Part–1: Introduction to the Nucleus, Nuclear Composition, Size and Nuclear Force

1.1 Learning Objectives

After studying Part–1, students should be able to:

1. Understand the structure of an atomic nucleus.
2. Define atomic number and mass number.
3. Write nuclear notation correctly.
4. Distinguish between isotopes, isobars and isotones.
5. Understand nuclear radius and its dependence on mass number.
6. Explain why nuclear density is nearly constant.
7. Understand the basic nature of nuclear force.
8. Compare nuclear force with electrostatic force.
9. Solve basic numerical problems involving nuclear size and composition.

1.2 What is a Nucleus?

The **nucleus** is the extremely small, dense central region of an atom.

It contains:

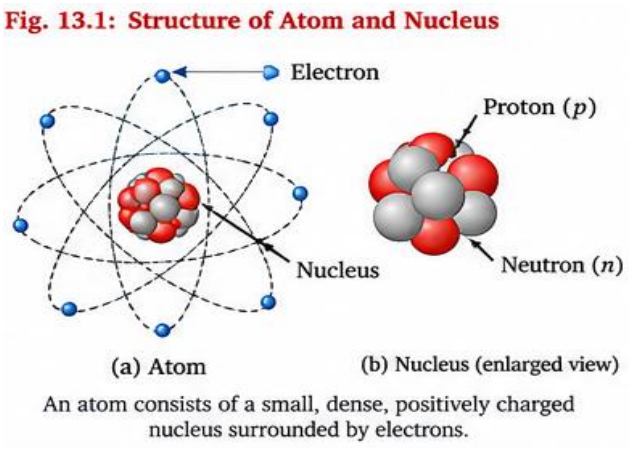
- **Protons** → positively charged
- **Neutrons** → electrically neutral

Protons and neutrons together are called **nucleons**.

Therefore,

Nucleons = Protons + Neutrons

The electrons are present outside the nucleus.



Basic structure

Atom = Nucleus + Electrons

Nucleus = Protons + Neutrons

Important observation:

The nuclear radius is extremely small compared with the atomic radius.

1.3 Atomic Number (Z)

The number of protons present in the nucleus of an atom is called its **atomic number**.

It is represented by: **Z = Number of protons**

For a neutral atom: **Number of electrons = Number of protons = Z**

Therefore,

$$\mathbf{Z = N_p = N_e}$$

Where:

- N_p = number of protons
- N_e = number of electrons

Example

For hydrogen: Z = 1

Therefore, hydrogen has:

- 1 proton

- 1 electron in the neutral atom

For carbon: Z = 6
Therefore, carbon has:

- 6 protons
- 6 electrons in a neutral carbon atom.

1.4 Mass Number (A)

The total number of nucleons present in the nucleus is called the **mass number**.
It is represented by A.
Therefore, **A = Number of protons + Number of neutrons**
If the number of neutrons is N: **A = Z + N**
Therefore, **N = A − Z**
This is one of the most important relations in the chapter.

1.5 Nuclear Notation

A nucleus is represented as: ${}^{A}_{Z}X$
Where:

- X = chemical symbol of element
- Z = atomic number
- A = mass number

Example 1: Carbon-12 ($^{12}_{6}$C)
Therefore: Z = 6; A = 12
N = A – Z Or N = 12 – 6 Or **N = 6**
Thus carbon-12 contains:

- 6 protons
- 6 neutrons
- 6 electrons in the neutral atom

Example 2: Sodium-23 $^{23}_{11}$Na
Therefore: Z = 11; A = 23, N = 23 – 11 Or **N = 12**
So the nucleus contains:

- 11 protons
- 12 neutrons

1.6 Important Point: Mass number is different from atomic mass

Students often confuse **mass number A** with **atomic mass**.
They are not exactly the same.
Mass Number
It is an integer: **A = Z + N**
It simply counts the number of nucleons.
Atomic Mass
Mass number is an integer representing the total number of nucleons, whereas atomic mass is the actual mass of a neutral atom expressed in atomic mass units (u).

1.7 Isotopes

Atoms having the **same atomic number Z** but **different mass numbers A** are called **isotopes**.

Therefore:
Same Z → Different A
Since: **N = A – Z;** different isotopes have different numbers of neutrons.

Example: Hydrogen Isotopes

Hydrogen has three important isotopes:

1. Protium → $^{1}_{1}H$
2. Deuterium → $^{2}_{1}H$
3. Tritium → $^{3}_{1}H$

All have: **Z = 1** but their neutron numbers are different.

Isotope	Z	A	Neutrons
$^{1}_{1}H$	1	1	0
$^{2}_{1}H$	1	2	1
$^{3}_{1}H$	1	3	2

Key Concept
Isotopes have similar chemical properties but may have different nuclear properties.

1.8 Isobars

Atoms having the **same mass number A** but **different atomic numbers Z** are called **isobars**.
Therefore:
Same A → Different Z
Example
$^{14}_{6}C$ and **$^{14}_{7}N$**
For carbon: A = 14, Z = 6
For nitrogen: A = 14, Z = 7
Therefore both have: **A = 14** but different numbers of protons.

1.9 Isotones

Atoms having the **same number of neutrons** but different atomic numbers are called **isotones**.
Since: **N = A − Z**
We can compare the neutron numbers.
Example
Consider: **$^{14}_{6}C$**

$$N = 14 - 6 = 8 \text{ and}$$

$^{15}_{7}N$

$$N = 15 - 7 = 8$$

Therefore both contain 8 neutrons.
Hence they are **isotones**.

1.10 Isotopes, Isobars and Isotones — Quick Comparison

Type	Same	Different
Isotopes	Z	A, N
Isobars	A	Z, N
Isotones	N	Z, A

Memory Trick

Isotopes → Same Z

Isobars → Same A
Isotones → Same N
This is very important for NEET/JEE.

1.11 Nuclear Size

The nucleus is extremely small. The nuclear radius is approximately given by:

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

Where:
$R_0 \approx 1.2 \times 10^{-15}$ m or **$R_0 \approx 1.2$ fm**
Where: **1 fm = 10^{-15} m**
Therefore: **$R \propto A^{1/3}$**

Important Consequences
For two nuclei: $R_1/R_2 = (A_1/A_2)^{1/3}$
This relation is frequently used in numerical problems.
Example
If: $A_1 = 8A_2$ then: $R_1/R_2 = (8)^{1/3}$
Therefore: **$R_1/R_2 = 2$**
So the first nucleus has twice the radius of the second nucleus.

1.12 Nuclear Volume

For approximately spherical nucleus: **$V = (4/3)\pi R^3$**
Since:

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

Therefore:

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

Hence:

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

Therefore:

$$V \propto A$$

This is an extremely important result.

1.13 Nuclear Density

Derivation

Nuclear density is: **ρ = Mass/Volume**
Or,

$$\rho = \frac{M}{V}$$

Approximate nuclear mass:

$$M \approx A m_N$$

Where: m_N is approximately the mass of one nucleon.
Since:

$$V = \frac{4}{3}\pi R^3$$

And,

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

Hence,

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

Therefore:

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

Or,

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

Hence:
It shows that nuclear density is independent of mass number.
That is, ρ ≈ constant

Important Conclusion

Nuclear density is approximately independent of the mass number A.
This is a very common conceptual question.
Thus nuclear density is approximately constant. Its value is of the order of: **$\rho \approx 10^{17}$ kg m^{-3}**

1.14 Why is Nuclear Density So High?

The nucleus contains almost the entire mass of an atom in an extremely small volume.
Therefore its density is enormously greater than ordinary matter.

Important comparison

$$\text{Atomic size} \approx 10^{-10}\text{m}$$

$$Nuclear\ size \approx 10^{-16} m$$

Thus:

$$\frac{R_{atom}}{R_{nucleus}} = 10^6$$

Volume Ratio:

$$\frac{V_{atom}}{V_{nucleus}} = \left(\frac{R_{atom}}{R_{nucleus}}\right)^3$$

Or,

$$\frac{V_{atom}}{V_{nucleus}} = (10^6)^3 = 10^{18}$$

The volume ratio is approximately:

$$V_{atom}/V_{nucleus} \approx 10^{18}$$

This explains why an atom is mostly empty space.

1.15 Nuclear Force

The protons inside a nucleus repel one another because they have positive charges.
According to Coulomb's law:

$$Fe = (1/4\pi\varepsilon_0)(q_1 q_2/r^2)$$

So there should be strong electrostatic repulsion between protons.
Yet the nucleus remains bound.

This is possible because of a much stronger short-range force called the:

Nuclear Force

Nuclear force acts between nucleons:

- proton–proton
- neutron–neutron
- proton–neutron

1.16 Main Properties of Nuclear Force

1. Very Strong

At nuclear distances, nuclear force is much stronger than the electrostatic force.

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2. Short Range

Nuclear force is significant only over distances of approximately: **1–2 fm**
Beyond a few femtometres, it becomes very small.

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3. Attractive at Intermediate Distance

Nuclear force is mainly attractive at typical nuclear distances. This helps bind nucleons together.

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4. Repulsive at Very Short Distance

At extremely small separations, nuclear force becomes strongly repulsive.
This prevents nucleons from collapsing into the same point.

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5. Approximately Charge Independent

The nuclear force between proton–proton, neutron–neutron and proton–neutron pairs is approximately the same when electromagnetic effects are neglected.

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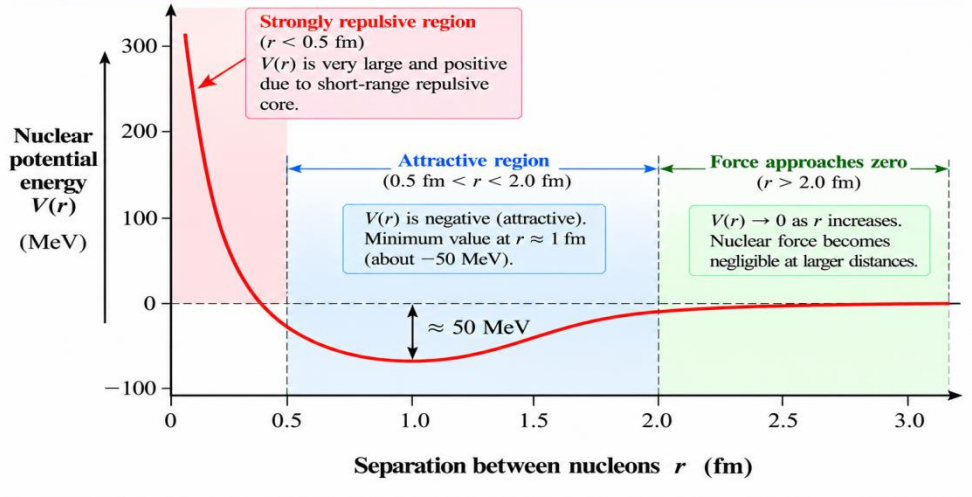
6. Saturation Property

A nucleon interacts strongly mainly with nearby nucleons rather than equally with every nucleon in the nucleus. This property is called: **Saturation of nuclear force**
It helps explain why nuclear density remains approximately constant.

