Topic E.1

STRUCTURE OF THE ATOM

Every Formula, Trick & Trap on a Page
& IB-Style Quick Reference

Topics Covered	Exam Relevance
The nuclear model	P1 & P2 (SL + HL)
Geiger–Marsden–Rutherford	Empty space + dense nucleus
Atomic spectra	Discrete photon transitions
Nuclear radius & density (HL)	$R = R_0 A^{1/3}$
Bohr model of hydrogen (HL)	$E_n = -13.6/n^2$ eV

The Big Picture — how E.1 fits together

STRUCTURE OF THE ATOM
probe the nucleus, then explain discrete spectra

- Structure: ^A_ZX, conserve A, Z
- Rutherford: tiny dense nucleus
- Spectra: $E_{ph} = \Delta E = hf$
- Nucleus HL only: $R = R_0 A^{1/3}$
- Rydberg + Bohr HL only: $E_n = -13.6/n^2$

1 Structure of Matter & the Nuclear Model

E.1 · SL + HL

Nuclear notation: ^A_ZX : $A =$ nucleon number, $Z =$ proton number, $N = A - Z$

Particle summary

Proton	charge $+e$	mass ≈ 1 u	in nucleus
Neutron	charge 0	mass ≈ 1 u	in nucleus
Electron	charge $-e$	mass $\approx m_p/1836$	orbits nucleus

Isotopes: same Z, different A (same element, different neutron count). **1 u** $= 1.66 \times 10^{-27}$ kg $= \frac{1}{12}$ mass of a $^{12}_{6}$C atom.

TRICK In any nuclear reaction, conserve A (top) and Z (bottom) **separately**. A γ-photon carries no A or Z.

NOTE A classical orbiting (accelerating) electron should radiate and spiral in — atoms are stable, so electron energies must be **quantised** (§3, §7).

FROM THE PHOTON QUESTION BANK

Unified mass unit is near-guaranteed recall ($\frac{1}{12}$ of carbon-12 — not a proton/neutron average, not oxygen-16). "Given p/n/e, write ^A_ZX": A =p+n, Z =p; electrons change *charge*, not notation. Equal-mass MCQ: smallest molar mass $\Rightarrow$ most atoms ($N \propto 1/M$).

2 Geiger–Marsden–Rutherford Evidence

E.1 · SL + HL

Setup & observations

	Observation	Conclusion
Setup: α source $\rightarrow$ collimator $\rightarrow$ thin **gold foil** $\rightarrow$ ZnS screen, in vacuum.	Most α pass straight through	atom is mostly **empty space**
	Few deflected $> 90°$	positive charge & mass in a tiny n
	$\sim$1 in 8000 back-scatter	nucleus is very small, dense, pos

Number vs angle follows an **inverse-square** (Coulomb) law $\Rightarrow$ disproved the plum-pudding model.

TRAP Geiger–Marsden gives **no** evidence for discrete energy levels — only empty space + dense positive nucleus. Energy-level evidence comes from *spectra*.

NOTE Scale: atom $\sim 10^{-10}$ m, nucleus $\sim 10^{-15}$ m, ratio $\sim 10^5$ ("nucleus a football $\Rightarrow$ atom 30 km across").

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Most-repeated trap in the topic. Also: large-angle back-scatter is what *disproved plum-pudding*; answer observation $\rightarrow$ conclusion in pairs.

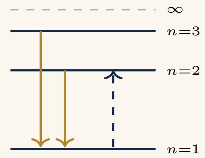
3 Atomic Spectra & Photon Transitions

E.1 · SL + HL

Photon energy: $E = hf = \dfrac{hc}{\lambda}$, $\quad h = 6.63 \times 10^{-34}$ J s

Transition: $E_{\text{photon}} = E_{\text{upper}} - E_{\text{lower}}$ (emit $\downarrow$, absorb $\uparrow$)

Emission vs absorption & energy levels



Emission: hot gas $\Rightarrow$ bright discrete lines on dark.
Absorption: white light through cool gas $\Rightarrow$ dark lines at the **same** λ.
Discrete because electrons occupy only fixed levels $\Rightarrow$ only specific ΔE $\Rightarrow$ specific λ.
Fingerprint: unique levels identify elements in stars & galaxies.

TRICK n levels $\Rightarrow \frac{n(n-1)}{2}$ lines. **Longest** $\lambda =$ **smallest** gap. Two-step cascade: $\frac{1}{\lambda} = \frac{1}{\lambda_1} + \frac{1}{\lambda_2}$ (reciprocals add).

TRAP Electrons absorb photons of **exactly** the gap energy — any other energy passes straight through. *Excited* (higher level) $\neq$ *ionised* ($E \geq 0$).

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Energy-level diagrams appear almost every session — mind the negative signs in ΔE; know count $= n(n-1)/2$, longest $\lambda =$ smallest gap, and J$\leftrightarrow$eV conversion.

