Cambridge AS & A Level · Physics 9702 · Notes

Particle physics AS

Read online at **pastopic.com/cambridge/physics-9702/notes/particle-physics**

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Read first: **Dynamics**

What you need to know

By the end of this topic you should be able to:

Atoms, nuclei and radiation

1. **Say what the α-particle scattering experiment tells us**: the atom has a nucleus that is charged, very small, and holds most of the atom's mass.
2. **Describe the nuclear atom**: protons and neutrons in a tiny nucleus, with electrons orbiting far outside it.
3. **Tell the nucleon number from the proton number**: the nucleon number A counts protons plus neutrons; the proton number Z counts protons only.
4. **Understand isotopes**: forms of the same element whose nuclei have the same number of protons but different numbers of neutrons.
5. **Read and write nuclide notation** ${}^{A}_{Z}\mathrm{X}$.
6. **Understand that nucleon number and charge are conserved** in nuclear processes.
7. **Describe α, β and γ radiation**: what each is made of, its mass and its charge. Both β^- (electrons) and β^+ (positrons) are included.
8. **Understand antiparticles**: same mass, opposite charge. The positron is the antiparticle of the electron.
9. **State which neutrino goes with which β decay**: an (electron) antineutrino is produced in β^- decay, and an (electron) neutrino in β^+ decay.
10. **Explain the energies**: α-particles from a nuclide have discrete energies, but β-particles have a continuous range, because an (anti)neutrino is emitted and takes a share of the energy.
11. **Write α and β decay equations** in nuclide notation, balancing the top and bottom numbers.
12. **Use the unified atomic mass unit (u)** as a unit of mass.

Fundamental particles

13. **Know that quarks are fundamental** and that there are six flavours: up, down, strange, charm, top and bottom.
14. **Recall the charge of each quark**, and that each antiquark has the opposite charge. No other quark properties are needed.
15. **Know that protons and neutrons are not fundamental**, and give their quark compositions.

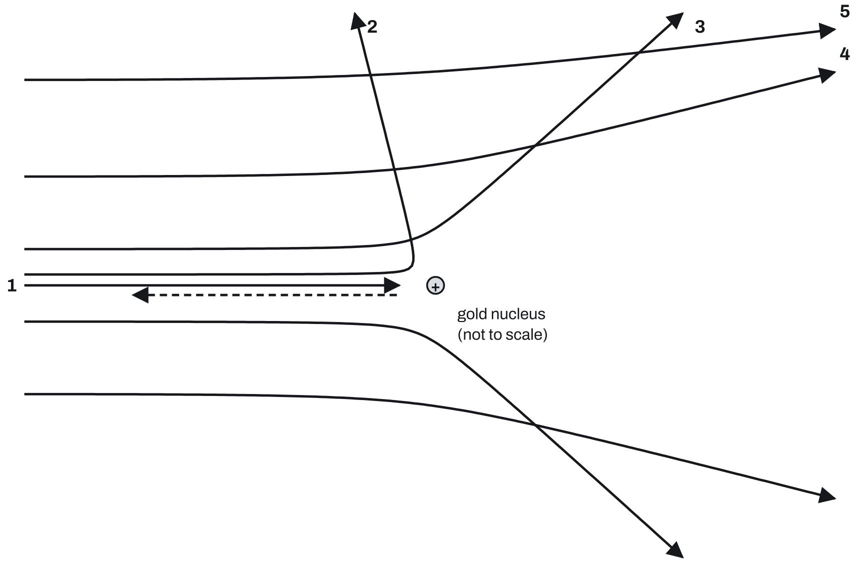
16. **Know the two kinds of hadron**: a baryon is three quarks; a meson is one quark and one antiquark.
17. **Describe the quark change** in β^- and in β^+ decay.
18. **Recall that electrons and neutrinos are fundamental particles called leptons.**

Half-life, the decay constant, binding energy and mass defect belong to the A Level topic on nuclear physics. The strong and weak interactions, lepton number and baryon number are not in the syllabus.

Understand it

The α-particle scattering experiment

A thin gold foil is placed in a vacuum and a narrow beam of α-particles is fired at it. A detector is moved around the foil to count how many α-particles come out at each angle. There are three results, and each tells you something about the atom.



1 head-on: straight back · 2 very close: more than 90° (very few)
3 about 44° · 4 about 15° · 5 far away: almost straight on (most)
the closer an alpha particle passes the nucleus, the more it is repelled

Result	What you can infer
Almost all α-particles go straight through, or are deflected by only a small angle.	The atom is **mostly empty space**, and the nucleus is **very small** compared with the atom.
A few are deflected by large angles.	There is a concentrated **charge** in the nucleus. The α-particles are repelled, so it has the same sign as theirs: positive.
A very small fraction are deflected by **more than 90°**, back towards the source.	The nucleus holds **most of the mass** of the atom: something light could not turn a heavy, fast α-particle round.

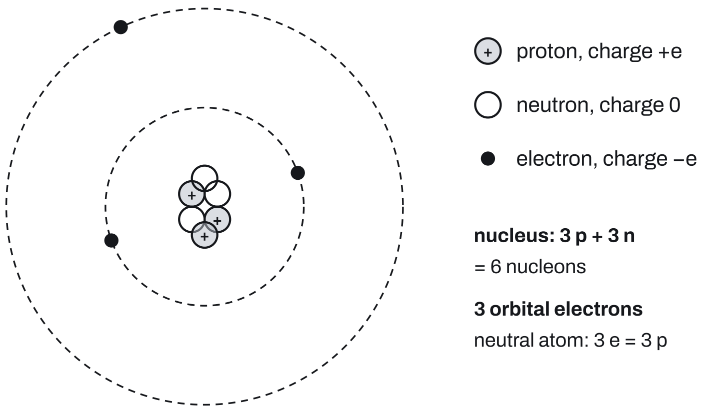
How the paths look (you may be asked to draw them):

- Every path bends **away** from the nucleus, because both are positive and they repel.

