

CHAPTER 13



WARM-UP: THINK LIKE A SCIENTIST

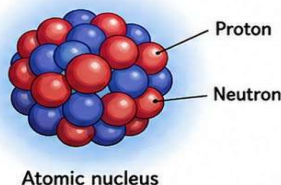
CHAPTER
Nuclei
CLASS 12 PHYSICS

Before You Begin...

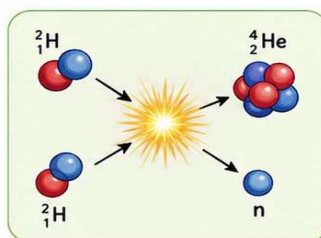
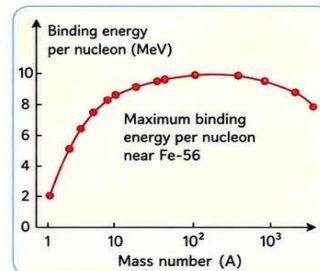


Observe & Predict

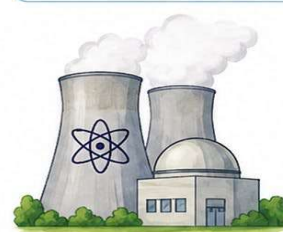
1. Why do nuclei remain stable despite the strong repulsion between protons?
2. What would happen if the strong nuclear force did not exist?
3. Why do lighter nuclei release more energy by fusion, while heavier nuclei release energy by fission?
4. Why are nuclear reactions used in power plants to produce electricity?
5. If radioactive decay did not exist, how would it affect the natural balance of elements on Earth?



Atomic nucleus



Nuclear fusion



Nuclear power plant



Write your ideas before studying the chapter.



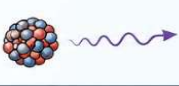
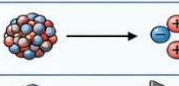
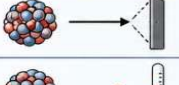
NUCLEI AROUND US



Real-Life Connections



CHAPTER 13
Nuclei
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Application / Device	How Nuclear Science Is Used
 Nuclear Power Plant (e.g., Tarapur, Kudankulam)	 Fission of heavy nuclei like ^{235}U releases large energy used to generate electricity.
 Medical Imaging (PET Scan) (e.g., Cancer diagnosis)	 Radioactive tracers (like ^{18}F) emit positrons which help in imaging internal organs.
 Cancer Treatment (Radiotherapy) (e.g., Cobalt-60 therapy)	 Radioactive isotopes emit gamma rays which destroy cancer cells.
 Smoke Detector (e.g., ^{241}Am)	 Alpha particles ionize air. Ionization current changes when smoke enters.
 Thickness Gauge (Industries)	 Beta particles pass through materials. Their absorption measures thickness.
 Radioisotope Thermoelectric Generator (RTG) (e.g., in space missions)	 Radioactive decay produces heat which is converted into electricity for spacecraft.



Did You Know? Nuclear science helps in producing energy, diagnosing diseases, treating cancer, exploring space and even keeping us safe!



Atoms may be tiny, but their impact is huge!

