Edexcel International A Level (IAL) Physics

Your notes

Particle Interactions & Conservation

Contents

Your notes

Baryons & Mesons

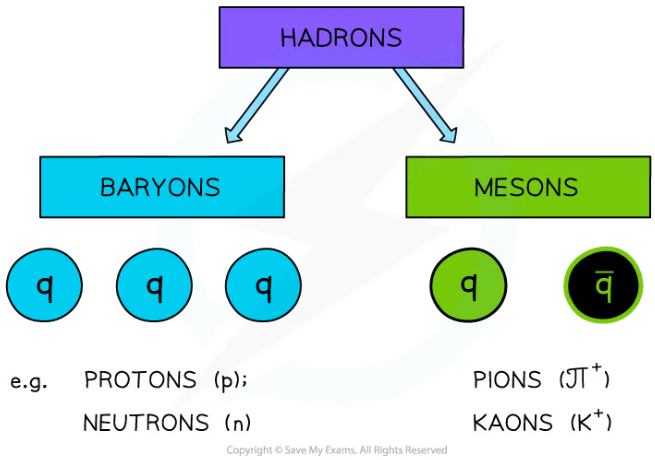
- All particles of **matter** are made up of either **quarks** and/or **leptons**
    - The **standard model** of particle physics categorises quarks and leptons by charge and mass

Generation	Quarks		Leptons	
I	u up $\left(+\frac{2}{3}e\right)$	d down $\left(-\frac{1}{3}e\right)$	e^- electron $(-1e)$	V_e electron neutrino (0)
II	c charm $\left(+\frac{2}{3}e\right)$	s strange $\left(-\frac{1}{3}e\right)$	μ^- muon $(-1e)$	V_μ muon neutrino (0)
III	t top $\left(+\frac{2}{3}e\right)$	b bottom $\left(-\frac{1}{3}e\right)$	τ^- tau $(-1e)$	V_τ tau neutrino (0)

Increasing mass

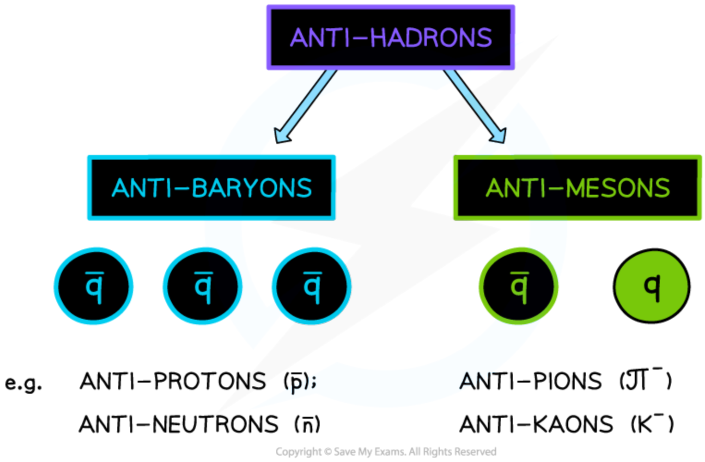
Quarks and leptons form the standard model of particle physics. The first generation of particles make up all ordinary matter

- **Hadrons** are made up of **quarks** and interact with the **strong nuclear force**
- **Baryons** and **mesons** are types of hadron
    - **Baryons** consist of **3 quarks**
    - **Mesons** consist of a **quark-antiquark pair**
- The most common baryons are protons and neutrons
- The most common mesons are pions and kaons



Your notes

Hadrons may be either a baryon or a meson. Both baryons and mesons interact with the strong nuclear force



Anti-hadrons may be either an anti-baryon or an anti-meson

- Quarks have never been discovered on their own, always in pairs or groups of three
- Note that all baryons or mesons have integer (whole number) charges eg. +1e, -2e etc.
- This means quarks in a baryon are either all quarks or all anti-quarks. Combination of quarks and anti-quarks don't exist in a baryon
  - e.g.

$\bar{u}ud$ WOULD NOT BE A QUARK COMBINATION THAT EXISTS

- The anti-particle of a meson is still a quark and anti-quark pair. The difference being the quark becomes the anti-quark and vice versa

Worked Example

The baryon Δ^{++} was discovered in a particle accelerator using accelerated positive pions on hydrogen targets.

Which of the following is the quark combination of this particle?