- The **closer** the α-particle passes the nucleus, the **larger** its deflection. A head-on one slows down, stops and comes straight back.
- Two α-particles with the same energy passing the same distance above and below the nucleus follow **mirror-image** paths.
- The paths curve smoothly; they do not bounce off a hard surface.

The results tell you about the **nucleus**: that it is small, charged and massive. They do **not** tell you that the nucleus contains protons and neutrons, or that the electrons have a particular charge.

The nuclear atom



not to scale: the nucleus is tiny compared with the atom

An atom has a tiny central **nucleus** made of **protons** and **neutrons** (together called **nucleons**), with **electrons** orbiting well outside it. The nucleus is tens of thousands of times smaller across than the atom.

Particle	Where	Charge	Mass
proton	nucleus	$+e$	about 1 u
neutron	nucleus	0	about 1 u
electron	orbits	$-e$	about $\frac{1}{1800}$ u

A **neutral atom** has as many electrons as protons. An **ion** has gained or lost electrons: the nucleus is unchanged. For example, an aluminium ion Al^{3+} (13 protons) has lost 3 electrons, so it has 10.

Nuclide notation and isotopes

A **nuclide** is one particular kind of nucleus, written

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

- A = **nucleon number** (mass number): protons **plus** neutrons.
- Z = **proton number** (atomic number): protons only. It decides which element X is.
- Number of neutrons $N = A - Z$.

For ${}^{27}_{13}\mathrm{Al}$: 13 protons, $27 - 13 = 14$ neutrons, and 13 electrons in a neutral atom.

Isotopes are nuclides of the **same element** (same Z, so the same number of protons) with **different numbers of neutrons** (so different A). ${}^{20}_{10}\mathrm{Ne}$ and ${}^{22}_{10}\mathrm{Ne}$ are isotopes: both have 10 protons, but they have 10 and 12 neutrons. Isotopes have the same nuclear charge, but different masses, so the heavier one has a **smaller charge-to-mass ratio**. Neutral atoms of isotopes have the same number of electrons.

The unified atomic mass unit

Nuclear masses are tiny, so they are often given in **unified atomic mass units**:

$$1\ \mathrm{u} = 1.66 \times 10^{-27}\ \mathrm{kg} \quad \text{(on the data sheet)}$$

A proton or a neutron has a mass of about 1 u, so a nucleus with nucleon number A has a mass of about A u. To use a mass in an equation such as $E_\mathrm{k} = \frac{1}{2}mv^2$, change it to kilograms: multiply by 1.66×10^{-27}.

- An electron: $\frac{9.11\times10^{-31}}{1.66\times10^{-27}} = 5.5 \times 10^{-4}$ u.
- A proton: $\frac{1.67\times10^{-27}}{1.66\times10^{-27}} = 1.006$ u, so "about 1 u" is fine.
- The **charge-to-mass ratio** of a particle is $\frac{q}{m}$ in C kg^{-1}. For a proton it is $\frac{1.60\times10^{-19}}{1.67\times10^{-27}} = 9.58 \times 10^{7}$ C kg^{-1}; for an electron it is $\frac{1.60\times10^{-19}}{9.11\times10^{-31}} = 1.76 \times 10^{11}$ C kg^{-1}, far larger.

α, β and γ radiation

Radiation	What it is	Mass	Charge	Symbol
α (alpha)	a helium nucleus: 2 protons + 2 neutrons	4 u	$+2e$	${}^{4}_{2}\alpha$ or ${}^{4}_{2}\mathrm{He}$
β^- (beta-minus)	an electron, made in the nucleus	5.5×10^{-4} u	$-e$	${}^{0}_{-1}\beta$ or ${}^{0}_{-1}\mathrm{e}$
β^+ (beta-plus)	a positron, made in the nucleus	5.5×10^{-4} u	$+e$	${}^{0}_{+1}\beta$ or ${}^{0}_{+1}\mathrm{e}$
γ (gamma)	electromagnetic radiation (photons)	0	0	γ

A β-particle is not a small nucleon: its mass is tiny but **not zero**. It does not exist inside the nucleus beforehand; it is **created** when a nucleon changes (see below).

Conservation and decay equations

In every nuclear process, **nucleon number** and **charge** are conserved. In an equation this means the **top numbers balance** and the **bottom numbers balance**. The bottom number of an electron is -1 and of a positron $+1$, because it stands for charge.

α decay: the nucleus loses 2 protons and 2 neutrons. A falls by 4, Z falls by 2.

$${}^{148}_{64}\mathrm{Gd} \rightarrow {}^{144}_{62}\mathrm{Sm} + {}^{4}_{2}\alpha$$

Check: top $148 = 144 + 4$; bottom $64 = 62 + 2$.

β⁻ decay: a neutron becomes a proton, and an electron and an electron **antineutrino** $\bar{\nu}$ are emitted. A stays the same, Z rises by 1.

$$^{32}_{15}\mathrm{P} \rightarrow {}^{32}_{16}\mathrm{S} + {}^{0}_{-1}\beta + {}^{0}_{0}\bar{\nu}$$

Check: top $32 = 32 + 0 + 0$; bottom $15 = 16 - 1 + 0$.

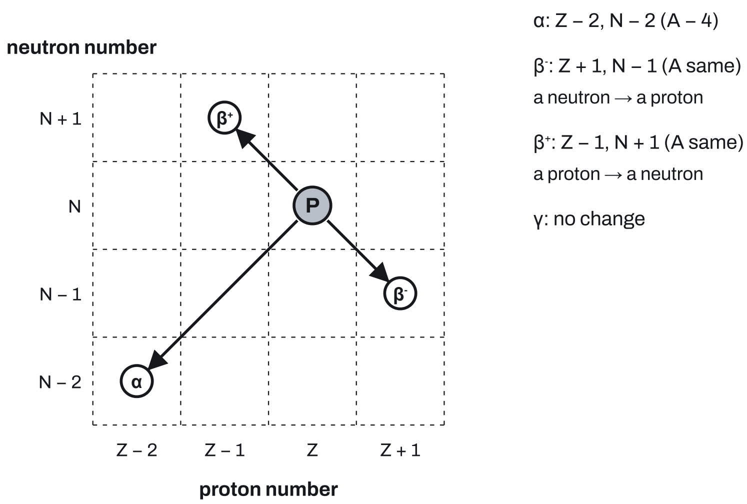
β⁺ decay: a proton becomes a neutron, and a positron and an electron **neutrino** ν are emitted. A stays the same, Z falls by 1.

$$^{38}_{19}\mathrm{K} \rightarrow {}^{38}_{18}\mathrm{Ar} + {}^{0}_{+1}\beta + {}^{0}_{0}\nu$$

Check: top $38 = 38$; bottom $19 = 18 + 1$.

