Exercise walk-through

11.2.1

Quark charges, classifying hadrons and the quark changes in beta decay

A-Level Physics

You must be able to

- understand that a quark is a fundamental particle and that there are six flavours: up, down, strange, charm, top and bottom
- recall and use the charge of each flavour of quark, and understand that its **antiquark 反夸克** has the opposite charge
- recall that protons and neutrons are not fundamental particles, and describe them in terms of their quark composition
- understand that a hadron may be either a **baryon 重子** (three quarks) or a **meson 介子** (one quark and one antiquark)
- describe the changes to quark composition that take place during β^- and β^+ decay
- recall that electrons and neutrinos are fundamental particles called **leptons 轻子**

1 The method

Method — Six flavours, and only two charges to learn

- **up, charm, top** each carry $+\frac{2}{3}e$.
- **down, strange, bottom** each carry $-\frac{1}{3}e$.
- Every **antiquark** carries the same size of charge with the **opposite sign**: $\overline{\mathrm{u}}$ is $-\frac{2}{3}e$, $\overline{\mathrm{d}}$ is $+\frac{1}{3}e$, $\bar{\mathrm{s}}$ is $+\frac{1}{3}e$.

No other property of a quark is examined, so three lines of table answer every charge question on this topic.

Method — Six flavours, and only two charges to learn

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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

Method — Getting a charge out of any composition

Write each quark's charge underneath it, then add. The mark is for the arithmetic, not for the final number on its own.

1. **Proton** (u u d): $\frac{2}{3} + \frac{2}{3} - \frac{1}{3} = +1$, so $+e$.
2. **Neutron** (u d d): $\frac{2}{3} - \frac{1}{3} - \frac{1}{3} = 0$.
3. **A uds baryon**: $\frac{2}{3} - \frac{1}{3} - \frac{1}{3} = 0$ as well – two different baryons, the same charge.
4. **A π^+ meson** (u$\overline{\text{d}}$): $\frac{2}{3} + \frac{1}{3} = +1$.

Running it backwards is just as common. *A meson carries $-e$; give a possible composition.* The most negative quark is $-\frac{1}{3}$ and the most negative antiquark is $-\frac{2}{3}$, so d$\overline{\text{u}}$ gives $-\frac{1}{3} - \frac{2}{3} = -1$.

- A meson can never reach $\pm 2e$: the largest a quark and an antiquark can manage together is $\frac{2}{3} + \frac{1}{3} = 1$.

Method — Getting a charge out of any composition

Write each quark's charge underneath it, then add.

baryon: three quarks

u	d	s	$= 0$
$+\frac{2}{3}e$	$-\frac{1}{3}e$	$-\frac{1}{3}e$	

meson: quark + antiquark

u	$\bar{\mathrm{d}}$	$= +e$
$+\frac{2}{3}e$	$+\frac{1}{3}e$	

Method — What class is it?

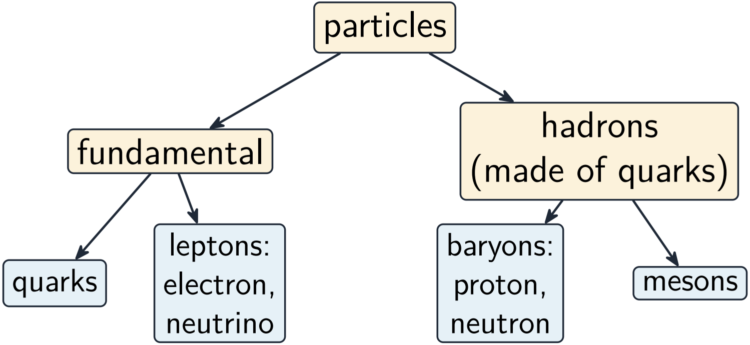
Two questions, asked in that order, settle any particle:

1. **Is it made of quarks?** If yes it is a **hadron**, and it is not fundamental. If no, it is fundamental.
2. **If it is a hadron, how many quarks?** Three makes a **baryon**, one quark with one antiquark makes a **meson**.

