

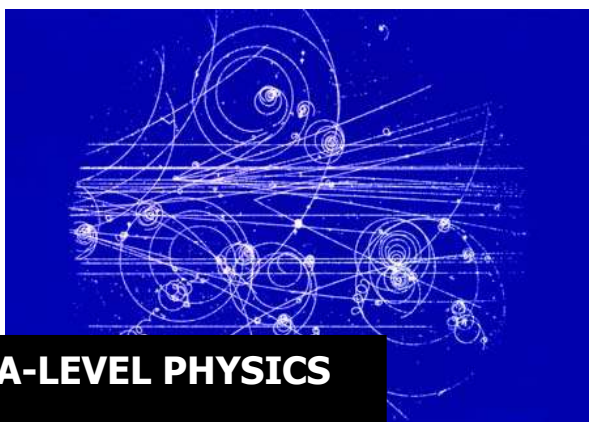


**ST MARY'S SCIENCE  
DEPARTMENT:  
PHYSICS**

**Volume  
One**

**A LEVEL PHYSICS YEAR 1  
STUDENT CLASS BOOK  
PARTICLES AND RADIATION  
3.2.1: PARTICLES**

<b>NAME</b>	
<b>PHYSICS CLASS</b>	
<b>MODULE TEACHER</b>	
<b>ALPS GRADE</b>	



**A-LEVEL PHYSICS  
TOPIC 2  
CLASS BOOK**

**THIS MUST  
BE BROUGHT  
TO ALL  
PHYSICS  
LESSONS.**



## Contents

### 3.2.1.1 Constituents of the Atom

### 3.2.1.2 Stable and Unstable Nuclei

### 3.2.1.3 Particles, Antiparticles and Photons

### 3.2.1.4 Particle Interactions

### 3.2.1.5 Classification of particles

### 3.2.1.6 Quarks and antiquarks

### 3.2.1.7 Applications of conservation laws

## Overview

This section introduces students both to the fundamental properties of matter, and to electromagnetic radiation and quantum phenomena. Through a study of these topics, students become aware of the way ideas develop and evolve in physics. They will appreciate the importance of international collaboration in the development of new experiments and theories in this area of fundamental research.

### **IMPORTANT NOTE**

This book, along with the preparatory reading notes and independent work, must be brought to all Physics lessons with the appropriate teacher.

This book may be used as a learning resource in lessons, you are not fully equipped to learn if this is not used in lesson.

This book may also be used as a revision resource for intervention, internal assessments and external assessments.

**Please keep this in your student file.**

There are several activities in this book which may not be covered in lessons.

**It is advised that students complete these activities outside of lessons as revision aides.**



## Definition List

Definitions you must learn...

Key Word	Definition
<b>Isotopes</b>	Nuclides with the same number of protons but different number of neutrons.
<b>Specific Charge</b>	The (overall) charge to mass ratio of a particle. = $\frac{\text{Overall Charge}}{\text{Rest Mass}}$
<b>Quarks</b>	Fundamental particles which exists in hadrons – they are not stable in isolation. No free quark has ever been observed.
<b>Pair Production</b>	When a particle and its corresponding anti-particle are produced from a photon with energy greater than the total rest energy of the 2 particles (with total energy $2E = hf$ ). The excess energy is lost as the kinetic energy of the particles.
<b>Annihilation</b>	When a particle and its corresponding anti-particle collide, they annihilate converted their kinetic energy and rest energies into 2 high energy photons (with energy $E=hf$ ).
<b>Hadron</b>	A particle made from quarks which interacts via the strong interaction.
<b>Anti-particles</b>	Particles with the same rest mass as the traditional particle but have opposite properties for every other property.
<b>Leptons</b>	A fundamental particle which does interact via the strong force.
<b>Exchange Particle</b>	A particle which transmits a fundamental force in the Universe. Also known as a virtual boson.
<b>Feynman Diagram</b>	A diagram which shows a particle interaction over time.
<b>Conservation Law</b>	A law where the total number of the property must the same before a decay as it is after it.
<b>Fundamental force</b>	A force which persists throughout the Universe due to the movement of exchange particles between other particles.
<b>Photon</b>	The exchange particle of the electromagnetic force and can be considered a particle of energy.
<b>Planck's Constant</b>	The proportionality constant between the energy contained in one photon with the frequency of the photon. It is given the symbol, $h$ .

### IMPORTANT NOTE

These definitions must be memorised by students.

You will be tested on these definitions.



## The Language of Measurement

The following subject specific vocabulary provides definitions of key terms used in the A-level Science specifications.

### Accuracy

A measurement result is considered accurate if it is judged to be close to the true value.

### Calibration

Marking a scale on a measuring instrument.

This involves establishing the relationship between indications of a measuring instrument and standard or reference quantity values, which must be applied.

For example, placing a thermometer in melting ice to see whether it reads 0 °C, to check if it has been calibrated correctly.

### Data

Information, either qualitative or quantitative, that has been collected.

### Errors

See also uncertainties.

### Measurement error

The difference between a measured value and the true value.

anomalies

These are values in a set of results which are judged not to be part of the variation caused by random uncertainty.

### Random error

These cause readings to be spread about the true value, due to results varying in an unpredictable way from one measurement to the next.

Random errors are present when any measurement is made and cannot be corrected. The effect of random errors can be reduced by making more measurements and calculating a new mean.

### Systematic error

These cause readings to differ from the true value by a consistent amount each time a measurement is made.

Sources of systematic error can include the environment, methods of observation or instruments used.

Systematic errors cannot be dealt with by simple repeats. If a systematic error is suspected, the data collection should be repeated using a different technique or a different set of equipment, and the results compared.

### Zero error

Any indication that a measuring system gives a false reading when the true value of a measured quantity is zero, e.g. the needle on an ammeter failing to return to zero when no current flows.

A zero error may result in a systematic uncertainty.

### Evidence

Data which has been shown to be valid.

**Fair test**

A fair test is one in which only the independent variable has been allowed to affect the dependent variable.

**Hypothesis**

A proposal intended to explain certain facts or observations.

**Interval**

The quantity between readings, e.g. a set of 11 readings equally spaced over a distance of 1 metre would give an interval of 10 centimetres.

**Precision**

Precise measurements are ones in which there is very little spread about the mean value. Precision depends only on the extent of random errors – it gives no indication of how close results are to the true value.

**Prediction**

A prediction is a statement suggesting what will happen in the future, based on observation, experience or a hypothesis.

**Range**

The maximum and minimum values of the independent or dependent variables; important in ensuring that any pattern is detected.

For example, a range of distances may be quoted as either:

'From 10 cm to 50 cm'

or

'From 50 cm to 10 cm'

**Repeatable**

A measurement is repeatable if the original experimenter repeats the investigation using same method and equipment and obtains the same results.

**Reproducible**

A measurement is reproducible if the investigation is repeated by another person, or by using different equipment or techniques, and the same results are obtained.

**Resolution**

This is the smallest change in the quantity being measured (input) of a measuring instrument that gives a perceptible change in the reading.

**Sketch graph**

A line graph, not necessarily on a grid, that shows the general shape of the relationship between two variables. It will not have any points plotted and although the axes should be labelled they may not be scaled.

**True value**

This is the value that would be obtained in an ideal measurement.

**Uncertainty**

The interval within which the true value can be expected to lie, with a given level of confidence or probability, e.g. "the temperature is  $20\text{ }^{\circ}\text{C} \pm 2\text{ }^{\circ}\text{C}$ , at a level of confidence of 95%.

**Validity**

Suitability of the investigative procedure to answer the question being asked. For example, an investigation to find out if the rate of a chemical reaction depended upon the concentration of one of the reactants would not be a valid procedure if the temperature of the reactants was not controlled.

**Valid conclusion**

A conclusion supported by valid data, obtained from an appropriate experimental design and based on sound reasoning.

**Variables**

These are physical, chemical or biological quantities or characteristics.

**Categoric variables**

Categoric variables have values that are labels. E.g. names of plants or types of material.

**Continuous variables**

Continuous variables can have values (called a quantity) that can be given a magnitude either by counting (as in the case of the number of shrimp) or by measurement (e.g. light intensity, flow rate etc.).

**Control variables**

A control variable is one which may, in addition to the independent variable, affect the outcome of the investigation and therefore must be kept constant or at least monitored.

**Dependent variables**

The dependent variable is the variable of which the value is measured for each change in the independent variable.

**Independent variables**

The independent variable is the variable for which values are changed or selected by the investigator.

**IMPORTANT NOTE**

These definitions must be memorised by students.

You will be tested on your knowledge of these definitions.



## TOPIC: 3.2.1.1 Constituents of the Atom

### SPEC CHECK

Specification	Completed?
Simple model of the atom, including the proton, neutron and electron. Charge and mass of the proton, neutron and electron in SI units and relative units.	
Specific charge of the proton and the electron, and of nuclei and ions.	
Proton number $Z$ , nucleon number $A$ , nuclide notation.	
Meaning of isotopes and the use of isotopic data.	

## NOTES

### The Nuclear Model

Previously seen in GCSE Physics Unit 2

These notes are brief.

More detailed notes are found in the student preparatory reading book.

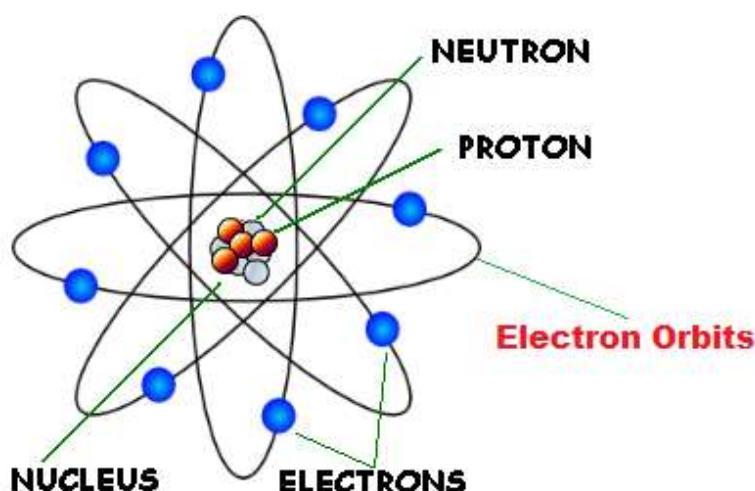
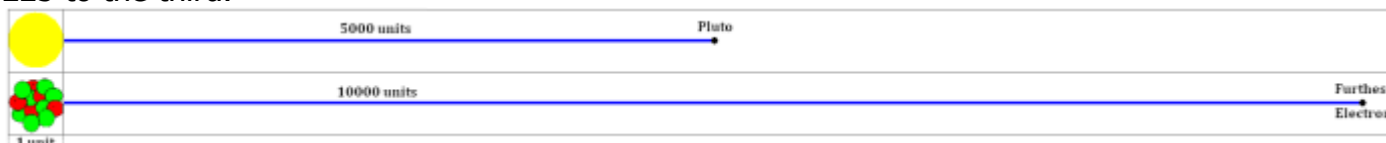
Please read the preparatory reading notes.

We know from Rutherford's experiment that the structure of an atom consists of positively charged protons and neutral neutrons in one place called the nucleus. The nucleus sits in the middle of the atom and has negatively charged electrons orbiting it.

At GCSE, we used charges and masses for the constituents relative to each other, the table above shows the actual charges and masses.

Almost all the mass of the atom is in the tiny nucleus which takes up practically no space when compared to the size of the atom. If we shrunk the Solar System so that the Sun was the size of a gold nucleus the furthest electron would be twice the distance to Pluto.

If the nucleus was a full stop it would be 25 m to the first electron shell, 100 to the second and 225 to the third.





## Notation

Previously seen in GCSE Physics Unit 2

We can represent an atom of element X in the following way:



Z is the proton number. This is the number of protons in the nucleus.

In an uncharged atom, the number of electrons orbiting the nucleus is equal to the number of protons.

*In Chemistry, it is called the atomic number*

A is the nucleon number. This is the total number of nucleons in the nucleus (protons + neutrons) which can be written as  $A = Z + N$ .

*In Chemistry, it is called the atomic mass number*

N is the neutron number. This is the number of neutrons in the nucleus.

## Isotopes

Previously seen in GCSE Physics Unit 2

Isotopes are different forms of an element.

They always have the same number of protons but have a different number of neutrons.

Since they have the same number of protons (and electrons) they behave in the same way chemically.

## Chlorine

If we look at Chlorine in the periodic table, we see that it is represented by  ${}^{35.5}_{17}Cl$ .

How can it have 18.5 neutrons? It can't!

There are two stable isotopes of Chlorine,  ${}^{35}_{17}Cl$  which accounts for  $\sim 75\%$  and  ${}^{37}_{17}Cl$  which accounts for  $\sim 25\%$ . So, the average of a large amount of Chlorine atoms is  ${}^{35.5}_{17}Cl$ .

The atomic mass number is an average number based on the abundance of isotopes found in the near Universe. This is an estimation based on our survey of our nearby Universe.



## Specific Charge

Specific charge is another title for the charge-mass ratio.

This is a measure of the charge per unit mass and is simply worked out by dividing the charge of a particle by its mass.

You can think of it as a how much charge (in Coulombs) you get per kilogram of the 'stuff'.

Constituent	Charge (C)	Mass (kg)	Charge-Mass Ratio (C kg <sup>-1</sup> ) or (C/kg)	
Proton	$1.6 \times 10^{-19}$	$1.673 \times 10^{-27}$	$1.6 \times 10^{-19} \div 1.673 \times 10^{-27}$	$9.58 \times 10^7$
Neutron	0.0	$1.675 \times 10^{-27}$	$0 \div 1.675 \times 10^{-27}$	0;0
Electron	$(-) 1.6 \times 10^{-19}$	$9.1 \times 10^{-31}$	$1.6 \times 10^{-19} \div 9.11 \times 10^{-31}$	$(-) 1.76 \times 10^{11}$

**The electron has the highest charge-mass ratio and the neutron has the lowest.**

### Exam Tip

When answering an examination question read whether the specific charge is concerning the atom, the ion or the nucleus.

An atom has no specific charge as it has no overall charge.

For a nucleus, you must use the number of protons as the basis for working out the overall charge.

For an ion, you must use the number of electrons gained or lost as the basis for working out the overall charge.

## Ions

Previously seen in GCSE Physics Unit 2

An atom may gain or lose electrons.

When this happens, the atoms become electrically charged (positively or negatively). We call this an ion.

If the atom gains an electron there are more negative charges than positive, so the atom is a negative ion.

Gaining one electron would mean it has an overall charge of **-1**, which means  **$-1.6 \times 10^{-19}\text{C}$** .  
Gaining two electrons would mean it has an overall charge of **-2**, which means  **$-3.2 \times 10^{-19}\text{C}$** .

If the atom loses an electron there are more positive charges than negative, so the atom is a positive ion.

Losing one electron would mean it has an overall charge of **+1**, which means  **$+1.6 \times 10^{-19}\text{C}$** .  
Losing two electrons would mean it has an overall charge of **+2**, which means  **$+3.2 \times 10^{-19}\text{C}$** .

### Note

Ionisation is normally caused by the atom colliding with a free-moving electron and giving the atom its energy.



**Additional Note Space**



**Additional Note Space**



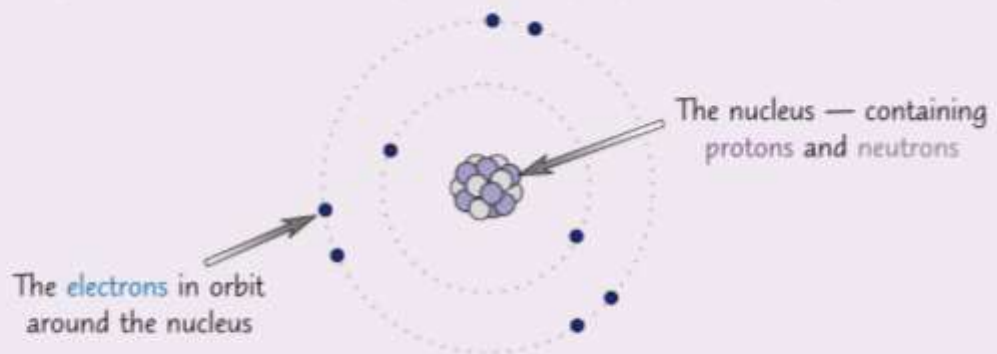
## REVISION SHEET

Highlight or underline the key information on the revision sheet to consolidate your understanding.

### *Atoms are made up of Protons, Neutrons and Electrons*

Inside **every atom**, there's a **nucleus** containing **protons** and **neutrons**. **Protons** and **neutrons** are both known as **nucleons**. **Orbiting** this core are the **electrons**. This is the **nuclear model** of the atom.

The diagram shows **neutral oxygen**, with **eight protons** and **eight electrons**.



The particles in an atom have different **properties**. Their charges and masses are so **tiny** that it's often easier to talk about their **relative charge** and **relative mass**.

Particle	Charge (coulombs, C)	Mass (kg)	Relative Charge	Relative Mass
Proton	$+1.60 \times 10^{-19}$	$1.67 \times 10^{-27}$	+1	1
Neutron	0	$1.67 \times 10^{-27}$	0	1
Electron	$-1.60 \times 10^{-19}$	$9.11 \times 10^{-31}$	-1	0.0005

### *The Proton Number is the Number of Protons in the Nucleus*

No... really.

The **proton number** is sometimes called the **atomic number**, and has the **symbol Z** (I'm sure it makes sense to someone). **Z** is just the **number of protons** in the nucleus.