MULTIPLE CHOICE QUESTIONS

1. A nucleus splits into two nuclear parts having radii in the ratio 1:2. Their velocities are in the ratio
(a) 8:1 (b) 6:1 (c) 4:1 (d) 2:1
2. The radius of a spherical nucleus as measured by electron scattering is 3.6 fm. What is the mass number of the nucleus most likely to be? (Given $R_0 = 1.2$ fm)
(a) 27 (b) 48 (c) 56 (d) 120
3. If the binding energy per nucleon of ^2H and ^4He nuclei are 1.1 MeV and 7.0 MeV respectively, then the energy released in the reaction $^2\text{H} + ^2\text{H} \rightarrow ^4\text{He}$ is:
(a) 23.6 MeV (b) 28.0 MeV (c) 5.9 MeV (d) 25.2 MeV
4. The radius of a nucleus of mass number A is proportional to:
(a) A (b) A^2 (c) $A^{1/3}$ (d) $A^{1/2}$
5. Which of the following particles has the smallest de Broglie wavelength, if all move with the same kinetic energy?
(a) Electron (b) Proton (c) Alpha particle (d) Neutron
6. If the nuclear radius of ^{27}Al is 3.6 Fermi, the approximate nuclear radius of ^{64}Cu (in Fermi) is:
(a) 2.4 (b) 4.8 (c) 3.6 (d) 5.2
7. The nuclear density of all nuclei is approximately the same because:
(a) All nuclei have the same mass (b) Nuclear radius $\propto A^{1/3}$ and mass $\propto A$
(c) Nuclei are all spherical in shape (d) All nuclei have same number of protons
8. The mass number of an atom is 40 and its atomic number is 18. Which of the following is correct?
(a) 18 protons, 18 electrons, 18 neutrons (b) 18 protons, 18 electrons, 22 neutrons (c) 22 protons, 22 electrons, 18 neutrons (d) 40 protons, 40 electrons, 18 neutrons
9. The binding energy per nucleon is maximum for:
(a) ^2H (b) ^{56}Fe (c) ^{235}U (d) ^{208}Pb
10. The mass defect of a nucleus is Δm . The binding energy per nucleon (for mass number A) is:
(a) $\Delta m \cdot c^2/A$ (b) $\Delta m \cdot c^2$ (c) $A \cdot \Delta m \cdot c^2$ (d) $\Delta m/(A \cdot c^2)$
11. If the binding energy of deuteron is 2.23 MeV, the mass defect (in amu) of deuteron is approximately:
(a) 0.0024 u (b) 0.0024 kg (c) 0.024 u (d) 0.24 u



Observe and Think:

Why do you think nature prefers iron (^{56}Fe) to be the most stable nucleus? What advantages might this provide in stars and galaxies?

12. Which of the following is NOT a correct statement about binding energy per nucleon?
(a) It is maximum for Fe-56 (b) It is nearly 8 MeV for nuclei in the middle of the periodic table (c) It decreases with increasing mass number for very heavy nuclei
(d) It is always greater for heavier nuclei than lighter nuclei
13. In the graph of binding energy per nucleon versus mass number, two nuclei can release energy by:

- (a) Fusion only (b) Fission only
 (c) Either fission or fusion depending on their mass number
 (d) Neither fission nor fusion
14. In a nuclear reactor, the function of the moderator is to:
 (a) Absorb fast neutrons (b) Slow down fast neutrons to thermal energies
 (c) Increase the energy of neutrons (d) Reflect neutrons back into the core
15. The energy released in nuclear fusion reactions is due to:
 (a) Decrease in binding energy per nucleon
 (b) Increase in binding energy per nucleon of the product over reactants
 (c) Emission of gamma rays (d) Conversion of protons into neutrons
16. In the fission of ^{235}U by a slow neutron, one of the products is ^{140}Ba . What is the other heavy fragment?
 (a) ^{93}Kr (b) ^{94}Kr (c) ^{92}Kr (d) ^{95}Kr
17. Given below are two statements:
 Statement I: The number of protons in an atom equals its atomic number Z .
 Statement II: Isotopes of an element have same mass number but different atomic numbers.
 In the light of the above statements, choose the most appropriate answer:
 (a) Both Statement I and Statement II are correct
 (b) Both Statement I and Statement II are incorrect
 (c) Statement I is correct but Statement II is incorrect
 (d) Statement I is incorrect but Statement II is correct
18. Nucleus X^{235} splits into two nuclei having the mass numbers in the ratio 2:1. The ratio of the radii of those two nuclei is
 (a) 2:1 (b) 1:2 (c) $2^{1/3}:1$ (d) $1:2^{1/3}$
19. The energy equivalent of 1 amu (atomic mass unit) in MeV is:
 (a) 931 MeV (b) 1.6 MeV (c) 931 eV (d) 9.31 MeV



Creative Scientific Thinking

Imagine a world where fusion reactors become common in every city. How would transportation, pollution, and electricity generation change?

20. In the nuclear reaction $^2_1\text{H} + ^2_1\text{H} \rightarrow ^3_2\text{He} + \text{n}$, the energy released is (given: mass of $^2_1\text{H} = 2.01410$ u; mass of $^3_2\text{He} = 3.01609$ u; mass of $\text{n} = 1.00867$ u; $1 \text{ u} = 931.5 \text{ MeV}/c^2$):
 (a) 3.27 MeV (b) 4.03 MeV (c) 2.23 MeV (d) 17.6 MeV

ANSWERS

1. a, 2. a, 3. a, 4. c, 5. c, 6. b, 7. b, 8. b, 9. b, 10. a,
 11. a, 12. d, 13. c, 14. b, 15. b, 16. a, 17. c, 18. c, 19. a, 20. a

ASSERTION- REASON BASED QUESTIONS

For these Questions two statements are given one labelled Assertion (A) and other labelled Reason (R). Select the correct answer to these questions from the options as given below

- If both Assertion and Reason are true and Reason is correct explanation of Assertion.
- If both Assertion and Reason are true but Reason is not the correct explanation of Assertion.
- If Assertion is true but Reason is false.
- If both Assertion and Reason are false.

