

Playing Particle-opoly!

Contents

1	Playing the Game	3
2	AQA-A Particles, Quantum Phenomena and Electricity Past Papers	3
2.1	AQA-A Particles, Quantum Phenomena and Electricity, Jan 2009 Q3	3
2.2	AQA-A Particles, Quantum Phenomena and Electricity, Jun 2009 Q3	5
2.3	AQA-A Particles, Quantum Phenomena and Electricity, Jan 2010 Q1	6
2.4	AQA-A Particles, Quantum Phenomena and Electricity, Jun 2010 Q1	7
2.5	AQA-A Particles, Quantum Phenomena and Electricity, Jan 2011 Q1	8
2.6	AQA-A Particles, Quantum Phenomena and Electricity, Jun 2011 Q1	9
2.7	AQA-A Particles, Quantum Phenomena and Electricity, Jan 2012 Q1	11
2.8	AQA-A Particles, Quantum Phenomena and Electricity, Jun 2012 Q1	12
2.9	AQA-A Particles, Quantum Phenomena and Electricity, Jan 2013 Q3	13
2.10	AQA-A Particles, Quantum Phenomena and Electricity, Jun 2013 Q2	14
2.11	AQA-A Particles, Quantum Phenomena and Electricity, Jun 2014 Q1	15
2.12	AQA-A Particles, Quantum Phenomena and Electricity, Jun 2015 Q2	17
2.13	AQA-A Particles, Quantum Phenomena and Electricity, Jun 2015 Q3	18
2.14	AQA-A Particles, Quantum Phenomena and Electricity, Jun 2016 Q2	19
3	Edexcel-A Physics On The Move Past Papers	20
3.1	Edexcel-A Physics On The Move, Jun 2010 Q18	20
3.2	Edexcel-A Physics On The Move, Jan 2011 Q11	22
3.3	Edexcel-A Physics On The Move, Jun 2013 R, Q14	23
3.4	Edexcel-A Physics On The Move, Jun 2014 Q18	24
3.5	Edexcel-A Physics On The Move, Jun 2015 Q12	26
4	OCR-A Fields, Particles and Frontiers of Physics Past Papers	27
4.1	OCR-A Fields, Particles and Frontiers of Physics, Jun 2010 Q7	27
4.2	OCR-A Fields, Particles and Frontiers of Physics, Jan 2011 Q9	28
5	OCR-A Nuclear and Particle Physics Option Past Papers	29
5.1	OCR-A Nuclear and Particle Physics, Jan 2010 Q6	29
5.2	OCR-A Nuclear and Particle Physics, June 2007 Q6	30
5.3	OCR-A Nuclear and Particle Physics, June 2009 Q5	31

Prerequisites

None.

Notes

None.

Document History

Date	Version	Comments
5 May 2017	1.0	Initial creation of the document.

1 Playing the Game

This document contains a number of past paper questions on particle physics from various exam boards and syllabi. Have a go!

Notice how similar a lot of these questions are...

The questions are written in black, my answers in red.

2 AQA-A Particles, Quantum Phenomena and Electricity Past Papers

2.1 AQA-A Particles, Quantum Phenomena and Electricity, Jan 2009 Q3

Figure 1 shows the Feynman diagram for a particular interaction.

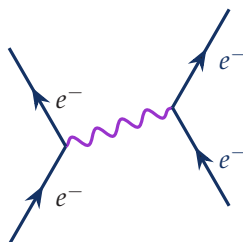


Figure 1: Feynman Diagram 1 : AQA-A Particles, Quantum Phenomena and Electricity, Jan 2009 Q3

(a) (i) State the type of interaction involved and name the exchange particle.

[2]

This is the electromagnetic interaction, causing two (similarly charged) electrons to repel. The exchange particle is the photon.

(ii) State **two** quantities other than energy and momentum, that are conserved in this interaction.

[2]

For this question you just need two of the quantum numbers that are conserved. So, for example, we could use lepton number and baryon number.

(b) Figure 2 shows the Feynman diagram for another type of interaction.

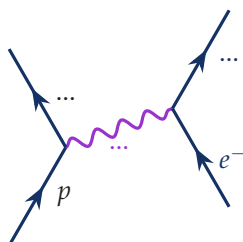


Figure 2: Feynman Diagram 2 : AQA-A Particles, Quantum Phenomena and Electricity, Jan 2009 Q3

(b) (i) Complete the diagram to show the two particles formed in the interaction and the exchange particle.

[3]

Figure 3 shows my answer to this part.

(ii) Name the type of interaction responsible for this exchange particle.

[1]

This is the weak interaction. That's because charge has to be transferred to the electron in the interaction.

You may have thought that there is another interaction that it would be possible to draw with the starting conditions in Figure 2. And you are right: *proton-electron attraction*. But this type of interaction is not covered in any of the A-Level syllabi, as the Feynman diagram is too difficult to draw!

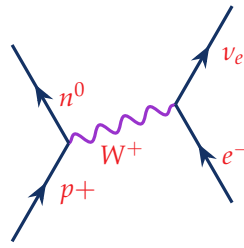


Figure 3: Feynman Diagram 3 : AQA-A Particles, Quantum Phenomena and Electricity, Jan 2009 Q3

(iii) Energy and momentum are conserved in this interaction. State **two** other quantities that must be conserved and show that they are conserved in this interaction.

[4]

Again, this is where you show the conservation of two quantum numbers. Here's I've listed a few.

	p^+	+	e^-	→	n^0	+	ν_e
Charge (Q):	+1	+	-1	→	0	+	0
Baryon Number (B):	$\frac{1}{3}$	+	0	→	$\frac{1}{3}$	+	0
Lepton Number (L):	0	+	+1	→	0	+	+1
Strangeness (S):	0	+	0	→	0	+	0

Table 1: Quantum Numbers : AQA-A Particles, Quantum Phenomena and Electricity, Jan 2009 Q3

(iv) The exchange particle in this interaction was discovered by experiment with a rest mass that had been predicted. Why is it important to test by experiment the prediction of a scientific theory?

[2]

I hate these kinds of questions!

Science works by going through the following process:

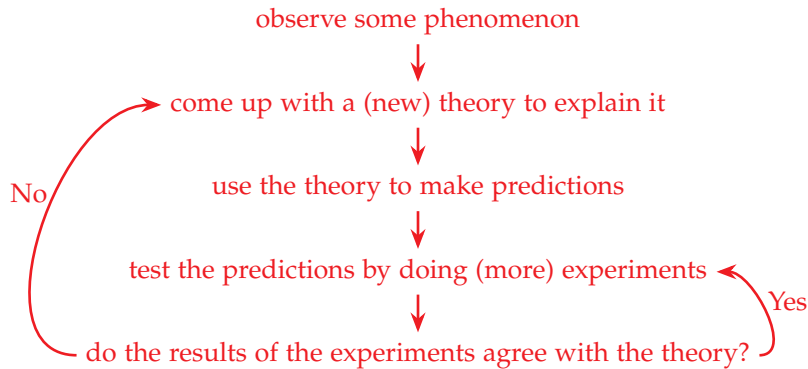


Figure 4: How Science Works

So theory and experiment go hand-in-hand. It is vital to test theories by doing experiments: if an experiment shows that a theory can't be right, you have to discard the theory and come up with a new one; if the experiment does agree with the theory, you should still keep trying to test the predictions of the theory until you have tested every possible prediction (it will probably take forever to test *all* the predictions!).

