FREE EDITION · NOTES + 3 SAMPLE MCQS

CUET · PHYSICS · CLASS XII · CODE 322

Nuclei

CUET unit: Nuclei

By **UniDrill** · NCERT-grounded study material

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📌 Snapshot

- Establishes the nucleus as the tiny (radius ~10^{-15} m), dense (~10^{17} kg/m^3) core that holds >99.9% of an atom's mass, with composition described by Z (protons) and N (neutrons).
- Introduces the atomic mass unit (1 u = 1.660539 × 10^{-27} kg ≡ 931.5 MeV/c^2) and the nuclear size law R = R_0A^(1/3), R_0 = 1.2 fm, which implies constant nuclear density.
- Develops Einstein's mass–energy relation E = mc^2 and uses it to define mass defect ΔM = [Zm? + (A–Z)m?] – M and binding energy Eb = ΔM·c^2; the BE/nucleon curve (peak ~8.75 MeV near A = 56) explains why fission of heavy nuclei and fusion of light nuclei both release energy.
- Describes nuclear force (short range ~few fm, strong, charge-independent, attractive beyond ~0.8 fm and strongly repulsive within, saturation) and the three radioactive decays (α, β, γ).
- Covers nuclear energy: fission of ^{235}U (~200 MeV per fissioning nucleus, basis of reactors and the atom bomb) and thermonuclear fusion (p-p cycle in the sun, 26.7 MeV per 4^{1}H → ^{4}He; basis of stellar energy and controlled fusion research).
- CUET tests numerical estimation (BE, nuclear density, Q-value, R-ratio), conceptual recall (definitions, force properties, decay types) and the binding-energy-curve reasoning.

📖 Detailed Notes

2.1 Core concepts

- The nucleus is ~10^4 times smaller in radius than the atom; its volume is ~10^{-12} times the atomic volume, yet it carries more than 99.9% of the atom's mass (NCERT §13.1, p. 306).
- Atomic mass unit (u) is defined as 1/12 the mass of a ^{12}C atom; 1 u = 1.660539 × 10^{-27} kg (NCERT §13.2, p. 306–307, Eq. 13.1).
- Atomic masses are measured by a mass spectrometer, which also reveals isotopes — atoms of the same element with the same chemical properties but different masses (NCERT §13.2, p. 307).

- Chlorine has two isotopes of masses 34.98 u and 36.98 u with abundances 75.4% and 24.6%; weighted average ≈ 35.47 u (NCERT §13.2, p. 307).
- Hydrogen has three isotopes (1.0078 u, 2.0141 u, 3.0160 u): protium, deuterium, tritium; tritium is unstable and made artificially (NCERT §13.2, p. 307).
- Proton mass m_p = 1.00727 u = 1.67262×10^{-27} kg; carries +e; number of protons = Z (atomic number) (NCERT §13.2, p. 307–308, Eq. 13.2).
- Neutron was discovered by James Chadwick (1932) when α-bombardment of beryllium produced neutral radiation that could knock protons out of light nuclei; neutron mass m_n = 1.00866 u = 1.6749×10^{-27} kg (NCERT §13.2, p. 308, Eq. 13.3).
- A free neutron is unstable (mean life ~1000 s) and decays into a proton, an electron and an antineutrino; it is stable inside the nucleus (NCERT §13.2, p. 308).
- Composition: Z = number of protons, N = number of neutrons, A = Z + N = mass number = total number of nucleons; nuclide notation $^{A}_{Z}X$ (NCERT §13.2, p. 308, Eq. 13.4).
- Isotopes (same Z, different N), isobars (same A), isotones (same N); gold has 32 isotopes from A = 173 to 204 (NCERT §13.2, p. 309).
- Size of nucleus: from electron and α-scattering, $R = R_0 A^{1/3}$ with R_0 = 1.2 fm; therefore volume ∝ A and nuclear density is constant, ≈ 2.3×10^{17} kg/m^3, independent of A (NCERT §13.3, p. 309, Eq. 13.5).
- Nuclear matter density (~10^{17} kg/m^3) is comparable to that of neutron stars and ~10^{14} times that of water (10^3 kg/m^3) (NCERT §13.3, p. 309 and Example 13.1, p. 310).
- Einstein's mass–energy relation $E = mc^2$ ($c \approx 3 \times 10^8$ m/s) shows mass is a form of energy; 1 g of matter is equivalent to 9×10^{13} J (NCERT §13.4.1, p. 310, Eq. 13.6 and Example 13.2).
- Mass defect $\Delta M = [Zm_p + (A - Z)m_n] - M$; for ^{16}O the measured nuclear mass (15.99053 u) is 0.13691 u less than constituent total (16.12744 u) (NCERT §13.4.2, p. 310–311, Eq. 13.7).
- Binding energy $E_b = \Delta M \cdot c^2$; energy needed to break a nucleus into its constituent nucleons. 1 u = 931.5 MeV/c^2; ΔM for ^{16}O ≡ 127.5 MeV (NCERT §13.4.2, p. 311, Eq. 13.8 and Example 13.3).
- Binding energy per nucleon $E_{bn} = E_b/A$; for the curve E_{bn} vs A: maximum ~8.75 MeV at A = 56, and 7.6 MeV at A = 238; E_{bn} is practically constant for $30 < A < 170$ and lower for light ($A < 30$) and heavy ($A > 170$) nuclei (NCERT §13.4.2, p. 312, Eq. 13.9, Fig. 13.1).
- Constancy of E_{bn} in the middle range is a consequence of saturation: a given nucleon interacts only with its near neighbours within the short range of the nuclear force (NCERT §13.4.2, p. 312–313).

