11.1.1 Decay equations, antiparticles and neutrinos

Name: _____ Class: _____ Date: _____ **Total: 28 marks**

KEY WORDS decay equation • antiparticle • positron • neutrino • antineutrino

Objective

Answer exam questions on **radioactive decay equations**: what every equation must conserve, the **antiparticles** and **neutrinos** that go with β-decay, following a decay chain, and the recoil of the nucleus left behind. Syllabus 11.1, learning outcomes 6, 8, 9 and 11.

You must be able to:

- state that nucleon number and charge are conserved in every nuclear process
- write α, β^- and β^+ decay equations, including the (anti)neutrino
- state what an antiparticle is, and that the positron is the antiparticle of the electron
- state which β-decay produces a neutrino and which an antineutrino
- follow a decay chain forwards and backwards
- use conservation of momentum to find the recoil speed of the nucleus left behind

1 Key knowledge and worked examples

■ Key knowledge: what a decay equation must balance

In every nuclear process the **nucleon number** (the top numbers) and the **charge** (the bottom numbers) are **conserved**: each adds up to the same total on both sides.

particle	symbol	effect on the nucleus
α-particle	${}^{4}_{2}\alpha$	A falls by 4, Z by 2
electron (β^-)	${}^{0}_{-1}\beta$	Z rises by 1, A unchanged
positron (β^+)	${}^{0}_{+1}\beta$	Z falls by 1, A unchanged
neutrino, antineutrino	${}^{0}_{0}\nu$, ${}^{0}_{0}\bar{\nu}$	no change
γ-ray photon	${}^{0}_{0}\gamma$	no change

■

- An **antiparticle** has the **same mass** as its particle and the **opposite charge**. The **positron** is the antiparticle of the electron.
- β^- decay emits an electron and an (electron) **antineutrino** .
- β^+ decay emits a positron and an (electron) **neutrino**.
- Each pair is one particle and one antiparticle: the electron goes with the **anti**neutrino, and the positron, itself an antiparticle, with the neutrino.

■ Worked example: writing decay equations

1. α **decay of uranium-238** – the α-particle carries off 4 nucleons and 2 protons, so the daughter nucleus, thorium, has

$$A_{\mathrm{Th}} = A_{\mathrm{U}} - 4 = 238 - 4 = 234$$

$$Z_{\mathrm{Th}} = Z_{\mathrm{U}} - 2 = 92 - 2 = 90$$

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

2. β^- **decay of strontium-90** – a neutron becomes a proton, so Z rises by one and A is unchanged; an antineutrino is emitted as well:

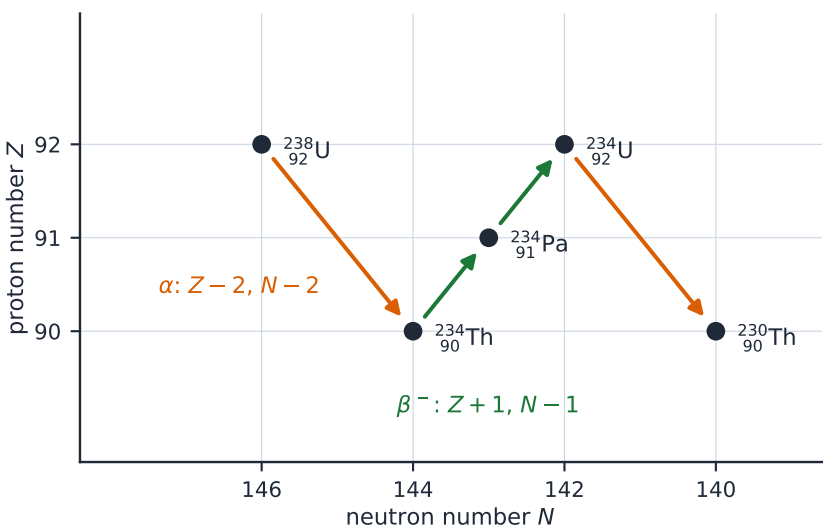
$$^{90}_{38}\mathrm{Sr} \rightarrow {}^{90}_{39}\mathrm{Y} + {}^{0}_{-1}\beta + {}^{0}_{0}\bar{\nu}$$

3. β^+ **decay of sodium-22** – a proton becomes a neutron, so Z falls by one; a neutrino is emitted as well:

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

- The (anti)neutrino is $^{0}_{0}$, so leaving it out does not upset the balance. That is exactly why it is easy to forget, and forgetting it costs a mark.

■ Worked example: a decay chain



On this grid every decay is the **same move every time**, which makes a long chain quick:

- α decay: $Z-2$ and $N-2$, down two and left two;
- β^- decay: $Z+1$ and $N-1$, up one and left one.

Working backwards. ${}^{238}_{92}\mathrm{U}$ decays in many steps to ${}^{206}_{82}\mathrm{Pb}$. How many α- and β^--particles are emitted?

