IB DP PHYSICS · THEME E NUCLEAR AND QUANTUM PHYSICS · E.1 · ~6 MIN READ

E.1 Structure of the atom

The Geiger–Marsden–Rutherford experiment, nuclear notation, emission and absorption spectra, discrete energy levels and photons, and (HL) nuclear radius and density, distance of closest approach and the Bohr model of hydrogen.

Rutherford scattering | Nuclear notation | Emission & absorption spectra | Energy levels | Photons E = hf | Nuclear radius (HL) | Bohr model (HL)

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No tag = **SL and HL** HL ONLY HL students only DATA BOOKLET given in the exam

M1 A1 how marks are awarded highlight = comes up again and again Test yourself at the end

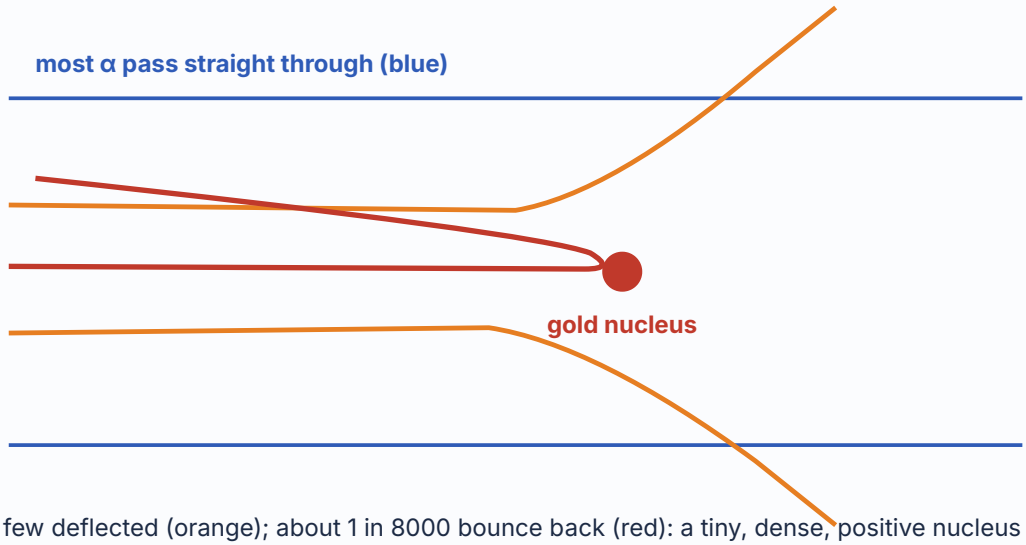
IN 30 SECONDS

- **Rutherford scattering** showed that an atom is mostly empty space with a tiny, dense, positive **nucleus**.
- **Nuclear notation** ${}^{A}_{Z}X$: A = nucleon (mass) number, Z = proton number; N = A − Z neutrons. **Isotopes** have the same Z, different N.
- Electrons in atoms have **discrete energy levels**. A transition between levels emits or absorbs a photon with **E = hf = ΔE**, so each element has its own line spectrum.
- **HL:** nuclear radius **$R = R_0A^{1/3}$** (so all nuclei have about the same density), closest-approach calculations, and the Bohr model with **$E = -13.6/n^2$ eV**.

BY THE END YOU CAN

- Describe the Geiger–Marsden–Rutherford experiment and what it showed.
- Use nuclear notation and identify isotopes.
- Explain emission and absorption spectra with energy levels and photons.
- Calculate photon energies, frequencies and wavelengths from energy-level transitions.
- Use $R = R_0A^{1/3}$ and explain why nuclear density is constant. HL
- Calculate the distance of closest approach and explain deviations from Rutherford scattering. HL
- Use the Bohr model of hydrogen. HL

1 The nuclear atom



a few deflected (orange); about 1 in 8000 bounce back (red): a tiny, dense, positive nucleus

Alpha particles fired at thin gold foil. The rare large deflections need a tiny, concentrated positive charge.