It's the **proton number** that **defines** the **element** — **no two elements** will have the **same** number of protons.

In a **neutral atom**, the number of **electrons** **equals** the number of **protons**.

The element's **reactions** and **chemical behaviour** depend on the number of **electrons**.

So the **proton number** tells you a lot about its **chemical properties**.

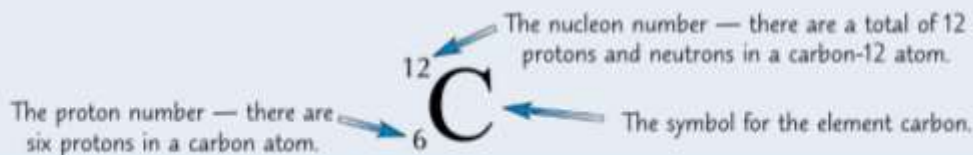
A particle with a different number of electrons to protons is called an ion.



## The Nucleon Number is the Total Number of Protons and Neutrons

The **nucleon number** is also called the **mass number**, and has the **symbol A** (\*shrug\*). It tells you how many **protons** and **neutrons** are in the nucleus. Since each **proton or neutron** has a relative **mass** of (approximately) **1** and the electrons weigh virtually nothing, the **number of nucleons** is the same as the **atom's relative mass**.

The nuclide notation of an element summarises information about its atomic structure:



## Isotopes have the Same Proton Number, but Different Nucleon Numbers

Atoms with the **same number of protons** but **different numbers of neutrons** are called **isotopes**.

**Example:** Hydrogen has three natural isotopes — hydrogen, deuterium and tritium.  
Hydrogen has 1 proton and 0 neutrons.  
Deuterium has 1 proton and 1 neutron.  
Tritium has 1 proton and 2 neutrons.

**Changing** the number of **neutrons doesn't affect** the atom's **chemical** properties.

The **number of neutrons** affects the **stability** of the nucleus though.

**Unstable nuclei** may be **radioactive** and **decay** over time into different nuclei that are more stable (see p.5).

## Radioactive Isotopes Can be Used to Find Out How Old Stuff Is

- 1) All living things contain the same percentage of radioactive **carbon-14** taken in from the atmosphere.
- 2) After they die, the amount of carbon-14 inside them **decreases** over time as it **decays** to stable elements.
- 3) Scientists can calculate the **approximate age** of archaeological finds made from dead **organic matter** (e.g. wood, bone) by using the **isotopic data** (amount of each isotope present) to find the percentage of **radioactive carbon-14** that's **left in** the object.

## The Specific Charge of a Particle is Equal to its Charge Over its Mass

The **specific charge** of a particle is the ratio of its charge to its mass, given in coulombs per kilogram ( $\text{C kg}^{-1}$ ). To calculate specific charge, you just divide the charge in C by the mass in kg.

You could be asked to find the specific charge of any particle, from a **fundamental particle** like an electron, to the nucleus of an atom or an ion.

**Example:** Calculate the specific charge of a proton.

A proton has a **charge** of  $+1.60 \times 10^{-19} \text{ C}$  and a **mass** of  $1.67 \times 10^{-27} \text{ kg}$  (see p.2).

So specific charge =  $(+1.60 \times 10^{-19}) \div (1.67 \times 10^{-27}) = 9.580... \times 10^7 = 9.58 \times 10^7 \text{ C kg}^{-1}$  (to 3 s.f.)

$$\text{Specific charge} = \frac{\text{charge}}{\text{mass}}$$

A fundamental particle is one that you can't break up into anything smaller.

In calculations, always give your answer to the smallest number of significant

### Practice Questions

**Credit:** CGP Revision Guide Editions



## SAMPLE QUESTION

**A1.** An atom of argon  ${}^{37}_{18}\text{Ar}$  is ionised by the removal of two orbiting electrons.

**A1.1** How many protons and neutrons are there in this ion?

[2 Marks]

**18 protons – this is the bottom number**

1 mark

**19 neutrons – this is the top number minus the bottom number**

1 mark

**A1.2** What is the charge, in C, of this ion?

[2 Marks]

**Overall Charge = 2 positive charges = 2 x specific charge of an electron**

1 mark

$$Q = 2 \times 1.60 \times 10^{-19} = 3.2 \times 10^{-19} \text{ C}$$

1 mark

Which constituent particle of this ion has

**A1.3** a zero charge per unit mass ratio,

[1 Mark]

**For this, the charge must be zero (as the mass cannot be zero) – the neutron.**

1 mark

**A1.4** the largest charge per unit mass ratio?

[1 Mark]

**For this, the mass must be very small (as it is mass/charge) – the electron**

1 mark

**A1.5** Calculate the percentage of the total mass of this ion that is accounted for by the mass of its electrons.

[3 Marks]

$$\% \text{ of total mass} = \text{mass of the electrons} / \text{mass of the entire atom} \quad 1 \text{ mark}$$

**For mass of the entire atom we can neglect the mass of the electrons – only consider the mass of the nucleons – as the mass of the electrons is tiny.**

$$(\%) = \frac{16 \times 9.11 \times 10^{-31}}{1.67 \times 10^{-27} \times 37}$$

$$= 2.36 \times 10^{-4}$$

1 mark

1 mark

**Use the correct sig figs and convert to percentage (x 100)**

$$= 2.36 \times 10^{-2} \%$$

1 mark

**Reference:** AQA A Level Physics Legacy Papers A



# SELF ASSESSMENT

**A1.1** ion of plutonium  $^{239}_{94}\text{Pu}$  has an overall charge of  $+1.6 \times 10^{-19}\text{C}$ .

For this ion state the number of

**[3 Marks]**

(i) protons .....

(ii) neutrons .....

(iii) electrons .....

**A1.2** Plutonium has several *isotopes*.

Explain the meaning of the word isotopes.

**[2 Marks]**

.....

.....

.....

.....

**Reference:** AQA A Level Physics Legacy Papers A

**A2.1** A stable atom contains 28 nucleons.

Write down a possible number of protons, neutrons and electrons contained in the atom.

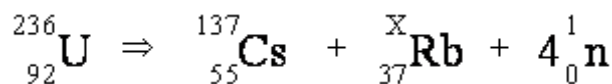
**[2 Marks]**

..... protons

..... neutrons

..... electrons

An unstable *isotope* of uranium may split into a caesium nucleus, a rubidium nucleus and four neutrons in the following process.



**A2.2** Explain what is meant by isotopes.

**[2 Marks]**

.....

.....



**A2.3** How many neutrons are there in the  $^{137}_{55}\text{Cs}$  nucleus?

[1 Mark]

.....

**A2.4** Calculate the ratio  $\frac{\text{charge}}{\text{mass}}$ , in C kg<sup>-1</sup>, for the  $^{236}_{92}\text{U}$  nucleus.

[3 Marks]

.....  
 .....  
 .....

**A2.5** Determine the value of **X** for the rubidium nucleus.

[2 Marks]

.....

**X** = .....

**A3.1** The most abundant isotope of cobalt is represented by  $^{59}_{27}\text{Co}$ .

How many protons, neutrons and orbital electrons are there in a neutral atom of this element?

[2 Marks]

..... protons  
 ..... neutrons  
 ..... electrons

**A3.2** How is the nuclide that has one less proton than the nickel nuclide,  $^{61}_{28}\text{Ni}$ , represented?

[2 Marks]

.....

**A3.3** The heaviest isotope of hydrogen, whose nucleon number is 3, is called tritium. How is tritium represented?

[1 Mark]

.....



**A3.4** Calculate the charge per unit mass, in  $\text{C kg}^{-1}$ , for a tritium nucleus.

**[2 Marks]**

.....

.....

.....

.....

**Reference:** AQA A Level Physics Legacy Papers A



## TOPIC: 3.2.1.2 Stable and Unstable Nuclei

### SPEC CHECK

Specification	Completed?
The strong nuclear force; its role in keeping the nucleus stable; short-range attraction up to approximately 3 fm, very-short range repulsion closer than approximately 0.5 fm.	
Unstable nuclei; alpha and beta decay.	
Equations for alpha decay, $\beta^-$ decay including the need for the neutrino.	
The existence of the neutrino was hypothesised to account for conservation of energy in beta decay.	
Demonstration of the range of alpha particles using a cloud chamber, spark counter or Geiger counter.	
Use of prefixes for small and large distance measurements.	

These notes are brief.

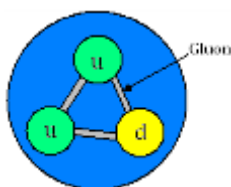
More detailed notes are found in the student preparatory reading book.

Please read the preparatory reading notes.

## NOTES

### The Strong Interaction

The strong nuclear force acts between quarks. Since Hadrons are the only particles made of quarks only they experience the strong nuclear force.

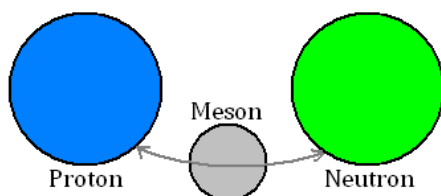


The strong nuclear force can also be called the strong interaction.

This is the force responsible for producing an atomic nucleus.

It is the strongest force in the Universe.

In both Baryons and Mesons, the quarks are attracted to each other by exchanging virtual particles called 'gluons'.



Force mechanisms work by transferring virtual particles between the particles called virtual particles.

The strong force virtual particle is called the gluon. Each fundamental force has its own virtual particle – this gives the force its properties.

On a larger scale the strong nuclear force acts between the Hadrons themselves, keeping them together.

At this level, we say that a pion ( $\pi$ ) is exchanged between the hadrons, this is the same as the gluon it is just named something else.

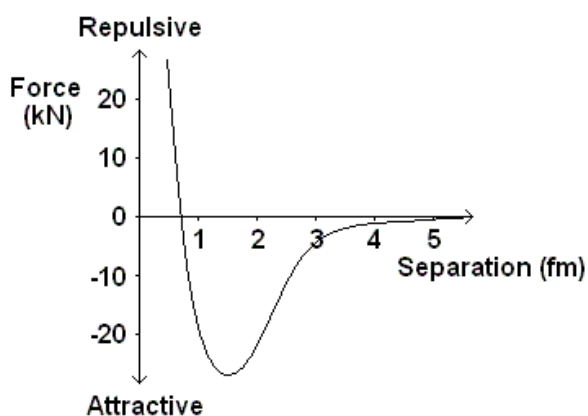
This is called the residual strong nuclear force as the force truly acts on the quark level.



## Force Graphs

### Neutron-Neutron or Neutron-Proton

Here is the graph of how the force varies between two neutrons or a proton and a neutron as the distance between them is increased.



The strong force can cause repulsion or attraction between two hadrons depending on the hadron separation.

The strong force does not affect any particle without quarks i.e. leptons.

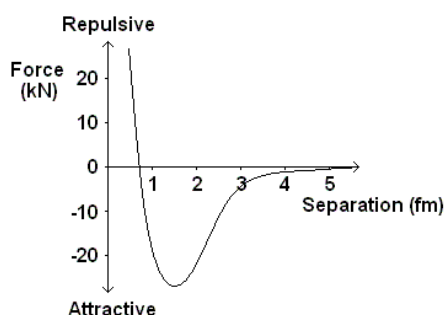
The strong force has a very small range however.

We can see that the force is very strongly repulsive at separations of less than  $0.7 \text{ fm}$  ( $\times 10^{-15} \text{ m}$ ). This prevents all the nucleons from crushing into each other.

Above this separation the force is strongly attractive with a peak around  $1.3 \text{ fm}$ . When the nucleons are separated by more than  $5 \text{ fm}$  they no longer experience the SNF.

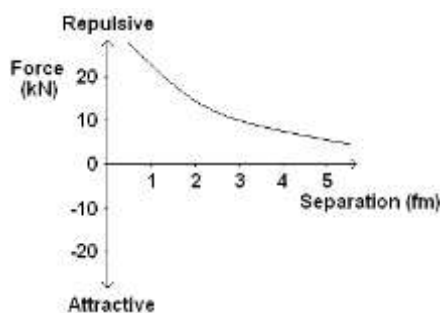
### Proton-Proton

The force-separation graphs for two protons is different. They both attract each other due to the SNF but they also repel each other due to the electromagnetic force which causes two like charges to repel.



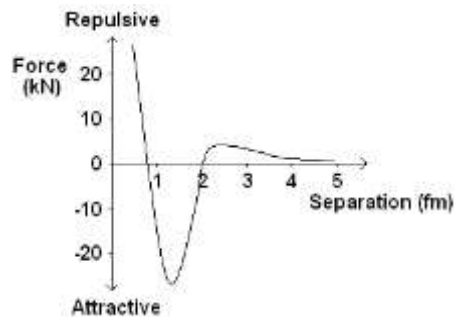
Graph A

Graph A shows how the strong nuclear force varies with the separation of the protons



Graph B

Graph B shows how the electromagnetic force varies with the separation of the protons



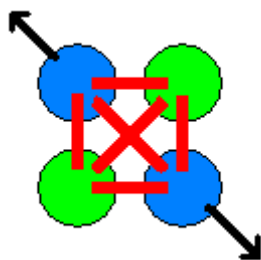
Graph C

Graph C shows the resultant of these two forces: repulsive at separations less than 0.7 fm, attractive up to 2 fm when the force becomes repulsive again.

### Neutrons – Nuclear Cement

In the lighter elements, the number of protons and neutrons in the nucleus is the same. As the nucleus gets bigger more neutrons are needed to keep it together.

Adding another proton means that all the other nucleons feel the strong force attraction. It also means that all the other protons feel the electromagnetic repulsion.

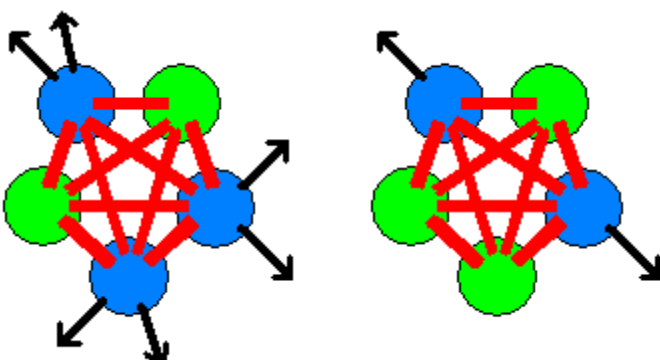


A stable nucleus contains particles which exert a much greater strong force attraction than electromagnetic repulsion.

An unstable nucleus contains particles which exert a similar sized strong force attraction and electromagnetic repulsion.

If the electromagnetic force was greater than strong force attraction, the nucleus could not form.

Adding another neutron adds to the strong force attraction between the nucleons but, since it is uncharged, it does not contribute to the electromagnetic repulsion.



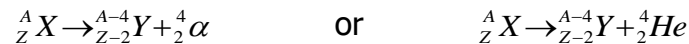
A large nucleus needs many more neutrons than protons as the strong force has a limited range compared to electromagnetic repulsion, this means that neutrons at either end of a large nucleus do not attract each other.

To compensate for this, more neutrons are placed inside the nucleus.



## Alpha Decay

When a nucleus decays in this way an alpha particle (a helium nucleus) is ejected from the nucleus.



You must remember the alpha decay nuclear equation.

### All the emitted alpha particles travelled at the same speed, meaning they had the same amount of energy.

The law of conservation of mass-energy is met, the energy of the nucleus before the decay is the same as the energy of the nucleus and alpha particle after the decay.

### Alpha decay is NOT due to the weak interaction but Beta decay IS

#### Beta Decay and the Neutrino

In beta decay a neutron in the nucleus changes to a proton and releases a beta particle (an electron).

The problem with beta decay was that the electrons had a range of energies so it appeared the law of conservation of mass-energy is violated, energy disappears.

To ensure this violation does not occur, there must be another particle being made with zero mass but variable speeds, the neutrino. This particle must take some of the energy.

So, the energy does not disappear, it is lost as the kinetic energy of the neutrinos, as the neutrinos leave with different kinetic energies, the beta particles have different energies.

In the following section, we will also discuss conservation laws and quark structure – this will be covered later in the course.

### REVIEW THIS SECTION AGAIN ONCE THIS HAS BEEN TAUGHT.

We can also see from the particle conservation laws that this is a forbidden interaction:  $n \rightarrow p + e^-$

Charge	Q: $0 \rightarrow +1 - 1$	$0 \rightarrow 0$	Charge is conserved
Baryon Number	B: $+1 \rightarrow +1 + 0$	$1 \rightarrow 1$	Baryon number is conserved
Lepton Number	L: $0 \rightarrow 0 + 1$	$0 \rightarrow 1$	Lepton number is NOT conserved

### To conserve lepton number in this decay, an (anti) neutrino must be produced also.

When a lepton is produced, an anti-neutrino of the same flavour is always produced.

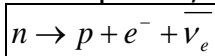
When an anti-lepton is produced, a neutrino of the same flavour is always produced.



In fact, there are two types of beta decay.

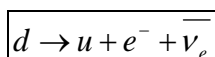
### Beta Minus ( $\beta^-$ ) Decay

In neutron-rich nuclei a neutron may decay into a proton, electron and an anti-electron neutrino.



