Unit 24 · Nuclear Physics

STUDY NOTES

WHAT NEB'S GRADE 11 EXAM ASKS

- **CDC's grid (2077):** Modern Physics (Units 24–26 together): 9 of 75 marks
- **The paper:** 11 MCQs × 1 · 8 short × 5 · 3 long × 8; 3 hours; 1 mark per expected point
- **MCQ (1 mark)**
  - what alpha scattering does or doesn't show; paths near a nucleus
  - protons, neutrons, isotopes; the most stable nucleus on the curve
  - binding energy per nucleon from a mass defect (× 931.5, ÷ A)
- **Long (8 marks, in parts)**
  - Rutherford's experiment: observations, conclusions; the nucleus's size from the alpha's kinetic energy (CDC's model paper: 2.00×10^{-10} J, gold Z = 79), and why the real radius is smaller
- **Short (5 marks, in parts)**
  - mass defect and binding energy of a nucleus; nuclear masses, not atomic
  - sketch the binding-energy curve; why fission and fusion both give energy
  - balance a reaction; energy from masses $(m_i - m_f)c^2$
  - chain reaction; fusion's conditions; the p–p chain

Key terms

Nucleus: tiny center holding all the + charge and nearly all the mass.

Distance of closest approach: where a head-on alpha stops; upper limit of the nuclear radius.

Nucleon: proton or neutron.

Atomic (proton) number Z: protons. **Mass (nucleon) number** A: nucleons. **Neutron number** $N = A - Z$.

Nuclide: a nucleus with given Z and N, written ${}^{A}_{Z}\mathrm{X}$.

Isotopes: same Z, different N. **Isotones**: same N. **Isobars**: same A.

Atomic mass unit (u): $\frac{1}{12}$ of a carbon-12 atom = 1.66×10^{-27} kg ≡ 931.5 MeV.

Mass defect (Δm): mass of the separate nucleons minus the nucleus's mass.

Binding energy: least energy to pull a nucleus apart into its nucleons; $\Delta m\, c^2$.

Binding energy per nucleon: binding energy ÷ A; how tightly bound.

Strong nuclear force: attraction between nucleons, range ≈ 1 fm.

Annihilation: particle + antiparticle → photons. **Pair production**: photon → particle + antiparticle.

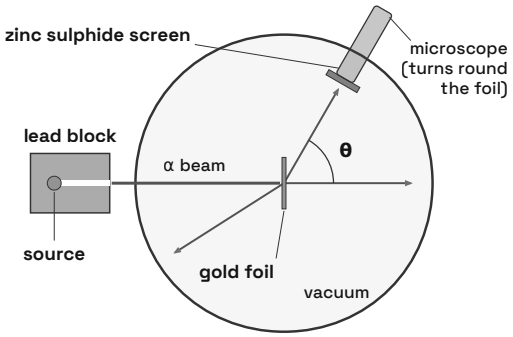
Fission: heavy nucleus splits into two of comparable mass. **Fusion**: light nuclei join.

Chain reaction: neutrons from one fission cause the next; **multiplication factor** k.

Formulas

$d = \dfrac{k(2e)(Ze)}{E_K} = \dfrac{2kZe^2}{E_K}$	head-on, $E_K = E_P$ **Use:** closest approach
$N = A - Z$	A nucleons, Z protons **Use:** neutrons
$R = r_0 A^{1/3}$	$r_0 \approx 1.2$ fm **Use:** nuclear radius
$E = mc^2,\ \Delta E = \Delta m\, c^2$	$c = 3.00 \times 10^8$ m/s **Use:** mass–energy
$\Delta m = Zm_p + Nm_n - m_{nucleus}$	nuclear masses **Use:** mass defect
$\mathrm{BE} = \Delta m\, c^2 = \Delta m(\mathrm{u}) \times 931.5$ MeV	1 MeV = 1.6×10^{-13} J **Use:** binding energy
$\Delta E = (m_i - m_f)c^2$	before − after **Use:** energy released

Rutherford's experiment



Alpha beam from a source in lead → thin gold foil → zinc sulphide screen on a microscope, turned to every angle θ.