2.2 AQA-A Particles, Quantum Phenomena and Electricity, Jun 2009 Q3

(a) The Σ^+ particle is a baryon with strangeness of -1 .

(i) How many quarks does the Σ^+ particle contain?

[1]

As the particle is a baryon, it must have three quarks in it.

(ii) How many of the quarks are strange?

[1]

One. The s quark has a strangeness of -1 and the \bar{s} quark has a strangeness of $+1$. So the only ways of getting a strangeness of -1 with three quarks would be to either have one s quark and two others (non- s type), or the three quarks $ss\bar{s}$. But $ss\bar{s}$ quarks would have a net charge of $-\frac{1}{3}$, so that wouldn't be possible.

Baryons have to be made of either three normal quarks or three anti-quarks to get an overall charge that's a whole number.

(b) The Σ^+ decays in the following reaction:



(i) State **two** quantities that are conserved in this reaction.

[2]

As well as mass/energy and momentum, you could have any of the quantum numbers of charge, lepton number or baryon number. You have to be careful about strangeness, so I'm not going to commit myself to that just yet!

(ii) State a quantity that is not conserved in this reaction.

[1]

Aha! They probably want strangeness here!! Yes: π mesons aren't strange, and neither is a neutron (that means they don't have an s or \bar{s} quark in them). Which means that the s quark in the Σ^+ particle must have been changed into a u or a d quark in the interaction.

(iii) What interaction is responsible for this reaction?

[1]

If strangeness isn't conserved, then this must be the weak interaction, as that's the only interaction involving quarks that can change the flavour of quarks. That is: from s to d , for example.

(iv) Into what particle will the neutron formed in this reaction eventually decay?

[1]

A proton. The proton is the only stable baryon: all other baryons have rest energies higher than the proton, so will eventually decay into one.

2.3 AQA-A Particles, Quantum Phenomena and Electricity, Jan 2010 Q1

(a) *Hadrons* are a group of particles composed of quarks. Hadrons can either be baryons or mesons.

(i) What property defines a hadron?

[1]

Hadrons are made of quarks. In the mark scheme for this question it refers to hadrons being affected by the strong nuclear force.

(ii) What is the quark structure of a baryon?

[1]

A baryon has three quarks. [They can either be all normal matter quarks, or all anti-matter quarks.]

(iii) What is the quark structure of a meson?

[1]

A meson is made of two quarks. [One will be a normal matter quark; the other an anti-quark.]

(b) State **one** similarity and **one** difference between a particle and its antiparticle.

[2]

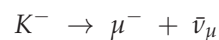
Mass/energy could be a similarity; charge, lepton number, baryon number or strangeness could be a difference.

(c) State the charge, baryon number and quark structure of the antiproton.

[2]

A proton has quark structure uud . So an anti-proton would have a quark structure of $\bar{u}\bar{u}\bar{d}$. That would mean it has a charge of -1 , and a baryon number of -1 . In the mark scheme they quoted the actual charge on the anti-proton (-1.6×10^{-19} C) so this question is ambiguous!

(d) The K^- is an example of a meson with strangeness 1. The K^- decays in the following way:



(i) State, with a reason, what interaction is responsible for this decay.

[2]

This will be the weak interaction, as only the weak interaction can change the flavour of quarks, or turn quarks into leptons.

(ii) State **two** properties, other than energy and momentum, that are conserved in this decay.

[2]

Here we go again: charge, baryon number, and lepton number will all be conserved. As it is the weak interaction, strangeness might not be conserved. And indeed it isn't here.

2.4 AQA-A Particles, Quantum Phenomena and Electricity, Jun 2010 Q1

A ${}_{11}^{22}\text{Na}$ nucleus decays, forming a new nucleus, by releasing a β^+ particle and one other particle which is difficult to detect.

(i) Name the particle which is difficult to detect.

[1]

This sounds like a neutrino! They're difficult to detect. Now if a β^+ particle is emitted, then there must also be a ν_e to preserve lepton number in the interaction.

(b) Write down the proton number and the nucleon number of the new nucleus.

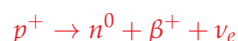
[2]

As the mass of the nucleus stays the same (electrons and positrons have very little mass compared to protons and neutrons), and a positive charge is emitted, then the new nucleus will be ${}_{10}^{22}\text{X}$.

(c) Name the baryon and each of the leptons formed as a result of this decay.

[3]

The equation for β^+ decay is



so the baryon will be the neutron, and the leptons are a positron and an electron neutrino.

(d) Give the quark structure for a neutron and a proton.

[1]

The neutron has the quark structure of udd , and the proton has a quark structure of uud .

(e) Complete the following Feynman diagram so that it represents β^+ decay.

[3]

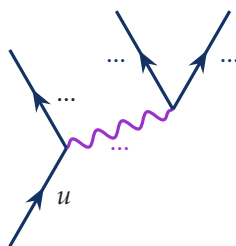


Figure 5: Feynman Diagram 1 : AQA-A Particles, Quantum Phenomena and Electricity, Jun 2010 Q1

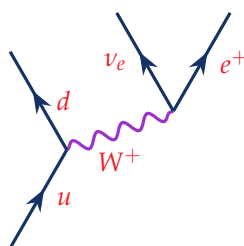


Figure 6: Feynman Diagram 2 : AQA-A Particles, Quantum Phenomena and Electricity, Jun 2010 Q1

2.5 AQA-A Particles, Quantum Phenomena and Electricity, Jan 2011 Q1

Sub-atomic particles can either be hadrons or leptons.

(a) (i) State one difference between these two groups of particles.

[1]

Leptons are fundamental particles, hadrons are not (they're made of quarks). You could also discuss the forces that each type are affected by: leptons are not affected by the strong force; hadrons are.

(ii) Give an example of a non-strange hadron and an example of a lepton.

[2]

A proton is a hadron that's not strange. Electrons are leptons. [There are lots of other possibilities for each of these here!]

(iii) Hadrons can be further divided into two groups. Name these two groups **and** state a difference between them.

[3]

Hadrons can either be mesons or baryons. Mesons are made of two quarks; baryons are made of three quarks.

(b) The Feynman Diagram in Figure 7 represents an interaction known as electron capture. State a conservation law obeyed in this interaction. Show how the property mentioned in the law is conserved.

