Particle physics

A-Level Physics

The nuclear atom

Geiger–Marsden α-particle scattering

Alpha particles α 粒子 fired at a thin gold foil were seen to:

- mostly pass straight through, with very little **deflection** 偏转,
- sometimes deflect through small angles,
- rarely (about 1 in 8000) deflect through angles greater than 90°.

From this Rutherford worked out:

- the atom is **mostly empty space** (most α-particles pass straight through),
- there is a tiny, dense, positively charged **nucleus** 原子核 at the centre (the rare large deflections need a concentrated charge to push the α away),
- almost all of the atom's mass is in this nucleus.

Order of magnitude: atom diameter $\sim 10^{-10}$ m, nucleus diameter $\sim 10^{-15}$ m — the nucleus is about 10^5 times smaller than the atom.

The three results and what each proves — the mark scheme pairs them exactly like this:

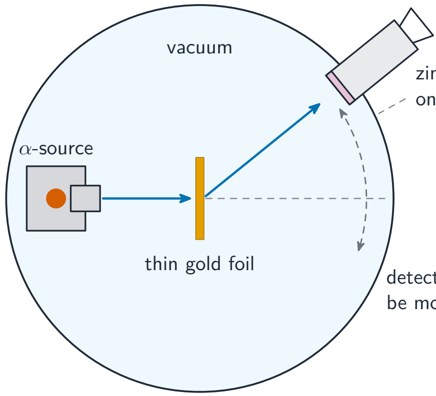
Observation	Conclusion
the vast majority pass straight through with little or no deflection	most of the atom is empty space
a small number are deflected through small angles	there is a concentrated positive charge (the nucleus) that repels the positive α-particles
a very small minority (about 1 in 8000) are deflected through more than 90°, some straight back	the nucleus is very small compared with the atom, and contains almost all of the atom's mass

Three details of the experiment are also asked: the foil is **thin** so that each α-particle meets at most one nucleus (and is not absorbed); the chamber is a **vacuum** so the α-particles are not stopped or scattered by air; gold is used because it can be beaten into a very thin sheet and has a heavy, highly charged nucleus.

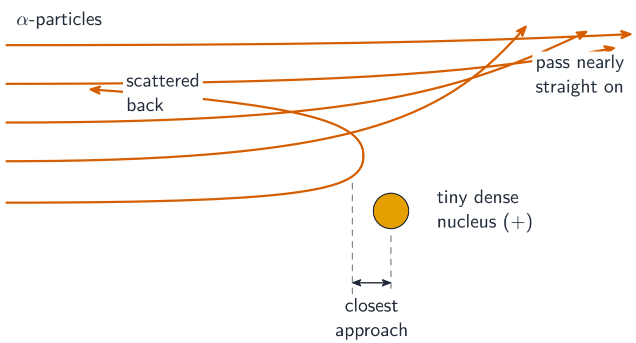
Worked example. Explain why a very small minority of the α-particles are scattered through angles greater than 90°.

Only an α-particle that approaches a nucleus almost **head-on** is turned back. The nucleus and the α-particle are both positive, so the **electrostatic** 静电 repulsion is very large at small separation, and the nucleus is much more massive than the α-particle, so it is the α-particle that is turned round. Because the nucleus is tiny, very few α-particles get that close — hence the small minority. As the α-particle approaches, its kinetic energy is converted to electric potential energy; at the point of closest approach it is momentarily at rest and all of its kinetic energy has become potential energy.

The deflection depends on how close the path passes to the nucleus: the smaller the distance, the larger the angle, and the paths are symmetrical about the line through the nucleus.



