Exercise walk-through

11.1.2

The three radiations: identity, behaviour in fields, and energy spectra

A-Level Physics

You must be able to

- describe a simple model of the nuclear atom, and distinguish **nucleon number 核子数** from **proton number 质子数**
- describe the composition, mass and charge of α-, β- and γ-radiation, including β^- (electrons) and β^+ (**positrons 正电子**)
- understand that an **antiparticle 反粒子** has the same mass and opposite charge to its particle
- state that **antineutrinos 反中微子** are produced in β^- decay and neutrinos in β^+ decay
- understand that α-particles have discrete energies but β-particles a continuous range, because a (anti)neutrino is emitted
- represent α- and β-decay by a decay equation, with nucleon number and charge conserved
- use the **unified atomic mass unit 统一原子质量单位** as a unit of mass

1 The method

Method — What the three radiations are

	composition	charge	mass
α	a **helium nucleus**: 2 protons and 2 neutrons	$+2e$	4 u
β^-	a fast-moving **electron**	$-e$	about $\frac{1}{1840}$ u
β^+	a fast-moving **positron**, the antiparticle of the electron	$+e$	about $\frac{1}{1840}$ u
γ	a high-energy **photon** – electromagnetic radiation	0	0

Method — What the three radiations are

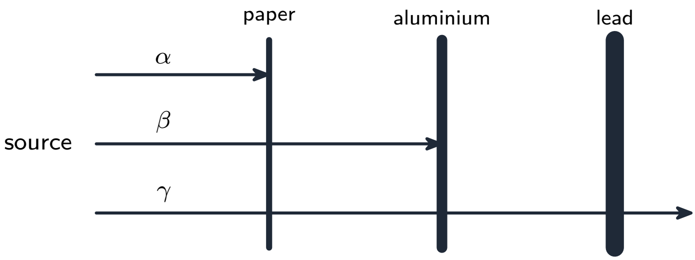
- An **antiparticle** has the **same mass** and the **opposite charge**. The positron is the electron's antiparticle: same mass, charge $+e$.
- The **unified atomic mass unit** is defined as $\frac{1}{12}$ of the mass of a carbon-12 atom, and 1 u $= 1.66 \times 10^{-27}$ kg. The mass of a nucleus in kilograms is therefore roughly its **nucleon number** $\times\ 1.66 \times 10^{-27}$ kg.

Method — Penetration and ionisation are opposite ends of the same fact

	stopped by	**ionising power**
α	a sheet of **paper**, or a few cm of air	**most** strongly ionising
β	a few **mm of aluminium**	intermediate
γ	only **reduced** by several cm of lead	**least** ionising

- The two columns are the **same fact seen twice**: an α particle has a large charge $(+2e)$ and moves slowly, so it interacts strongly and often with the atoms it passes, **ionising** many of them. Each ionisation costs it energy, so it loses all its energy within a very short distance – it is the **least penetrating** precisely **because** it is the most ionising.
- γ carries no charge, so it interacts only rarely; it ionises little and travels far.

Method — Penetration and ionisation are opposite ends of the same fact



Method — In a magnetic field

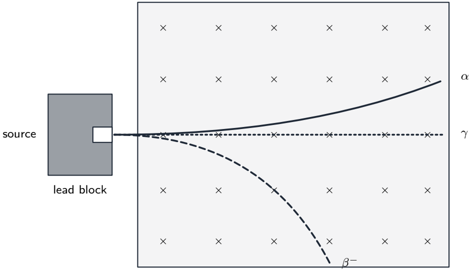
Three separate questions, three separate reasons – give all three:

1. **Which way?** α is **positive** and β^- is **negative**, so they are deflected in **opposite** directions. (β^+ would go the same way as α.)
2. **How much?** From $r = \dfrac{mv}{Bq}$, a smaller mass gives a smaller radius, which is a **sharper** curve. A β particle has roughly $\frac{1}{7000}$ of an α's mass, so it is deflected far more.
3. **And γ?** It has **no charge**, so the magnetic force Bqv on it is **zero**, and it is **not deflected at all**.

- In an **electric** field the same three answers hold, with the force qE instead: α towards the negative plate, β^- towards the positive plate, γ undeflected.