- Assertion (A): The binding energy per nucleon in very heavy nuclei is less than that in medium-mass nuclei.
Reason (R): Very heavy nuclei have a larger proportion of neutrons, which reduces nuclear stability.
- Assertion (A): Nuclear forces are charge independent.
Reason (R): The nuclear force between neutron-neutron, proton-proton, and proton-neutron pairs are approximately equal.
- Assertion (A): Nuclear fusion cannot occur at room temperature.
Reason (R): Nuclear fusion requires extremely high temperatures (of the order of 10^7 K) to overcome the Coulomb repulsion between nuclei.
- Assertion (A): Isotopes of an element have similar chemical properties.
Reason (R): Isotopes have the same number of electrons and hence the same electronic configuration.
- Assertion (A): The nucleus of an atom has greater density than its outer electronic shells.
Reason (R): Almost the entire mass of an atom is concentrated in its tiny nucleus, whereas electrons have negligible mass.
- Assertion (A): The mass of a nucleus is less than the sum of the masses of its constituent protons and neutrons.
Reason (R): The mass defect is converted into binding energy, which holds the nucleus together.
- Assertion (A): The binding energy per nucleon is a measure of the instability of a nucleus.
Reason (R): A higher binding energy per nucleon means the nucleons are not tightly bound and the nucleus is more stable.



Physics in Real Life

How does nuclear energy help submarines remain underwater for long durations?

- Assertion (A): Heavy nuclei tend to be unstable and undergo radioactive decay.
Reason (R): In heavy nuclei, the repulsive electrostatic forces between protons are sufficiently balanced by the attractive nuclear forces
- Assertion (A): Nuclear fission is accompanied by the release of a large amount of energy.
Reason (R): The binding energy per nucleon of the fission fragments is greater than that of the original nucleus.
- Assertion(A): Distance of closest approach of α -particle to the nucleus is always greater than the size of the nucleus.
Reason(R): Strong nuclear repulsion does not allow α -particle to reach the surface of nucleus

ANSWERS

1. a, 2. a, 3. a, 4. a, 5. a, 6. a, 7. d, 8. c, 9. a, 10. a

SHORT ANSWER QUESTIONS (2 & 3 MARK)

1. Define atomic mass unit (amu). What is its value in kg and MeV?
2. What are isotopes and isobars? Give one example of each.
3. State two properties of nuclear forces that distinguish them from gravitational and electromagnetic forces.
4. Show that the density of nuclear matter is independent of mass number A. (Given: nuclear radius $R = R_0 A^{1/3}$ where $R_0 = 1.2 \times 10^{-15} \text{ m}$)
5. Why do heavy nuclei have more neutrons than protons? Explain briefly.
6. Define binding energy of a nucleus. Write the expression for binding energy in terms of mass defect.
7. What is mass defect of a nucleus? How is it related to binding energy?
8. Draw a rough sketch of the graph showing the variation of binding energy per nucleon with mass number. Mark the position of ^{56}Fe on the graph.
9. Why is it not possible to use ^{238}U as a nuclear fuel for fission reactors (unlike ^{235}U)?
10. Find the binding energy of ^4He nucleus. Given: mass of $^4\text{He} = 4.002602 \text{ u}$, mass of proton = 1.007825 u , mass of neutron = 1.008665 u , $1 \text{ u} = 931.5 \text{ MeV}/c^2$.
11. Calculate the energy released per fission of ^{235}U given that the average binding energy per nucleon of U-235 is 7.6 MeV and that of fission products is 8.5 MeV . Mass number of fission fragments ≈ 235 .
12. Explain with the help of a suitable graph, how the binding energy per nucleon varies with mass number. Using this graph, explain the source of energy in nuclear fission and nuclear fusion.
13. Explain the working principle of a nuclear reactor. Name the main components and state the function of each.
14. What are nuclear forces? State four important properties of nuclear forces that distinguish them from other fundamental forces.
15. Calculate the binding energy of the nucleus of $^{56}_{26}\text{Fe}$. Comment on why iron has the most stable nucleus. (Given: $M(^{56}\text{Fe}) = 55.9349 \text{ u}$; $m_p = 1.00728 \text{ u}$; $m_n = 1.00867 \text{ u}$; $1 \text{ u} = 931.5 \text{ MeV}$)



Amazing Facts About Nuclei

One gram of nuclear fuel can produce energy equal to tons of coal.