1.17 Nuclear Force vs Electrostatic Force

Property	Nuclear Force	Electrostatic Force
Nature	Strong nuclear interaction	Electromagnetic
Range	Very short	Infinite in principle
Strength at nuclear distance	Very strong	Comparatively weaker
Acts between	Nucleons	Charged particles
Attractive/repulsive	Mainly attractive, repulsive at very short range	Attractive or repulsive
Saturation	Yes	No

Figure 13.2 : Nuclear potential energy versus distance



1.18 Solved Examples

1. Number of Neutrons

For the nucleus: $^{235}_{92}U$, find the number of protons and neutrons.

Solution

Atomic number: Z = 92

Therefore: **Number of protons = 92**

Mass number: A = 235

Number of neutrons: N = A − Z

N = 235 – 92 Or **N = 143**

Answer: Protons = 92, Neutrons = 143

2. Nuclear Radius

Find the approximate radius of a nucleus having: **A = 64**

Given: $R_0 = 1.2$ fm

Using:

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

Since: $64^{(1/3)} = 4$

Therefore: $R = 1.2 \times 4$

Or, **R = 4.8 fm**

Hence: **$R = 4.8 \times 10^{-15}$ m**

3. Radius Ratio

Compare the radii of nuclei having: $A_1 = 27$, $A_2 = 216$

Using:

$$R_1/R_2 = (A_1/A_2)^{(1/3)}$$

Therefore:

$$R_1/R_2 = (27/216)^{(1/3)} = (1/8)^{(1/3)}$$

Hence: **$R_1/R_2 = 1/2$**

1.19 NEET/JEE Quick Concepts

Concept 1: If mass number becomes 8 times: **R becomes 2 times.**
Because: $R \propto A^{(1/3)}$

Concept 2: If mass number becomes 27 times: **R becomes 3 times.**

Concept 3: If A becomes 8 times: Volume becomes: **8 times** because: $V \propto A$

Concept 4: Nuclear density does not significantly depend on A.
Therefore: $\boldsymbol{\rho_1 \approx \rho_2}$ for ordinary nuclei.

Concept 5: The number of neutrons is: $\mathbf{N = A - Z}$
Never use $A - 1$.

1.20 JEE Insight

The relation: $\mathbf{R = R_0 A^{(1/3)}}$ is much more important than simply memorising the value of R_0.
From this one relation, you can immediately obtain: $\mathbf{R \propto A^{(1/3)}}$, $\mathbf{V \propto A}$; $\boldsymbol{\rho \approx}$ **constant**
These three results can solve many multiple-choice questions without lengthy calculations.

Part 2: Mass Defect and Nuclear Binding Energy

2.1 Learning Objectives

After studying Part 2, students will be able to:

1. Understand the mass of a nucleus.
2. Explain the concept of mass defect.
3. Calculate mass defect using nuclear masses.
4. Calculate mass defect using atomic masses.
5. Understand Einstein's mass-energy relation.
6. Calculate nuclear binding energy.
7. Convert mass defect into MeV.
8. Understand the relation between binding energy and nuclear stability.
9. Calculate binding energy per nucleon.
10. Solve Board, NEET and JEE level numerical problems.

2.2 Mass of a Nucleus

A nucleus contains:

- Z protons
- N neutrons

Therefore: **A = Z + N**

If the masses of a proton and neutron are m_p and m_n respectively, then the total mass of the individual free nucleons would be:

$$M_{free} = Zm_p + Nm_n$$

However, the actual mass of the nucleus is slightly smaller than this value.

Let the actual nuclear mass be: **Mnucleus** then:

$$\mathbf{M_{nucleus} < (Zm_p + Nm_n)}$$

The difference is called the: **Mass Defect**

2.3 Mass Defect

Mass defect is defined as the difference between: **Mass of separated nucleons** and **Actual mass of the nucleus.**

Therefore:

$$\mathbf{\Delta m = [Zm_p + Nm_n] - M_{nucleus}}$$

Since: $\mathbf{N = A - Z}$

We can also write:

$$\mathbf{\Delta m = [Zm_p + (A - Z)m_n] - M_{nucleus}}$$

This missing mass has been converted into energy during the formation of the nucleus.

2.4 Why Does Mass Defect Occur?

Suppose Z protons and N neutrons are initially separated.

Their total mass is: $\mathbf{Zm_p + Nm_n}$

When these nucleons come together to form a nucleus, the nuclear force binds them.

Energy is released during this process.

According to Einstein's mass-energy relation: $\mathbf{E = mc^2}$

Therefore, the released energy corresponds to a decrease in mass.

Thus: **Mass defect → Binding energy**
This is one of the most important ideas in nuclear physics.

2.5 Einstein's Mass-Energy Relation

Einstein's famous relation is: $\mathbf{E = mc^2}$
For a mass defect Δm: $\mathbf{E = \Delta mc^2}$
Therefore nuclear binding energy is: $\mathbf{B.E. = \Delta mc^2}$
Where:

- Δm = mass defect
- c = speed of light
- B.E. = nuclear binding energy

2.6 Nuclear Binding Energy

The **binding energy of a nucleus** is the minimum energy required to completely separate the nucleus into its constituent protons and neutrons.
Equivalently:
It is the energy released when the individual nucleons combine to form the nucleus.
Therefore:

$$\textbf{Binding energy} = \Delta mc^2$$

Two equivalent interpretations

Breaking nucleus apart: Nucleus → Protons + Neutrons requires energy.
Forming nucleus: Protons + Neutrons → Nucleus releases energy.
The magnitude of this energy is the nuclear binding energy.

2.7 Binding Energy Using Nuclear Masses

If the mass of the nucleus is given directly, then:

$$\Delta m = Zm_p + Nm_n - M_{nucleus}$$

Therefore:

$$B.E. = [Zm_p + Nm_n - M_{nucleus}]\, c^2$$

This is the direct formula.

2.8 Binding Energy Using Atomic Masses

This is extremely important for **NEET/JEE numerical problems**.
Usually, the mass of a neutral atom is given rather than the mass of the bare nucleus.
Suppose the atomic mass is: **Matom**
A neutral atom contains:

- Z protons
- N neutrons
- Z electrons

Therefore: Mass of separated particles:

$$Zm_p + Nm_n + Zm_e$$

But:

$$M_{atom} = M_{nucleus} + Zm_e$$

Therefore, when atomic masses are used, electron masses cancel.
The mass defect becomes:

Formula

$$\boxed{\Delta m = Zm_H + Nm_n - M_{atom}}$$

Where:

- m_H = mass of hydrogen atom
- m_n = mass of neutron
- M_{atom} = mass of neutral atom

This is the most convenient formula when **atomic masses** are given.
Binding Energy:

$$BE = \Delta m \times 931.5\ MeV$$

2.9 Why is Hydrogen Atom Mass Used?

Instead of using the proton mass directly, we can use the mass of a hydrogen atom:

$$m_H = m_p + m_e$$

This automatically accounts for the electron mass.
Thus:

$$\Delta m = Zm_H + Nm_n - M_{atom}$$

This formula is especially useful in numerical problems involving atomic mass tables.

2.10 Important Formula Comparison

If nuclear masses are given:

$$\Delta m = Zm_H + Nm_n - M_{nucleus}$$

If atomic masses are given:

$$\Delta m = Zm_H + Nm_n - M_{atom}$$

Students should first check **which type of mass is given**.

2.11 Conversion of Mass Defect into Energy

In nuclear physics, mass is often expressed in atomic mass unit: **1 u = 1.6605 × 10^{-27} kg**
Using: **E = Δmc²**
We get: **1 u × c² ≈ 931.5 MeV**
Therefore:

Very Important Shortcut

Binding Energy (MeV) = Δm (u) × 931.5

This is one of the highest-use formulas in the chapter.

2.12 Master Binding Energy Formula

If mass defect is given in atomic mass unit: **B.E. = Δm × 931.5 MeV**
If mass defect is given in kilograms: **B.E. = Δm c²**
If mass defect is given in grams, convert it into kg first.

2.13 Derivation of 1 u = 931.5 MeV

We know: **1 u = 1.6605 × 10^{-27} kg** and: **c = 3 × 10^8 m/s**
Therefore:
$E = mc^2$

Or,

$$E = (1.6605 \times 10^{-27})\ (3 \times 10^{8})^{2} \text{ Or } E \approx 1.494 \times 10^{-10} \text{ J}$$

Now: **1 eV = 1.602 × 10^{-19} J**

Therefore:

$$E \approx 9.315 \times 10^{8} \text{ eV}$$

Hence: **E ≈ 931.5 MeV**

Therefore:

1 u c^2 ≈ 931.5 MeV

Or,

1 u ≈ 931.5 MeV/c^2

2.14 Binding Energy Per Nucleon

The total binding energy does not provide the complete picture when comparing nuclei of different sizes.

Therefore, we define: **Binding Energy Per Nucleon as**

B.E./A = Total Binding Energy / Mass Number

Therefore: **Binding energy per nucleon = B.E./A**

Unit: **MeV per nucleon** or: **MeV/nucleon**

2.15 Importance of Binding Energy Per Nucleon

Binding energy per nucleon gives an indication of how strongly the nucleons are bound within a nucleus.

Generally:

Higher binding energy per nucleon → greater nuclear stability

However, in detailed nuclear physics, stability also depends on factors such as proton-neutron ratio and other nuclear effects.

For the present level, the important comparison is:

Higher B.E./A generally indicates a more tightly bound nucleus.

