CIE International A Level Physics

Topic 11

Particle Physics

Revision Booklet

This booklet covers:

- Atoms, Nuclei and Radiation
- Types of Radiation: α, β and γ
- Radioactive Decay Equations
- Fundamental Particles: Quarks
- Hadrons, Baryons and Mesons
- Leptons and Beta Decay

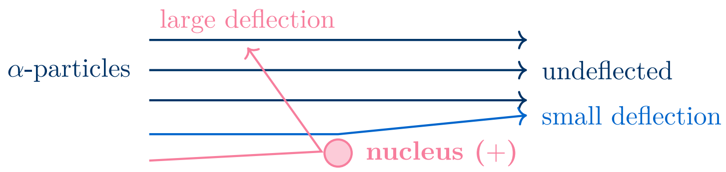
Atoms, Nuclei and Radiation

The Nuclear Atom

The **Geiger–Marsden** α-particle scattering experiment (directed α-particles at thin gold foil) showed:

- Most α-particles passed straight through $\Rightarrow$ the atom is mostly empty space.
- A small fraction were deflected through large angles $\Rightarrow$ a dense, positively charged nucleus exists.
- A very few bounced back ($> 90°$) $\Rightarrow$ the nucleus is very small compared to the atom.

Rutherford scattering diagram



Nuclear Notation

A **nuclide** is a specific nuclear species characterised by its proton and nucleon numbers:

$$^{A}_{Z}\mathrm{X}$$

- A = **nucleon number** (mass number): total number of protons + neutrons.
- Z = **proton number** (atomic number): number of protons.
- Number of neutrons $N = A - Z$.
- **Isotopes**: atoms of the same element (same Z) with different numbers of neutrons (different A).

Conservation Laws in Nuclear Processes

In every nuclear reaction or decay, the following are always conserved:

- **Nucleon number** A (total count of protons + neutrons).
- **Charge** (equivalently, proton number Z).

These two conservation laws are the key tool for balancing decay equations.

Unified Atomic Mass Unit

The **unified atomic mass unit** (u) is defined as exactly $\frac{1}{12}$ of the mass of a carbon-12 atom.

$$1\ \mathrm{u} = 1.661 \times 10^{-27}\ \mathrm{kg}$$

Approximate masses: proton ≈ 1 u; neutron ≈ 1 u; electron ≈ 0.00055 u.

Types of Radiation: α, β and γ

Radiation	Composition	Charge	Mass	Stopped by
α (alpha)	2 protons + 2 neutrons (helium-4 nucleus)	$+2e$	4 u	A few cm of air; thin paper
β^- (beta-minus)	Electron (e^-)	$-e$	≈ 0 ($\frac{1}{1836}$ u)	A few mm of aluminium
β^+ (beta-plus)	Positron (e^+)	$+e$	≈ 0 ($\frac{1}{1836}$ u)	Annihilates with electron
γ (gamma)	Electromagnetic wave / photon	0	0	Several cm of lead

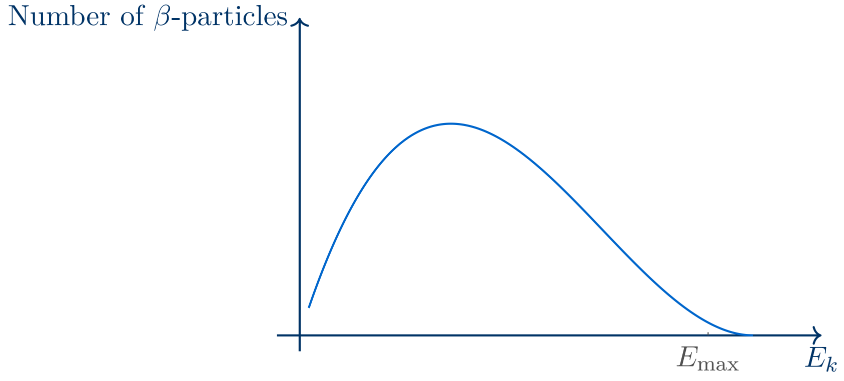
Antiparticles

Every particle has a corresponding **antiparticle** with:

- The **same mass** as the particle.
- The **opposite charge** (and opposite quantum numbers).
- The **positron** (β^+, e^+) is the antiparticle of the electron (e^-).
- When a particle meets its antiparticle they **annihilate**, producing energy (usually two γ-ray photons).