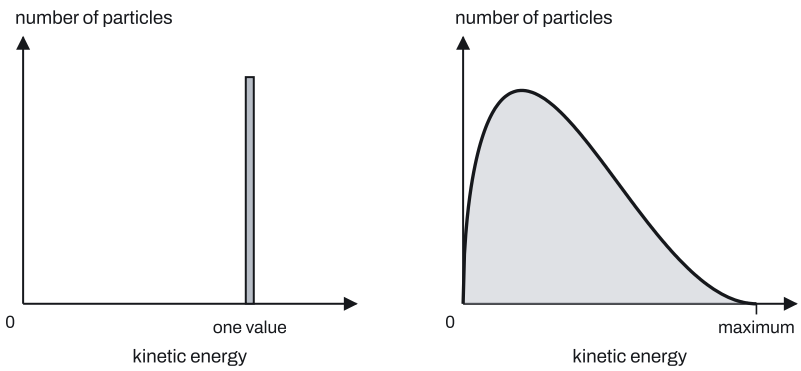
γ emission changes neither A nor Z: the nucleus just loses energy.

Conservation works for any nuclear reaction, not only decays. When a uranium-235 nucleus absorbs a neutron and splits into xenon-140 and strontium-94, the top numbers give the number of free neutrons: $235 + 1 = 140 + 94 + n$, so $n = 2$. The bottom numbers check it: $92 + 0 = 54 + 38$.



The chart shows the same rules. Questions sometimes plot neutron number (or nucleon number) against proton number and ask you to mark the daughter nucleus: count the squares.

Why α energies are discrete but β energies are continuous



α decay: discrete energy **β decay: continuous range**

Every nucleus of one nuclide releases the **same energy** when it decays.

- In **α decay** there are only **two** products: the α-particle and the daughter nucleus. Conservation of momentum and energy fixes how the energy is shared, so every α-particle from that nuclide has the **same** kinetic energy: the energies are **discrete**.
- In **β decay** there are **three** products: the β-particle, the daughter nucleus and the (anti)neutrino. The energy can be shared between the β-particle and the (anti)neutrino in any proportion, so the β-particles have a **continuous range** of kinetic energies, from almost zero up to a maximum. A β-particle at the maximum energy has taken nearly all of it; for any other β-particle the (anti)neutrino carries the rest.

This is the reason the neutrino was proposed: without a third particle, β energies would be discrete too. So a spectrum with a **continuous range** means β decay; a single sharp value means α decay. The **sign** of the charge then tells you β^- or β^+.

Particles and antiparticles

Every particle has an **antiparticle** with the **same mass** and the **opposite charge**. The **positron** is the antiparticle of the electron: mass 9.11×10^{-31} kg, charge $+e$. The antineutrino is the antiparticle of the neutrino (both are uncharged). An antiproton has the proton's mass and charge $-e$.

Quarks

A **fundamental particle** is one that **cannot be split into anything smaller**: it has no smaller particles inside it. Quarks and leptons are fundamental. Protons and neutrons are **not**: each is made of three quarks.

There are six **flavours** of quark. You must remember their charges:

Flavour	Symbol	Charge	Antiquark	Antiquark charge
up	u	$+\frac{2}{3}e$	$\bar{\text{u}}$	$-\frac{2}{3}e$
down	d	$-\frac{1}{3}e$	$\bar{\text{d}}$	$+\frac{1}{3}e$

Flavour	Symbol	Charge	Antiquark	Antiquark charge
strange	s	$-\frac{1}{3}e$	$\bar{\mathrm{s}}$	$+\frac{1}{3}e$
charm	c	$+\frac{2}{3}e$	$\bar{\mathrm{c}}$	$-\frac{2}{3}e$
top	t	$+\frac{2}{3}e$	$\bar{\mathrm{t}}$	$-\frac{2}{3}e$
bottom	b	$-\frac{1}{3}e$	$\bar{\mathrm{b}}$	$+\frac{1}{3}e$

A memory aid: **u, c, t** are $+\frac{2}{3}$; **d, s, b** are $-\frac{1}{3}$. Put a bar on it and flip the sign. There are six flavours of antiquark as well.

- **Proton** = uud: $\frac{2}{3}+\frac{2}{3}-\frac{1}{3}=+1$, charge $+e$.
- **Neutron** = udd: $\frac{2}{3}-\frac{1}{3}-\frac{1}{3}=0$.

To find the quarks in a nucleus, count protons and neutrons: each proton gives 2 up and 1 down, each neutron 1 up and 2 down. A $^{27}_{13}\mathrm{Al}$ nucleus (13 protons, 14 neutrons) has $2\times13+14=40$ up quarks and $13+2\times14=41$ down quarks.