2.16 Example of Binding Energy Per Nucleon

Suppose a nucleus has: Mass number: **A = 20**

Total binding energy: **B.E. = 160 MeV**

Then:

$$B.E./A = 160/20$$

Therefore: **B.E./A = 8 MeV/nucleon**

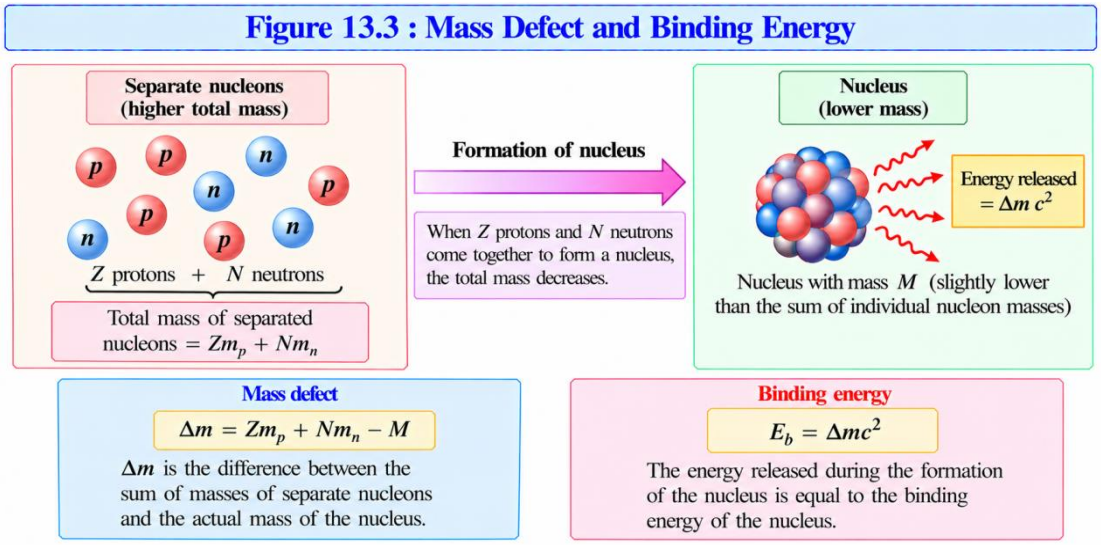
2.17 Mass Defect and Binding Energy — Physical Picture

The process can be represented as:

Separated nucleons → Nuclear force acts → Nucleus forms → Energy is released→ Mass decreases slightly

Therefore: **Mass defect ↔ Binding energy**

More precisely: **B.E. = Δmc^2**



2.18 Energy Level Representation of Binding

A useful diagram can represent the idea as:

Separated nucleons

E = 0

↓

Energy gap = **Binding Energy**

↓

Lower level:

Bound nucleus

E = −B.E.

The negative energy indicates that the bound nucleus has lower energy than the separated nucleons.

Therefore, energy equal to the binding energy must be supplied to separate the nucleus completely.

2.19 Solved Examples

1. Mass Defect

Consider a nucleus containing: Z = 2 protons, N = 2 neutrons

Suppose: m_p = 1.0073 u, m_n = 1.0087 u, and nuclear mass: Mnucleus = 4.0015 u

Find the mass defect.

Solution

Mass of individual nucleons: $Zm_p + Nm_n = 2(1.0073) + 2(1.0087) = 2.0146 + 2.0174 = 4.0320$ u

Therefore: $\Delta m = 4.0320 - 4.0015$

Or,

$\Delta m = 0.0305$ u

2. Binding Energy

Using: **$\Delta m = 0.0305$ u**

Binding energy: B.E. = $\Delta m \times 931.5$ Or B.E. = 0.0305×931.5

Therefore: **B.E. ≈ 28.4 MeV**

So the nucleus has approximately: **28.4 MeV** of binding energy.

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3. Binding Energy Per Nucleon

For the nucleus in the previous example: A = 4, B.E. ≈ 28.4 MeV
Therefore: B.E./A = 28.4/4
Or,

B.E./A ≈ 7.1 MeV/nucleon

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4. Atomic Mass Method

Suppose a nucleus has: A = 12, Z = 6 and atomic mass: **Matom = 12.0000 u**
Given: $m_H = 1.0078$ u, $m_n = 1.0087$ u. Find the mass defect.

Step 1: Find neutron number

$$N = A - Z \text{ Or } N = 12 - 6 \text{ Or } \mathbf{N = 6}$$

Step 2: Use atomic mass formula

$\Delta m = Zm_H + Nm_n - Matom$
Or

$$\Delta m = 6(1.0078) + 6(1.0087) - 12.0000$$

Calculating:
$6(1.0078) = 6.0468$ u
$6(1.0087) = 6.0522$ u
Total: 12.0990 u
Therefore: $\Delta m = 12.0990 - 12.0000$ Or $\mathbf{\Delta m = 0.0990\ u}$

Step 3: Binding energy

B.E. = 0.0990 × 931.5 Or **B.E. ≈ 92.0 MeV**
This example demonstrates why the **atomic-mass formula** is very useful.

2.20 Mass Defect Does Not Mean Mass is "Lost"

A common misconception is: "Some mass disappears."
A better statement is:
The mass difference corresponds to an equivalent amount of energy released during nuclear binding.
According to: **$E = mc^2$;** mass and energy are related.
Thus the total mass-energy is conserved.

2.21 NEET/JEE High-Yield Relations

Relation 1: B.E. = Δm × 931.5 MeV

Relation 2: B.E./A = Total B.E./A
More correctly:

$$\text{Binding Energy per Nucleon} = \frac{\text{Total Binding Energy}}{\text{Mass Number}}$$

Relation 3: For the same nucleus: **B.E. ∝ Δm**

Relation 4: If mass defect doubles: **Binding energy doubles.**

Relation 5: If two nuclei have the same A but different binding energies:
The nucleus with greater B.E./A is more tightly bound.

Relation 6: For a nucleus: **A = Z + N**
Always calculate N before applying the mass-defect formula.

2.22 JEE Insight

A very useful way to approach numerical problems is:

Step 1: Identify: **A and Z**
Step 2: Calculate: **N = A − Z**
Step 3: Check whether the given masses are: **nuclear masses** or **atomic masses**
Step 4: Calculate Δm.
Step 5: Convert: **Δm → Binding Energy** using: **B.E. = Δm × 931.5 MeV**
Step 6: If required:

$$B.E.per\ nucleon = \frac{Total\ B.E.}{A}$$

Part 3: Binding Energy per Nucleon, Nuclear Stability & Binding Energy Curve

3.1 Learning Objectives

After studying Part 3, students will be able to:

1. Understand the significance of binding energy per nucleon.
2. Compare the stability of different nuclei.
3. Understand the variation of B.E./A with mass number.
4. Interpret the binding-energy curve.
5. Understand the role of the proton-neutron ratio.
6. Explain why very light nuclei can release energy by fusion.
7. Explain why very heavy nuclei can release energy by fission.
8. Solve numerical problems involving B.E./A.
9. Interpret binding-energy graphs for Board/NEET/JEE questions.

3.2 Why the Binding Energy Curve is Important

The curve explains two major nuclear energy processes.

Fusion

Light nuclei combine to form a heavier nucleus with higher B.E./A.
Therefore energy can be released.

Fission

A very heavy nucleus splits into medium-mass nuclei having higher B.E./A.
Therefore energy can be released.

3.3 Why Do We Need Binding Energy Per Nucleon?

Suppose two nuclei have: Nucleus A: **Total B.E. = 100 MeV,**
Nucleus B: **Total B.E. = 200 MeV**
We cannot immediately say that nucleus B is more stable because the two nuclei may contain different numbers of nucleons.
Therefore, we compare:

Binding Energy Per Nucleon

B.E. per nucleon = Total Binding Energy / A
Or:

$$\boldsymbol{B.E./A = B.E. \div A}$$

Where, A is the mass number.

3.4 Example

Consider two nuclei:
Nucleus X: A = 20; B.E. = 160 MeV
Therefore: B.E./A = 160/20 **= 8 MeV/nucleon**
Nucleus Y: A = 40, B.E. = 280 MeV
B.E./A = 280/40 **= 7 MeV/nucleon**
Although nucleus Y has greater **total binding energy**, nucleus X has greater **binding energy per nucleon**.

Thus X is more tightly bound per nucleon.

3.5 Nuclear Stability

The binding energy per nucleon gives an important indication of how strongly nucleons are bound inside a nucleus.
In general:
Higher B.E./A → greater nuclear stability and: **Lower B.E./A → weaker average binding**
However, nuclear stability is not determined by B.E./A alone. The neutron-proton ratio and other nuclear effects also matter.
For most CBSE/NEET/JEE comparisons, B.E./A is the key quantity.

3.6 Binding Energy Curve

The variation of binding energy per nucleon with mass number A is represented by the:

Binding Energy Curve

The general behaviour is:

Region 1: Very Light Nuclei

For very small A: **B.E./A is relatively low.**
As A increases, B.E./A increases rapidly.

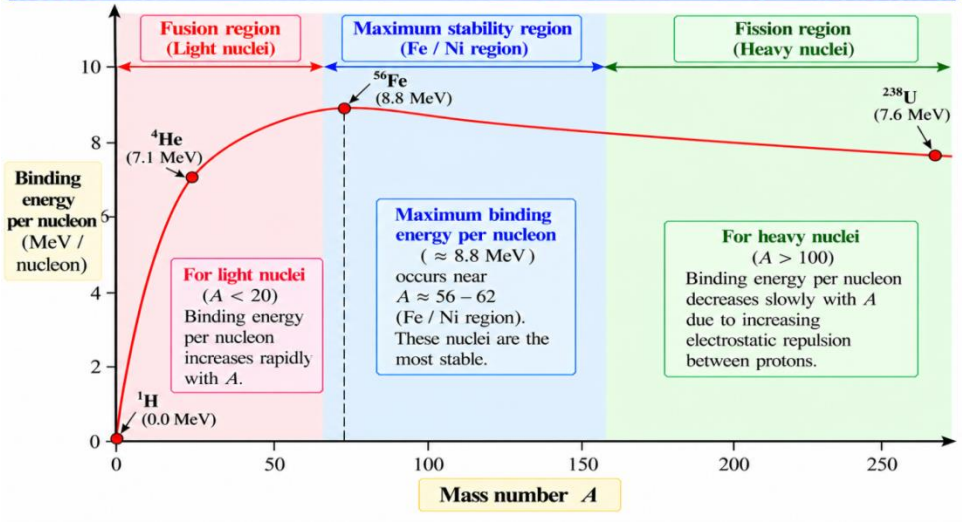
Region 2: Medium-Mass Nuclei

B.E./A reaches a maximum in the region of: **A ≈ 56–62**
The maximum is approximately: **8.8 MeV/nucleon**
The maximum binding energy per nucleon occurs in the iron-nickel region. The exact maximum depends on the particular nucleus considered.

Region 3: Heavy Nuclei

For heavy nuclei: B.E./A gradually decreases.
Thus very heavy nuclei are, on average, less tightly bound per nucleon than nuclei near the maximum region.