[2]

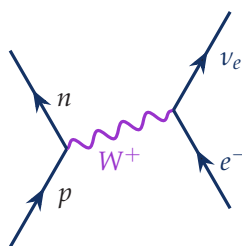


Figure 7: Feynman Diagram : AQA-A Particles, Quantum Phenomena and Electricity, Jan 2011 Q1

All the following are conserved in this interaction: mass/energy, momentum, charge, lepton number, baryon number and strangeness. Here's how the last four are conserved:

	p^+	+	e^-	\rightarrow	n^0	+	ν_e
Charge (Q):	+1	+	-1	\rightarrow	0	+	0
Baryon Number (B):	$\frac{1}{3}$	+	0	\rightarrow	$\frac{1}{3}$	+	0
Lepton Number (L):	0	+	+1	\rightarrow	0	+	+1
Strangeness (S):	0	+	0	\rightarrow	0	+	0

Table 2: Quantum Numbers : AQA-A Particles, Quantum Phenomena and Electricity, Jan 2011 Q1

2.6 AQA-A Particles, Quantum Phenomena and Electricity, Jun 2011 Q1

(a) (i) Name two baryons.

[2]

Mr and Mrs Baryon, who live next-door-but-one to me. No - protons and neutrons are baryons. There are lots of others.

(ii) State the quark structure of the pion π^+ .

[2]

Pions are mesons which are only made of u and d quarks (or their anti-quarks), so a π^+ will be $u\bar{d}$ to get a charge of +1.

(b) (i) The K^+ kaon is a strange particle. Give **one** characteristic of a strange particle that makes it different from a particle that is not strange.

[1]

Strange particles contain either s or \bar{s} quarks.

(ii) One of the following equations represent a possible decay of the K^+ kaon.

$$K^+ \rightarrow \pi^+ + \pi^0$$

$$K^+ \rightarrow \mu^+ + \bar{\nu}_\mu$$

State, with a reason, which one of these decays is not possible.

[1]

	K^+	\rightarrow	π^+	$+$	π^0
Charge (Q):	+1	\rightarrow	+1	$+$	0
Baryon Number (B):	0	\rightarrow	0	$+$	0
Lepton Number (L):	0	\rightarrow	0	$+$	0
Strangeness (S):	+1	\rightarrow	0	$+$	0

Table 3: Quantum Numbers 1 : AQA-A Particles, Quantum Phenomena and Electricity, Jun 2011 Q1

For this interaction, everything looks good. Charge, baryon number and lepton number are all conserved; strangeness isn't, but it doesn't have to be in weak interactions.

	K^+	\rightarrow	μ^+	$+$	$\bar{\nu}_\mu$
Charge (Q):	+1	\rightarrow	+1	$+$	0
Baryon Number (B):	0	\rightarrow	0	$+$	0
Lepton Number (L):	0	\rightarrow	-1	$+$	-1
Strangeness (S):	+1	\rightarrow	0	$+$	0

Table 4: Quantum Numbers 2 : AQA-A Particles, Quantum Phenomena and Electricity, Jun 2011 Q1

For this interaction, things don't look quite so good. Charge and baryon number are conserved; strangeness isn't, but it doesn't have to be in weak interactions. The problem is that the lepton number isn't conserved.

(c) Another strange particle, X , decays in the following way:

$$X \rightarrow \pi^- + p$$

(i) State what interaction is involved in this decay.

[1]

This has to be the weak interaction. That's because X has to contain either an s or an \bar{s} quark (because it's strange). However, pions and protons don't contain strange quarks, so the flavour of the strange quark in X has been changed. Only the weak interaction can do that.

(ii) Show that X must be a neutral particle.

[1]

Well, charge has to be conserved in this interaction. The total charge on the right is zero (protons have a charge of $+1$), so the total charge on the left must be zero too.

(iii) Deduce whether X is a meson, baryon or lepton, explaining how you arrive at your answer.

[2]

X can't be a lepton, because you don't get strange leptons (only quarks can be strange). So is it a meson or a baryon? Let's check out the baryon number on both sides. Aha! On the right we have a meson and a baryon: total baryon number $+1$. So the baryon number on the left must be $+1$ as well. X is a baryon.

(iv) Which particle in this interaction is the most stable?

[1]

The proton is the most stable hadron.

2.7 AQA-A Particles, Quantum Phenomena and Electricity, Jan 2012 Q1

(a) The table gives information about some fundamental particles. Complete the table by filling in the missing information.

[7]

particle	quark structure	charge	strangeness	baryon number
	uud		0	
Sigma^+	uus	+1		
	$u\bar{d}$		0	0

Table 5: Particle Properties 1 : AQA-A Particles, Quantum Phenomena and Electricity, Jan 2012 Q1

particle	quark structure	charge	strangeness	baryon number
proton	uud	+1	0	+1
Sigma^+	uus	+1	-1	+1
π^+	$u\bar{d}$	+1	0	0

Table 6: Particle Properties 2 : AQA-A Particles, Quantum Phenomena and Electricity, Jan 2012 Q1

(b) Each of the particles in the table has an antiparticle.

(i) Give **one** example of a baryon particle **and** its corresponding antiparticle.

[1]

A proton and an anti-proton. There are lots of others.

(ii) State the quark structure of an anti-baryon.

[1]

An anti-baryon contains three anti-quarks.

(iii) Give **one** property of an antiparticle that is the same for its corresponding particle and **one** property that is different.

[2]

Mass/energy could be a similarity; charge, lepton number, baryon number or strangeness could be a difference.

2.8 AQA-A Particles, Quantum Phenomena and Electricity, Jun 2012 Q1

(a) The K^- meson has strangeness -1 .

(i) State the quark composition of a meson.

[1]

A meson consists of a quark and an anti-quark.

(ii) State the baryon number of the K^- meson.

[1]

If K^- is a meson, it's not a baryon, so it will have a baryon number of zero.

(iii) What is the quark composition of the K^- meson?

[1]

Well, if it's strange, and has a charge of -1 , it must have an s quark in it. To make the charge up to -1 , we will need a \bar{u} quark as well.

(b) Figure 8 shows a Feynman diagram for a possible decay of the strange quark.

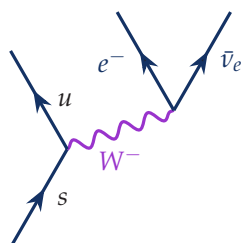


Figure 8: Feynman Diagram : AQA-A Particles, Quantum Phenomena and Electricity, Jun 2012 Q1

(i) Which interaction is responsible for this decay?

[1]

That's the weak interaction. The big W in the middle tells you that! Amongst other things of course, like the flavour of the s quark changing into a u quark.

(ii) Energy and momentum are conserved when the W^- particle is produced. State **two** other quantities that are also conserved and **one** that is not.

[3]

Charge, baryon number and lepton number are allways conserved; strangeness might not be. And in this case it isn't, as the strange s quark turns into the non-strange u quark.

(iii) Complete this equation for the decay of a K^- meson.

$$K^- \rightarrow \dots + \dots + \dots$$

[2]

From the picture, the s quark in the K^- turns into a u quark. The \bar{u} quark (see part (a)(iii)) will be unaffected. That means the K^- turns into a $u\bar{u}$ particle: and that's a π^0 . So:

$$K^- \rightarrow \pi^0 + e^- + \bar{\nu}_e$$

2.9 AQA-A Particles, Quantum Phenomena and Electricity, Jan 2013 Q3

(a) (i) State how many quarks there are in a baryon.