- alpha = helium nucleus, +2e, ≈ 5% of c

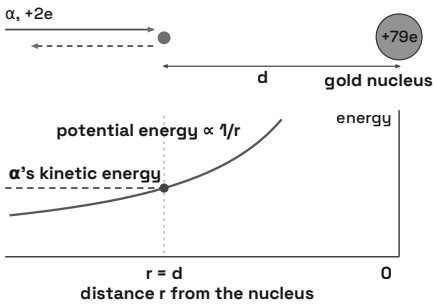
- gold: beaten thinnest; **thin foil** so each alpha meets at most one nucleus
- Geiger and Marsden (1909–13) counted flashes (scintillations) by eye

Observations → conclusions

1. most pass straight → atom mostly **empty**
2. a few turned through large angles → + charge and mass in a **tiny** center
3. about 1 in 8000 over 90° → huge force from one heavy, **positive** nucleus

- paths: pushed **away**; aimed closer → turned **more**

Closest approach



Head-on: the alpha slows; at d all its E_K is E_P.

1. $E_K = E_P$ at d
2. $E_P = \dfrac{k(2e)(Ze)}{d}$
3. $d = \dfrac{2kZe^2}{E_K}$

- alpha never touches → nucleus radius **less than** d; doubling E_K halves d
- 4.0 MeV on gold → 5.7×10^{-14} m; 7.7×10^{-13} J → 4.7×10^{-14} m
- real gold radius ≈ 7×10^{-15} m (fast electrons); nuclei ≈ 10^{-15} m, atoms ≈ 10^{-10} m

Atom, nuclides, units

- proton found 1919 (Rutherford); neutron 1932 (Chadwick): helium 2 × charge, 4 × mass
- electrons in a cloud, not planet-like orbits
- $^{16}_{8}$O: 8 p, 8 n; $^{56}_{26}$Fe: 26 p, 30 n
- particles: $^{1}_{1}$p, $^{1}_{0}$n, $^{0}_{-1}$e, $^{0}_{+1}$e, $^{4}_{2}$He, γ, ν
- isotopes: same chemistry (same electrons); ^{1}H, ^{2}H, ^{3}H
- memory: isoto**p**es **p**rotons, isoto**n**es **n**eutrons, isob**a**rs **A**
- $1\text{ u} = \dfrac{1}{6.02 \times 10^{26}}\text{ kg} = 1.66 \times 10^{-27}\text{ kg}$
- m_p 1.007 276 u, m_n 1.008 665 u, m_e 0.000 549 u
- **atomic** mass includes Z electrons; nucleus = atomic − Zm_e

Size and density

- $V = \frac{4}{3}\pi r_0^3 A \propto A$: nucleons packed like marbles
- density $= \dfrac{1\text{ u}}{\frac{4}{3}\pi r_0^3} \approx 2.3 \times 10^{17}\text{ kg/m}^3$, the **same** for all nuclei (A cancels)
- gold-197: 7.0 fm; uranium-238: 7.4 fm, 3.9 × helium-4

Mass and energy

- He nucleus 6.6447×10^{-27} kg vs 2p + 2n 6.6950×10^{-27} → 5.03×10^{-29} kg → 4.53×10^{-12} J = 28.3 MeV
- energy has mass: hot tea, stretched spring, moving car
- e.g. torch 10 W for 10 h → 4.0×10^{-12} kg; 9.0×10^{13} J → 1.0×10^{-3} kg; 5.0×10^{13} J → 5.6×10^{-4} kg
- 1 u × c^2 = 1.492×10^{-10} J = **931.5 MeV**
- mass–energy conserved in a closed system

Annihilation and pair production

- $e^- + e^+$ at rest → 2 photons of $m_e c^2$ = **0.51 MeV** each (8.2×10^{-14} J); PET scans
- pair production needs ≥ **1.02 MeV**, near a nucleus (it takes the momentum); 0.80 MeV → no