Figure 13.4 : Binding Energy per Nucleon



3.7 Why Does B.E./A increase for Light Nuclei?

For light nuclei, adding nucleons increases the number of attractive nuclear interactions.
As a result, the average binding per nucleon increases.
Therefore: **B.E./A increases with A** for the lighter nuclei.
This increase does not continue indefinitely.

3.8 Why Does B.E./A decrease for Heavy Nuclei?

As the nucleus becomes very large, the number of protons increases.
Protons repel each other due to electrostatic force.
The electrostatic repulsion becomes increasingly important in heavy nuclei.
Therefore the average binding per nucleon begins to decrease.
Thus: **Very heavy nuclei have lower B.E./A than medium-mass nuclei.**

3.9 Role of Nuclear Force

Nuclear force is:

- very strong
- short-range
- approximately saturated

This means that a nucleon interacts strongly mainly with nearby nucleons.
It does not attract every nucleon in a large nucleus equally.
In contrast, electrostatic repulsion between protons has a much longer range.
Therefore, as the nucleus becomes very large:
proton-proton repulsion becomes increasingly significant.
This contributes to the decrease in B.E./A for heavy nuclei.

3.10 Nuclear Stability and Proton-Neutron Ratio

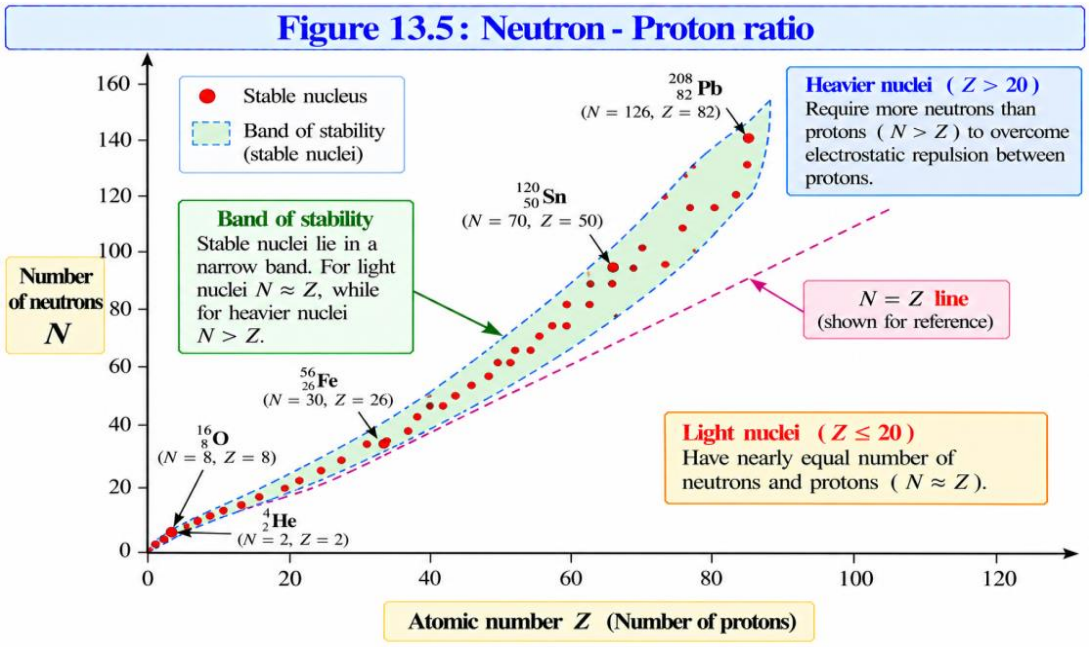
For stable nuclei, the number of neutrons and protons is related to the nuclear size.
Let: **N = Number of neutrons, Z = Number of protons,**
Then: **N/Z = neutron-to-proton ratio**

Light Nuclei

For lighter stable nuclei: $\mathbf{N/Z \approx 1}$
Examples include nuclei in which neutron and proton numbers are relatively comparable.

Heavy Nuclei

For heavier stable nuclei: $\mathbf{N/Z > 1}$
More neutrons are required relative to protons.
Why?
Because neutrons contribute to the attractive nuclear interaction without adding electrostatic repulsion.
Thus extra neutrons help provide additional nuclear binding in heavy nuclei.



3.11 Band of Stability

A plot of neutron number N versus proton number Z shows a region where stable nuclei are found. This region is called the: **Band of Stability**
For light nuclei: **N ≈ Z,** As Z increases: **N/Z increases**
Therefore, stable heavy nuclei have: **N > Z**
Nuclei outside the stable region may undergo radioactive decay to move toward greater stability.
We will study radioactive decay in detail in **Part 4**.

3.12 Energy Release and Nuclear Stability

A nuclear reaction can release energy if the products are more tightly bound than the original nuclei.
That means:
Total B.E. of products > Total B.E. of reactants
Then the difference can appear as released energy.
Thus:
Energy released = Increase in total binding energy
For a reaction: Reactants → Products approximately:

$$Q = B.E._{products} - B.E._{reactants}$$

For a reaction in which the initial and final nuclear rest masses are compared consistently:

$$Q = \Delta BE$$

A positive Q-value indicates energy release.

3.13 Connection with Fusion

Consider very light nuclei. Their B.E./A is relatively low.
If they combine to form a nucleus whose B.E./A is higher, the products are more tightly bound.
Therefore: **Total binding energy increases** and energy can be released.
This process is called: **Nuclear Fusion**
Example:

Hydrogen isotopes can combine through a sequence of nuclear reactions to ultimately form helium, releasing energy.
We will study the actual fusion process in detail in Part 5.

3.14 Connection with Fission

Very heavy nuclei have lower B.E./A than medium-mass nuclei.
If a heavy nucleus splits into medium-mass nuclei: **B.E./A of products can be higher.**
Therefore total binding energy increases. The excess energy is released.
This process is called: **Nuclear Fission**
Example:
Uranium-235 can undergo fission after absorbing a neutron.
Detailed treatment will come in Part 5.

3.15 Why Iron/Nickel Region is Important

The binding energy per nucleon reaches its maximum in the neighbourhood of iron/nickel.
The value is approximately: **8.8 MeV/nucleon**
Therefore nuclei in this region are among the most tightly bound nuclei.
This explains an important fact:
Light nuclei can release energy by moving toward the maximum through **fusion**.
Heavy nuclei can release energy by moving toward the maximum through **fission**.
Thus the binding-energy curve provides a unified explanation of both processes.

3.16 Total Binding Energy vs Binding Energy Per Nucleon

These two quantities should not be confused.

Total Binding Energy B.E. measures the total energy needed to completely separate all nucleons. It generally increases as A increases.

Binding Energy Per Nucleon B.E./A measures average binding per nucleon.
It first increases, reaches a maximum, and then decreases slowly for heavy nuclei.

3.17 Important Comparison

Quantity	Meaning
Mass defect	Difference between free-nucleon mass and nuclear mass
Binding energy	Energy equivalent of mass defect
Total B.E.	Total binding of the nucleus
B.E./A	Average binding per nucleon
Higher B.E./A	Generally stronger average binding

3.18 Solved Examples

1. Two nuclei have:

Nucleus A: A = 10, B.E. = 70 MeV

Nucleus B: A = 20, B.E. = 150 MeV

Which has greater binding energy per nucleon?

Solution

For A: B.E./A = 70/10 **= 7 MeV/nucleon**
For B: B.E./A = 150/20 **= 7.5 MeV/nucleon**

Therefore: **Nucleus B has greater binding energy per nucleon.**

---

2. A nucleus has: A = 56 and: B.E./A = 8.8 MeV/nucleon. Find total binding energy.
Solution
B.E. = A × (B.E./A)
Therefore: B.E. = 56 × 8.8 Or **B.E. = 492.8 MeV**

---

3. Energy Released

Suppose a nuclear reaction changes the total binding energy from:
Initial: **180 MeV**
Final: **205 MeV**
Then: Q = B.E.final − B.E.initial
Q = 205 – 180 Or **Q = +25 MeV**
Therefore: **25 MeV energy is released.**

---

4. Fusion Concept

Suppose two light nuclei initially have total binding energy: **20 MeV** and the products have total binding energy: **35 MeV**. Find Q.
Then: Q = 35 – 20
Or,
Q = 15 MeV
Therefore: **15 MeV is released.**
The important point is not merely that the nucleus becomes heavier, but that the **total binding energy increases**.

---

5. Fission Concept

Suppose a heavy nucleus has total binding energy: **1500 MeV** and after fission, the products have total binding energy: **1800 MeV.** Find Q.
Then: Q = 1800 – 1500
Or,
Q = 300 MeV
Therefore approximately: **300 MeV energy is released** ignoring the detailed kinetic-energy accounting of the actual reaction.

3.19 NEET/JEE Shortcut

When a question gives: **B.E./A of reactants and products,** first calculate the **total binding energy**: **Total B.E. = A × (B.E./A)**
Then compare the totals.
Do not compare B.E./A values alone when the numbers of nucleons are different.

3.20 Example of the Shortcut

Suppose:
Nucleus X:
A = 10,
B.E./A = 7 MeV/ nucleon

Then: B.E. = 10 × 7 **= 70 MeV**
Nucleus Y:
A = 20,
B.E./A = 8 MeV/nucleon
Then: B.E. = 20 × 8 **= 160 MeV**
If they participate in a reaction, use the **total binding energies** to determine the energy change.

3.21 Board Exam Important Statement

The binding energy per nucleon is a measure of the average energy required to remove a nucleon from the nucleus.
A high value indicates that nucleons are, on average, strongly bound.

3.22 JEE Insight — Graph-Based Questions

Suppose a question gives a binding-energy curve and asks:
Which region corresponds to fusion?
Look at the **left side**, where light nuclei move toward the maximum.
Which region corresponds to fission?
Look at the **right side**, where heavy nuclei move toward the maximum.
Where is maximum stability?
Near the **maximum of B.E./A**, around the iron/nickel region.
Why is energy released?
Because the final configuration has greater total binding energy.

Part 3 — Most Important Five Points

1. $BE_{total} = A \times (BE/A)$
2. Maximum B.E./A is around the **iron/nickel region**.
3. Higher B.E./A generally means stronger average nuclear binding.
4. Light nuclei can release energy by **fusion** as they move toward higher B.E./A.
5. Heavy nuclei can release energy by **fission** as the products move toward higher B.E./A.

Part 3 Memory Line

"Nuclei near the maximum of the binding-energy-per-nucleon curve are very tightly bound; light nuclei can release energy by moving upward through fusion, while heavy nuclei can release energy by moving upward through fission."