Method — In a magnetic field

Three separate questions, three separate reasons – give all three



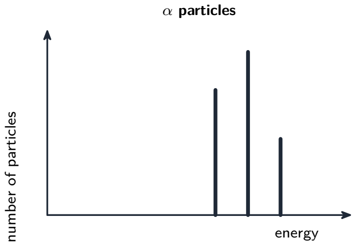
magnetic field into the page

Three separate reasons. **Direction:** α is positive and β^- negative, so they curve *opposite* ways. **Amount:** $r = \frac{mv}{Bq}$, and a β particle has about $\frac{1}{7000}$ of an α's mass, so it curves far more sharply. **γ:** it carries no charge, so the magnetic force on it is zero and it goes straight on.

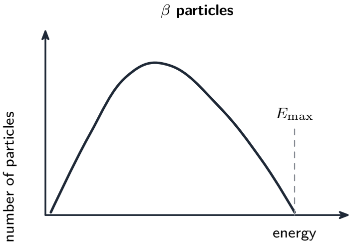
Method — Why β energies are continuous and α energies are not

- In an α **decay** the energy released is shared between only **two** bodies: the α particle and the recoiling daughter nucleus. Conservation of momentum and energy then fixes the α's share exactly, so every α from that decay route has the **same, discrete** energy.
- In a β **decay** a **third** particle is emitted – an **antineutrino** in β^- decay, a **neutrino** in β^+ decay. The energy is shared between the β particle and the neutrino in **any** proportion, so the β takes anything from nearly zero up to a maximum E_{max}.
- E_{max} is the energy the β would have if the neutrino took none, and it is the same for every decay of that nuclide. It is the only fixed feature of the spectrum.
- Historically this is **why the neutrino was proposed at all**: without it, β decay appeared to break conservation of energy.

Method — Why β energies are continuous and α energies are not



a few **discrete** energies,
one for each decay route



a **continuous** range, from
nearly zero up to a maximum

An α decay shares its energy between only two bodies, the α and the recoiling nucleus, so the α's share is fixed: a **discrete** energy. A β decay emits a **third** particle – an antineutrino in β^-, a neutrino in β^+ – and the energy is shared between the two of them in any proportion, so the β takes anything from nearly zero up to $E_{\max}$.

Method — Writing the equation

$$^{218}_{84}\mathrm{Po} \rightarrow \; ^{214}_{82}\mathrm{Pb} + \; ^{4}_{2}\alpha \qquad\qquad ^{214}_{82}\mathrm{Pb} \rightarrow \; ^{214}_{83}\mathrm{Bi} + \; ^{0}_{-1}\beta + \overline{\nu}_{\mathrm{e}}$$

- **Nucleon number** and **charge** (proton number) are conserved: the top numbers balance and the bottom numbers balance, separately.
- An α decay lowers the nucleon number by **4** and the proton number by **2**; a β^- decay leaves the nucleon number **unchanged** and raises the proton number by **1**.
- The **antineutrino carries no charge and no nucleon number**, so it does not disturb the balance – which is exactly why it is so easy to leave out, and why leaving it out costs a mark.

2 Practice

Practice 2.1 ▪ 3 marks

State the composition of α, β^- and β^+ radiation.

Solution 2.1

Method: What the three radiations are — p.4

Worked steps

- α: a **helium nucleus** – two protons and two neutrons **B1**
- β^-: a fast-moving **electron** **B1**
- β^+: a fast-moving **positron**, the antiparticle of the electron **B1**

Practice 2.2 ▪ 3 marks

Explain why α radiation is the **most** strongly ionising but the **least** penetrating.

Solution 2.2

Method: Penetration and ionisation are opposite ends of the same fact — p.6

Worked steps

- an α particle has a **large charge** of $+2e$ and moves comparatively slowly, so it interacts strongly with the atoms it passes **B1**
- it therefore **ionises** a great many atoms per unit distance **B1**
- each ionisation takes energy from it, so it loses all its energy within a very short distance: it is least penetrating **because** it is most ionising **B1**

Practice 2.3 ▪ 3 marks

A source emitting α, β^- and γ radiation is placed in a magnetic field. State which two are deflected in opposite directions, and explain why the third is not deflected at all.

Solution 2.3

Method: In a magnetic field — p.8

Worked steps

- α and β^- are deflected in **opposite** directions **B1**
- because α carries a positive charge and β^- a negative one **B1**
- γ has **no charge**, so the magnetic force Bqv on it is zero and it travels straight on **B1**

Practice 2.4 ▪ 2 marks

Explain why a β particle is deflected much more sharply than an α particle in the same magnetic field.

Solution 2.4

Method: In a magnetic field — p.8

Worked steps

- the radius of the path is $r = \dfrac{mv}{Bq}$, so a smaller mass gives a smaller radius and a sharper curve **B1**
- a β particle has roughly $\frac{1}{7000}$ of the mass of an α particle, so it is deflected far more **B1**

Practice 2.5 ▪ 2 marks

State the mass in kilograms of one unified atomic mass unit, and state what the unit is defined against.