Energies of Emitted Particles

- **α-particles** are emitted with **discrete (fixed) energies**: each decay of a given nuclide always releases an α-particle of the same kinetic energy, giving a sharp line spectrum.
- **β-particles** have a **continuous range of energies** from zero up to a maximum: the total energy of the decay is shared between the β-particle and an (anti)neutrino, which can take any share — hence the continuous spectrum.
- **(Anti)neutrinos** are produced in β-decay to account for this energy sharing and to conserve momentum and angular momentum.



Continuous β energy spectrum

Common Mistake

Students often state that β-particles have a fixed energy like α-particles. They do not — the continuous spectrum is direct evidence for neutrino emission. The **maximum** β energy equals the total energy available from the decay (as if no neutrino were present).

Radioactive Decay Equations

Alpha decay

In α-decay, the nucleus emits a helium-4 nucleus (${}^{4}_{2}\alpha$). Both A and Z decrease:

$${}^{A}_{Z}\text{X} \longrightarrow {}^{A-4}_{Z-2}\text{Y} + {}^{4}_{2}\alpha$$

Example:

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

Check: A: $238 = 234 + 4$ ✓; Z: $92 = 90 + 2$ ✓

Beta-minus decay (β^-)

A neutron converts to a proton; an electron and an electron antineutrino are emitted. A is unchanged; Z increases by 1:

$${}^{A}_{Z}\text{X} \longrightarrow {}_{Z+1}^{\ \ A}\text{Y} + {}^{\ \ 0}_{-1}\text{e} + \bar{\nu}_e$$

Example:

$${}^{14}_{6}\text{C} \longrightarrow {}^{14}_{7}\text{N} + {}^{\ \ 0}_{-1}\text{e} + \bar{\nu}_e$$

Beta-plus decay (β^+)

A proton converts to a neutron; a positron and an electron neutrino are emitted. A is unchanged; Z decreases by 1:

$${}^{A}_{Z}\text{X} \longrightarrow {}_{Z-1}^{\ \ A}\text{Y} + {}^{\ \ 0}_{+1}\text{e} + \nu_e$$

Gamma emission

γ-radiation accompanies α or β decay when the daughter nucleus is left in an excited state. Neither A nor Z changes:

$${}^{A}_{Z}\text{X}^* \longrightarrow {}^{A}_{Z}\text{X} + \gamma$$

Decay Equation Summary

Decay	ΔA	ΔZ	Particles emitted
α	-4	-2	${}^{4}_{2}\alpha$
β^-	0	$+1$	${}^{0}_{-1}\text{e}$, $\bar{\nu}_e$
β^+	0	-1	${}^{0}_{+1}\text{e}$, ν_e
γ	0	0	γ photon

Fundamental Particles: Quarks

Quarks

A **quark** is a fundamental, point-like particle. There are **six flavours** of quark (and six corresponding antiquarks):

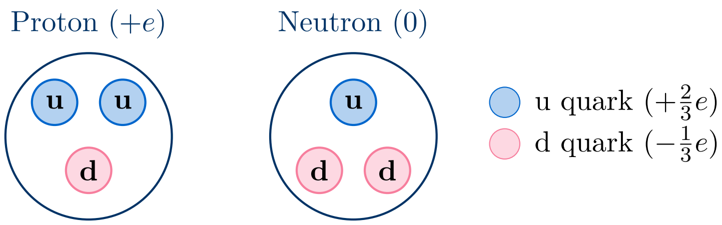
Flavour	Symbol	Charge
up	u	$+\frac{2}{3}e$
down	d	$-\frac{1}{3}e$
strange	s	$-\frac{1}{3}e$
charm	c	$+\frac{2}{3}e$
top	t	$+\frac{2}{3}e$
bottom	b	$-\frac{1}{3}e$

Antiquark	Symbol	Charge
anti-up	$\bar{\text{u}}$	$-\frac{2}{3}e$
anti-down	$\bar{\text{d}}$	$+\frac{1}{3}e$
anti-strange	$\bar{\text{s}}$	$+\frac{1}{3}e$
anti-charm	$\bar{\text{c}}$	$-\frac{2}{3}e$
anti-top	$\bar{\text{t}}$	$-\frac{2}{3}e$
anti-bottom	$\bar{\text{b}}$	$+\frac{1}{3}e$

Only up and down quarks are required for protons and neutrons; strange, charm, top and bottom are examined only for their charges.