4 Nuclear Radius & Density

E.1 · HL only

Nuclear radius: $R = R_0 A^{1/3}$, $R_0 = 1.2 \times 10^{-15}$ m $= 1.2$ fm

Nuclear density: $\rho = \dfrac{m_u}{\frac{4}{3}\pi R_0^3} \approx 2.3 \times 10^{17}$ kg m^{-3} (constant, all nuclei)

Ratio method

$\dfrac{R_Y}{R_X} = \left(\dfrac{A_Y}{A_X}\right)^{1/3}$. e.g. $A: 2 \to 16$ gives $8^{1/3} = 2$, so $R_Y = 2R_X$; density unchanged. Find A from R: $A = (R/R_0)^3$.

TRICK Density constant: $V \propto A$ and $m \propto A$, so the A cancels ($\rho = m_u / \frac{4}{3}\pi R_0^3$). Nucleons pack like identical marbles.

TRAP Never say density rises with A. It is $\sim$constant $\approx 10^{14}\times$ ordinary matter.

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$R = R_0 A^{1/3}$ is the **most-examined HL formula** here — scale with the cube root or cube to find A; "density constant" is a near-permanent distractor.

5 Closest Approach & Deviations from Rutherford

E.1 · HL only

Closest approach: $E_k = \dfrac{k\, q_\alpha q_{\text{nuc}}}{d} = \dfrac{k(2e)(Ze)}{d} \Rightarrow d = \dfrac{k(2e)(Ze)}{E_k}$

Deviations at high energy

Low energy: pure Coulomb $\Rightarrow$ Rutherford formula fits. **High energy:** α enters the range of the **strong nuclear force** $\Rightarrow$ fewer large-angle deflections than predicted.
Deviations $\Rightarrow$ (I) evidence for the strong force ✓ (II) estimate of nuclear radius ✓ (III) occur at *low* energy $\times$ (only HIGH).

TRICK At closest approach **all** KE $\to$ electric PE; rearrange $E_k = kq_1q_2/d$ for d.

TRAP d is from the nucleus **centre**; if $d \gg R$, Rutherford still holds.

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Two marks routinely lost: α charge is $2e$, and convert MeV→J before substituting. "Deviations at low energy" is the standard wrong option.

6 Hydrogen Spectrum & the Rydberg Formula

E.1 · HL only

Rydberg formula: $\frac{1}{\lambda} = R_H\left(\frac{1}{n_1^2} - \frac{1}{n^2}\right), \quad R_H = 1.097 \times 10^7\ \text{m}^{-1},\ n > n_1$

Spectral series (by lower level n_1)

Lyman $n_1{=}1$ (UV) **Balmer** $n_1{=}2$ (visible) **Paschen** $n_1{=}3$ (IR) Brackett/Pfund $n_1{=}4/5$ (IR)

NOTE Rydberg and Bohr describe the *same* lines: substitute $E_n = -13.6/n^2$ into $1/\lambda = (E_{\text{up}} - E_{\text{low}})/hc$ to recover Rydberg.

FROM THE PHOTON QUESTION BANK

Know the series by region; "which is visible?" → Balmer. Watch the common-denominator algebra and significant figures.

7 The Bohr Model of Hydrogen

E.1 · HL only

Energy levels: $E_n = \frac{-13.6}{n^2}$ eV

Angular momentum: $mvr = \frac{nh}{2\pi} = n\hbar$

Radius / speed: $r_n = n^2 a_0,\ a_0 = 5.29 \times 10^{-11}$ m; $\quad v_n \propto 1/n$

Hydrogen levels (memorise) & ratios

n	E_n	state
1	-13.6 eV	ground
2	-3.40 eV	1st excited
3	-1.51 eV	2nd excited
∞	0	ionised

$L_n = n\hbar \Rightarrow L_2/L_1 = 2$
$r_n \propto n^2 \Rightarrow r_2/r_1 = 4$
$v_n \propto 1/n \Rightarrow v_2/v_1 = \frac{1}{2}$
Ionisation from n: $|E_n| = 13.6/n^2$ eV

TRAP Bohr works **only** for hydrogen / one-electron ions (He^+, Li^{2+}). Never use $-13.6/n^2$ for neutral helium or heavier.

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Angular momentum quantised $L = nh/2\pi$ (ratios collapse to a ratio of n). A favourite MCQ removes one electron from an isotope and asks if $-13.6/n^2$ applies; and to identify which listed equations are genuinely Bohr-model.

Exam-readiness self-check

Concept	Level	Confidence
Structure, notation, ^A_ZX, isotopes, u	SL+HL	□□□□□
Rutherford evidence & conclusions	SL+HL	□□□□□
Spectra, energy levels, $E = hf$	SL+HL	□□□□□
Nuclear radius & constant density	HL	□□□□□
Closest approach & deviations	HL	□□□□□
Hydrogen spectrum & Rydberg	HL	□□□□□
Bohr model & ratios	HL	□□□□□