A. uuu **B.** $cd\bar{s}$ **C.** $\bar{u}d$ **D.** $\bar{c}\bar{c}\bar{c}$

ANSWER: A

STEP 1 — SINCE IT'S A BARYON, IT'S MADE UP OF THREE QUARKS
THIS RULES OUT OPTION C (A MESON)

STEP 2 — BARYONS ARE MADE UP OF 3 QUARKS OR ANTI-BARYONS MADE UP OF 3 ANTI-QUARKS
THIS RULES OUT OPTION B (YOU CANNOT HAVE A COMBINATION OF QUARKS AND ANTIQUARKS)

STEP 3 — THE Δ^{++} BARYON HAS A CHARGE OF +2 (FROM THE ++)

STEP 4 — ADDING UP THE CHARGES OF THE QUARKS IN A AND D
A. $uuu = +2/3 + 2/3 + 2/3 = +2$
D. $\bar{c}\bar{c}\bar{c} = -2/3 - 2/3 - 2/3 = -2$

STEP 5 — ITS QUARK COMBINATION MUST THEREFORE BE uuu (OPTION A)

Your notes

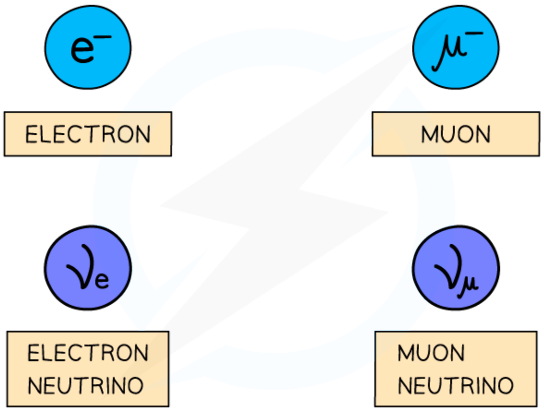
Examiner Tips and Tricks

- Remembering quark combinations is useful for the exam
- However, as long as you can remember the charges for each quark, it is easy to figure out the combination by making sure the combination of quarks adds up to the total charge of the particle (just like in the worked example!)

Leptons & Photons

Leptons

- **Leptons** are a group of **fundamental** (elementary) particles
  - This means they are not made up of any other particles (no quarks)
- Leptons interact with other particles via the **weak**, **electromagnetic** or **gravitational** interactions
  - Unlike hadrons (baryons & mesons), leptons **do not** interact via the strong nuclear force
- The most common leptons are:
  - The electron, e^-
  - The electron neutrino, ν_e
  - The muon, μ^-
  - The muon neutrino, ν_μ



The most common leptons are the electron and muon, along with their associated neutrinos

- The muon is similar to the electron but is 200 times more **massive**
- Electrons and muons **both** have a charge of -1e
- Electrons have a mass of 0.0005 u
- Muons have a mass of 0.11 u
- Neutrinos are the most abundant leptons in the universe and have **no charge** and **negligible** mass (almost 0)
- Although quarks are fundamental particles too, they are not classed as leptons

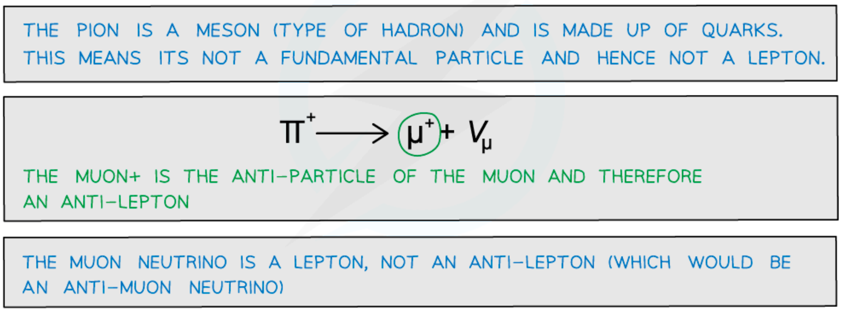
Worked Example

Circle all the anti-leptons in the following decay equation.

$$\pi^{+} \longrightarrow \mu^{+} + \nu_{\mu}$$

Answer:

Your notes



Photons

- Photons are a group of particles which mediate the **electromagnetic interaction**
  - They are **uncharged**
  - They have zero **mass**
- They are sometimes called "exchange bosons" because they mediate one of the fundamental forces (electromagnetism)
  - For example, the electrostatic repulsion between two electrons is understood in terms of **exchanging photons**