Part 4: Radioactivity and Radioactive Decay

4.1 Learning Objectives

After studying Part 4, students will be able to:

1. Understand the phenomenon of radioactivity.
2. Distinguish α, β and γ radiations.
3. Understand radioactive decay as a spontaneous process.
4. Define decay constant.
5. Derive the radioactive decay law.
6. Calculate the number of undecayed nuclei after time t.
7. Understand activity and its SI unit.
8. Derive the relation between activity and number of nuclei.
9. Understand half-life and mean life.
10. Derive the relations between λ, $T_{1/2}$ and τ.
11. Solve radioactive decay numericals.
12. Interpret N–t, activity–time and ln N–t graphs.

4.2 What is Radioactivity?

Some atomic nuclei are unstable. An unstable nucleus can spontaneously transform into another nucleus while emitting radiation. This spontaneous process is called:

Radioactivity

The emitted radiations are mainly:

- **Alpha (α) particles**
- **Beta (β) particles**
- **Gamma (γ) rays**

Radioactivity is a **nuclear phenomenon**.

4.3 Why Does Radioactivity Occur?

A nucleus can be unstable because of factors such as:

- unsuitable neutron-to-proton ratio,
- very large nuclear size,
- strong proton-proton electrostatic repulsion,
- excess nuclear energy.

The unstable nucleus tends to transform into a more stable configuration.

4.4 Important Characteristics of Radioactive Decay

Radioactive decay is:

1. Spontaneous

It occurs naturally without external triggering.

2. Random

We cannot predict exactly when a particular nucleus will decay.
We can, however, predict the behaviour of a **large collection of nuclei statistically**.

3. Independent of ordinary physical conditions

For ordinary radioactive decay, the decay rate is essentially unaffected by:

- temperature,

- pressure,
- chemical state.

4. A nuclear process

The process involves changes in the nucleus, not merely the electronic configuration.

4.5 Alpha Radiation

An alpha particle is essentially a helium nucleus.
It contains:

- 2 protons
- 2 neutrons

Therefore: **Charge = +2e; Mass ≈ 4 u**
An alpha particle can be represented as: **$^{4}_{2}He$ Or α**

4.6 Beta Radiation

Beta radiation is associated with beta particles.
There are two types:

- β^-
- β^+

β^- decay

A neutron transforms into a proton with emission of an electron and an antineutrino:

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

The atomic number increases by 1, while the mass number remains unchanged.

β^+ decay

A proton transforms into a neutron with emission of a positron and a neutrino:

$$p \rightarrow n + e^+ + \nu_e$$

The atomic number decreases by 1, while the mass number remains unchanged.
Where:

- e^- = electron
- e^+ = positron
- $\bar{\nu}_e$ = electron antineutrino
- ν_e = electron neutrino

4.7 Gamma Radiation

Gamma radiation consists of high-energy electromagnetic photons.
Therefore: **Charge = 0, Rest mass = 0**
Gamma emission usually occurs when an excited nucleus moves to a lower nuclear energy state.

4.8 α, β and γ — Comparison

Property	α	β	γ
Nature	Helium nucleus	Electron/positron	EM radiation
Charge	+2e	−e or +e	0
Rest mass	≈ 4 u	Very small	0
Penetrating power	Low	Moderate	Very high
Ionising power	Very high	Moderate	Relatively low
Speed	Less than c	Close to c	c in vacuum
Deflection in electric/magnetic field	Deflected slightly	Deflected strongly	Not deflected

Note: The direction and magnitude of deflection depend on the charge-to-mass ratio, particle velocity and the applied field.

Important Memory

Ionising power: $\alpha > \beta > \gamma$

Penetrating power: $\gamma > \beta > \alpha$

4.9 Radioactive Decay Equation (JEE/NEET Enrichment)

Consider a radioactive sample containing: **N** undecayed nuclei at time t.

The number of nuclei that decay in a small time interval dt is proportional to N and dt.

Therefore: $-dN \propto N\,dt$

Introducing the proportionality constant λ: $-dN = \lambda N\,dt$ or: $dN/N = -\lambda dt$

Where: λ = **decay constant**

4.10 Decay Constant

The decay constant λ represents the probability per unit time for decay of an individual nucleus, in the statistical description of radioactive decay.

Its SI unit is: s^{-1}

It is also called: **activity constant** or **disintegration constant** in some contexts.

Important

A larger λ means faster decay.

A smaller λ means slower decay.

4.11 Derivation of Radioactive Decay Law

Starting with: $dN/N = -\lambda dt$

Integrating:

From initial number: N_0 at: $t = 0$ to: N at time: t

We obtain: $\int dN/N = -\lambda \int dt$

Therefore: $\ln(N/N_0) = -\lambda t$

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

Therefore: **Radioactive Decay Law:** $N = N_0 e^{-\lambda t}$

This is one of the most important formulas of the chapter.

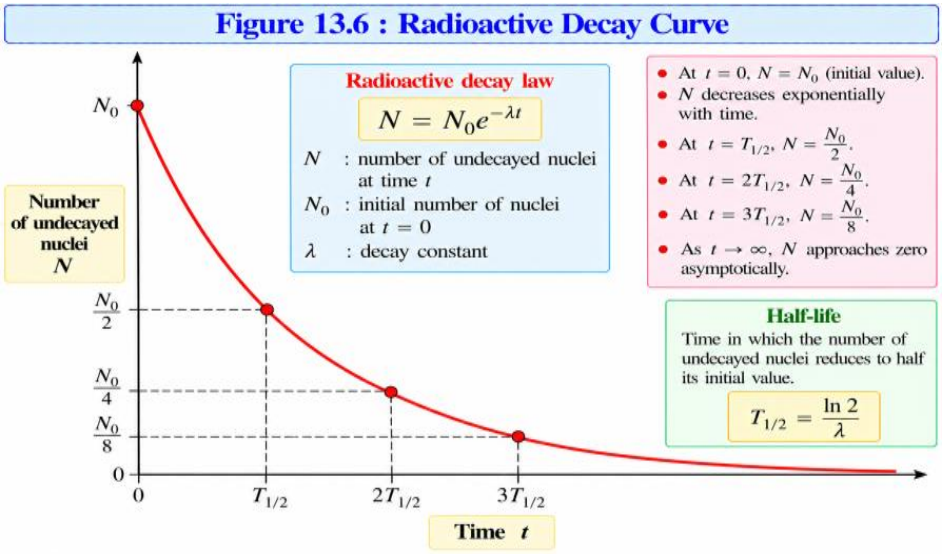
4.12 Alternative Form of Decay Law

Taking natural logarithm: $\ln N = \ln N_0 - \lambda t$

This equation has the form: $y = c + mx$

Therefore, a plot of: $\ln N$ vs t is a straight line.

Its: **Slope** $= -\lambda$ and: **Intercept** $= \ln N_0$



4.13 Fraction of Nuclei Remaining

From: $\mathbf{N = N_0 e^{-\lambda t}}$,
We get: $\mathbf{N/N_0 = e^{-\lambda t}}$
Thus: **Fraction remaining** $\mathbf{= e^{-\lambda t}}$

4.14 Fraction Decayed

Initial number: $\mathbf{N_0}$
Remaining: $\mathbf{N}$
Therefore number decayed: $\mathbf{N_0 - N}$
Fraction decayed: $\mathbf{(N_0 - N)/N_0}$
Using the decay law: **Fraction decayed** $\mathbf{= 1 - e^{-\lambda t}}$

4.15 Percentage Remaining

Percentage remaining $\mathbf{= (N/N_0) \times 100}$
Therefore: **Percentage remaining** $\mathbf{= 100 e^{-\lambda t}}$

4.16 Percentage Decayed

Percentage decayed $\mathbf{= [1 - e^{-\lambda t}] \times 100}$
This formula is useful in numerical problems.

4.17 Activity of a Radioactive Sample

The activity is the number of radioactive disintegrations per unit time.
Therefore:

$$\mathbf{Activity = -dN/dt}$$

From:

$$\mathbf{-dN/dt = \lambda N}$$

We get:

$$\mathbf{A = \lambda N}$$

Where:

- A = activity
- λ = decay constant
- N = number of undecayed nuclei

4.18 SI Unit of Activity

The SI unit of activity is: **Becquerel (Bq)**
1 Bq = 1 disintegration per second
Therefore: **1 Bq = 1 s^{-1}**
Another older unit is the curie: **1 Ci = 3.7 × 10^{10} Bq**
For modern SI calculations, **Bq** is preferred.

4.19 Activity as a Function of Time

Since: **A = λN** and: **$N = N_0 e^{-\lambda t}$** therefore:

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

At t = 0: **$A_0 = \lambda N_0$**
Hence:

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

Therefore activity decreases exponentially with time in exactly the same way as the number of undecayed nuclei.

4.20 Half-Life

The half-life of a radioactive substance is the time required for the number of undecayed nuclei to become half its initial value.
It is represented by: **$T_{1/2}$**
At: **$t = T_{1/2}$,**
We have: **$N = N_0/2$**
Using:

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

We get:

$$\frac{N_2}{2} = N_0 e^{-\lambda t}$$

Therefore:

$$\frac{1}{2} = e^{-\lambda t}$$

Taking logarithm:

$$ln\left(\frac{1}{2}\right) = ln\left(e^{-\lambda t}\right)$$

Or,

$$\ln 1 - \ln 2 = (-\lambda t)\ln(e)$$

Or,

$$\ln 2 = \lambda t \Rightarrow t = \frac{\ln 2}{\lambda}$$

Hence:

$$t = T_{1/2} = \frac{ln\, 2}{\lambda}$$

Since: **ln 2 ≈ 0.693**

Therefore:

$$T_{1/2} = \frac{0.693}{\lambda}$$

Or:

$$\lambda = \frac{0.693}{T_{1/2}}$$

This is one of the most important numerical formulas.

