain in binding energy for nucleon is about 0.9 MeV.

Hence, the total gain in binding energy is 240×0.9 MeV or 216 MeV.

The disintegration energy in fission events first appears as the kinetic energy of the fragments and neutrons. Eventually, it is transferred to the surrounding matter appearing as heat. The source of energy in nuclear reactors, which produce electricity, is nuclear fission.

(ii) Power generated by the reactor

$= 10000 \text{ MW} = 10^{10} \text{ W (or J s}^{-1})$.

$\therefore$ Electrical energy generated in one year

$= (10^{10} \text{ J s}^{-1}) \times (365 \times 24 \times 60 \times 60)\text{s}$

$= 3.1536 \times 10^{17}$ J.

Thermal energy released per U^{235} fission is

$200 \text{ MeV} = 200 \text{ MeV} \times (1.60 \times 10^{-13} \text{ J/MeV})$

$\simeq 3.20 \times 10^{-11}$ J.

Since, the efficiency of reactor is 25%, the electrical energy obtained per U^{235} fission is

$$3.20 \times 10^{-11} \text{ J} \times \frac{25}{100} \simeq 8.0 \times 10^{-12} \text{ J}.$$

$\therefore$ Number of fissions of U^{235} occurring per year is $\frac{3.1536 \times 10^{17} \text{ J}}{8.0 \times 10^{-12} \text{ J}} = 3.942 \times 10^{28}$.

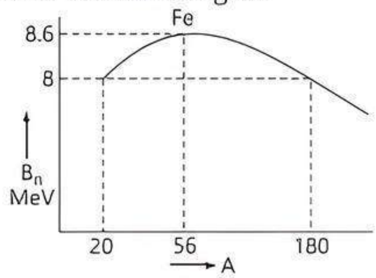
Since, 1 mole of U^{235} having a mass of 235 g, has 6.023×10^{23} atoms, the mass consumed per year is

$$\frac{235 \text{ g}}{6.023 \times 10^{23} \text{ atoms}} \times (3.942 \times 10^{28} \text{ atoms})$$

$$\simeq 1.538 \times 10^7 \text{ g} \simeq 1.538 \times 10^4 \text{ kg}$$

Q 2. Draw a plot of the binding energy per nucleon as a function of mass number for a large number of nuclei. Explain the energy release in the process of nuclear fission from the above plot. Write a typical nuclear reaction in which a large amount of energy is released in the process of nuclear fission.

Ans. The variation of binding energy per nucleon *versus* mass number is shown in figure.



The binding energy curve indicates that binding energy for nucleon of heavy nuclei is less than that of middle nuclei. Clearly a heavy nucleus breaks into two lighter nuclei then binding energy per nucleon will increase and energy will be released in the process. This process is called nuclear fission. Nuclear fission reaction is

$${}^{235}_{92}U + {}^1_0n \longrightarrow {}^{141}_{56}Ba + {}^{92}_{36}Kr + 3({}^1_0n) + 200 \text{ MeV}$$

(slow neutron)

Chapter Test

Multiple Choice Questions

Q 1. The equivalent energy of 1g of substance is:

a. 9×10^{13} J b. 6×10^{12} J c. 3×10^{13} J d. 6×10^{13} J

Q 2. The curve of binding energy per nucleon as a function of atomic mass number has a sharp peak for helium nucleus. This implies that helium nucleus is: *(CBSE 2023)*

a. radioactive b. unstable

c. easily fissionable

d. more stable nucleus than its neighbours

Assertion and Reason Type Questions

Directions (Q.Nos. 3-4): *In the following questions, statement of Assertion (A) is followed by a statement of Reason (R). Mark the correct choice as:*

a. Both Assertion (A) and Reason (R) are true and Reason (R) is the correct explanation of Assertion (A).

b. Both Assertion (A) and Reason (R) are true but Reason (R) is not the correct explanation of Assertion (A).

c. Assertion (A) is true but Reason (R) is false.

d. Both Assertion (A) and Reason (R) are false.

Q 3. Assertion (A): Density of all the nuclei is same.

Reason (R): Radius of nucleus is directly proportional to the cube root of the mass number.

Q 4. Assertion (A): Electrons do not experience strong nuclear force.

Reason (R): Strong nuclear force is charge independent.

Fill in the blanks

Q 5. Density of nuclear matter is the ratio of .... of nucleus and its volume.

Q 6. .... is the phenomenon of fusing two or more lighter nuclei forming a single heavy nucleus.

