11.2 Quarks and hadrons

Name: _____ Class: _____ Date: _____ **Total: 35 marks**

KEY WORDS quark • antiquark • hadron • baryon • meson

Objective

Answer exam questions on **quarks** and **hadrons**: the six quark flavours and their charges, antiquarks, the quark make-up of protons and neutrons, and the difference between a **baryon** and a **meson**. Syllabus 11.2, learning outcomes 1 to 4.

You must be able to:

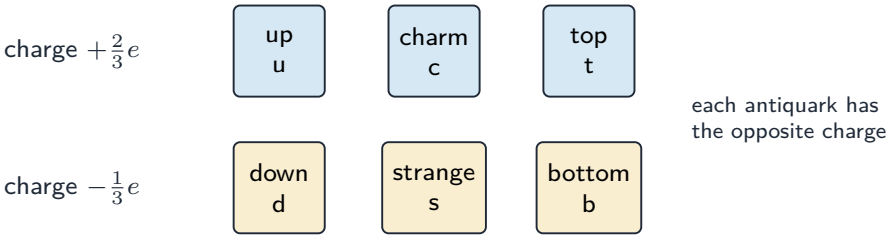
- name the six flavours of quark and recall the charge of each
- state that an antiquark has the opposite charge to its quark
- give the quark composition of a proton, a neutron and their antiparticles
- find the charge of a hadron from its quarks, and a possible composition from its charge
- classify a hadron as a baryon or a meson

1 Key knowledge and worked examples

■ **Key knowledge: use these earlier methods**

- **Scattering evidence**: most alpha particles pass through, showing that the atom is mostly empty space; a small fraction deflect through large angles, showing concentrated positive charge and mass in a small nucleus.
- **Nuclear bookkeeping**: in ${}^{A}_{Z}X$, protons $= Z$ and neutrons $= A - Z$. Alpha decay changes (A, Z) by $(-4, -2)$; beta-minus changes it by $(0, +1)$; beta-plus by $(0, -1)$; gamma changes neither.
- **A decay chain**: count alpha emissions from the change in A, then account for their change in Z before counting beta emissions. Include the appropriate neutrino or antineutrino when writing a beta equation.

■ Key knowledge: six flavours, two charges



flavours	charge	antiquark charge
up, charm, top	$+\frac{2}{3}e$	$-\frac{2}{3}e$
down, strange, bottom	$-\frac{1}{3}e$	$+\frac{1}{3}e$

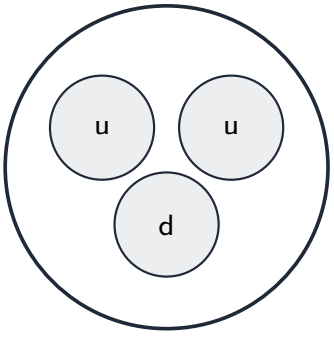
- A **quark** is a **fundamental particle** : it is not made of anything smaller.
- Each quark has an **antiquark** with the same mass and the **opposite charge**, written with a bar: $\bar{u}$, $\bar{d}$, $\bar{s}$.
- No other property of a quark is examined, so this table answers every charge question on the topic.

■ Key knowledge: hadrons

A particle made of quarks is a **hadron**. There are two kinds.

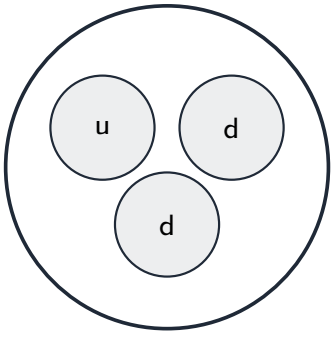
hadron	made of	examples
baryon	three quarks	proton uud, neutron udd
meson	one quark and one antiquark	π^+ meson $u\bar{d}$

proton (charge $+1$)



$+\frac{2}{3}+\frac{2}{3}-\frac{1}{3}=+1$

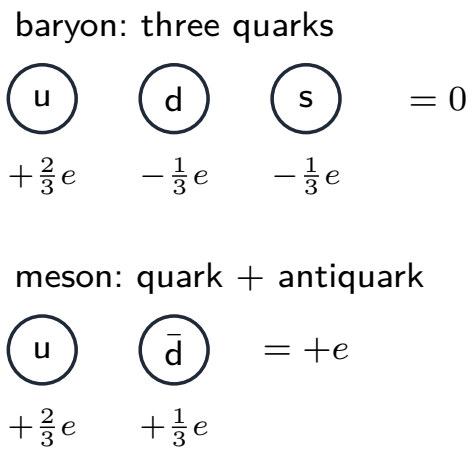
neutron (charge 0)



$+\frac{2}{3}-\frac{1}{3}-\frac{1}{3}=0$

- Protons and neutrons are **not fundamental**: each is made of three quarks.
- An antibaryon is made of three antiquarks: the **antiproton** is $\bar{u}\bar{u}\bar{d}$ and the **antineutron** is $\bar{u}\bar{d}\bar{d}$.