- A heavy A = 240 nucleus splitting into two A = 120 fragments releases energy (fission); two light nuclei ($A \leqslant 10$) fusing into a heavier one also release energy (fusion — source of the sun's energy) (NCERT §13.4.2, p. 313).
- Nuclear force: (i) much stronger than Coulomb and gravitational forces between the same particles; (ii) very short range — falls rapidly to zero beyond a few fm, leading to saturation; potential energy minimum near $r_0 \approx 0.8$ fm — attractive for $r > 0.8$ fm, strongly repulsive for $r < 0.8$ fm; (iii) charge-independent (n-n, p-n and p-p nuclear forces are approximately equal); has no simple mathematical form (NCERT §13.5, p. 313–314, Fig. 13.2).
- Radioactivity was discovered by A. H. Becquerel in 1896 by accident — uranium-potassium sulphate blackened a wrapped photographic plate (NCERT §13.6, p. 314).
- Three natural radioactive decays: (i) α-decay (emission of a helium nucleus ^4_2He); (ii) β-decay (emission of electrons or positrons — particles with the same mass as electrons but opposite charge); (iii) γ-decay (emission of high-energy photons of hundreds of keV or more) (NCERT §13.6, p. 314).
- For the same mass of fuel, nuclear sources produce $\sim 10^6$ times more energy than chemical sources: 1 kg of ^{235}U fission yields $\sim 10^{14}$ J versus $\sim 10^7$ J from 1 kg of coal burning (NCERT §13.7, p. 314).
- Fission of ^{235}U by a thermal neutron produces intermediate-mass fragments and 2–4 more neutrons; e.g. $^1_0n + ^{235}_{92}U \rightarrow ^{236}_{92}U \rightarrow ^{144}_{56}Ba + ^{89}_{36}Kr + 3\ ^1_0n$; fragments are radioactive and emit β to reach stable end products. $Q \approx 200$ MeV per fission (estimated as $240 \times 0.9 \approx 216$ MeV from the Ebn curve) (NCERT §13.7.1, p. 315, Eqs. 13.10–13.12).
- Disintegration energy in fission first appears as kinetic energy of fragments and neutrons, then transfers to surroundings as heat; nuclear reactors use controlled fission, atom bombs use uncontrolled fission (NCERT §13.7.1, p. 315).
- Fusion releases energy when light nuclei combine: e.g. $^1_1H + ^1_1H \rightarrow ^2_1H + e^+ + \nu + 0.42$ MeV; $^2_1H + ^2_1H \rightarrow ^3_2He + n + 3.27$ MeV; $^2_1H + ^2_1H \rightarrow ^3_1H + ^1_1H + 4.03$ MeV (NCERT §13.7.2, p. 315, Eq. 13.13).
- For fusion the two positively charged nuclei must overcome the Coulomb barrier (~400 keV for two protons), requiring temperatures $\sim 3 \times 10^9$ K from $(3/2)kT \approx 400$ keV; this is called thermonuclear fusion (NCERT §13.7.2, p. 316).
- The sun's interior is at 1.5×10^7 K — lower than the average value above, so fusion in the sun involves high-energy protons of the tail of the distribution; the p–p cycle effectively converts $4\ ^1H + 2e^- \rightarrow ^4_2He + 2\nu + 6\gamma + 26.7$ MeV (NCERT §13.7.2, p. 316, Eqs. 13.14–13.15).
- Once the sun's hydrogen depletes (~5×10^9 y from now), the core will collapse, heat further, and ignite helium → carbon fusion (~10^8 K); successively higher elements can form in stellar cores, but no element heavier than the Ebn-peak region can be produced by fusion (NCERT §13.7.2, p. 316–317).

