11.2.1 Beta decay at the quark level, and leptons

Name: _____ Class: _____ Date: _____ **Total: 26 marks**

KEY WORDS lepton • beta decay β • fundamental particle • neutrino • positron

Objective

Answer exam questions on **β-decay at the quark level** and on **leptons** : which quark changes flavour in β^- and β^+ decay, what is emitted with it, and which particles are fundamental. Syllabus 11.2, learning outcomes 5 and 6.

You must be able to:

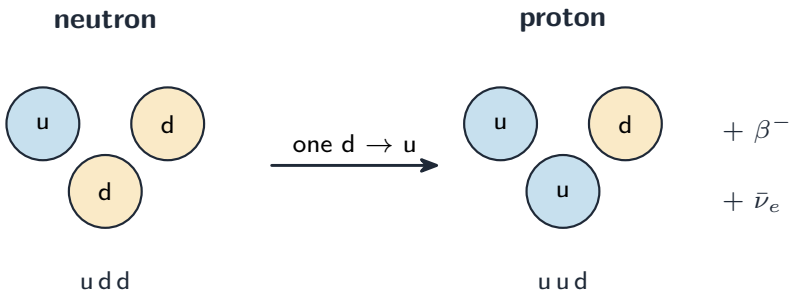
- describe the change of quark in β^- and β^+ decay, and what it does to the nucleon
- write the quark equation of each decay, including the two leptons, and check its charge
- recall that electrons and neutrinos are fundamental particles called leptons
- classify a particle as a lepton, a baryon or a meson

1 Key knowledge and worked examples

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

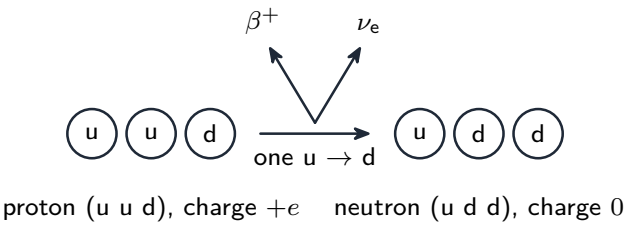
- **Scattering evidence**: most alpha particles pass through, showing that the atom is mostly empty space; a small fraction deflect through large angles, showing concentrated positive charge and mass in a small nucleus.
- **Nuclear bookkeeping**: in ${}^{A}_{Z}X$, protons $= Z$ and neutrons $= A - Z$. 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: one quark changes flavour

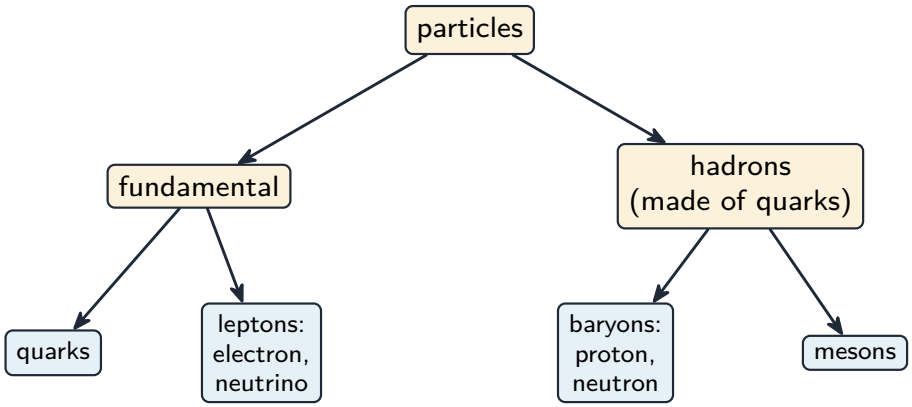


decay	quark change	nucleon change	leptons emitted
β^-	d → u	neutron → proton	electron, antineutrino
β^+	u → d	proton → neutron	positron, neutrino

- β^- decay: $\mathrm{d} \rightarrow \mathrm{u} + \mathrm{e}^- + \bar{\nu}_\mathrm{e}$
- β^+ decay: $\mathrm{u} \rightarrow \mathrm{d} + \mathrm{e}^+ + \nu_\mathrm{e}$
- The other two quarks are spectators, so the nucleon is still there: the **nucleon number does not change**.
- The proton number rises by one in β^- decay and falls by one in β^+ decay.



■ Key knowledge: leptons, and what is fundamental



- **Leptons** are fundamental particles: the **electron** and the **(electron) neutrino**, and their antiparticles, the **positron** and the **antineutrino**.
- A β^--particle **is** an electron and a β^+-particle **is** a positron, so both are leptons.
- Two questions classify any particle. *Is it made of quarks?* If not, it is fundamental: a quark or a lepton. If it is, it is a **hadron**, and not fundamental. *How many quarks?* Three make a **baryon**; a quark and an antiquark make a **meson**.