[1]

Baryons have three quarks.

(ii) Hadrons fall into two groups, baryons being one of them. State the name that is given to the other group of hadrons.

[1]

Mesons.

(iii) Give **two** properties of hadrons that distinguish them from leptons.

[2]

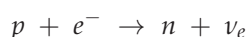
Hadrons are made of quarks and so are not fundamental, whereas leptons are fundamental. Hadrons experience the strong nuclear force, whereas leptons don't.

(b) What are the exchange particles for the electromagnetic and weak interactions?

[2]

The photon is the exchange particle for the electromagnetic interaction, and the W^+ and W^- bosons are the exchange particles for the weak interaction.

(c) The following equation shows electron capture.



(i) Draw a Feynman diagram that represents this interaction.

[3]

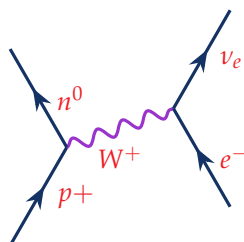


Figure 9: Feynman Diagram : AQA-A Particles, Quantum Phenomena and Electricity, Jan 2013 Q3

(ii) Explain why, when electron capture occurs, a neutrino rather than an antineutrino is produced.

[1]

This is so that lepton number is conserved in the interaction:

$$\begin{array}{ccccccc}
 & p^+ & + & e^- & \rightarrow & n^0 & + & \nu_e \\
 \text{Lepton Number (L):} & 0 & + & +1 & \rightarrow & 0 & + & +1
 \end{array}$$

Table 7: Quantum Numbers : AQA-A Particles, Quantum Phenomena and Electricity, Jan 2013 Q3

2.10 AQA-A Particles, Quantum Phenomena and Electricity, Jun 2013 Q2

A positron is emitted from a nucleus when a proton changes to a neutron in the nucleus. The Feynman diagram for the quark interaction is shown in Figure 10.

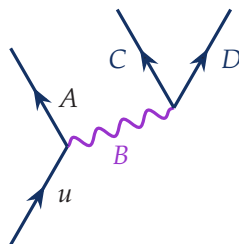


Figure 10: Feynman Diagram : AQA-A Particles, Quantum Phenomena and Electricity, Jun 2013 Q2

(a) Identify the particles labelled A, B, C and D in the diagram.

[3]

- A: a d quark;
- B: a W^+ boson;
- C and D: an e^+ and a ν_e

(b) (i) State the interaction responsible for this process.

[1]

The weak interaction. You know that because the u quark is changing flavour, or because the W^+ boson is involved.

(ii) State which letter in Figure 10 represents an exchange particle.

[1]

B (the W^+ boson) is the exchange particle.

(iii) State **one** difference between this exchange particle and a photon.

[1]

The W^+ boson has mass and charge, whereas photons have neither. Photons also have a much greater range (theoretically infinite!) than W bosons.

(c) Energy and momentum have to be conserved in this process. State **two** other quantities that need to be conserved and show that they are conserved in the process.

[4]

Here we go again: the quantum numbers that are always conserved in any interaction are the charge, lepton number and baryon number. The quantum number that's not always conserved in weak interactions is the strangeness, although in this particular weak interaction, it is conserved.

	p^+	\rightarrow	n^0	$+$	e^+	$+$	ν_e
Charge (Q):	+1	\rightarrow	0	$+$	+1	$+$	0
Baryon Number (B):	+1	\rightarrow	+1	$+$	0	$+$	0
Lepton Number (L):	0	\rightarrow	0	$+$	-1	$+$	+1
Strangeness (S):	0	\rightarrow	0	$+$	0	$+$	0

Table 8: Quantum Numbers : AQA-A Particles, Quantum Phenomena and Electricity, Jun 2013 Q2

2.11 AQA-A Particles, Quantum Phenomena and Electricity, Jun 2014 Q1

(a) The positive kaon, K^+ , has a strangeness of +1.

(i) What is the quark structure of the K^+ ?

[1]

If it's got a strangeness of +1, it must have an \bar{s} quark in it. Kaons are mesons, so it must have one more quark in it, which will be a normal matter quark. To get a whole number charge, the quark has to be a u quark.

(ii) What is the baryon number of the K^+ ?

[1]

Kaons are mesons, so they will have a baryon number of 0.

(iii) What is the antiparticle of the K^+ ?

[1]

The anti-particle of the K^+ will be the K^- , made of the opposite quarks: $\bar{u}s$.

(b) The K^+ may decay into a neutrino and an antimuon in the following way.

$$K^+ \rightarrow \nu_\mu + \mu^+$$

(i) Complete Table ?? using ticks and crosses as indicated in the first row.

Classification	K^+	ν_μ	μ^+
lepton	×	✓	✓
charged particle			
hadron			
meson			

Table 9: Particle Properties 1 : AQA-A Particles, Quantum Phenomena and Electricity, Jun 2014 Q1

[3]

Classification	K^+	ν_μ	μ^+
lepton	×	✓	✓
charged particle	✓	×	✓
hadron	✓	×	×
meson	✓	×	×

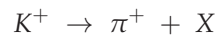
Table 10: Particle Properties 2 : AQA-A Particles, Quantum Phenomena and Electricity, Jun 2014 Q1

(ii) In this decay, charge, energy and momentum are conserved. Give another quantity that is conserved in this decay and one that is not conserved.

[2]

Charge, baryon number and lepton number will always be conserved. Strangeness might not be: in this interaction it isn't.

(c) Another possible decay of the K^+ is shown in the following equation,



(i) Identify X by circling **one** option from the following list:

- electron
- muon
- negative pion
- neutral pion
- neutrino
- neutron
- positron

[1]

- electron: not possible as lepton number wouldn't be conserved;
- muon: not possible as lepton number wouldn't be conserved;
- negative pion: not possible as charge wouldn't be conserved;
- neutral pion: possible as charge, lepton number and baryon number would all be conserved;
- neutrino: not possible as lepton number wouldn't be conserved;
- neutron: not possible as baryon number wouldn't be conserved;
- positron: not possible as lepton number wouldn't be conserved.

So it must be a π^0 then.

(ii) Give **one** reason for your choice in part (c)(i).

[1]

See above.

2.12 AQA-A Particles, Quantum Phenomena and Electricity, Jun 2015 Q2

The equation shows an interaction between a proton and a negative kaon that results in the formation of particle, X .



(a) State and explain whether X is a charged particle.

[2]

As protons have a positive charge, the net charge on the left is zero. So the net charge on the right must be zero too. So X must have a charge of -1 .

(b) State and explain whether X is a lepton, baryon or meson.

[2]

Kaons are mesons, and so would have a baryon number of 0. Protons are baryons, so the net baryon number on the left is $+1$. So the net baryon number on the right is $+1$. So X must be a baryon.

(c) State the quark structure of the K^- , K^+ and the K^0 .