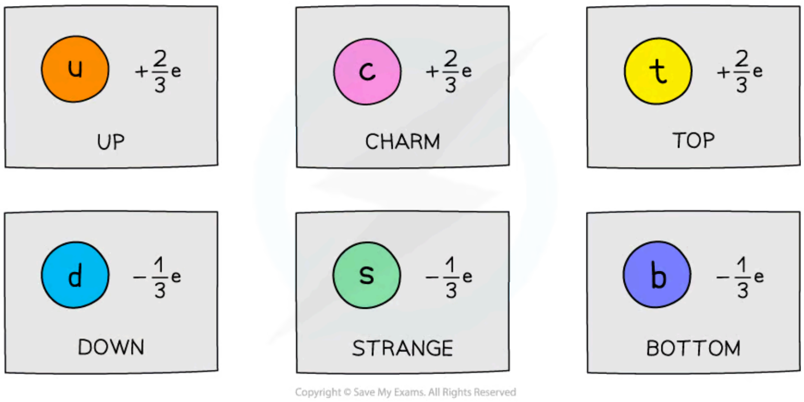
Examiner Tips and Tricks

In some topics, you may need to use the **energy** of a photon. This is given by the equation $E = hf = \frac{hc}{\lambda}$.

Symmetry of the Standard Model

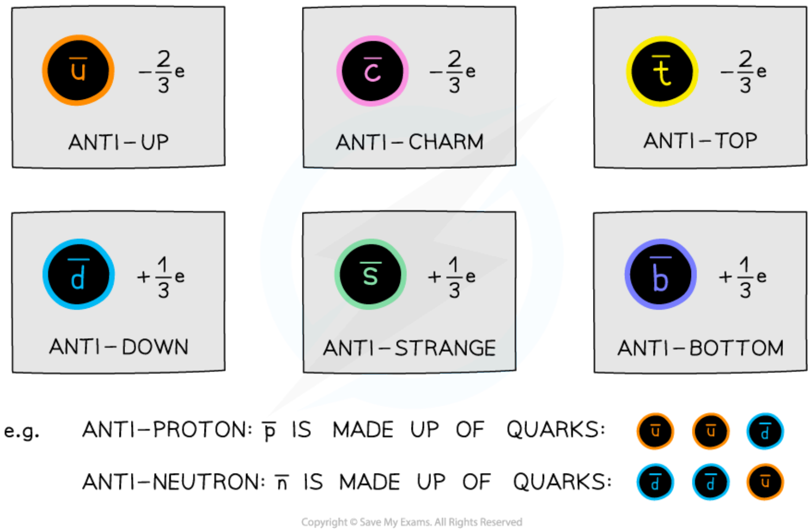
- The first four quarks discovered were:
  - The up quark
  - The down quark
  - The strange quark
  - The charm quark
- The **symmetry** of the standard model predicted a **third generation** of particles, namely the **top** and **bottom** quark
  - Experiments were carried out to discover these, and eventually they were found as predicted
- Therefore, the three generations of quarks are and their respectively charges are:

Your notes



The three generations of quarks. e is the charge of an electron.

- They each have their own anti-quark, which has the opposite charge



Three generations of anti-quarks. These have the same properties as the quarks except opposite charges.

Examiner Tips and Tricks

You will **not** be expected to describe the strong nuclear force in your exam, but you **should** understand that photon is the exchange particle for the electromagnetic force and that it has zero charge and mass.

Your notes

Your notes

Properties of Antimatter

- The universe is made up of **matter** particles (protons, neutrons, electrons etc.)
- All matter particles have antimatter counterparts
  - Antimatter particles are **identical** to their matter counterpart but with the **opposite** charge
- This means if a particle is positive, its antimatter particle is negative and vice versa
- Common matter-antimatter pairs are shown in the diagram below:

Matter	Charge	Antimatter	Charge
Electron e^-	−1	Positron e^+	+1
Proton p	+1	Anti-proton $\bar{p}$	−1
Neutron n	0	Anti-neutron $\bar{n}$	0
Neutrino ν	0	Anti-neutrino $\bar{\nu}$	0

This table summarises the electric charge for typical particle-antiparticle pairs

- Apart from electrons, the corresponding antiparticle pair has the same name with the prefix **'anti-'** and a line above the corresponding matter particle symbol
- A neutral particle, such as a neutron or neutrino or photon, **is its own antiparticle**

Mass of Matter & Antimatter

- Although antimatter particles have the opposite charges to their matter counterparts, they still have **identical mass and rest mass-energy**
  - The rest mass-energy of a particle is the energy equivalent to the mass of the particle at rest

Your notes

Particle/ Antiparticle	Mass (kg)	Rest Mass Energy (MeV)
Proton/ antiproton	$1.67(3) \times 10^{-27}$	938.257
Neutron/ antineutron	$1.67(5) \times 10^{-27}$	939.551
Electron/ positron	9.11×10^{-31}	0.510999
Neutrino/ antineutrino	0	0

This table summarises typical particle-antiparticle pair masses and rest mass energies

Examiner Tips and Tricks

Though you will not need to memorise individual masses or rest-mass energies, you are expected to remember the mass of a particle-antiparticle pair is **identical** but they have the **opposite** electric charge.