1. **α-particles** – only α decay changes A, by 4 each time:

$$n_\alpha = \frac{A_\mathrm{U} - A_\mathrm{Pb}}{4} = \frac{238-206}{4} = 8$$

2. **Where the α decays alone would leave Z:**

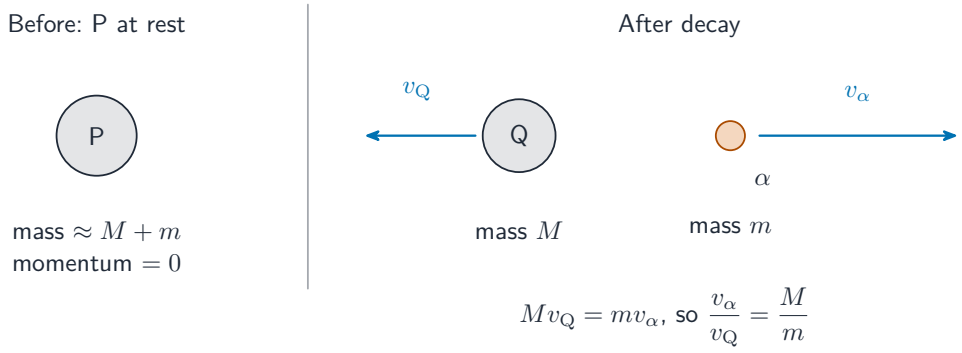
$$Z = Z_\mathrm{U} - 2n_\alpha = 92 - 2\times 8 = 76$$

3. **β^--particles** – each adds one to Z, which must finish at 82:

$$n_\beta = Z_\mathrm{Pb} - Z = 82 - 76 = 6$$

So the chain emits **8 α-particles and 6 β^--particles**.

■ Worked example: the recoil of the daughter nucleus



Momentum is conserved too. A nucleus at rest has zero momentum, so after it decays the α-particle and the daughter nucleus move off in **opposite directions** with **equal-sized momenta**.

A stationary nucleus emits an α-particle (mass 4 u) at $1.5\times10^7\ \frac{\mathrm{m}}{\mathrm{s}}$, leaving a daughter nucleus of mass 234 u.

1. **Conservation of momentum**, zero in total before and after:

$$m_\alpha v_\alpha = m_\mathrm{D} v_\mathrm{D}$$

2. **The recoil speed** – rearrange; the masses can stay in u, because only their ratio matters:

$$v_\mathrm{D} = \frac{m_\alpha v_\alpha}{m_\mathrm{D}} = \frac{(4\ \mathrm{u})(1.5\times10^7\ \frac{\mathrm{m}}{\mathrm{s}})}{234\ \mathrm{u}} = 2.6\times10^5\ \frac{\mathrm{m}}{\mathrm{s}}$$

2 Practice

Now use the methods above.

2.1 State the **two** quantities that must balance on each side of a nuclear decay equation. [2]

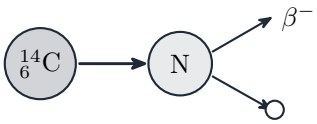
2.2 State what is meant by an **antiparticle**, and name the antiparticle of the electron. [2]

antiparticle

2.3 Radium-226, $^{226}_{88}\text{Ra}$, decays by α emission to radon (Rn). Write the decay equation. [2]

$^{226}_{88}\text{Ra}$

2.4 Complete the β^- decay equation, and name the third particle emitted: $^{14}_{6}\text{C} \rightarrow \quad \text{N} + {}^{0}_{-1}\beta+$? [2]



2.5 Write the complete decay equation for the β^+ decay of $^{11}_{6}\text{C}$ to boron (B), including the third particle. [2]

$^{11}_{6}\text{C}$

2.6 A stationary nucleus emits an α-particle at $1.8 \times 10^7 \ \frac{\text{m}}{\text{s}}$. The daughter nucleus has a mass of 208 u. Calculate the recoil speed of the daughter nucleus. [2]

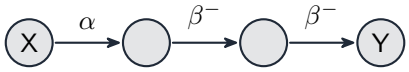
$1.8 \times 10^7 \ \text{m s}^{-1}$

208 u

3 Exam-style questions

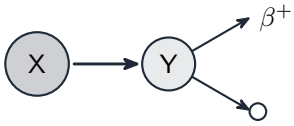
3.1 A nucleus emits an α-particle and then two β^--particles. What is the overall change to the nucleus? [1]

	nucleon number	proton number
A	falls by 4	unchanged
B	falls by 4	falls by 2
C	falls by 4	rises by 2
D	unchanged	falls by 2



3.2 Which particle is emitted together with a positron in β^+ decay? [1]

- ☐ **A** an electron
- **B** an electron antineutrino
- **C** an electron neutrino
- **D** an α-particle



3.3 A nuclide X decays by β^- emission to a nuclide Y. Nuclide Y then decays by β^+ emission to a nuclide Z.

State how the proton number of Z compares with that of X, and name the particle emitted alongside the β-particle in **each** of the two decays. [3]

3.4 A nucleus of radium-228, $^{228}_{88}\text{Ra}$, decays in a series of steps to a nucleus X, emitting 5 α-particles and 4 β^--particles in total. Determine the number of protons and the number of neutrons in X. [3]

$^{228}_{88}\text{Ra}$

5

3.5 A stationary nucleus of polonium-210, $^{210}_{84}\text{Po}$, decays by α emission to an isotope of lead (Pb).

(a) Write the decay equation. [2]

$^{210}_{84}\text{Po}$

$1.6 \times 10^7\ \text{m}\,\text{s}^{-1}$

(b) State **three** quantities that are conserved in the decay. [2]

(c) The α-particle leaves with a speed of $1.6 \times 10^7\ \dfrac{\text{m}}{\text{s}}$. Calculate the speed of the lead nucleus. [3]

(d) Explain why the lead nucleus moves in the opposite direction to the α-particle. [1]