Exercise walk-through

Fundamental particles ▪ 11.2

eXercise

You must be able to

- recall the six **quark** flavours and their charges, and classify **hadrons** (baryons/mesons)
- give the **quark composition** of protons, neutrons and their **antiparticles**
- describe quark changes in β^- and β^+ decay; classify particles as **leptons**

Method — Quarks

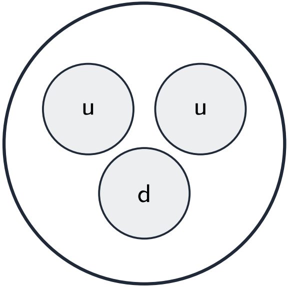
A **quark** is a fundamental particle. Six flavours: **up, charm, top** (charge $+\frac{2}{3}e$) and **down, strange, bottom** (charge $-\frac{1}{3}e$). Each **antiquark** has the **opposite** charge ($\bar{\mathrm{u}} = -\frac{2}{3}e$, $\bar{\mathrm{d}} = +\frac{1}{3}e$).

Method — Hadrons

Particles made of quarks are **hadrons**: a **baryon** $=$ 3 quarks; a **meson** $=$ 1 quark $+$ 1 antiquark. Protons and neutrons are **baryons** (not fundamental):

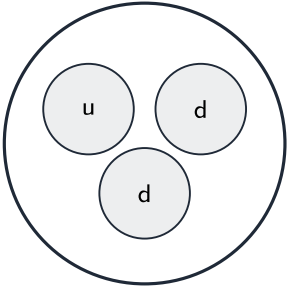
Method — Hadrons

proton (charge $+1$)



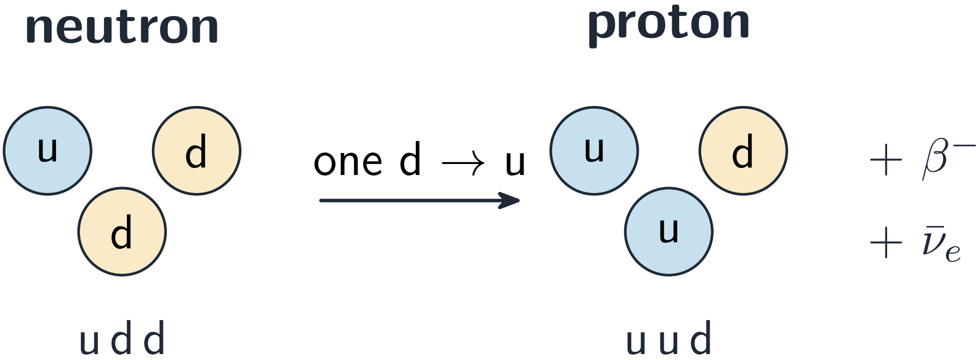
$+\frac{2}{3}+\frac{2}{3}-\frac{1}{3}=+1$

neutron (charge 0)



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

Method — Hadrons



Beta decay changes a quark and the nucleus

Method — Antiparticles

Every particle has an **antiparticle** with the **same mass** but **opposite charge**. The **positron** is the antiparticle of the electron (charge $+e$, and like the electron it is a **lepton**). An **antiproton** is made of the **antiquarks** of a proton: $\bar{\mathrm{u}}\bar{\mathrm{u}}\bar{\mathrm{d}}$, charge $-\frac{2}{3}-\frac{2}{3}+\frac{1}{3}=-1$ (i.e. $-e$).

Method — β-decay in quarks and leptons

- β^- decay: a **down** quark $\rightarrow$ **up** quark, so a neutron becomes a proton: $\mathrm{d} \rightarrow \mathrm{u} + \beta^- + \bar{\nu}_e$.
- β^+ decay: an **up** quark $\rightarrow$ **down** quark, so a proton becomes a neutron: $\mathrm{u} \rightarrow \mathrm{d} + \beta^+ + \nu_e$. In nuclear form, e.g. ${}^{12}_{7}\mathrm{N} \rightarrow {}^{12}_{6}\mathrm{C} + {}^{0}_{+1}\beta + {}^{0}_{0}\nu$.

Electrons, positrons and neutrinos are fundamental particles called **leptons**.

