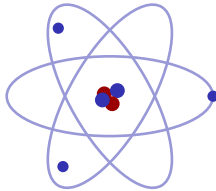


Particle Physics

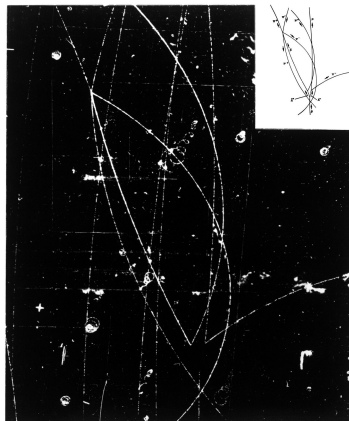
AS Physics ■ Topic 11

A-Level Physics



What we will cover

- 1 The nuclear atom 11.1
- 2 Decay equations 11.1.1
- 3 The three radiations 11.1.2
- 4 Quarks and hadrons 11.2
- 5 β -decay and leptons 11.2.1
- 6 Recap



Production and decay of neutral lambda and anti-lambda hyperons



Sheet 11.1 – what you need to know

You must be able to:

- say what the α -scattering results prove about the **nucleus**
- describe the nuclear atom: protons, neutrons, orbital electrons
- count protons, neutrons and electrons from ${}^A_Z\text{X}$, for atoms and ions
- convert between u and kg, and find a charge-to-mass ratio

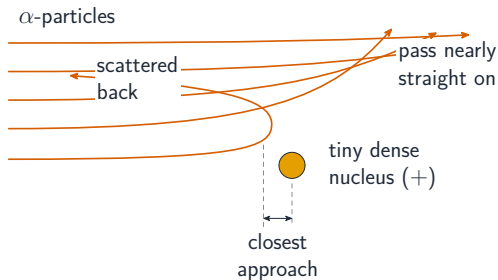
What the exam asks

“Draw a labelled diagram to represent a simple model of the arrangement of the protons, neutrons and electrons in a tritium atom.” [2]

“State the nuclide notation in the form ${}^A_Z\text{X}$ for this nucleus of copper.” [1]

“State which of the three particles (proton, neutron or β^+ particle) has the largest ratio of charge to mass.” [1]

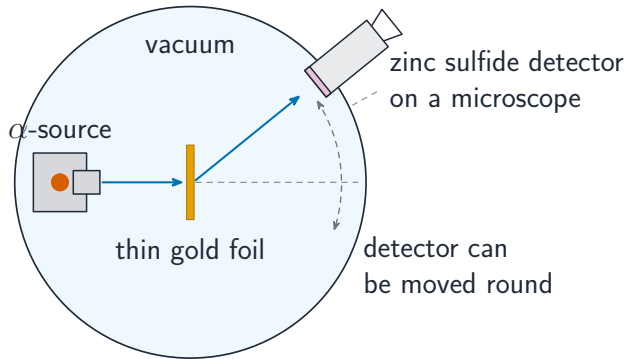
α -particle scattering



- mostly pass straight through, with very little **deflection**,
- sometimes deflect through small angles,
- rarely (about 1 in 8000) deflect through angles greater than 90° .
- so: a **tiny, dense, positively charged nucleus** at the centre
- the atom is **mostly empty space** (most α -particles pass straight through),

The experiment itself

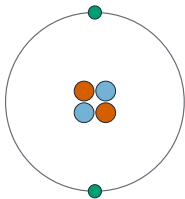
Almost every α went straight through; a very few came **straight back**. That is only possible if the positive charge sits in a tiny, massive core.



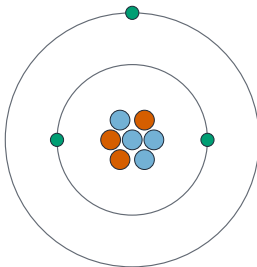
The nuclear model

The rare large deflections need a **tiny, dense, positively charged nucleus** at the centre to push the α away.

a) helium



b) lithium



- proton (charge $+e$) ● neutron (no charge)
● electron (charge $-e$)

- **protons** ($+e$) and **neutrons** (0) in the nucleus, ≈ 1 u each
- **electrons** ($-e$) around it, $\frac{1}{1836}$ of the mass