Charge	Q: $0 \rightarrow +1 - 1 + 0$	$0 \rightarrow 0$	Charge is conserved
Baryon Number	B: $+1 \rightarrow +1 + 0 + 0$	$1 \rightarrow 1$	Baryon number is conserved
Lepton Number	L: $0 \rightarrow 0 + 1 - 1$	$0 \rightarrow 0$	Lepton number is conserved

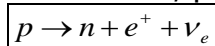
In terms of quarks beta minus decay looks like this:  $dud \rightarrow uud + e^- + \bar{\nu}_e$  which simplifies to:



Charge	Q: $-\frac{1}{3} \rightarrow +\frac{2}{3} - 1 + 0$	$-\frac{1}{3} \rightarrow -\frac{1}{3}$	Charge is conserved
Baryon Number	B: $+\frac{1}{3} \rightarrow +\frac{1}{3} + 0 + 0$	$\frac{1}{3} \rightarrow \frac{1}{3}$	Baryon number is conserved
Lepton Number	L: $0 \rightarrow 0 + 1 - 1$	$0 \rightarrow 0$	Lepton number is conserved

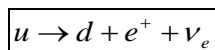
### Beta Plus ( $\beta^+$ ) Decay

In proton-rich nuclei a proton may decay into a neutron, positron and an electron neutrino.



Charge	Q: $+1 \rightarrow 0 + 1 + 0$	$1 \rightarrow 1$	Charge is conserved
Baryon Number	B: $+1 \rightarrow +1 + 0 + 0$	$1 \rightarrow 1$	Baryon number is conserved
Lepton Number	L: $0 \rightarrow 0 - 1 + 1$	$0 \rightarrow 0$	Lepton number is conserved

In terms of quarks beta plus decay looks like this:  $uud \rightarrow dud + e^+ + \nu_e$  which simplifies to:



Charge	Q: $+\frac{2}{3} \rightarrow -\frac{1}{3} + 1 + 0$	$\frac{2}{3} \rightarrow \frac{2}{3}$	Charge is conserved
Baryon Number	B: $+\frac{1}{3} \rightarrow +\frac{1}{3} + 0 + 0$	$\frac{1}{3} \rightarrow \frac{1}{3}$	Baryon number is conserved
Lepton Number	L: $0 \rightarrow 0 - 1 + 1$	$0 \rightarrow 0$	Lepton number is conserved

### Strangeness

The weak interaction is the only interaction that causes a quark to change into a different type of quark. In beta decay up quarks and down quarks are changed into one another.

**In some decays, an up or down quark can change into a strange quark meaning strangeness is not conserved.**

**During the weak interaction, there can be a change in strangeness of  $\pm 1$ .**

**Strangeness cannot change in the strong interaction – this makes certain decays forbidden in the strong but not the weak.**

#### Note

A decay via the weak interaction takes much longer to happen than via the strong interaction.

Therefore many particles with strangeness take a long time to decay and still exist in the Universe.

#### Note

Strangeness was another 'quantum number' invented to explain why certain decays did not happen when they should according to the other numbers.

It was strange.



**Additional Note Space**



**Additional Note Space**



## REVISION SHEET

Highlight or underline the key information on the revision sheet to consolidate your understanding.

### The Strong Nuclear Force Binds Nucleons Together

There are several different **forces** acting on the nucleons in a nucleus. The two you already know about are **electrostatic** forces from the protons' electric charges, and **gravitational** forces due to the masses of the particles.

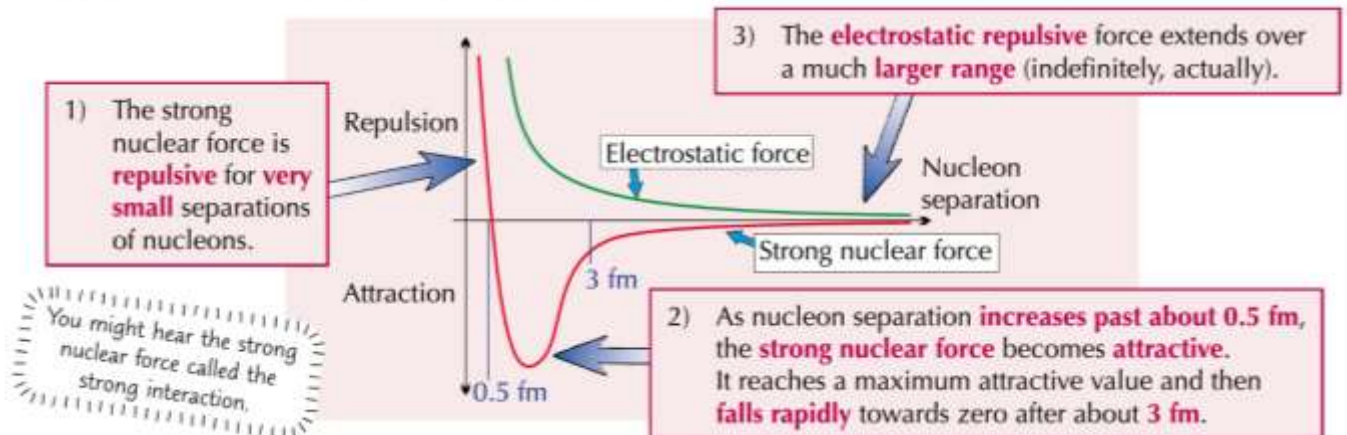
If you do the calculations (don't worry, you don't have to) you find the repulsion from the **electrostatic force** is much, much **bigger** than the **gravitational** attraction. If these were the only forces acting in the nucleus, the nucleons would **fly apart**. So there must be **another attractive force** that **holds the nucleus together** — called the **strong nuclear force**. (The gravitational force is so small, you can just ignore it.)

The **strong nuclear force** is quite **complicated**:

- 1) To **hold the nucleus together**, it must be an **attractive force** that's **stronger** than the electrostatic force.
- 2) Experiments have shown that the strong nuclear force has a **very short range**. It can only hold nucleons together when they're separated by up to a **few femtometres** ( $1 \text{ fm} = 1 \times 10^{-15} \text{ m}$ ) — the size of a nucleus.
- 3) The **strength** of the strong nuclear force **quickly falls** beyond this distance (see the graph below).
- 4) Experiments also show that the strong nuclear force **works equally between all nucleons**. This means that the size of the force is the same whether it's proton-proton, neutron-neutron or proton-neutron.
- 5) At **very small separations**, the strong nuclear force must be **repulsive** or it would **crush** the nucleus to a **point**.

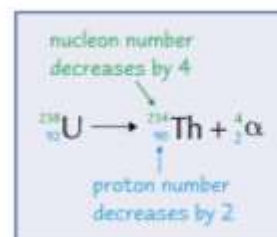
### The Size of the Strong Nuclear Force Varies with Nucleon Separation

The **strong nuclear force** can be plotted on a **graph** to show how it changes with the **distance of separation** between **nucleons**. If the **electrostatic force** is also plotted, you can see the **relationship** between these **two forces**.



### $\alpha$ Emission Happens in Very Big Nuclei

- 1) **Alpha emission** only happens in **very big** nuclei, like **uranium** and **radium**.
- 2) The **nuclei** of these atoms are just **too massive** for the strong nuclear force to keep them stable.
- 3) When an alpha particle is **emitted**:



The **proton number** decreases by **two**, and the **nucleon number** decreases by **four**.

Alpha particles have a very **short range** — only a few cm in air. This can be seen by observing the tracks left by alpha particles in a **cloud chamber**. You could also use a **Geiger counter** (a device that measures the amount of ionising radiation). Bring it up close to the alpha source, then **move it away** slowly and observe how the **count rate drops**.



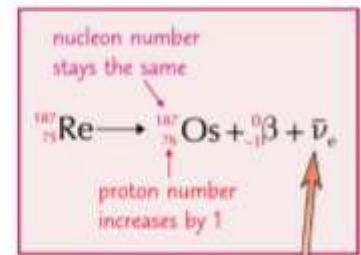


### $\beta^-$ Emission Happens in Neutron-Rich Nuclei

- 1) **Beta-minus** (usually just called beta) decay is the emission of an **electron** from the **nucleus** along with an **antineutrino**.
- 2) Beta decay happens in isotopes that are unstable due to being '**neutron rich**' (i.e. they have too many more **neutrons** than **protons** in their nucleus).
- 3) When a nucleus ejects a beta particle, one of the **neutrons** in the nucleus is **changed** into a **proton**.

The **proton number increases by one**, and the **nucleon number stays the same**.

Beta particles have a much greater range than alpha particles.



In beta decay, you get a **tiny neutral particle** called an **antineutrino** released. This antineutrino carries away some **energy** and **momentum**.

### Neutrinos Were First Hypothesised Due to Observations of Beta Decay

- 1) Scientists originally thought that the **only** particle emitted from the nucleus during beta decay was an **electron**.
- 2) However, observations showed that the **energy** of the particles **after** the **beta decay** was **less** than it was **before**, which didn't fit with the principle of **conservation of energy** (p. 64).
- 3) In 1930 Wolfgang Pauli suggested **another particle** was being emitted too, and it carried away the **missing energy**. This particle had to be **neutral** (or charge wouldn't be **conserved** in beta decay) and had to have **zero** or **almost zero** mass (as it had never been **detected**).
- 4) Other discoveries led to Pauli's theory becoming accepted and the particle was named the **neutrino**. (We now know this particle was an antineutrino — p. 6).
- 5) The neutrino was eventually observed 25 years later, providing evidence for Pauli's hypothesis.

**Credit:** CGP Revision Guide Editions



## SAMPLE QUESTION

**A1.** Alpha decay is a process by which an unstable *isotope* of an element may decay.

**A1.1** State what is meant by isotopes.

[2 Marks]

**same atomic number/number of protons**

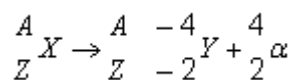
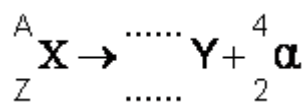
1 mark

**different mass/nucleon number/different number of neutrons**

1 mark

**A1.2** Complete this equation for alpha decay.

[2 Marks]



1 mark

**A1.3** Calculate the specific charge of an alpha particle, stating an appropriate unit.

[4 Marks]

**Specific Charge = Charge/ Mass**

$$\frac{q}{m} = \frac{2 \times 1.6 \times 10^{-19}}{4 \times 1.67 \times 10^{-27}}$$

1 mark

$$\frac{q}{m} = 4.8 \times 10^7 \text{ Ckg}^{-1}$$

**A1.4** Explain why the alpha particle, once outside the nucleus, is unaffected by the strong nuclear force.

[2 Marks]

**strong nuclear force is short range**

1 mark

**no effect at distances larger 3 fm  
(except any distance less than 10 fm)**

1 mark

**Reference:** AQA A Level Physics June 2011 Examination Unit 1



# SELF ASSESSMENT

**A1.** Name the constituent of an atom which

**A1.1** has zero charge,

[1 Mark]

.....  
 .....

**A1.2** has the largest charge to mass ratio,

[1 Mark]

.....  
 .....

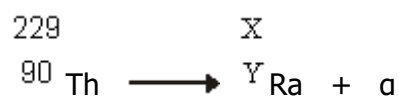
**A1.3** when removed leaves a different isotope of the element.

[1 Mark]

.....  
 .....

An  $\alpha$  particle is the same as a nucleus of helium,  ${}^4_2\text{He}$ .

The equation



represents the decay of thorium by the emission of an  $\alpha$  particle.

Determine

**A1.4** the values of **X** and **Y**, shown in the equation,

[1 Mark]

X = .....

Y = .....



**A1.5** the ratio  $\frac{\text{mass of } {}^X_Y\text{Ra nucleus}}{\text{mass of } \alpha \text{ particle}}$

[2 Marks]

.....

.....

.....

**Reference:** AQA A Level Physics Legacy A Examinations

**A2.1** Determine the charge, in C, of a  ${}^{239}_{92}\text{U}$  nucleus.

[1 Mark]

.....

.....

**A2.2** A positive ion with a  ${}^{239}_{92}\text{U}$  nucleus has a charge of  $4.80 \times 10^{-19}$  C. Determine how many electrons are in this ion.

[3 Marks]

.....

.....

.....

.....

**A2.3** A  ${}^{239}_{92}\text{U}$  nucleus may decay by emitting **two**  $\beta^-$  particles to form a plutonium nucleus  ${}^X_Y\text{Pu}$ . State what **X** and **Y** represent and give the numerical value of each.

[4 Marks]

X

.....

.....

Y

.....

.....

**Reference:** AQA A Level Physics Legacy A Examinations



**A3.** A neutral atom of a radium isotope may be represented by  ${}^{228}_{88}\text{Ra}$ .

**A3.1** Name the constituents of this atom and state how many of each are present.

**[3 Marks]**

.....

.....

.....

.....

**A3.2** Which constituent of an atom has the largest specific charge?

**[1 Mark]**

.....

.....

**A3.3** This isotope of radium decays by  $\beta^-$  decay to form an element with symbol, Ac. Write down an equation that represents this decay.

**[4 Marks]**

.....

.....

.....

.....

**A3.4**  ${}^A_Z\text{Ra}$  is a neutral atom of a different isotope of radium. State a possible value for **A** and for **Z**.

**[2 Marks]**

A: .....

Z: .....

**Reference:** AQA A Level Physics June 2012 Examination Unit 1



## TOPIC: 3.2.1.3 Particles, Antiparticles and Photons

### SPEC CHECK

Specification	Completed?
For every type of particle, there is a corresponding antiparticle.	
Comparison of particle and antiparticle masses, charge and rest energy in MeV.	
Know that the positron, antiproton, antineutron and antineutrino are the antiparticles of the electron, proton, neutron and neutrino respectively.	
Photon model of electromagnetic radiation, the Planck constant. $E = hf = hc/\lambda$	
Knowledge of annihilation and pair production and the energies involved.	
Detection of gamma radiation	
Determine the frequency and wavelength of the two gamma photons produced when a 'slow' electron and a 'slow' positron annihilate each other.	

These notes are brief.

More detailed notes are found in the student preparatory reading book.

Please read the preparatory reading notes.

## NOTES

### Antimatter

British Physicist Paul Dirac predicted a particle of equal mass to an electron but of opposite charge (positive).

This particle is called a positron and is the electron's *antiparticle*.

#### Note

Most anti-particles go by the prefix anti- e.g. anti-proton. However, the anti-electron is called the positron as it was discovered and named before this convention was established.

Every particle has its own antiparticle. An antiparticle has the same mass as the particle version but has opposite charge. An antiproton has a negative charge; an anti-electron has a positive charge but an antineutron is also uncharged like the particle version.

American Physicist Carl Anderson observed the positron in a cloud chamber, backing up Dirac's theory.

**Anti-particles have opposite Charge, Baryon Number, Lepton Number and Strangeness.**

**If they are made from quarks the antiparticle is made from antiquarks**

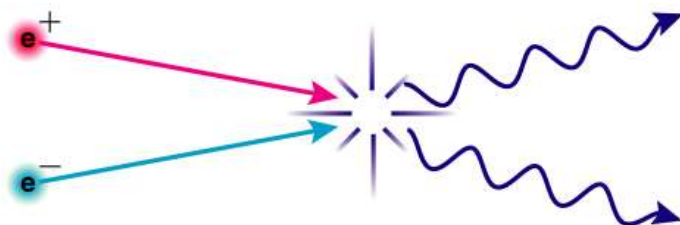
#### Note

Anti-particles have the opposite properties to that of particles except they have the same **rest** mass.



## Annihilation

Whenever a particle and its antiparticle meet they annihilate each other. Annihilation is the process by which mass is converted into energy, particle and antiparticle are transformed into two photons of energy.



To conserve momentum, two photons of energy are produced – not one.

This is why....

$E = hf$  for annihilation

A particle and anti-particle produces 2 photons.

Mass and energy are interchangeable and can be converted from one to the other. Mass can be considered to be an extreme potential energy store. Einstein linked energy and mass with the equation:

$$E = mc^2$$

You can think of it like money; whether you have dollars or pounds you would still have the same amount of money. So, whether you have mass or energy you still have the same amount.

The law of conservation of energy can now be referred to as the conservation of mass-energy. **The total mass-energy before is equal to the total mass-energy after.**

## Photon

Max Planck had the idea that light could be released in 'chunks' or packets of energy. Einstein named these wave-packets photons.

The energy carried by a photon is given by the equation:

$$E = hf$$

Since  $c = f\lambda$  we can also write this as:  $E = \frac{hc}{\lambda}$

Where  $h = \text{Planck's Constant} = 6.63 \times 10^{-34} \text{Js}$

This is the theory that energy (light) can exist as particles.

The energy of which is only determined by the frequency (colour) of the photon.

This went against the work of Young carrying out light wave diffraction, there it was theorised that light was a wave.

## How is there anything at all?

When the Big Bang happened matter and antimatter was produced and sent out expanding in all directions. A short time after this there was an imbalance in the amount of matter and antimatter. Since there was more matter all the antimatter was annihilated leaving matter to form protons, atoms and everything around us.



## Pair Production

Pair production is the opposite process to annihilation, energy is converted into mass. A single photon of energy is converted into a particle-antiparticle pair. (This happens to obey the conservation laws including momentum)



To conserve momentum, one photon of energy makes a particle and anti-particles

This is why....

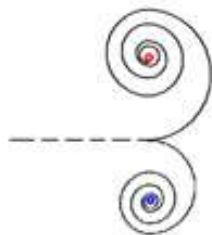
**$2E = hf$  for pair production**

There are two particles produced for one photon.

This can only happen if the photon has enough mass-energy to "pay for the rest mass".

Let us image mass and energy as the same thing, if two particles needed 10 "bits" and the photon had 8 bits there is not enough for pair production to occur.

If two particles needed 10 bits to make and the photon had 16 bits the particle-antiparticle pair is made and the left over is converted into their kinetic energy.



The particle and anti-particle would need kinetic energy to escape their opposite charge attraction to each other.

As this would lead to annihilation.

If pair production occurs in a magnetic field the particle and antiparticle will move in circles of opposite direction but only if they are charged.