Applying Conservation Laws

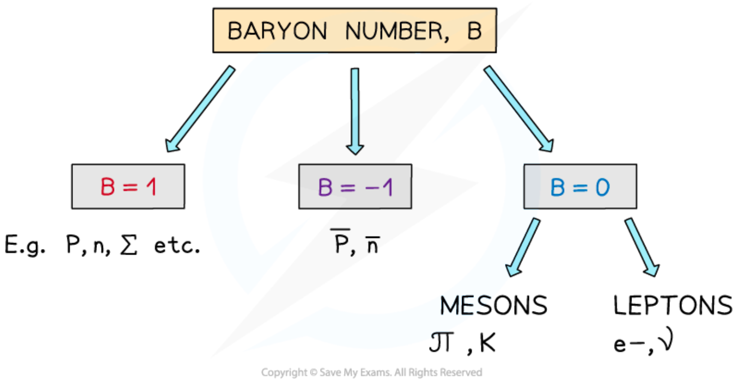
- When particles interact, they must obey a set of laws associated to the type of particles involved
  - These laws are governed by numbers called **quantum numbers**
- Quantum numbers that are **always conserved** (i.e., they are the same before and after an interaction) are:
  - Charge, Q
  - Baryon number, *B*
  - Lepton number, *L*
- Using these quantum numbers, physicists are able to determine whether certain interactions are **possible** or not
  - In other words, an interaction that does **not** conserve charge, baryon or lepton number is **not allowed** by the laws of physics

Conservation of Charge

- The charge of a particle **Q**, is the charge carried by that particle
  - Protons have a charge **Q = +1**
  - Electrons have a charge **Q = –1**
  - Up quarks have a charge **Q = +2/3**
  - Neutral particles, like photons and neutrinos, have a charge **Q = 0**

Conservation of Baryon Number

- The baryon number, ***B***, is the number of baryons in an interaction
- ***B*** depends on whether the particle is a baryon, anti-baryon or neither
  - Baryons have a baryon number ***B*** **= +1**
  - Anti-baryons have a baryon number ***B*** **= –1**
  - Particles that are not baryons have a baryon number ***B*** **= 0**



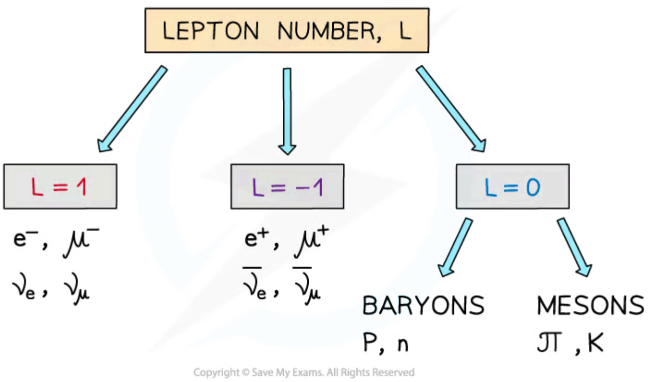
The baryon number of a particle depends if it is a baryon, anti-baryon or neither

- The up (u), down (d) and strange (s) quark have a baryon number of 1/3 each
- This means that the anti-up, anti-down and anti-strange quarks have a baryon number of -1/3 each
- **Note:** The baryon number of each quark is provided on the datasheet

- The implication of this is that baryons are made up of all quarks and anti-baryons are made up of all anti-quarks
- There are no baryons (yet) that have a combination of quarks and anti-quarks e.g. up, anti-down, down
- The reason being that this would equate to a baryon number that is not a whole number (integer)

Conservation of Lepton Number

- Similar to baryon number, the lepton number, ***L*** is the number of leptons in an interaction
- ***L*** depends on whether the particle is a lepton, anti-lepton or neither
    - Leptons have a lepton number ***L*** = +1
    - Anti-leptons have a lepton number ***L*** = -1
    - Particles that are not leptons have a lepton number ***L*** = 0
- Lepton number is a quantum number and is conserved in all interactions
- This is helpful for knowing whether an interaction is able to happen



The lepton number depends on if the particle is a lepton, anti-lepton, or neither

Worked Example

Show that baryon number is conserved in β^- decay.