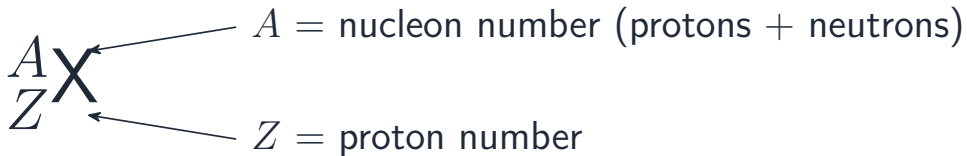
Nuclide notation and isotopes

A nucleon number
 Z proton number
 X

- neutrons $N = A - Z$
- **isotopes** : same Z , different numbers of **neutrons** and so different A (e.g. ${}^{12}_6\text{C}$, ${}^{14}_6\text{C}$) – chemically alike, nuclearly different

In every nuclear process the **nucleon** number A and the **charge** are conserved. Balance both to write any decay equation.

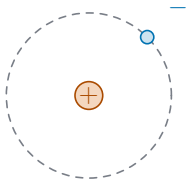
Reading the notation



Top is the **nucleon number** A , bottom the **proton number** Z . **Isotopes** share Z and differ in A .

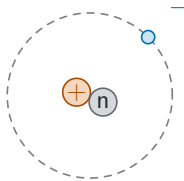
Isotopes of hydrogen

same proton number $Z = 1$: the same element; different nucleon number A



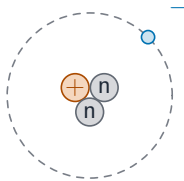
hydrogen-1

${}^1_1\text{H}$: 1 proton, 0 neutrons
1 electron



hydrogen-2 (deuterium)

${}^2_1\text{H}$: 1 proton, 1 neutron
1 electron



hydrogen-3 (tritium)

${}^3_1\text{H}$: 1 proton, 2 neutrons
1 electron

Isotopes: the same number of protons, so the same element; different numbers of **neutrons**, so a different nucleon number A .

Counting the particles

protons	Z
neutrons	$N = A - Z$
electrons, neutral atom	Z
electrons, ion of charge $+ne$	$Z - n$

The ion ${}^{56}_{26}\text{Fe}^{3+}$

protons, the proton number: $Z = 26$

neutrons, nucleon number minus proton number:
 $N = A - Z = 56 - 26 = 30$

electrons: $+3e$ means three have been lost:
 $n_e = Z - 3 = 26 - 3 = 23$

A negative ion has **gained** electrons: ${}^{35}_{17}\text{Cl}^-$ has
 $Z + 1 = 18$.

Unified atomic mass unit

The **unified atomic mass unit** , symbol u, is set so that one atom of ${}^1_6\text{C}$ has a mass of exactly 12 u.

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

proton

$$\approx 1.007 \text{ u}$$

neutron

$$\approx 1.009 \text{ u}$$

electron

$$\approx 5.5 \times 10^{-4} \text{ u}$$

A **nucleon** is about 1 u, so the nucleon number A is very nearly the mass in u.

A mass in kg, and a charge-to-mass ratio

An α -particle, ${}^4_2\text{He}$

the mass is about A u:

$$m = A \times 1 \text{ u} = 4 \times 1.66 \times 10^{-27} \text{ kg} = 6.64 \times 10^{-27} \text{ kg}$$

the charge is $2e$, from the two protons:

$$\frac{Q}{m} = \frac{2e}{m} = \frac{2 \times 1.60 \times 10^{-19} \text{ C}}{6.64 \times 10^{-27} \text{ kg}} = 4.8 \times 10^7 \text{ C kg}^{-1}$$

$1 \text{ u} = 1.66 \times 10^{-27} \text{ kg}$:
one twelfth of the mass of a
carbon-12 atom.

A proton and a neutron are
each about 1 u , so a nucleus is
about $A \text{ u}$.

Running it backwards

A nucleus of 40 nucleons has $\frac{Q}{m} = 4.8 \times 10^7 \text{ C kg}^{-1}$: how many protons?

its mass: $m = A \times 1 \text{ u} = 40 \times 1.66 \times 10^{-27} \text{ kg} = 6.64 \times 10^{-26} \text{ kg}$

its charge is Ze , so

$$Z = \frac{(Q/m) \times m}{e} = \frac{(4.8 \times 10^7 \text{ C kg}^{-1})(6.64 \times 10^{-26} \text{ kg})}{1.60 \times 10^{-19} \text{ C}} = 19.9$$

a whole number of protons: $Z = 20$, so the nuclide is ${}^{40}_{20}\text{Ca}$

Keep every figure until the last step, then round: rounding early can move the answer by a whole proton.



