A LEVEL PHYSICS 9702 · AS LEVEL · TOPIC 11 · ~7 MIN READ

Particle physics

What α-particle scattering tells us about the nucleus, nuclide notation and isotopes, α, β^-, β^+ and γ radiation, antiparticles and neutrinos, decay equations, and quarks, hadrons and leptons with the quark changes in β decay.

α-particle scattering | Nuclear model | Nucleon & proton number | Isotopes | α, β^-, β^+, γ | Antiparticles | Neutrinos | Decay equations

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Paper tag = **where it is examined** DATA & FORMULAE given in the exam C1 A1 B1 how marks are awarded

highlight = comes up again and again Test yourself at the end

IN 30 SECONDS

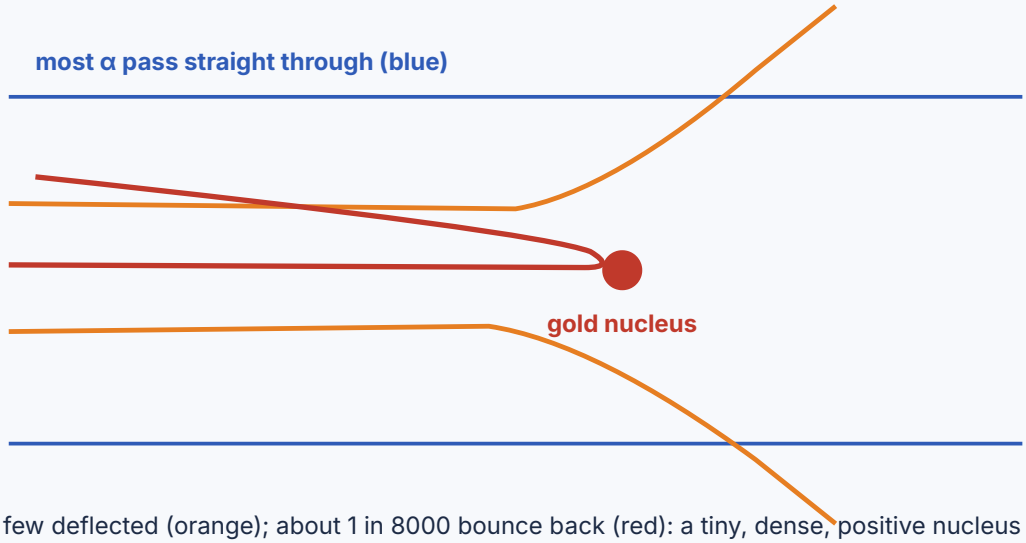
- **α-particle scattering** showed that an atom's positive charge and almost all its mass are concentrated in a tiny nucleus.
- **Nuclide notation** ${}^{A}_{Z}X$: A = nucleon number (protons + neutrons), Z = proton number. Isotopes have the same Z but different numbers of neutrons.
- **In every nuclear process** nucleon number and charge are conserved.
- **β^- decay** emits an electron and an electron antineutrino (a neutron becomes a proton: d → u). **β^+ decay** emits a positron and an electron neutrino (u → d).
- **Quarks** (up, down, strange, charm, top, bottom) are fundamental. Baryons are three quarks; mesons are a quark and an antiquark. Electrons and neutrinos are leptons, also fundamental.

BY THE END YOU CAN

- Infer the size and nature of the nucleus from α-particle scattering.
- Use nuclide notation and the terms nucleon number, proton number and isotope.
- Describe α, β^-, β^+ and γ radiation and write balanced decay equations.
- Explain antiparticles, and why β-particles have a continuous energy spectrum.
- Describe protons and neutrons in terms of quarks and the quark changes in β decay.

1 The nuclear atom

α-particle scattering



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

Most α-particles pass straight through; a few are deflected; a very few bounce back.

Observation	Inference
Most α-particles pass straight through the gold foil	most of the atom is empty space
A few are deflected through small angles	there is a concentration of positive charge that repels them
A very small fraction (about 1 in 8000) are deflected by more than 90°	the positive charge and most of the mass are concentrated in a very small, dense nucleus

- **The simple nuclear model:** a tiny nucleus (diameter about 10^{-15} to 10^{-14} m) of protons and neutrons, surrounded by orbital electrons (atom diameter about 10^{-10} m).

