11.1.2 The three radiations and their energies

Name: _____ Class: _____ Date: _____ **Total: 37 marks**

KEY WORDS alpha particle α • beta particle β • gamma radiation γ • ionisation • energy spectrum

Objective

Answer exam questions on **α-, β- and γ-radiation**: what each one is made of, its mass and its charge, how those decide its behaviour in matter and in a field, and why every α-particle from one decay has the **same** energy while β-particles have a **continuous range** of energies. Syllabus 11.1, learning outcomes 7 and 10.

You must be able to:

- describe the composition, mass and charge of α-, β^--, β^+- and γ-radiation
- use the mass and charge to explain penetration, ionisation and deflection in a field
- explain why α-particles have discrete energies but β-particles a continuous range
- sketch the energy spectra of α- and β-particles

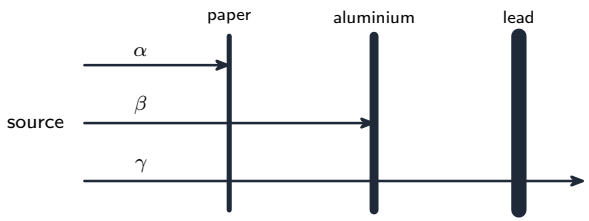
1 Key knowledge and worked examples

■ Key knowledge: what the three radiations are

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

- The **positron** is the antiparticle of the electron: the same mass, the opposite charge.
- γ-radiation is electromagnetic. It is emitted when a nucleus left in an excited state drops to a lower energy, so it changes neither A nor Z.
- 1 u $= 1.66 \times 10^{-27}$ kg, so an α-particle has a mass of about $m = A \times 1$ u $= 4 \times 1.66 \times 10^{-27}$ kg $= 6.6 \times 10^{-27}$ kg.

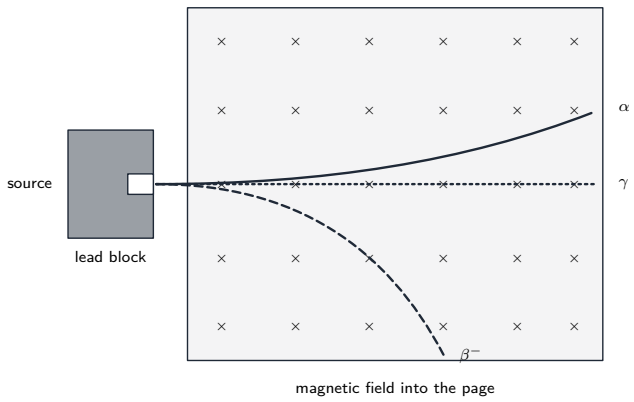
■ Key knowledge: penetration and ionisation



	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 and moves slowly, so it ionises many atoms along its path. Each ionisation costs it energy, so it stops within a short distance: it is the **least penetrating because it is the most ionising**.
- γ carries no charge, so it interacts rarely; it ionises little and travels far.

■ Key knowledge: deflection in a field



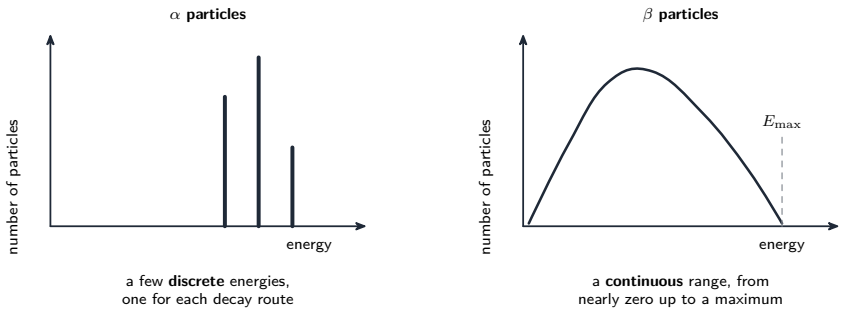
Three separate reasons. **Direction:** α is positive and β^- negative, so they curve *opposite* ways. **Amount:** $r = \frac{mv}{Bq}$, and a β particle has about $\frac{1}{7000}$ of an α's mass, so it curves far more sharply. **γ:** it carries no charge, so the magnetic force on it is zero and it goes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

Three questions, three reasons; give all three.

1. **Which way?** α is **positive** and β^- is **negative**, so they are deflected in **opposite** directions. β^+ goes the same way as α.

2. **How much?** A β-particle has about $\frac{1}{7000}$ of the mass of an α-particle, so it is deflected **far more** sharply.
3. **And γ?** It has **no charge**, so there is no force on it and it is **not deflected**.