The α-scattering experiment — α-particles strike a thin gold foil in a vacuum



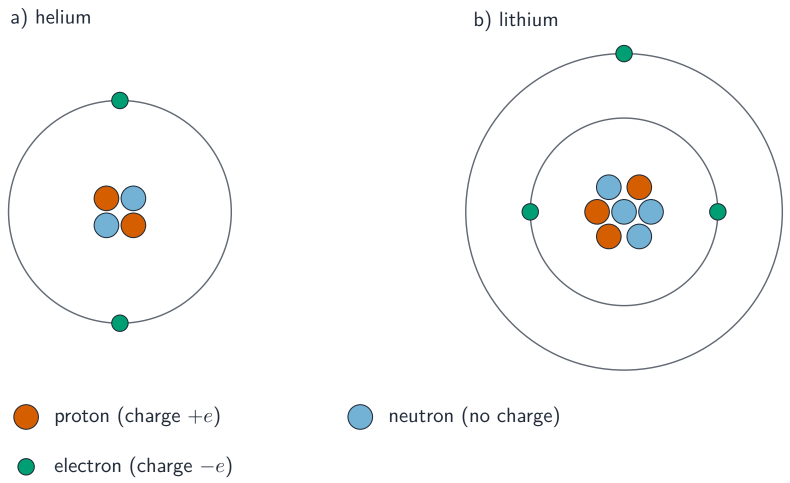
Most α-particles pass nearly straight through; a few are deflected sharply by the tiny nucleus

Simple nuclear model

An atom has:

- a central nucleus of **protons** 质子 (positive, charge $+e$) and **neutrons** 中子 (no charge),
- **electrons** 电子 (charge $-e$) around the nucleus.

The proton and neutron have almost the same mass (≈ 1 u); the electron is about $\frac{1}{1836}$ of the proton's mass.



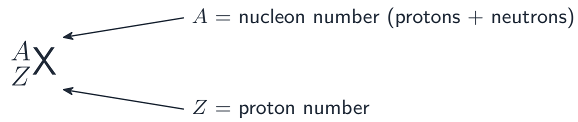
Simple models of a helium atom and a lithium atom (not to scale)

Worked example. Describe the structure of an atom of uranium-238, $^{238}_{92}$U.

A nucleus containing 92 protons and $238 - 92 = 146$ neutrons, with 92 electrons in orbit around it. "Orbital electrons" is the syllabus phrase — the electrons are outside the nucleus, and the neutral atom has as many electrons as protons.

Notation and key numbers

For a **nuclide** 核素 written ^A_ZX:



Nuclide notation: nucleon number on top, proton number below

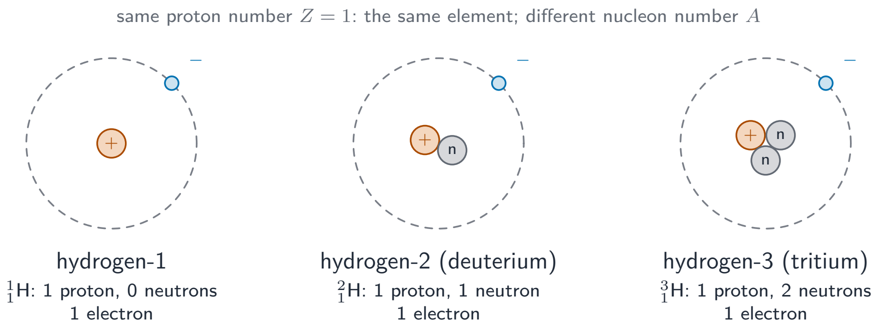
- **proton number** 质子数 Z (also the atomic number): the number of protons. It fixes the element.
- **nucleon number** 核子数 A (also the mass number): the total number of **nucleons** 核子 (protons + neutrons).
- number of neutrons $N = A - Z$.

A neutral atom has the same number of electrons as protons.

Isotopes

Isotopes 同位素 are atoms of the same element (same Z) with different numbers of neutrons (different A). They behave the same chemically but differently in the nucleus. Example: $^{12}_{6}$C and $^{14}_{6}$C are isotopes of carbon.

The examiner's wording: isotopes are nuclei (or atoms) with the **same number of protons** but **different numbers of neutrons** — equivalently the same proton number Z and different nucleon numbers A. Hydrogen has three:



The three isotopes of hydrogen: the same one proton, different numbers of neutrons

Worked example. Tritium, $^3_1$H, is an isotope of hydrogen. State the numbers of protons, neutrons and electrons in a neutral tritium atom, and give the quark composition of its nucleus.