[3]

The Kaons are mesons, and so consist of a quark and an anti-quark. They also have a strange quark (or an anti-strange quark) in them.

So a K^- must be $\bar{u}s$ to get the charge to -1 .

A K^+ must be $u\bar{s}$ to get the charge to $+1$.

And a K^0 must be $d\bar{s}$ to get the charge to 0, or indeed $s\bar{d}$: that's the \bar{K}^0 . It can't be $s\bar{s}$ as that wouldn't be strange: it would in fact be a π^0 .

(d) Strangeness is conserved in the interaction. Determine, explaining your answer, the quark structure of X .

[3]

	K^-	+	p^+	\rightarrow	K^+	+	K^0	+	X
Charge (Q):	-1	+	+1	\rightarrow	+1	+	0	+	-1
Baryon Number (B):	0	+	+1	\rightarrow	0	+	0	+	+1
Lepton Number (L):	0	+	0	\rightarrow	0	+	0	+	0
Strangeness (S):	-1	+	0	\rightarrow	+1	+	-1	+	-1

Table 11: Quantum Numbers 1 : AQA-A Particles, Quantum Phenomena and Electricity, Jun 2015 Q2

So, if we are told that the neutral kaon on the right of this interaction is K^0 (rather than \bar{K}^0), and if strangeness is conserved, then X must have a strangeness of -1 . It is a baryon with a charge of -1 , so its quark structure must be dds (that's actually a Σ^- particle!).

Just playing devil's advocate for a moment, let's think about the possibility of the neutral kaon being a K^0 particle:

	K^-	+	p^+	\rightarrow	K^+	+	\bar{K}^0	+	X
Charge (Q):	-1	+	+1	\rightarrow	+1	+	0	+	-1
Baryon Number (B):	0	+	+1	\rightarrow	0	+	0	+	+1
Lepton Number (L):	0	+	0	\rightarrow	0	+	0	+	0
Strangeness (S):	-1	+	0	\rightarrow	+1	+	+1	+	-3

Table 12: Quantum Numbers 2 : AQA-A Particles, Quantum Phenomena and Electricity, Jun 2015 Q2

So, if we are told that the neutral kaon on the right of this interaction is \bar{K}^0 , and if strangeness is conserved, then X must have a strangeness of -3 . It is a baryon with a charge of -1 , so its quark structure must be sss (that's actually an Ω^- particle!).

2.13 AQA-A Particles, Quantum Phenomena and Electricity, Jun 2015 Q3

(a) Baryons, mesons and leptons are affected by particle interactions. Write an account of these interactions. Your account should:

- include the names of the interactions
- identify the groups of particles that are affected by the interaction
- identify the exchange particles involved in the interaction
- give examples of two of the interactions you mention.

The quality of your written communication will be assessed in your answer.

[6]

There are three interactions that affect subatomic particles:

The electromagnetic interaction This interaction acts between charged particles, and the exchange particle for this interaction is the photon. An example of this kind of interaction is the repulsion between two neighbouring electrons:

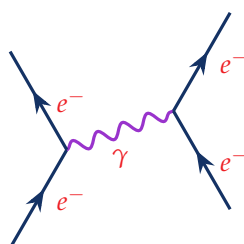


Figure 11: Feynman Diagram 1 : AQA-A Particles, Quantum Phenomena and Electricity, Jun 2015 Q3

The weak interaction This interaction acts on quarks and leptons, and the exchange particles for this interaction are the W^+ and W^- bosons. The weak interaction changes the flavour of quarks. So for example, a u quark could be turned into a d quark:

$$u^{\frac{2}{3}} \rightarrow d^{-\frac{1}{3}} + W^+$$

and then the W^+ decays into a positron and an electron neutrino:

$$W^+ \rightarrow e^+ + \nu_e$$

The strong interaction This is an interaction that only acts on quarks. Quark flavour is conserved. This is the force that holds baryons and mesons together (where the exchange particle is the gluon), and is also the force responsible for holding protons and neutrons together inside nuclei (where the exchange particles are pions).

(b) Draw a labelled Feynman diagram that represents a particle interaction.

[3]

The Feynman diagram for the weak interaction discussed above is shown here:

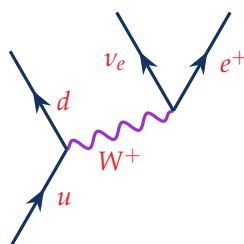


Figure 12: Feynman Diagram 2 : AQA-A Particles, Quantum Phenomena and Electricity, Jun 2015 Q3

2.14 AQA-A Particles, Quantum Phenomena and Electricity, Jun 2016 Q2

The positive kaon (K^+) has a strangeness of +1.

(a) Which one of the following is the quark composition of the positive kaon?

- $\bar{u}s$
- $uu\bar{s}$
- $u\bar{s}$
- $\bar{d}\bar{d}s$

[1]

Kaons are mesons, so they consist of a quark and an anti-quark. That eliminates the $uu\bar{s}$ and $\bar{d}\bar{d}s$ options. $\bar{u}s$ would have a charge of -1 , so the answer must be $u\bar{s}$.

(b) The equation shows a possible decay of the positive kaon.

$$K^+ \rightarrow \mu^+ + \nu_\mu$$

(i) Show that lepton number is conserved in this decay.

[1]

$$\begin{array}{rcl} & K^+ & \rightarrow \mu^+ + \nu_\mu \\ \text{Lepton number:} & 0 & \rightarrow -1 + +1 \end{array}$$

(ii) State a quantity that is not conserved in this decay.

[1]

It's got to be strangeness, hasn't it:

$$\begin{array}{rcl} & K^+ & \rightarrow \mu^+ + \nu_\mu \\ \text{Strangeness:} & +1 & \rightarrow 0 + 0 \end{array}$$

(iii) Complete the following table using ticks to indicate correct classifications for each particle. The first column has been completed for you.

[3]

	Charged	Hadron	Meson	Baryon	Lepton
K^+	✓				
μ^+	✓				
ν_μ					

Table 13: Particle Properties 1 : AQA-A Particles, Quantum Phenomena and Electricity, Jun 2016 Q2

	Charged	Hadron	Meson	Baryon	Lepton
K^+	✓	✓	✓	×	×
μ^+	✓	×	×	×	✓
ν_μ	×	×	×	×	✓

Table 14: Particle Properties 2 : AQA-A Particles, Quantum Phenomena and Electricity, Jun 2016 Q2

(c) The positive kaon can also decay to form a π^+ and one other particle X. Deduce the identity of X.

[3]

$$\begin{array}{rcl} & K^+ & \rightarrow \pi^+ + X \\ \text{Charge:} & +1 & \rightarrow +1 + 0 \\ \text{Baryon number:} & 0 & \rightarrow 0 + 0 \\ \text{Lepton number:} & 0 & \rightarrow 0 + 0 \\ \text{Strangeness:} & +1 & \rightarrow 0 + ? \end{array}$$

So...X is neutral and it's not a baryon or a lepton. So the only thing left would be the neutral pion, π^0 .