■ Key knowledge: discrete α energies, continuous β energies



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 $E_{\max}$.

- In α **decay** the energy released is shared between only **two** bodies, the α-particle and the recoiling nucleus. Conservation of momentum fixes the split, so every α-particle from that decay has the **same, discrete** energy.
- In 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 (anti)neutrino in **any** proportion, so β energies form a **continuous range** from nearly zero up to a maximum.
- The maximum is the energy a β-particle has when the (anti)neutrino takes almost none. It is the same for every decay of that nuclide.

■ Worked example: how an α decay shares its energy

A stationary nucleus of ${}^{210}_{84}\text{Po}$ decays to ${}^{206}_{82}\text{Pb}$ and an α-particle, releasing 5.41 MeV as kinetic energy.

1. **Momentum** – the parent was at rest, so the two products have equal and opposite momenta, of the same size p.
2. **Kinetic energy from momentum** – combine $E_\text{k} = \frac{1}{2}mv^2$ with $p = mv$:

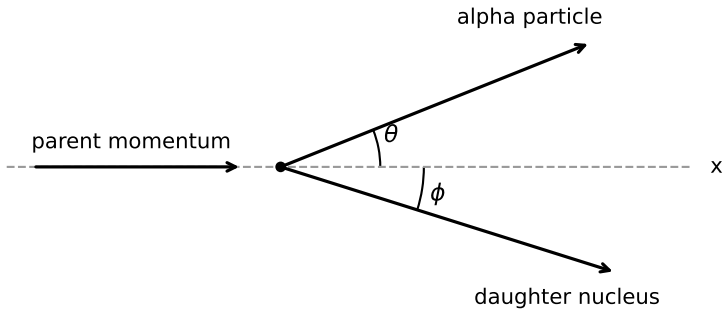
$$E_\text{k} = \frac{p^2}{2m}$$

   With the same p for both, each share is inversely proportional to the mass.
3. **The α-particle's share**:

$$E_\alpha = E \times \frac{m_\text{Pb}}{m_\text{Pb} + m_\alpha} = 5.41\ \text{MeV} \times \frac{206\ \text{u}}{206\ \text{u} + 4\ \text{u}} = 5.31\ \text{MeV}$$

4. **Why that makes it discrete** – every decay splits the same energy between the same two bodies in the same ratio, so every α-particle has 5.31 MeV. A β decay has three products, and no fixed split.

■ Key knowledge: a moving nucleus decays



Use conservation of momentum **along each axis separately**. Choose x along the parent's initial velocity, so the initial transverse momentum is zero. If the products move on opposite sides of x, their transverse momenta cancel: $m_\alpha v_\alpha \sin\theta = m_d v_d \sin\phi$. Along x, their momenta add to the parent's initial momentum.

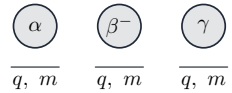
Worked example. Products have momenta 2.0×10^{-20} and 1.0×10^{-20} kg m/s. The daughter moves 30° below x. Transverse conservation gives $\sin\theta = p_d \sin\phi / p_\alpha = (1.0 \times 10^{-20} \sin 30°)/(2.0 \times 10^{-20}) = 0.25$, so the alpha particle moves at 14.5° above x. The initial total momentum is not zero; only its transverse component is zero.

2 Practice

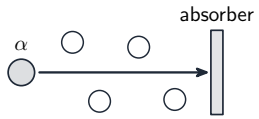
Now use the methods above.

2.1 State the composition of α-, β^-- and β^+-radiation. [3]

2.2 State the charge and the mass, in u, of an α-particle, a β^--particle and a γ-ray photon. [3]

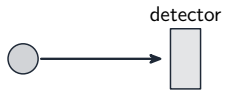


2.3 Explain why α-radiation is the **most** strongly ionising but the **least** penetrating. [3]



2.4 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. [3]

2.5 Explain why β-particles are emitted with a **continuous range** of energies. [2]



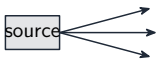
3 Exam-style questions

3.1 Which option gives the charge and the approximate mass of a β^--particle? [1]

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

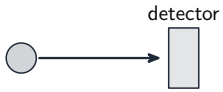
3.2 Every particle emitted by a radioactive source has the same kinetic energy. Which radiation is the source emitting? [1]

A α-particles
B β^--particles
C β^+-particles
D both β^-- and β^+-particles



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

(a) Sketch, on the same axes of number of particles against energy, the energy spectrum expected for α-particles from one decay and for β-particles from one decay. [2]

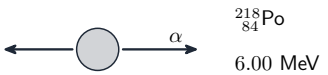


(b) Explain why β-particles are emitted with a continuous range of energies while α-particles are not. [4]

3.4 A stationary nucleus of $^{218}_{84}$Po decays by α emission. Every α-particle from this decay has a kinetic energy of 6.00 MeV.

