

THEME E · NUCLEAR AND QUANTUM PHYSICS

SL & HL

≈ 30 min read

IB Physics E.1 Structure of the Atom — Notes (SL & HL)

Written by Evan Kotronis for the IB Diploma Physics course (first assessment 2025). Everything outside the purple boxes is for SL and HL. E.1 has five additional HL understandings — the distance of closest approach, deviations from Rutherford scattering, nuclear radius and density, and the Bohr model of hydrogen (its energy levels and its quantised angular momentum) — and each sits in a purple **HL** box next to the SL idea it extends.



SL E.1 questions



HL E.1 questions



Flashcards



Atomic energy levels simulation

What this page covers

- ✓ The Geiger–Marsden–Rutherford α -scattering experiment and how it revealed the nucleus
- ✓ Nuclear notation ${}_Z^AX$: nucleon number, proton number and chemical symbol
- ✓ Emission and absorption line spectra as evidence that atoms have discrete energy levels
- ✓ Emission and absorption of photons when an electron moves between energy levels
- ✓ Photon frequency and the energy-level difference: $E = hf$
- ✓ Using emission and absorption spectra to identify the elements in a sample or a star
- ✓ Nuclear radius $R = R_0 A^{1/3}$ and why all nuclei have about the same density (HL)
- ✓ Why scattering departs from Rutherford's prediction at high energies (HL)

- ✓ The distance of closest approach in a head-on collision, from energy conservation (HL)
- ✓ The energy levels of hydrogen in the Bohr model, $E = -\frac{13.6}{n^2} \text{ eV}$ (HL)
- ✓ Quantised angular momentum, $mvr = \frac{nh}{2\pi}$, as the origin of quantised orbits and energies (HL)

In one minute

- Firing α particles at thin gold foil: almost all pass straight through, a few are deflected through large angles, about 1 in 8000 bounce back. So the atom is mostly empty space, with its positive charge and almost all its mass in a tiny **nucleus**.
- A nuclide is written ${}_Z^AX$: A = nucleon number, Z = proton number; neutron number $N = A - Z$.
- Electrons in atoms can only have certain **discrete energies**. Moving down a level emits a photon; moving up a level needs a photon of exactly the right energy.
- Photon energy = energy-level difference: $\Delta E = hf = \frac{hc}{\lambda}$. $1 \text{ eV} = 1.60 \times 10^{-19} \text{ J}$.
- Each element has its own set of levels, so its own line spectrum — a “fingerprint” that identifies it in a lab gas or a distant star.
- HL: $R = R_0 A^{1/3}$, so nuclear density is the same for all nuclei (about $2 \times 10^{17} \text{ kg m}^{-3}$). Closest approach: $E_k = \frac{kq_1q_2}{d}$. Bohr: $mvr = \frac{nh}{2\pi}$ gives $E = -\frac{13.6}{n^2} \text{ eV}$.

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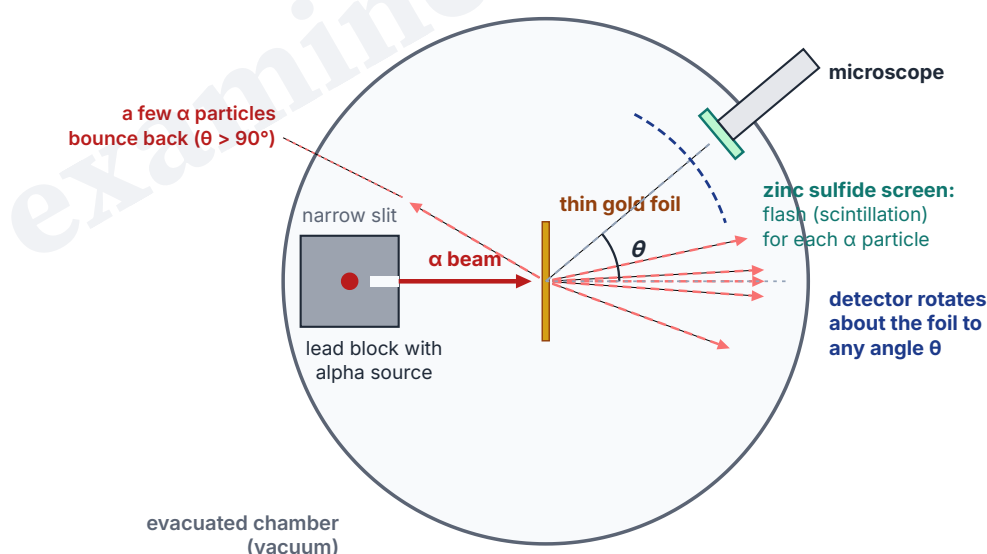
1. The Geiger–Marsden–Rutherford experiment

2. Nuclear notation and (HL) nuclear radius

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| 3. HL: closest approach and high-energy scattering | 8. Exam tips |
| 4. Line spectra and energy levels | 9. Common misconceptions |
| 5. Photons and atomic transitions | 10. How this topic connects |
| 6. Spectra and chemical composition | 11. Key equations |
| 7. HL: the Bohr model of hydrogen | 12. Check your understanding |

How did the Geiger–Marsden–Rutherford experiment reveal the nucleus?

In the early 1900s the accepted picture of the atom was Thomson's "plum-pudding" model: positive charge spread evenly through the whole atom, with tiny electrons embedded in it. In 1909–1911 Geiger and Marsden, working under Rutherford, tested this by firing α particles at a very thin gold foil.



Top view of the apparatus. α particles from the source pass through a thin gold foil in an evacuated chamber; a zinc sulfide screen, viewed through a microscope, flashes each time an α particle hits it, and can be moved to any scattering angle θ .

The set-up and why each part matters

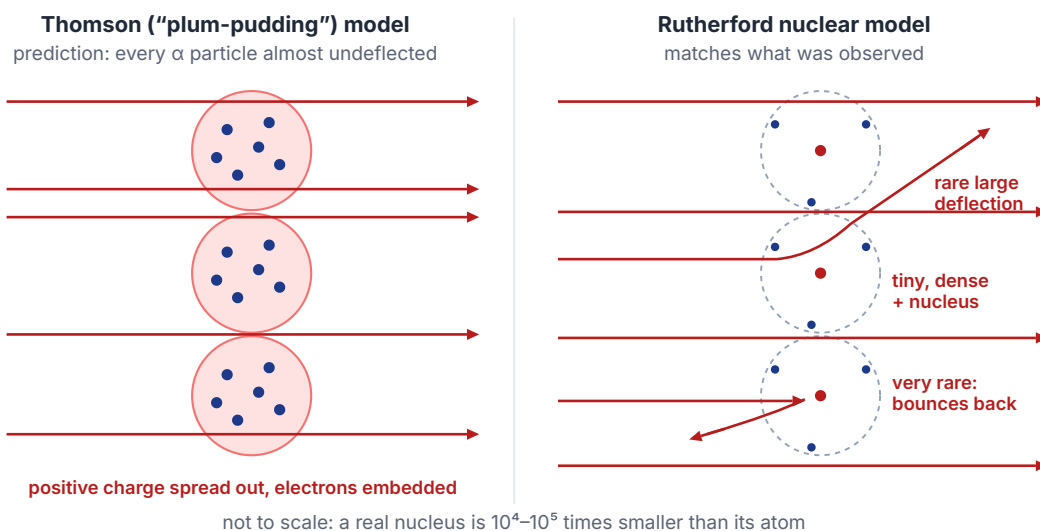
- **α source in a lead block with a narrow slit:** gives a narrow beam of α particles, all of about the same energy, moving in one direction.

