A-LEVEL PHYSICS • EXERCISE SHEET

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

Name: ____________ Class: ________ Date: __________ **Total: 30 marks**

KEY WORDS nucleus 原子核 • proton 质子 • isotope 同位素 • radioactive 放射性 • neutron 中子

Objective

Sheets 11.1 and 11.1.1 cover the nuclear atom, the scattering evidence and decay chains. This sheet is the remaining third of 11.1: **what the three radiations actually are**, how each behaves in a magnetic or electric field and in an absorber, why an α particle has a **discrete** energy while a β particle has a **continuous range**, and writing a full decay equation with the **neutrino** 中微子 in it. This sheet covers syllabus 11.1.

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 Worked examples

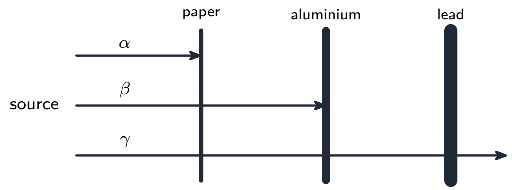
Study these first. Each one shows a **method** that a question later on this sheet needs.

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

- 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 $1\ \text{u} = 1.66 \times 10^{-27}$ kg. The mass of a nucleus in kilograms is therefore roughly its **nucleon number** $\times\ 1.66 \times 10^{-27}$ kg.

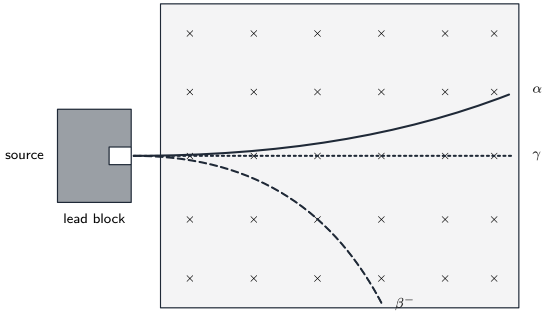
Penetration and ionisation are opposite ends of the same fact



	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.

In a magnetic field



magnetic field into the page

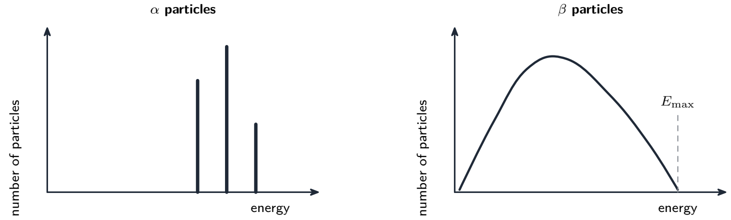
Three separate reasons. **Direction:** α is positive and β^- negative, so they curve *opposite* ways. **Amount:** $r = \dfrac{mv}{Bq}$, and a β particle has about $\frac{1}{7000}$ of an α's mass, so it curves far more sharply. **γ:** it carries no charge, so the magnetic force on it is zero and it goes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

Three 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.

■ 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 $E_{\max}$.

- 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.

■ Writing the equation

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

- **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

Now use the methods above.

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

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

2.3 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]

2.4 Explain why a β particle is deflected much more sharply than an α particle in the same magnetic field. [2]

2.5 State the mass in kilograms of one unified atomic mass unit, and state what the unit is defined against. [2]

3 Exam-style questions

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

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

3.2 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 route 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]

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

(a) Write the nuclear equation for the α decay. [2]

(b) Write the nuclear equation for the β^- decay, including the third particle emitted. [3]

(c) State the **two** quantities that are conserved in both equations. [2]

(d) 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. [2]

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