Solution 2.5

Method: What the three radiations are — p.4

Worked steps

- $1\ \mathrm{u} = 1.66 \times 10^{-27}$ kg **B1**
- it is defined as **one twelfth of the mass of a carbon-12 atom** **B1**

3 Exam-style

Exam-style 3.1 ▪ 1 mark

Which row gives the charge and the approximate mass of a β^- particle?

	charge	**mass**
A	$-e$	4 u
B	$-e$	$\frac{1}{1840}$ u
C	$+e$	$\frac{1}{1840}$ u
D	0	0

Solution 3.1

Method: In a magnetic field — p.8

Worked steps

B

- a β^- particle is an electron: charge $-e$ and mass about $\frac{1}{1840}$ u **B1**

Exam-style 3.2 ▪ 6 marks

The energies of the particles emitted in radioactive decay can be measured.

Exam-style 3.2 (a) ▪ 2 marks

Sketch, on the same axes of number of particles against energy, the energy spectrum expected for α particles from one decay route and for β particles from one decay.

Solution 3.2 (a)

Method: Why β energies are continuous and α energies are not — p.10

Worked steps

- the α spectrum drawn as **one or a few sharp, discrete lines** B1
- the β spectrum drawn as a **continuous curve** rising from near zero, peaking, and falling to zero at a maximum energy B1

Exam-style 3.2 (b) ▪ 4 marks

Explain why β particles are emitted with a continuous range of energies while α particles are not.

Solution 3.2 (b)

Worked steps

- in an α decay the energy released is shared between only **two** bodies, the α particle and the recoiling nucleus **B1**
- conservation of energy and momentum then fixes the α particle's share exactly, so it is **discrete** **B1**
- in a β decay a **third** particle is emitted: an **antineutrino** in β^- decay **B1**
- the available energy is shared between the β particle and the antineutrino in **any** proportion, so the β particle's energy ranges continuously from nearly zero to a maximum **B1**

Exam-style 3.3 ▪ 10 marks

A nucleus of $^{218}_{84}$Po decays by α emission to an isotope of lead, which then decays by β^- emission to an isotope of bismuth (proton number 83).

Exam-style 3.3 (a) ▪ 2 marks

Write the nuclear equation for the α decay.

Solution 3.3 (a)

Method: Why β energies are continuous and α energies are not — p.10

Worked steps

- the nucleon number falls by 4 and the proton number by 2 **B1**

$$^{218}_{84}\text{Po} \rightarrow\ ^{214}_{82}\text{Pb} +\ ^{4}_{2}\alpha$$ **A1**

Exam-style 3.3 (b) ▪ 3 marks

Write the nuclear equation for the β^- decay, including the third particle emitted.

Solution 3.3 (b)

Worked steps

- the nucleon number is unchanged and the proton number rises by 1 **B1**
- the β^- particle is written ${}^{0}_{-1}\beta$ **B1**

$$ {}^{214}_{82}\mathrm{Pb} \rightarrow {}^{214}_{83}\mathrm{Bi} + {}^{0}_{-1}\beta + \overline{\nu}_{\mathrm{e}} $$ **A1**

- the third particle is an **antineutrino**; it carries no charge and no nucleon number, so the balance is unaffected

Exam-style 3.3 (c) ▪ 2 marks

State the **two** quantities that are conserved in both equations.

Solution 3.3 (c)

Worked steps

- **nucleon number** B1
- **charge**, equivalently proton number B1

Exam-style 3.3 (d) ▪ 2 marks

Every α particle from the polonium decay has the same energy, 6.00 MeV. State what this tells you about how the energy is shared, and explain.

Solution 3.3 (d)

Worked steps

- the energy is shared between **only two** bodies: the α particle and the recoiling daughter nucleus **B1**
- conservation of momentum and energy then fixes each share exactly, so every α from this route carries the same energy – no third particle is emitted **B1**

Exam-style 3.3 (e) ▪ 1 mark

Calculate the approximate mass, in kg, of a $^{218}_{84}\text{Po}$ nucleus. Take $1\ \text{u} = 1.66 \times 10^{-27}$ kg.

Solution 3.3 (e)

Worked steps

- the mass is about the nucleon number times 1 u **B1**

$$m \approx 218 \times 1.66 \times 10^{-27}\ \text{kg} = \mathbf{3.6 \times 10^{-25}}\ \text{kg}$$