Quark Composition of Proton and Neutron

Particle	Quarks	Charge calculation	Total charge
Proton	uud	$\frac{2}{3}e + \frac{2}{3}e - \frac{1}{3}e$	$+e$
Neutron	udd	$\frac{2}{3}e - \frac{1}{3}e - \frac{1}{3}e$	0



Hadrons, Baryons and Mesons

Hadrons

A **hadron** is any particle made of quarks. Hadrons are subdivided into two classes:

- **Baryons**: composed of **three quarks** (qqq). Examples: proton (uud), neutron (udd).
- **Mesons**: composed of **one quark and one antiquark** ($q\bar{q}$). Examples: pion ($\pi^+ = u\bar{d}$).

Protons and neutrons are **not** fundamental particles — they are baryons made of quarks.

Class	Quark content	Example	Charge
Baryon	qqq (three quarks)	Proton (uud)	$+e$
Baryon	qqq (three quarks)	Neutron (udd)	0
Meson	$q\bar{q}$ (quark + antiquark)	π^+ ($u\bar{d}$)	$+e$
Meson	$q\bar{q}$ (quark + antiquark)	π^- ($\bar{u}d$)	$-e$
Meson	$q\bar{q}$ (quark + antiquark)	π^0 ($u\bar{u}$ or $d\bar{d}$)	0

Leptons and Beta Decay

Leptons

Leptons are fundamental (point-like, not made of quarks) particles. The leptons required at A-level are:

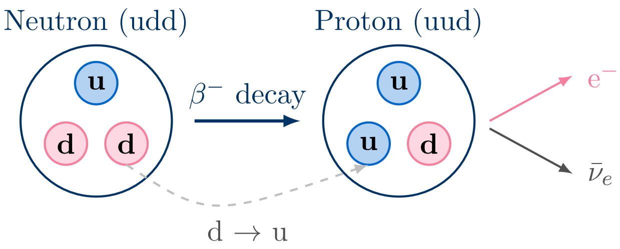
- **Electron** (e^-) — charge $-e$.
- **Positron** (e^+) — antiparticle of electron; charge $+e$.
- **Electron neutrino** (ν_e) — charge 0; produced in β^+ decay.
- **Electron antineutrino** ($\bar{\nu}_e$) — charge 0; produced in β^- decay.

Quark Changes in Beta Decay

Beta decay occurs because a quark changes flavour inside a nucleon:

Decay	Quark change	Nucleon change	Particles emitted
β^-	d → u	Neutron → Proton	$e^- + \bar{\nu}_e$
β^+	u → d	Proton → Neutron	$e^+ + \nu_e$

Quark-level picture of β^- decay



Neutrinos vs Antineutrinos

This is a common source of error in exams:

- β^- decay produces an **electron anti**neutrino ($\bar{\nu}_e$) — the antiparticle of the neutrino.
- β^+ decay produces an **electron neutrino** (ν_e).

A helpful check: the lepton number must be conserved. In β^-, a lepton of number $+1$ (the electron) is created alongside a lepton of number -1 (the antineutrino), giving net lepton number zero — matching the original nucleon.

Key Facts Summary

Particle	Symbol	Charge	Type
Proton	p	$+e$	Baryon (uud)
Neutron	n	0	Baryon (udd)
Electron	e^-	$-e$	Lepton
Positron	e^+	$+e$	Lepton (antiparticle of e^-)
Electron neutrino	ν_e	0	Lepton
Electron antineutrino	$\bar{\nu}_e$	0	Lepton
α-particle	${}^4_2\alpha$	$+2e$	Baryon (not fundamental)

Quark charges (to recall): u: $+\frac{2}{3}e$; d: $-\frac{1}{3}e$; s: $-\frac{1}{3}e$; c: $+\frac{2}{3}e$; t: $+\frac{2}{3}e$; b: $-\frac{1}{3}e$

Antiquark charge = opposite of quark charge.

Conservation laws in every nuclear/particle process: nucleon number A; charge Z; lepton number.