- **Vacuum:** α particles have a range of only a few centimetres in air; without the vacuum they would be stopped or scattered by air molecules.
- **Very thin gold foil** (a few hundred atoms thick): gold can be beaten very thin, so most α particles meet at most one nucleus closely, and the scattering can be interpreted as single events. Gold nuclei are also very massive, so they barely recoil.
- **Movable zinc sulfide detector:** each α particle produces a tiny flash (scintillation). The number of flashes per minute was counted at many angles θ , including $\theta > 90^\circ$.

What was observed and what it means

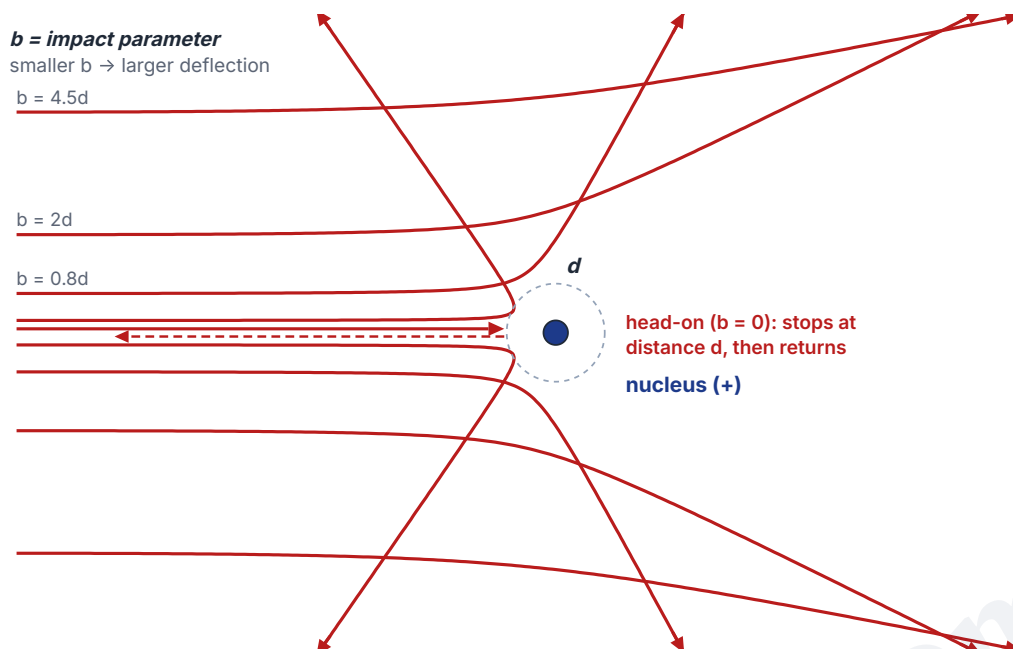
Observation	Conclusion
Almost all α particles passed straight through, or were deflected by only a few degrees.	Most of the atom is empty space .
A small fraction were deflected through large angles.	The positive charge is concentrated in a very small region; only α particles passing very close to it feel a large repulsive force.
Roughly 1 in 8000 was scattered back ($\theta > 90^\circ$).	That region contains almost all the mass of the atom — a light object could not reverse a fast, heavy α particle.

The nuclear model of the atom: almost all the mass and all the positive charge of an atom are concentrated in a tiny central nucleus, with electrons occupying the mostly empty space around it.



Left: the plum-pudding model spreads the positive charge thinly, so the electric force on an α particle is always small and no large deflections are expected. Right: in the nuclear model, α particles that pass very close to a tiny, massive nucleus are strongly repelled.

- The plum-pudding model could not explain the large-angle scattering: a thinly spread positive charge exerts only a weak force, and the electrons are far too light (about $1/7300$ of the α mass) to deflect an α particle significantly.
- From the numbers scattered at each angle, Rutherford estimated that the nucleus has a radius of the order of 10^{-15} – 10^{-14} m, while the atom is about 10^{-10} m across — some 10^4 – 10^5 times bigger.
- The force involved is the **electric repulsion** between the positive α particle and the positive nucleus (D.2). The closer the α particle's path is to the nucleus, the larger the deflection.



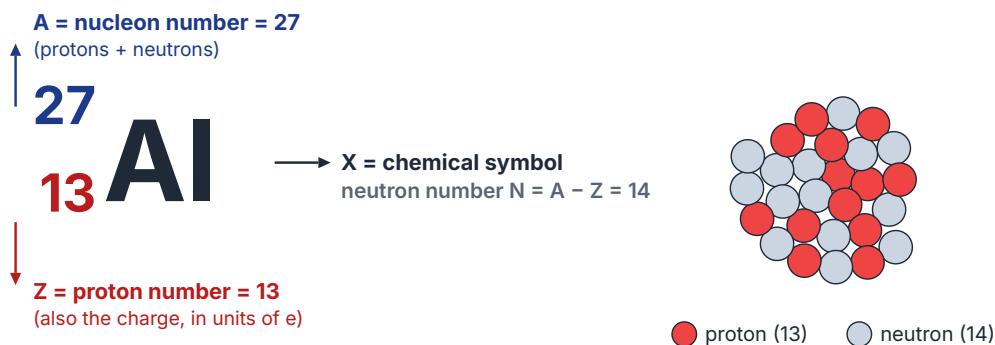
Paths of α particles computed for an inverse-square repulsion from a fixed nucleus. b is the impact parameter (the perpendicular distance of the initial path from the nucleus) in units of the head-on distance of closest approach d . Smaller b gives a larger deflection; a head-on particle stops and returns along its path.

SL: only a qualitative account of this experiment is required — describe the set-up, the observations and the conclusions. HL students also need the distance of closest approach and the deviations from Rutherford scattering at high energies (section 3), which use the nuclear radius from section 2.

What does nuclear notation tell you?

The nucleus contains protons and neutrons, together called **nucleons**. A nucleus is described by two numbers, written either side of the chemical symbol.

In the nuclear notation ${}^A_Z\text{X}$, A is the nucleon number (the total number of protons and neutrons), Z is the proton number (the number of protons) and X is the chemical symbol of the element.



Nuclear notation for aluminium-27: 13 protons and $27 - 13 = 14$ neutrons. The same notation is used for particles: the α particle is a helium-4 nucleus.

- **Neutron number** $N = A - Z$.
- Z fixes the element (and so its chemistry). A neutral atom has Z electrons; an ion with charge $+q$ has $Z - q/e$ electrons.
- The charge of the nucleus is $+Ze$; its mass is approximately A atomic mass units ($A \times 1.661 \times 10^{-27}$ kg), because the electrons contribute very little mass.
- For particles the bottom number is the **charge** in units of e : electron ${}^0_{-1}e$, proton 1_1p , neutron 1_0n , α particle ${}^4_2\text{He}$ or ${}^4_2\alpha$.
- You do not need to recall chemical symbols — questions give them.

WORKED EXAMPLE 1 Easy · State / Calculate

An aluminium nucleus is written ${}^{27}_{13}\text{Al}$. (a) State the number of protons and of neutrons in the nucleus. (b) State the number of electrons in an Al^{3+} ion. (c) Calculate the charge of the nucleus.

(a) Protons = $Z = 13$; neutrons $N = A - Z = 27 - 13 = 14$

(b) The neutral atom has 13 electrons; the $3+$ ion has lost 3, leaving **10 electrons**.

(c) $Q = Ze = 13 \times 1.60 \times 10^{-19} = 2.08 \times 10^{-18} \text{ C}$

HL How does nuclear radius depend on nucleon number?