(a) State the composition, the charge and the mass, in u, of an α-particle. [2]

(b) Explain why every α-particle from this decay has the same energy. [2]

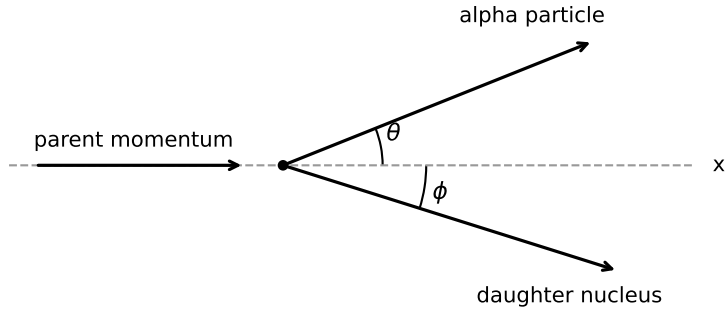


(c) The daughter nucleus has a mass of 214 u. Show that its kinetic energy is about 0.11 MeV. [3]

(d) The daughter nucleus later decays by β^- emission. Explain why the β^--particles emitted have a range of energies up to a maximum value. [2]

(e) Calculate the approximate mass, in kg, of a $^{218}_{84}$Po nucleus. Take 1 u = 1.66×10^{-27} kg. [1]

3.5 A moving nucleus emits an alpha particle at angle θ above its original direction. The daughter nucleus has momentum 3.0×10^{-20} kg m/s at 20° below that direction. The alpha particle has momentum 2.0×10^{-20} kg m/s. Determine θ and the parent's initial momentum. [5]



Solutions

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

2.1

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

2.2

- α: charge $+2e$, mass 4 u
- β^-: charge $-e$, mass about $\frac{1}{1840}$ u
- γ: charge 0, mass 0

2.3

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

2.4

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

2.5

- a β decay also emits an (anti)**neutrino**
- the energy released is **shared** between the β-particle and the (anti)neutrino in varying proportions, so the β energy varies

3.1 B

- a β^--particle is an electron: charge $-e$ and mass about $\frac{1}{1840}$ u
- **A** gives an α-particle's mass; **C** is a positron; **D** is a γ-ray photon

3.2 A

- in α decay the energy is shared between only two bodies, so every α-particle from one decay has the same energy
- in both kinds of β decay a (anti)neutrino takes a varying share, so the β energies vary

3.3

(a)

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

(b)

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

3.4

(a) two protons and two neutrons, a **helium nucleus**

- charge $+2e$ and mass 4 u

(b) the energy is shared between **only two** bodies, the α-particle and the recoiling daughter nucleus

- conservation of momentum fixes each share, so every α-particle from this decay has the same energy; no third particle is emitted

(c) the two momenta are equal in size, and $E_\mathrm{k} = \dfrac{p^2}{2m}$, so each energy is inversely proportional to the mass

$$\frac{E_\mathrm{D}}{E_\alpha} = \frac{m_\alpha}{m_\mathrm{D}}$$

$$E_\mathrm{D} = E_\alpha \times \frac{m_\alpha}{m_\mathrm{D}} = 6.00\ \mathrm{MeV} \times \frac{4\ \mathrm{u}}{214\ \mathrm{u}} = \mathbf{0.112}\ \mathrm{MeV}$$

(d) an **antineutrino** is emitted as well as the β^--particle

- the energy released is shared between them in varying proportions; the maximum is when the antineutrino takes almost none

(e) the mass of a nucleus is about A u

$$m = A \times 1\ \mathrm{u} = 218 \times 1.66 \times 10^{-27}\ \mathrm{kg} = \mathbf{3.6 \times 10^{-25}}\ \mathrm{kg}$$

3.5

- Transverse momentum: $0 = p_\alpha \sin\theta - p_d \sin 20°$.
- $\sin\theta = p_d \sin 20°/p_\alpha = 3.0 \sin 20°/2.0 = 0.513$.
- $\theta = \sin^{-1}(0.513) = 30.9°$.
- Longitudinal momentum: $p_0 = p_\alpha \cos\theta + p_d \cos 20°$.
- $p_0 = 2.0 \times 10^{-20} \cos 30.9° + 3.0 \times 10^{-20} \cos 20° = 4.53 \times 10^{-20}$ kg m s^{-1}.