Structure of the atom

E.1 · SL and AHL

How do you look inside an atom?

> Almost all the mass of an atom is in a tiny, positive nucleus.

- Fire alpha particles at **gold foil** and watch where they go.
- Rare large-angle returns test a concentrated, massive scattering centre.
- This unit: nucleus $\rightarrow$ notation $\rightarrow$ spectra $\rightarrow$ energy levels.

Models of the atom

Plum pudding (1904)

Positive charge spread through the atom.

Weak field everywhere, only small deflections.

Nuclear (1911)

Tiny, massive, positive nucleus.

Mostly empty space.

Three models of the atom



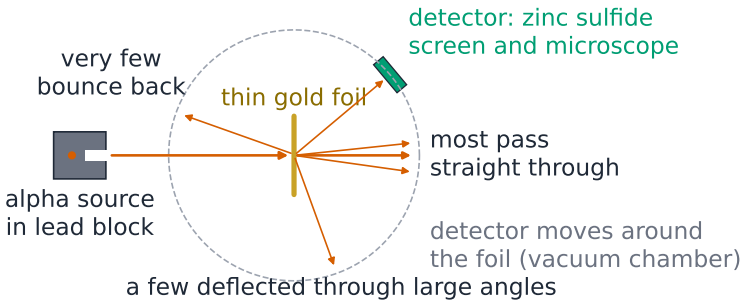
plum pudding (1904)
spread-out positive charge

nuclear (1911)
tiny dense nucleus, empty space

Bohr (1913)
fixed energy levels: line spectra

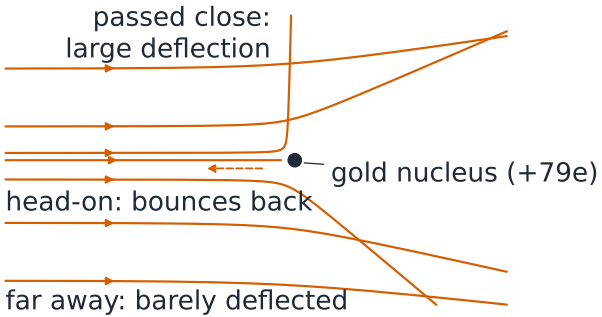
Each model was changed by new evidence

The Geiger–Marsden experiment



- Thin **gold foil**, **evacuated** chamber, detector moved to each angle.
- Most pass through, a few deflect strongly, very few bounce back.

Paths near a nucleus



- The repulsion is strong only very close to the nucleus.
- Only particles aimed almost at a nucleus deflect strongly.

Check: what bouncing back shows

Your turn

A small fraction of fast alpha particles return through large angles from a thin foil. Which conclusion is supported by the scattering evidence?

A. The atom is mostly empty space
B. Electrons are spread through the atom
C. The positive charge and mass are in a tiny nucleus
D. Gold atoms are larger than alpha particles

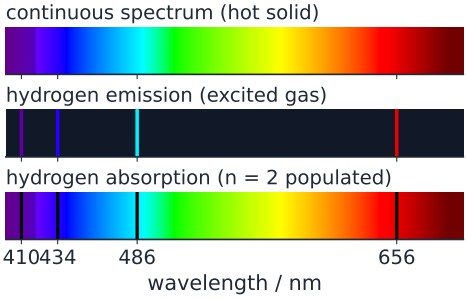
Nuclear notation

- A **nucleon number**, Z **proton number**, neutrons $A - Z$.
- Gold-197 has 79 protons and 118 neutrons.

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

Isotopes have the same Z but different numbers of neutrons.

Three kinds of spectrum



- The same transition has matching emission/absorption wavelengths; populations affect which lines appear.
- **Discrete** lines are evidence for discrete energy levels.

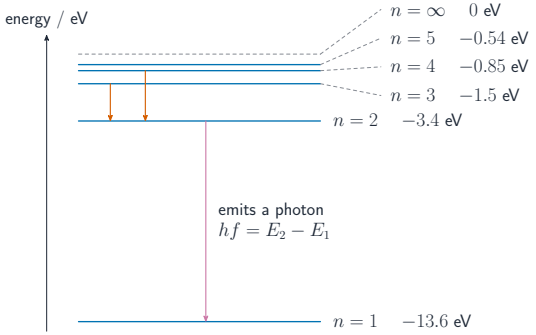
Photons and energy levels

- Falling one level emits one **photon**; absorbing one lifts the electron.
- From -1.51 to -3.40 eV gives 1.89 eV, the 656 nm red line.

$$hf = E_{\text{upper}} - E_{\text{lower}}$$

Bound-to-bound absorption needs an allowed gap and an occupied lower state; ionisation is also possible.

Hydrogen's energy levels



- Bound levels have negative energy; zero is the ionisation threshold.
- Six possible sample transitions; at most three photons in one four-level cascade.

Check: a photon energy

Your turn

Levels $-2.0 \to -5.0$ eV. Use 1 eV $= 1.60 \times 10^{-19}$ J and h $= 6.63 \times 10^{-34}$ J s. Find the emitted photon frequency.