Scattering experiments (with α particles or high-energy electrons) show that the radius of a nucleus depends only on its number of nucleons:

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

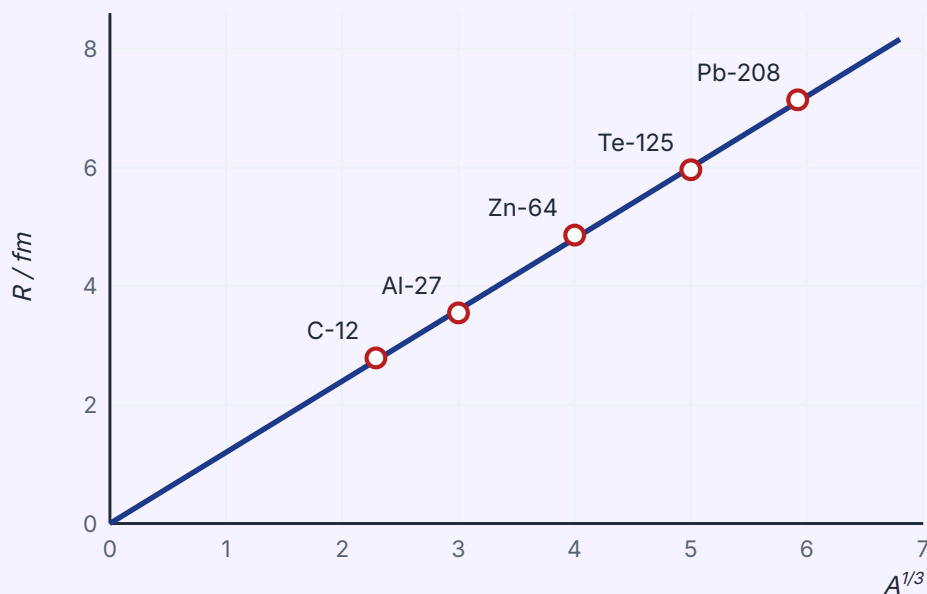
- R = nuclear radius (m), A = nucleon number, $R_0 = 1.20 \times 10^{-15}$ m (the Fermi radius, a constant in the data booklet). The equation is in the data booklet.
- $R^3 \propto A$: the **volume** of a nucleus is proportional to the number of nucleons. Nucleons are packed together like marbles in a bag, each taking up the same volume.
- A graph of R against $A^{1/3}$ is a straight line through the origin with gradient R_0 .

What does this mean for nuclear density?

The mass of a nucleus is about Au (with $u = 1.661 \times 10^{-27}$ kg), so

$$\rho = \frac{m}{V} = \frac{Au}{\frac{4}{3}\pi R_0^3 A} = \frac{3u}{4\pi R_0^3}$$

- A cancels: **every nucleus has the same density**, about 2.3×10^{17} kg m⁻³ (this result is not in the data booklet; derive it).
- This is about 10^{13} times the density of ordinary solids — evidence again that the atom is mostly empty space and the mass is concentrated in the nucleus.
- Constant density suggests that each nucleon is bound only to its near neighbours, consistent with a short-range strong force (E.3).



Nuclear radius R against $A^{1/3}$ for five nuclides (data of worked example 2), with the best-fit straight line. Use it to answer worked example 2 (a).

WORKED EXAMPLE 2 HL · Medium · Determine (graph) / Show that

Electron-scattering experiments give the following nuclear radii.

Nuclide	C-12	Al-27	Zn-64	Te-125	Pb-208
$A^{1/3}$	2.29	3.00	4.00	5.00	5.92
R / fm	2.79	3.55	4.86	5.96	7.14

(a) Use the graph above to determine R_0 . (b) Show that the density of nuclear matter is about $2 \times 10^{17} \text{ kg m}^{-3}$. (c) A nuclide has a nucleon number of 216. State the ratio of its radius to that of Al-27.

(a) The line passes through the origin, so $R = R_0 A^{1/3}$ holds. Gradient from a large triangle on the line: $\frac{\Delta R}{\Delta(A^{1/3})} = \frac{4.80 \text{ fm}}{4.00} = R_0 = 1.20 \text{ fm} = 1.20 \times 10^{-15} \text{ m}$

(b) $\rho = \frac{3u}{4\pi R_0^3} = \frac{3 \times 1.661 \times 10^{-27}}{4\pi \times (1.20 \times 10^{-15})^3} = 2.29 \times 10^{17} \text{ kg m}^{-3} \approx 2 \times 10^{17} \text{ kg m}^{-3}$

$$(c) \frac{R_{216}}{R_{27}} = \left(\frac{216}{27} \right)^{1/3} = 8^{1/3} = \mathbf{2.0} \text{ — eight times the nucleons, twice the radius.}$$

HL: How close can an α particle get to a nucleus?

HL What is the distance of closest approach?

An α particle heading straight at a nucleus slows down as it is repelled, stops momentarily, and is pushed back. At the turning point all of its initial kinetic energy has become electric potential energy. Assuming the nucleus is fixed (it is much more massive) and the α particle starts far away ($E_p \approx 0$):

$$E_k = \frac{kq_1q_2}{d} \implies d = \frac{kq_1q_2}{E_k}$$

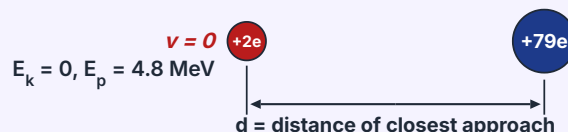
- d = distance of closest approach (m), $k = 8.99 \times 10^9 \text{ N m}^2 \text{ C}^{-2}$, $q_1 = 2e$ for an α particle, $q_2 = Ze$ for the nucleus (C), E_k = initial kinetic energy of the α particle (J).
- $E_p = \frac{kq_1q_2}{r}$ is in the data booklet (D.2); setting it equal to E_k is Rutherford's energy-conservation argument and is not printed as a separate equation.
- $d \propto \frac{1}{E_k}$: double the energy and the α particle gets twice as close. d is an **upper limit** for the nuclear radius — the α particle has not touched the nucleus.

far away



gold nucleus
(assumed fixed)

closest approach (head-on)



energy conservation: $E_k (\text{far away}) = kq_1q_2 / d$

Head-on approach of a 4.8 MeV α particle to a gold nucleus. Far away the energy is all kinetic; at the distance of closest approach the α particle is momentarily at rest and the energy is all electric potential energy.

WORKED EXAMPLE 3 HL · Medium · Calculate / Deduce

α particles of kinetic energy 4.8 MeV are fired at gold nuclei ($^{197}_{79}\text{Au}$).

- Calculate the distance of closest approach for a head-on collision.
- Calculate the radius of a gold nucleus using $R = R_0 A^{1/3}$, and deduce whether the strong nuclear force affects these α particles.
- Estimate the minimum kinetic energy an α particle would need to just reach the surface of the gold nucleus. (Radius of an α particle = $R_0 \times 4^{1/3}$.)

(a) $E_k = 4.8 \times 10^6 \times 1.60 \times 10^{-19} = 7.68 \times 10^{-13} \text{ J}$

$$d = \frac{kq_1q_2}{E_k} = \frac{8.99 \times 10^9 \times (2 \times 1.60 \times 10^{-19}) \times (79 \times 1.60 \times 10^{-19})}{7.68 \times 10^{-13}}$$

d = $4.7 \times 10^{-14} \text{ m}$ ($4.73 \times 10^{-14} \text{ m}$, 47 fm)

(b) $R = 1.20 \times 10^{-15} \times 197^{1/3} = 7.0 \times 10^{-15} \text{ m}$ (6.98 fm). The α particle stops 6.8 nuclear radii from the centre — about 40 fm outside the surface, far beyond the few-femtometre range of the strong force — so **only the electric force acts** and the scattering follows Rutherford's prediction.

(c) Contact when $d = R_{\text{Au}} + R_{\alpha} = 6.98 + 1.90 = 8.89 \text{ fm}$.