- Controlled thermonuclear fusion aims at steady power at ~10^8 K; the fuel becomes a plasma (ions + electrons) that must be confined without a material container — a challenge being pursued internationally including India (NCERT §13.7.3, p. 317).
- A summary table lists the physical quantities atomic mass unit (u), decay constant λ (s^{-1}), half-life $T_{1/2}$ (s), mean life τ (s) — the time at which the number of nuclei is reduced to e^{-1} of the initial value — and activity R (Bq) (NCERT Summary table, p. 319).
- Stability requires the n:p ratio to be near 1:1 for light nuclei, rising to about 3:2 for heavy nuclei (extra neutrons offset proton repulsion); only ~10% of known isotopes are stable (NCERT Points to Ponder #8, p. 320).
- The chain-reaction picture for ^{235}U: each fission releases 2–3 neutrons that can in turn fission other ^{235}U nuclei; if at least one neutron per fission causes the next, the reaction sustains. A nuclear reactor uses moderators (e.g. heavy water) to slow neutrons to thermal energies where the ^{235}U fission cross-section is largest, and control rods (e.g. cadmium) to absorb excess neutrons (NCERT §13.7.1, p. 315; Summary p. 319).
- The thermonuclear-fusion path in the sun's core (the proton–proton chain) is slow because it requires the weak-interaction conversion of two protons into a deuteron with positron and neutrino emission; that slowness gives the sun a stable ~10^{10}-y main-sequence lifetime (NCERT §13.7.2, p. 316).
- Q-value of a nuclear reaction is the c^2 times the difference between initial and final rest masses; $Q > 0$ indicates an exothermic (energy-releasing) reaction, $Q < 0$ an endothermic one that requires energy input. The same definition applies to α, β, γ decays and to fission/fusion (NCERT Summary point 9, p. 319).
- Activity of a radioactive sample $R = \lambda N$ decays per second; SI unit becquerel (Bq). The older unit curie (Ci) ≡ 3.7×10^{10} Bq, originally the activity of 1 g of ^{226}Ra. Half-life $T_{1/2}$ and mean life τ are related by $T_{1/2} = \tau \ln 2 \approx 0.693\,\tau$ (NCERT Summary table p. 319).

2.2 Definitions to memorise

Term	Definition	Page
Atomic mass unit (u)	1/12 of the mass of one ^{12}C atom; 1 u = 1.660539×10^{-27} kg = 931.5 MeV/c^2	306–307, 311
Isotope	Atomic species of the same element (same Z) differing in mass (different N)	307, 309
Isobar	Nuclides with the same mass number A (e.g. $^3_1$H and $^3_2$He)	309
Isotone	Nuclides with the same neutron number N but different Z (e.g. $^{198}_{80}$Hg and $^{197}_{79}$Au)	309
Nucleon	A proton or a neutron; total nucleons = mass number A	308