$Z=1$ proton; $A-Z=3-1=2$ neutrons; 1 electron (neutral, so electrons = protons). The nucleus is one proton (uud) and two neutrons (udd, udd): **4 up quarks and 5 down quarks**. Charge check: $4\times\frac{2}{3}-5\times\frac{1}{3}=+1$, the proton number. A "labelled diagram" of the atom is the nucleus (1 p, 2 n) with one electron orbiting outside it.

Conservation laws in nuclear processes

In any nuclear process:

- nucleon number A is conserved (total A before = total A after),
- **charge** is conserved (this is **conservation of charge** 电荷守恒).

These two rules let you balance decay and reaction equations.

Unified atomic mass unit

The **unified atomic mass unit** 统一原子质量单位, symbol u, is set so that an atom of ${}^{12}_{6}\mathrm{C}$ has mass exactly 12 u. Numerically,

$$1\ \mathrm{u} = 1.661\times10^{-27}\ \mathrm{kg}.$$

A proton has mass ≈ 1.007 u; a neutron ≈ 1.009 u; an electron $\approx 5.5\times10^{-4}$ u.

Worked example. A nucleus X has 14 nucleons and p protons. Its charge-to-mass ratio is $4.1\times10^{7}\ \mathrm{C\ kg^{-1}}$. Find p and identify X.

Charge $= pe$; mass ≈ 14 u. So $\dfrac{pe}{14\mathrm{u}} = 4.1\times10^{7}$, giving $p = \dfrac{4.1\times10^{7}\times14\times1.66\times10^{-27}}{1.60\times10^{-19}} = 5.96\approx6$. Six protons and 14 nucleons: X is carbon-14, ${}^{14}_{6}\mathrm{C}$. Keep every figure until the end, then round to the nearest whole number of protons.

Radioactive emissions

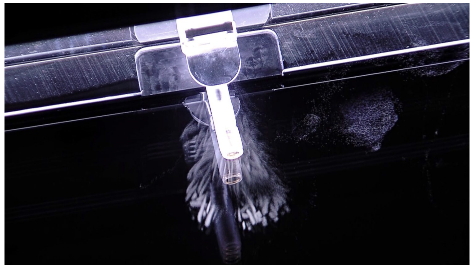
An unstable nucleus rearranges itself and gives out one of three kinds of **radiation** 辐射. This is **radioactive** 放射性 decay. Each kind has its own properties.

α-radiation

- **Made of**: a helium-4 nucleus, ${}^{4}_{2}\alpha$ (two protons + two neutrons).
- **Mass**: ≈ 4 u.
- **Charge**: $+2e$.
- **Range in air**: a few cm. Stopped by a sheet of paper.
- **Ionising power**: strong — it is good at **ionising** 电离.

- **Energy spectrum**: **discrete** 分立 (one decay gives α-particles at one or a few sharp energies).

A **cloud chamber** 云室 makes the tracks visible: each α-particle leaves a short, straight, thick trail of tiny droplets as it ionises the air. The short equal lengths show the α-particles all carry about the same energy.



Alpha-particle tracks in a cloud chamber, fanning out from an americium-241 source

β-radiation

Two types of **beta particle** β 粒子:

- β^-: a fast electron, given out when a neutron turns into a proton.
- β^+: a **positron** 正电子 (the electron's antiparticle), given out when a proton in a proton-rich nucleus turns into a neutron.

Properties (both types):

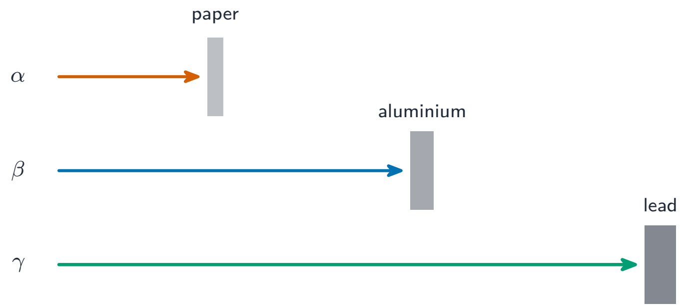
- **Mass**: $\approx 1/1836$ u (much less than α).
- **Charge**: $-e$ for β^-, $+e$ for β^+.
- **Range in air**: about 1 m. Stopped by a few mm of aluminium.
- **Energy spectrum**: **continuous** 连续 up to a maximum (see below).