Answer:

Step 1: Write down the equation for beta-minus decay

$$n \rightarrow p + e^- + \bar{\nu}_e$$

Step 2: Determine the baryon number on both sides of the equation

$$1 = 1 + 0 + 0$$

Step 3: Write a conclusion

Since the total baryon number is equal on both sides of the equation, baryon number is conserved in beta minus decay

Worked Example

If the lepton number is conserved in the following decay, identify whether particle X should be a neutrino or anti-neutrino

$$n + \mu^+ \rightarrow p + X$$

Answer:

Step 1: Determine the lepton number of all the particles on both sides of the equation

Your notes

- $0 + (-1) = 0 + X$

Step 2: Identify the lepton number of X

- If the lepton number must be conserved, X must also have a lepton number of –1

Step 3: State the identity of particle X

- Particle X is an anti-neutrino

Examiner Tips and Tricks

Identifying the charge, baryon number or lepton number of an unknown particle can be some of the easiest questions if the correct values for each particle are memorised! The most common mistake is thinking that the electron has a lepton number of –1 because it's charge is negative, it has a lepton number of +1 and it's the **positron** that has a lepton number of -1.

Your notes

Particle Interaction Equations

- All particle interactions must obey a set of conservation laws. These are conservation of:
  - Charge, **Q**
  - Baryon number, ***B***
  - Lepton Number, ***L***
  - Energy (or mass-energy)
  - Momentum
- Quantum numbers such as **Q**, ***B* and *L*** can only take **discrete** values (ie. 0, +1, −1, 1/2)
- To know whether a particle interaction can occur, check whether each quantum number is equal on both sides of the equation
  - If even one of them, apart from strangeness in weak interactions, is not conserved then the interaction cannot occur

Worked Example

A reaction that is proposed to create antiprotons in a laboratory is shown below:

$$^{1}_{1}p + ^{1}_{1}p \rightarrow ^{1}_{1}p + ^{1}_{1}p + ^{0}_{1}\pi^{+} + ^{-1}_{-1}\overline{p}$$

Determine whether this reaction is permitted.

Answer:

Step 1: Determine conservation of charge Q

- There are two protons on the left hand side
- There are two protons on the right hand side, with a positively charged pion (Q = +1) and an antiproton (Q = –1)
- Therefore charge **is conserved**, because:

$$1 + 1 = 1 + 1 + 1 + (-1)$$

Step 2: Determine conservation of baryon number, *B*

- There are two baryons on the left hand side, each with a baryon number B = +1 (protons are baryons)
- On the right hand side
  - Two protons each with baryon number +1
  - One pion, with a baryon number 0 (it is a **meson**)
  - One anti-proton with a baryon number –1
- Therefore baryon number **is not conserved**, because:

$$1 + 1 = 1 + 1 + 0 + (-1)$$

Step 3: Conclude whether this reaction is permitted

- This reaction is **not permitted**
- Because baryon number is not conserved

Worked Example

The equation for β^- decay is

$$n \rightarrow p + e^- + \bar{\nu}_e$$

Using the quark model of beta decay, prove that the charge is conserved in this equation.

Answer:

STEP 1	β^- DECAY IS WHEN A DOWN QUARK CHANGES TO AN UP QUARK THIS CHANGES A NEUTRON INTO A PROTON
STEP 2	CHARGE OF THE LEFT HAND SIDE OF THE EQUATION THE QUARK COMPOSITION OF A NEUTRON IS **udd**
STEP 3	ADDING UP THE QUARK CHARGES: $+2/3 - 1/3 - 1/3 = 0$ THE LEFT HAND SIDE HAS A CHARGE OF 0
STEP 4	CHARGE ON THE RIGHT HAND SIDE OF THE EQUATION THE QUARK COMPOSITION OF A PROTON IS **uud**
STEP 5	ADD UP THE QUARK CHARGES: $+2/3 + 2/3 - 1/3 = +1$
STEP 6	THE ELECTRONS CHARGE IS -1 THE ANTI-NEUTRINOS CHARGE IS 0 THE RIGHT HAND SIDE HAS A CHARGE OF $+1 - 1 + 0 = 0$
STEP 7	SINCE THE CHARGES ARE EQUAL ON BOTH SIDES, IT IS CONSERVED IN THE BETA DECAY EQUATION

Examiner Tips and Tricks

Note:

- Quantum numbers for any exotic particles will be given in the question

Your notes

- Additional information can always be deduced using the information provided

Your notes