Term	Definition	Page
Mass number A	A = Z + N, total number of protons and neutrons	308
Nuclear radius	$R = R_0A\text{^}(1/3)$; R_0 = 1.2 fm	309
Mass defect ΔM	ΔM = [Zm⍰ + (A − Z)m⍰] − M (always positive)	311
Binding energy Eb	$E_b = \Delta M \cdot c^2$ — energy needed to separate a nucleus into its nucleons	311
Binding energy per nucleon Ebn	Eb / A — average energy per nucleon to separate nucleus	312
Nuclear force	Strong, short-range, charge-independent attractive force binding nucleons; saturates	313–314
α-decay	Decay emitting $^{4}_{2}He$	314
β-decay	Decay emitting an electron or a positron	314
γ-decay	Decay emitting a high-energy photon (hundreds of keV or more)	314
Fission	Heavy nucleus splits into two intermediate-mass fragments + neutrons	315
Thermonuclear fusion	Fusion at very high temperature so nuclei overcome Coulomb barrier	316
Q-value	Q = (sum of initial masses − sum of final masses)c^2	319
Half-life $T_{1/2}$	Time taken for one-half of the initial nuclei to decay	319
Mean life τ	Time at which N is reduced to e^{-1} of initial value	319
Activity R	Measure of activity of a radioactive source (Bq = s^{-1})	319
Decay constant λ	Disintegration constant (s^{-1})	319
Proton (m⍰)	Hydrogen nucleus; charge +e, mass 1.00727 u	307–308
Neutron (m⍰)	Neutral nucleon discovered by Chadwick (1932); mass 1.00866 u	308
Z (atomic number)	Number of protons in the nucleus	308
N (neutron number)	Number of neutrons in the nucleus	308
Chain reaction	Self-sustaining series of fissions in which neutrons from one event trigger the next	315
Moderator	Material (e.g. heavy water) used in a reactor to slow fast neutrons to thermal energies	319
Saturation of nuclear force	Each nucleon interacts only with its nearest neighbours within the short range of the strong force	312–314

2.3 Diagrams / processes to remember

- **Fig. 13.1 — Binding energy per nucleon vs mass number A**: peak ~8.75 MeV at A = 56 (Fe-56 region), 7.6 MeV at A = 238, low for A < 30; flat for 30 < A < 170. Use to argue why fission of heavy and fusion of light nuclei release energy (NCERT p. 312).
- **Fig. 13.2 — Nucleon-nucleon potential energy vs separation**: minimum near $r_0 \approx$ 0.8 fm; attractive for $r > r_0$, strongly repulsive for $r < r_0$, force vanishes beyond a few fm (NCERT p. 313).
- **Mass spectrometer**: experimental basis of accurate atomic-mass measurement and isotope detection (NCERT §13.2, p. 307).
- **Geiger–Marsden α-scattering**: distance of closest approach of a 5.5 MeV α to gold $\approx 4.0 \times 10^{-14}$ m, giving an upper bound on nuclear size (NCERT §13.3, p. 309).
- **Chadwick's experiment**: $\alpha + {}^{9}Be \rightarrow$ neutron emission; energy-momentum conservation proves neutral particle (not photon) of mass ≈ proton mass (NCERT §13.2, p. 308).
- **^{235}U fission scheme**: $n + {}^{235}U \rightarrow {}^{236}U^* \rightarrow {}^{144}Ba + {}^{89}Kr + 3n$ (and other channels), Q ≈ 200 MeV/fission (NCERT §13.7.1, p. 315).
- **Solar p-p cycle**: net reaction $4\,{}^{1}H + 2e^- \rightarrow {}^{4}He + 2\nu + 6\gamma + 26.7$ MeV (NCERT §13.7.2, p. 316).

2.4 Common confusions / NTA trap points

- Mass defect formula uses the **proton and neutron masses** (m?, m?) when M is the **nuclear** mass; if atomic masses (including electrons) are used, the electron masses must cancel — students often mix the two conventions. NCERT computes ^{16}O nuclear mass = 15.99053 u after subtracting 8 electron masses from 15.99493 u (NCERT §13.4.2, p. 311).
- $R_0 = 1.2 \times 10^{-15}$ m = 1.2 fm — distractors often quote 1.2×10^{-14} m or 1.2×10^{-13} m. $R \propto A^{1/3}$, so volume ∝ A and **density is independent of A** (NCERT §13.3, p. 309).
- Nuclear force is **charge-independent** ($F_{nn} \approx F_{np} \approx F_{pp}$ as nuclear forces). NTA traps say "nuclear force is electromagnetic" or "depends on charge" — both wrong (NCERT §13.5, p. 314).
- The Ebn peak is near **A = 56** at ~8.75 MeV, NOT at uranium or at A = 238 (where Ebn = 7.6 MeV). Confusing the peak with the high-A end is a classic trap (NCERT §13.4.2, p. 312).
- β-decay emits **electrons OR positrons** — not "protons" or "alpha"; positrons have the **same mass as electrons** and opposite charge (NCERT §13.6, p. 314).
- A **free neutron** decays with mean life ~1000 s; **bound** neutrons inside a nucleus are stable. NTA may swap this with "neutron is always stable" or "proton decays" (NCERT §13.2, p. 308).