Nuclides and isotopes

Nucleon number (A) — the total number of protons and neutrons in a nucleus.

Proton number (Z) — the number of protons in a nucleus.

Isotopes — nuclides of the same element (same proton number) with different numbers of neutrons.

- **Example:** ${}^{56}_{26}\mathrm{Fe}$ has 26 protons and 56 − 26 = 30 neutrons; a neutral atom also has 26 electrons.
- **Unified atomic mass unit:** 1 u = 1.66 × 10^{-27} kg (one-twelfth of the mass of a carbon-12 atom). A proton or neutron is about 1 u.

COMMON MISTAKE

Putting the nucleon and proton numbers the wrong way round, or writing the neutron number as the nucleon number. Both were 2024 Paper 2 errors.

2 Radiation and decay

α, β and γ

Radiation	Composition	Charge	Mass	Typical speed
α	helium nucleus, 2 protons + 2 neutrons	+2e	4 u	about 0.05c
β^-	electron	−e	1/1840 u	up to about 0.99c
β^+	positron (antielectron)	+e	1/1840 u	up to about 0.99c
γ	electromagnetic radiation (photon)	0	0	c

Antiparticle — a particle with the same mass as its corresponding particle but opposite charge (and other opposite quantum numbers). The positron is the antiparticle of the electron.

Decay equations

- **Balance both rows:** the top numbers (nucleon number) and the bottom numbers (charge/proton number) must add up on each side.

$$^{238}_{92}\mathrm{U} \rightarrow {}^{234}_{90}\mathrm{Th} + {}^{4}_{2}\alpha$$

α decay: A − 4, Z − 2

$$^{14}_{6}\mathrm{C} \rightarrow {}^{14}_{7}\mathrm{N} + {}^{0}_{-1}\mathrm{e} + \bar{\nu}$$

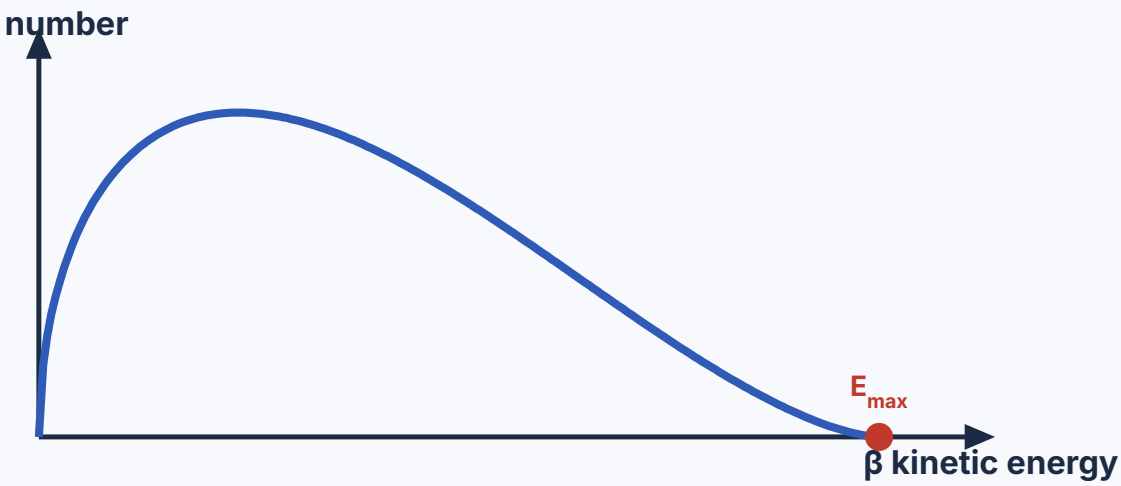
β^- decay: A unchanged, Z + 1, an electron antineutrino is emitted

$$^{22}_{11}\mathrm{Na} \rightarrow {}^{22}_{10}\mathrm{Ne} + {}^{0}_{+1}\mathrm{e} + \nu$$

β^+ decay: A unchanged, Z − 1, an electron neutrino is emitted

- **γ emission** changes neither A nor Z; the nucleus loses energy (often just after α or β decay).

Energy spectra



A continuous spread: the missing energy is carried by a neutrino.

β-particles have a continuous range of kinetic energies up to a maximum.

