FREE NOTES · NCERT + JEE/NEET LEVEL

Nuclei

Composition of the nucleus, size and density, mass defect, binding energy and its curve, nuclear force, radioactivity, half-life, fission and fusion. With graphs and solved numericals.

01 Composition of the nucleus
02 Isotopes, isobars, isotones
03 Nuclear size & density
04 Mass-energy & mass defect
05 Binding energy per nucleon curve
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07 Radioactivity
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01 Composition of the nucleus

A nucleus contains **protons** (Z) and **neutrons** (N), together called **nucleons**. Mass number A = Z + N. Written ${}^{A}_{Z}X$, e.g. ${}^{238}_{92}U$.

$1\ \text{u (atomic mass unit)} = 1.66 \times 10^{-27}\ \text{kg} = 931.5\ \text{MeV/c}^2$

$m_p = 1.00728\ \text{u},\ m_n = 1.00866\ \text{u}$

The neutron was discovered by Chadwick in 1932 (by bombarding beryllium with alpha particles).

02 Isotopes, isobars, isotones

Name	Same	Example
Isotopes	Z (protons)	${}^{1}H$, ${}^{2}H$, ${}^{3}H$; ${}^{12}C$, ${}^{14}C$
Isobars	A (mass number)	${}^{3}H$ and ${}^{3}He$
Isotones	N (neutrons)	${}^{198}Hg$ and ${}^{197}Au$ (118 each)

Isotopes have the same chemistry (same electrons) but different physics (different mass).

03 Nuclear size & density

$$R = R_0\ A^{(1/3)},\ R_0 \approx 1.2\ \text{fm}$$

1 fm (fermi) = 10^{-15} m. Volume ∝ A.

ALL NUCLEI HAVE THE SAME DENSITY!

Mass ∝ A and volume ∝ A ⇒ **nuclear density is about the same for every nucleus**: ≈ 2.3 × 10^{17} kg/m³ (10^{14} times water). A spoonful of nuclear matter would weigh billions of kilograms! (This happens in neutron stars.)

04 Mass-energy & mass defect

$$E = m\ c^2$$

Einstein: mass and energy can convert into each other. 1 u ⇒ 931.5 MeV.

MASS DEFECT

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

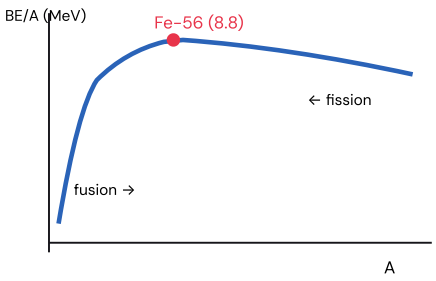
A nucleus has **less** mass than the sum of its separate nucleons. This "missing" mass is the binding energy.

BINDING ENERGY

$$BE = \Delta m \times 931.5\ \text{MeV}\ (\Delta m \text{ in u})$$

The energy needed to break the nucleus into separate nucleons. BE per nucleon = BE/A (a measure of stability).

05 Binding energy per nucleon curve



Medium nuclei (A ≈ 30–170) are the most stable

- Peak: **Fe-56** (≈ 8.8 MeV), the most stable.
- Nearly flat from A = 30 to 170 (≈ 8 MeV): evidence that the nuclear force is short-range.
- Light nuclei (A < 30) combine into larger ones ⇒ BE/A rises ⇒ energy released: **fusion**.
- Heavy nuclei (A > 170) split into smaller ones ⇒ energy released: **fission**.

06 Nuclear force

- The **strongest** force (~100 times the electric force).
- **Very short range** (~2–3 fm). Nothing beyond that.
- Charge-independent: the same between p–p, n–n and p–n.
- Becomes **repulsive** below ~0.8 fm (so the nucleus doesn't collapse).
- Saturation: each nucleon binds only to its near neighbours (so BE/A is nearly constant).