Sheet 11.1.1 – what you need to know

You must be able to:

- balance nucleon number and **charge** in every decay equation
- write α , β^- and β^+ equations with the (anti)neutrino
- state what an **antiparticle** is
- follow a decay chain, and find the recoil of the daughter nucleus

What the exam asks

“State the name of the other lepton that is emitted.” [1]

“Determine the proton number and the nucleon number of nucleus S.” [2]

“State and explain whether the nuclei in the sample are undergoing α -decay, β^+ decay or β^- decay.” [2]

Practise on exercise sheet 11.1.1, then try the real exam questions on past-paper sheet 11.1.1.

Writing decay equations

α decay of U-238: find the daughter

the α takes 4 nucleons and 2 protons:

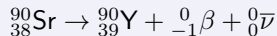
$$A_{\text{Th}} = A_{\text{U}} - 4 = 238 - 4 = 234$$

$$Z_{\text{Th}} = Z_{\text{U}} - 2 = 92 - 2 = 90$$

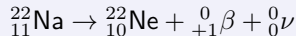


β^- and β^+ : A unchanged, Z moves by one

a neutron becomes a proton, with an antineutrino:



a proton becomes a neutron, with a neutrino:

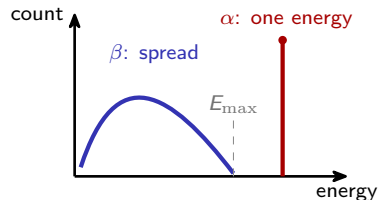


Top numbers balance, bottom numbers balance. The (anti)neutrino is ${}_0^0$, so leaving it out still balances – and still loses the mark.

Antiparticles and the neutrino

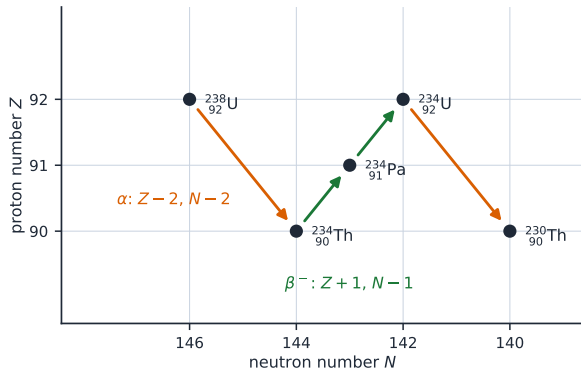
Every particle has an **antiparticle** : same mass, opposite charge (positron = anti-electron). β -decay always emits a third particle:

- β^- : an **antineutrino** $\bar{\nu}_e$
- β^+ : a **neutrino** ν_e



α : energy shared by 2 bodies
→ discrete. β : shared by 3 →
continuous – the neutrino takes
a varying share.

A decay chain, worked backwards



$$\alpha: Z-2, N-2. \quad \beta^-: Z+1, N-1.$$

$^{238}_{92}\text{U}$ decays to $^{206}_{82}\text{Pb}$

only α changes A , by 4 each time:

$$n_{\alpha} = \frac{A_{\text{U}} - A_{\text{Pb}}}{4} = \frac{238 - 206}{4} = 8$$

where the α decays alone leave Z :

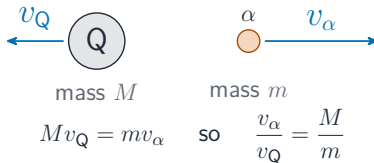
$$Z = Z_{\text{U}} - 2n_{\alpha} = 92 - 2 \times 8 = 76$$

each β^- adds one to Z :

$$n_{\beta} = Z_{\text{Pb}} - Z = 82 - 76 = 6$$

The recoil of the daughter nucleus

before: P at rest, momentum = 0 after: equal and opposite momenta



Zero total momentum

$$m_\alpha v_\alpha = m_D v_D$$

opposite directions, equal-sized momenta

α (4 u) at $1.5 \times 10^7 \frac{\text{m}}{\text{s}}$; daughter 234 u

$$v_D = \frac{m_\alpha v_\alpha}{m_D} = \frac{(4 \text{ u})(1.5 \times 10^7 \frac{\text{m}}{\text{s}})}{234 \text{ u}} = 2.6 \times 10^5 \frac{\text{m}}{\text{s}}$$