γ-radiation

- **Made of**: a high-energy **photon** 光子 — part of the **electromagnetic spectrum** 电磁波谱.
- **Mass**: zero (rest mass).
- **Charge**: zero.
- **Range in air**: large (follows the inverse-square law). Strongly **attenuated** 衰减 by several cm of lead or about a metre of concrete.
- **Ionising power**: weakest.

- **Energy spectrum**: discrete (a **gamma ray** γ 射线 is given out as the nucleus drops between two nuclear energy levels).

A nucleus often gives out a γ-photon as a "tidy-up" step after an α or β decay leaves the **daughter nucleus** 子核 in an **excited state** 激发态.



Penetrating power: α is stopped by paper, β by aluminium, γ only attenuated by lead

Mass and charge, side by side — a table question asks for exactly these, in units of u and e:

Particle	Mass	Charge
proton	1 u (1.007 u)	$+e$
neutron	1 u (1.009 u)	0
electron, β^-	$\frac{1}{1836}$ u (5.5×10^{-4} u)	$-e$
positron, β^+	$\frac{1}{1836}$ u	$+e$
α-particle	4 u	$+2e$
γ-photon	0	0
neutrino, antineutrino	almost zero	0

Worked example. Compare an α-particle with a β^+ particle in terms of their masses and charges (3 marks).

Both are positively charged, but the α-particle's charge ($+2e$) is twice that of the β^+ ($+e$). The α-particle's mass (4 u) is about 7300 times the mass of the β^+ (5.5×10^{-4} u). Give a ratio, not just "heavier": *twice the charge* and *about 7000 times the mass* are the marking points.

Because they carry charge, α- and β-particles are deflected by electric and magnetic fields — in opposite directions for opposite signs, the light β far more than the heavy α — while γ-rays, being uncharged, pass straight through.

Antiparticles, neutrinos and antineutrinos

Every particle has an **antiparticle** 反粒子 with the **same mass** but **opposite charge**. The positron is the antiparticle of the electron.

In β-decay, a third particle is always given out as well:

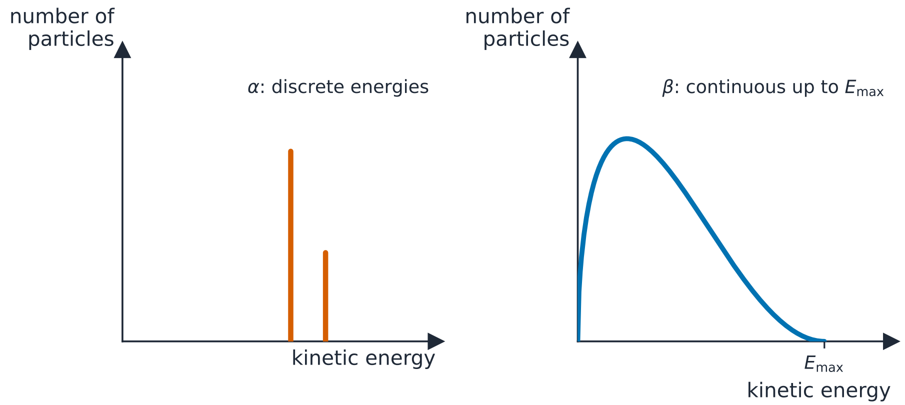
- β^- decay: an **antineutrino** 反中微子 $\bar{\nu}_e$.
- β^+ decay: a **neutrino** 中微子 ν_e.

Neutrinos and antineutrinos have zero charge, very small mass, and barely interact — they are very hard to detect, but they must be there to balance energy, **momentum** 动量 and other conserved quantities in β-decay.