- **Fundamental:** quarks, and the **leptons** – the electron, the neutrino, and their antiparticles the positron and the antineutrino.
- **Not fundamental:** protons, neutrons, every baryon and every meson, and an α-particle, which is a whole helium nucleus.
- A β^- particle *is* an electron and a β^+ particle *is* a positron, so both are leptons and both are fundamental.

Method — What class is it?

Two questions, asked in that order, settle any particle



Method — The quark change in β-decay

One quark changes flavour; the other two are spectators.

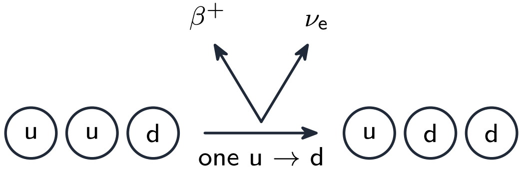
- β^+: an **up** quark becomes a **down** quark, so a proton becomes a neutron.
  $\mathrm{u} \rightarrow \mathrm{d} + \beta^+ + \nu_\mathrm{e}$.
- β^-: a **down** quark becomes an **up** quark, so a neutron becomes a proton.
  $\mathrm{d} \rightarrow \mathrm{u} + \beta^- + \overline{\nu}_\mathrm{e}$.

Check the charge across the β^+ equation: $+\frac{2}{3}$ on the left, and $-\frac{1}{3} + 1 + 0 = +\frac{2}{3}$ on the right.

- The **nucleon number never changes** in β-decay, because the nucleon is still there – it has only swapped one quark, so a proton becomes a neutron or the other way round.

Method — The quark change in β-decay

One quark changes flavour; the other two are spectators.



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

Method — Antiparticles and antihadrons

An antiparticle has the **same mass** and the **opposite charge**. For a hadron, replace every quark by its antiquark:

- **antiproton** $\overline{\mathrm{u}}\overline{\mathrm{u}}\overline{\mathrm{d}}$: $-\frac{2}{3} - \frac{2}{3} + \frac{1}{3} = -1$, so $-e$ as expected.
- **antineutron** $\overline{\mathrm{u}}\overline{\mathrm{d}}\overline{\mathrm{d}}$: $-\frac{2}{3} + \frac{1}{3} + \frac{1}{3} = 0$ – the same charge as the neutron, which is why an antineutron is not simply “a neutron with the opposite charge”.

2 Practice

Practice 2.1 ▪ 2 marks

State the charge, in terms of e, of a **strange** quark and of an **anti-charm** quark.

Solution 2.1

Method: Six flavours, and only two charges to learn — p.4

Worked steps

- strange quark: $-\frac{\mathbf{1}}{\mathbf{3}}\mathbf{e}$ **B1**
- anti-charm quark: the charm quark is $+\frac{2}{3}e$, so its antiquark is $-\frac{\mathbf{2}}{\mathbf{3}}\mathbf{e}$ **B1**

Practice 2.2 ▪ 2 marks

A baryon consists of the quarks u, u and s. Calculate its charge in terms of e.

Solution 2.2

Method: Getting a charge out of any composition — p.6

Worked steps

- write each charge: $+\frac{2}{3}e$, $+\frac{2}{3}e$, $-\frac{1}{3}e$ **M1**

$$\frac{2}{3}e+\frac{2}{3}e-\frac{1}{3}e=+\mathbf{e}$$ **A1**

Practice 2.3 ▪ 2 marks

A meson has a charge of $-e$. Give a possible quark and antiquark composition, and show that it gives this charge.

Solution 2.3

Method: Getting a charge out of any composition — p.6

Worked steps

- a meson is one quark and one antiquark; take d and $\bar{\mathrm{u}}$ **M1**

$$-\frac{1}{3}e - \frac{2}{3}e = -\mathbf{e}$$ **A1**

- $\mathrm{s}\bar{\mathrm{u}}$ or $\mathrm{b}\bar{\mathrm{u}}$ would do just as well

Practice 2.4 ▪ 2 marks

From this list, state which particles are **fundamental**: electron, neutron, quark, meson.

Solution 2.4

Method: What class is it? — p.8

Worked steps

- **electron** and **quark** B1 B1
- a neutron is three quarks and a meson is a quark with an antiquark, so neither is fundamental

Practice 2.5 ▪ 3 marks

Give the quark composition of an **antineutron**, and show that its charge is zero.