Worked Examples

Example 1 — Completing a Decay Equation

Question: Complete the following decay equation and identify the type of decay:

$$^{210}_{84}\text{Po} \longrightarrow {}^{A}_{Z}\text{X} + {}^{4}_{2}\alpha$$

Solution

Conserve nucleon number A: $210 = A + 4 \Rightarrow A = \mathbf{206}$
Conserve charge Z: $84 = Z + 2 \Rightarrow Z = \mathbf{82}$ (lead, Pb)

$$^{210}_{84}\text{Po} \longrightarrow {}^{206}_{82}\text{Pb} + {}^{4}_{2}\alpha$$

This is **alpha decay** — the nucleon number decreases by 4 and the proton number by 2.

Example 2 — Identifying Decay Type from Equation

Question: Identify the particle X and the type of decay in:

$$^{90}_{38}\text{Sr} \longrightarrow {}^{90}_{39}\text{Y} + {}^{0}_{-1}\text{e} + X$$

Solution

A is conserved: $90 = 90 + 0 + 0$ ✓
Z: $38 = 39 + (-1) + 0$ ✓
The emitted particles are an electron (β^-) and X. This is β^- decay, so X must be an **electron antineutrino**: $X = \bar{\nu}_e$.

$$^{90}_{38}\text{Sr} \longrightarrow {}^{90}_{39}\text{Y} + {}^{0}_{-1}\text{e} + \bar{\nu}_e$$

Example 3 — Quark Composition and Charge

Question: (a) State the quark composition of an antiproton. (b) Calculate its charge.

Solution

(a) The proton has quark composition uud. The antiproton is its antiparticle, so every quark is replaced by its antiquark:

$$\text{Antiproton} = \bar{\text{u}}\bar{\text{u}}\bar{\text{d}}$$

(b) Charge $= -\frac{2}{3}e + (-\frac{2}{3}e) + \frac{1}{3}e = -\frac{3}{3}e = \mathbf{-e}$
This confirms the antiproton has charge $-e$, equal in magnitude but opposite in sign to the proton.

Example 4 — Quark Changes in β^+ Decay

Question: A proton undergoes β^+ decay. Write a full decay equation and describe the quark-level change.

Solution

$$^{1}_{1}\mathrm{p} \longrightarrow {}^{1}_{0}\mathrm{n} + {}^{0}_{+1}\mathrm{e} + \nu_e$$

At the quark level, one **up quark converts to a down quark**:

$$\text{Proton (uud)} \longrightarrow \text{Neutron (udd)} + \mathrm{e}^+ + \nu_e$$

Charge check: $+e \to 0 + e + 0$ ✓; Nucleon number: $1 = 1 + 0 + 0$ ✓

Practice Exam Questions

Section A — Short Answer Questions

Q1. Describe the key observations from the α-particle scattering experiment and explain what each tells us about atomic structure.

[4 marks]

Q2. Distinguish between nucleon number and proton number. Define the term *isotope.*

[3 marks]

Q3. State the composition, charge and approximate mass (in u) of α-, β^-- and γ-radiation.

[5 marks]

Q4. Explain why β-particles have a continuous energy spectrum, whereas α-particles from a given nuclide have a fixed energy.

[3 marks]

Section B — Longer Structured Questions

Q5. The nuclide ${}^{226}_{88}\mathrm{Ra}$ undergoes α-decay.

(a) Write a balanced nuclear equation for this decay, identifying the daughter nuclide.

[2 marks]

(b) State the two conservation laws used to balance the equation.

[2 marks]

(c) Explain why the α-particles emitted in this decay all have the same kinetic energy.

[2 marks]

Q6. The nuclide ${}^{14}_{6}\mathrm{C}$ undergoes β^{-} decay.

(a) Write a full balanced equation for this decay, including all particles emitted.

[2 marks]

(b) Describe the quark-level change that occurs during this decay.

[2 marks]

(c) State and explain whether the β^- particles emitted have a fixed or continuous range of energies.

[2 marks]

Q7. (a) State what is meant by a *hadron* and distinguish between a baryon and a meson.

[3 marks]

(b) The particle π^+ is a meson with quark composition $\mathrm{u\bar{d}}$. Show that this gives a charge of $+e$.

[2 marks]

(c) State the quark composition of an antiproton and calculate its charge.

[2 marks]

(d) Explain why electrons are *not* classified as hadrons.