Why β has a continuous spectrum (and α does not)

In α-decay the **energy** 能量 released is shared between just two particles (the daughter nucleus and the α). Conservation of momentum and energy then fixes the α's energy to one value (discrete).

In β-decay the energy is shared between **three** particles (the daughter nucleus, the β, and the (anti)neutrino). The β can take any share from zero up to a maximum, so its energy spectrum is continuous.



α-particles from one decay have fixed (discrete) energies; β-particles share the energy with an (anti)neutrino, so their spectrum is continuous up to a maximum

Worked example. The energy spectrum of the β^- particles from a source is continuous, from zero up to a maximum. Explain why (3 marks).

Each decay releases a fixed amount of energy. That energy is shared between the β^- particle, the **antineutrino** and the recoiling daughter nucleus. The antineutrino can take any share, so the β^- particle is left with any energy from zero up to the maximum — the maximum being when the antineutrino carries away almost none. (For an α-particle there are only two bodies, so momentum conservation fixes the share and the energy is discrete.)

Writing decay equations

A general α-decay:

$$^{A}_{Z}\mathrm{X} \rightarrow {}^{A-4}_{Z-2}\mathrm{Y} + {}^{4}_{2}\alpha$$

(check: $A = (A-4)+4$, $Z = (Z-2)+2$.)

A general β^- decay:

$$^{A}_{Z}\mathrm{X} \rightarrow {}^{A}_{Z+1}\mathrm{Y} + {}^{0}_{-1}\beta + \bar{\nu}_{\mathrm{e}}.$$

A general β^+ decay:

$$^{A}_{Z}\mathrm{X} \rightarrow {}^{A}_{Z-1}\mathrm{Y} + {}^{0}_{+1}\beta + \nu_{\mathrm{e}}.$$

Worked example. Uranium-238, $^{238}_{92}\mathrm{U}$, decays by α-emission; carbon-14, $^{14}_{6}\mathrm{C}$, decays by β^--emission. Find each daughter nuclide.

α-decay lowers A by 4 and Z by 2; β^--decay leaves A unchanged and raises Z by 1:

$$^{238}_{92}\mathrm{U} \rightarrow {}^{234}_{90}\mathrm{Th} + {}^{4}_{2}\alpha, \qquad ^{14}_{6}\mathrm{C} \rightarrow {}^{14}_{7}\mathrm{N} + {}^{0}_{-1}\beta + \bar{\nu}_{\mathrm{e}}.$$

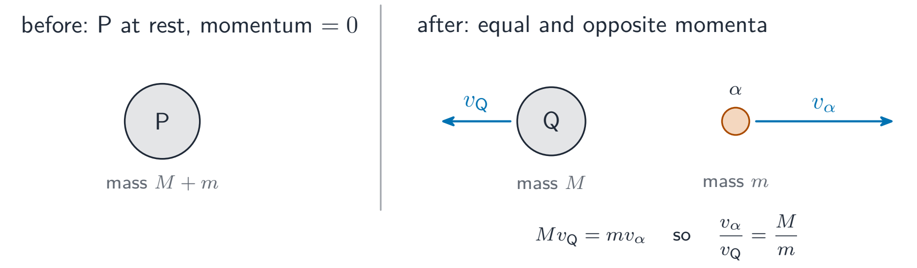
Determine quantitatively the changes. α-emission: A decreases by 4, Z decreases by 2. β^--emission: A unchanged, Z increases by 1. β^+-emission: A unchanged, Z decreases by 1. γ-emission: no change in either. A decay chain that ends at a known nuclide is solved from these: the number of α-decays is $(A_{\mathrm{start}} - A_{\mathrm{end}})/4$, and then the number of β^--decays makes Z come out right.

Worked example. Thorium-230, $^{230}_{90}\mathrm{Th}$, decays in stages, by α- and β^--emission, to lead-206, $^{206}_{82}\mathrm{Pb}$. Find the number of each kind of decay.