07 Radioactivity

An unstable nucleus spontaneously emits radiation to become more stable (discovered by Becquerel in 1896).

	Alpha (α)	Beta (β^-)	Gamma (γ)
What it is	He nucleus ^4_2He	Electron (+ antineutrino)	High-energy photon
Charge	+2e	-e	0
Effect on A, Z	$A-4, Z-2$	A same, $Z+1$	No change
Ionising power	Highest	Medium	Lowest
Penetrating power	Lowest (stopped by paper)	Medium (aluminium)	Highest (thick lead)

Inside the nucleus in β^- decay: $n \rightarrow p + e^- + \bar{\nu}$. In β^+: $p \rightarrow n + e^+ + \nu$ (Z - 1).

08 Decay law & half-life

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

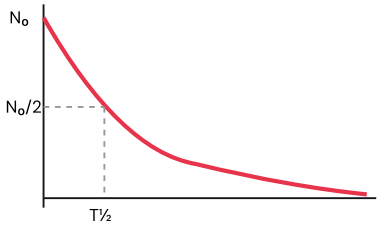
Activity $R = \lambda N = R_0\, e^{(-\lambda t)}$

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

Mean life $\tau = 1/\lambda = 1.44\, T_{1/2}$

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

Activity unit: becquerel (1 decay/s); curie = 3.7×10^{10} Bq.



Exponential decay

REMEMBER

Half-life doesn't depend on temperature, pressure or chemical state. You can't predict when a single atom will decay (random); the law holds only for many atoms. Carbon dating (C-14, $T_{1/2} \approx 5730$ years) uses this.

09 Nuclear fission

A heavy nucleus absorbs a neutron and splits into two medium nuclei, releasing energy and 2–3 new neutrons.

$$^{235}\mathrm{U} + \mathrm{n} \rightarrow {}^{141}\mathrm{Ba} + {}^{92}\mathrm{Kr} + 3\mathrm{n} + \sim 200\ \mathrm{MeV}$$

- The new neutrons can split more U ⇒ **chain reaction**.
- Uncontrolled ⇒ atom bomb. Controlled ⇒ **nuclear reactor** (electricity).
- In a reactor: the **moderator** (heavy water, graphite) slows neutrons; **control rods** (cadmium, boron) absorb extra neutrons; the **coolant** carries away heat.
- Multiplication factor K = 1: steady (critical). K > 1: grows (bomb).

10 Nuclear fusion

Light nuclei combine into a heavier nucleus, releasing energy. This powers the Sun and stars: hydrogen → helium.

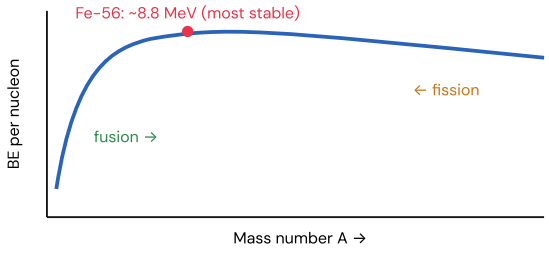
$$^{2}\mathrm{H} + {}^{3}\mathrm{H} \rightarrow {}^{4}\mathrm{He} + \mathrm{n} + 17.6\ \mathrm{MeV}$$

Bringing nuclei close requires overcoming repulsion ⇒ **very high temperatures** (~10^7 K) are needed: a **thermonuclear** reaction. Fusion releases more energy per nucleon than fission and leaves less radioactive waste.

11 JEE Extra + Tricks

JEE LEVEL

- Nuclear radius $R = R_0 A^{1/3}$ ($R_0 \approx 1.2$ fm) ⇒ nuclear density is the same for all nuclei (~2.3×10^{17} kg/m³).
- Decay: $N = N_0(½)^{t/T}$; mean life $\tau = 1/\lambda = 1.44\ T_{½}$; activity $A = \lambda N$.
- α decay: A − 4, Z − 2; β^-: Z + 1 (A same); γ: no change. Number of α = ΔA/4; β = 2α − ΔZ.
- Q-value = (mass of reactants − mass of products) × 931.5 MeV/u.
- BE per nucleon peaks near Fe-56 (~8.8 MeV): fusion of light and fission of heavy nuclei both release energy.