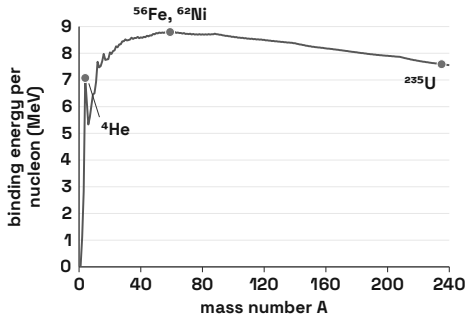
Strong force

- p–p in a nucleus: electric repulsion ≈ 10^{36} × gravity → gravity can't hold it
- strong force: attractive, protons and neutrons alike, not electrons
- stronger than the electric force within a nucleus; range ≈ 1 fm; repulsive below ≈ 0.5 fm
- neutrons add attraction without repulsion → heavy nuclei have more neutrons (Pb-208: 82 p, 126 n)

Mass defect and binding energy

1. separate nucleons: $Zm_p + Nm_n$
2. Δm = that − $m_{nucleus}$
3. BE = $\Delta m \times 931.5$ MeV (or Δmc^2 in J)
4. per nucleon: $\div A$

- deuteron: 2.015 941 − 2.013 553 = 0.002 388 u → **2.2 MeV**, 1.1 MeV per nucleon
- U-235 (nuclear 234.993 422 u): Δm 1.915 u → 1784 MeV (2.86×10^{-10} J), 7.6 MeV per nucleon
- He-4: 0.03039 u → 28.31 MeV, 7.08 per nucleon; Ca-40: 0.3674 u → 342 MeV
- C-12 Δm 0.0990 u → 92.2 MeV → 7.68 per nucleon
- Be-9: 5 n, 0.06248 u; Be-8: 0.06069 u → 56.5 MeV, 7.07 per nucleon; 2 He-4 → Be-8 loses 0.09 MeV: Be-8 less tightly bound
- BE is **not** stored inside: the nucleus has **less** energy than its nucleons apart



Binding energy per nucleon against A: steep rise, peaks at He-4, C-12, O-16, top ≈ 8.8 MeV near Fe-56 and Ni-62, slow fall to 7.6 MeV at U.

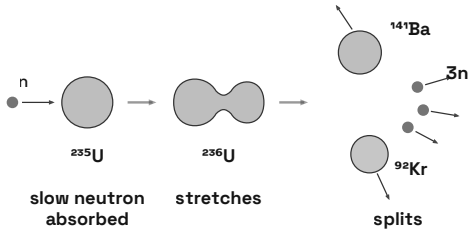
- ^{1}H: zero; most nuclei 7–9 MeV (short range: only neighbors count)
- top: nickel-62 by a hair (8.795 vs 8.790 MeV for Fe-56)
- fall beyond: every proton repels every other
- **fusion** (left) and **fission** (right) both move **towards the peak** → more total BE → energy out
- alpha decay: daughter + alpha more bound than parent
- iron can give energy neither way

Nuclear reactions

Conserved: charge (lower numbers), nucleon number (upper numbers), mass–energy, momentum

- e.g. $^{14}_{7}\mathrm{N} + {}^{4}_{2}\mathrm{He} \rightarrow {}^{17}_{8}\mathrm{O} + {}^{1}_{1}\mathrm{H}$ (1919, first made transmutation)
- Rn-220 → Po-216 (A 216, Z 84) + α: 0.006 876 u → 6.40 MeV
- Be-7 electron capture: 0.857 MeV
- energy from BE: after − before; D + T → 28.3 − 10.7 = 17.6 MeV; U → Rb + Cs ≈ 160 MeV

Fission

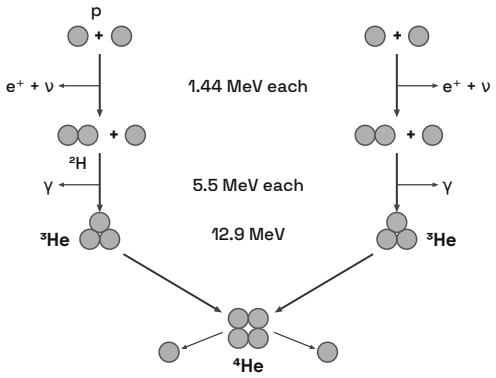


Slow neutron + U-235 → U-236 → Ba-141 + Kr-92 + 3 fast neutrons.

