A-LEVEL PHYSICS • EXERCISE SHEET

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

Name: ____________ Class: ________ Date: __________ **Total: 31 marks**

KEY WORDS quark 夸克 • hadron 强子 • baryon 重子 • fundamental 基本粒子 • meson 介子

Objective

Build the skills to answer exam questions on **fundamental particles** 基本粒子 that sheet 11.2 only starts: all six **quark** 夸克 flavours rather than just up and down, working out a **hadron** 强子 charge from any quark composition, deciding what class a particle belongs to, and the quark change in β^+ decay as well as β^-. This sheet covers syllabus 11.2, learning outcomes 1 to 6.

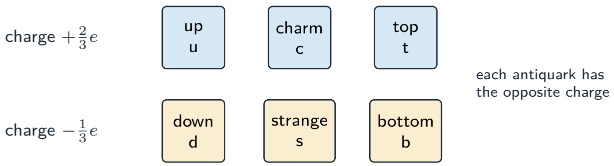
You must be able to:

- 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 Worked examples

Study these first. Each one shows a **method** that a question later on this sheet needs.

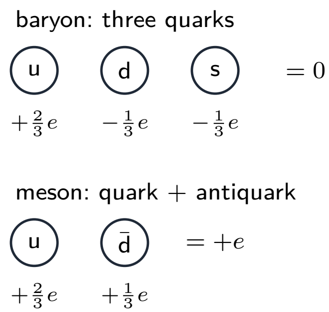
Six flavours, and only two charges to learn



- **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**: $\bar{\text{u}}$ is $-\frac{2}{3}e$, $\bar{\text{d}}$ is $+\frac{1}{3}e$, $\bar{\text{s}}$ 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.

Getting a charge out of any composition



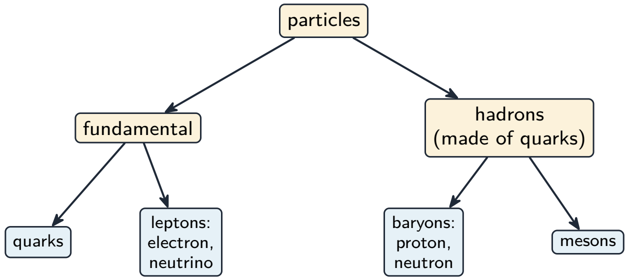
Write each quark's charge underneath it, then add. The mark is for the arithmetic, not for the final number on its own.

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$\bar{\text{d}}$): $\frac{2}{3} + \frac{1}{3} = +1$.

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$\bar{\text{u}}$ 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 $\frac{2}{3} + \frac{1}{3} = 1$.

What class is it?

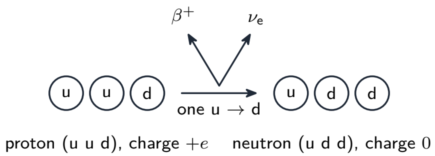


Two questions, asked in that order, settle any particle:

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.

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

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.

■ Antiparticles and antihadrons

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

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

2 Practice

Now use the methods above.

2.1 State the charge, in terms of e, of a **strange** quark and of an **anti-charm** quark. [2]

2.2 A baryon consists of the quarks u, u and s. Calculate its charge in terms of e. [2]

2.3 A meson has a charge of $-e$. Give a possible quark and antiquark composition, and show that it gives this charge. [2]

2.4 From this list, state which particles are **fundamental**: electron, neutron, quark, meson. [2]

2.5 Give the quark composition of an **antineutron**, and show that its charge is zero. [3]

3 Exam-style questions

3.1 A hadron consists of three quarks and has a total charge of $+2e$. What is its quark composition? [1]

A u u d
B u u u
C u d d
D u u s

3.2 Explain why a meson can never have a charge of $+2e$. [3]

3.3 A nucleus decays by β^+ emission.

(a) State the change in quark composition that takes place. [1]

(b) Write an equation for this change, including the lepton that is emitted with the β^+ particle. [2]

(c) Explain why the nucleon number of the nucleus does not change. [2]

(d) Name the lepton emitted in β^- decay, and state how it differs from the one emitted in β^+ decay. [2]

3.4 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. [4]

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

(a) Give a possible quark composition, and show that it gives this charge. [3]

(b) State whether this hadron is a baryon or a meson, and give the reason. [2]

Solutions

Each answer shows the steps, then the **result**.

2.1

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

2.2

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

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

2.3

- a meson is one quark and one antiquark; take d and ū

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

- sū or bū would do just as well

2.4

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

2.5

- an antineutron is the antiparticle of the neutron (u d d), so it is **ūd̄d̄**
- each antiquark has the opposite charge to its quark

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

3.1 B

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

3.2

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

3.3

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

(b) the lepton emitted with a positron is a neutrino

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

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

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

(d) an (electron) **antineutrino** is emitted in β^{-} decay

- 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

3.4

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

3.5

(a) three quarks, so a possible set is d, d, d

$$-\tfrac{1}{3}e - \tfrac{1}{3}e - \tfrac{1}{3}e = -\mathbf{e}$$

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

(b) a **baryon**

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