(The deflection of charges in magnetic fields will be covered in A Level Physics)

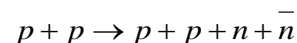
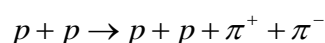
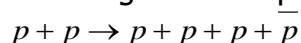
Pair production can occur spontaneously but must occur near a nucleus which recoils to help conserve momentum. It can also be made to happen by colliding particles.

At CERN protons are accelerated and fired into each other.

If they have enough kinetic energy when they collide particle-antiparticle pair may be created from the energy.

Therefore, the particles are sped up to high speeds, they have more kinetic energy when moving at these speeds, this can be turned into the rest mass of larger, more exotic particles (particles which were around at the start of the Universe).

The following are examples of the reactions that have occurred:



In all we can see that the conservation laws of particle physics (including momentum) are obeyed.



**Additional Note Space**



**Additional Note Space**

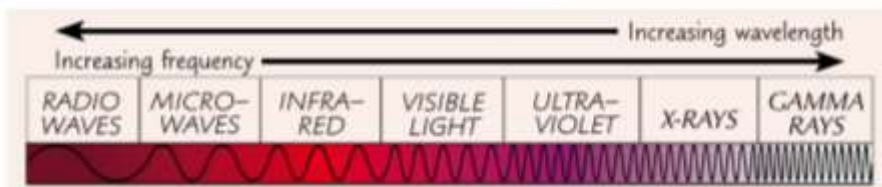


## REVISION SHEET

Highlight or underline the key information on the revision sheet to consolidate your understanding.

### Photons are Packets of Electromagnetic Radiation

Visible light is just one type of electromagnetic radiation. The **electromagnetic spectrum** is a continuous spectrum of **all** the possible frequencies of electromagnetic radiation.



The **frequency**  $f$  and **wavelength**  $\lambda$  are linked by  $f = \frac{c}{\lambda}$ , where  $c = 3.00 \times 10^8 \text{ ms}^{-1}$  is the **speed of light** in a vacuum (sometimes called the speed of light **in vacuo**).

Electromagnetic radiation exists as **photons** of energy (page 16).

The **energy** of a photon depends on the frequency of the radiation:

$$E = hf = \frac{hc}{\lambda}$$

$h$  is the Planck constant, equal to  $6.63 \times 10^{-34} \text{ Js}$ .

### Every Particle has an Antiparticle

- Each particle has a **matching antiparticle** with the **same mass and rest energy** (more later), but with **opposite charge** (amongst other things).
- For instance, an **antiproton** is a **negatively-charged** particle with the same mass as the **proton**, and the **antineutrino** is the antiparticle of the **neutrino** — it doesn't do much either.

Particle/Antiparticle	Symbol	Relative Charge	Mass (kg)	Rest Energy (MeV)
proton	$p$	+1	$1.67(3) \times 10^{-27}$	938(3)
antiproton	$\bar{p}$	-1		
neutron	$n$	0	$1.67(5) \times 10^{-27}$	939(6)
antineutron	$\bar{n}$			
electron	$e^-$	-1	$9.11 \times 10^{-31}$	0.51(1)
positron	$e^+$	+1		
neutrino	$\nu_e$	0	0	0
antineutrino	$\bar{\nu}_e$			

These are actually an electron-neutrino and an electron-antineutrino (p. 12).

Luckily, in the exam you'll be given all the **masses** in kg and **rest energies**



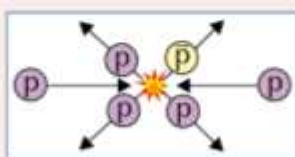
in MeV of each of these particles and their antiparticles. You just need to remember that the **mass** and **rest energy** are the **same** for a particle and its antiparticle. Neutrinos and antineutrinos are incredibly tiny — you can assume they have zero mass and zero rest energy.

1 MeV =  $1 \times 10^6$  eV.  
There's more on eV (electron volts) on p. 18.

### You can Create Matter and Antimatter from Energy

You've probably heard about the **equivalence** of energy and mass. It all comes out of Einstein's Special Theory of Relativity. **Energy** can turn into **mass** and **mass** can turn into **energy** if you know how. The **rest energy** of a particle is just the 'energy equivalent' of the particle's **mass**, measured in MeV. You can work it all out using the formula  $E = mc^2$ , but you won't be expected to do the calculations for AS.

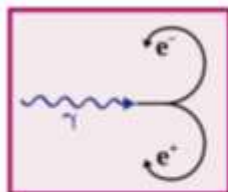
When **energy** is converted into **mass** you get **equal amounts** of **matter** and **antimatter**.



Fire **two protons** at each other at high speed and you'll end up with a lot of **energy** at the point of impact. This energy might be converted into **more particles**. If an extra **proton** is formed then there will always be an **antiproton** to go with it. It's called **pair production**.

### Each Particle-Antiparticle Pair is Produced from a Single Photon

**Energy** that gets **converted** into **matter** and **antimatter** is in the form of a **photon** (p.16). Pair production only happens if **one photon** has enough energy to produce that much mass — only **gamma ray** photons have enough energy. It also tends to happen near a **nucleus**, which helps conserve momentum.



The particle tracks are curved because there's usually a magnetic field present in particle physics experiments. They curve in opposite directions because of the opposite charges on the electron and positron.

You usually get **electron-positron** pairs produced (rather than any other pair) — because they have a relatively **low mass**.

The **minimum energy** for a photon to undergo **pair production** is the **total rest energy** of the particles produced.

The particle and antiparticle each have a rest energy of  $E_0$ , so:

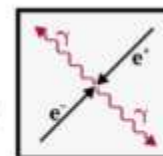
$$E_{\min} = hf_{\min} = 2E_0$$

### The Opposite of Pair-Production is Annihilation

When a **particle** meets its **antiparticle** the result is **annihilation**. All the **mass** of the particle and antiparticle gets converted back to **energy**. Antiparticles can usually only exist for a fraction of a second before this happens, so you don't get them in ordinary matter.



OR



An annihilation is between a particle-antiparticle pair, which both have a rest energy  $E_0$ . **Both** photons need to have a **minimum energy**,  $E_{\min}$ , which when added together equals at least  $2E_0$  for **energy** to be **conserved** in this interaction. So  $2E_{\min} = 2E_0$  and:

$$E_{\min} = hf_{\min} = E_0$$

The electron and positron annihilate and their mass is converted into the energy of a pair of gamma ray photons to conserve momentum.

**Example:** Calculate the maximum wavelength of one of the photons produced when an electron and positron annihilate each other.

For annihilation, minimum photon energy  $E_{\min} = hf_{\min} = E_0$ . Remember  $f = \frac{c}{\lambda}$ , so  $\frac{hc}{\lambda_{\max}} = E_0$ .

$$\text{So } \lambda_{\max} = \frac{hc}{E_0} = \frac{(6.63 \times 10^{-34}) \times (3.00 \times 10^8)}{(0.511 \times 10^6) \times (1.60 \times 10^{-19})} = 2.432... \times 10^{-12} = 2.43 \times 10^{-12} \text{ m (to 3 s.f.)}$$

The Planck constant is in J, so you need to convert  $E_0$  from MeV to J.



## SAMPLE QUESTION

**Q1.** Under certain circumstances it is possible for a photon to be converted into an electron and a positron.

**Q1.1** State what this process is called.

[1 Mark]

**Pair production**

1 mark

**Q1.2** A photon must have a minimum energy in order to create an electron and a positron.

Calculate the minimum energy of the photon in joules. Give your answer to an appropriate number of significant figures.

[3 Marks]

**energy = 2 × rest mass energy (as 1 photon creates 2 particles)**

**energy = 2 × 0.510999**

**energy = 1.021998 MeV**

1 mark

**Convert to Joules – Give the answers to the correct sig figs (3).** 1 mark

**energy = 1.021998 × 1.60 × 10<sup>-13</sup> = 1.64 × 10<sup>-13</sup> J**

1 mark

**Q1.3** A photon of slightly higher energy than that calculated in part (b) is converted into an electron and a positron.

State what happens to the excess energy.

[3 Marks]

**It gets transferred to kinetic energy (of electron and positron)** 1 mark

**Q1.4** Describe what is likely to happen to the positron shortly after its creation.

**It meets an electron and they annihilate**

1 mark

**This converts into two or more photons, which are observed as gamma rays**

1 mark

(2)

**Reference:** AQA A Level Physics January 2013 Examination Unit 1



## SELF ASSESSMENT

**Q1.** Under certain conditions a  $\gamma$  photon may be converted into an electron and a positron.

**Q1.1** What is this process called?

[1 Mark]

.....  
.....

**Q1.2** Explain why there is a minimum energy of the  $\gamma$  photon for this conversion to take place and what happens when a  $\gamma$  photon has slightly more energy than this value.

[2 Marks]

.....  
.....  
.....  
.....

**Q1.3** Using values from the data sheet calculate this minimum energy in MeV.

[1 Mark]

.....  
.....

**Q1.4** Under suitable conditions, a  $\gamma$  photon may be converted into two other particles rather than an electron and positron.  
Give an example of the two other particles it could create.

[1 Mark]

.....  
.....

**Reference:** AQA A Level Physics Legacy A Examination

**A2.1** Pair production can occur when a photon interacts with matter. Explain the process of pair production.

[2 Marks]

.....  
.....  
.....



**Q2.2** Explain why pair production cannot take place if the frequency of the photon is below a certain value.

**[3 Marks]**

.....

.....

.....

.....

**Q2.3** Energy and momentum are conserved during pair production. State two other quantities that must also be conserved.

**[2 Marks]**

.....

.....

**Reference:** AQA A Level Physics June 2012 Examination Unit 1

**Q3.1** State the name of the antiparticle of a positron.

**[1 Mark]**

.....

.....

**Q3.2** Describe what happens when a positron and its antiparticle meet.

**[2 Marks]**

.....

.....

**Reference:** AQA A Level Physics Legacy B Examinations





The general term for exchange particles is *bosons* and they are fundamental particles like quarks and leptons.

### Ice Skating Analogy

Imagine two people on ice skates that will represent the two bodies experiencing a force.

If A throws a bowling ball to B, A slides back when they release it and B moves back when they catch it. Repeatedly throwing the ball back and forth moves A and B away from each other, the force causes repulsion.

The analogy falls a little short when thinking of attraction.

Imagine that A and B are exchanging a boomerang (bear with it), throwing it behind them pushes A towards B, B catches it from behind and moves towards A. The force causes attraction.

### Which Particle for What Force

Each of the interactions/forces has its own exchange particles.

Interaction/Force	Exchange Particle			What is acts upon
Strong Nuclear	Gluons (name when between quarks)	Pions (name when between Baryons)		Nucleons (Hadrons)
Electromagnetic	Virtual Photon			Charged particles
Weak Nuclear	$W^+$	$W^-$	$Z^0$	All particles
Gravitational	Graviton			Particles with masses

### Borrowing Energy to Make Particles

The exchange particles are made from 'borrowed' energy, borrowed from where? From nowhere! Yukawa used the Heisenberg Uncertainty Principle to establish that a particle of mass-energy  $\Delta E$  could exist for a time  $\Delta t$  if  $\Delta E \cdot \Delta t \leq h$  where  $h$  is Planck's constant.

This means that a heavy particle can only exist for a short time while a lighter particle may exist for longer.

**$h$  is Planck's Constant,  $h = 6.63 \times 10^{-34} \text{ J s}$ .**

The W/Z and pion boson have a rest mass, this means the force they produce has a finite range. The photon and graviton have no rest mass, this means the force has an infinite range.

In 1947 the exchange particle of the strong nuclear interaction was observed in a cloud chamber. By 2017, the only exchange particle which has not been observed is the graviton. This could either be because gravity is very weak or gravity is not actually a force.

### Lending Money Analogy

Think of making exchange particles in terms of lending somebody some money.

If you lend somebody £50 you would want it paid back soon.

If you lend somebody 50p you would let them have it for longer before paying you back.



## Feynman Diagrams

American Physicist called Richard Feynman came up with a way of visualising forces and exchange particles. Below are some examples of how Feynman diagrams can represent particle interactions.

The most important things to note when dealing with Feynman diagrams are the arrows and the exchange particles, the lines do not show us the path that the particles take only which come in and which go out.

**The arrows tell us which particles are present before the interaction and which are present after the interaction.**

**The wave represents the interaction taking place with the appropriate exchange particle labelled.**

The particles at the bottom of the diagram represent the particles before the interaction.

The particles at the top of the diagram represent the particles after the interaction.

The angle of the lines is irrelevant. This is not the movement of the particles.

You can only join lines with arrows if you include a 'wavy line' of the exchange particle.

It is possible to represent an anti-particle with particle notation with the arrow moving in the opposite direction.

Two 'wavy lines' can never be joined to each other.

### Examples

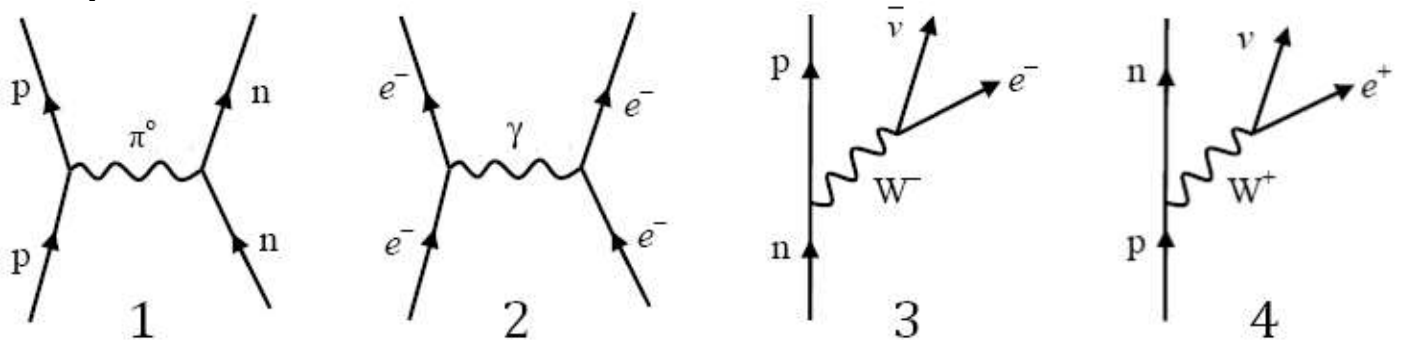


Diagram 1 represents the strong interaction. A proton and neutron are attracted together by the exchange of a neutral pion.

Diagram 2 represents the electromagnetic interaction. Two electrons repel each other by the exchange of a virtual photon.

Diagram 3 represents beta minus decay. A neutron decays due to the weak interaction into a proton, an electron and an anti-electron neutrino

Diagram 4 represents beta plus decay. A proton decays into a neutron, a positron and an electron neutrino.

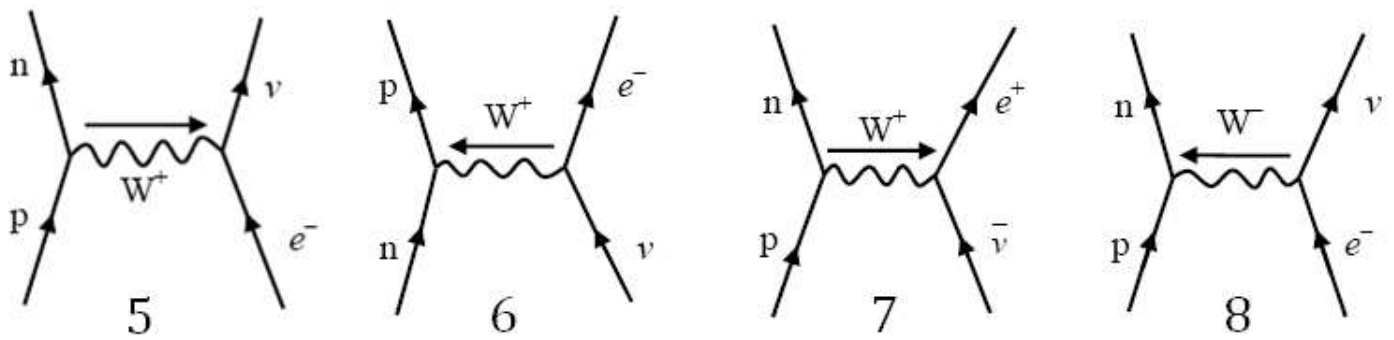


Diagram 5 represents electron capture. A proton captures an electron and becomes a neutron and an electron neutrino.

Diagram 6 represents a neutrino-neutron collision. A neutron absorbs a neutrino and forms a proton and an electron.

Diagram 7 represents an antineutrino-proton collision. A proton absorbs an antineutrino and emits a neutron and an electron.

Diagram 8 represents an electron-proton collision. They collide and emit a neutron and an electron neutrino.

### Getting the Exchange Particle

The aspect of Feynman diagrams that students often struggle with is labelling the exchange particle and the direction to draw it.

Look at what you start with:

If it is positive and becomes neutral, you can think of it as throwing away its positive charge so the  $W$  boson will be positive. This is the case in electron capture.

If it is positive and becomes negative, you can think of it as gaining negative to neutralise it so the  $W$  boson will be negative. This is the case in electron-proton collisions.

If it is neutral and becomes positive, we can think of it either as gaining positive ( $W^+$  boson) or losing negative ( $W^-$  boson in the opposite direction).

**Work out where the charge is going and label it.**



**Additional Note Space**



**Additional Note Space**



## REVISION SHEET

Highlight or underline the key information on the revision sheet to consolidate your understanding.