3 Edexcel-A Physics On The Move Past Papers

3.1 Edexcel-A Physics On The Move, Jun 2010 Q18

In 1961 Murray Gell-Mann predicted the existence of a new particle called an omega minus (Ω^-). It was subsequently discovered in 1964. At this time the quark model consisted of three particles, the properties of which are given in the table.

Quark	Charge	Predicted Mass (MeV)
up (u)	$+\frac{2}{3}$	4
down (d)	$-\frac{1}{3}$	4
strange (s)	$-\frac{1}{3}$	80

(a) Explain what a charge of $+\frac{2}{3}$ means.

[1]

This means $\frac{2}{3}$ of the charge of a proton, so $\frac{2}{3} \times 1.6 \times 10^{-19}$ C.

(b) State the predicted mass of, and the charge on a \bar{s} .

[2]

As the \bar{s} is the anti-particle of the s quark, it will have the same mass and the opposite charge. So the mass will be 80 MeV and the charge will be $+\frac{1}{3}$.

(c) Convert $4 \text{ MeV}/c^2$ to kg.

[3]

$$\begin{aligned}
 4 \text{ MeV}/c^2 &= 4 \cdot 10^6 \text{ eV} \\
 &= 4 \cdot 10^6 \cdot 1.6 \times 10^{-19} \text{ J} \\
 &= \frac{4 \cdot 10^6 \cdot 1.6 \times 10^{-19}}{(3.0 \times 10^8)^2} \text{ kg} \\
 &= 7.11 \times 10^{-30} \text{ kg}
 \end{aligned}$$

(d) The event which led to the discovery of the omega minus particle can be summarised as follows. A negative kaon collided with a stationary proton and produced a positive kaon, a neutral kaon and the omega minus.

(i) Kaons K consist of combinations of either an up or down quark plus a strange quark. The omega minus consists of three strange quarks.

Complete the following table by ticking the appropriate boxes.

[2]

	Meson	Baryon	Nucleon	Lepton
Negative Kaon				
Omega Minus				

As the kaon consists of two quarks, it must be a meson, which means it's not a baryon, nucleon or lepton.

As the Ω^- consists of three quarks, it must be a baryon, which means it's not a meson or a lepton. Only protons and neutrons are nucleons.

	Meson	Baryon	Nucleon	Lepton
Negative Kaon	✓	×	×	×
Omega Minus	×	✓	×	×

(ii) Write an equation using standard particle symbols to summarise this event.

[2]



(iii) The negative kaon consists of $\bar{u}s$. Deduce the quark structure of the other two kaons involved in this event.

[2]

The K^+ will be the anti-particle of the K^- , so it will have the quark structure of $u\bar{s}$.

If kaons consist of either up or down quarks plus a strange quark, then a K^0 must be $\bar{d}s$ to give a net charge of zero.

(iv) The total mass of the three particles created after this event is larger than the total mass of the two particles before. Discuss the quantities that must be conserved in interactions between particles and use an appropriate conservation law to explain this increase in mass.

[5]

Quantities that are always conserved in interactions are mass/energy, momentum, charge, lepton number and baryon number.

To explain the increase in mass, that extra mass could come from the kinetic energies of the colliding particles through Einstein's mass-energy equivalence principle, $E = mc^2$, and the conservation of mass/energy of the interaction.

3.2 Edexcel-A Physics On The Move, Jan 2011 Q11

A particle called a B meson has been observed to decay into an anti-proton plus lambda (Λ) particle. The lambda particle consisted of an up, a down and a charm a quark.

The following table summarises the charges on these quarks.

Quark	Charge
up (u)	$+\frac{2}{3}$
down (d)	$-\frac{1}{3}$
charm (c)	$+\frac{2}{3}$

(a) Circle the correct word from the list below to describe the lambda particle.

- Baryon
- Lepton
- Meson
- Anti-particle

[1]

It must be a baryon, so that the baryon number is conserved in the interaction:

(b) Calculate the charge on a lambda particle.

[1]

If the Λ particle has an up, a down and a charm quark in it, it must have a net charge of $+\frac{2}{3} - \frac{1}{3} + \frac{2}{3} = +1$. That means it's charge will be $+1.6 \times 10^{-19}$ C.

(c) Write an equation using standard particle symbols for this decay.

[2]

$$B^0 \rightarrow p^- + \Lambda^+$$

The B meson must have a charge of 0 as charge is conserved in interactions.

3.3 Edexcel-A Physics On The Move, Jun 2013 R, Q14

Hadrons are a group of particles composed of quarks. Hadrons can be either baryons or mesons.

(a) (i) State the quark structure of a baryon.

[1]

Baryons contain three quarks. These have to be either three normal matter quarks, or three anti-quarks.

(ii) State the quark structure of a meson.

[1]

Mesons consist of two quarks. One has to be a normal matter quark, and the other an anti-quark.

(b) State **one** similarity, and **one** difference between a particle and it's anti-particle.

[2]

Mass/energy could be a similarity; charge, lepton number, baryon number or strangeness could be a difference.

(c) (i) The table gives some of the properties of up, down and strange quarks.

Quark	Charge	Strangeness
u	$+\frac{2}{3}$	0
d	$-\frac{1}{3}$	0
s	$-\frac{1}{3}$	-1

One or more of these quarks combine to form a K^+ , a meson with a strangeness of +1.

Write down the quark combination of the K^+ .

[1]

K^+ must be $u\bar{s}$ to have a charge of +1 and a strangeness of +1.

(ii) The K^+ can decay in the following way:

$$K^+ \rightarrow \mu^+ + \nu_\mu$$

K^- is the anti-particle of the K^+ .

Complete the equation below by changing each particle to it's corresponding anti-particle in order to show an allowed decay for the K^- meson.

$$K^- \rightarrow$$

[2]

$$K^- \rightarrow \mu^- + \bar{\nu}_\mu$$

(iii) The rest mass of the K^+ is $494 \text{ MeV}/c^2$.

Calculate, in Joules, how much energy is released if a K^+ meets and annihilates a K^- .

[3]

If a K^+ annihilates a K^- , the total amount of mass/energy liberated will be

$$\begin{aligned} 2 \cdot 494 \text{ MeV} &= 2 \cdot 494 \cdot 10^6 \text{ eV} \\ &= 2 \cdot 494 \cdot 10^6 \cdot 1.6 \times 10^{-19} \text{ J} \\ &= 1.58 \times 10^{-10} \text{ J} \end{aligned}$$

3.4 Edexcel-A Physics On The Move, Jun 2014 Q18

Subatomic particles such as pions are produced after collisions between protons that have been accelerated in a cyclotron.

(a) Explain briefly the role of electric and magnetic fields in the cyclotron.

[5]

The electric field applies a force to the charged particles, causing them to accelerate as they pass between the dees. It is only when the charged particles are between the dees that this force acts on them.

The magnetic field keeps the charged particles within the cyclotron by applying a force at right angles to their direction of motion, causing them to move along circular paths within the dees. To do this, the magnetic field needs to be normal to the plane containing the dees.