Observation	Conclusion
most α particles pass straight through	the atom is mostly empty space
a few are deflected through large angles	there is a concentrated positive charge
about 1 in 8000 bounce back	the nucleus is tiny and contains almost all the mass

- **Before Rutherford** the "plum pudding" model spread positive charge through the whole atom; it could not produce large deflections.

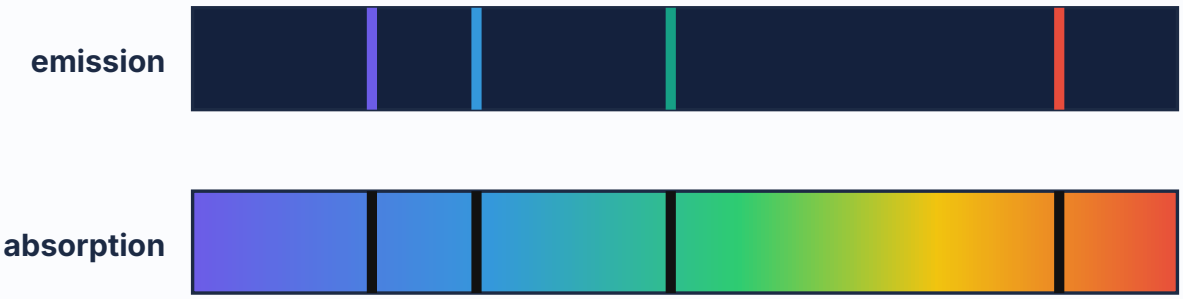
2 Nuclear notation

$$^{A}_{Z}X$$

A = nucleon number (protons + neutrons), Z = proton number (atomic number)

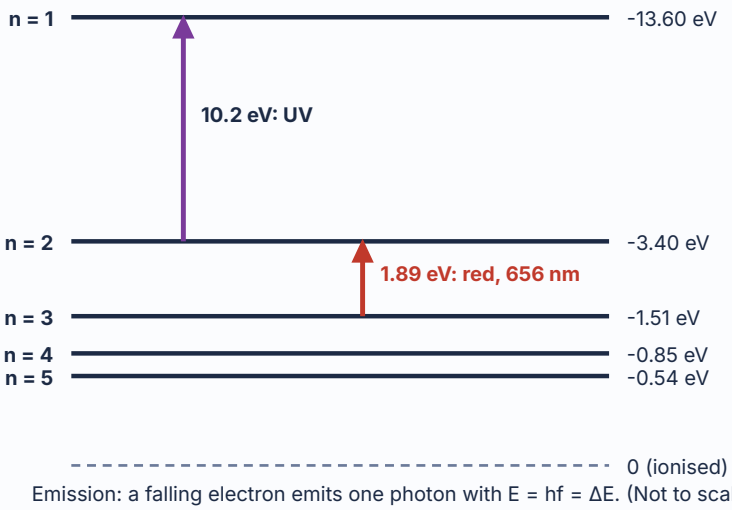
- **Example:** $^{238}_{92}U$ has 92 protons and 238 − 92 = 146 neutrons. $^{235}_{92}U$ is an isotope of it with 143 neutrons.
- **Units:** atomic masses are given in u (unified atomic mass units); 1 u = 1.66 × 10^{-27} kg ≈ 931.5 MeV c^{-2}.

3 Energy levels and spectra



Same element, same wavelengths: bright lines from a hot gas,
dark lines when white light passes through a cooler gas.

Bright lines from a glowing gas match the dark lines when light shines through the same cool gas.



Energy levels of hydrogen. Each downward arrow is a possible photon.

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

photon energy; $h = 6.63 \times 10^{-34}$ J s

- **Emission:** an excited electron drops to a lower level and emits a photon of energy equal to the gap. **Absorption:** a photon is absorbed only if its energy exactly matches a gap; the electron jumps up.
- **Electronvolt:** 1 eV = 1.60×10^{-19} J, the energy an electron gains through 1 V.

WORKED EXAMPLE

Find the wavelength of the photon emitted when hydrogen's electron falls from n = 3 (−1.51 eV) to n = 2 (−3.40 eV).