16. In the nuclear reaction: $^{235}_{92}\text{U} + ^1_0\text{n} \rightarrow ^{139}_{56}\text{Ba} + ^{94}_{36}\text{Kr} + x(^1_0\text{n})$, find x. Also calculate the energy released per fission, given: $m(^{235}\text{U}) = 235.0439 \text{ u}$; $m(^{139}\text{Ba}) = 138.9088 \text{ u}$; $m(^{94}\text{Kr}) = 93.9341 \text{ u}$; $m(\text{n}) = 1.00867 \text{ u}$; $1 \text{ u} = 931.5 \text{ MeV}$.
17. (i) How is the size of a nucleus found experimentally? Write the relation between the radius and mass number of a nucleus.
(ii) Prove that the density of a nucleus independent of its mass number.
18. Draw the graph showing the variation of binding energy per nucleon with mass number. What inference you get from this graph. Also explain the importance of binding energy curve.
19. A nucleus with mass number, $A = 240$ and $\text{BE}/A = 7.6 \text{ MeV}$ breaks into two fragments each of $A = 120$ with $\text{BE}/A = 8.5 \text{ MeV}$. Calculate the released energy.

20. Draw a plot of potential energy of a pair of nucleons as a function of their separations. Mark the regions where the nuclear force is (i) attractive and (ii) repulsive. Write any two characteristic features of nuclear forces.

ANSWERS

1. Atomic mass unit (amu) is defined as 1/12th of the mass of a carbon-12 atom. $1 \text{ amu} = 1.66 \times 10^{-27} \text{ kg} = 931.5 \text{ MeV}/c^2$.
2. Isotopes are atoms with same atomic number but different mass numbers (e.g., ^1H and ^2H). Isobars are atoms with same mass number but different atomic numbers (e.g., ^{14}C and ^{14}N).
3. Nuclear forces are very strong but short-ranged, and they are independent of electric charge.
4. Density $\rho = \text{Mass}/\text{Volume} \propto A/R^3$. Since $R = R_0 A^{1/3}$, therefore $R^3 \propto A$. Hence ρ becomes independent of mass number A .
5. Heavy nuclei contain more neutrons to reduce electrostatic repulsion between protons and increase nuclear stability.
6. Binding energy is the energy required to separate a nucleus into its nucleons. $BE = (\Delta m)c^2$.
7. Mass defect is the difference between the sum of masses of nucleons and the actual nuclear mass. Binding energy is given by $BE = (\Delta m)c^2$.
8. Binding energy per nucleon increases rapidly, reaches maximum near ^{56}Fe , and then decreases slowly for heavier nuclei.
9. ^{238}U is not fissile with slow neutrons, whereas ^{235}U readily undergoes fission chain reaction.
10. Mass defect $\Delta m = [2(1.007825) + 2(1.008665) - 4.002602] = 0.030378 \text{ u}$. Binding energy = $0.030378 \times 931.5 \approx 28.3 \text{ MeV}$.
11. Energy released = $(8.5 - 7.6) \times 235 = 211.5 \text{ MeV}$.
12. Binding energy per nucleon rises up to ^{56}Fe and then decreases slowly. Energy in fission and fusion is released because products have greater binding energy per nucleon.
13. A nuclear reactor works on controlled nuclear fission. Fuel produces fission, moderator slows neutrons, control rods control reaction, coolant removes heat, and shielding protects from radiation.
14. Nuclear forces act between nucleons. They are very strong, short-ranged, charge independent, and show saturation property.



Challenge Your Brain

Why do scientists continue researching fusion reactors despite the enormous technological difficulties?