4.21 Meaning of Half-Life

Suppose initially: **$N_0 = 1000$**
After one half-life: **500**
After two half-lives: **250**
After three half-lives: **125**
After four half-lives: **62.5**

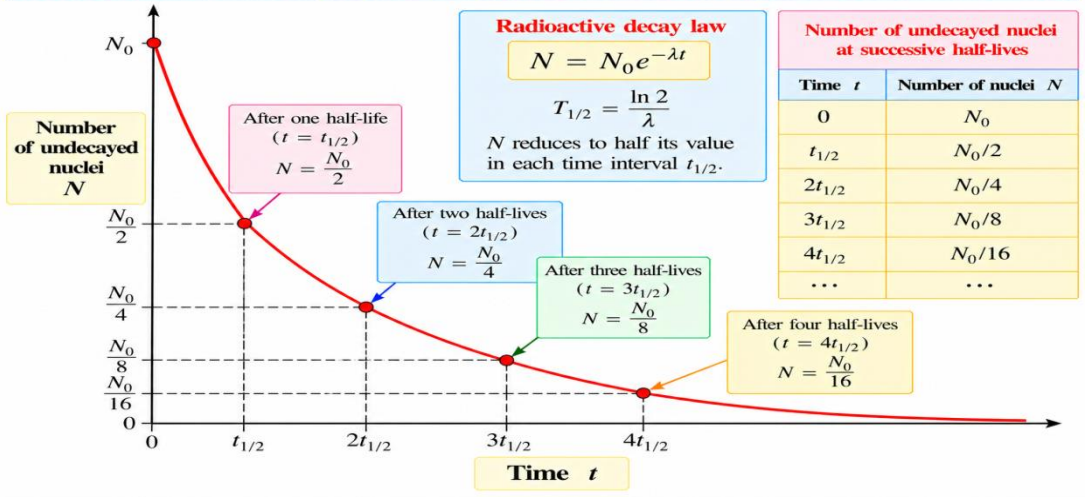
Thus: **Time**	**Remaining fraction**
0	1
$T_{1/2}$	1/2
$2T_{1/2}$	1/4
$3T_{1/2}$	1/8
$4T_{1/2}$	1/16

Therefore, after n half-lives: **$N = N_0/2^n$**
After four half-lives, the expected remaining number is 62.5 for an initial population of 1000. The actual number of nuclei in a particular sample must be an integer.

4.22 Radioactive Decay in Terms of Half-Life

Since: **$t = nT_{1/2}$** we can write: **$N = N_0(1/2)^n$** or: **$N = N_0(1/2)^{(t/T_{1/2})}$**
Similarly: **$A = A_0(1/2)^{(t/T_{1/2})}$**

Figure 13.7 : Half- Life Graph



4.23 Mean Life

The mean life of a radioactive nucleus is represented by: τ

For exponential radioactive decay: $\tau = 1/\lambda$

Therefore: $\lambda = 1/\tau$

Since: $T_{1/2} = 0.693/\lambda$

And:

$\tau = 1/\lambda$

We get:

$T_{1/2} = 0.693\tau$

or:

$\tau = T_{1/2}/0.693$

Therefore: $\tau \approx 1.44T_{1/2}$

4.24 Important Relations — Decay Constant, Half-Life and Mean Life

Decay constant: $\lambda = 1/\tau$

Half-life: $T_{1/2} = 0.693/\lambda$

Mean life: $\tau = 1/\lambda$

Combined relation: $T_{1/2} = 0.693\tau$ and: $\tau \approx 1.44T_{1/2}$

4.25 Mean Life of a Radioactive Nucleus

For radioactive decay: $N = N_0e^{-\lambda t}$

The average lifetime of the nuclei in a radioactive sample is: $\tau = 1/\lambda$

Thus: $\tau = 1/\lambda$

This result is fundamental for exponential decay.

4.26 Decay Constant and Half-Life — Conceptual Understanding

If: λ **is large** then: $T_{1/2}$ **is small** because: $T_{1/2} = 0.693/\lambda$

Therefore the substance decays rapidly.

If: λ **is small** then: $T_{1/2}$ **is large**

Therefore the substance decays slowly.

4.27 Solved Examples:

1. Decay Constant

A radioactive substance has half-life: $T_{1/2} = 10$ **days** Find its decay constant.

Answer:

Using: $\lambda = 0.693/T_{1/2}$

Therefore: $\lambda = 0.693/10$

Or,

$\lambda = 0.0693\ day^{-1}$

If the answer is required in s^{-1}, convert 10 days into seconds before calculating.

---

2. Remaining Nuclei

Initially there are: $N_0 = 8000$ radioactive nuclei. If three half-lives have passed, find the number remaining.

Answer:
Using: $\mathbf{N = N_0/2^n}$
Here: n = 3
Therefore: N = 8000/8
Or, **N = 1000**

---

3. Time for a Given Fraction

A radioactive sample has half-life: $\mathbf{T_{1/2} = 5\ h}$
After how much time will one-eighth of the original nuclei remain?
Answer:
We know: $\mathbf{1/8 = (1/2)^3}$
Therefore: **3 half-lives** are required.
Hence: t = 3 × 5
Or, **t = 15 h**

4. Activity

A radioactive sample contains: $\mathbf{N = 2 \times 10^{10}}$ **nuclei** and: $\boldsymbol{\lambda = 0.02\ s^{-1}}$**.** Find its activity.
Answer:
Using: $\mathbf{A = \lambda N}$
Therefore: $A = 0.02 \times 2 \times 10^{10}$ Or $\mathbf{A = 4 \times 10^8\ Bq}$

---

5. Activity After Two Half-Lives

Answer:
Initial activity: $\mathbf{A_0 = 800\ Bq}$
After two half-lives: $\mathbf{A = A_0/2^2}$
Or
A = 800/4
Or
A = 200 Bq

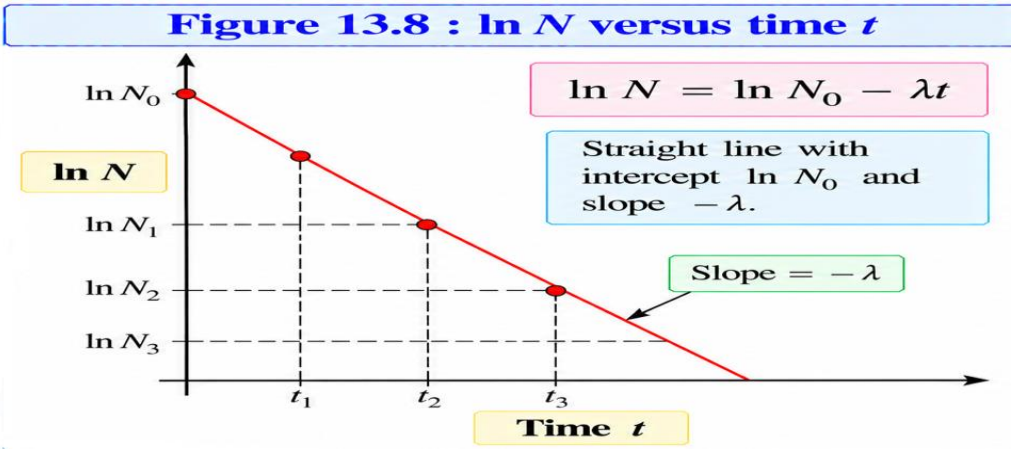
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6. Mean Life

A radioactive substance has: $\boldsymbol{\lambda = 0.05\ s^{-1}}$**.** Find its mean life.
Answer:
Using: $\boldsymbol{\tau = 1/\lambda}$
Therefore: $\tau = 1/0.05$ Or $\boldsymbol{\tau = 20\ s}$
Its half-life is: $T_{1/2} = 0.693 \times 20 \approx \mathbf{13.86\ s}$

4.28 Graph: ln N vs Time

From the decay equation: $\mathbf{N = N_0 e^{-\lambda t}}$
Taking logarithm: $\mathbf{\ln N = \ln N_0 - \lambda t}$
Therefore,
plotting: **ln N vs t** gives a straight line.
Its slope is: $\mathbf{Slope = -\lambda}$ and y-intercept: $\mathbf{Intercept = \ln N_0}$



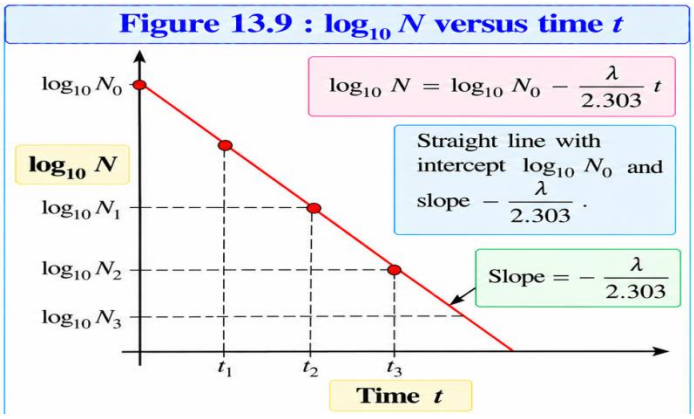
4.29 Graph: $\log_{10} N$ vs Time

If common logarithm is used:

From: $N = N_0 e^{-\lambda t}$ we obtain: $\log_{10} N = \log_{10} N_0 - (\lambda/2.303)t$

Therefore: **Slope = $-\lambda/2.303$**

This relation can be useful in JEE-level graph questions.



4.30 Radioactive Decay and Nuclear Equation

A radioactive decay can be represented generally as:

Parent nucleus → Daughter nucleus + Radiation

The parent nucleus decreases with time.

The daughter nucleus increases correspondingly, although detailed decay chains may involve several successive decays.

4.31 Important Nuclear Changes in α and β Decay

Alpha decay

When a nucleus emits α: **A → A – 4; Z → Z − 2**

Therefore:

$$^{A}_{Z}X \rightarrow ^{A-4}_{Z-2}Y + ^{4}_{2}He$$

Beta-minus decay

For β^-: **A remains unchanged: Z → Z + 1**

Therefore:

$$_{Z}^{A}X \rightarrow {}_{Z+1}^{A}Y + e^{-} + \bar{\nu}$$

Beta-plus decay

For β^+: **A remains unchanged: Z → Z − 1**
Therefore:

$$_{Z}^{A}X \rightarrow {}_{Z-1}^{A}Y + e^{+} + \nu$$

Gamma decay

For γ emission: **A remains unchanged: Z remains unchanged**
Only the nuclear energy state changes.

4.32 Important Conservation Laws

Radioactive decay obeys conservation principles, including conservation of:

- electric charge
- energy
- momentum
- angular momentum

In beta decay, neutrino/antineutrino emission is important for satisfying the relevant conservation laws.