Hadrons: baryons and mesons

Particles made of quarks are called **hadrons**. There are two classes:

Class	Made of	Examples	Possible charges
baryon	three quarks (or three antiquarks)	proton uud, neutron udd, ssc	-2 to $+2$
meson	one quark and one antiquark	$\mathrm{b\bar{t}}$, $\mathrm{u\bar{b}}$	-1, 0 or $+1$

- The quarks in a baryon **do not** have to be the same flavour, and often are not.
- A baryon of charge $+2e$ needs three quarks of $+\frac{2}{3}e$ each, all three from u, c or t; nothing else adds up to $+2$.
- The meson $\mathrm{b\bar{t}}$ has charge $-\frac{1}{3}-\frac{2}{3}=-1$; the meson $\mathrm{u\bar{b}}$ has charge $+\frac{2}{3}+\frac{1}{3}=+1$.
- Baryons and mesons are both hadrons, so neither is fundamental. The proton is a baryon and a hadron, never a meson.
- To find the antiparticle of a hadron, replace each quark by its antiquark. The baryon ccd (charge $+\frac{2}{3}+\frac{2}{3}-\frac{1}{3}=+1$) has antiparticle $\mathrm{\bar{c}\bar{c}\bar{d}}$ with charge -1 and the same mass.

Leptons

Leptons are the other group of fundamental particles in this course: the **electron** and the **(electron) neutrino**, and their antiparticles, the **positron** and the **antineutrino**. Leptons are not made of quarks, so they are not hadrons.

Particle	Fundamental?	Class
quark, antiquark	yes	(quark)

Particle	Fundamental?	Class
electron, positron, neutrino, antineutrino	yes	lepton
proton, neutron	no	hadron, baryon
meson	no	hadron
α-particle	no	a nucleus of 2 protons + 2 neutrons

β decay and the quarks

Inside a nucleon, one quark changes flavour.

- **β⁻ decay**: a neutron (udd) becomes a proton (uud). **A down quark changes to an up quark**:

$$\mathrm{d} \rightarrow \mathrm{u} + {}^{0}_{-1}\mathrm{e} + \bar{\nu}$$

- **β⁺ decay**: a proton (uud) becomes a neutron (udd). **An up quark changes to a down quark**:

$$\mathrm{u} \rightarrow \mathrm{d} + {}^{0}_{+1}\mathrm{e} + \nu$$

Charge is conserved in each: for β⁻, $-\frac{1}{3} = +\frac{2}{3} - 1 + 0$; for β⁺, $+\frac{2}{3} = -\frac{1}{3} + 1 + 0$.

Link the pairs: **β⁻ goes with the antineutrino** (an antiparticle); **β⁺, the positron (itself an antiparticle), goes with the neutrino**. After β⁻ decay the nucleus has one more up quark and one fewer down quark; after β⁺, the reverse.

Key facts and formulas

"Given" means it is on the data sheet in the exam. "Learn it" means you must remember it.

Formula	Status
$1\ \mathrm{u} = 1.66 \times 10^{-27}$ kg	Given
$e = 1.60 \times 10^{-19}$ C; $m_\mathrm{e} = 9.11 \times 10^{-31}$ kg; $m_\mathrm{p} = 1.67 \times 10^{-27}$ kg	Given
$A = Z + N$ (nucleons = protons + neutrons)	Learn it
α: $A \rightarrow A - 4$, $Z \rightarrow Z - 2$; β⁻: $Z \rightarrow Z + 1$; β⁺: $Z \rightarrow Z - 1$; γ: no change	Learn it
α: mass 4 u, charge $+2e$; β⁻: charge $-e$; β⁺: charge $+e$; β mass 5.5×10^{-4} u	Learn it
Quark charges: u, c, t $= +\frac{2}{3}e$; d, s, b $= -\frac{1}{3}e$; antiquarks opposite	Learn it
Proton uud, neutron udd; baryon = 3 quarks, meson = quark + antiquark	Learn it
β⁻: $\mathrm{d} \rightarrow \mathrm{u} + \mathrm{e}^- + \bar{\nu}$; β⁺: $\mathrm{u} \rightarrow \mathrm{d} + \mathrm{e}^+ + \nu$	Learn it
Charge-to-mass ratio $= \dfrac{q}{m}$ (C kg⁻¹)	Learn it
$E_\mathrm{k} = \frac{1}{2}mv^2$, momentum $p = mv$ (from Dynamics)	Learn it

How to do it

In the Paper 1 and Paper 2 questions we have tagged for this topic (140 different questions, 2021–2025; 5 more appear on two papers), the types came up this often. 42 of the 140 questions mix two or more types, so the counts add up to more than 140.

Question type	Questions
Decay equations and decay chains	48
Quark compositions and charges	47
β decay: neutrinos, quark changes and energy spectra	39
Classifying particles	37
Atoms, nuclides and isotopes	19
Masses, charges and momentum of α, β and γ	18
α-particle scattering	14

1. Decay equations and decay chains (48 questions)

1. **Write each nuclide as** ${}^{A}_{Z}\mathrm{X}$, with the α-particle as ${}^{4}_{2}\alpha$, β⁻ as ${}^{0}_{-1}\beta$ and β⁺ as ${}^{0}_{+1}\beta$.
2. **Balance the top numbers** (nucleon number) and **the bottom numbers** (charge) separately.
3. **Include the (anti)neutrino** in any β equation ("all the particles involved"): ${}^{0}_{0}\bar{\nu}$ for β⁻, ${}^{0}_{0}\nu$ for β⁺.

Variations you will meet:

- **Missing numbers** (P, Q, R, S in an equation): solve top and bottom lines separately.
- **Decay chain, how many α and β⁻?** The change in A comes only from α: number of α $= \frac{\Delta A}{4}$. Each α lowers Z by 2, each β⁻ raises it by 1: number of β⁻ $= Z_{\text{final}} - (Z_{\text{start}} - 2 \times \text{number of } \alpha)$. Worked in Example 4.
- **Proton and neutron numbers after a chain**: A and Z from the counts, then $N = A - Z$. Alternatively: each α takes 2 neutrons, each β⁻ turns one neutron into a proton.
- **Same element again?** Add up the changes in Z (-2 for each α, $+1$ for each β⁻, -1 for each β⁺). If the total is zero, the final nucleus is an **isotope** of the original element (with a different A if any α was emitted).
- **Is the final nucleus a different element?** Any net change in Z means yes.
- **Nuclear reactions** (a neutron absorbed, fission): balance the top line to find how many neutrons come out, and the bottom line to find Z.
- **Chart questions** (N or A against Z): α moves 2 left and 2 down on an N–Z chart (4 down on an A–Z chart); β⁻ moves 1 right and 1 down on N–Z (straight right on A–Z).
- **Comparing charges of nuclei**: charge follows Z. After β⁻ the daughter has **more** charge; after β⁺ or α, **less**; isotopes have **the same**. Name the nucleus each time, not "it".
- **What is conserved in a decay?** Nucleon number, charge (and in α decay proton number), momentum and mass–energy. Not "mass" on its own.