15. Mass defect $\Delta m = [26(1.00728) + 30(1.00867) - 55.9349] = 0.52808 \text{ u}$. Binding energy = $0.52808 \times 931.5 \approx 492 \text{ MeV}$. Iron is most stable due to maximum binding energy per nucleon.
16. By conservation of mass number, $x = 3$. Mass defect $\Delta m = 0.18366 \text{ u}$. Energy released = $0.18366 \times 931.5 \approx 171 \text{ MeV}$.
17. (i) The size of a nucleus is determined experimentally by alpha-particle scattering experiments. The relation between nuclear radius and mass number is:
 $R = R_0 A^{1/3}$ where $R_0 = 1.2 \times 10^{-15} \text{ m}$. (ii) Volume of nucleus: $V = (4/3)\pi R^3$ Since, $R = R_0 A^{1/3}$,
Therefore, $V \propto A$ Mass of nucleus: $M \propto A$, Hence density, $\rho = M/V \propto A/A = \text{constant}$, Thus nuclear density is independent of mass number.

18. The binding energy per nucleon rises rapidly for light nuclei, reaches maximum near ^{56}Fe , and then decreases slowly for heavy nuclei.

Inferences: • ^{56}Fe is the most stable nucleus. Light nuclei release energy by fusion.

• Heavy nuclei release energy by fission.

Importance:

• Explains nuclear stability. Explains energy production in stars. Explains nuclear fission and fusion.

19. Initial total binding energy: $\text{BE}_i = 240 \times 7.6 = 1824 \text{ MeV}$

Final total binding energy: $\text{BE}_f = 240 \times 8.5 = 2040 \text{ MeV}$

Energy released: $E = \text{BE}_f - \text{BE}_i$, $E = 2040 - 1824$, $E = 216 \text{ MeV}$

20. The potential energy curve shows:

• Attractive force at intermediate separations. • Repulsive force at very small separations. Regions:
• Attractive region: $0.8 \text{ fm} < r < 2 \text{ fm}$ • Repulsive region: $r < 0.8 \text{ fm}$

Two characteristics of nuclear forces:

1. Nuclear forces are very strong but short-ranged.
2. Nuclear forces are charge independent.



Build Your Own Analogy

Research and prepare a short report on India's major nuclear power plants.

LONG ANSWER QUESTIONS

1. (a) Explain mass defect and binding energy. Derive the relation: $\text{B.E.} = \Delta m \times c^2$. (b) Draw and explain the B.E. per nucleon vs mass number graph. Identify the peak. (c) Using this graph, explain how energy is released in (i) nuclear fission and (ii) nuclear fusion. (d) Calculate the mass defect of ^4He if its atomic mass is 4.002602 u .
2. (a) Explain nuclear fission. Write the reaction for fission of ^{235}U and calculate the energy released per fission. (b) Explain the working of a nuclear reactor with a labelled diagram. State the function of the moderator, control rods, coolant, and reflector. (c) Why is a chain reaction possible in ^{235}U but not in natural uranium (predominantly ^{238}U)?
3. (a) What is nuclear fusion? State the conditions necessary for fusion to occur. Write the fusion reaction occurring in the sun. (b) Calculate the energy released in the following fusion reaction: $^2_1\text{H} + ^3_1\text{H} \rightarrow ^4_2\text{He} + \text{n}$ ($m(^2\text{H}) = 2.01410 \text{ u}$, $m(^3\text{H}) = 3.01604 \text{ u}$, $m(^4\text{He}) = 4.00260 \text{ u}$, $m(\text{n}) = 1.00867 \text{ u}$) (c) Compare nuclear fission and fusion on the basis of: (i) fuel required (ii) energy released per nucleon (iii) radioactive waste.
4. (a) What are nuclear forces? List four of their important properties. (b) Show that the nuclear density is almost constant for all nuclei. (c) Why do lighter nuclei tend to undergo fusion while heavier nuclei tend to undergo fission? Explain using the B.E./nucleon curve. (d) The nuclear radii of ^1_1H and $^{208}_{82}\text{Pb}$ are R_1 and R_2 respectively. Calculate the ratio R_2/R_1 . ($M_h = 1$, $M_{\text{Pb}} = 208$)
5. (i) What characteristic property of nuclear force explains the constancy of binding energy per nucleon (BE/A) in the range of mass number 'A' lying $30 < A < 170$? (ii) Show that the density of nucleus over a wide range of nuclei is constant- independent of mass number.