(b) The mass of a pion is 2.5×10^{-28} kg. Calculate the mass of a pion in GeV/c^2 .

[3]

$$\begin{aligned}
 2.5 \times 10^{-28} \text{ kg} &= 2.5 \times 10^{-28} \cdot (3.0 \times 10^8)^2 \text{ J} \\
 &= \frac{2.5 \times 10^{-28} \cdot (3.0 \times 10^8)^2}{1.6 \times 10^{-19}} \text{ eV} \\
 &= \frac{2.5 \times 10^{-28} \cdot (3.0 \times 10^8)^2}{1.6 \times 10^{-19} \cdot 10^9} \text{ GeV}/c^2 \\
 &= 0.141 \text{ GeV}/c^2
 \end{aligned}$$

(c) The table shows the charge of some quarks.

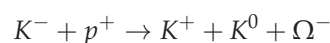
Quark	Charge
<i>u</i>	$+\frac{2}{3}$
<i>d</i>	$-\frac{1}{3}$
<i>s</i>	$-\frac{1}{3}$

Explain what is meant by a charge of $+\frac{2}{3}$.

[1]

This means $\frac{2}{3}$ of the charge on a proton, so $+\frac{2}{3} \cdot 1.6 \times 10^{-19} \text{ C}$.

(d) The omega minus (Ω^-) particle consists of three strange quarks and is produced by the following interaction:



Kaons are mesons and consist of a strange quark and either an up or a down quark.

(i) Complete the table to show a possible quark combination for each kaon.

Particle	Quark Combination
K^-	
K^+	
K^0	

[3]

The Kaons are mesons, and so consist of a quark and an anti-quark. They also have a strange quark (or an anti-strange quark) in them.

So a K^- must be $\bar{u}s$ to get the charge to -1 .

A K^+ must be $u\bar{s}$ to get the charge to $+1$.

And a K^0 must be $d\bar{s}$ to get the charge to 0, or indeed $s\bar{d}$: that's the \bar{K}^0 . It can't be $s\bar{s}$ as that wouldn't be strange: it would in fact be a π^0 .

Particle	Quark Combination
K^-	$\bar{u}s$
K^+	$u\bar{s}$
K^0	$d\bar{s}$

(ii) The total mass of the particles produced in this interaction is greater than the total mass of the two particles that collided. Explain this increase in mass.

[3]

To explain the increase in mass, that extra mass could come from the kinetic energies of the colliding particles through Einstein's mass-energy equivalence principle, $E = mc^2$, and the conservation of mass/energy of the interaction.

3.5 Edexcel-A Physics On The Move, Jun 2015 Q12

Pions belong to a group of particles called mesons. Pions can be used in a form of radiotherapy to treat brain tumours.

(a) The table lists some quarks and their charges.

Quark	Charge
u	$+\frac{2}{3}$
d	$-\frac{1}{3}$
s	$-\frac{1}{3}$

From the list below, circle the quark combination which could correspond to a π^- pion.

- dds
- $\bar{u}d$
- $\bar{u}\bar{u}\bar{d}$
- $u\bar{s}$

[1]

Mesons only have two quarks in them so the answer can't be dds or $\bar{u}\bar{u}\bar{d}$. $u\bar{s}$ would give a charge of +1, so a π^- meson is made of $\bar{u}d$ quarks.

(b) The mass of a pion is $140 \text{ MeV}/c^2$. Calculate the mass of the pion in kg.

[3]

$$\begin{aligned}
 140 \text{ MeV}/c^2 &= 140 \cdot 10^6 \text{ eV} \\
 &= 140 \cdot 10^6 \cdot 1.6 \times 10^{-19} \text{ J} \\
 &= \frac{140 \cdot 10^6 \cdot 1.6 \times 10^{-19}}{(3.0 \times 10^8)^2} \text{ kg} \\
 &= 2.49 \times 10^{-28} \text{ kg}
 \end{aligned}$$

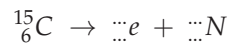
4 OCR-A Fields, Particles and Frontiers of Physics Past Papers

4.1 OCR-A Fields, Particles and Frontiers of Physics, Jun 2010 Q7

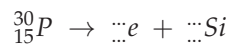
There are two types of beta decay, beta-plus and beta-minus. An isotope of carbon $^{15}_6\text{C}$ decays by beta emission into an isotope of nitrogen $^{15}_7\text{N}$. An isotope of phosphorus $^{30}_{15}\text{P}$ decays by beta emission into an isotope of silicon $^{30}_{14}\text{Si}$.

(a) Complete the following decay equations for the carbon and phosphorus isotopes.

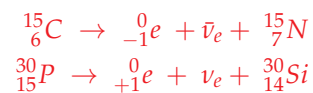
(i) Carbon decay:



(ii) Phosphorus decay:



[3]



(b) State the two beta decays in terms of a quark model of the nucleons.

[2]

For β^- decay:



For β^+ decay:



(c) Name the force responsible for beta decay.

[1]

This is the weak interaction as it changes the flavour of quarks, and involves leptons.

4.2 OCR-A Fields, Particles and Frontiers of Physics, Jan 2011 Q9

(a) (i) Complete Table 15 to show the quark composition and charge for neutrons and protons.
[2]

	Quark Composition	Charge
neutron		
proton		

Table 15: Hadron Composition : OCR-A Fields, Particles and Frontiers of Physics, Jan 2011 Q9

	Quark Composition	Charge
neutron	<i>udd</i>	0
proton	<i>uud</i>	+1

(ii) Complete Table 16 to show the composition of quarks.
[2]

quark	charge	baryon number	strangeness
up		$+\frac{1}{3}$	
down			

Table 16: Quark Composition : OCR-A Fields, Particles and Frontiers of Physics, Jan 2011 Q9

quark	charge	baryon number	strangeness
up	$+\frac{2}{3}$	$+\frac{1}{3}$	0
down	$-\frac{1}{3}$	$+\frac{1}{3}$	0

(b) When a neutron decays it can produce particles that include an electron.

(i) Complete the decay equation below for a neutron.

$${}^1_0n \rightarrow$$

[2]

$${}^1_0n \rightarrow {}^1_1p + {}^0_{-1}e + \bar{\nu}_e$$

(ii) Name the interaction responsible for the decay of the neutron.

[1]

It's the weak interaction because it changes the flavour of quarks and affects leptons.

(iii) Electrons and neutrons belong to different groups of particles. Name the group of particles to which each belongs.

[1]

Electrons are leptons; neutrons are baryons (or hadrons).

5 OCR-A Nuclear and Particle Physics Option Past Papers

5.1 OCR-A Nuclear and Particle Physics, Jan 2010 Q6

(a) Describe briefly the quark model of hadrons. Illustrate your answer by referring to the composition of **one** hadron. Include in your answer the names of **all** the known quarks.

Give as much information as you can about **one** particular quark.

