

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

■

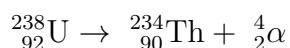
- An **antiparticle** has the **same mass** as its particle and the **opposite charge**. The **positron** is the antiparticle of the electron.
- β^- decay emits an electron and an (electron) **antineutrino**.
- β^+ decay emits a positron and an (electron) **neutrino**.
- Each pair is one particle and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

■ **Worked example: writing decay equations**

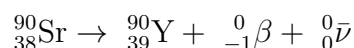
1. α **decay of uranium-238** – the α -particle carries off 4 nucleons and 2 protons, so the daughter nucleus, thorium, has

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

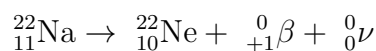
$$Z_{\text{Th}} = Z_{\text{U}} - 2 = 92 - 2 = 90$$



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:

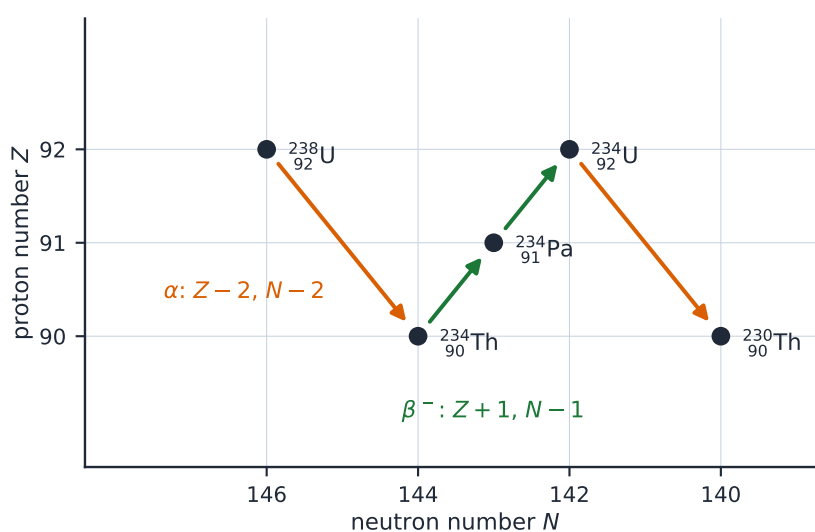


3. β^+ **decay of sodium-22** – a proton becomes a neutron, so Z falls by one; a neutrino is emitted as well:



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

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

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

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

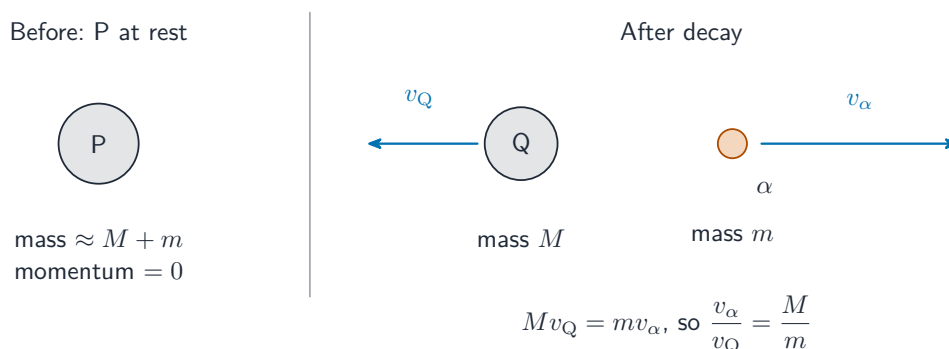
$$Z = Z_{\text{U}} - 2n_{\alpha} = 92 - 2 \times 8 = 76$$

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

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

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 $1.5 \times 10^7 \frac{\text{m}}{\text{s}}$, leaving a daughter nucleus of mass 234 u.

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

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

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

$$v_{\text{D}} = \frac{m_{\alpha}v_{\alpha}}{m_{\text{D}}} = \frac{(4 \text{ u})(1.5 \times 10^7 \frac{\text{m}}{\text{s}})}{234 \text{ u}} = 2.6 \times 10^5 \frac{\text{m}}{\text{s}}$$

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]



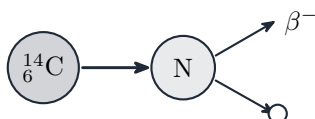
2.2 State what is meant by an **antiparticle**, and name the antiparticle of the electron. [2]

antiparticle

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



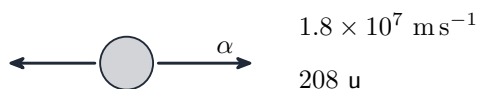
2.4 Complete the β^- decay equation, and name the third particle emitted: $^{14}_6\text{C} \rightarrow \text{N} + {}^0_{-1}\beta + ?$ [2]