A. 4.8×10^{14} Hz

B. 7.2×10^{14} Hz

C. 1.2×10^{15} Hz

D. 1.7×10^{15} Hz

Spectra reveal composition

In the laboratory

Discharge tubes and flame tests.

Identify an unknown gas.

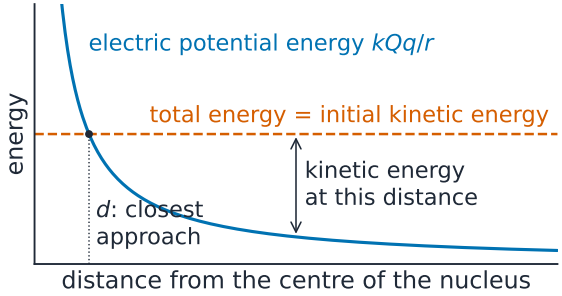
In space

Dark lines in starlight.

Elements in stars and gas clouds.

> Match several attributed lines on a common wavelength scale; use approved sources and viewing equipment.

Distance of closest approach



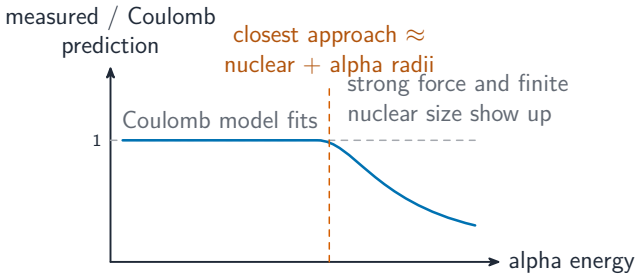
- All the kinetic energy becomes electric potential energy.
- 5.0 MeV on gold gives 4.5×10^{-14} m, an upper limit for R.

When Rutherford scattering fails

> Departures test the limits of a point-charge electric model; they are not universally a downward count change.

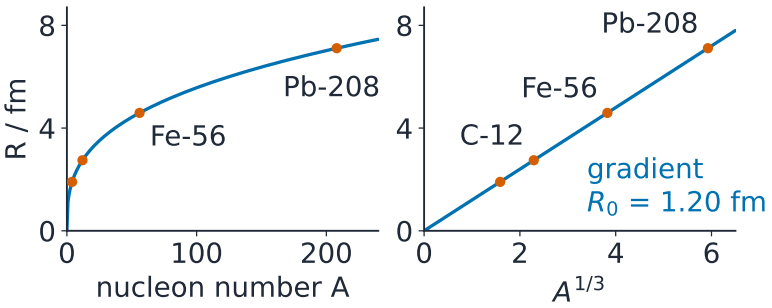
- At sufficiently close approach, finite size and short-range nuclear interactions can matter.
- Interpreting the deviation needs the target, probe, energy and scattering model.

Where Rutherford scattering fails



The alpha has reached the nucleus: the strong force acts

Nuclear radius



- $R_0 = 1.20 \times 10^{-15}$ m; gold-197 has $R = 7.0$ fm.
- Eight times the nucleons gives twice the radius.

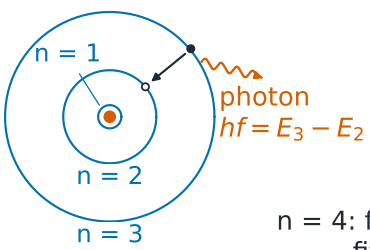
Nuclear density

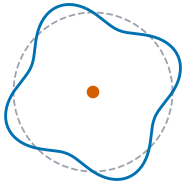
- A cancels in the approximate spherical model; actual nuclei have shape and distribution limits.
- About 10^{14} times the density of water.

$$\rho = \frac{3m_u}{4\pi R_0^3} \approx 2.3 \times 10^{17}\ \mathrm{kg\,m^{-3}}$$

Nucleons pack together like balls in a bag.

The Bohr model





n = 4: four whole wavelengths fit around the orbit

- Quantised **angular momentum** gives allowed radii and energies.
- An electron wave fits a whole number of wavelengths around the orbit.

Bohr's two equations

- $n = 3$ to $n = 2$ gives $13.6(1/4 - 1/9) = 1.89$ eV.
- The -13.6 eV coefficient is for hydrogen; one-electron ions need a nuclear-charge factor.

$$mvr = \frac{nh}{2\pi} \qquad E = -\frac{13.6}{n^2}\ \mathrm{eV}$$

Quantised **angular momentum** causes the quantised energy.

Exam tips

> One transition, one **photon**, one frequency.

- Link each scattering observation to its conclusion.
- Convert eV to joules before using $E = hf$.
- Distinguish all possible sample transitions from one electron's cascade.

Check yourself

Try these

Explain why the plum-pudding model could not explain the results.

Find photon energy in eV for 434 nm. Use $h = 6.63 \times 10^{-34}$ J s, $c = 3.00 \times 10^{8}$ m/s and 1 eV $= 1.60 \times 10^{-19}$ J.

AHL. Find closest approach for a head-on 4.0 MeV alpha on gold, $Z = 79$. Use $k = 8.99 \times 10^{9}$ N m^2/C^2 and $e = 1.60 \times 10^{-19}$ C, with negligible recoil.