Binding energy per nucleon curve

12 Solved numericals

Q1. Radius of ^{27}Al? (R_o = 1.2 fm)
R = 1.2 × 27^(1/3) = 1.2 × 3 = 3.6 fm. **Ans: 3.6 fm**

Q2. ^4He has mass 4.0026 u. Binding energy? (m_p = 1.0073, m_n = 1.0087)
Δm = 2(1.0073) + 2(1.0087) − 4.0026 = 4.0320 − 4.0026 = 0.0294 u. BE = 0.0294 × 931.5 ≈ 27.4 MeV, per nucleon ≈ 6.8 MeV. **Ans: ≈ 27.4 MeV**

Q3. Z and A of ^{238}U after 1 α and 2 β^- decays?
α: A 234, Z 90. 2β^-: Z 92, A 234 ⇒ $^{234}_{92}U$ (an isotope). **Ans: A = 234, Z = 92**

Q4. Half-life 10 days. How much remains after 40 days?
n = 4 ⇒ $N_o/16$ = 6.25%. **Ans: 1/16**

Q5. Half-life 693 s. Decay constant and mean life?
λ = 0.693/693 = 10^{-3} s^{-1}. τ = 1000 s. **Ans: 10^{-3} s^{-1}, 1000 s**

Q6. Energy if 1 g of mass is fully converted?
E = 10^{-3} × 9 × 10^{16} = 9 × 10^{13} J. **Ans: 9 × 10^{13} J**

13 Common mistakes

- Thinking nuclear density depends on A (it's the same for all).
- Reducing A in β^- decay (A stays the same, Z + 1).
- Thinking half-life depends on temperature.
- Treating mean life and half-life as equal (τ = 1.44 T½).
- Reversing the directions of fusion and fission on the curve.

14 Formula sheet

Radius	$R = 1.2\ A^{(1/3)}\ \text{fm}$
Mass-energy	$E = mc^2,\ 1\ u = 931.5\ \text{MeV}$
Mass defect	$\Delta m = Zm_p + Nm_n - M$
Binding energy	$BE = \Delta m \times 931.5\ \text{MeV}$
Alpha / beta	$A - 4, Z - 2\ /\ Z + 1$
Decay law	$N = N_0 e^{(-\lambda t)},\ R = \lambda N$
Half-life, mean life	$0.693/\lambda,\ 1/\lambda$
After n half-lives	$N_0/2^n$

15 Practice questions

1. Ratio of radii of nuclei with A = 8 and A = 64?
2. Which nucleus is the most stable?
3. Source of the Sun's energy?
4. How many half-lives for 75% to decay?

ANSWERS

1) (8/64)^(1/3) = 1 : 2 · 2) Fe-56 · 3) Fusion (H → He) · 4) 2

16 Quick revision: 5 minutes before the exam

NUCLEUS

- R = 1.2 A^(1/3) fm; same density.
- Isotopes Z, isobars A, isotones N same.
- Nuclear force: strong, short-range, charge-independent.

ENERGY

- BE = Δm × 931.5 MeV.
- Peak Fe-56, ~8.8 MeV.
- Light ⇒ fusion; heavy ⇒ fission.

RADIOACTIVITY

- α: A − 4, Z − 2; β^-: Z + 1.
- Ionising α > β > γ; penetration reversed.
- $T_{1/2} = 0.693/\lambda$; $\tau = 1/\lambda$.

REACTOR

- Moderator: slows neutrons.
- Control rods: absorb neutrons.
- Fusion: ~10^7 K.

Have a doubt? Ask the AI Doubt Solver at padhaiadda.netlify.app, or take the mock test on this chapter.