Sheet 11.1.2 – what you need to know

You must be able to:

- describe the composition, mass and charge of α , β^- , β^+ and γ
- explain penetration, ionisation and deflection from mass and charge
- explain why α energies are **discrete** and β energies **continuous**
- sketch the two energy spectra

What the exam asks

“Suggest why the β^- particles are emitted with a range of different energies.” [2]

“State an observation about β -decay that is explained by the existence of neutrinos.” [1]

“State and explain the differences between the electric force on the β^- particle and the electric force on the α -particle.” [3]

Practise on exercise sheet 11.1.2, then try the real exam questions on past-paper sheet 11.1.2.

Three kinds of radiation

 α

He nucleus
+2e, ≈ 4 u
stopped by paper
discrete energy

 β

fast electron/positron
 $\pm e$, tiny mass
stopped by Al
continuous energy

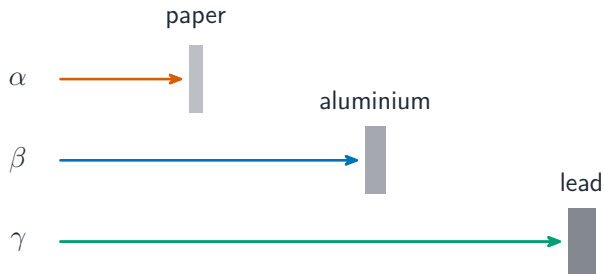
 γ

photon
0 charge, 0 mass
attenuated by lead
discrete energy

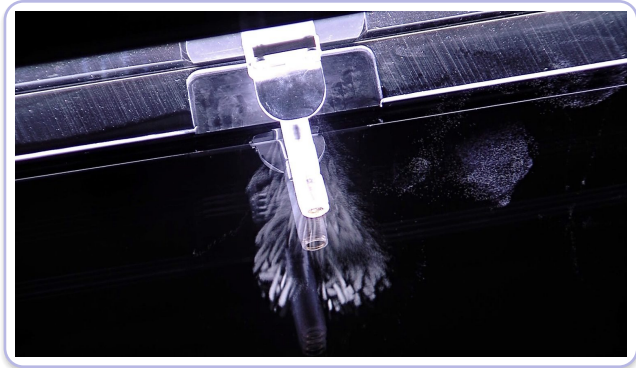
Penetrating power

- α – paper
- β – a few mm of aluminium
- γ – only attenuated by lead

Ionising power is the reverse order: α strongest.



Tracks in a cloud chamber



α tracks are short, straight and thick – heavily ionising, quickly stopped.

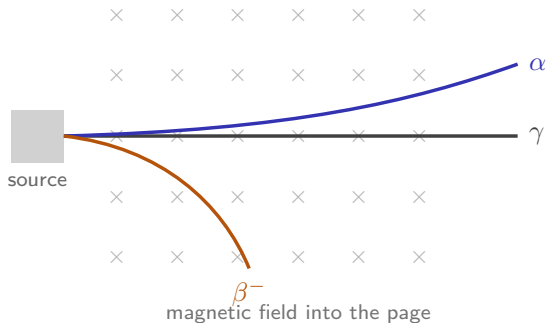
A γ -ray is a photon, not a particle

- made of a high-energy **photon** – part of the **electromagnetic spectrum**
- **zero** rest mass, **zero** charge
- long range in air; **attenuated** rather than stopped – several cm of lead, or a metre of concrete
- weakest **ionising** power of the three
- a **discrete** energy spectrum: the nucleus drops between two nuclear energy levels

It is usually a **tidy-up** step: an α or β decay leaves the **daughter nucleus** in an **excited state**, and the γ carries off the surplus.

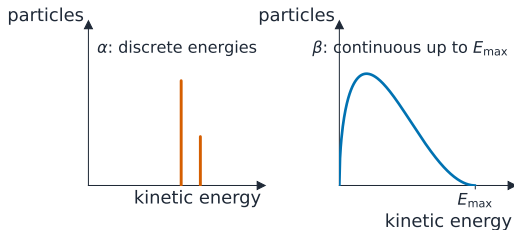
That is why γ alone never changes A or Z .

Deflection in a field



- 1 Which way? α is positive and β^- negative: **opposite** ways. β^+ goes the way α does.
- 2 How much? A β -particle has about $\frac{1}{7000}$ of the mass of an α : it curves **far more**.
- 3 And γ ? No charge, no force: **straight on**.