Solution 2.5

Method: Getting a charge out of any composition — p.6

Worked steps

- an antineutron is the antiparticle of the neutron (u d d), so it is $\mathbf{\bar{u}\bar{d}\bar{d}}$ B1
- each antiquark has the opposite charge to its quark M1

$$-\tfrac{2}{3}e + \tfrac{1}{3}e + \tfrac{1}{3}e = \mathbf{0}$$ A1

3 Exam-style

Exam-style 3.1 ▪ 1 mark

A hadron consists of three quarks and has a total charge of $+2e$. What is its quark composition?

A u u d

B u u u

C u d d

D u u s

Solution 3.1

Method: Getting a charge out of any composition — p.6

A u u d

B u u u ✓

C u d d

D u u s

Worked steps

B

- u u u gives $\frac{2}{3}+\frac{2}{3}+\frac{2}{3}=+2$ **B1**
- A gives $+1$, C gives 0 and D gives $+1$

Exam-style 3.2 ▪ 3 marks

Explain why a meson can never have a charge of $+2e$.

Solution 3.2

Method: Getting a charge out of any composition — p.6

Worked steps

- a meson is one quark and one antiquark **B1**
- the largest charge a quark can carry is $+\frac{2}{3}e$ and the largest an antiquark can carry is $+\frac{1}{3}e$ **B1**
- the most they can add to is $+e$, so $+2e$ is impossible **B1**

Exam-style 3.3 ▪ 7 marks

A nucleus decays by β^+ emission.

Exam-style 3.3 (a) ▪ 1 mark

State the change in quark composition that takes place.

Solution 3.3 (a)

> Method: The quark change in β-decay — p.10

Worked steps

an **up** quark changes into a **down** quark, so a proton becomes a neutron B1

Exam-style 3.3 (b) ▪ 2 marks

Write an equation for this change, including the lepton that is emitted with the β^+ particle.

Solution 3.3 (b)

Worked steps

the lepton emitted with a positron is a neutrino **M1**

$$\mathrm{u} \rightarrow \mathrm{d} + \beta^{+} + \nu_{\mathrm{e}}$$ **A1**

Exam-style 3.3 (c) ▪ 2 marks

Explain why the nucleon number of the nucleus does not change.

Solution 3.3 (c)

Worked steps

the nucleon is still there: it has only changed one of its quarks, so a proton has become a neutron **B1**

- the number of nucleons is therefore unchanged, though the proton number falls by one **B1**

Exam-style 3.3 (d) ▪ 2 marks

Name the lepton emitted in β^- decay, and state how it differs from the one emitted in β^+ decay.

Solution 3.3 (d)

Worked steps

an (electron) **antineutrino** is emitted in β^- decay **B1**

- it is the **antiparticle** of the neutrino emitted in β^+ decay: the same mass, and it is matter's counterpart rather than the particle itself **B1**

Exam-style 3.4 ▪ 4 marks

For each of these particles, state whether it is **fundamental**, and if it is not, state whether it is a baryon or a meson: proton, positron, π^+ meson, electron antineutrino.

Solution 3.4

Method: What class is it? — p.8

Worked steps

- **proton**: not fundamental, a **baryon** (three quarks) **B1**
- **positron**: **fundamental** (a lepton) **B1**
- π^+ **meson**: not fundamental, a **meson** (a quark and an antiquark) **B1**
- **electron antineutrino**: **fundamental** (a lepton) **B1**

Exam-style 3.5 ▪ 5 marks

A hadron consists of three quarks and carries a charge of $-e$.

Exam-style 3.5 (a) ▪ 3 marks

Give a possible quark composition, and show that it gives this charge.

Solution 3.5 (a)

Method: Getting a charge out of any composition — p.6

Worked steps

three quarks, so a possible set is d, d, d **M1**

$$-\frac{1}{3}e - \frac{1}{3}e - \frac{1}{3}e = -\mathbf{e}$$ **M1** **A1**

- d d s and d s s also give $-e$

Exam-style 3.5 (b) ▪ 2 marks

State whether this hadron is a baryon or a meson, and give the reason.

Solution 3.5 (b)

Worked steps

a **baryon** B1

- a baryon is three quarks, while a meson is one quark and one antiquark B1