ANSWERS

1. (a) Mass defect (Δm) is the difference between the sum of masses of individual nucleons and the actual mass of the nucleus.

$$\Delta m = [Zm_p + (A-Z)m_n] - M$$
 Binding energy (B.E.) is the energy required to separate a nucleus completely into its nucleons.
 According to Einstein's mass-energy relation: $E = mc^2$
 Therefore: $B.E. = \Delta m \times c^2$.
 (b) The binding energy per nucleon increases rapidly for light nuclei, reaches a maximum near iron (^{56}Fe), and then decreases slowly for heavy nuclei. The peak occurs near ^{56}Fe with maximum B.E./nucleon ≈ 8.8 MeV, indicating maximum nuclear stability.
 (c) In nuclear fission, heavy nuclei split into medium-mass nuclei having higher binding energy per nucleon, releasing energy. In nuclear fusion, light nuclei combine to form heavier nuclei with greater binding energy per nucleon, releasing enormous energy.
 (d) $\Delta m = [2(1.007825) + 2(1.008665)] - 4.002602$
 $\Delta m = 4.03298 - 4.002602 \quad \Delta m = 0.030378 \text{ u}$
2. (a) Nuclear fission is the process in which a heavy nucleus splits into two lighter nuclei with release of energy and neutrons.
 Reaction: $^{235}_{92}\text{U} + ^1_0\text{n} \rightarrow ^{141}_{56}\text{Ba} + ^{92}_{36}\text{Kr} + 3^1_0\text{n} + \text{Energy}$
 Average energy released per fission ≈ 200 MeV.
 (b) A nuclear reactor works on controlled nuclear fission.
 Components and functions:
 - Fuel (^{235}U): Undergoes fission
 - Moderator: Slows down neutrons
 - Control rods: Absorb excess neutrons
 - Coolant: Removes heat
 - Reflector: Prevents neutron leakage
 - Shielding: Protects from radiation
 Heat produced converts water into steam, which rotates turbines to generate electricity.
 (c) ^{235}U is fissile and undergoes fission with slow neutrons, whereas ^{238}U does not undergo fission with slow neutrons. Hence sustained chain reaction is possible only in ^{235}U .
3. (a) Nuclear fusion is the process in which two light nuclei combine to form a heavier nucleus with release of energy.
 Conditions required:
 - Very high temperature ($\sim 10^7$ K), High pressure, High density, Fusion reaction in the Sun: $4^1_1\text{H} \rightarrow ^4_2\text{He} + \text{Energy}$
 (b) Reaction:
 $^2_1\text{H} + ^3_1\text{H} \rightarrow ^4_2\text{He} + ^1_0\text{n}$
 Initial mass = $2.01410 + 3.01604 = 5.03014 \text{ u}$
 Final mass = $4.00260 + 1.00867 = 5.01127 \text{ u}$
 $\Delta m = 5.03014 - 5.01127, \Delta m = 0.01887 \text{ u}$
 Energy released: $E = 0.01887 \times 931.5, E \approx 17.6 \text{ MeV}$
 (c) Fusion:
 - Fuel: Heavy nuclei
 - Energy per nucleon: Lower
 - Radioactive waste: More
 Fusion:
 - Fuel: Light nuclei
 - Energy per nucleon: Higher
 - Radioactive waste: Very less

4. (a) Nuclear forces are forces acting between nucleons inside the nucleus.
Properties:
1. Very strong 2. Short-ranged 3. Charge independent 4. Show saturation property
(b) Nuclear radius: $R = R_0 A^{1/3}$
Volume: $V \propto R^3 \propto A$, Mass: $M \propto A$, Density: $\rho = M/V \propto A/A$
Therefore, nuclear density is almost constant for all nuclei.
(c) Light nuclei have lower binding energy per nucleon, so fusion increases stability and releases energy.
Heavy nuclei also have lower binding energy per nucleon compared to iron, so fission produces more stable nuclei and releases energy.
(d) Using: $R = R_0 A^{1/3}$, $R_2/R_1 = (208/1)^{1/3}$, $R_2/R_1 \approx 5.94$, Therefore: $R_2/R_1 \approx 6$
5. (i) The saturation property of nuclear forces explains the constancy of binding energy per nucleon (BE/A) for $30 < A < 170$, because each nucleon interacts only with its nearest neighbours.
(ii) Nuclear radius $R = R_0 A^{1/3}$. Hence volume $V \propto R^3 \propto A$, while nuclear mass $M \propto A$. Therefore, $\rho = M/V \propto A/A = \text{constant}$, showing nuclear density is independent of mass number.