2. Quark compositions and charges (47 questions)

1. **Write each quark's charge** from the table (u, c, t $+\frac{2}{3}$; d, s, b $-\frac{1}{3}$; antiquarks flipped).
2. **Add them up.** Show the sum, e.g. $\frac{2}{3}+\frac{2}{3}-\frac{1}{3}=+1$.
3. **Convert to coulombs if asked**: multiply by 1.60×10^{-19} C.

Variations you will meet:

- **"Show that the charge of the proton is $+e$"** or "the neutron is uncharged": give the quarks (uud, udd), each charge, and the sum.
- **Missing quark**: charge of the missing one $=$ total charge $-$ sum of the others, then choose a flavour with that charge (for $-\frac{1}{3}e$: d, s or b; for $+\frac{2}{3}e$: u, c or t). If the question says the flavours are all different, pick one not already used. For a meson, the missing one must be an **antiquark** if the other is a quark.
- **All quarks the same flavour**: charge of each $=\frac{\text{total}}{3}$, then choose a flavour with that charge. If each must be $-\frac{2}{3}e$ or $+\frac{1}{3}e$, they are antiquarks.
- **Is this charge possible?** A meson (quark + antiquark) gives only -1, 0 or $+1$. A charge of $\pm2e$ means a **baryon**, never a meson: $+2e$ is three of u, c, t; $-2e$ is three antiquarks from $\bar{\mathrm{u}}$, $\bar{\mathrm{c}}$, $\bar{\mathrm{t}}$ (each $-\frac{2}{3}e$).
- **Quarks in a nucleus**: up $=2Z+N$, down $=Z+2N$.
- **Antiparticle of a hadron**: flip every quark to its antiquark; the charge flips, the mass is the same.
- **Charge change when one quark changes flavour**: up to down is a change of $-\frac{2}{3}-\frac{1}{3}=-1$, i.e. e in size.
- **Number of flavours**: six quarks, six antiquarks.

3. β decay: neutrinos, quark changes and energy spectra (39 questions)

1. **Decide which β**: β^- means a neutron becomes a proton (Z up by 1); β^+ means a proton becomes a neutron (Z down by 1).
2. **Name the partner**: β^- with an (electron) **antineutrino**, β^+ with an (electron) **neutrino**.
3. **Give the quark change**: β^- is **down → up**; β^+ is **up → down**.

Variations you will meet:

- **"Describe the change to the quark composition"**: say which quark changes to which (a down quark changes to an up quark). Listing the quarks of the neutron is not enough.
- **"Explain the origin of the β particle"**: it is created when a neutron in the nucleus changes to a proton (β^-), or a proton to a neutron (β^+). It was not there before.
- **Equation in terms of fundamental particles**: use quarks, not nucleons: $\mathrm{d}\to\mathrm{u}+\mathrm{e}^-+\bar{\nu}$. Show charge conservation: $-\frac{1}{3}=\frac{2}{3}+(-1)+0$.
- **Why a continuous range of energies?** Energy released per decay is fixed, but it is **shared** between the β-particle and the (anti)neutrino in varying proportions.
- **From a spectrum**: a continuous range means β; a single value (or a few sharp values) means α. With "positively charged particles with a continuous range", it is β^+.

- **Antimatter version**: in the decay of an antiparticle, replace every particle in the normal decay by its antiparticle (electron ↔ positron, neutrino ↔ antineutrino, quark ↔ antiquark).

4. Classifying particles (37 questions)

1. **Ask what it is made of**: nothing smaller → fundamental (quark or lepton); three quarks → baryon; quark + antiquark → meson.
2. **Baryons and mesons are hadrons.** Leptons are not hadrons.
3. **Give the reason** when asked to "explain": "a proton is not fundamental because it is made of (three) quarks."

Variations you will meet:

- **"State what is meant by a fundamental particle"**: a particle that cannot be divided into smaller particles.
- **Lists**: pick out the fundamental particles (quarks, electrons, positrons, neutrinos, antineutrinos, leptons as a group) or the hadrons (protons, neutrons, baryons, mesons).
- **Tick tables** (baryon / hadron / lepton): a neutron is both a hadron and a baryon; a positron is a lepton; a neutrino is a lepton.
- **Name the class**: electrons, positrons and neutrinos are **leptons**; baryons and mesons are **hadrons**; the fundamental particles that make up hadrons are **quarks**.
- **Hadrons in a nucleus**: every nucleon is a baryon, so a nucleus with A nucleons has A hadrons, all baryons and no mesons.
- **Antiparticle properties**: same mass, opposite charge. Compare a quark and its antiquark the same way.
- **Meson or baryon, and why?** Count the quarks: three → baryon; one quark and one antiquark → meson.

5. Atoms, nuclides and isotopes (19 questions)

1. **Read A and Z** from ${}^{A}_{Z}\mathrm{X}$: protons $= Z$, neutrons $= A - Z$, electrons in a neutral atom $= Z$.
2. **For an ion**, adjust the electrons only: charge $+ne$ means n fewer electrons, $-ne$ means n more.
3. **Isotopes**: same Z, different N.

Variations you will meet:

- **"What do the numbers represent?"**: top = nucleon number (protons + neutrons); bottom = proton number.
- **Table of nucleons and total particles**: in a neutral atom, total particles $= A + Z$, so $Z = \text{total} - A$. Two nuclides with the same Z are isotopes.
- **Table of neutrons and nucleons**: $Z = A - N$; same Z → isotopes.
- **Draw a labelled model atom**: protons and neutrons together in a small central nucleus; the right number of electrons shown **separate** from the nucleus, all labelled.
- **Describe the structure of a named atom**: give the number of protons and neutrons in the nucleus **and** the number of orbiting electrons.