### Forces are Caused by Particle Exchange

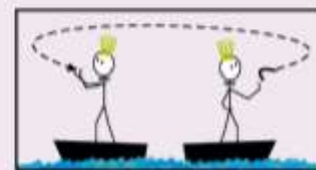
You can't have **instantaneous action at a distance** (according to Einstein, anyway). So, when two particles **interact**, something must **happen** to let one particle know that the other one's there. That's the idea behind **exchange particles**.

- 1) **Repulsion** — Each time the **ball** is **thrown or caught** the people get **pushed apart**. It happens because the ball carries **momentum**.



Particle exchange also explains **attraction**, but you need a bit more imagination.

- 2) **Attraction** — Each time the **boomerang** is **thrown or caught** the people get **pushed together**. (In real life, you'd probably fall in first.)



These exchange particles are called **gauge bosons**.

The **repulsion** between two **protons** is caused by the **exchange** of **virtual photons**, which are the gauge bosons of the **electromagnetic** force. Gauge bosons are **virtual** particles — they only exist for a **very short time**.

### There are Four Fundamental Forces

**All forces in nature** are caused by four **fundamental** forces — the strong nuclear force, the weak nuclear force, the electromagnetic force and gravity. Each one has its **own gauge boson** and these are the ones you have to learn:

Type of Interaction	Gauge Boson	Particles Affected
electromagnetic	virtual photon (symbol, $\gamma$ )	charged particles only
weak	$W^+$ , $W^-$	all types
strong	pions ( $\pi^+$ , $\pi^-$ , $\pi^0$ )	hadrons only

Particle physicists never **bother** about **gravity** because it's so incredibly **feeble** compared with the other types of interaction. Gravity only really **matters** when you've got **big masses** like **stars and planets**.

In the **strong nuclear force**, pions are described as being exchanged between **nucleons**. You might also see it described as **gluons** being exchanged between **quarks** (p. 13).

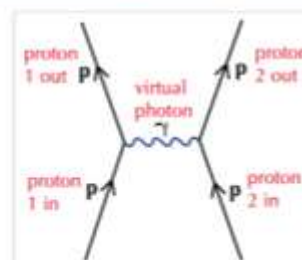
### The Larger the Mass of the Gauge Boson, the Shorter the Range of the Force

- 1) The **W bosons** have a **mass** of about **100 times that of a proton**, which gives the weak force a **very short range**. Creating a **virtual W particle** uses **so much energy** that it can only exist for a **very short time** and it **can't travel far**.
- 2) On the other hand, the **photon** has **zero mass**, which gives you a force with **infinite range**.

### You can use Diagrams to Show What's Going In and What's Coming Out

**Particle interactions** can be hard to get your head around. A **neat way of solving problems** is by **drawing simple diagrams** of particle interactions rather than doing **calculations**.

- 1) **Gauge bosons** are represented by **wiggly lines** (technical term).
- 2) Other **particles** are represented by **straight lines**.

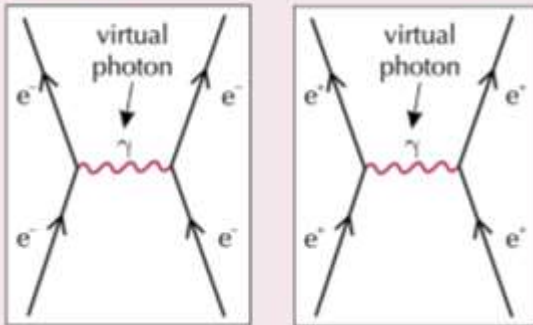




**You Need to Be Able to Draw Diagrams of these Interactions**

**Electromagnetic Repulsion**

This is the easiest of the lot. When two particles with **equal charges** get close to each other, they **repel**.



two electrons repelling each other

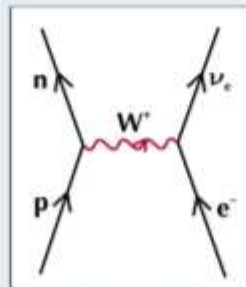
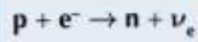
two positrons repelling each other

**RULES FOR DRAWING PARTICLE INTERACTION DIAGRAMMS:**

- 1) Incoming particles start at the bottom of the diagram and move upwards.
- 2) The **baryons** (p.10) and **leptons** (p.12) can't cross from one side to the other.
- 3) Make sure the charges on both sides balance. The **W bosons** carry **charge** from one side of the diagram to the other.
- 4) A **W<sup>-</sup>** particle going to the **left** has the same effect as a **W<sup>+</sup>** particle going to the **right**.

**Electron Capture and Electron-proton Collisions**

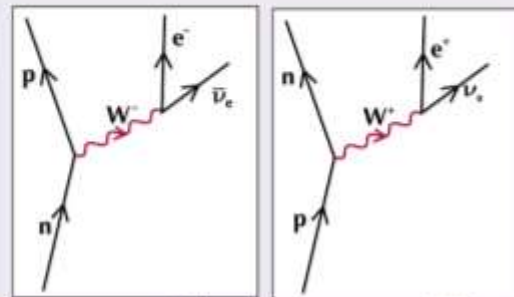
Electrons and protons are of course attracted by the **electromagnetic interaction** between them, but if a proton **captures** an electron, the **weak interaction** can make this interaction happen.



electron capture

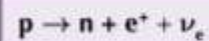
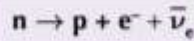
You also need to know about **electron-proton collisions**, where an electron **collides** with a proton. The equation is just the same as electron capture but in the diagram a **W<sup>-</sup> boson** goes from the **electron** to the **proton** instead of a **W<sup>+</sup>** travelling the other way.

**Beta-plus and Beta-minus Decay**



$\beta^-$  decay

$\beta^+$  decay



You get an **antineutrino** in  $\beta^-$  decay and a **neutrino** in  $\beta^+$  decay so that **lepton number** (p.12) is conserved.

You'll see on p.14 that when a proton changes to a neutron or vice versa, it has to be the weak interaction.

**Credit:** CGP Revision Guide Editions



## SAMPLE QUESTION

**A1.1** Explain what is meant by an *exchange particle*.

[2 Marks]

**moves between one object and another/carrier acting on two particles**

1 mark

**gives rise to the force between the particles**

1 mark

**A1.2** Name the exchange particle that mediates the strong force.

[1 Mark]

**Gluons or pions**

**A1.3** The weak nuclear force acts over a much shorter distance than the strong force. Explain **two** differences between the relevant exchange particles that account for this.

[2 Marks]

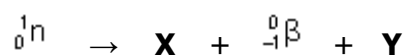
**gluons lighter/(w) bosons more massive**

1 mark

**gluons have longer range/(w) bosons have shorter range**

1 mark

**A1.4** The following equation shows the  $\beta^-$  decay of a free neutron.



Identify each of the particles **X** and **Y**.

Show the appropriate nucleon and proton number for each of the particles.

[2 Marks]

**X**       ${}^1_1\text{p}$

1 mark

**Y**       ${}^0_0\bar{\nu}$

1 mark

**These answers can be in either order – a neutron decays to form a proton (the most stable baryon) and an antineutrino is always formed when an electron forms.**

**Reference:** AQA A Level Physics June 2011 Examination Unit 1



# SELF ASSESSMENT

**A1.1** Give an example of an exchange particle other than a  $W^+$  or  $W^-$  particle, and state the fundamental force involved when it is produced.

[2 Marks]

Exchange Particle .....

Fundamental Interaction .....

**A1.2** State what roles exchange particles can play in an interaction.

[2 Marks]

.....  
 .....

From the following list of particles,

$p \quad \bar{n} \quad \nu_e \quad e^- \quad \mu^- \quad \pi^+$

identify **all** the examples of

[4 Marks]

**A1.3** hadrons, .....

**A1.4** leptons, .....

**A1.5** antiparticles, .....

**A1.6** charged particles. ....

**Reference:** AQA A Level Physics Legacy A Examinations

**A2.** The equation

$$p \longrightarrow n + \beta^+ + \nu_e$$

represents the emission of a positron from a proton.

Draw the Feynman diagram that corresponds to the positron emission represented in the equation.

[4 Marks]



Complete the following table using ticks ✓ and crosses ✗.

[4 Marks]

particle	fundamental particle	meson	baryon	lepton
p				
n				
$\beta^-$				
$\nu_e$				

**Reference:** AQA A Level Physics Legacy A Examinations

**A3.1** State the role of **exchange particles** in the creation of forces between particles.

[1 Mark]

.....

.....

**A3.2** Complete the table below to show an exchange particle that is responsible for each of the forces mentioned.

[3 Marks]

Interaction	exchange particle responsible
weak nuclear force	
strong force	
electromagnetic force	

**Reference:** AQA A Level Physics January 2011 Unit 1 Examination



## TOPIC: 3.2.1.5 Classification of Particles

### SPEC CHECK

Specification	Completed?
Hadrons are subject to the strong interaction.	
The two classes of hadrons: <ul style="list-style-type: none"> <li>• baryons (proton, neutron) and antibaryons (antiproton and antineutron)</li> <li>• mesons (pion, kaon).</li> </ul>	
Baryon number as a quantum number.	
Conservation of baryon number.	
The proton is the only stable baryon into which other baryons eventually decay.	
The pion as the exchange particle of the strong nuclear force.	
The kaon as a particle that can decay into pions.	
Leptons: electron, muon, neutrino (electron and muon types only) and their antiparticles.	
Lepton number as a quantum number; conservation of lepton number for muon leptons and for electron leptons.	
The muon as a particle that decays into an electron.	
Strange particles as particles that are produced through the strong interaction and decay through the weak interaction (e.g. kaons).	
Strangeness (symbol $s$ ) as a quantum number to reflect the fact that strange particles are always created in pairs.	
Conservation of strangeness in strong interactions.	
Strangeness can change by 0, +1 or -1 in weak interactions.	
Appreciation that particle physics relies on the collaborative efforts of large teams of scientists and engineers to validate new knowledge.	
Cosmic ray showers as a source of high energy particles including pions and kaons; observation of stray tracks in a cloud chamber; use of two Geiger counters to detect a cosmic ray shower.	



These notes are brief.

More detailed notes are found in the student preparatory reading book.

Please read the preparatory reading notes.

## NOTES

### Hadrons

Hadrons, the Greek for 'heavy' are not fundamental particles they are all made from smaller particles, quarks. Hadrons are defined as particles which interact due to the strong interaction.

The properties of a hadron are due to the combined properties of the quarks that it is made from.

There are two categories of Hadrons: Baryons and Mesons – due to how many quarks they have.

Below are the quark compositions of the different particles – we will investigate quarks further in the next section.

### Baryons Made from three quarks

Proton	Charge (Q)	Baryon Number (B)	Strangeness (S)
u	$+\frac{2}{3}$	$+\frac{1}{3}$	0
u	$+\frac{2}{3}$	$+\frac{1}{3}$	0
d	$-\frac{1}{3}$	$+\frac{1}{3}$	0
<b>p</b>	<b>+1</b>	<b>+1</b>	<b>0</b>

Neutron	Charge (Q)	Baryon Number (B)	Strangeness (S)
d	$-\frac{1}{3}$	$+\frac{1}{3}$	0
u	$+\frac{2}{3}$	$+\frac{1}{3}$	0
d	$-\frac{1}{3}$	$+\frac{1}{3}$	0
<b>n</b>	<b>0</b>	<b>+1</b>	<b>0</b>

The proton is the only stable free hadron; all others eventually decay into a proton.

Inside the nucleus, the nucleus also becomes stable due to the increased strong force.

### Mesons Made from a quark and an antiquark

Pion Plus	Charge (Q)	Baryon Number (B)	Strangeness (S)
u	$+\frac{2}{3}$	$+\frac{1}{3}$	0
$\bar{d}$	$+\frac{1}{3}$	$-\frac{1}{3}$	0
<b><math>\pi^+</math></b>	<b>+1</b>	<b>0</b>	<b>0</b>

Pion Minus	Charge (Q)	Baryon Number (B)	Strangeness (S)
$\bar{u}$	$-\frac{2}{3}$	$-\frac{1}{3}$	0
d	$-\frac{1}{3}$	$+\frac{1}{3}$	0
<b><math>\pi^-</math></b>	<b>-1</b>	<b>0</b>	<b>0</b>

Pion Zero	Charge (Q)	Baryon Number (B)	Strangeness (S)
u	$+\frac{2}{3}$	$+\frac{1}{3}$	0
$\bar{u}$	$-\frac{2}{3}$	$-\frac{1}{3}$	0
<b><math>\pi^0</math></b>	<b>0</b>	<b>0</b>	<b>0</b>

Pion Zero	Charge (Q)	Baryon Number (B)	Strangeness (S)
d	$-\frac{1}{3}$	$+\frac{1}{3}$	0
$\bar{d}$	$+\frac{1}{3}$	$-\frac{1}{3}$	0
<b><math>\pi^0</math></b>	<b>0</b>	<b>0</b>	<b>0</b>

Kaon Plus	Charge (Q)	Baryon Number (B)	Strangeness (S)
u	$+\frac{2}{3}$	$+\frac{1}{3}$	0
$\bar{s}$	$+\frac{1}{3}$	$-\frac{1}{3}$	+1
<b><math>K^+</math></b>	<b>+1</b>	<b>0</b>	<b>+1</b>

Kaon Minus	Charge (Q)	Baryon Number (B)	Strangeness (S)
$\bar{u}$	$-\frac{2}{3}$	$-\frac{1}{3}$	0
s	$-\frac{1}{3}$	$+\frac{1}{3}$	-1
<b><math>K^-</math></b>	<b>-1</b>	<b>0</b>	<b>-1</b>



<b>Kaon Zero</b>	<b>Charge (Q)</b>	<b>Baryon Number (B)</b>	<b>Strangeness (S)</b>
d	$-\frac{1}{3}$	$+\frac{1}{3}$	0
$\bar{s}$	$+\frac{1}{3}$	$-\frac{1}{3}$	+1
<b>K<sup>0</sup></b>	<b>0</b>	<b>0</b>	<b>+1</b>

<b>Anti-Kaon Zero</b>	<b>Charge (Q)</b>	<b>Baryon Number (B)</b>	<b>Strangeness (S)</b>
$\bar{d}$	$+\frac{1}{3}$	$-\frac{1}{3}$	0
s	$-\frac{1}{3}$	$+\frac{1}{3}$	-1
<b><math>\bar{K}^0</math></b>	<b>0</b>	<b>0</b>	<b>-1</b>

If a particle has a strangeness attached it has been named a kaon.

Kaons take a long time to decay, since in kaon decay, strangeness is not conserved, so it must decay via the weak interaction, taking a long time.

### Anti-Hadrons

Anti-hadrons are made from the opposite quarks as their Hadron counterparts, for example a proton is made from the quark combination uud and an antiproton is made from the combination  $\bar{u}\bar{u}\bar{d}$ . Anti-hadrons have the opposite properties compared to hadrons except they have the same rest mass.

We can see that a  $\pi^+$  and a  $\pi^-$  are particle and antiparticle of each other.

<b>Anti-Proton</b>	<b>Charge (Q)</b>	<b>Baryon Number (B)</b>	<b>Strangeness (S)</b>
$\bar{u}$	$-\frac{2}{3}$	$-\frac{1}{3}$	0
$\bar{u}$	$-\frac{2}{3}$	$-\frac{1}{3}$	0
$\bar{d}$	$+\frac{1}{3}$	$-\frac{1}{3}$	0
<b><math>\bar{p}</math></b>	<b>-1</b>	<b>-1</b>	<b>0</b>

<b>Anti Neutron</b>	<b>Charge (Q)</b>	<b>Baryon Number (B)</b>	<b>Strangeness (S)</b>
$\bar{d}$	$+\frac{1}{3}$	$-\frac{1}{3}$	0
$\bar{u}$	$-\frac{2}{3}$	$-\frac{1}{3}$	0
$\bar{d}$	$+\frac{1}{3}$	$-\frac{1}{3}$	0
<b><math>\bar{n}</math></b>	<b>0</b>	<b>-1</b>	<b>0</b>

Mesons are their own anti-particles due to their combinations of quarks.

You need to know all the quark combination shown on this page as they may ask you to recite any of them.

### Fundamental Particles

A fundamental particle is a particle which is not made of anything smaller.

Baryons and Mesons are made from quarks so they are not fundamental, but quarks themselves are.

The only other known fundamental particles are Bosons (Exchange Particles) and Leptons.

### Leptons

Leptons are a family of particles that are much lighter than Baryons and Mesons and are not subject to the strong interaction. There are six leptons in total, three of them are charged and three are uncharged.

The charged particles are electrons, muons and taus. The muon and tau are like the electron but bigger. The muon is roughly 200 times bigger and the tau is 3500 times bigger (twice the size of a proton). The lighter the particle, the easier it is to produce via pair production, this makes the electron the most abundant.

Each of the charged leptons has its own neutrino. If a decay involves a neutrino and a muon, it will be a muon neutrino, not a tau neutrino or electron neutrino.



The neutrino is a charge less, almost massless particle. It isn't affected by the strong interaction or EM force and barely by gravity. It is almost impossible to detect.

Lepton		Charge (Q)	Lepton Number (L)	Anti-Lepton		Charge (Q)	Lepton Number (L)
Electron	$e^-$	-1	+1	Anti-Electron	$e^+$	+1	-1
Electron Neutrino	$\nu_e$	0	+1	Anti-Electron Neutrino	$\bar{\nu}_e$	0	-1
Muon	$\mu^-$	-1	+1	Anti-Muon	$\mu^+$	+1	-1
Muon Neutrino	$\nu_\mu$	0	+1	Anti-Muon Neutrino	$\bar{\nu}_\mu$	0	-1
Tau	$\tau^-$	-1	+1	Anti Tau	$\tau^+$	+1	-1
Tau Neutrino	$\nu_\tau$	0	+1	Anti Tau Neutrino	$\bar{\nu}_\tau$	0	-1

### Number Reminders

There may be a clue to the charge of a particle;  $n^+$ ,  $K^+$  and  $e^+$  have a positive charge.