CASE STUDY-BASED QUESTIONS

1. Binding Energy and Nuclear Stability

The binding energy of a nucleus is the energy required to completely separate its nucleons. It equals $\Delta m \times c^2$, where Δm is the mass defect. The binding energy per nucleon (BEN) curve peaks near ^{56}Fe (~ 8.8 MeV/nucleon). For lighter nuclei ($A < 56$), the BEN increases — energy can be released by nuclear fusion. For heavier nuclei ($A > 56$), the BEN decreases — energy can be released by nuclear fission. This explains why both fusion (light nuclei) and fission (heavy nuclei) are exothermic reactions, forming products with greater BEN.

(i). The binding energy per nucleon is approximately 7.6 MeV for ^{235}U . If the average BEN of fission products is 8.5 MeV, the approximate energy released per fission event (for 235 nucleons) is:

- (a) 20 MeV (b) 211.5 MeV (c) 100 MeV (d) 1 GeV

(ii). Which of the following nuclei has the highest binding energy per nucleon?

- (a) ^2_1H (b) ^4_2He (c) $^{56}_{26}\text{Fe}$ (d) $^{235}_{92}\text{U}$

(iii). The mass defect of ^4_2He is 0.0304 u. Its binding energy is approximately:

- (a) 28.3 MeV (b) 7.1 MeV (c) 56.5 MeV (d) 14.2 MeV

(iv). For which of the following processes is the binding energy per nucleon of the product greater than that of the reactants?

- (a) Fission of ^{235}U only (b) Fusion of hydrogen nuclei only
(c) Both (a) and (b) (d) Neither (a) nor (b)

2. Nuclear Fission and Chain Reaction

When ^{235}U absorbs a slow (thermal) neutron, it splits into two medium-mass fragments along with 2–3 fast neutrons and energy (~ 200 MeV). These secondary neutrons can cause further fissions — a chain reaction. For a self-sustaining chain reaction, the multiplication factor k must equal 1 (critical state). In a nuclear reactor, control rods (e.g., cadmium) absorb excess neutrons to maintain $k = 1$.

A moderator (e.g., heavy water or graphite) slows fast neutrons to thermal energies, increasing the probability of fission. The coolant removes heat to generate steam for electricity.

(i). The minimum mass of fissile material required for a self-sustaining chain reaction is called:

- (a) Critical temperature (b) Critical mass (c) Threshold mass (d) Activation mass

(ii). The material used in control rods of a nuclear reactor is:

- (a) Uranium (b) Graphite (c) Heavy water (d) Cadmium

(iii). For a sub-critical nuclear reactor, the neutron multiplication factor k is:

- (a) $k = 1$ (b) $k > 1$ (c) $k < 1$ (d) $k = 0$

(iv). The energy released per fission of ^{235}U (~200 MeV) is primarily in the form of:

- (a) Kinetic energy of neutrons only (b) Gamma rays only
(c) Kinetic energy of fission fragments, neutrons, and gamma rays
(d) Heat energy of the moderator

ANSWERS

(i).b (ii). c (iii).a (iv). c

(i).b (ii). d (iii). c (iv). c

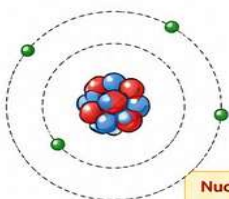


Nuclei



1 NUCLEUS & NUCLEONS

- The nucleus is the small, dense central region of an atom containing protons and neutrons.
- More than 99.9% mass of the atom is concentrated in the nucleus.



Nucleons:
Protons and neutrons are collectively called nucleons.

2 ATOMIC MASS UNIT (amu)

The unit of mass used to express mass of an atom is called atomic mass unit. Atomic mass unit is defined as $1/12^{\text{th}}$ of the mass of carbon ($^{12}_6\text{C}$) atom.



- 1 amu or 1 u = 1.660539×10^{-27} kg
- Mass of proton (m_p) = 1.00727 u
- Mass of neutron (m_n) = 1.00866 u
- Mass of electron (m_e) = 0.000549 u

Relation between amu and MeV
1 amu = 931 MeV

3 COMPOSITION OF NUCLEUS

Atomic Number (Z)

Number of protons present in the nucleus of an atom.