4.33 NEET/JEE Quick Shortcuts

Shortcut 1: After n half-lives: $N = N_0/2^n$

Shortcut 2: Remaining fraction: $N/N_0 = 1/2^n$

Shortcut 3: Decayed fraction: $1 - 1/2^n$

Shortcut 4: After one half-life: **50% remains, 50% decays**

Shortcut 5: After two half-lives: **25% remains, 75% decays**

Shortcut 6: After three half-lives: **12.5% remains, 87.5% decays**

Shortcut 7: Activity follows exactly the same exponential law as N: $A/A_0 = N/N_0$

Part 4 Master Memory Line

"Radioactive decay is random for an individual nucleus but predictable statistically for a large number of nuclei."
And the three formulas to remember first are:
$N = N_0e^{-\lambda t}$
$A = \lambda N$
$T_{1/2} = 0.693/\lambda$

Part 5: Nuclear Fission, Fusion & Nuclear Reactor

5.1 Learning Objectives

After studying Part 5, students will be able to:

1. Understand nuclear fission.
2. Explain energy release in fission.
3. Understand the role of neutron-induced fission.
4. Understand chain reaction.
5. Define critical mass.
6. Understand the basic principle of a nuclear reactor.
7. Identify the main components of a reactor.
8. Understand nuclear fusion.
9. Explain why fusion releases energy.
10. Compare fission and fusion.
11. Understand mass-energy conversion in nuclear reactions.
12. Solve basic energy-release numerical problems.

5.2 Nuclear Fission

The splitting of a heavy nucleus into two or more lighter nuclei, accompanied by the release of a large amount of energy, is called:

Nuclear Fission

A typical example is the fission of uranium-235.

A neutron is absorbed by uranium-235: $^{235}_{92}\mathbf{U} + ^{1}_{0}\mathbf{n} \rightarrow ^{236}_{92}\mathbf{U}^{*}$

The excited uranium nucleus can then split into two medium-mass nuclei along with additional neutrons and energy.

A representative reaction is: $^{235}_{92}\mathbf{U} + ^{1}_{0}\mathbf{n} \rightarrow ^{141}_{56}\mathbf{Ba} + ^{92}_{36}\mathbf{Kr} + 3\,^{1}_{0}\mathbf{n} + \mathbf{Energy}$

The exact fission products can vary.

5.3 Why Does Fission Release Energy?

Recall the binding-energy curve.

Heavy nuclei have a lower: **Binding energy per nucleon** than medium-mass nuclei.

When a heavy nucleus splits into medium-mass nuclei: **B.E./A increases**

Therefore the total binding energy of the products is greater.

Hence: **Energy is released.**

The approximate energy release per fission of U-235 is of the order of: **200 MeV**

The exact value depends on the particular fission channel.

5.4 Fission Energy from Mass Defect

For a nuclear reaction:

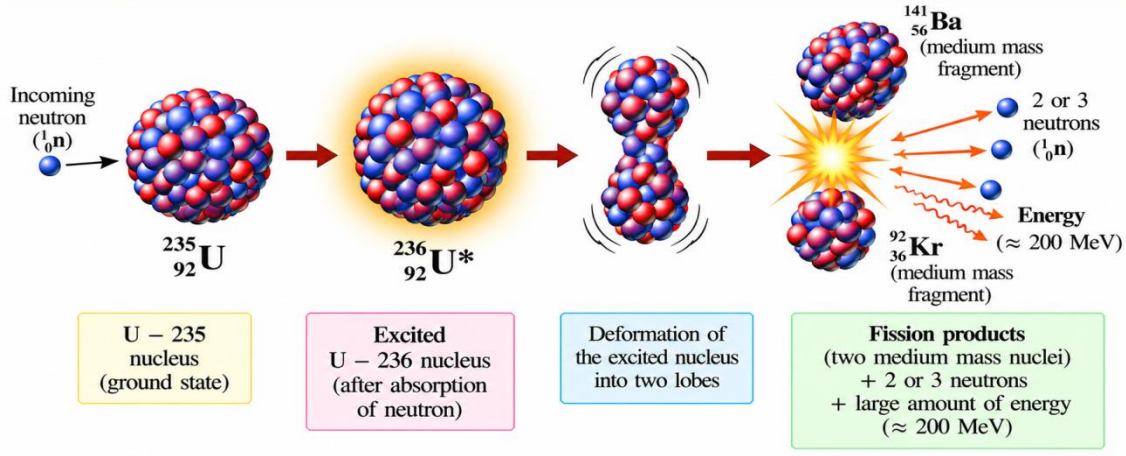
Reactants → Products + Energy

If: **M initial > M final** then the mass difference is: **Δm = M initial – M final** and the released energy is: **$Q = \Delta mc^2$**

If masses are in atomic mass units: **$Q(\text{MeV}) = \Delta m(u) \times 931.5$**

This is the basic numerical method for nuclear reaction energy.

Figure 13.10 : Nuclear Fission



5.5 Neutron-Induced Fission

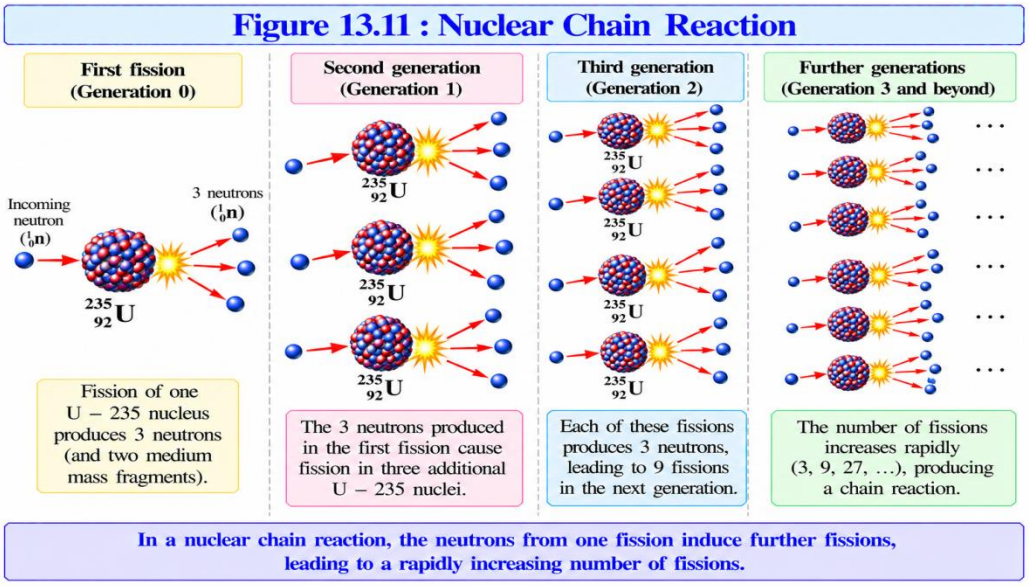
A slow neutron can be absorbed by U-235.
The resulting nucleus: **U-236*** is highly excited and unstable.
It can deform and split. This process is called: **Neutron-induced fission.**

5.6 Why Can One Fission Lead to More Fissions?

During fission, additional neutrons are released.
These neutrons can cause fission in other U-235 nuclei.
Thus one fission can initiate another.
This produces a: **Nuclear Chain Reaction**

5.7 Nuclear Chain Reaction

The sequence can be represented as:
One fission
↓
2–3 neutrons released
↓
These neutrons cause additional fissions
↓
More neutrons released
↓
Still more fissions
Thus the process can become self-sustaining.



5.8 Controlled and Uncontrolled Chain Reaction

Controlled chain reaction

The number of fissions is controlled so that the reaction proceeds at a manageable rate.
This principle is used in: **Nuclear reactors**

Uncontrolled chain reaction

If the reaction proceeds extremely rapidly without control, a very large amount of energy can be released in a short time.
For educational purposes, the key distinction is: **Reactor → controlled chain reaction**

5.9 Critical Mass

Critical mass is the minimum mass of fissile material required to sustain a nuclear chain reaction under specified conditions.
It depends on factors such as:

- material
- shape
- density
- neutron leakage
- surrounding materials

Therefore, critical mass is not simply a universal fixed number for every situation.

5.10 Subcritical, Critical and Supercritical States

Subcritical

Too many neutrons escape.
The chain reaction decreases.

Critical

The chain reaction is self-sustaining at a steady rate.

Supercritical

The number of neutrons increases from generation to generation.
In a reactor, the operating condition is controlled around the critical state.

5.11 Nuclear Reactor

A nuclear reactor is a system in which a controlled nuclear chain reaction is maintained to produce useful energy.
The main purpose is to convert:
Nuclear energy → Thermal energy → Mechanical energy → Electrical energy

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5.12 Main Components of a Nuclear Reactor

A typical reactor includes:

1. **Fuel**
2. **Moderator**
3. **Control rods**
4. **Coolant**
5. **Shielding**
6. **Heat exchanger / steam generator**
7. **Turbine**
8. **Generator**

5.13 Nuclear Fuel

The fuel contains a fissile material. Examples include isotopes such as:

- Uranium-235
- Plutonium-239

For the basic school-level discussion, U-235 is the standard example.
The fuel undergoes fission and releases energy.

5.14 Moderator

The moderator slows down fast neutrons. Common moderator materials include:

- ordinary water
- heavy water
- graphite

A moderator is important in reactor designs where slow neutrons are more effective in sustaining the desired fission chain reaction.

5.15 Control Rods

Control rods absorb neutrons. Common control materials include substances containing:

- cadmium
- boron
- hafnium

By adjusting the position of control rods, the neutron population and therefore the reactor power can be controlled.

Important

Control rods → absorb neutrons
Moderator → slows neutrons
Do not confuse these two functions.