It will only have a baryon number if it **IS** a baryon. Mesons and Leptons have a Baryon Number of zero.

It will only have a lepton number if it **IS** a lepton. Baryons and Mesons have a Lepton Number of zero.

It will only have a strangeness if it is made from a strange quark. Leptons have a strangeness of zero, as they contain no quarks.

**Additional Note Space**



**Additional Note Space**



# REVISION SHEET

Highlight or underline the key information on the revision sheet to consolidate your understanding.

## **Hadrons are Particles that Feel the Strong Nuclear Force** (e.g. Protons and Neutrons)

- 1) The **nucleus** of an atom is made up of **protons** and **neutrons** (déjà vu).
- 2) Since the **protons** are **positively charged** they need a strong force to hold them together. This is called the **strong nuclear force** or the **strong interaction** (who said physicists lack imagination...). See page 4 for details.
- 3) **Not all particles** can feel the **strong nuclear force** — the ones that **can** are called **hadrons**.
- 4) Hadrons aren't **fundamental** particles. They're made up of **smaller particles** called **quarks** (see pages 13–15).
- 5) There are **two** types of **hadrons** — **baryons** (and anti-baryons) and **mesons**. They're classified according to the number of **quarks** that make them up, but don't worry about that for now.

(Leptons are an example of particles that **can't**. See page 12.)

## **Protons and Neutrons are Baryons**

- 1) It's helpful to think of **protons** and **neutrons** as **two versions** of the **same particle** — the **nucleon**. They just have **different electric charges**.
- 2) **Protons** and **neutrons** are both **baryons**.
- 3) There are **other baryons** that you don't get in normal matter — like **sigmas** ( $\Sigma$ ) — they're **short-lived** and you **don't** need to **know about them** (woohoo!).



Baryon and Meson felt the strong interaction.

## **The Proton is the Only Stable Baryon**

All **baryons** — except the proton — are **unstable**. This means that they **decay** to become other **particles**. The **particles** a baryon ends up as depends on what it started as, but it **always** includes a **proton**. **Protons** are the only **stable baryons** — they don't decay (as far as we know).

All baryons except protons decay to a **proton**.

Some theories predict that protons should decay with a very long half-life, but there's no evidence for it at the moment.

## **Antiprotons and Antineutrons are Antibaryons**

The **antiparticles** of protons and neutrons — **antiprotons** and **antineutrons** — are **antibaryons**. But, if you remember from page 7, **antiparticles** are **annihilated** when they meet the corresponding **particle** — which means that you **don't** find **antibaryons** in ordinary matter.

## **Antiprotons and Antineutrons are Antibaryons**

The **antiparticles** of protons and neutrons — **antiprotons** and **antineutrons** — are **antibaryons**. But, if you remember from page 7, **antiparticles** are **annihilated** when they meet the corresponding **particle** — which means that you **don't** find **antibaryons** in ordinary matter.

## **The Number of Baryons in an Interaction is called the Baryon Number**

The **baryon number** is the number of baryons. (A bit like **nucleon number** but including unusual baryons like  $\Sigma$  too.) The **proton** and the **neutron** each have a baryon number **B = +1**. **Antibaryons** have a baryon number **B = -1**. **Other particles** (i.e. things that aren't baryons) are given a baryon number **B = 0**.

Baryon number is a **quantum number** that must be **conserved** in any interaction — that means it can only take on a **certain set of values** (so you can't have 2.7981 baryons, or 1.991112 baryons... you get the idea).

When an **interaction** happens, the **baryon number** on either side of the interaction has to be the **same**. You can use this fact to **predict** whether an **interaction** will **happen** — if the numbers don't match, it can't happen.

The **total baryon number** in **any** particle interaction **never changes**.



## Neutrons are Baryons that Decay into Protons

You saw on pages 5 and 9 that **beta decay** involves a **neutron** changing into a **proton**. This happens when there are many **more neutrons** than **protons** in a nucleus or when a **neutron** is **by itself, outside** of a nucleus. **Beta decay** is caused by the **weak interaction** (see page 14).

When a neutron decays, it forms a **proton**, an **electron** and an **antineutrino**:



**Electrons** and **antineutrinos** aren't baryons (they're **leptons**, as you'll see on the next page), so they have a baryon number **B = 0**. **Neutrons** and **protons** are baryons, so have a baryon number **B = 1**. This means that the **baryon numbers** on both sides are **equal** (to 1), so the interaction **can** happen.

## The Mesons You Need to Know About are Pions and Kaons

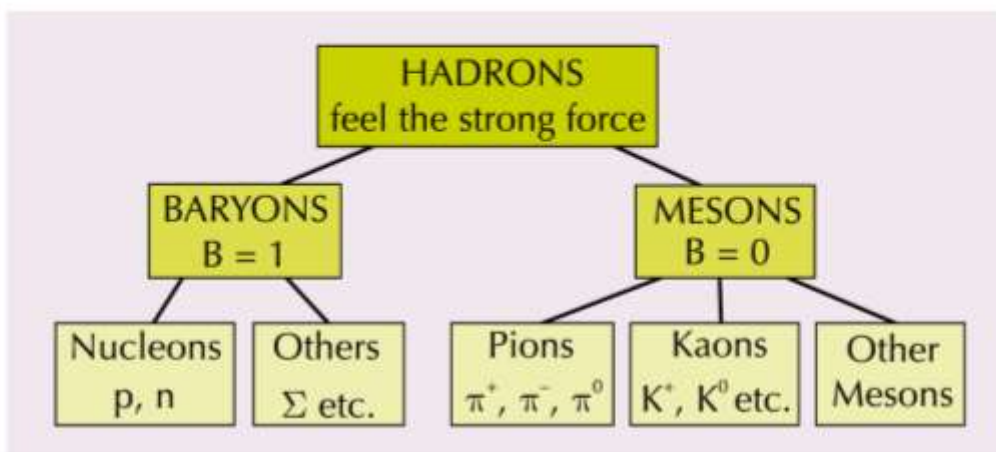
The second type of hadron you need to know about is the **meson**.

- 1) **All mesons** are **unstable** and have **baryon number B = 0** (because they're not baryons).
- 2) **Pions** ( $\pi$ -mesons) are the **lightest mesons**. You get **three versions** with different **electric charges** —  $\pi^{+}$ ,  $\pi^{0}$  and  $\pi^{-}$ . You get **loads** of pions in **high-energy particle collisions** like those studied at the **CERN** particle accelerator.
- 3) **Kaons** (**K**-mesons) are **heavier** and more **unstable** than **pions**. You get different ones like  $K^{+}$  and  $K^{0}$ . Kaons have a very **short lifetime** and **decay into pions**.
- 4) Pions and kaons were **discovered** in **cosmic rays** — cosmic ray showers are a source of both particles. You can observe the tracks of these particles with a **cloud chamber** (see p.4).
- 5) Mesons **interact** with **baryons** via the **strong force**.



## Summary of Hadron Properties

**DON'T PANIC** if you don't understand all this yet. For now, just **learn** these properties. You'll need to work through to the end of page 15 to see how it **all fits together**.





### Leptons (e.g. Electrons and Neutrinos) **Don't Feel the Strong Nuclear Force**

- 1) **Leptons** are **fundamental particles** and they **don't** feel the **strong nuclear force**. They only really **interact** with other particles via the **weak interaction** (along with a bit of gravitational force and the electromagnetic force as well if they're charged).
- 2) **Electrons** ( $e^-$ ) are **stable** and very **familiar**, but — you guessed it — there are also **other leptons**, such as the **muon** ( $\mu^-$ ), that are just like **heavy electrons**.
- 3) **Muons** are **unstable**, and **decay** eventually into **ordinary electrons**.
- 4) The **electron** and **muon** leptons each come with their **own neutrino**,  $\nu_e$  and  $\nu_\mu$ .
- 5) **Neutrinos** have **zero** or **almost zero mass**, and **zero electric charge** — so they don't do much. **Neutrinos** only take part in **weak interactions** (see p.14). In fact, a neutrino can **pass right through the Earth** without **anything** happening to it.

### You Have to Count the Types of Lepton Separately

Like the baryon number, the **lepton number** is just the number of **leptons**. Each **lepton** is given a **lepton number** of **+1**, but the **electron** and **muon** types of lepton have to be **counted separately**. You get **different** lepton numbers,  $L_e$  and  $L_\mu$ .

All the leptons and lepton-neutrinos have their own **antiparticle** too — no surprises there. They have the **opposite charge** and **lepton numbers** to their matching particles. For example, the antimuon  $\mu^+$  has charge =  $+1$ ,  $L_e = 0$  and  $L_\mu = -1$ .

Name	Symbol	Charge	$L_e$	$L_\mu$
electron	$e^-$	-1	+1	0
electron-neutrino	$\nu_e$	0	+1	0
muon	$\mu^-$	-1	0	+1
muon-neutrino	$\nu_\mu$	0	0	+1

**Credit:** CGP Revision Guide Editions



## SAMPLE QUESTION

**A1.1** The table gives information about some fundamental particles. Complete the table by filling in the missing information.

[7 Marks]

particle	quark structure	charge	strangeness	baryon number
	uud		0	
Sigma +	uus	+ 1		
	ud		0	0

particle	quark structure	charge	strangeness	baryon number
proton ✓	uud	+ 1 ✓	0	1 ✓
sigma+	uus	+1	-1 ✓	1 ✓
$\pi^+$ ✓	ud	+1 ✓	0	0

**A proton has 3 quarks of uud – it is known that it has a charge of +1.**

**It is a baryon – it has a Baryon number of 1.**

**Sigma has a strange quark; it must have a negative strangeness. It has 3 quarks – it is a baryon – it has a Baryon number of 1.**

**Pi plus is made from those 2 quarks; it must have a positive charge (look at the plus in the name).**

Each of the particles in the table has an antiparticle.

**A1.2** Give **one** example of a baryon particle **and** its corresponding antiparticle.

[1 Mark]

Particle: **Proton (any baryon)**

Antiparticle: **Antiproton (the corresponding antibaryon)**

1 mark

**A1.3** Give **one** property of an antiparticle that is the same for its corresponding particle and **one** property that is different.

[2 Marks]

Same

**Same rest mass.**

1 mark

Different

**Opposite charge, Baryon number, Lepton Number**

1 mark



# SELF ASSESSMENT

**A1.**The equation

$$p \longrightarrow n + \beta^+ + \nu_e$$

represents the emission of a positron from a proton.

**A1.1** Energy and momentum are conserved in this emission.  
What other quantities are conserved in this emission?

**[3 Marks]**

.....

.....

.....

.....

.....

.....

**A1.2** Draw the Feynman diagram that corresponds to the positron emission represented in the equation.

**[4 Marks]**

**A1.3** Complete the following table using ticks ✓ and crosses ✗.

**[4 Marks]**

particle	fundamental particle	meson	baryon	lepton
p				
n				
$\beta^+$				
$\nu_e$				

**Reference:** AQA A Level Physics Legacy A Examinations



**A2.** The list of sub-atomic particles below contains particles that are either hadrons or leptons:

**electron muon neutrino neutron pi-meson proton**

**A2.1** Complete the table below by adding the names of the particles to the correct box.

**[4 Marks]**

Hadrons	
Leptons	

**A2.2** Underline the names of the particles that are baryons.

**[2 Marks]**

**Reference:** AQA A Level Physics Legacy B Examinations

**Q3.** Mesons that contain a strange (or anti-strange) quark are known as K-mesons or kaons. Mesons are a sub-group of a larger group of particles.

**Q3.1** State the name of this larger group of particles.

**[1 Mark]**

.....

.....

**Q3.2** Determine the charge on a kaon with a quark structure of  $u\bar{s}$ .

**[1 Mark]**

.....

.....

A proposed decay for this kaon is



**Q3.3** Apply the law of conservation of strangeness to the proposed decay.

**[1 Mark]**

.....

.....

**Q3.3** Comment on whether this decay is possible.

**[1 Mark]**

.....

.....

**Reference:** AQA A Level Physics January 2013 Unit 1 Examination



## TOPIC: 3.2.1.6 Quarks and Antiquarks

### SPEC CHECK

Specification	Completed?
Properties of quarks and antiquarks: charge, baryon number and strangeness.	
Combinations of quarks and antiquarks required for baryons (proton and neutron only), antibaryons (antiproton and antineutron only) and mesons (pion and kaon only).	
Only knowledge of up (u), down (d) and strange (s) quarks and their antiquarks will be tested.	
The decay of the neutron should be known.	

## NOTES

### Rutherford Scattering

Previously in GCSE Physics Unit 2

Rutherford fired a beam of alpha particles at a thin gold foil. If the atom had no inner structure the alpha particles would only be deflected by very small angles.

Some of the alpha particles were scattered at large angles by the nuclei of the atoms.

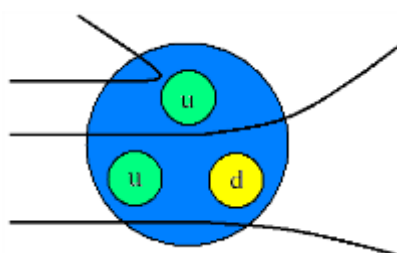
From this Rutherford deduced that the atom was mostly empty space with most of the mass situated in the centre. Atoms were made from smaller particles.

These notes are brief.

More detailed notes are found in the student preparatory reading book.

Please read the preparatory reading notes.

### Smaller Scattering



When electrons were fired at protons, the scattering pattern formed three separate regions.

This showed that the proton was made from 3 quarks. It is a hadron.

In 1968 Physicists conducted a similar experiment to Rutherford's but they fired a beam of high energy electrons at nucleons (protons and neutrons).

The results they obtained were like Rutherford's; some of the electrons were deflected by large angles.

If the nucleons had no inner structure the electrons would only be deflected by small angles.

These results showed that protons and neutrons were made of three smaller particles, each with a fractional charge.



## Quarks

These smaller particles were named quarks and are thought to be fundamental particles (not made of anything smaller). There are six different quarks and each one has its own antiparticle.

We need to know about the three below as we will be looking at how larger particles are made from different combinations of quarks and antiquarks.

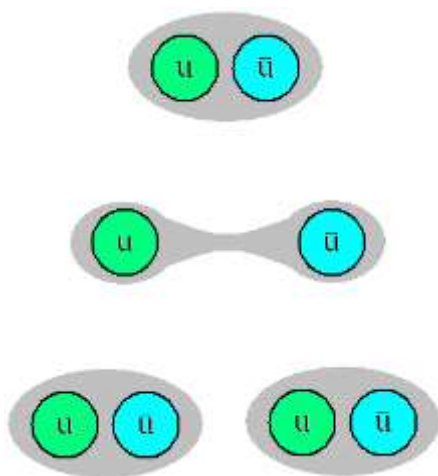
Quark	Charge (Q)	Baryon Number (B)	Strangeness (S)	Anti-Quark	Charge (Q)	Baryon Number (B)	Strangeness (S)
d	$-\frac{1}{3}$	$+\frac{1}{3}$	0	$\bar{d}$	$+\frac{1}{3}$	$-\frac{1}{3}$	0
u	$+\frac{2}{3}$	$+\frac{1}{3}$	0	$\bar{u}$	$-\frac{2}{3}$	$-\frac{1}{3}$	0
s	$-\frac{1}{3}$	$+\frac{1}{3}$	-1	$\bar{s}$	$+\frac{1}{3}$	$-\frac{1}{3}$	+1

The other three are Charm, Bottom and Top.

Quark	Charge	Baryon No.	Strangeness	Charmness	Bottomness	Topness
d	$-\frac{1}{3}$	$+\frac{1}{3}$	0	0	0	0
u	$+\frac{2}{3}$	$+\frac{1}{3}$	0	0	0	0
s	$-\frac{1}{3}$	$+\frac{1}{3}$	-1	0	0	0
c	$+\frac{2}{3}$	$+\frac{1}{3}$	0	+1	0	0
b	$-\frac{1}{3}$	$+\frac{1}{3}$	0	0	-1	0
t	$+\frac{2}{3}$	$+\frac{1}{3}$	0	0	0	+1

## Free Quarks

Quarks never appear on their own. The energy required to pull two quarks apart is so massive that it is enough to make two new particles. A quark and an antiquark are created, another example of pair production.



### Note

Free quarks can never exist by themselves.

**The properties of Baryon numbers, Lepton Numbers and Charge can never exist as fractions.**

A particle called a neutral pion is made from an up quark and an antiup quark. Moving these apart creates another up quark and an antiup quark. We now have two pairs of quarks.



Trying to separate two quarks made two more quarks.

### **Particle Classification**

Now that we know that quarks are the smallest building blocks we can separate all other particles into two groups, those made from quarks and those that aren't made from quarks.

**Hadrons** – Heavy and made from quarks. Experience EM, strong, weak and gravitational force.  
Leptons – Light and not made from smaller quarks. Experience EM, weak and gravitational force.

**YOU MUST BE ABLE TO DISCUSS PARTICLE DECAYS AND PROPERTIES IN BOTH PARTICLE TERMS AND QUARK TERMS.**

**PLEASE REVIEW THE DECAY SECTION AGAIN.**

**Additional Note Space**



**Additional Note Space**



# REVISION SHEET

Highlight or underline the key information on the revision sheet to consolidate your understanding.