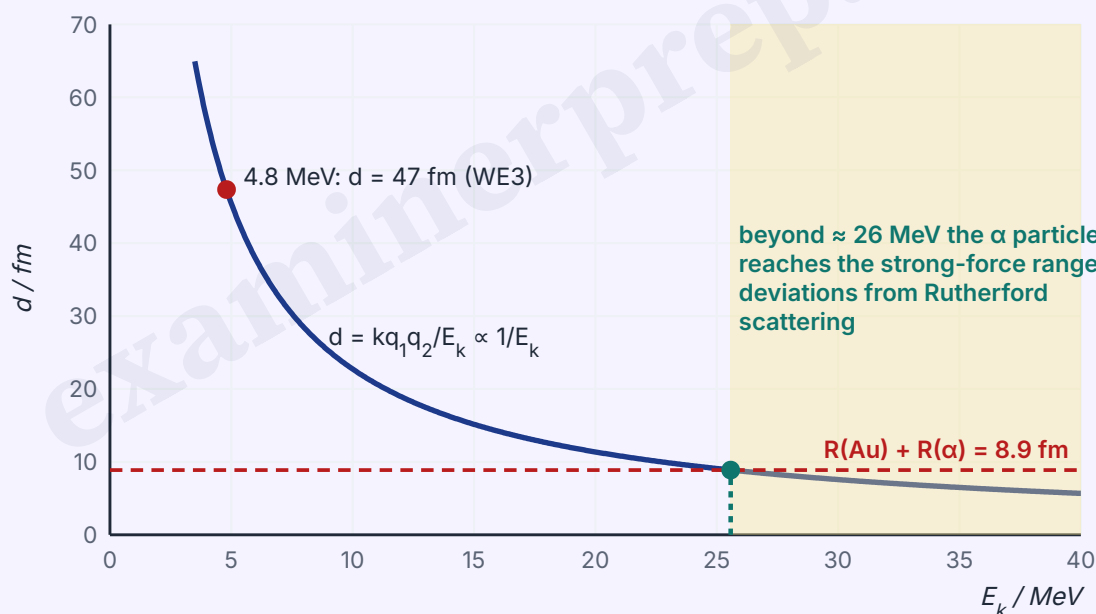
$$E_k = \frac{kq_1q_2}{d} = \frac{8.99 \times 10^9 \times 2 \times 79 \times (1.60 \times 10^{-19})^2}{8.89 \times 10^{-15}} = 4.09 \times 10^{-12}$$

$$\frac{4.09 \times 10^{-12}}{1.60 \times 10^{-13}} = \mathbf{26 \text{ MeV}} \text{ (25.6 MeV)}$$

Use the charges $2e$ and $79e$ — not the nucleon numbers 4 and 197. Using A instead of Z is a classic error.

HL Why does scattering deviate from Rutherford's prediction at high energies?

Rutherford's analysis assumes that the only force between the α particle and the nucleus is the electric (Coulomb) repulsion. This works as long as the α particle never gets close enough to touch the nucleus.



Distance of closest approach against initial kinetic energy for α particles on gold, $d = kq_1q_2/E_k$. Above about 26 MeV the α particle would reach the nuclear surface (8.9 fm), the strong nuclear force acts, and the measured scattering departs from Rutherford's prediction.

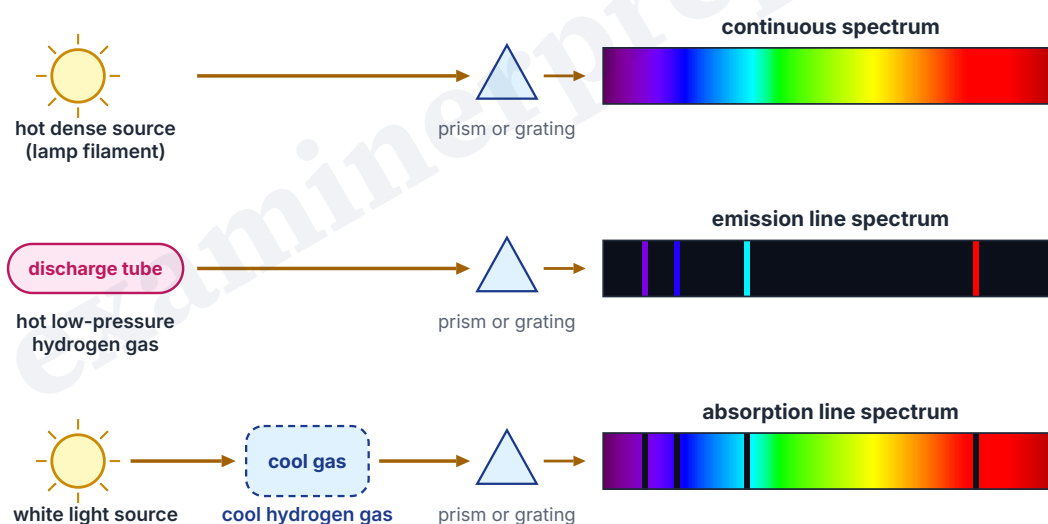
- At high enough kinetic energy, d becomes as small as the sum of the radii of the α particle and the nucleus. The α particle then comes within range of the **strong nuclear force**, which is attractive and acts only over a few femtometres.
- From that energy upwards, the number of α particles scattered at large angles is **fewer than predicted** by Rutherford's formula: the extra

attraction (and nuclear reactions) changes the paths.

- The energy at which the deviation starts can be used to **estimate the nuclear radius** — and it is consistent with $R = R_0 A^{1/3}$. This is also evidence for the short range of the strong force (E.3).
- In IB questions on scattering the energies are low enough that only the electric force needs to be considered, unless the question is specifically about deviations.

What do line spectra tell us about atoms?

Light from a source can be split into its wavelengths with a prism or a diffraction grating (C.3). Three kinds of spectrum are seen.

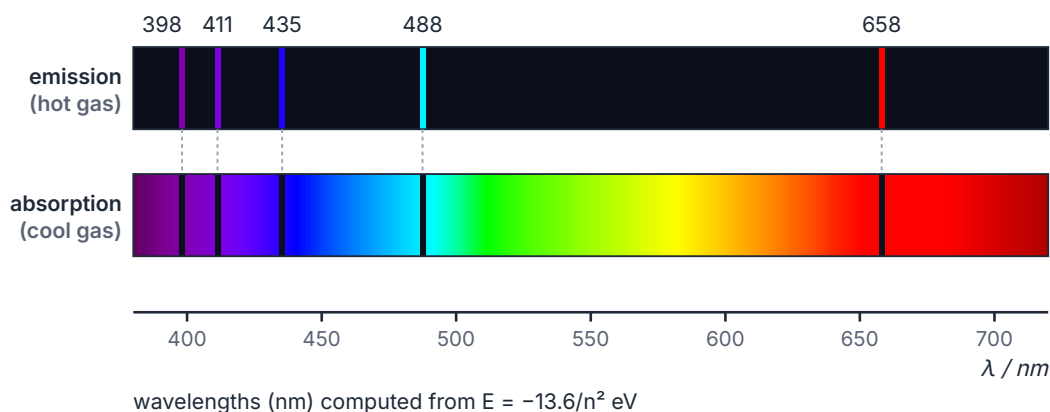


A hot dense source gives a continuous spectrum. A hot low-pressure gas gives bright lines (emission). White light passing through a cool gas gives a continuous spectrum crossed by dark lines (absorption) at exactly the same wavelengths as the emission lines of that gas.

Spectrum	How it is produced	What it looks like
Continuous	hot, dense matter (a lamp filament, the surface of a star)	all wavelengths present, no gaps
Emission line	a hot, low-pressure gas whose atoms have been excited, e.g. by an electric discharge	bright lines at certain wavelengths on a dark background
Absorption line	white light passing through a cooler gas	a continuous spectrum with dark lines at certain wavelengths

Emission and absorption line spectra are evidence that the electrons in an atom can only have certain discrete (quantised) energies: the atom can only emit or absorb photons whose energies equal the differences between these energy levels.

- If an atom's electrons could have *any* energy, atoms could emit and absorb photons of any energy, and every gas would give a continuous spectrum. They do not.
- Each line corresponds to one particular energy difference. A **discrete** set of lines means a discrete set of energy levels.
- The dark absorption lines of a gas lie at exactly the same wavelengths as its bright emission lines: the same energy differences are involved, in the opposite direction.



