

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:

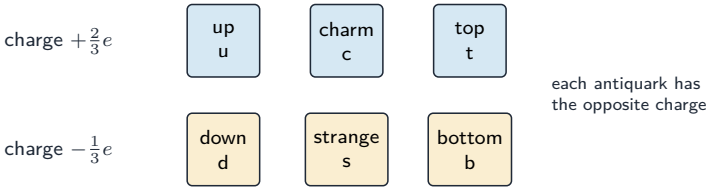
- name the six flavours of quark and recall the charge of each
- state that an antiquark has the opposite charge to its quark
- give the quark composition of a proton, a neutron and their antiparticles
- find the charge of a hadron from its quarks, and a possible composition from its charge
- classify 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 ${}^A_ZX$, 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	$-\frac{1}{3}e$	$+\frac{1}{3}e$

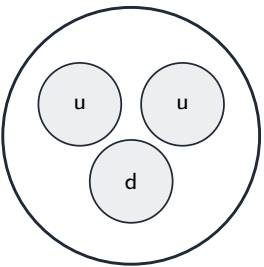
- A **quark** is a **fundamental particle** : it is not made of anything smaller.
- Each quark has an **antiquark** with the same mass and the **opposite charge**, written with a bar: $\bar{u}$, $\bar{d}$, $\bar{s}$.
- No other property of a quark is examined, so this table answers every charge question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

■ Key knowledge: hadrons

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

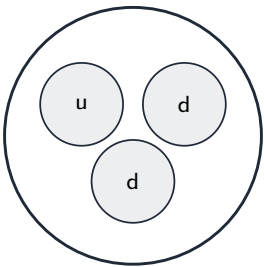
hadron	made of	examples
baryon	three quarks	proton uud, neutron udd
meson	one quark and one antiquark	π^+ meson $u\bar{d}$

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

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. Write each one, then add: the mark is for the sum, not only the total.

1. **Proton**, u u d:

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

2. **Neutron**, u d d:

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

3. **A π^+ meson**, u $\bar{d}$:

$$Q = q_u + q_{\bar{d}} = +\frac{2}{3}e + \frac{1}{3}e = +e$$

4. **Antiproton**, $\bar{u}\bar{u}\bar{d}$ – every charge is reversed:

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

■ 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 $-\frac{2}{3}e$ ($\bar{u}$, $\bar{c}$ or $\bar{t}$).

3. **Check** – $d\bar{u}$ works:

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

- 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 ${}^A_ZX$ 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.

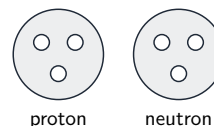
2.1 State what is meant by a **fundamental particle**, and name **two** flavours of quark. [2]

fundamental particle

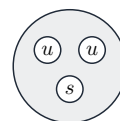
2.2 State the charge, in terms of e , of an **up** quark, a **strange** quark and an **anti-charm** quark. [3]

u s $\bar{c}$

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



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



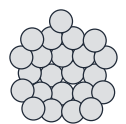
2.5 A meson has a charge of $+e$. Give a possible quark composition other than $u\bar{d}$, and show that it gives this charge. [2]



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]

Solutions

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

2.1

- a particle that is not made of any smaller particles
- any two of: up, down, strange, charm, top, bottom

2.2

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

2.3

- proton: **u u d**
- neutron: **u d d**

2.4

- the charge is the sum of the quarks' charges

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

2.5

- a quark and an antiquark adding to $+e$, for example $u\bar{s}$

$$Q = q_u + q_{\bar{s}} = +\frac{2}{3}e + \frac{1}{3}e = +e$$

- $c\bar{d}$, $c\bar{s}$ or $u\bar{b}$ would do as well

2.6

- the antineutron is made of the antiquarks of u d d: $\bar{u}\bar{d}\bar{d}$
- each antiquark has the opposite charge to its quark

$$Q = q_{\bar{u}} + q_{\bar{d}} + q_{\bar{d}} = -\frac{2}{3}e + \frac{1}{3}e + \frac{1}{3}e = 0$$

2.7

- $N_u = A + Z = 23 + 11 = 34$.
- $N_d = 2A - Z = 46 - 11 = 35$.
- $N_u + N_d = 34 + 35 = 69 = 3A$.
- $q = (2N_u - N_d)e/3 = (68 - 35)e/3 = 11e$, agreeing with $Z = 11$.

3.1 B

- a baryon is **three quarks**, like the proton uud and the neutron udd
- **C** describes a meson

3.2 B

- the charge is the sum of the quarks' charges

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

- **A** and **D** give $+e$; **C** gives 0

3.3

- 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 $+\frac{1}{3}e$
- so the most they can add up to is $+e$, and $+2e$ is impossible

3.4

(a) three quarks, for example d d d

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

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

(b) a **baryon**

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

3.5

(a) a particle that is not made of smaller particles

- Q is **not** fundamental: a meson is made of a quark and an antiquark

(b) a meson is one quark and one antiquark, and the antiquark has the opposite charge to its quark

- for example $u\bar{u}$

$$Q = q_u + q_{\bar{u}} = +\frac{2}{3}e - \frac{2}{3}e = 0$$

(c) the mass in kg

$$m = 0.67 \text{ u} \times \frac{1.66 \times 10^{-27} \text{ kg}}{1 \text{ u}} = 1.11 \times 10^{-27} \text{ kg}$$

- from $E_k = \frac{1}{2}mv^2$

$$v = \sqrt{\frac{2E_k}{m}} = \sqrt{\frac{2 \times 2.1 \times 10^{-16} \text{ J}}{1.11 \times 10^{-27} \text{ kg}}} = \mathbf{6.2 \times 10^5 \frac{m}{s}}$$