Two bodies or three: the energy spectra



- α decay: the energy is shared by **two** bodies, so momentum fixes the split: one **discrete** energy
- β decay: a **third** particle, the (anti)neutrino, takes a varying share: a **continuous** range up to a maximum
- the maximum is the energy the β has when the (anti)neutrino takes almost none

Why the neutrino had to exist

The problem

In β -decay the emitted electron comes out with a *range* of energies, not the single value a two-body decay demands.

The fix

A third particle carries off the rest. Neutrinos and antineutrinos have zero charge, very small mass, and barely interact.

What it saves

They are hard to detect, but they must be there to balance energy, **momentum** and the other conserved quantities.

Counting nucleons

The **nucleon number** A is the total number of **nucleons** – protons plus neutrons – and it balances on both sides of every decay equation.

A conservation law that appears to fail is a prediction: something unseen is carrying the difference.

How an α decay shares its energy

The parent was at rest, so both products have momentum of the same size p . With $E_k = \frac{1}{2}mv^2$ and $p = mv$:

$$E_k = \frac{p^2}{2m}$$

Same p : each share is inversely proportional to the mass.



the α -particle's share:

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

Every decay splits the same energy the same way, so every α has 5.31 MeV: **discrete**.



Sheet 11.2 – what you need to know

You must be able to:

- name the six quark flavours and recall each charge
- give an **antiquark** the opposite charge
- give the quark composition of protons, neutrons and their antiparticles
- find a hadron's charge, and tell a **baryon** from a **meson**

What the exam asks

“State the quark composition of a proton.” [1]

“Determine, in terms of the elementary charge e , the charge of the hadron.” [2]

“Determine a possible quark composition of a hadron with a charge of $+2e$. Explain your reasoning.” [2]

Practise on exercise sheet 11.2, then try the real exam questions on past-paper sheet 11.2.

Quarks, in detail

charge $+\frac{2}{3}e$

up
u

charm
c

top
t

charge $-\frac{1}{3}e$

down
d

strange
s

bottom
b

each antiquark has
the opposite charge

Only **u** and **d** build ordinary matter – a proton is uud, a neutron udd. The other four appear only at high energy.

Hadrons: baryons and mesons

Particles built from quarks are **hadrons** :

baryons

three quarks
proton (u u d), neutron (u d d)

mesons

one quark + one antiquark
e.g. $\pi^+ = u\bar{d}$

Protons and neutrons are **not** fundamental – they are baryons.

The charge of any composition

baryon: three quarks

$$\begin{array}{ccc} \textcircled{u} & \textcircled{d} & \textcircled{s} \\ +\frac{2}{3}e & -\frac{1}{3}e & -\frac{1}{3}e \end{array} = 0$$

meson: quark + antiquark

$$\begin{array}{cc} \textcircled{u} & \textcircled{\bar{d}} \\ +\frac{2}{3}e & +\frac{1}{3}e \end{array} = +e$$

The charge of a hadron is the sum of its quarks' charges

proton, uud:

$$Q = q_u + q_u + q_d = +\frac{2}{3}e + \frac{2}{3}e - \frac{1}{3}e = +e$$

neutron, udd:

$$Q = q_u + q_d + q_d = +\frac{2}{3}e - \frac{1}{3}e - \frac{1}{3}e = 0$$

$$\pi^+, u\bar{d}: Q = q_u + q_{\bar{d}} = +\frac{2}{3}e + \frac{1}{3}e = +e$$

$$\text{antiproton, } \bar{u}\bar{d}: Q = -\frac{2}{3}e - \frac{2}{3}e + \frac{1}{3}e = -e$$

The mark is for the sum: write each charge, then add.

A composition from a charge

A meson has a charge of $-e$: give a possible composition

a meson is one quark and one antiquark

most negative quark: $-\frac{1}{3}e$ (d, s, b)

most negative antiquark: $-\frac{2}{3}e$ ($\bar{u}$, $\bar{c}$, $\bar{t}$)

$$d\bar{u}: Q = q_d + q_{\bar{u}} = -\frac{1}{3}e - \frac{2}{3}e = -e$$

A meson can never carry $\pm 2e$: the most a quark and an antiquark can add up to is $\frac{2}{3}e + \frac{1}{3}e = e$.