α-decays: $(230-206)/4 = 6$. Six α-decays alone would lower Z by 12, to 78; the final Z is 82, so there are $82 - 78 = 4$ β^--decays.

A nucleus at rest recoils. When a stationary nucleus emits an α-particle, momentum is conserved: the daughter nucleus and the α-particle move off in **opposite directions** with momenta of **equal magnitude**. Since $p = mv$, the lighter α-particle

moves much faster, and since $E_{\mathrm{k}} = p^2/2m$ it also takes most of the kinetic energy — the shares are in inverse proportion to the masses.

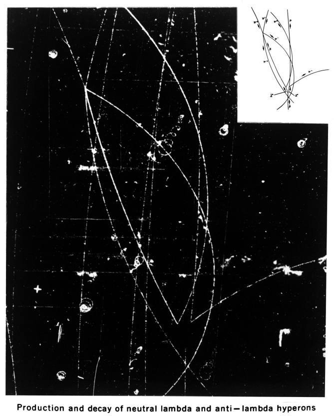


A nucleus at rest decays: the daughter recoils with momentum equal and opposite to the α-particle's

Worked example. A stationary nucleus P of mass 243 u emits an α-particle of mass 4 u at 1.5×10^7 m s^{-1}. Find the speed of the daughter nucleus Q and the ratio of the kinetic energy of the α-particle to that of Q.

Q has mass $243-4 = 239$ u. Momentum: $239v_{\mathrm{Q}} = 4\times1.5\times10^7$, so $v_{\mathrm{Q}} = 2.5\times10^5$ m s^{-1}, in the opposite direction to the α-particle. Kinetic energies: $\dfrac{E_\alpha}{E_{\mathrm{Q}}} = \dfrac{p^2/2m_\alpha}{p^2/2m_{\mathrm{Q}}} = \dfrac{m_{\mathrm{Q}}}{m_\alpha} = \dfrac{239}{4} \approx 60$. The α-particle takes about 98% of the energy released.

Fundamental particles



A bubble chamber reveals the curved tracks of charged particles.

Where the particles come from: a linear accelerator uses electric fields to drive charged particles fast enough to probe the nucleus

Some particles are **fundamental particles** 基本粒子 (point-like, with no smaller parts as far as we know); others are built from fundamental ones.

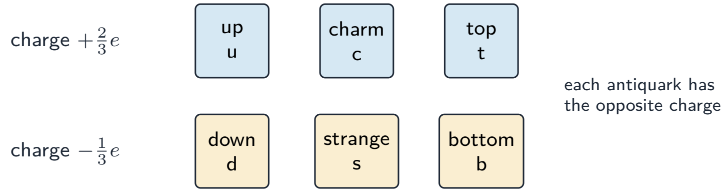
The one-mark definition: *a fundamental particle is one that cannot be broken down into smaller particles* (it has no internal structure). Electrons, neutrinos and quarks are fundamental; protons and neutrons are not.

Quarks

A **quark** 夸克 is a fundamental particle. There are six **flavours** 味:

- **up** (u), charge $+\frac{2}{3}e$,
- **down** (d), charge $-\frac{1}{3}e$,
- **charm** (c), charge $+\frac{2}{3}e$,
- **strange** (s), charge $-\frac{1}{3}e$,
- **top** (t), charge $+\frac{2}{3}e$,
- **bottom** (b), charge $-\frac{1}{3}e$.

Each quark has an **antiquark** 反夸克 with the same size of charge but the opposite sign: $\bar{u}$ (charge $-\frac{2}{3}e$), $\bar{d}$ (charge $+\frac{1}{3}e$). No other quark property is tested.



The six quarks: up/charm/top carry $+\frac{2}{3}e$, down/strange/bottom carry $-\frac{1}{3}e$

Written as the table a question asks you to complete:

Quark	**Charge**	**Antiquark**	**Charge**
up (u), charm (c), top (t)	$+\frac{2}{3}e$	ū, c̄, t̄	$-\frac{2}{3}e$
down (d), strange (s), bottom (b)	$-\frac{1}{3}e$	d̄, s̄, b̄	$+\frac{1}{3}e$

Worked example. By reference to quark composition, show that the charge of a proton is $+1.6 \times 10^{-19}$ C.