5.16 Coolant

The coolant removes heat generated by fission. Examples include:

- water
- heavy water
- carbon dioxide
- helium
- liquid metals in some reactor designs

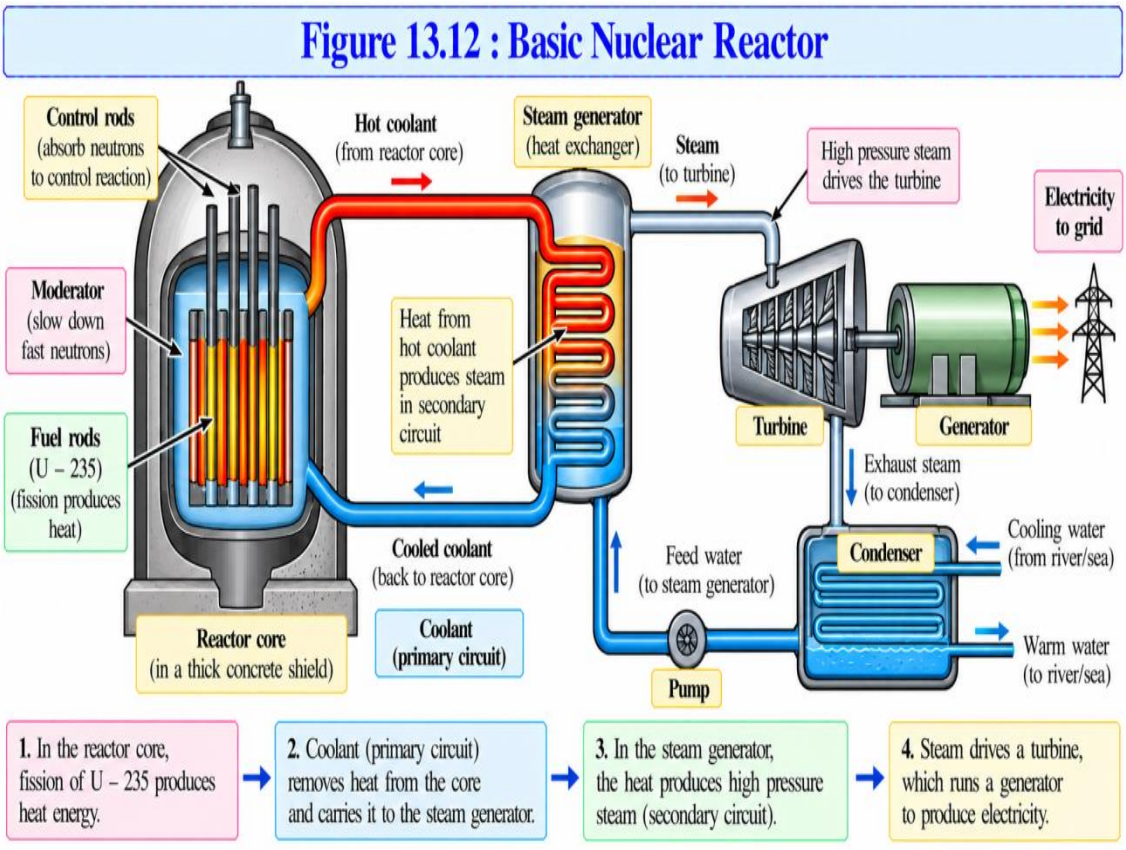
The choice depends on reactor design.

5.17 Shielding

Radiation shielding is used to reduce radiation exposure outside the reactor system.
Materials such as:

- concrete
- steel
- water

may be used in appropriate shielding structures.



5.18 Energy Conversion in a Reactor

The sequence is:

Nuclear energy

↓

Heat energy

↓

Steam energy

↓

Mechanical energy of turbine

↓

Electrical energy

This is an important conceptual question.

5.19 Nuclear Fusion

Nuclear fusion is the process in which two or more light nuclei combine to form a heavier nucleus, accompanied by energy release under suitable conditions.

The important example is fusion of hydrogen isotopes.

A simplified overall reaction is:

Hydrogen nuclei → Helium nucleus + energy

In stars, a chain of nuclear reactions converts hydrogen into helium.

5.20 Example of Fusion

One important fusion reaction is: $^{2}_{1}H + ^{3}_{1}H \rightarrow ^{4}_{2}He + ^{1}_{0}n + 17.6\ MeV$

This reaction involves:

- deuterium
- tritium

and produces:

- helium-4
- neutron
- approximately 17.6 MeV energy

This is a standard example used in nuclear physics.

5.21 Why Does Fusion Release Energy?

Light nuclei have relatively low binding energy per nucleon.

When they combine to form a nucleus with greater binding energy per nucleon:

B.E./A increases

Therefore: **Total binding energy increases** and energy is released.

Thus fusion is explained directly by the: **Binding Energy Curve**

5.22 Conditions Required for Fusion

Fusion requires nuclei to come sufficiently close for the strong nuclear force to act.

However, positively charged nuclei repel one another due to electrostatic force.

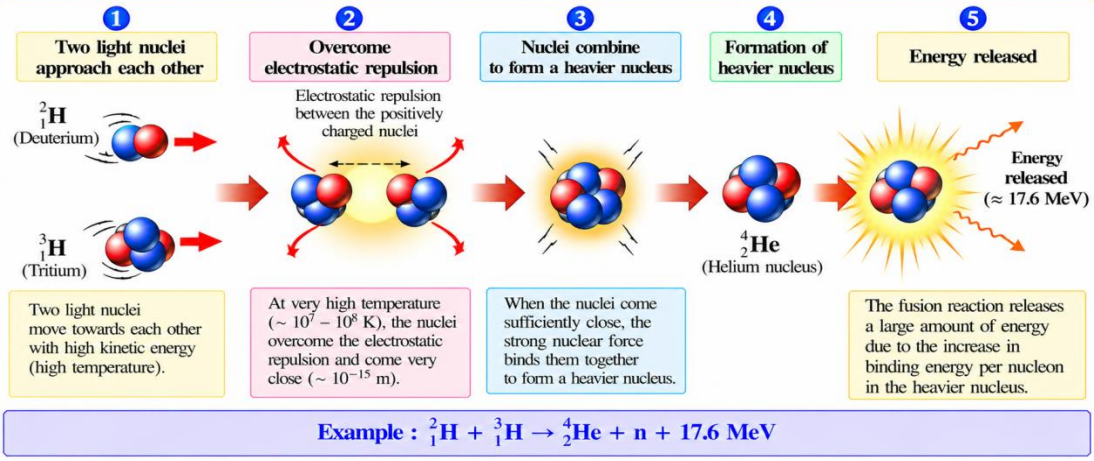
Therefore extremely high temperatures and suitable confinement conditions are required in practical fusion systems.

At very high temperatures, matter exists as a plasma.

5.23 Fusion in the Sun and Stars

The Sun produces energy through nuclear fusion.
In the broadest sense: **Hydrogen → Helium + Energy**
The released energy ultimately reaches Earth as radiation.
Fusion is therefore the fundamental energy source of the Sun and other main-sequence stars.

Figure 13.13 : Nuclear Fusion



5.24 Fission vs Fusion

Property	Fission	Fusion
Basic process	Heavy nucleus splits into medium-mass nuclei with higher binding energy per nucleon.	Light nuclei combine to form a more tightly bound nucleus with higher binding energy per nucleon.
Starting nuclei	Heavy	Light
Products	Medium-mass nuclei	Heavier nucleus
Energy source	Increase in B.E./A	Increase in B.E./A
Example	U-235 fission	D-T fusion
Chain reaction	Possible	Not a conventional chain reaction
Conditions	Controlled neutron-induced reaction in reactors	Very high temperature and confinement required
Natural example	Some radioactive nuclei undergo fission spontaneously	Stars

5.25 Important Difference

Fission-
One heavy nucleus → smaller nuclei
Fusion-
Small nuclei → larger nucleus

But both can release energy because the products can have: **higher binding energy per nucleon.**

5.26 Energy Released in Fusion

For the D-T reaction:

$$^{2}_{1}H + ^{3}_{1}H \rightarrow ^{4}_{2}He + ^{1}_{0}n + 17.6\ MeV$$

The energy can also be calculated from mass defect:

$$Q = \Delta mc^2$$

Or:

$$Q = \Delta m \times 931.5\ MeV$$

Where, Δm is the mass difference in atomic mass units.

5.27 Solved Examples

1. Fusion Energy

For a fusion reaction, suppose: Mass of reactants = 5.0300 u. Mass of products = 5.0110 u. Find the energy released.

Answer:

Step 1: Mass defect

Δm = 5.0300 − 5.0110 **= 0.0190 u**

Step 2: Energy

Q = 0.0190 × 931.5 ≈ **17.7 MeV**

Thus approximately: **17.7 MeV** is released.

---

2. Energy from Fission

Suppose the mass defect in a fission reaction is: **Δm = 0.20 u.** Find energy released.

Answer:

$Q = \Delta m \times 931.5$

Then: Q = 0.20 × 931.5

Or, **Q = 186.3 MeV**

Thus the energy release is approximately: **186 MeV**

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3. Total Energy from Many Fissions

Suppose one fission releases approximately: **200 MeV. Find the total energy.**

Answer:

Let n be the number of fission events.

Then:

Total energy = n × 200 MeV

To convert to joules: **1 eV = 1.602 × 10^{-19} J**

Therefore: **1 MeV = 1.602 × 10^{-13} J**

Hence: **E total = n × 200 × 1.602 × 10^{-13} J**

This is useful for JEE-level energy calculations.

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4. Q Value

Consider a nuclear reaction in which: Total binding energy of reactants: **150 MeV;** Total binding energy of products: **170 MeV. Find Q.**

Answer:

$$Q = B.E_{.Products} - B.E_{.Reactants}$$

Then: Q = 170 – 150 **= +20 MeV**
Therefore: **20 MeV is released.**

5.28 Nuclear Energy and Mass-Energy Equivalence

The energy released in nuclear reactions originates from the difference in rest mass between reactants and products.
The fundamental relation is: **$E = mc^2$**
For a nuclear reaction: **$Q = (M_{initial} - M_{final})c^2$**
If atomic masses are used appropriately: **$Q(MeV) = \Delta m(u) \times 931.5$**

5.29 Conservation of Mass Number

In a nuclear reaction:
Total mass number before = Total mass number after
For example: **$^{235}_{92}U + ^{1}_{0}n \rightarrow ^{141}_{56}Ba + ^{92}_{36}Kr + 3^{1}_{0}n$**
Check:
Left: 235 + 1 = 236
Right: 141 + 92 + 3 = 236
Therefore mass number is conserved.

5.30 Conservation of Charge

Similarly:
Total atomic number (charge) before = Total atomic number (charge) after
For: **$^{235}_{92}U + ^{1}_{0}n \rightarrow ^{141}_{56}Ba + ^{92}_{36}Kr + 3^{1}_{0}n$**
Left: 92 + 0 = 92
Right: 56 + 36 + 0 = 92
Therefore charge is conserved.

5.31 NEET/JEE Quick Concepts

Concept 1: Energy release is related to: **Increase in total binding energy.**

Concept 2: For nuclear reaction: **$Q = B.E._{products} - B.E._{reactants}$**

Concept 3: For mass difference: **$Q = \Delta mc^2$**

Concept 4: If Δm is in u: **$Q = \Delta m \times 931.5$ MeV**

Concept 5: Reactor: **controlled fission**

Concept 6: Sun: **fusion**

Concept 7: Moderator: **slows neutrons**

Concept 8: Control rods: **absorb neutrons**

PART 5 MASTER MEMORY LINE

"Fission splits heavy nuclei, fusion combines light nuclei; both can release energy because the products have greater binding energy per nucleon."

Remember four words for nuclear reactor: **Fuel → Moderator → Control Rods → Coolant**