2.5 Write the complete decay equation for the β^+ decay of $^{11}_6\text{C}$ to boron (B), including the third particle. [2]



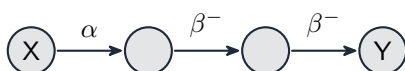
2.6 A stationary nucleus emits an α -particle at $1.8 \times 10^7 \frac{\text{m}}{\text{s}}$. The daughter nucleus has a mass of 208 u. Calculate the recoil speed of the daughter nucleus. [2]



3 Exam-style questions

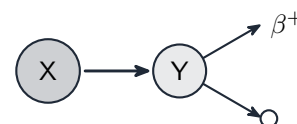
3.1 A nucleus emits an α -particle and then two β^- -particles. What is the overall change to the nucleus? [1]

	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]

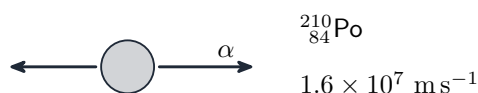


3.4 A nucleus of radium-228, $^{228}_{88}\text{Ra}$, decays in a series of steps to a nucleus X, emitting 5 α -particles and 4 β^- -particles in total. Determine the number of protons and the number of neutrons in X. [3]



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]



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

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

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

Solutions

Each answer shows the steps, then the **result**.

2.1

- the **nucleon number** (the top numbers)
- the **charge**, which is the proton number (the bottom numbers)

2.2

- an antiparticle has the **same mass** as its particle but the **opposite charge**
- the antiparticle of the electron is the **positron**

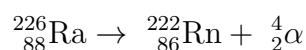
2.3

- the α -particle carries off 4 nucleons and 2 protons

$$A_{\text{Rn}} = A_{\text{Ra}} - 4 = 226 - 4 = 222$$

$$Z_{\text{Rn}} = Z_{\text{Ra}} - 2 = 88 - 2 = 86$$

- the equation



2.4

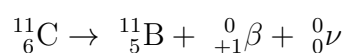
- the nucleon number is unchanged and the proton number rises by one



- the third particle is an (electron) **antineutrino**

2.5

- the nucleon number is unchanged and the proton number falls by one



- the third particle is an (electron) **neutrino**, because this is β^+ decay

2.6

- the total momentum is zero before and after, so $m_\alpha v_\alpha = m_D v_D$

$$v_D = \frac{m_\alpha v_\alpha}{m_D} = \frac{(4 \text{ u})(1.8 \times 10^7 \frac{\text{m}}{\text{s}})}{208 \text{ u}} = \mathbf{3.5 \times 10^5 \frac{\text{m}}{\text{s}}}$$

3.1 A

- the α -particle lowers the nucleon number by 4 and the proton number by 2; each β^- raises the proton number by 1

$$\Delta Z = \Delta Z_\alpha + 2 \Delta Z_\beta = -2 + 2 \times (+1) = 0$$

- **B** forgets the two β^- decays; **C** counts them twice

3.2 C

- β^+ decay emits a positron and an electron **neutrino**
- **B**, the antineutrino, goes with β^- decay

3.3

- β^- decay raises the proton number by one and β^+ decay lowers it by one, so Z has the **same proton number as X**
- the β^- decay also emits an (electron) **antineutrino**
- the β^+ decay also emits an (electron) **neutrino**

3.4

- each α takes away 2 protons and 2 neutrons; each β^- turns a neutron into a proton

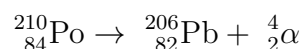
$$Z_X = Z_{\text{Ra}} - 2n_\alpha + n_\beta = 88 - 2 \times 5 + 4 = \mathbf{82}$$

- radium-228 has $N = A - Z = 228 - 88 = 140$ neutrons

$$N_X = N_{\text{Ra}} - 2n_\alpha - n_\beta = 140 - 2 \times 5 - 4 = \mathbf{126}$$

3.5

- (a) the nucleon number falls by 4 and the proton number by 2



- (b) any three of: **nucleon number**, **charge** (proton number), **momentum**, **mass-energy**

- (c) the momentum is zero before the decay, so it is zero after

$$m_\alpha v_\alpha = m_{\text{Pb}} v_{\text{Pb}}$$

- rearrange, with the masses in u

$$v_{\text{Pb}} = \frac{m_\alpha v_\alpha}{m_{\text{Pb}}} = \frac{(4 \text{ u})(1.6 \times 10^7 \frac{\text{m}}{\text{s}})}{206 \text{ u}} = \mathbf{3.1 \times 10^5 \frac{\text{m}}{\text{s}}}$$

- (d) the total momentum stays zero, so the two momenta must be equal in size and **opposite in direction**