A proton is uud: charge $= \frac{2}{3}e + \frac{2}{3}e - \frac{1}{3}e = +e = +1.6 \times 10^{-19}$ C. Write the three fractions and their sum — the mark is for the arithmetic, not the answer.

Hadrons: baryons and mesons

Particles built from quarks are **hadrons** 强子. Two types:

- **baryons** 重子 — three quarks. Examples: proton (u u d), neutron (u d d). Charge check: $\frac{2}{3} + \frac{2}{3} - \frac{1}{3} = +1$ for the proton; $\frac{2}{3} - \frac{1}{3} - \frac{1}{3} = 0$ for the neutron.
- **mesons** 介子 — one quark and one antiquark (for example π^+ is ud̄).

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

"Compare baryons and mesons in terms of their constituent particles" (2 marks): both are hadrons made of quarks; a baryon is three quarks (or three antiquarks, for an antibaryon), a meson is one quark and one antiquark. Any charge you are given must come out of the quark charges:

Worked example. (a) A meson has charge $-1e$. Give a possible quark composition. (b) A meson Q has charge 0. Give a possible composition. (c) A baryon is made of three quarks of different flavours, u, d and s. Find its charge. (d) Give the quark composition of an antineutron and its charge.

(a) dū: $-\frac{1}{3} - \frac{2}{3} = -1$ (sū also works). (b) uū: $+\frac{2}{3} - \frac{2}{3} = 0$ (or dd̄). (c) uds: $\frac{2}{3} - \frac{1}{3} - \frac{1}{3} = 0$. (d) The antineutron is the antiparticle of udd, so it is ūd̄d̄: $-\frac{2}{3} + \frac{1}{3} + \frac{1}{3} = 0$ — the same mass and charge as the neutron, since both have charge zero.

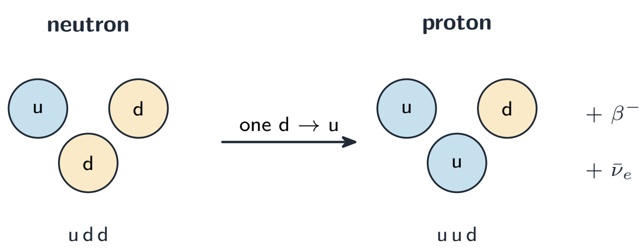
Quark changes in β-decay

In β^- decay a neutron turns into a proton; in quark terms, **one down quark turns into an up quark**:

$$d \to u + \beta^- + \bar{\nu}_e.$$

In β^+ decay a proton turns into a neutron; **one up quark turns into a down quark**:

$$u \to d + \beta^+ + \nu_e.$$



Beta-minus decay: one down quark becomes an up quark, turning a neutron into a proton

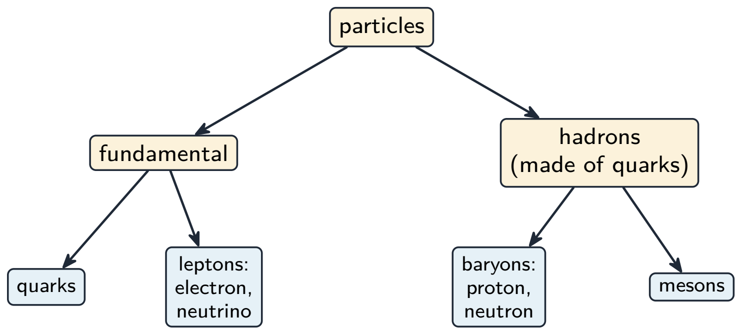
"Describe β^+ decay in terms of the fundamental particles involved" (2 marks): an up quark in a proton changes into a down quark, so the proton becomes a neutron, and a positron and an electron neutrino are emitted — $u \to d + \beta^+ + \nu_e$. For β^- decay swap the roles: a down quark becomes an up quark, emitting an electron and an electron antineutrino. Name the (anti)neutrino: it is the "other lepton" the question asks for, and it is what makes the β energy continuous.