- neutron: no charge, not repelled, even slow
- $^{1}_{0}\mathrm{n} + {}^{235}_{92}\mathrm{U} \rightarrow {}^{141}_{56}\mathrm{Ba} + {}^{92}_{36}\mathrm{Kr} + 3\,{}^{1}_{0}\mathrm{n}$: 0.186 u → **173 MeV**
- atomic masses OK in a reaction when electrons balance
- ≈ 205 MeV on average: fragments' KE 168, neutrons 5, prompt γ 7, later β and γ 15, antineutrinos 10
- 3.1×10^{-28} kg → 2.8×10^{-11} J; 3.6×10^{10} fissions for 1 J
- U-235 + n → Xe-144 + Sr-90 + 2n: 1964 − 1786 ≈ 180 MeV
- $k < 1$ subcritical, dies out; $k = 1$ critical, **reactor** (control rods); $k > 1$ supercritical, **bomb**

Fusion

- needs nuclei within ≈ fm against huge repulsion
- **very high temperature** (≈ 10^7 K; Sun's core 1.5×10^7 K): fast enough
- **very high density** (Sun's core 1.5×10^5 kg/m^3): frequent collisions



p–p chain: twice p + p → ^{2}H + e^{+} + ν, ^{2}H + p → ^{3}He + γ; then ^{3}He + ^{3}He → ^{4}He + 2p.

1. ${}^{1}_{1}\mathrm{p} + {}^{1}_{1}\mathrm{p} \rightarrow {}^{2}_{1}\mathrm{H} + {}^{0}_{+1}\mathrm{e} + \nu$: 1.44 MeV (with the positron's annihilation)
2. ${}^{2}_{1}\mathrm{H} + {}^{1}_{1}\mathrm{p} \rightarrow {}^{3}_{2}\mathrm{He} + \gamma$: 5.5 MeV
3. ${}^{3}_{2}\mathrm{He} + {}^{3}_{2}\mathrm{He} \rightarrow {}^{4}_{2}\mathrm{He} + 2\,{}^{1}_{1}\mathrm{p}$: 12.9 MeV

- overall $4\,{}^{1}_{1}\mathrm{H} \rightarrow {}^{4}_{2}\mathrm{He} + 2e^{+} + 2\nu + 2\gamma$: **26.7 MeV**
- first step not 2.2 MeV: a proton becomes a heavier neutron, a positron is made
- D + D → ^{3}He + n 3.26 MeV; D + T → ^{4}He + n 17.6 MeV; D + ^{3}He → ^{4}He + p 18.3 MeV
- Sun: ≈ 7 billion years in all, 4.6 gone

COMMON MISTAKES

✗ most alphas bounce back
✓ most go **straight through**; ≈ 1 in 8000 over 90°.

✗ d is the nucleus's radius
✓ an **upper limit**; the radius is smaller.

✗ nucleus mass = sum of its nucleons
✓ **less**, by Δm.

✗ atomic mass with bare protons
✓ nuclear mass, or atomic masses with hydrogen atoms.

✗ high BE = energy stored
✓ energy already **given out**.

✗ greatest total BE = most stable
✓ greatest BE **per nucleon**.

✗ only fission releases energy
✓ fusion too: both towards the peak.

✗ energy forgotten in MeV/J
✓ 1 MeV = 1.6×10^{-13} J; 1 u = 931.5 MeV.

✗ reactor $k > 1$
✓ **k = 1**.

✗ pair production from 0.51 MeV
✓ **1.02 MeV** (two particles).