■ Worked example: checking the charge of a quark change

Charge is conserved when a quark changes flavour: the charge before equals the total charge after.

1. β^- **decay**, $\mathrm{d} \to \mathrm{u} + \mathrm{e}^- + \bar{\nu}_\mathrm{e}$:

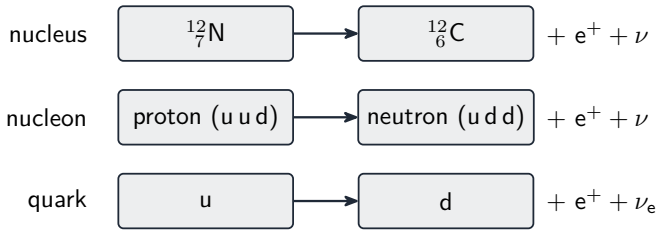
$$q_\mathrm{d} = q_\mathrm{u} + q_{\mathrm{e}^-} + q_{\bar{\nu}} \;\Rightarrow\; -\tfrac{1}{3}e = +\tfrac{2}{3}e - e + 0$$

2. β^+ **decay**, $\mathrm{u} \to \mathrm{d} + \mathrm{e}^+ + \nu_\mathrm{e}$:

$$q_\mathrm{u} = q_\mathrm{d} + q_{\mathrm{e}^+} + q_\nu \;\Rightarrow\; +\tfrac{2}{3}e = -\tfrac{1}{3}e + e + 0$$

■ Worked example: from the nucleus down to the quark

Nitrogen-12 decays by β^+ emission to carbon-12:



$$^{12}_{7}\mathrm{N} \to \; ^{12}_{6}\mathrm{C} + \; ^{0}_{+1}\beta + \; ^{0}_{0}\nu$$

1. **The nucleus** – the proton number falls from 7 to 6 while the nucleon number stays 12, so one proton has become a neutron.

2. **The nucleon** – a proton, u u d, has become a neutron, u d d.
3. **The quark** – one up quark has become a down quark, emitting a positron and a neutrino: $\mathrm{u} \to \mathrm{d} + \mathrm{e}^{+} + \nu_{\mathrm{e}}$.

■ **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 the charge of a **positron**, and the class of fundamental particle it belongs to. [2]

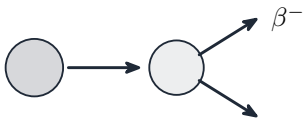
positron

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

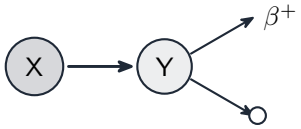
electron neutron

quark meson

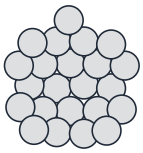
2.3 Describe the change in quark composition during β^{-} decay, and name the **two** leptons emitted. [3]



2.4 Name the **two** fundamental particles emitted in β^{+} decay, and explain why neither of them is a hadron. [2]



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

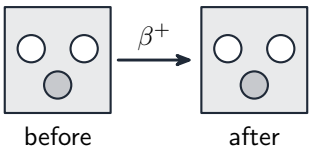


$^{23}_{11}$Na nucleus

3 Exam-style questions

3.1 Which quark change takes place in β^+ decay? [1]

- **A** up → down
- **B** down → up
- **C** up → strange
- **D** down → strange



3.2 Which particle is a lepton? [1]

- **A** proton
- **B** neutron
- **C** π^+ meson
- **D** electron antineutrino

lepton

3.3 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]

proton

positron

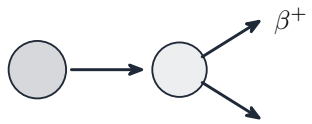
π^+ meson

electron antineutrino

3.4 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 with the electron in β^- decay, and state how it is related to the one emitted in β^+ decay. [2]

Solutions

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

2.1

- $+e$, the opposite of the electron's charge
- it is a **lepton**

2.2

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

2.3

- a **down** quark changes into an **up** quark
- so a neutron, u d d, becomes a proton, u u d
- an **electron** and an electron **antineutrino** are emitted

2.4

- a **positron** and an electron **neutrino**
- a hadron is made of quarks; these are leptons, which are fundamental and contain no quarks

2.5

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

3.1 A

- in β^+ decay an up quark becomes a down quark, so a proton becomes a neutron
- **B** is β^- decay

3.2 D

- the leptons are the electron, the neutrino and their antiparticles
- **A** and **B** are baryons and **C** is a meson, all made of quarks

3.3

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

3.4

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

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

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

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

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

(d) an electron **antineutrino**

- it is the **antiparticle** of the electron neutrino emitted in β^{+} decay