The visible lines of hydrogen drawn to scale, with wavelengths computed from $E = -13.6/n^2$ eV and data-booklet constants: 658, 488, 435, 411 and 398 nm. (Measured values are 656, 486, 434, 410 and 397 nm; the small difference comes from rounding the constants.) All are transitions down to $n = 2$.

How are photons emitted and absorbed in atomic transitions?

An electron in an atom occupies one of a set of **energy levels**. The lowest is the **ground state** ($n = 1$); higher levels are **excited states**. The energies are negative because the electron is bound: energy must be supplied to remove it completely (to $E = 0$, the level $n = \infty$).

When an electron moves from a higher energy level to a lower one, the atom emits a single photon whose energy equals the energy difference between the levels. A photon is absorbed only if its energy exactly equals the difference between the electron's level and a higher level, or is at least enough to ionise the atom.

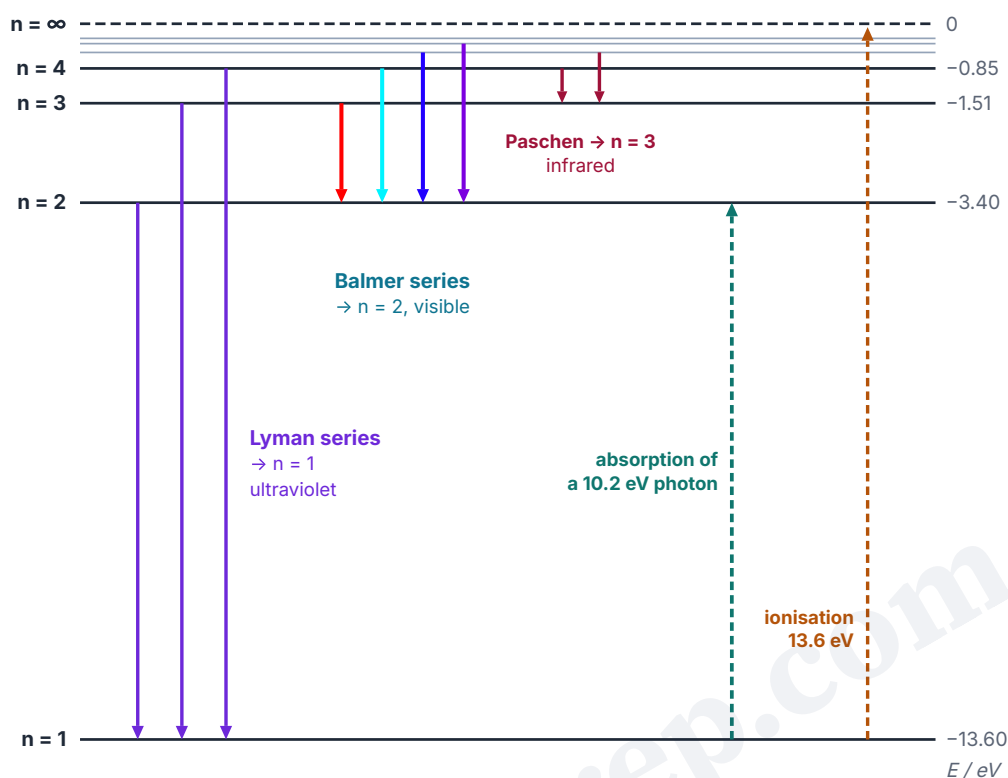
$$\Delta E = hf \qquad \Delta E = \frac{hc}{\lambda}$$

- $\Delta E = E_{\text{upper}} - E_{\text{lower}}$ = energy difference between levels = photon energy (J), $h = 6.63 \times 10^{-34}$ J s (Planck constant), f = photon frequency (Hz), $c = 3.00 \times 10^8$ m s⁻¹, λ = wavelength (m).
- $E = hf$ is in the data booklet; $E = \frac{hc}{\lambda}$ follows from $c = f\lambda$ (C.2). The data booklet also gives $hc = 1.99 \times 10^{-25}$ J m = 1.24×10^{-6} eV m.

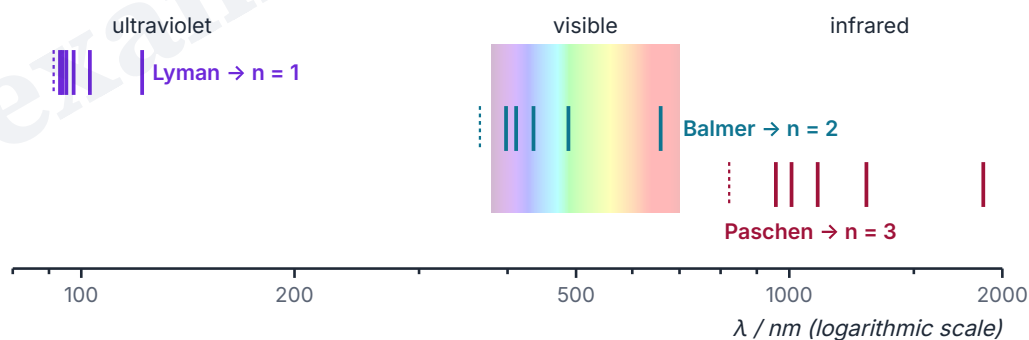
- Energies of atomic levels are usually quoted in **electronvolts**: $1 \text{ eV} = 1.60 \times 10^{-19} \text{ J}$ (the energy gained by an electron accelerated through 1 V). Convert to joules before using h in J s.
- Larger energy gap $\rightarrow$ higher frequency $\rightarrow$ **shorter wavelength**. A 650 nm red photon carries $3.06 \times 10^{-19} \text{ J} = 1.91 \text{ eV}$; visible photons (700–400 nm) carry about 1.8–3.1 eV.

Emission and absorption, step by step

- **Excitation**: an atom is raised to a higher level by absorbing a photon of exactly the right energy (or by collisions in a hot gas or discharge tube).
- **Emission**: the excited state is unstable; the electron soon drops to a lower level, possibly in several steps. Each step emits one photon of energy equal to that step's gap — so an atom excited to $n = 3$ can emit one photon ($3 \rightarrow 1$) or two photons ($3 \rightarrow 2$, then $2 \rightarrow 1$).
- **Ionisation**: if the electron receives at least the energy needed to reach $E = 0$, it leaves the atom. From the ground state of hydrogen this is 13.6 eV ($2.18 \times 10^{-18} \text{ J}$), the **ionisation energy**.
- With n levels available, the number of possible emission lines is $\frac{n(n-1)}{2}$ (every pair of levels gives one line).



Energy levels of hydrogen drawn to scale (E / eV). Transitions down to $n = 1$ give the ultraviolet Lyman series, down to $n = 2$ the visible Balmer series (arrows coloured by their computed wavelengths), and down to $n = 3$ the infrared Paschen series. Absorption of a 10.2 eV photon lifts an electron from $n = 1$ to $n = 2$; 13.6 eV ionises the atom.



dashed line = series limit (electron falls from $n = \infty$)

All three hydrogen series on a logarithmic wavelength scale. Within each series the lines crowd together towards the series limit (dashed), which corresponds to an electron falling from $n = \infty$: 91.4 nm for Lyman, 366 nm for Balmer and 823 nm for Paschen (values from $E = -13.6/n^2$ eV).

TRY IT YOURSELF

E.1 Atomic energy levels simulation: excite electrons to higher levels, watch them drop back and see which wavelengths appear in the spectrum. Check that the photon energy always equals the gap between the two levels.