Leptons

Leptons 轻子 are fundamental particles that are not made of quarks. The leptons you need are the **electron** and the **electron neutrino**, with their antiparticles the **positron** and the **electron antineutrino**. (Heavier leptons — the muon and tau — exist but are not tested.) Asked for "two different leptons", give *electron* and *neutrino*.

Classifying particles

To answer "which are fundamental?": **quarks** and **leptons** (electrons, positrons, neutrinos, antineutrinos) are fundamental; protons, neutrons, baryons, mesons and hadrons are **not** — they are built from quarks.



Fundamental particles (quarks, leptons) versus hadrons (baryons, mesons)

Worked example. In the list — antineutrino, β^+ particle, neutron, positron, proton — underline the hadrons.

Neutron and proton (three quarks each). The antineutrino and the positron are leptons; the β^+ particle *is* a positron. The same list asked as "which are not fundamental?" has the same answer: neutron and proton.

Antimatter. Every particle has an antiparticle of the same mass and opposite charge; a positron and an electron are alike in mass (and in the size of their charge) and differ in the sign of their charge. An **antihydrogen** atom is an antiproton (charge $-e$, made of $\bar{u}\bar{u}\bar{d}$) with a positron in orbit.

Definitions the examiner accepts

A definition question is marked against fixed wording. Learn these exactly, and give one answer only.

Term	Definition
proton number Z	the number of protons in a nucleus
nucleon number A	the total number of protons and neutrons in a nucleus
isotopes	nuclei of the same element (same number of protons) with different numbers of neutrons

Term	Definition
nuclide	a nucleus with a particular number of protons and a particular number of neutrons
unified atomic mass unit	one twelfth of the mass of an atom of carbon-12
antiparticle	a particle with the same mass as the corresponding particle but the opposite charge
fundamental particle	a particle that cannot be broken down into smaller particles
hadron	a particle made of quarks: a baryon (three quarks) or a meson (a quark and an antiquark)
lepton	a fundamental particle that is not made of quarks, such as the electron or the neutrino
α-particle	a helium-4 nucleus: two protons and two neutrons, charge $+2e$, mass 4 u
β^- / β^+ particle	an electron / a positron emitted from a nucleus when a neutron becomes a proton / a proton becomes a neutron

Exam tips

- Describe the **nuclear atom** (a small, dense, positive nucleus) using the alpha-scattering evidence — pair each observation with its conclusion.
- Compare α, β and γ by **charge, mass, ionising power and penetration**; when asked to compare two particles, give the ratio (”twice the charge”, ”about 7000 times the mass”).
- Use quark composition (proton *uud*, neutron *udd*) and check that **charge and nucleon number balance** in every equation you write.
- In β^- decay a neutron becomes a proton, an electron and an antineutrino; in β^+ decay a proton becomes a neutron, a positron and a neutrino. Name the (anti)neutrino every time.
- A nucleus at rest that decays gives its two products **equal and opposite momentum**, so the lighter one is faster and carries most of the kinetic energy.
- For a decay chain, count the α-decays from the change in A first, then fix Z with β-decays.

Common mistakes

- Concluding “the nucleus is positive” from the *straight-through* result. That result shows empty space; the large-angle deflections show the concentrated positive charge.
- Defining isotopes by “different mass” only. The mark needs *same number of protons, different number of neutrons*.
- Writing ${}^{0}_{-1}\beta$ for β^+ decay. A positron is ${}^{0}_{+1}\beta$, and Z goes *down* by one.
- Forgetting the (anti)neutrino in a β-decay equation, or putting a neutrino with β^-. β^- goes with the antineutrino, β^+ with the neutrino.
- Saying protons or neutrons are fundamental. Only quarks and leptons are.
- Giving a meson as “two quarks”. It is a quark **and an antiquark**.
- Treating an antiquark’s charge as the same sign as the quark’s. $\bar{u}$ is $-\frac{2}{3}e$, $\bar{d}$ is $+\frac{1}{3}e$.