- The Coulomb-barrier estimate for two protons (~400 keV) gives an "average" temperature of ~3×10^9 K; the sun's interior is only 1.5×10^7 K — fusion proceeds via the tail of the distribution, **not** because the average proton energy is sufficient (NCERT §13.7.2, p. 316).
- Half-life $T_{1/2}$ and mean life τ are **different**: mean life is the time at which N falls to e^{-1} of the initial value, not to half (NCERT Summary table, p. 319).
- Confusing **atomic mass** (includes electron masses) with **nuclear mass** (no electrons) when computing ΔM and Eb. Atomic-mass tables include Z electrons; if both sides of the reaction have the same number of electrons, they cancel and atomic masses can be used directly.
- The Ebn curve is sometimes drawn upside down by students. The peak is at the **top** (~8.75 MeV at $A \approx 56$); deeper binding → larger Ebn → greater stability.
- For ^{235}U the fission is induced by a **thermal** (slow) neutron — not a fast one. Fast neutrons mostly cause inelastic scattering off ^{238}U.
- Saturation of the nuclear force is what makes **Eb roughly linear in A** (so Ebn is constant) — many students wrongly think saturation refers to the n:p ratio.
- The decay $^4_2$He emitted in α-decay is the **doubly charged helium-4 nucleus**; the daughter has Z − 2 and A − 4 compared with the parent. Be careful with charge/mass bookkeeping.

2.5 Key formulas table

Quantity	Symbol / Formula	NCERT reference
Atomic mass unit	$1\ u = 1.660539 \times 10^{-27}$ kg = 931.5 MeV/c^2	§13.2, Eq. 13.1, p. 306–307
Mass number	$A = Z + N$	§13.2, Eq. 13.4, p. 308
Nuclide notation	^A_ZX	§13.2, p. 308
Nuclear radius	$R = R_0$ A^(1/3); $R_0 = 1.2$ fm	§13.3, Eq. 13.5, p. 309
Nuclear density	$\rho = 3\ m_{?} / (4\pi R_0^3) \approx 2.3 \times 10^{17}$ kg/m^3	§13.3, Ex. 13.1, p. 310
Einstein mass–energy	$E = mc^2$	§13.4.1, Eq. 13.6, p. 310
Mass defect	$\Delta M = [Z\ m_{?} + (A - Z)\ m_{?}] - M$	§13.4.2, Eq. 13.7, p. 311
Binding energy	$Eb = \Delta M \cdot c^2$	§13.4.2, Eq. 13.8, p. 311
Binding energy per nucleon	$Ebn = Eb / A$	§13.4.2, Eq. 13.9, p. 312
Peak Ebn	~8.75 MeV at $A \approx 56$	§13.4.2, Fig. 13.1, p. 312
Equilibrium separation in nuclear force	$r_0 \approx 0.8$ fm	§13.5, Fig. 13.2, p. 313
Q-value of nuclear reaction	$Q = (\Sigma$ m_initial $- \Sigma$ m_final$)\ c^2$	Summary 9, p. 319

Quantity	Symbol / Formula	NCERT reference
^{235}U fission energy	Q ≈ 200 MeV per fission	§13.7.1, p. 315
Solar p-p net reaction	$4\,^{1}H + 2e^{-} \rightarrow \,^{4}He + 2\nu + 6\gamma$ + 26.7 MeV	§13.7.2, Eq. 13.14–13.15, p. 316
Coulomb barrier for two protons	≈ 400 keV	§13.7.2, p. 316
Required fusion temperature	$T \approx 3 \times 10^{9}$ K (avg)	§13.7.2, p. 316
Half-life ↔ mean life	$T_{1/2} = \tau \ln 2 \approx 0.693\ \tau$	Summary, p. 319
Activity	$R = \lambda N$	Summary, p. 319
SI unit of activity	becquerel Bq = decay/s	Summary, p. 319
Curie	$1\ Ci = 3.7 \times 10^{10}$ Bq	Summary, p. 319
Mass equivalent	$1\ g \equiv 9 \times 10^{13}$ J	§13.4.1, Ex. 13.2, p. 310