Worked example: the charge of any composition



The charge of a hadron is the sum of its quarks' charges. Write each one, then add: the mark is for the sum, not only the total.

1. **Proton**, u u d:
$$Q = q_{\text{u}} + q_{\text{u}} + q_{\text{d}} = +\tfrac{2}{3}e + \tfrac{2}{3}e - \tfrac{1}{3}e = +e$$
2. **Neutron**, u d d:
$$Q = q_{\text{u}} + q_{\text{d}} + q_{\text{d}} = +\tfrac{2}{3}e - \tfrac{1}{3}e - \tfrac{1}{3}e = 0$$
3. **A π^+ meson**, u$\bar{\text{d}}$:
$$Q = q_{\text{u}} + q_{\bar{\text{d}}} = +\tfrac{2}{3}e + \tfrac{1}{3}e = +e$$
4. **Antiproton**, $\bar{\text{u}}\bar{\text{u}}\bar{\text{d}}$ – every charge is reversed:
$$Q = q_{\bar{\text{u}}} + q_{\bar{\text{u}}} + q_{\bar{\text{d}}} = -\tfrac{2}{3}e - \tfrac{2}{3}e + \tfrac{1}{3}e = -e$$

Worked example: a composition from a charge

A meson has a charge of $-e$. Give a possible quark composition.

1. **What it is made of** – a meson is one quark and one antiquark.
2. **The most negative choices** – a quark can give at most $-\frac{1}{3}e$ (d, s or b), and an antiquark $-\frac{2}{3}e$ ($\bar{\text{u}}$, $\bar{\text{c}}$ or $\bar{\text{t}}$).
3. **Check** – d$\bar{\text{u}}$ works:
$$Q = q_{\text{d}} + q_{\bar{\text{u}}} = -\tfrac{1}{3}e - \tfrac{2}{3}e = -e$$

- The same reasoning shows that a meson can never carry $\pm 2e$: the largest a quark and an antiquark can add up to is $\frac{2}{3}e + \frac{1}{3}e = e$.

Key knowledge: count quarks in a whole nucleus

A nucleus ${}^{A}_{Z}X$ has Z protons (uud) and $A - Z$ neutrons (udd). Thus $N_u = 2Z + (A - Z) = A + Z$ and $N_d = Z + 2(A - Z) = 2A - Z$. Check $N_u + N_d = 3A$ and $q = (2N_u - N_d)e/3 = Ze$.

Worked example. Carbon-14 has six protons and eight neutrons: $N_u = A + Z = 14 + 6 = 20$ and $N_d = 2A - Z = 28 - 6 = 22$. In beta-minus decay one down quark becomes up, so the daughter has 21 up and 21 down quarks.

2 Practice

Now use the methods above.

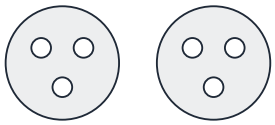
2.1 State what is meant by a **fundamental particle**, and name **two** flavours of quark. [2]

fundamental particle

2.2 State the charge, in terms of e, of an **up** quark, a **strange** quark and an **anti-charm** quark. [3]

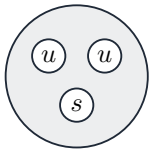
u s $\bar{c}$

2.3 State the quark composition of a proton and of a neutron. [2]



proton neutron

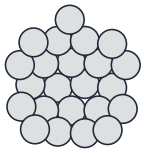
2.4 A baryon consists of the quarks u, u and s. Calculate its charge in terms of e. [2]



2.5 A meson has a charge of $+e$. Give a possible quark composition other than $u\bar{d}$, and show that it gives this charge. [2]

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

2.7 Find the numbers of up and down quarks in $^{23}_{11}\text{Na}$. Check the total number and nuclear charge. [4]



$^{23}_{11}\text{Na}$ nucleus

3 Exam-style questions

3.1 What is a **baryon** made of? [1]

- ☐ **A** two quarks
- **B** three quarks
- **C** one quark and one antiquark
- **D** one quark and one lepton

baryon

3.2 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

$+2e$

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

$+2e$

3.4 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]

3.5 A meson Q is studied in a particle laboratory. The unified atomic mass unit is 1.66×10^{-27} kg.

(a) State what is meant by a **fundamental particle**, and state whether Q is one. [2]

(b) Q has a charge of zero. Determine one possible quark composition for Q, and explain why it gives zero charge. [2]

1.66×10^{-27} kg

0.67 u

(c) Q has a mass of 0.67 u and a kinetic energy of 2.1×10^{-16} J. Calculate its speed. [3]