## Quarks are Fundamental Particles

Quarks are the **building blocks** for **hadrons** (baryons and mesons). Antiparticles of hadrons are made from **antiquarks**.

- 1) To make **protons** and **neutrons** you only need two types of quark — the **up** quark (**u**) and the **down** quark (**d**).
- 2) An extra one called the **strange** quark (**s**) lets you make more particles with a property called **strangeness**.

## Strangeness is Only Conserved Some of the Time

- 1) **Strangeness**, like baryon number, is a **quantum number** (see p.10) — it can only take a certain set of values.
- 2) Strange particles, such as kaons, are **created** via the **strong** interaction but **decay** via the **weak** interaction.
- 3) Here's the catch — strangeness is **conserved** in the **strong interaction**, but **not** in the **weak interaction** (p.14).
- 4) That means strange particles are **always produced in pairs** (e.g.  $K^+$  and  $K^-$ ).  
One has a strangeness of +1, and the other has a strangeness of -1, so the overall strangeness of 0 is **conserved**.

## Quarks and Antiquarks have Opposite Properties

The **antiquarks** have **opposite properties** to the quarks — as you'd expect.

QUARKS	Name	Symbol	Charge	Baryon number	Strangeness
	up	u	$+\frac{2}{3}$	$+\frac{1}{3}$	0
	down	d	$-\frac{1}{3}$	$+\frac{1}{3}$	0
	strange	s	$-\frac{1}{3}$	$+\frac{1}{3}$	-1

ANTIQUARKS	Name	Symbol	Charge	Baryon number	Strangeness
	anti-up	$\bar{u}$	$-\frac{2}{3}$	$-\frac{1}{3}$	0
	anti-down	$\bar{d}$	$+\frac{1}{3}$	$-\frac{1}{3}$	0
	anti-strange	$\bar{s}$	$+\frac{1}{3}$	$-\frac{1}{3}$	+1

## Baryons are Made from Three Quarks

Evidence for quarks came from **hitting protons** with **high-energy electrons**.

The way the **electrons scattered** showed that there were **three concentrations of charge** (quarks) **inside** the proton.



Proton = **uud**

Total charge

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

Baryon number

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



Antiproton =  **$\bar{u}\bar{u}\bar{d}$**

Total charge

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

Baryon number

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



Neutron = **udd**

Total charge

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

Baryon number

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



Antineutron =  **$\bar{u}\bar{d}\bar{d}$**

Total charge

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

Baryon number

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

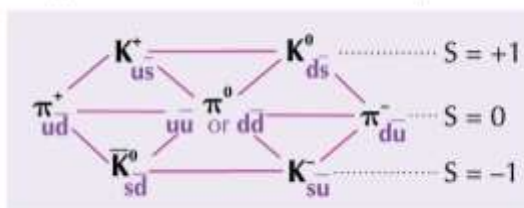


### Mesons are a Quark and an Antiquark

**Pions** are just made from combinations of **up**, **down**, **anti-up** and **anti-down** quarks.

**Kaons** have **strangeness** so you need to put in **s** quarks as well (remember, the **s** quark has a strangeness of  $S = -1$ ).

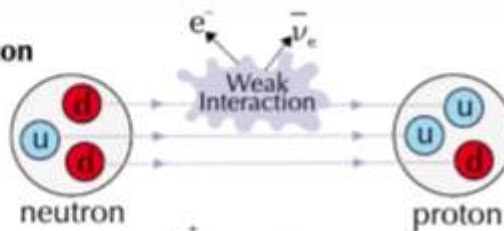
Before we move on, it's worth mentioning that the  $\pi^-$  meson is just the **antiparticle** of the  $\pi^+$  meson, the  $K^-$  meson is the antiparticle of the  $K^+$  meson, and the **antiparticle** of a  $\pi^0$  meson is **itself**. It all makes sense when you look at the quark compositions to the right...



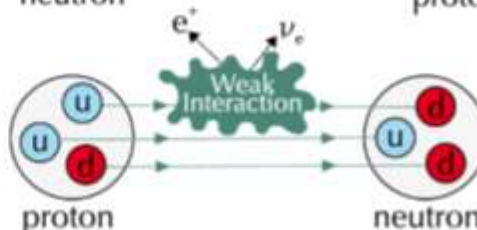
Physicists love patterns. Gaps in patterns like this predicted the existence of particles that were actually found later in experiments. Great stuff.

### The Weak Interaction is something that Changes the Quark Type

In  $\beta^-$  decay a **neutron** is changed into a **proton** — in other words **udd** changes into **uud**. It means turning a **d** quark into a **u** quark. Only the weak interaction can do this.



Some unstable isotopes like **carbon-11** decay by  $\beta^+$  emission. In this case a **proton** changes to a **neutron**, so a **u** quark changes to a **d** quark and we get:



### We're Still Searching for Particles

As time goes on, our knowledge and understanding of particle physics **changes**.

- New theories** are created to try to explain observations from experiments. Sometimes, physicists hypothesise a new **particle** and the **properties** they expect it to have. E.g. the **neutrino** was hypothesised due to observations of beta decay.
- Experiments** to try to find the existence of this new particle are then carried out. Results from different experiments are **combined** to try to **confirm** the new particle. If it exists, the theory is **more likely** to be correct and the scientific community start to accept it — it's **validated**.
- It's not quite that simple though. Experiments in particle physics often need particles travelling at incredibly **high speeds** (close to the speed of light). This can only be achieved using **particle accelerators**. These huge pieces of equipment are very **expensive** to build and run. This means that **large groups** of scientists and engineers from all over the **world** have to **collaborate** to be able to fund these experiments.

Simon was practising quack confinement.

**Credit:** CGP Revision Guide Editions





# SELF ASSESSMENT

**Q1.** Leptons, mesons and baryons are three classes of sub-atomic particles.

**Q1.1** Some classes of particles are fundamental; others are not. Circle the correct category for each of these three classes.

**[1 Mark]**

leptons	fundamental/not fundamental
mesons	fundamental/not fundamental
baryons	fundamental/not fundamental

**Q1.2** Name the class of particles of which the proton is a member.

**[1 Mark]**

.....

.....

**Q1.3** By referring to the charges on up and down quarks explain how the proton has a charge of  $+1e$ .

**[2 Marks]**

.....

.....

**Reference:** AQA A Level Physics Legacy B Examinations

**Q2.** Neutrons were discovered when beryllium,  ${}^9_4\text{Be}$ , was bombarded with alpha particles.

An alpha particle knocked a neutron out of a beryllium nucleus producing a carbon nucleus, **C**.

**Q2.1** Write down the equation that describes this reaction.

**[2 Marks]**

.....

.....

**Q2.2** Describe the quark substructure of a neutron.

**[1 Mark]**

.....

.....



**Q2.3** Describe how the quark substructure of a meson differs from that of a baryon such as a neutron.

**[1 Mark]**

.....  
.....

**Reference:** AQA A Level Physics Legacy B Examinations

**Q3.** A carbon-14 nucleus undergoes  $\beta^-$  decay, forming a new nucleus, releasing a  $\beta^-$  particle and one other particle which is difficult to detect.

**Q3.1** Write down the proton number and the nucleon number of the new nucleus.

**[2 Marks]**

Proton Number .....

Nucleon Number .....

**Q3.2** Name the particle which is difficult to detect.

**[1 Mark]**

.....  
.....

**Q3.3** Name the baryons and leptons involved in the decay.

**[2 Marks]**

Baryons .....

Leptons .....

**Q3.4** Give the quark structure for the neutron and the proton.

**[2 Marks]**

Neutron .....

Proton .....

Hence state the quark transformation that occurs during  $\beta^-$  decay.

.....  
.....

**Reference:** AQA A Level Physics Legacy A Examinations



## TOPIC: 3.2.1.7 Applications of Conservation Laws

### SPEC CHECK

Specification	Completed?
Change of quark character in $\beta^-$ and in $\beta^+$ decay.	
Application of the conservation laws for charge, baryon number, lepton number and strangeness to particle interactions.	
Students should recognise that energy and momentum are conserved in interactions.	

These notes are brief.

More detailed notes are found in the student preparatory reading book.

Please read the preparatory reading notes.

## NOTES

### Conservation Laws

For a particle interaction to occur the following reaction will never be observed (will never happen).

**Charge:** Must be conserved (same total value before as the total value after)

**Baryon Number:** Must be conserved

**Lepton Number:** Must be conserved

**Strangeness:** Conserved in electromagnetic and Strong Interaction.

Strangeness have to be conserved in Weak Interaction. It can vary by  $\pm 1$ .

### Examples

In pair production a photon of energy is converted into a particle and its antiparticle

	$\gamma$	$\rightarrow$	$e^-$	$+$	$e^+$				
Q	0	$\rightarrow$	-1	+	+1	0	$\rightarrow$	0	Conserved
B	0	$\rightarrow$	0	+	0	0	$\rightarrow$	0	Conserved
L	0	$\rightarrow$	+1	+	-1	0	$\rightarrow$	0	Conserved
S	0	$\rightarrow$	0	+	0	0	$\rightarrow$	0	Conserved

Let us look at beta plus decay as we knew it at GCSE. A neutron decays into a proton and releases an electron.

	n	$\rightarrow$	p	+	$e^-$				
Q	0	$\rightarrow$	+1	+	-1	0	$\rightarrow$	0	Conserved
B	+1	$\rightarrow$	+1	+	0	+1	$\rightarrow$	+1	Conserved
L	0	$\rightarrow$	0	+	+1	0	$\rightarrow$	+1	Not Conserved
S	0	$\rightarrow$	0	+	0	0	$\rightarrow$	0	Conserved

This contributed to the search for and discovery of the neutrino.

In addition, energy/mass and momentum need to be conserved in a particle interaction – remember the rules learnt in mechanics regarding energy and momentum.

**YOU MUST BE ABLE TO APPLY THE CONSERVATION RULES FOR BOTH QUARK PROPERTIES AND PARTICLE PROPERTIES.**

**PLEASE REVIEW THE PREVIOUS SECTION ON DECAYS AGAIN.**



**Additional Note Space**



**Additional Note Space**



# REVISION SHEET

Highlight or underline the key information on the revision sheet to consolidate your understanding.

## Four Properties are Conserved in Particle Interactions

### Charge is Always Conserved

In **any** particle interaction, the **total charge** after the interaction must equal the total charge before the interaction.

Energy and momentum are also always conserved in particle interactions.

### Baryon Number is Always Conserved

Just like with charge, in **any** particle interaction, the **baryon number** after the interaction must equal the baryon number before the interaction.



Dylan was committed to conserving strangeness.

### Strangeness is Conserved in Strong Interactions

The **only** way to change the **type** of quark is with the **weak interaction**, so in strong interactions there has to be the same number of strange quarks at the beginning as at the end. In weak interactions, strangeness can change by  $-1$ ,  $0$  or  $+1$ . The interaction  $K^- + p \rightarrow n + \pi^0$  is fine for **charge** and **baryon number** but not for **strangeness** — so it won't happen. The negative kaon has an **s** quark in it.

### Conservation of Lepton Number is a Bit More Complicated

The **different types** of lepton number have to be conserved **separately**.

- For example, the interaction  $\pi^- \rightarrow \mu^- + \bar{\nu}_\mu$  has  $L_\mu = 0$  at the start and  $L_\mu = 1 - 1 = 0$  at the end, so it's OK. Similarly,  $n \rightarrow p + e^- + \bar{\nu}_e$  is fine.  $L_e = 0$  at the start and  $L_e = 1 - 1 = 0$  at the end.
- On the other hand, the interaction  $\nu_\mu + \mu^- \rightarrow e^- + \nu_e$  can't happen. At the start  $L_\mu = 2$  and  $L_e = 0$ , but at the end  $L_\mu = 0$  and  $L_e = 2$ .

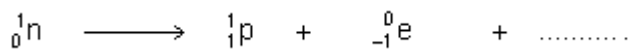
Lepton number is a quantum number, just like baryon number and strangeness.

**Credit:** CGP Revision Guide Editions



## SAMPLE QUESTION

**A1.** The following is an incomplete equation for the decay of a free neutron.



**A1.1** Complete the equation by writing into the space, the symbol for the missing particle.

**[2 Marks]**

**As an electron is produced in the decay, the electron anti-neutrino must also be produced.** 1 mark

**A1.2** Use the principles of conservation of charge, baryon number and lepton number to demonstrate that the decay is possible.

**[3 Marks]**

Conservation of charge

$$0 \rightarrow 1 + (-1) + 0$$

1 mark

**This is the same before and after – it is conserved.**

1 mark

Conservation of baryon number

$$1 \rightarrow 1 + 0 + 0$$

1 mark

**This is the same before and after – it is conserved.**

1 mark

Conservation of lepton number

$$0 \rightarrow 0 + 1 + (-1)$$

1 mark

**This is the same before and after – it is conserved.**

1 mark

**Reference:** A Level Physics Legacy B Examination Papers



## SELF ASSESSMENT

**Q1.1** Give the number of nucleons and the number of electrons in an atom of  $^{22}_{11}\text{Na}$ .

**[2 Marks]**

Nucleons .....

Electrons .....

**Q1.2** The isotope  $^{22}_{11}\text{Na}$  is a positron emitter. In positron emission an up quark undergoes the following change,

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

Show that charge, lepton number and baryon number are conserved in this decay.

**[3 Marks]**

Charge .....

Lepton number .....

Baryon number .....

**Q1.3** Describe what happens when a positron collides with an electron.

**[2 Marks]**

.....  
 .....

**Reference:** A Level Physics Legacy A Examination Papers

**Q2.** A physicist, who is attempting to analyse a nuclear event, suggests that a  $\pi^-$  particle and a proton collided and were annihilated with the creation of a neutron, a  $\pi^+$  particle, and a  $K^-$  particle.

$\pi$  and  $K$  particles are mesons. The baryon and lepton numbers of both these mesons are zero.

**Q2.1** Write down the equation that represents this interaction.

**[1 Mark]**

.....  
 .....



**Q2.2** Show, in terms of the conservation of charge, baryon number and lepton number, that this transformation is permitted.

**[4 Marks]**

.....

.....

.....

.....

.....

.....

**Reference:** A Level Physics Legacy B Examination Papers

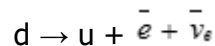
**Q3.1** State the combination of quarks that makes up a neutron.

**[1 Mark]**

.....

.....

When a neutron decays, a down quark changes into an up quark as shown by the following reaction.



**Q3.2** Show, in terms of the conservation of charge, baryon number and lepton number, that this transformation is permitted.

**[3 Marks]**

.....

.....

.....

.....

**Q3.3** State the products arising from the decay of an anti-down quark,  $\bar{d}$ .

**[1 Mark]**

.....

.....

**Reference:** A Level Physics Legacy B Examination Papers



## REVISION CHECKLIST

Specification reference	Checklist questions	
3.2.1.1	Can you represent a simple model of the atom, including the proton, neutron, and electron?	<input type="checkbox"/>
3.2.1.1	Can you describe charge and mass of the proton, neutron, and electron in SI units and relative units?	<input type="checkbox"/>
3.2.1.1	Can you explain the specific charge of the proton and the electron, and of nuclei and ions?	<input type="checkbox"/>
3.2.1.1	Can you define and use 'proton number $Z$ , nucleon number $A$ ' nuclide notation?	<input type="checkbox"/>
3.2.1.1	Can you recognise and use the ${}^A_ZX$ notation?	<input type="checkbox"/>
3.2.1.1	Can you define isotopes and use isotopic data?	<input type="checkbox"/>
3.2.1.2	Can you explain the strong nuclear force and its role in keeping the nucleus stable?	<input type="checkbox"/>
3.2.1.2	Can you describe short-range attraction up to approximately 3 fm and very-short range repulsion closer than approximately 0.5 fm?	<input type="checkbox"/>
3.2.1.2	Can you describe unstable nuclei; alpha and beta decay?	<input type="checkbox"/>
3.2.1.2	Can you use equations for alpha decay and $\beta^-$ decay, including the need for the neutrino?	<input type="checkbox"/>
3.2.1.2	Can you explain how the existence of the neutrino was hypothesised to account for conservation of energy in beta decay?	<input type="checkbox"/>
3.2.1.3	Can you explain that, for every type of particle, there is a corresponding antiparticle?	<input type="checkbox"/>
3.2.1.3	Can you compare particle and antiparticle mass, charge, and rest energy in MeV?	<input type="checkbox"/>



Specification reference	Checklist questions	
3.2.1.3	Can you explain that the positron, antiproton, antineutron, and antineutrino are the antiparticles of the electron, proton, neutron, and neutrino respectively?	<input type="checkbox"/>
3.2.1.3	Can you use the photon model of electromagnetic radiation and the Planck constant?	<input type="checkbox"/>
3.2.1.3	Can you explain annihilation and pair production, and the energies involved?	<input type="checkbox"/>
3.2.1.4	Can you explain the four fundamental interactions: gravity, electromagnetic, weak nuclear, and strong nuclear?	<input type="checkbox"/>
3.2.1.4	Can you describe the concept of exchange particles to explain forces between elementary particles?	<input type="checkbox"/>
3.2.1.4	Can you explain the electromagnetic force and virtual photons as the exchange particle?	<input type="checkbox"/>
3.2.1.4	Can you describe the weak interaction limited to $\beta^-$ and $\beta^+$ decay, electron capture, and electron–proton collisions?	<input type="checkbox"/>
3.2.1.4	Can you describe $W^+$ and $W^-$ as exchange particles?	<input type="checkbox"/>
3.2.1.4	Can you draw simple diagrams to represent reactions or interactions in terms of incoming and outgoing particles, and exchange particles?	<input type="checkbox"/>
3.2.1.5	Can you explain that hadrons are subject to the strong interaction?	<input type="checkbox"/>