Case Study Based Question

Q 7. The density of nuclear matter is the ratio of the mass of a nucleus to its volume. As the volume of a nucleus is directly proportional to its mass number A, so the density of nuclear matter is independent of the size of the nucleus. Thus, the nuclear matter behaves like a liquid of constant density. Different nuclei are like drops of this liquid, of different sizes but of same density.

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

Volume of nucleus

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

$$\therefore \text{ Nuclear density, } \rho_{nu} = \frac{\text{Mass of nucleus}}{\text{Volume of nucleus}}$$

$$\text{or} \quad \rho_{nu} = \frac{mA}{\frac{4}{3}\pi R_0^3 A} = \frac{3m}{4\pi R_0^3}$$

Clearly, nuclear density is independent of mass number A or the size of the nucleus.

The nuclear mass density is of the order 10^{17} kg m^{-3}. This density is very large as compared to the density of ordinary matter, say water, for which $\rho = 1.0 \times 10^3$ kg m^{-3}.

Read the given passage carefully and give the answer of the following questions:

(i) The nuclear radius of $^{16}_{8}O$ is 3×10^{-15}m. The density of nuclear matter is:

a. 2.9×10^{34} kg m^{-3} b. 1.2×10^{17} kg m^{-3}
c. 1.6×10^{27} kg m^{-3} d. 2.4×10^{17} kg m^{-3}

(ii) What is the density of hydrogen nucleus in SI unit? Given, $R_0 = 1.1$ fermi and $m_p = 1.007825$ amu.

a. 2.98×10^{17} kg m^{-3} b. 3.0×10^{34} kg m^{-3}
c. 1.99×10^{11} kg m^{-3} d. 7.85×10^{17} kg m^{-3}

(iii) Density of a nucleus is:

a. more for lighter elements and less for heavier elements
b. more for heavier elements and less for lighter elements
c. very less compared to ordinary matter
d. a constant

(iv) If the nucleus of $^{27}_{13}Al$ has a nuclear radius of about 3.6 fm, then $^{125}_{52}Te$ would have its radius approximately as:

a. 9.6 fm b. 12 fm c. 4.8 fm d. 6 fm

Very Short Answer Type Questions

Q 8. Calculate the energy equivalent of 1 g of substance.

Q 9. Given the mass of iron nucleus as 55.85u and A = 56, find the nuclear density.

Short Answer Type-I Questions

Q 10. Define the term mass defect. How is it related to stability of the nucleus? *(CBSE 2023)*

Q 11. What is nuclear chain reaction? Explain with example.

Q 12. When four hydrogen nuclei combine to form a helium nucleus, estimate the amount of energy in MeV released in this process of fusion (neglect the masses of electrons and neutrons). Given

(i) mass of $^{1}_{1}H = 1.007825$ u

(ii) mass of helium nucleus = 4.002603 u and 1 u = 931 MeV/c^2.

Short Answer Type-II Questions

Q 13. Show that the density of nucleus over a wide range of nuclei is constant and independent of mass number.

Q 14. We are given the following atomic masses:

$^{238}_{92}U = 238.05079$ u

$^{4}_{2}He = 4.00260$ u

$^{234}_{90}Th = 234.04363$ u

$^{1}_{1}H = 1.00783$ u

$^{237}_{91}Pa = 237.05121$ u

Here the symbol Pa is for the element protactinium (Z = 91).

(i) Calculate the energy released during the alpha decay of $^{238}_{92}U$.

(ii) Show that $^{238}_{92}U$ cannot spontaneously emit a proton.

Q 15. (i) Distinguish between nuclear fission and fusion giving an example of each.

(ii) Explain the release of energy in nuclear fission and fusion on the basis of binding energy per nucleon curve. *(CBSE 2023)*

Long Answer Type Questions

Q 16. Draw a plot of the binding energy per nucleon as a function of mass number for a large number of nuclei. Explain the energy release in the process of nuclear fission from the above plot. Write a typical nuclear reaction in which a large amount of energy is released in the process of nuclear fission.

Q 17. (i) Explain giving necessary reactions, how energy is released during: (a) fission, (b) fusion.

(ii) If both the number of protons and neutrons are conserved in a nuclear reaction like

$$^{12}_{6}C + ^{12}_{6}C \longrightarrow ^{20}_{10}Ne + ^{4}_{2}He$$

In what way, is the mass converted into the energy? Explain.