WORKED EXAMPLE 4 Medium · Show that / Determine / Explain

An atom of a gas has four energy levels: -10.4 eV, -5.0 eV, -2.6 eV and -1.2 eV. (a) State the number of different photon energies that can be emitted. (b) Show that the shortest emitted wavelength is about 1.4×10^{-7} m. (c) Determine which emission line, if any, is in the visible range (about 400–700 nm). (d) Light containing photons of 5.4 eV and 6.0 eV passes through the gas, with all its atoms in the ground state. Explain which photons are absorbed.

(a) Four levels: $\frac{4 \times 3}{2} = \mathbf{6 \text{ lines}}$. The gaps are 5.4, 7.8, 9.2, 2.4, 3.8 and 1.4 eV.

(b) Shortest wavelength $\leftrightarrow$ largest gap: $\Delta E = -1.2 - (-10.4) = 9.2 \text{ eV} = 9.2 \times 1.60 \times 10^{-19} = 1.47 \times 10^{-18} \text{ J}$

$$\lambda = \frac{hc}{\Delta E} = \frac{6.63 \times 10^{-34} \times 3.00 \times 10^8}{1.47 \times 10^{-18}} = \mathbf{1.35 \times 10^{-7} \text{ m}} \approx 1.4 \times 10^{-7} \text{ m}$$

(c) Visible photons have about 1.8–3.1 eV; only the 2.4 eV gap ($-2.6 \rightarrow -5.0$ eV) fits. $\lambda = \frac{6.63 \times 10^{-34} \times 3.00 \times 10^8}{2.4 \times 1.60 \times 10^{-19}} = \mathbf{518 \text{ nm}}$ (green). The other lines are ultraviolet (230, 159, 135, 327 nm) or infrared (888 nm).

(d) From the ground state the possible gaps are 5.4, 7.8 and 9.2 eV. The **5.4 eV photons are absorbed** (they exactly match the $-10.4 \rightarrow -5.0$ eV transition). The **6.0 eV photons pass through**: no transition needs exactly 6.0 eV, and a photon cannot give up only part of its energy.

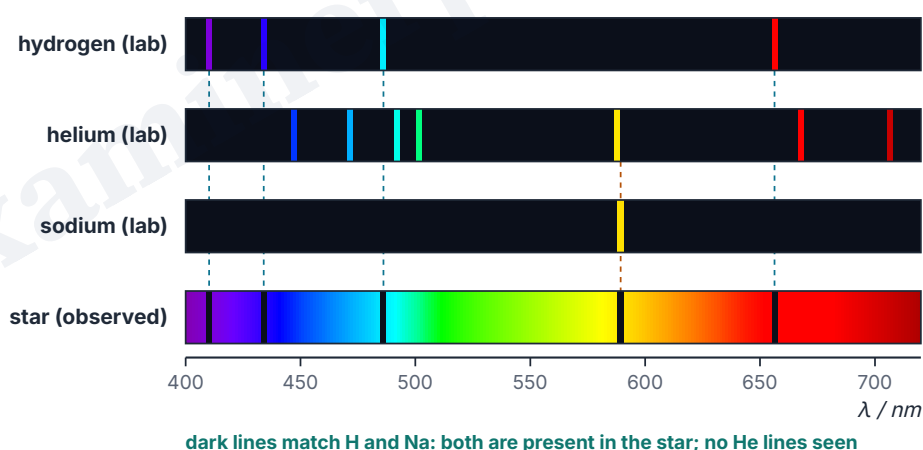
How do spectra reveal chemical composition?

Every element has its own arrangement of energy levels, so its own unique set of spectral lines. A line spectrum is a **fingerprint** of the element that produced it.

The wavelengths of the lines in an emission or absorption spectrum identify the elements present in the source or in the gas the light has passed

through, because each element has a unique set of energy levels.

- **In the lab:** heat a sample or pass a discharge through it, measure the emission wavelengths, and compare them with known spectra of the elements. All of an element's lines must be present (at the right wavelengths) to confirm it.
- **In stars:** light from the hot, dense interior passes through the cooler outer layers (the atmosphere) of the star. Atoms there absorb particular wavelengths, giving an absorption spectrum. Matching the dark lines with laboratory emission lines shows which elements are present in the star's atmosphere. Helium was first identified from an unexplained yellow line in the Sun's spectrum (1868), years before it was found on Earth.
- The **brightness** of the lines also carries information: how strong an absorption line is depends on how much of the element is present and on how many of its atoms are in the right starting level, which depends on the temperature of the gas.



Laboratory emission spectra of hydrogen, helium and sodium (measured wavelengths) compared with the absorption spectrum of a star. Every dark line in the star matches a hydrogen or sodium emission line, so both elements are present in its atmosphere. Helium's 588 nm line lies close to the sodium lines, but none of its other lines appear, so there is no evidence of helium.

WORKED EXAMPLE 5 Hard · Determine / Explain

The spectrum of a star shows a dark line at 486 nm. (a) Calculate the energy, in eV, of a photon of this wavelength. (b) Using the energy-level diagram of hydrogen above (levels -13.6 , -3.40 , -1.51 , -0.85 eV), identify the transition responsible and explain how the dark line is formed. (c) A

student says the absorbed light is re-emitted by the atoms, so the line should not be dark. Explain why it still appears dark.

$$\begin{aligned} \text{(a)} \quad E &= \frac{hc}{\lambda} = \frac{6.63 \times 10^{-34} \times 3.00 \times 10^8}{486 \times 10^{-9}} = 4.09 \times 10^{-19} \text{ J}; \\ \frac{4.09 \times 10^{-19}}{1.60 \times 10^{-19}} &= \mathbf{2.56 \text{ eV}} \end{aligned}$$

(b) Look for a gap of 2.56 eV: $-0.85 - (-3.40) = 2.55 \text{ eV} \checkmark$. The transition is **$n = 2 \rightarrow n = 4$ (absorption) in hydrogen**. Continuous light from the star's hot interior passes through cooler hydrogen in its atmosphere. Hydrogen atoms with electrons in $n = 2$ absorb photons of exactly 2.55 eV, so light of this wavelength is removed from the beam, leaving a dark line at 486 nm.

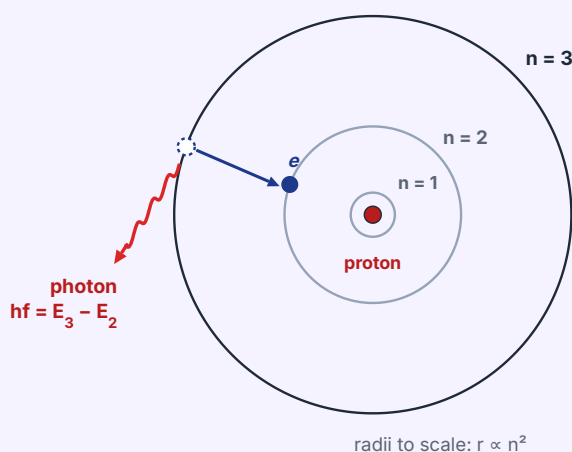
(c) The excited atoms do re-emit photons of this energy, but **in all directions** (and sometimes in several smaller steps of different wavelengths). Only a small fraction travels on towards the observer, so the intensity at 486 nm is much lower than at neighbouring wavelengths — the line is darker, not black.

The match is 2.55 vs 2.56 eV because the data are rounded. The atoms must start in $n = 2$, not $n = 1$: from the ground state the smallest gap is 10.2 eV (ultraviolet).

HL: How does the Bohr model explain the energy levels of hydrogen?

HL The Bohr model

Rutherford's nuclear atom had a problem: an electron orbiting a nucleus is accelerating, and classical physics predicts that an accelerating charge radiates energy continuously, so the electron should spiral into the nucleus — and the atom should emit a continuous spectrum. In 1913 Bohr proposed a model of hydrogen that kept the nucleus and the orbits but added a quantum rule.