**Z = Number of protons
= Number of electrons
(in a neutral atom)**

Mass Number (A)

Total number of protons and neutrons in the nucleus.

**A = Number of protons (Z)
+ Number of neutrons (N)
= Number of electrons
+ Number of neutrons**

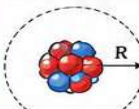
$$A = Z + N$$

4 SIZE & DENSITY OF NUCLEUS

Size of Nucleus

Nuclear sizes of different elements are assumed to be spherical.

Volume $\propto$ Mass number (A)



$$R \propto A^{1/3}$$

$$R = R_0 A^{1/3}$$

Where, $R_0 = 1.2 \times 10^{-15}$ m is the nuclear radius.

Nuclear Density

Density of nuclear matter,

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

$$\Rightarrow \rho = 2.38 \times 10^{17} \text{ kg/m}^3$$

Where, m = average mass of one nucleon and $R_0 = 1.2 \text{ fm} = 1.2 \times 10^{-15} \text{ m}$

$\Rightarrow$ Nuclear density (ρ) does not depend on A (mass number).

5 MASS DEFECT

The sum of the masses of neutrons and protons forming a nucleus is more than the actual mass of the nucleus. This difference of masses is known as mass defect.

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

Where,

Z = atomic number
A = mass number
 m_p = mass of one proton
 m_n = mass of one neutron
M = mass of nucleus



6 MASS-ENERGY RELATION

Einstein's mass-energy equivalence equation is given by

$$E = mc^2$$

Where,

E = energy
m = mass of nucleus
c = speed of light = 3×10^8 m/s



Mass can be converted into energy and energy into mass.

7 NUCLEAR FORCES

- Short ranged (2–3 fm) strong attractive forces which hold protons and neutrons together in against of Columbian repulsive forces between positively charged particles.
- The nuclear force between neutron–neutron, proton–neutron and proton–proton is approximately the same.
- The nuclear force does not depend on the electric charge.



Range $\approx 2 - 3 \text{ fm}$

8 NUCLEAR ENERGY

When nucleons form a nucleus, the mass of nucleus is slightly less than the sum of individual masses of nucleons. This mass is stored as nuclear energy in the form of mass defect.

Also, transmutation of less stable nuclei into more tightly bound nuclei provides an excellent possibility of releasing nuclear energy.

Two distinct ways of obtaining energy from nucleus are:

- Nuclear Fission
- Nuclear Fusion



9 NUCLEAR FISSION AND NUCLEAR FUSION

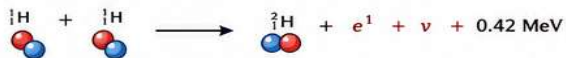
Nuclear Fission

The phenomenon of splitting of heavy nuclei (usually $A > 230$) into lighter nuclei of nearly equal masses is known as nuclear fission.



Nuclear Fusion

The phenomenon of fusing or combining of two lighter nuclei into a single heavy nucleus is called nuclear fusion.



[The energy released during nuclear fusion is known as thermonuclear energy.]

10 BINDING ENERGY

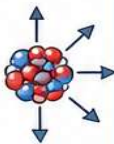
Binding energy of a nucleus is the minimum energy required to separate its nucleons and place them at rest at infinite distance apart.

Using Einstein's mass-energy relation,

$$\Delta E = (\Delta mc^2)$$

Hence, binding energy of the nucleus is

$$\Delta E = [Zm_p + (A - Z)m_n - M] c^2$$



11 AVERAGE BINDING ENERGY PER NUCLEON

It is the average energy required to extract a nucleon from the nucleus to infinite distance.

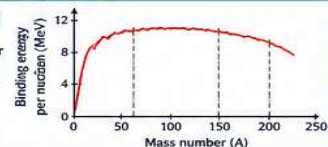
$$\text{Average binding energy per nucleon} = \frac{\text{Total binding energy}}{\text{Mass number (A)}}$$



12 BINDING ENERGY CURVE AND NUCLEAR STABILITY

Binding Energy Curve

Plot of the binding energy per nucleon versus the mass number A for a large number of nuclei.



Nuclear Stability

The stability of a nucleus is determined by the value of its binding energy per nucleon. 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.



KEY CONSTANTS



Nuclear radius constant : $R_0 = 1.2 \times 10^{-15} \text{ m}$ (1.2 fm)



Speed of light : $c = 3 \times 10^8 \text{ m/s}$



1 amu = 931 MeV