- **Charge-to-mass ratio of a nucleus**: $\dfrac{Ze}{A \times 1.66 \times 10^{-27}}$. Given the ratio and A, find Z (it must come out as a whole number). An isotope with more neutrons has a smaller ratio.

6. Masses, charges and momentum of α, β and γ (18 questions)

1. **Recall the table**: α 4 u and $+2e$; β⁻ $-e$; β⁺ $+e$; both β about 5.5×10^{-4} u; γ no mass, no charge (electromagnetic radiation).
2. **Change u to kg** for any calculation: $m = (\text{mass in u}) \times 1.66 \times 10^{-27}$.
3. **Use the right equation** (from Dynamics): $E_\text{k} = \frac{1}{2}mv^2, p = mv$.

Variations you will meet:

- **"Compare" α and β⁻**: α has much more mass (about 7000 times) and twice the size of charge, and the opposite sign.
- **Speed from kinetic energy**: $v = \sqrt{\frac{2E_\text{k}}{m}}$. A meson of mass 0.53 u with 3.4×10^{-14} J: $v = \sqrt{\frac{2\times3.4\times10^{-14}}{0.53\times1.66\times10^{-27}}} = 8.8 \times 10^6$ m s⁻¹. Square the speed when going the other way.
- **Recoil in α decay** (stationary nucleus): momentum before is zero, so the α-particle and daughter move in **opposite directions** with equal momentum: $4v_\alpha = (A-4)v_\text{d}$ with masses in u. Use the **daughter's** mass, $A - 4$, not the parent's.
- **Moving parent**: momentum before $=$ momentum after, in each direction (resolve for angles).
- **Order of charge-to-mass ratio**: work out $\frac{q}{m}$ for each; the electron's is by far the largest.
- **Number of α-particles from a beam current**: $N = \frac{It}{2e}$, since each carries $2e = 3.2 \times 10^{-19}$ C.
- **In an electric field**: force $\propto q$, acceleration $\propto \frac{q}{m}$.

7. α-particle scattering (14 questions)

1. **Match each result to its inference**: most go straight through → mostly empty space, nucleus very small; a few deflected through large angles → charged nucleus; a very few through more than 90° → most of the mass in the nucleus.
2. **Answer about the result the question gives**, not everything you know about the atom.
3. **For drawn paths**: repelled away from the nucleus; closer pass → bigger deflection; symmetric paths above and below.

Variations you will meet:

- **Which conclusion can't be drawn?** That the nucleus contains protons and neutrons, or anything about electron charges.
- **What changes when an α is deflected?** Its momentum (direction). Its charge, proton number and nucleon number don't.
- **More large-angle deflections** come from a thicker foil (more nuclei in the path), a metal with more protons per nucleus (a bigger charge), or slower α-particles.
- **Head-on collision**: the gold nucleus recoils slowly because its mass is much greater.

- **Why large deflections are rare**: the nucleus is tiny, so few α-particles pass close to one.

Worked examples

The bold codes show where marks are earned, as in Cambridge mark schemes. The number is how many marks.

- **A1** accuracy mark: for a correct answer; it needs the M mark before it.
- **B1** mark for a correct result on its own, with no method needed.

Example 1

Strontium-90, ${}^{90}_{38}\mathrm{Sr}$, decays by β⁻ emission to form an isotope of yttrium (Y).

(a) State the number of protons, neutrons and electrons in a neutral atom of strontium-90. **[2]**

(b) Write the decay equation, including all the particles involved. **[3]**

(c) Determine the numbers of up quarks and down quarks in a strontium-90 nucleus. **[2]**

(d) State the change to the quark composition of a nucleon during the decay. **[1]**

Solution

(a) Protons $= 38$ and electrons $= 38$. **A1** Neutrons $= 90 - 38 = 52$. **A1**

(b) ${}^{90}_{38}\mathrm{Sr} \rightarrow {}^{90}_{39}\mathrm{Y} + {}^{0}_{-1}\beta + {}^{0}_{0}\bar{\nu}$ Yttrium: 90 on top, 39 below. **B1** β-particle: 0 on top, -1 below. **B1** An (electron) antineutrino is shown. **B1**

(c) Each proton is uud and each neutron udd. **C1** Up $= 2 \times 38 + 52 = 128$; down $= 38 + 2 \times 52 = 142$. **A1**

(d) A down quark changes to an up quark. **B1**

Example 2

(a) A baryon has charge $-e$. Its three quarks all have different flavours. Two of them are a strange quark and a bottom quark. (i) Determine the charge of the third quark, in terms of e. **[2]** (ii) State its flavour. **[1]**

(b) A meson consists of a charm quark and a bottom antiquark. Calculate its charge in coulombs. **[2]**

(c) State the quark composition, the charge and the mass (compared with the baryon's) of the antiparticle of the baryon in (a). **[2]**

Solution

(a)(i) Charge of the third quark $= -1 - \left(-\frac{1}{3} - \frac{1}{3}\right)$ **C1** $= -\frac{1}{3}e$. **A1** (ii) Down (the only $-\frac{1}{3}$ flavour not already used). **B1**

(b) $+\frac{2}{3}e + \frac{1}{3}e = +1e$ **C1** $= +1.60 \times 10^{-19}$ C. **A1**

(c) Anti-down, anti-strange and anti-bottom ($\mathrm{\bar{d}\bar{s}\bar{b}}$); charge $+e$. **B1** Same mass as the baryon. **B1**

Example 3

A stationary platinum-190 nucleus $^{190}_{78}\mathrm{Pt}$ decays by emitting an α-particle to form an isotope of osmium (Os). The α-particle moves off at 1.2×10^{7} m s^{-1}.