1. $\Delta E = 3.40 - 1.51 = 1.89$ eV $= 3.02 \times 10^{-19}$ J M1
2. $\lambda = hc/\Delta E = 6.63 \times 10^{-34} \times 3.00 \times 10^{8}/3.02 \times 10^{-19}$ M1
3. **$= 6.6 \times 10^{-7}$ m (656 nm, red)** A1

COMMON MISTAKE

Using the energy of one level instead of the gap between two. The photon carries the **difference**, ΔE.

EXAM TIP

Spectral lines are discrete because energy levels are discrete. That sentence earns the explanation mark in most "why lines?" questions.

4 Size and density of the nucleus HL

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

$R_0 = 1.20 \times 10^{-15}$ m (1.20 fm)

WORKED EXAMPLE

Find the radius of a lead-208 nucleus and the density of nuclear matter.

1. $R = 1.20 \times 10^{-15} \times 208^{1/3} =$ **7.1×10^{-15} m** A1
2. density $= A \times 1.66 \times 10^{-27}/(\frac{4}{3}\pi R_0^3 A)$ — the A cancels M1
3. **$= 2.3 \times 10^{17}$ kg m^{-3}, the same for every nucleus** A1

Distance of closest approach HL ONLY

- A head-on α particle stops where its kinetic energy has all become electric potential energy: $E_k = k(2e)(Ze)/d$.

WORKED EXAMPLE

A 5.0 MeV α particle is fired head-on at a gold nucleus (Z = 79). Find the distance of closest approach.

1. $E_k = 5.0 \times 10^6 \times 1.6 \times 10^{-19} = 8.0 \times 10^{-13}$ J M1
2. $d = k(2e)(79e)/E_k = 8.99 \times 10^9 \times 158 \times (1.6 \times 10^{-19})^2/8.0 \times 10^{-13}$ M1
3. **$= 4.5 \times 10^{-14}$ m: an upper limit for the nuclear radius** A1

- **Deviations:** at higher energies the α particles get close enough to feel the **strong nuclear force**, and scattering no longer follows the Coulomb-only prediction. This gives an estimate of the nuclear radius.

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5 The Bohr model of hydrogen HL

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

energy of level n in hydrogen

$$mvr = \frac{nh}{2\pi}$$ DATA BOOKLET

the electron's angular momentum is quantised

- **Bohr's idea:** the electron orbits only in allowed orbits where its angular momentum is a whole number of h/2π. It works for hydrogen but fails for atoms with more electrons; quantum mechanics (E.2) replaces it.

WORKED EXAMPLE

Find the ionisation energy of hydrogen from its ground state, and the photon energy for n = 4 → n = 2.

1. ionisation: 0 − (−13.6) = **13.6 eV** A1
2. **E_4 = −0.85 eV, E_2 = −3.40 eV: photon 2.55 eV (486 nm, blue-green)** M1 A1

LINKING QUESTION

The energy-level idea explains greenhouse absorption (B.2), the photoelectric effect (E.2) and how astronomers read stellar composition and redshift (C.5, E.5).

IDEA FOR YOUR IA / EXPLORATION

Use a diffraction grating and a hydrogen or helium discharge tube to measure line wavelengths, and compare them with predicted energy-level gaps.

Test yourself — cover the answers first

QUICK CHECK

1. What did the large-angle α scattering show?
2. How many neutrons are in $^{14}_{6}C$?
3. What is an isotope?
4. Why do atoms give line spectra rather than continuous ones?
5. Convert 2.0 eV to joules.
6. HL What happens to nuclear radius if A is multiplied by 8?

EXAM-STYLE

7. A photon of wavelength 122 nm is absorbed by hydrogen in its ground state. Which level does the electron reach?
8. HL Find the ratio of the radii of ^{216}Po and ^{27}Al nuclei.

Show answers

1. a tiny, dense, positive nucleus
2. 8
3. same number of protons, different number of neutrons
4. energy levels are discrete, so only certain photon energies occur
5. 3.2×10^{-19} J
6. it doubles
7. $E = hc/\lambda = 1.63 \times 10^{-18}$ J = 10.2 eV
   $-13.6 + 10.2 = -3.4$ eV
   n = 2
8. $R \propto A^{1/3}$
   $(216/27)^{1/3} = 8^{1/3}$
   2

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