🎯 Practice MCQs

📊 PYQ Alignment

Across CUET (UG) 2023–2025, Nuclei has consistently delivered ~8–12 MCQs per year for Physics aspirants. The standard mix is: a direct numerical on nuclear radius ratio (R ∝ A^(1/3)), a binding-energy calculation using ΔM and 1 u = 931.5 MeV/c^2, a recall question on the Ebn curve peak (A ≈ 56, ~8.75 MeV), a definition-based question separating isotopes/isobars/isotones, a property-of-nuclear-force statement question, a match-the-column on $\alpha/\beta/\gamma$ decays, and an assertion–reason on fission/fusion energetics. Numerical estimation of nuclear density and Q-value of a given reaction are also routine.

CUET 2025 — Actual PYQs from this chapter

Q.43 (CUET 2025) Which statements about nuclear properties are correct? (A) Nuclear radius $R = R_0 A^{1/3}$ (B) Nuclear volume ∝ mass number (C) Density increases with radius (D) Density independent of mass number Choose correct option:

- A) (A), (B), (C) B) (A), (B), (D) C) (A), (D) D) (B), (C) Tests: Nuclear radius, volume and density — $R = R_0 A^{(1/3)}$, ρ independent of A Answer: Not in extracted key

Q.45 (CUET 2025) Which statements about nuclear forces are correct? (A) Electrostatic repulsion between protons can exceed nuclear force (B) Electrostatic repulsion is smaller in small nuclei (C) Gravitational force between nucleons is much smaller than nuclear force (D) Binding energy per nucleon constant because nuclear force is long-range Choose correct option:

- A) (A) and (D) B) (B) and (C) C) (C) and (D) D) (A) only Tests: Nuclear force vs Coulomb force, gravitational force; binding energy per nucleon Answer: Not in extracted key

Q.49 (CUET 2025) In the nuclear reaction n + ^{235}U → ^{140}Xe + ^{94}Sr + 2n Values of a and b are:

- A) a = 38, b = 94 B) a = 94, b = 38 C) a = 94, b = 40 D) a = 96, b = 38 Tests: Nuclear fission of ^{235}U — conservation of A and Z (a = 94, b = 38) Answer: Not in extracted key

CUET 2024 — Actual PYQs from this chapter

Q.27 (CUET 2024) Density ratio of nuclei with mass numbers A and B:

- A) A:B B) √A:√B C) A^2:B^2 D) 1:1 Tests: Constancy of nuclear density (independent of A) Answer: Not in extracted key

CUET 2023 — Actual PYQs from this chapter

Q.36 (CUET 2023) Energy released when two nuclei of masses (m_1) and (m_2) combine to form nucleus of mass (M):

- A) ((m_1 + m_2 - M)c^2) B) ((M - (m_1 + m_2))c^2) C) ((M - m_1 + m_2)c^2) D) ((M + m_1 - m_2)c^2) Tests: Mass defect and Q-value: $\Delta E = (m_1 + m_2 - M)c^2$ Answer: Not in extracted key

Q.37 (CUET 2023) The nuclear force is:

- A) Strong, short range, charge independent B) Attractive, long range C) Strong, attractive and charge dependent D) Strong, short range and repulsive Tests: Properties of nuclear force Answer: Not in extracted key

Q.39 (CUET 2023) Match the following nuclear reactions. List I List II A. (^{222}Rn → ^{218}Po) α particle B. (^{214}Bi → ^{214}Po) β particle C. (^{234}Th → ^{234}U) γ particle D. (^{22}Na → ^{22}Ne) β^+ particle Options:

- A) A-II, B-III, C-IV, D-I B) A-III, B-II, C-IV, D-I C) A-II, B-I, C-IV, D-III D) A-I, B-III, C-II, D-IV Tests: α, β, γ decays — daughter nuclei Answer: Not in extracted key