(a) Write the decay equation. **[2]**

(b) Calculate the speed of the osmium nucleus just after the decay. **[2]**

(c) Calculate the kinetic energy of the α-particle. **[2]**

(d) Calculate the charge-to-mass ratio of the osmium nucleus. **[2]**

(e) Explain why every α-particle emitted by platinum-190 has the same kinetic energy, but the β-particles from a β^{-} emitter do not. **[2]**

Solution

(a) $^{190}_{78}\mathrm{Pt} \rightarrow {}^{186}_{76}\mathrm{Os} + {}^{4}_{2}\alpha$ α-particle $^{4}_{2}$ **B1**; osmium $^{186}_{76}$ **B1**

(b) Momentum before $= 0$, so $4 \times 1.2 \times 10^{7} = 186\,v$ (masses in u) **C1** $v = 2.6 \times 10^{5}$ m s^{-1} (in the opposite direction). **A1**

(c) $E_{\mathrm{k}} = \frac{1}{2}mv^{2} = \frac{1}{2} \times (4 \times 1.66 \times 10^{-27}) \times (1.2 \times 10^{7})^{2}$ **C1** $= 4.8 \times 10^{-13}$ J. **A1**

(d) Charge $= 76e$ and mass $= 186$ u: $\dfrac{q}{m} = \dfrac{76 \times 1.60 \times 10^{-19}}{186 \times 1.66 \times 10^{-27}}$ **C1** $= 3.9 \times 10^{7}$ C kg^{-1}. **A1**

(e) The α decay has only two products, so the fixed energy released is always shared in the same way. **B1** In β decay an antineutrino is also emitted, and the energy is shared between the β-particle and the antineutrino in different proportions, giving a continuous range. **B1**

Example 4

(a) In the α-particle scattering experiment, most α-particles pass straight through a thin gold foil, but a very small number are deflected through more than 90°. State what may be inferred from each of these two results. **[3]**

(b) A uranium-235 nucleus $^{235}_{92}\mathrm{U}$ decays in a series of α and β^{-} emissions to form lead-207, $^{207}_{82}\mathrm{Pb}$. (i) Determine the number of α-particles and the number of β^{-} particles emitted. **[3]** (ii) Calculate the number of neutrons in the lead-207 nucleus, and show that this agrees with your answer to (i). **[2]**

Solution

(a) Most pass straight through: the atom is mostly empty space (the nucleus is very small). **B1** Deflected through more than 90°: the nucleus is charged **B1** and contains most of the mass of the atom. **B1**

(b)(i) Only α changes A: $\dfrac{235-207}{4}=7$ α-particles. **A1** After 7 α the proton number would be $92-2\times7=78$. **C1** It is 82, so $82-78=4$ β^- particles. **A1**

(ii) $207-82=125$ neutrons. **A1** Uranium-235 has $235-92=143$; each α removes 2 and each β^- turns 1 into a proton: $143-7\times2-4=125$. ✓ **B1**

Common mistakes

- **Neutrino and antineutrino swapped.** The November 2021, March 2022 and June 2023 reports all describe this. β^- comes with an **antineutrino**, β^+ with a **neutrino**.
- **β^+ and β^- confused.** The November 2021, November 2022, March 2023 and March 2025 reports all note it. In β^+ decay a **proton** becomes a neutron and Z **falls** by 1.
- **Quark change the wrong way round.** The March 2022 report (for β^+) and the June 2023 report (for β^-) both describe it. β^-: down → up. β^+: up → down.
- **Describing the nucleon, not the quark change.** The June 2021 and June 2023 reports describe answers that gave the quark composition of a single nucleon, and the March 2021 report answers that only said a neutron changes into a proton, when the change of quark was asked for. Write "a down quark changes to an up quark".
- **Nucleon number confused with neutron number.** The March 2021 report mentions this twice and the March 2022 report once. Nucleon number counts protons **and** neutrons; α decay lowers it by 4 but the neutron number by only 2.
- **Leaving the (anti)neutrino out of the equation.** The June 2022 and November 2022 reports describe this; the June 2022 report also mentions a β^+ particle written without its top and bottom numbers. Write ${}^{0}_{+1}\beta$ and ${}^{0}_{0}\nu$.
- **Nucleons in a "fundamental particle" equation.** The November 2022 report describes candidates who wrote neutron → proton when an equation in fundamental particles was asked for. Use quarks: $\mathrm{d}\to\mathrm{u}+\mathrm{e}^-+\bar{\nu}$.
- **Wrong antiquark charges.** The June 2022 report mentions a down antiquark given as $-\frac{1}{3}e$, and the March 2025 report says the weakest candidates did not seem to know the difference between quarks and antiquarks. Flip the sign.
- **Wrong charm charge.** The June 2023 report mentions wrong charm charges, and the November 2022 report a total of $+e$ where the three $+\frac{2}{3}e$ quarks give $+2e$. Charm is $+\frac{2}{3}e$, like up.
- **Meson structure.** The November 2022 and June 2023 reports say many did not know that a meson is one quark and one **antiquark**; the March 2023 report describes some who gave a baryon's structure instead.
- **"A baryon's quarks must all be the same flavour."** The June 2022 report calls this a common misconception. They may be different.
- **"A proton is fundamental."** The June 2021 report calls this a common misconception. It is made of quarks, and say so when you explain.