Specification reference	Checklist questions	
3.2.1.6	Can you describe the properties of quarks and antiquarks in terms of charge, baryon number, and strangeness?	<input type="checkbox"/>
3.2.1.6	Can you explain the combinations of quarks and antiquarks required for baryons (proton and neutron only), antibaryons (antiproton and antineutron only), and mesons (pion and kaon only)?	<input type="checkbox"/>
3.2.1.6	Can you show the decay of the neutron?	<input type="checkbox"/>
3.2.1.7	Can you explain the change of quark character in $\beta^-$ and $\beta^+$ decay?	<input type="checkbox"/>
3.2.1.7	Can you apply the conservation laws for charge, baryon number, lepton number and strangeness to particle interactions, given the necessary data?	<input type="checkbox"/>
3.2.1.7	Can you recognise that energy and momentum are conserved in interactions?	<input type="checkbox"/>



## DATASHEET

### DATA - FUNDAMENTAL CONSTANTS AND VALUES

Quantity	Symbol	Value	Units
speed of light in vacuo	$c$	$3.00 \times 10^8$	$\text{m s}^{-1}$
permeability of free space	$\mu_0$	$4\pi \times 10^{-7}$	$\text{H m}^{-1}$
permittivity of free space	$\epsilon_0$	$8.85 \times 10^{-12}$	$\text{F m}^{-1}$
magnitude of the charge of electron	$e$	$1.60 \times 10^{-19}$	C
the Planck constant	$h$	$6.63 \times 10^{-34}$	J s
gravitational constant	$G$	$6.67 \times 10^{-11}$	$\text{N m}^2 \text{kg}^{-2}$
the Avogadro constant	$N_A$	$6.02 \times 10^{23}$	$\text{mol}^{-1}$
molar gas constant	$R$	8.31	$\text{J K}^{-1} \text{mol}^{-1}$
the Boltzmann constant	$k$	$1.38 \times 10^{-23}$	$\text{J K}^{-1}$
the Stefan constant	$\sigma$	$5.67 \times 10^{-8}$	$\text{W m}^{-2} \text{K}^{-4}$
the Wien constant	$\alpha$	$2.90 \times 10^{-3}$	m K
electron rest mass (equivalent to $5.5 \times 10^{-4}$ u)	$m_e$	$9.11 \times 10^{-31}$	kg
electron charge/mass ratio	$\frac{e}{m_e}$	$1.76 \times 10^{11}$	$\text{C kg}^{-1}$
proton rest mass (equivalent to 1.00728 u)	$m_p$	$1.67(3) \times 10^{-27}$	kg
proton charge/mass ratio	$\frac{e}{m_p}$	$9.58 \times 10^7$	$\text{C kg}^{-1}$
neutron rest mass (equivalent to 1.00867 u)	$m_n$	$1.67(5) \times 10^{-27}$	kg
gravitational field strength	$g$	9.81	$\text{N kg}^{-1}$
acceleration due to gravity	$g$	9.81	$\text{m s}^{-2}$
atomic mass unit (1u is equivalent to 931.5 MeV)	u	$1.661 \times 10^{-27}$	kg

#### ALGEBRAIC EQUATION

quadratic equation  $x = \frac{-b \pm \sqrt{b^2 - 4ac}}{2a}$

#### ASTRONOMICAL DATA

Body	Mass/kg	Mean radius/m
Sun	$1.99 \times 10^{30}$	$6.96 \times 10^8$
Earth	$5.97 \times 10^{24}$	$6.37 \times 10^6$

#### GEOMETRICAL EQUATIONS

arc length =  $r\theta$

circumference of circle =  $2\pi r$

area of circle =  $\pi r^2$

curved surface area of cylinder =  $2\pi r h$

area of sphere =  $4\pi r^2$

volume of sphere =  $\frac{4}{3}\pi r^3$



**Particle Physics**

Class	Name	Symbol	Rest energy/MeV
photon	photon	$\gamma$	0
lepton	neutrino	$\nu_e$	0
		$\nu_\mu$	0
	electron	$e^\pm$	0.510999
	muon	$\mu^\pm$	105.659
mesons	$\pi$ meson	$\pi^\pm$	139.576
		$\pi^0$	134.972
	K meson	$K^\pm$	493.821
		$K^0$	497.762
baryons	proton	p	938.257
	neutron	n	939.551

**Properties of quarks**

antiquarks have opposite signs

Type	Charge	Baryon number	Strangeness
<b>u</b>	$+\frac{2}{3}e$	$+\frac{1}{3}$	0
<b>d</b>	$-\frac{1}{3}e$	$+\frac{1}{3}$	0
<b>s</b>	$-\frac{1}{3}e$	$+\frac{1}{3}$	-1

**Properties of Leptons**

	Lepton number
Particles: $e^-, \nu_e; \mu^-, \nu_\mu$	+1
Antiparticles: $e^+, \bar{\nu}_e, \mu^+, \bar{\nu}_\mu$	-1

**Photons and energy levels**

photon energy  $E = hf = hc / \lambda$   
 photoelectricity  $hf = \phi + E_{k(\max)}$   
 energy levels  $hf = E_1 - E_2$   
 de Broglie wavelength  $\lambda = \frac{h}{p} = \frac{h}{mv}$

**Waves**

wave speed  $c = f\lambda$  period  $f = \frac{1}{T}$   
 first harmonic  $f = \frac{1}{2l} \sqrt{\frac{T}{\mu}}$   
 fringe spacing  $w = \frac{\lambda D}{s}$  diffraction grating  $d \sin \theta = n\lambda$   
 refractive index of a substance s,  $n = \frac{c}{c_s}$   
 for two different substances of refractive indices  $n_1$  and  $n_2$ ,  
 law of refraction  $n_1 \sin \theta_1 = n_2 \sin \theta_2$   
 critical angle  $\sin \theta_c = \frac{n_2}{n_1}$  for  $n_1 > n_2$

**Mechanics**

moments moment =  $Fd$   
 velocity and acceleration  $v = \frac{\Delta s}{\Delta t}$   $a = \frac{\Delta v}{\Delta t}$   
 equations of motion  $v = u + at$   $s = \left(\frac{u+v}{2}\right)t$   
 $v^2 = u^2 + 2as$   $s = ut + \frac{at^2}{2}$   
 force  $F = ma$   
 force  $F = \frac{\Delta(mv)}{\Delta t}$   
 impulse  $F \Delta t = \Delta(mv)$   
 work, energy and power  $W = F s \cos \theta$   
 $E_k = \frac{1}{2} m v^2$   $\Delta E_p = mg\Delta h$   
 $P = \frac{\Delta W}{\Delta t}, P = Fv$   
 efficiency =  $\frac{\text{useful output power}}{\text{input power}}$

**Materials**

density  $\rho = \frac{m}{v}$  Hooke's law  $F = k \Delta L$   
 Young modulus =  $\frac{\text{tensile stress}}{\text{tensile strain}}$  tensile stress =  $\frac{F}{A}$   
 tensile strain =  $\frac{\Delta L}{L}$   
 energy stored  $E = \frac{1}{2} F \Delta L$



## Electricity

current and pd  $I = \frac{\Delta Q}{\Delta t} \quad V = \frac{W}{Q} \quad R = \frac{V}{I}$

resistivity  $\rho = \frac{RA}{L}$

resistors in series  $R_T = R_1 + R_2 + R_3 + \dots$

resistors in parallel  $\frac{1}{R_T} = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3} + \dots$

power  $P = VI = I^2R = \frac{V^2}{R}$

emf  $\varepsilon = \frac{E}{Q} \quad \varepsilon = I(R + r)$

## Circular motion

magnitude of angular speed  $\omega = \frac{v}{r}$

$$\omega = 2\pi f$$

centripetal acceleration  $a = \frac{v^2}{r} = \omega^2 r$

centripetal force  $F = \frac{mv^2}{r} = m\omega^2 r$

## Simple harmonic motion

acceleration  $a = -\omega^2 x$

displacement  $x = A \cos(\omega t)$

speed  $v = \pm \omega \sqrt{(A^2 - x^2)}$

maximum speed  $v_{\max} = \omega A$

maximum acceleration  $a_{\max} = \omega^2 A$

for a mass-spring system  $T = 2\pi \sqrt{\frac{m}{k}}$

for a simple pendulum  $T = 2\pi \sqrt{\frac{l}{g}}$

## Thermal physics

energy to change temperature  $Q = mc\Delta\theta$

energy to change state  $Q = ml$

gas law  $pV = nRT$   
 $pV = NkT$

kinetic theory model  $pV = \frac{1}{3} N m (c_{\text{rms}})^2$

kinetic energy of gas molecule  $\frac{1}{2} m (c_{\text{rms}})^2 = \frac{3}{2} kT = \frac{3RT}{2N_A}$

## Gravitational fields

force between two masses  $F = \frac{Gm_1m_2}{r^2}$

gravitational field strength  $g = \frac{F}{m}$

magnitude of gravitational field strength in a radial field  $g = \frac{GM}{r^2}$

work done  $\Delta W = m\Delta V$

gravitational potential  $V = -\frac{GM}{r}$   
 $g = -\frac{\Delta V}{\Delta r}$

## Electric fields and capacitors

force between two point charges  $F = \frac{1}{4\pi\epsilon_0} \frac{Q_1Q_2}{r^2}$

force on a charge  $F = EQ$

field strength for a uniform field  $E = \frac{V}{d}$

work done  $\Delta W = Q\Delta V$

field strength for a radial field  $E = \frac{1}{4\pi\epsilon_0} \frac{Q}{r^2}$

electric potential  $V = \frac{1}{4\pi\epsilon_0} \frac{Q}{r}$

$$E = \frac{\Delta V}{\Delta r}$$

capacitance  $C = \frac{Q}{V}$

$$C = \frac{A\epsilon_0\epsilon_r}{d}$$

capacitor energy stored  $E = \frac{1}{2} QV = \frac{1}{2} CV^2 = \frac{1}{2} \frac{Q^2}{C}$

capacitor charging  $Q = Q_0(1 - e^{-t/RC})$

decay of charge  $Q = Q_0 e^{-t/RC}$

time constant  $RC$



## Magnetic fields

<i>force on a current</i>	$F = BIl$
<i>force on a moving charge</i>	$F = BQv$
<i>magnetic flux</i>	$\Phi = BA$
<i>magnetic flux linkage</i>	$N\Phi = BAN \cos \theta$
<i>magnitude of induced emf</i>	$\varepsilon = N \frac{\Delta \Phi}{\Delta t}$
	$N\Phi = BAN \cos \theta$
<i>emf induced in a rotating coil</i>	$\varepsilon = BAN\omega \sin \omega t$
<i>alternating current</i>	$I_{\text{rms}} = \frac{I_0}{\sqrt{2}} \quad V_{\text{rms}} = \frac{V_0}{\sqrt{2}}$
<i>transformer equations</i>	$\frac{N_s}{N_p} = \frac{V_s}{V_p}$
	$\text{efficiency} = \frac{I_s V_s}{I_p V_p}$

## Nuclear physics

<i>the inverse square law for <math>\gamma</math> radiation</i>	$I = \frac{k}{x^2}$
<i>radioactive decay</i>	$\frac{\Delta N}{\Delta t} = -\lambda N, N = N_0 e^{-\lambda t}$
<i>activity</i>	$A = \lambda N$
<i>half-life</i>	$T_{1/2} = \frac{\ln 2}{\lambda}$
<i>nuclear radius</i>	$R = R_0 A^{1/3}$
<i>energy-mass equation</i>	$E = mc^2$

## OPTIONS

### Astrophysics

1 astronomical unit	$= 1.50 \times 10^{11} \text{ m}$
1 light year	$= 9.46 \times 10^{15} \text{ m}$
1 parsec	$= 206265 \text{ AU} = 3.08 \times 10^{16} \text{ m}$ $= 3.26 \text{ light year}$

$$\text{Hubble constant, } H = 65 \text{ km s}^{-1} \text{ Mpc}^{-1}$$

$$M = \frac{\text{angle subtended by image at eye}}{\text{angle subtended by object at unaided eye}}$$

<i>in normal adjustment</i>	$M = \frac{f_o}{f_e}$
<i>Rayleigh criterion</i>	$\theta \approx \frac{\lambda}{D}$
<i>magnitude equation</i>	$m - M = 5 \log \frac{d}{10}$
<i>Wien's law</i>	$\lambda_{\text{max}} T = 2.9 \times 10^{-3} \text{ m K}$
<i>Stefan's law</i>	$P = \sigma AT^4$
<i>Schwarzschild radius</i>	$R_s \approx \frac{2GM}{c^2}$
<i>Doppler shift for <math>v \ll c</math></i>	$\frac{\Delta f}{f} = -\frac{\Delta \lambda}{\lambda} = \frac{v}{c}$
<i>red shift</i>	$z = -\frac{v}{c}$
<i>Hubble's law</i>	$v = Hd$

### Medical physics

<i>lens equations</i>	$P = \frac{1}{f}$ $m = \frac{v}{u}$ $\frac{1}{f} = \frac{1}{u} + \frac{1}{v}$
<i>threshold of hearing</i>	$I_0 = 1.0 \times 10^{-12} \text{ W m}^{-2}$
<i>intensity level</i>	$\text{intensity level} = 10 \log \frac{I}{I_0}$
<i>absorption</i>	$I = I_0 e^{-\mu x}$ $\mu_m = \frac{\mu}{\rho}$
<i>ultrasound imaging</i>	$Z = \rho c$ $\frac{I_r}{I_i} = \left( \frac{Z_2 - Z_1}{Z_2 + Z_1} \right)^2$
<i>half-lives</i>	$\frac{1}{T_B} = \frac{1}{T_B} + \frac{1}{T_P}$



## Engineering physics

moment of inertia  $I = \Sigma mr^2$

angular kinetic energy  $E_k = \frac{1}{2} I \omega^2$

equations of angular motion

$$\omega_2 = \omega_1 + \alpha t$$

$$\omega_2^2 = \omega_1^2 + 2\alpha\theta$$

$$\theta = \omega_1 t + \frac{\alpha t^2}{2}$$

$$\theta = \frac{(\omega_1 + \omega_2) t}{2}$$

torque  $T = I \alpha$

$$T = F r$$

angular momentum angular momentum =  $I \omega$

angular impulse  $T \Delta t = \Delta(I \omega)$

work done  $W = T \theta$

power  $P = T \omega$

thermodynamics  $Q = \Delta U + W$

$$W = p \Delta V$$

adiabatic change  $pV^\gamma = \text{constant}$

isothermal change  $pV = \text{constant}$

heat engines

$$\text{efficiency} = \frac{W}{Q_H} = \frac{Q_H - Q_C}{Q_H}$$

$$\text{maximum theoretical efficiency} = \frac{T_H - T_C}{T_H}$$

work done per cycle = area of loop

input power = calorific value  $\times$  fuel flow rate

$$\text{indicated power} = \frac{\text{area of } p - V \text{ loop}}{\text{number of cycles per second}} \times \text{number of cylinders}$$

output or brake power  $P = T \omega$

friction power = indicated power - brake power

heat pumps and refrigerators

refrigerator:  $COP_{\text{ref}} = \frac{Q_C}{W} = \frac{Q_C}{Q_H - Q_C}$

heat pump:  $COP_{\text{hp}} = \frac{Q_H}{W} = \frac{Q_H}{Q_H - Q_C}$

## Turning points in physics

electrons in fields  $F = \frac{eV}{d}$

$$F = Bev$$

$$r = \frac{mv}{Be}$$

$$\frac{1}{2} mv^2 = eV$$

Millikan's experiment  $\frac{QV}{d} = mg$

$$F = 6\pi\eta r v$$

Maxwell's formula  $c = \frac{1}{\sqrt{\mu_0 \epsilon_0}}$

$$\lambda = \frac{h}{p} = \frac{h}{\sqrt{2meV}}$$

special relativity

$$t = \frac{t_0}{\sqrt{1 - \frac{v^2}{c^2}}}$$

$$l = l_0 \sqrt{1 - \frac{v^2}{c^2}}$$

$$E = mc^2 = \frac{m_0 c^2}{\sqrt{1 - \frac{v^2}{c^2}}}$$

## Electronics

resonant frequency  $f_0 = \frac{1}{2\pi \sqrt{LC}}$

Q-factor  $Q = \frac{f_0}{f_B}$

operational amplifiers: open loop  $V_{\text{out}} = A_{\text{OL}}(V_+ - V_-)$

inverting amplifier  $\frac{V_{\text{out}}}{V_{\text{in}}} = -\frac{R_f}{R_{\text{in}}}$

non-inverting amplifier  $\frac{V_{\text{out}}}{V_{\text{in}}} = 1 + \frac{R_f}{R_1}$

summing amplifier  $V_{\text{out}} = -R_f \left( \frac{V_1}{R_1} + \frac{V_2}{R_2} + \frac{V_3}{R_3} + \dots \right)$

difference amplifier  $V_{\text{out}} = (V_+ - V_-) \frac{R_f}{R_1}$

Bandwidth requirement:

for AM bandwidth =  $2f_M$

for FM bandwidth =  $2(\Delta f + f_M)$



### **Acknowledgements**

This document has been produced by Mr J Turnbull.

All relevant information has been credited in the document.

This document has been produced for educational purposes only.

This document has been produced for the AQA A Level Physics Specification.

### **Student Voice**

If you when using this document, you believe there is an improvement to made, please state this in the space below....

Only constructive and reasoned feedback will be considered.