A baryon of charge $+2e$ must be
 $uuu: 3 \times \frac{2}{3}e = 2e$.



Sheet 11.2.1 – what you need to know

You must be able to:

- describe the quark change in β^- and β^+ decay
- write each change with its two **leptons**, and check the charge
- recall that electrons and neutrinos are fundamental leptons
- classify a particle as a lepton, a baryon or a meson

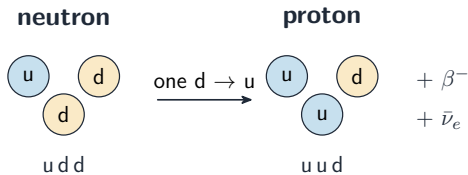
What the exam asks

“Describe the change to the quark composition of the nucleon.” [1]

“State the equation for β^- decay in terms of the fundamental particles involved.” [1]

“State the name of the group (class) of fundamental particles to which the positron and neutrino belong.” [1]

Practise on exercise sheet 11.2.1, then try the real exam questions on past-paper sheet 11.2.1.

β -decay at the quark level

decay	quark	leptons emitted
β^-	$d \rightarrow u$	electron, antineutrino
β^+	$u \rightarrow d$	positron, neutrino

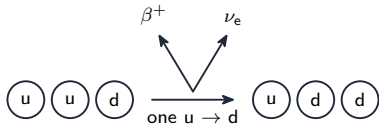
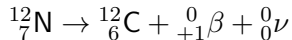
Charge is conserved in the change

$$q_d = q_u + q_{e^-} + q_{\bar{\nu}}: \quad -\frac{1}{3}e = +\frac{2}{3}e - e + 0$$

$$q_u = q_d + q_{e^+} + q_{\nu}: \quad +\frac{2}{3}e = -\frac{1}{3}e + e + 0$$

The other two quarks are spectators: the nucleon is still there, so the **nucleon number does not change**.

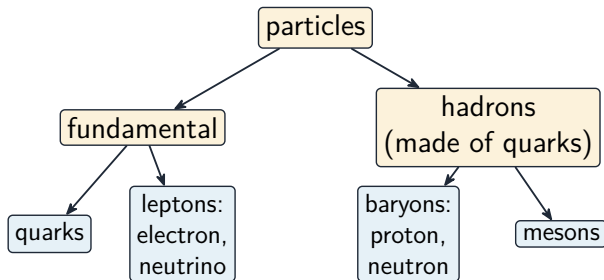
From the nucleus down to the quark



proton (u u d), charge $+e$ neutron (u d d), charge 0

- 1 **nucleus:** Z falls from 7 to 6, A stays 12, so a proton has become a neutron
- 2 **nucleon:** uud has become udd
- 3 **quark:** $u \rightarrow d + e^+ + \nu_e$

Classifying particles



Fundamental: **quarks** and **leptons** (electron, neutrino).

Built from quarks: protons, neutrons, baryons, mesons.



Exam tips

- Describe the **nuclear atom** (a small, dense, positive nucleus) using the alpha-scattering evidence.
- Compare α , β and γ by **charge, mass, ionising power and penetration**.
- Use quark composition (proton uud , neutron udd) and check that **charge and nucleon number balance** in an equation.
- In β^- decay a neutron becomes a proton, an electron and an antineutrino.



Topic 11 – key takeaways

1

Nuclear atom

a tiny, dense, positive nucleus; A_ZX counts it; $1\text{ u} = 1.66 \times 10^{-27}\text{ kg}$

2

Decay equations

nucleon number and charge balance; β^- with $\bar{\nu}$, β^+ with ν

3

Energies

α : two bodies, discrete; β : three bodies, continuous

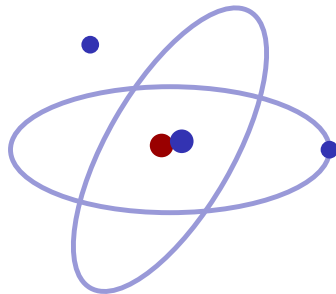
4

Quarks

baryon qqq , meson $q\bar{q}$; in β -decay one quark changes flavour

Check yourself

- 1 What did the rare large α deflections show?
- 2 $^{226}_{88}\text{Ra}$ decays by α – the daughter's A and Z ?
- 3 Which radiation is a photon?
- 4 Quark content of a neutron?



Answers 1. a tiny dense nucleus 2. $A = 222$, $Z = 86$ 3. γ 4. u d d