[5]

Hadrons are made of quarks, which are fundamental particles. Hadrons can either be baryons (made of three quarks), or mesons (made of two quarks). There are six different quarks: up, down; strange, charm; and top, bottom. Their charge, baryon number and strangeness are summarised in the following table:

Quark	Charge	Baryon Number	Strangeness
up	$+\frac{2}{3}$	$+\frac{1}{3}$	0
down	$-\frac{1}{3}$	$+\frac{1}{3}$	0
charm	$+\frac{2}{3}$	$+\frac{1}{3}$	0
strange	$-\frac{1}{3}$	$+\frac{1}{3}$	-1
top	$+\frac{2}{3}$	$+\frac{1}{3}$	0
bottom	$-\frac{1}{3}$	$+\frac{1}{3}$	0

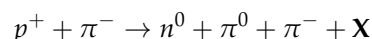
The charge, baryon number and (usually!!) strangeness are also conserved in quark reactions.

Each of the above quarks also has its own anti-quark, which has exactly the opposite values of the three quantum numbers.

Quarks are held together by gluons (the strong nuclear force).

A proton has a quark composition of **uud**; a neutron has a quark composition of **udd**.

A proton (p^+) can interact with a π^- particle to produce the three particles shown and an unknown particle X.



The charge, baryon number and strangeness of the π^- and π^0 particles are shown in the following table:

	Charge	Baryon Number	Strangeness
π^-	-1	0	0
π^0	0	0	0

(b) (i) Assuming that the strangeness is conserved in this reaction, find the charge, baryon number and strangeness of particle X.

[3]

X has a charge of +1, a baryon number of 0 and a strangeness of 0:

	p^+	π^-	\rightarrow	n^0	π^0	π^-	X
Charge	1	-1	\rightarrow	0	0	-1	1
Baryon Number	1	0	\rightarrow	1	0	0	0
Strangeness	0	0	\rightarrow	0	0	0	0
Lepton Number	0	0	\rightarrow	0	0	0	0

(b) (ii) Suggest what particle X is.

[1]

If X is the only other product of the reaction, it can't be a lepton, as the lepton numbers on both sides of the equation would not be the same. So it must be a hadron. As it has a baryon number of 0 it must be a meson; it has a charge of +1 and a strangeness of 0 so it could well be a π^+ particle.

5.2 OCR-A Nuclear and Particle Physics, June 2007 Q6

(a) (i) Name the group of particles of which the electron and the positron are members.
[1]

They are leptons.

(a) (ii) Name another member of this group.
[1]

Any of the six neutrinos would do, as would a muon or a tauon.

(b) (i) State the quark composition of the neutron.
[1]

A neutron has three quarks: up, down, down.

(b) (ii) Complete the table to show the charge Q, baryon number B and strangeness S for the quarks in the neutron.

Quark	Q	B	S

[2]

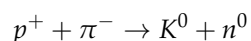
Here's the updated table:

Quark	Q	B	S
up	$+\frac{2}{3}$	$+\frac{1}{3}$	0
down	$-\frac{1}{3}$	$+\frac{1}{3}$	0

(b) (iii) Hence deduce the values of Q, B and S for the neutron.
[1]

A neutron has no charge (Q = 0); it is a baryon (B = 1); it has no strangeness (S = 0).

It is suggested that a proton (p^+) can react with a pi particle (π^-) to form a kaon K^0 and a neutron thus:



(c) Using the data in the following table, deduce whether this reaction is possible.

Particle	Quark Composition
π^-	$\bar{u}d$
K^0	$d\bar{s}$

[4]

Test each of the quantum numbers in turn:

	p^+	π^-	\rightarrow	K^0	n^0	Result
Charge	1	-1	\rightarrow	0	0	OK
Baryon Number	1	0	\rightarrow	0	1	OK
Strangeness	0	0	\rightarrow	1	0	NOT CONSERVED
Lepton Number	0	0	\rightarrow	0	0	OK

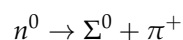
Strangeness can change in weak interactions. But in the only weak interactions we know of at A-Level, leptons are produced by the decaying W particles. As there aren't any leptons produced by this reaction, it can't be a weak interaction. So it must be a strong interaction, where strangeness needs to be conserved. So the reaction is NOT possible.

5.3 OCR-A Nuclear and Particle Physics, June 2009 Q5

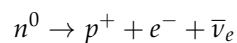
This question is about the stability of baryons.

(a) The following are four suggested baryon decay reactions.

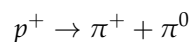
Reaction 1:



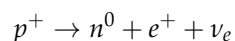
Reaction 2:



Reaction 3:



Reaction 4:



By comparing values of charge Q, baryon number B and strangeness S, deduce which of these reactions might be possible, giving a reason for each.

Particle	Q	B	S
Σ^0	0	1	-1
π^+	+1	0	0
π^0	0	0	0

[6]

Reaction 1:

	n^0	\rightarrow	Σ^0	π^+	Result
Charge	0	\rightarrow	0	1	NOT OK
Baryon Number	1	\rightarrow	1	0	OK
Strangeness	0	\rightarrow	-1	0	NOT OK
Lepton Number	0	\rightarrow	0	0	OK

Reaction 1 is not possible because charge and strangeness are not conserved.

Reaction 2:

	n^0	\rightarrow	p^+	e^-	$\bar{\nu}_e$	Result
Charge	0	\rightarrow	1	-1	0	OK
Baryon Number	1	\rightarrow	1	0	0	OK
Strangeness	0	\rightarrow	0	0	0	OK
Lepton Number	0	\rightarrow	0	1	-1	OK

Reaction 2 is possible because charge, baryon number, strangeness (and lepton number) are all conserved.

Reaction 3:

	p^+	\rightarrow	π^+	π^0	Result
Charge	1	\rightarrow	1	0	OK
Baryon Number	1	\rightarrow	0	0	NOT OK
Strangeness	0	\rightarrow	0	0	OK
Lepton Number	0	\rightarrow	0	0	OK

Reaction 3 is not possible because baryon number is not conserved.

Reaction 4:

	p^+	\rightarrow	n^0	e^+	ν_e	Result
Charge	1	\rightarrow	0	1	0	OK
Baryon Number	1	\rightarrow	1	0	0	OK
Strangeness	0	\rightarrow	0	0	0	OK
Lepton Number	0	\rightarrow	0	-1	+1	OK

Reaction 4 is possible because charge, baryon number, strangeness and lepton number are all conserved.

(b) When a baryon decays, another baryon is always produced. Explain this.

Because baryon number needs to be conserved in reactions.

(c) Use the data below to explain why a free proton is stable but a free neutron is not. Give the relevant nuclear equation.

Particle	Rest Mass (MeV)
electron	0.51
proton	938.27
neutron	939.57
all other baryons	>1000

[4]

Since there is no baryon with a lower rest mass than the proton, then there is no particle that the proton can decay into and achieve a lower energy state. However, a neutron can decay into a proton and an electron, and achieve a lower energy state (by shedding mass - which is equivalent to shedding energy). The reaction would be:



(d) State the circumstance in which a neutron is stable.

[1]

A neutron is stable when it is inside a nucleus.