

Exercise walk-through

11.2.1

Beta decay at the quark level, and leptons

A-Level Physics

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

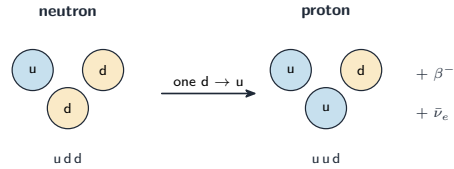
- classify a particle as a lepton, a baryon or a meson

1 Key knowledge and worked examples

■ Key knowledge: use these earlier methods

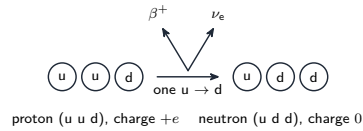
- **Scattering evidence:** most alpha particles pass through, showing that the atom is mostly empty space; a small fraction deflect through large angles, showing concentrated positive charge and mass in a small nucleus.
- **Nuclear bookkeeping:** in ${}^A_ZX$, protons = Z and neutrons = $A - Z$. Alpha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

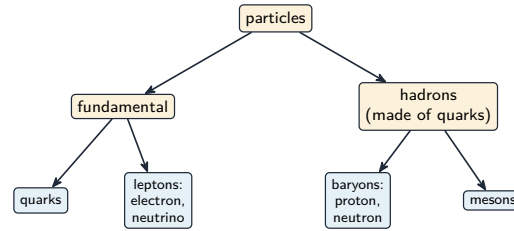


decay	quark change	nucleon change	leptons emitted
β ⁻	d → u	neutron → proton	electron, antineutrino
β ⁺	u → d	proton → neutron	positron, neutrino

- β⁻ decay: d → u + e⁻ + ν_e⁻
- β⁺ decay: u → d + e⁺ + ν_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**, $d \rightarrow u + e^- + \bar{\nu}_e$:

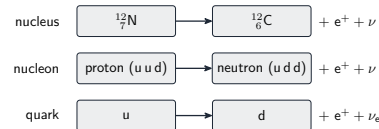
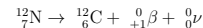
$$q_d = q_u + q_{e^-} + q_{\bar{\nu}} \Rightarrow -\frac{1}{3}e = +\frac{2}{3}e - e + 0$$

2. β^+ **decay**, $u \rightarrow d + e^+ + \nu_e$:

$$q_u = q_d + q_{e^+} + q_{\nu} \Rightarrow +\frac{2}{3}e = -\frac{1}{3}e + e + 0$$

■ Worked example: from the nucleus down to the quark

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



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: $u \rightarrow d + e^+ + \nu_e$.

■ **Key knowledge: count quarks in a whole nucleus**

A nucleus ${}_Z^AX$ 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.

Exercises 2.1·2.2

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

Exercises 2.1·2.2

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

positron

2.1

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

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

electron

neutron

quark

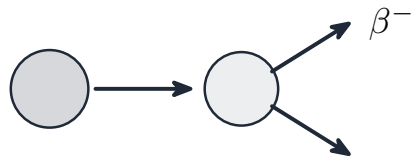
meson

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

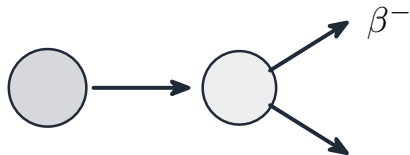
Exercise 2.3

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



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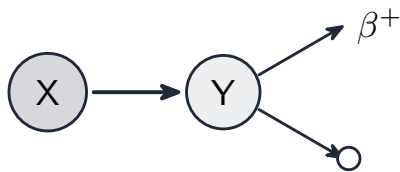


2.3

- 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

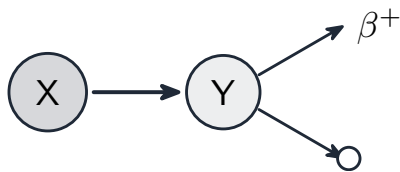
Exercise 2.4

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



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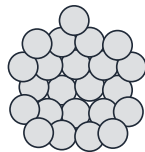


2.4

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

Exercise 2.5

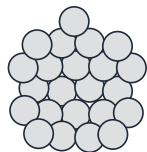
2.5 Find the numbers of up and down quarks in ${}_{11}^{23}\text{Na}$. Check the total number and nuclear charge. [4]



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

Exercise 2.5

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

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 $Z = 11$.

Exercise 3.1

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

[1]

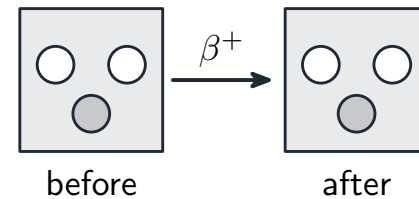
☐

A up $\rightarrow$ down

B down $\rightarrow$ up

C up $\rightarrow$ strange

D down $\rightarrow$ strange



Exercise 3.1

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

[1]

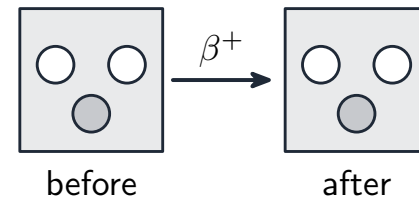
☐

A up $\rightarrow$ down

B down $\rightarrow$ up

C up $\rightarrow$ strange

D down $\rightarrow$ strange



3.1 A

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

Exercise 3.2

3.2 Which particle is a lepton?

[1]

☐

A proton

B neutron

C π^+ meson

D electron antineutrino

lepton

Exercise 3.2

3.2 Which particle is a lepton?

[1]

☐

A proton

B neutron

C π^+ meson

D electron antineutrino

lepton

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

Exercise 3.3

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

Exercise 3.3

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

3.3

- **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

Exercise 3.4 (a)

3.4 A nucleus decays by β^+ emission.

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

[1]

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

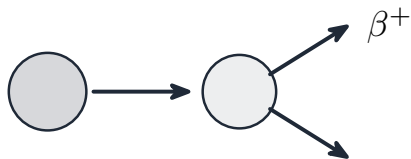
[1]

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

Exercise 3.4 (b)

3.4 A nucleus decays by β^+ emission.

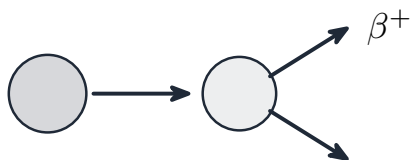
(b) Write an equation for this change, including the lepton that is emitted with the β^+ -particle. [2]



Exercise 3.4 (b)

3.4 A nucleus decays by β^+ emission.

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



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

$$u \rightarrow d + e^+ + \nu_e$$

Exercise 3.4 (c)

3.4 A nucleus decays by β^+ emission.

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

[2]

Exercise 3.4 (c)

3.4 A nucleus decays by β^+ emission.

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

(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

Exercise 3.4 (d)

3.4 A nucleus decays by β^+ emission.

(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]

Exercise 3.4 (d)

3.4 A nucleus decays by β^+ emission.

(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]

(d) an electron **antineutrino**

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