Bohr model of hydrogen

- electron in a circular orbit, held by the electric force of the proton
- **only orbits with $mvr = nh/2\pi$ allowed** ($n = 1, 2, 3, \dots$): L is quantised
- no radiation while in an allowed orbit
- photon emitted or absorbed only in a jump between orbits: $hf = \Delta E$

result: $r \propto n^2$, $E = -13.6/n^2$ eV

The Bohr model of hydrogen. Orbit radii are drawn to scale ($r \propto n^2$). An electron moving from $n = 3$ to $n = 2$ emits one photon of energy $E_3 - E_2$.

- The electron moves in a circular orbit around the proton; the centripetal force is the electric attraction (A.2, D.2).
- **Only orbits in which the angular momentum is a whole-number multiple of $\frac{h}{2\pi}$ are allowed:**

$$mvr = \frac{nh}{2\pi} \quad n = 1, 2, 3, \dots$$

- m = electron mass (kg), v = orbital speed (m s^{-1}), r = orbit radius (m), n = principal quantum number, h = Planck constant. mvr is the angular momentum L of the electron (A.4). In the data booklet.
- In an allowed orbit the electron does **not** radiate. A photon is emitted or absorbed only when the electron moves between allowed orbits, with $hf = \Delta E$.

Because only certain values of angular momentum are allowed, only certain radii are allowed, and therefore only certain energies. The result is

$$E = -\frac{13.6}{n^2} \text{ eV}$$

- E = total energy of the electron (kinetic + electric potential) in level n , in eV. In the data booklet. Applies to **hydrogen only**.
- $n = 1$: -13.6 eV; $n = 2$: -3.40 eV; $n = 3$: -1.51 eV; $n = 4$: -0.85 eV; $n \rightarrow \infty$: 0. The levels crowd together towards $E = 0$, exactly as the

spectral series crowd towards their limits.

- The allowed radii increase as n^2 : $r_n = n^2 r_1$, with $r_1 = 5.29 \times 10^{-11} \text{ m}$ (the Bohr radius; given in questions when needed).

Where do $r \propto n^2$ and $E \propto -1/n^2$ come from? (not required to reproduce)

Centripetal force = electric force: $\frac{mv^2}{r} = \frac{ke^2}{r^2}$. Eliminating v with $v = \frac{nh}{2\pi mr}$ gives $r = \frac{n^2 h^2}{4\pi^2 kme^2} \propto n^2$. The total energy is $E = \frac{1}{2}mv^2 - \frac{ke^2}{r} = -\frac{ke^2}{2r} \propto -\frac{1}{n^2}$. With precise values of the constants, $r_1 = 5.29 \times 10^{-11} \text{ m}$ and $E_1 = -13.6 \text{ eV}$. The key point for the exam: quantising L quantises r , which quantises E .

Successes: the model reproduces the measured wavelengths of all the hydrogen series and the 13.6 eV ionisation energy. **Limitations** (see How this topic connects): it works only for hydrogen and other one-electron systems, it cannot predict the relative brightness of the lines, and it gives no reason for the quantisation rule — the electron is not really a particle on a fixed circular track (E.2, matter waves).

WORKED EXAMPLE 6 HL · Hard · Calculate / Determine / Comment

In the Bohr model of hydrogen, the radius of orbit n is $r_n = n^2 \times 5.29 \times 10^{-11} \text{ m}$. For an electron in the $n = 2$ orbit: (a) calculate its orbital speed; (b) calculate the energy, in J, needed to ionise the atom from this level; (c) the electron drops from $n = 5$ to $n = 2$ — determine the wavelength of the photon and state the region of the spectrum; (d) calculate the kinetic energy and the electric potential energy of the electron in $n = 2$, in eV, and comment on their sum.

(a) $r_2 = 4 \times 5.29 \times 10^{-11} = 2.116 \times 10^{-10} \text{ m}$.

$$v = \frac{nh}{2\pi mr} = \frac{2 \times 6.63 \times 10^{-34}}{2\pi \times 9.110 \times 10^{-31} \times 2.116 \times 10^{-10}}$$

$v = 1.09 \times 10^6 \text{ m s}^{-1}$

$$\text{(b)} E_2 = -\frac{13.6}{2^2} = -3.40 \text{ eV}; \text{ ionisation energy from } n = 2 \text{ is } 3.40 \text{ eV} \\ = 3.40 \times 1.60 \times 10^{-19} = \mathbf{5.44 \times 10^{-19} \text{ J}}$$

$$\text{(c)} E_5 = -\frac{13.6}{25} = -0.544 \text{ eV}; \Delta E = -0.544 - (-3.40) = \\ 2.856 \text{ eV} = 4.57 \times 10^{-19} \text{ J}$$

$$\lambda = \frac{hc}{\Delta E} = \frac{6.63 \times 10^{-34} \times 3.00 \times 10^8}{4.57 \times 10^{-19}} = \mathbf{435 \text{ nm} — \text{visible (violet),}}$$

a Balmer line

$$\text{(d)} E_k = \frac{1}{2}mv^2 = \frac{1}{2} \times 9.110 \times 10^{-31} \times (1.095 \times 10^6)^2 = 5.46 \times \\ 10^{-19} \text{ J} = \mathbf{3.41 \text{ eV}}$$

$$E_p = -\frac{ke^2}{r} = -\frac{8.99 \times 10^9 \times (1.60 \times 10^{-19})^2}{2.116 \times 10^{-10}} = -1.09 \times \\ 10^{-18} \text{ J} = \mathbf{-6.80 \text{ eV}}$$

Sum: $3.41 + (-6.80) = -3.39 \text{ eV}$, which agrees with $E_2 = -3.40 \text{ eV}$ (the difference is rounding in the constants). The total energy is negative — the electron is bound — and $E_k = -\frac{1}{2}E_p$, so $E = -E_k$.

Exam tips for E.1

EXAM TIP 1 — EXPLAIN AN ABSORPTION SPECTRUM FULLY

A full explanation needs a chain: continuous light passes through the gas → electrons absorb photons and move to higher levels → only photons whose energy equals an energy-level difference are absorbed → photon energy is linked to frequency ($E = hf$), so **particular wavelengths** are missing.

“Dark lines appear” on its own earns nothing: link the lines to specific frequencies or wavelengths.

EXAM TIP 2 — GAPS, NOT LEVELS; EV VERSUS J

The photon energy is the **difference** between two levels, never the value of one level. Before using $h = 6.63 \times 10^{-34} \text{ J s}$, convert eV to J ($\times 1.60 \times 10^{-19}$) — or use $hc = 1.24 \times 10^{-6} \text{ eV m}$ directly. A wavelength of about 10^{-25} m is the tell-tale sign of an energy left in eV.

EXAM TIP 3 — GEIGER-MARSDEN: PAIR EACH OBSERVATION WITH A CONCLUSION

Questions ask what the results show. Pair them: most go straight through $\rightarrow$ mostly empty space; a few large deflections $\rightarrow$ charge concentrated in a small region; a very few bounce back $\rightarrow$ that region holds most of the mass. Say “positive charge and most of the mass”, not just “a nucleus”. Mention the vacuum and the thin foil if asked about the set-up.

EXAM TIP 4 — COUNTING LINES AND ORDERING WAVELENGTHS

With n levels there are $n(n - 1)/2$ possible emission lines. The largest gap gives the highest frequency and the shortest wavelength; the smallest gap gives the longest wavelength. In multiple-choice questions on energy-level diagrams, check each option's arrow direction (down = emission, up = absorption) as well as its length.

EXAM TIP 5 — HL: Z FOR CHARGE, A FOR SIZE

In $d = \frac{kq_1q_2}{E_k}$ use the charges $2e$ and Ze ; in $R = R_0A^{1/3}$ use the nucleon number A . Convert MeV to J ($\times 1.60 \times 10^{-13}$). For the Bohr model, $E = -13.6/n^2 \text{ eV}$ applies only to hydrogen — a question about another atom will give its levels.