- **α-particles from one nuclide have discrete (fixed) energies,** because the decay produces only two products, which share the energy in a fixed way.
- **β-particles have a continuous range of energies,** because a third particle (the antineutrino or neutrino) is emitted and shares the released energy in varying proportions.

COMMON MISTAKE

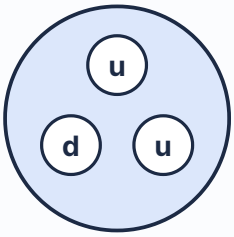
Describing β energies as discrete, or describing the continuous spectrum without saying that another particle (the (anti)neutrino) must be emitted. Both lost marks in 2024 Paper 2.

3 Fundamental particles

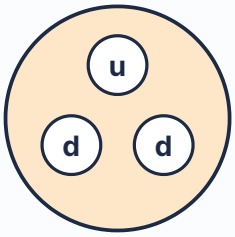
Quarks

Quark	Symbol	Charge
up	u	+⅔e
down	d	−⅓e
strange	s	−⅓e
charm	c	+⅔e
top	t	+⅔e
bottom	b	−⅓e

- **Antiquarks** (ū, d̄, …) have the opposite charge: ū is −⅔e, d̄ is +⅓e.
- **Hadrons** are made of quarks: a **baryon** has three quarks (proton uud, neutron udd); a **meson** has a quark and an antiquark (e.g. π^+ = ud̄, charge +⅔ + ⅓ = +1).
- **Leptons** are fundamental and are not made of quarks: electrons, positrons and neutrinos.



proton: uud, +⅔ +⅔ −⅓ = +1



neutron: udd, +⅔ −⅓ −⅓ = 0

β^- decay:
$d \rightarrow u + e^- + \bar{\nu}$
(neutron → proton)
β^+ decay:
$u \rightarrow d + e^+ + \nu$
(proton → neutron)

Quark charges: u, c, t = +⅔e; d, s, b = −⅓e. Antiquarks have the opposite charge.

Meson = quark + antiquark (e.g. $\pi^+ = u\,\bar{d}$). Baryon = three quarks.

Protons and neutrons are not fundamental; their charges come from their quarks.

Quark changes in β decay

- **β^-:** a neutron becomes a proton: udd → uud, so one **d quark changes to a u quark**: $d \rightarrow u + e^- + \bar{\nu}$
- **β^+:** a proton becomes a neutron: uud → udd, so one **u quark changes to a d quark**: $u \rightarrow d + e^+ + \nu$.
- **Check the charge:** d (−⅓) → u (+⅔) + e^- (−1) + $\bar{\nu}$(0): −⅓ = +⅔ − 1 ✓.

COMMON MISTAKE

Swapping β^+ and β^- (2024 Paper 1). β^-: neutron → proton, electron and antineutrino. β^+: proton → neutron, positron and neutrino.

LINKING QUESTION

Mass–energy and binding energy explain why nuclei decay in Nuclear physics; positrons annihilate with electrons in PET scanning in Medical physics; and charge quantisation links to Electricity.

Test yourself — cover the answers first

QUICK CHECK

1. State one conclusion from the fact that most α-particles pass straight through gold foil.
2. How many neutrons are in $^{235}_{92}U$?
3. Which particle is emitted with the electron in β^- decay?
4. What is the quark composition of a neutron?
5. What is the charge of a meson made of s and $\bar{u}$?

EXAM-STYLE

6. Polonium-210 (Z = 84) emits an α-particle. Write the decay equation and name the daughter's proton number.
7. Explain why the energy of β-particles from a sample is continuous, while α-particles have discrete energies.
8. A particle consists of an up quark and an anti-down quark. State whether it is a baryon or meson and find its charge.

Show answers

1. most of the atom is empty space
2. 143
3. an electron antineutrino
4. udd
5. $-\frac{1}{3} - \frac{2}{3} = -1$ (e)
6. $^{210}_{84}Po \rightarrow {}^{206}_{82}Pb + {}^{4}_{2}\alpha$; Z = 82
7. β decay produces three particles (daughter, β, (anti)neutrino) sharing the energy in variable proportions; α decay has two products with fixed shares
8. meson; $+\frac{2}{3} + \frac{1}{3} = +1e$

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