- **Weak definition of a fundamental particle.** The November 2022 report says "used to build other particles" is not enough. It **cannot be divided into smaller particles**.
- **β-particle mass zero or 1 u.** The November 2021 report calls this a common misconception. It is an electron's mass, about 5.5×10^{-4} u.
- **α-particle charge taken as e.** The June 2021 report says this was the most common mistake when counting α-particles from a current. It is $2e = 3.2 \times 10^{-19}$ C.
- **Scattering: facts instead of inferences.** The March 2021 and June 2021 reports describe answers that wrote general facts about the atom, or described the α-particle, instead of what the given result shows. The March 2021 and June 2021 reports both say few candidates stated that most of the **mass** is in the nucleus; the June 2021 report adds that "all of the charge of the atom is in the nucleus" is a mistake.
- **Atom vs nucleus.** The November 2022 report notes candidates who described a named atom without its orbiting electrons. An atom includes its electrons; a nucleus does not.
- **Continuous range missed.** The November 2021 and November 2022 reports say few candidates explained the β energies by the energy being **shared** with the antineutrino.
- **"Mass" as a conserved quantity.** The March 2025 report says "mass" and "energy" were common wrong answers for quantities conserved in a decay, while few gave nucleon number or proton number. Say **mass–energy**, **momentum**, **charge**, **nucleon number**.
- **Recoil with the wrong mass.** The November 2021 report describes using the parent's mass for the daughter, and the March 2025 report using proton numbers instead of nucleon numbers. The daughter of an α decay has $A - 4$.
- **Not squaring the speed** in $\frac{1}{2}mv^2$: the November 2021 report mentions it in two questions.

How to get the marks

- **Definitions and statements** (key words):
  - Fundamental particle: **cannot be divided** into smaller particles.
  - Isotopes: same element, **same number of protons**, **different numbers of neutrons**.
  - Antiparticle: **same mass, opposite charge**.
  - Baryon: **three quarks**; meson: **a quark and an antiquark**; both are **hadrons**.
  - Leptons: electrons, positrons, neutrinos, antineutrinos.
- **Decay equations**: every particle with its top and bottom numbers, including ${}^{0}_{0}\bar{\nu}$ or ${}^{0}_{0}\nu$. Mark schemes give separate marks for the daughter, the β-particle and the (anti)neutrino.
- **"Show that" the charge is…**: name the quarks, write each charge, and add them. Just stating uud is not enough.
- **Quark changes**: "a **down** quark changes to an **up** quark" (β^-); "an **up** quark changes to a **down** quark" (β^+).
- **"Explain" a classification**: give the quark content as the reason ("a meson, because it is one quark and one antiquark"), and say which particle is which.
- **"State and explain" which decay**: two points, one from the charge (positive → β^+ or α; negative → β^-) and one from the energy (continuous → β, discrete → α).

- **Scattering**: link each result to its inference ("most pass through, **so** the atom is mostly empty space"). Say "most of the **mass**", not "the nucleus has mass".
- **Calculations**: symbol equation first, mass changed from u to kg, answer with unit to 2 or 3 significant figures. A value of Z from a charge-to-mass ratio should come out as a whole number.
- **Comparisons** ("less than, greater than or the same"): state the answer, then the reason with the proton numbers of the named nuclei.
- **Multiple choice**: work it out first. Wrong options swap neutrino and antineutrino, swap up and down, use A for N, or give a meson three quarks.

Quick check

1. State the charge of each particle and whether it is a meson or a baryon: (a) $\mathrm{b\bar{u}}$ (b) $\mathrm{\bar{d}\bar{d}\bar{c}}$. (c) A hadron has charge $-2e$. Can it be a meson? State what it could be made of.
2. Oxygen-15, $^{15}_{8}\mathrm{O}$, decays by β⁺ emission to nitrogen (N). Write the decay equation, state the change of quark flavour, and state the number of neutrons in the nitrogen nucleus.
3. A chlorine-37 ion $^{37}_{17}\mathrm{Cl}$ has a charge of -1.60×10^{-19} C. State the numbers of protons, neutrons and electrons in it. How does chlorine-35 differ from chlorine-37?
4. A nucleus has 19 nucleons and a charge-to-mass ratio of 4.57×10^{7} C kg^{-1}. Determine its proton number.
5. In a β$^-$ decay the energy released, shared between the β-particle and the antineutrino, is 3.1×10^{-14} J. One β-particle has a kinetic energy of 1.2×10^{-14} J. Ignoring the recoil of the nucleus, how much energy did the antineutrino take?

Answers

1. (a) $-\frac{1}{3} - \frac{2}{3} = -1$, so charge $-e$; a quark and an antiquark: a **meson**. (b) $+\frac{1}{3} + \frac{1}{3} - \frac{2}{3} = 0$; three antiquarks: a **baryon** (as an aside: the antiparticle of the baryon ddc). (c) Not a meson: a quark–antiquark pair gives at most $\pm 1e$. It is a **baryon** of three antiquarks, each of charge $-\frac{2}{3}e$, from $\bar{\mathrm{u}}$, $\bar{\mathrm{c}}$, $\bar{\mathrm{t}}$: for example $\bar{\mathrm{u}}\bar{\mathrm{u}}\bar{\mathrm{c}}$, $-\frac{2}{3} - \frac{2}{3} - \frac{2}{3} = -2$.
2. ${}^{15}_{8}\mathrm{O} \rightarrow {}^{15}_{7}\mathrm{N} + {}^{0}_{+1}\beta + {}^{0}_{0}\nu$. An up quark changes to a down quark. Nitrogen-15 has $15 - 7 = 8$ neutrons (one more than oxygen-15's 7).
3. 17 protons, $37 - 17 = 20$ neutrons, and $17 + 1 = 18$ electrons (charge $-e$ means one extra electron). Chlorine-35 has the same 17 protons but only 18 neutrons: they are isotopes.
4. $Z = \dfrac{4.57 \times 10^{7} \times 19 \times 1.66 \times 10^{-27}}{1.60 \times 10^{-19}} = 9.0$, so $Z = 9$.
5. $3.1 \times 10^{-14} - 1.2 \times 10^{-14} = 1.9 \times 10^{-14}$ J.

Past questions to try

- **9702/22/O/N/22 Q7**: the structure of a named atom, the charge-to-mass ratio of an α-particle, and baryons made of up and down quarks.
- **9702/23/M/J/22 Q7**: a β^+ decay equation with its neutrino, the quark change, and a hadron of charge $-2e$.
- **9702/22/O/N/21 Q7**: recoil momentum in α decay, kinetic energy of the α-particle, and plotting a β^- decay on an N–Z chart.
- **9702/22/F/M/21 Q7**: what the two scattering results show, a decay sequence back to an isotope, and the quark change.