Common misconceptions

Misconception	Why it is wrong	Correct idea
The α particles bounced back because they hit the nucleus.	At the energies used they never touch it.	They are repelled by the electric force and turn round before reaching the nucleus.
The electrons deflected the α particles.	An electron has about $1/7300$ of the α particle's mass.	Large deflections are caused by the massive, positively charged nucleus.
An atom can absorb part of a photon's energy.	A photon is absorbed whole or not at all.	Only photons whose energy exactly equals a level difference are absorbed (or any photon with enough energy to ionise).
The dark lines in an absorption spectrum mean no light at all at that wavelength.	The absorbed energy is re-emitted, but in all directions.	The lines are much fainter than their surroundings, not completely black.
Energy levels are negative, so the electron has negative energy "missing".	Zero is chosen as the energy of a free electron at rest far from the atom.	Negative means bound: $ E $ is the energy needed to remove the electron.
(HL) A larger nucleus is denser because it has more nucleons.	$V \propto R^3 \propto A$, so mass and volume both scale with A .	All nuclei have the same density, about $2.3 \times 10^{17} \text{ kg m}^{-3}$.

How this topic connects

Closest approach in α scattering: an energy-conservation calculation

Treat the α particle and the nucleus as an isolated system (A.3) with the nucleus fixed. Far away the potential energy is zero and all the energy is kinetic. At the turning point of a head-on approach the α particle is momentarily at rest, so all the energy is electric potential energy, $E_p = \frac{kq_1q_2}{r}$ (D.2). Equating the two gives

$d = \frac{kq_1q_2}{E_k}$: for a 4.8 MeV α particle on gold, 4.7×10^{-14} m. The same argument, using gravitational potential energy, gives the escape speed of a planet (D.1).

Spectral lines and starlight: reading composition and temperature

Starlight is analysed with a diffraction grating (C.3). The positions of the absorption lines identify the elements in the star's atmosphere, since each element has its own energy levels. Which lines are strong also depends on temperature: for example, strong hydrogen Balmer lines need many atoms with electrons already in $n = 2$, which happens only in a fairly narrow temperature range. Combined with the peak wavelength of the continuous spectrum (Wien's law, B.2) and the luminosity, this lets astronomers classify stars and place them on the Hertzsprung–Russell diagram (E.5).

The limits of the Bohr model

The Bohr model gives the correct energy levels and spectral wavelengths for hydrogen (and one-electron ions such as He^+), but it fails for any atom with two or more electrons, because it ignores the forces between the electrons. Even for hydrogen it cannot predict the relative intensities of the lines, and it simply postulates the quantisation of angular momentum and the absence of radiation in allowed orbits without explaining them. Later, the wave nature of the electron (E.2) gave a reason for quantisation and replaced fixed orbits with a probability description. Bohr's model is still used because it explains discrete levels and line spectra simply — an example of a superseded model that remains valid within its limits.

Tools & inquiry — measuring line spectra (NOS: evidence and models)

- **Measuring wavelengths:** view a gas discharge tube (hydrogen, helium, neon, sodium vapour) through a spectroscope. With a diffraction grating of known line spacing, measure the angle θ of each line and use $n\lambda = d \sin \theta$ (C.3, HL); higher orders reduce the percentage uncertainty in θ . SL students can compare line positions against a calibrated scale.
- **Calibration:** a lamp with well-known lines (for example sodium at 589 nm) checks the grating spacing and reveals systematic errors in the angle

scale.

- **From wavelength to energy levels:** convert each wavelength to a photon energy in eV and look for gaps that add up (e.g. $4 \rightarrow 2 = 4 \rightarrow 3 + 3 \rightarrow 2$) to build an energy-level diagram from data.
- **Safety:** discharge tubes run at high voltage and can emit ultraviolet; do not touch the tube or look at it for long periods.
- **NOS — evolving models:** Thomson's model was rejected because it could not explain large-angle scattering; Rutherford's nuclear model could not explain line spectra or the stability of atoms; Bohr's quantised orbits explained hydrogen's spectrum but not other atoms. Each model was kept, modified or replaced in response to new evidence.
- **NOS — inference:** nobody has seen a nucleus. Its existence and size are inferred from the statistics of thousands of scattering events — an example of indirect evidence.

Key equations

Equation	Use	Level	In data booklet?
$N = A - Z$	neutron number from nuclear notation	SL & HL	no
$E = hf$	photon energy and frequency; ΔE between levels	SL & HL	yes
$E = \frac{hc}{\lambda}$	photon energy from wavelength	SL & HL	no — combine $E = hf$ and $c = f\lambda$; hc is given as a constant
$1 \text{ eV} = 1.60 \times 10^{-19} \text{ J}$	converting level energies	SL & HL	yes (value of e)
$\frac{n(n-1)}{2}$	number of emission lines from n levels	SL & HL	no
$R = R_0 A^{1/3}$	nuclear radius; $R_0 = 1.20 \times 10^{-15} \text{ m}$	HL	yes
$\rho = \frac{3u}{4\pi R_0^3}$	nuclear density (same for all nuclei)	HL	no — derive from $R = R_0 A^{1/3}$
$E_k = \frac{kq_1q_2}{d}$	distance of closest approach (head-on)	HL	no — set E_k equal to $E_p = \frac{kq_1q_2}{r}$, which is in the booklet (D.2)
$E = -\frac{13.6}{n^2} \text{ eV}$	energy levels of hydrogen (Bohr)	HL	yes
$mvr = \frac{n\hbar}{2\pi}$	quantisation of angular momentum (Bohr)	HL	yes

Check your understanding

1. A uranium nucleus is ${}_{92}^{238}\text{U}$. State the numbers of protons, neutrons and electrons in a neutral uranium atom.

Protons = $Z = 92$; neutrons = $A - Z = 238 - 92 = 146$; electrons = 92 (a neutral atom has as many electrons as protons).

2. Sodium vapour emits yellow light of wavelength 590 nm. Calculate the energy difference between the two levels involved, in eV.

$$E = \frac{hc}{\lambda} = \frac{6.63 \times 10^{-34} \times 3.00 \times 10^8}{590 \times 10^{-9}} = 3.37 \times 10^{-19} \text{ J} = \frac{3.37 \times 10^{-19}}{1.60 \times 10^{-19}} = 2.11 \text{ eV}.$$

3. Hydrogen atoms are excited to the $n = 5$ level. State the maximum number of different wavelengths they can emit as they return to the ground state.

Five levels are involved ($n = 1$ to 5): $\frac{5 \times 4}{2} = 10$ different transitions, so up to 10 wavelengths.

4. Explain why only a few α particles were scattered through large angles in the Geiger–Marsden experiment.

A large deflection needs a large repulsive force, which only occurs very close to the nucleus. The nucleus is tiny compared with the atom, so only the very few α particles whose paths happen to pass very near a nucleus are strongly deflected; the rest pass through mostly empty space.

5. (HL) Nucleus X has nucleon number 189. (a) Compare its radius and density with those of Li-7. (b) α particles approach X head-on; their kinetic energy is doubled. State the effect on the distance of closest approach.

(a) $R \propto A^{1/3}$: $\left(\frac{189}{7}\right)^{1/3} = 27^{1/3} = 3$, so its radius is three times as large; its density is the same (all nuclei $\approx 2.3 \times 10^{17} \text{ kg m}^{-3}$). (b) $d \propto \frac{1}{E_k}$, so the distance of closest approach halves.

Practise E.1 with exam-style questions

Original Paper 1A, 1B and 2 questions on the structure of the atom, with full mark schemes. Tick the questions you want and print them as your own test.

SL E.1 questions

HL E.1 questions

Revise and explore

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SL students: D.4 and E.2 are HL only — the previous SL page is [D.3 Motion in electromagnetic fields](#) and the next is [E.3 Radioactive decay](#).