[1 mark]

Mark Scheme and Answers

Q1. Most α-particles pass straight through $\Rightarrow$ atom is mostly empty space [1]; small fraction deflected through large angles $\Rightarrow$ concentrated positive charge (nucleus) exists [1]; very few back-scattered $\Rightarrow$ nucleus is very small / very dense [1]; all deflections from positive charge are consistent with electrostatic repulsion [1].

Q2. Nucleon number (A): total number of protons + neutrons in a nucleus [1]; **proton number** (Z): number of protons only [1]; **isotopes**: atoms of the same element (same Z) with different numbers of neutrons (different A) [1].

Q3. α: 2 protons + 2 neutrons; charge $+2e$; mass 4 u [2]. β^-: electron; charge $-e$; mass ≈ 0 ($\frac{1}{1836}$ u) [2]. γ: electromagnetic radiation/photon; charge 0; mass 0 [1].

Q4. In β-decay, an (anti)neutrino is also emitted [1]; the total energy is shared between the β-particle and the (anti)neutrino in varying proportions [1]; so the β-particle can have any energy from zero to a maximum — continuous spectrum [1]. For α: only two products (daughter + α); by conservation of energy and momentum, the α always takes the same fixed share [implied/bonus].

Q5(a). ${}^{226}_{88}\text{Ra} \to {}^{222}_{86}\text{Rn} + {}^{4}_{2}\alpha$ [2] (1 mark if equation has correct concept but arithmetic error).

Q5(b). Conservation of nucleon number A [1]; conservation of charge (proton number Z) [1].

Q5(c). Only two products (daughter + α) [1]; by conservation of energy and momentum, the α always receives the same fixed kinetic energy (discrete energy levels) [1].

Q6(a). ${}^{14}_{6}\text{C} \to {}^{14}_{7}\text{N} + {}^{0}_{-1}\text{e} + \bar{\nu}_e$ [2].

Q6(b). A down quark converts to an up quark (d $\to$ u) [1]; inside a neutron, converting it to a proton [1].

Q6(c). Continuous range [1]; because the energy is shared between the β^- particle and the antineutrino in varying proportions [1].

Q7(a). A hadron is a particle made of quarks [1]; a baryon consists of three quarks [1]; a meson consists of one quark and one antiquark [1].

Q7(b). Charge $= +\frac{2}{3}e + \frac{1}{3}e$ [1] $= +e$ ✓[1].

Q7(c). $\bar{\text{u}}\bar{\text{u}}\bar{\text{d}}$ [1]; charge $= -\frac{2}{3}e - \frac{2}{3}e + \frac{1}{3}e = -e$ [1].

Q7(d). Electrons are leptons, not composed of quarks / not hadrons by definition [1].

Revision Checklist

Use this checklist to track your understanding. Tick each box when you are confident:

	Learning Objective	Confidence (1–3)
☐	Describe the α-scattering experiment and interpret its results	
☐	Describe the nuclear model: protons, neutrons and orbital electrons	
☐	Distinguish nucleon number (A) from proton number (Z)	
☐	Define isotopes and use the notation ${}^{A}_{Z}X$	
☐	State that nucleon number and charge are conserved in nuclear processes	
☐	Describe composition, mass and charge of α, β^-, β^+ and γ	
☐	State that a positron is the antiparticle of an electron (same mass, opposite charge)	
☐	State that $\bar{\nu}_e$ is produced in β^- decay and ν_e in β^+ decay	
☐	Explain why β-particles have a continuous energy spectrum	
☐	Write balanced α- and β-decay equations	
☐	Use the unified atomic mass unit (u)	
☐	State the six quark flavours and recall their charges	
☐	State the quark composition of the proton (uud) and neutron (udd)	
☐	Distinguish hadrons (baryons: qqq; mesons: q$\bar{\text{q}}$) from leptons	
☐	Describe the quark change in β^- (d→u) and β^+ (u→d) decay	
☐	Recall that electrons and neutrinos are leptons	

Key: 1 = Need more work   2 = Getting there   3 = Confident

Good luck with your revision!

Particle physics is really just careful bookkeeping. Every decay equation is balanced by two rules — conserve A, conserve Z — and every quark change in β-decay is just one quark swapping flavour. Get those two ideas solid and the whole topic clicks into place.