Practice 2.1 ▪ 2 marks

State what a **quark** is, and name **two** flavours.

Solution 2.1

Method: Quarks

Worked steps

A **fundamental particle** (with no smaller parts); any two flavours of: up, down, charm, strange, top, bottom B1 B1.

Practice 2.2 ▪ 2 marks

State the charge of an **up** quark and a **down** quark.

Solution 2.2

Method: Quarks

Worked steps

up $= +\frac{2}{3}e$; down $= -\frac{1}{3}e$ **B1** **B1**.

Practice 2.3 ▪ 2 marks

State the **quark composition** of a proton and of a neutron.

Solution 2.3

Method: Hadrons

Worked steps

proton $= \mathbf{u\ u\ d}$; neutron $= \mathbf{u\ d\ d}$ B1 B1.

Practice 2.4 ▪ 2 marks

State the charge of a **positron** and the class of fundamental particle it belongs to.

Solution 2.4

Worked steps

charge $= +e$ **B1**; it is a **lepton** **B1**.

Exam-style 3.1 ▪ 1 mark

A **baryon** consists of:

A two quarks

B three quarks

C one quark and one antiquark

D one quark

Solution 3.1

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

Worked steps

B — three quarks.

Exam-style 3.2 ▪ 2 marks

Show that the quark composition **u u d** gives a total charge of $+1$.

Solution 3.2

Method: Hadrons

Worked steps

$+\frac{2}{3}+\frac{2}{3}-\frac{1}{3}$ **M1** $=\frac{4}{3}-\frac{1}{3}=+1$ **A1**.

Exam-style 3.3 ▪ 1 mark

An **antiproton** is the antiparticle of a proton.

(a) State the **quark composition** of an antiproton.

(b) Show that its total charge is $-e$.

Solution 3.3

Worked steps

(b) $\bar{\mathrm{u}} = -\frac{2}{3}e$ and $\bar{\mathrm{d}} = +\frac{1}{3}e$ **M1**; total $= -\frac{2}{3} - \frac{2}{3} + \frac{1}{3} = -1$, i.e. $-e$ **A1**.

Exam-style 3.4 ▪ 3 marks

Describe the change in **quark composition** during β^- decay, and name the lepton emitted.

Solution 3.4

Method: Hadrons

Worked steps

A **down** quark changes into an **up** quark **B1**, so u d d (neutron) becomes u u d (proton) **B1**; an **electron** (the β^- particle), together with an antineutrino, is emitted **B1**.

Exam-style 3.5 ▪ 1 mark

A meson Q and a nucleus of radium-228 are 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**.

(b) Q is a meson with a charge of zero. **Determine** one possible quark composition for Q, and explain why your answer gives zero charge.

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

(d) **State** the number of electrons in a neutral atom of radium-228, ${}^{228}_{88}\text{Ra}$.

(e) A radium-228 nucleus decays in a series of steps to a nucleus X, emitting **5** α-particles and **4** β^- particles in total. **Determine** the number of protons and the number of neutrons in X.

Solution 3.5

Method: Hadrons

Worked steps

(a) A particle that **cannot be subdivided** into anything smaller B1.
(b) A meson is a **quark and an antiquark** B1; any pair such as u$\bar{u}$ $(+\frac{2}{3}e - \frac{2}{3}e = 0)$ or d$\bar{d}$ $(-\frac{1}{3}e + \frac{1}{3}e = 0)$ gives zero charge, because the antiquark carries exactly the opposite charge to the quark B1.
(c) $E_K = \frac{1}{2}mv^2$ with $m = 0.67 \times 1.66 \times 10^{-27} = 1.11 \times 10^{-27}$ kg M1; $2.1 \times 10^{-16} = \frac{1}{2}(1.11 \times 10^{-27})v^2$ M1; $v = 6.1 \times 10^5$ m s^{-1} A1.
(d) 88 — a neutral atom has as many electrons as protons A1.
(e) Each α removes 2 protons and 2 neutrons; each β^- turns a neutron into a proton,

Solution 3.5

so it adds a proton and removes a neutron **M1**. Protons: $88 - (5 \times 2) + 4 = 82$ **A1**.
Nucleons: $228 - (5 \times 4) = 208$, so neutrons $= 208 - 82 = 126$ **A1**.