

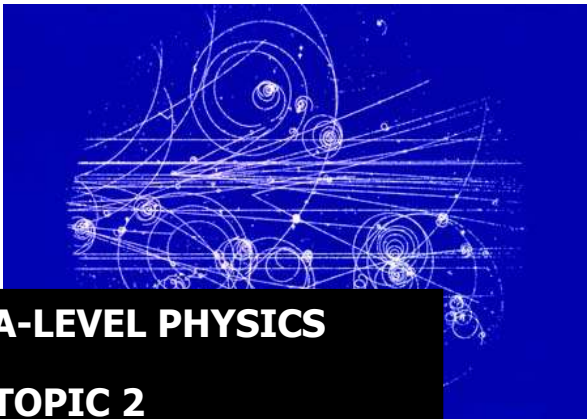


**ST MARY'S SCIENCE
DEPARTMENT:
PHYSICS**

**Volume
One**

**A LEVEL PHYSICS YEAR 1
PREPARATORY READING BOOK
PARTICLES AND RADIATION
3.2.1: PARTICLES**

NAME	
PHYSICS CLASS	
MODULE TEACHER	
ALPS GRADE	



**A-LEVEL PHYSICS
TOPIC 2
READING 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 booklet provides the basic information and knowledge needed to access the A-Level Physics course.

Over the course of the year, you will be directed to read this information in both lessons and in your spare time.

Ensure all information in this booklet is understood and remembered before examinations.

IMPORTANT NOTE

This booklet, along with the student workbook, must be brought to all Physics lessons with the appropriate teacher.

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

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

Please keep this in your student file.

As part of this course you are expected to **read through this preparatory reading book** and **complete the independent study tasks**.

This work will not be assessed but will be monitored by your class teacher.

This must be completed by the deadline set by your class teacher.



Definition List

Definitions you must learn...

Key Word	Definition
Isotopes	Nuclides with the same number of protons but different number of neutrons.
Specific Charge	The (overall) charge to mass ratio of a particle. = $\frac{\text{Overall Charge}}{\text{Rest Mass}}$
Quarks	Fundamental particles which exists in hadrons – they are not stable in isolation. No free quark has ever been observed.
Pair Production	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.
Annihilation	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 $E=hf$).
Hadron	A particle made from quarks which interacts via the strong interaction.
Anti-particles	Particles with the same rest mass as the traditional particle but have opposite properties for every other property.
Leptons	A fundamental particle which does interact via the strong force.
Exchange Particle	A particle which transmits a fundamental force in the Universe. Also known as a virtual boson.
Feynman Diagram	A diagram which shows a particle interaction over time.
Conservation Law	A law where the total number of the property must the same before a decay as it is after it.
Fundamental force	A force which persists throughout the Universe due to the movement of exchange particles between other particles.
Photon	The exchange particle of the electromagnetic force and can be considered a particle of energy.
Planck's Constant	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



VIDEO COURSE OVERVIEW

To watch a video looking at all of the concepts in electric fields, please scan one of the following codes with your smartphone.



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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.	

Student Checklist

Have I.....	Yes or No?
Read through the notes of this section?	
Highlighted/underlined the key concepts of this section?	
Made my own notes based on the notes of this section?	
Brought the notes to be used in lesson?	



The Nuclear Model

Prior Knowledge Link

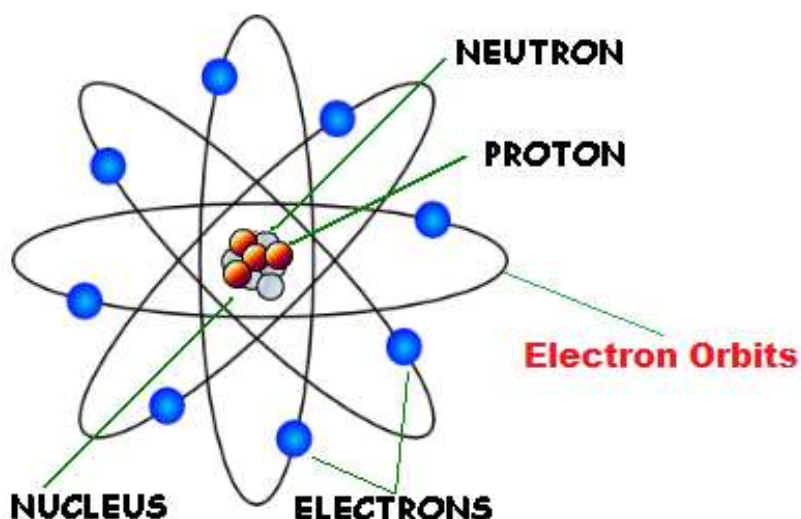
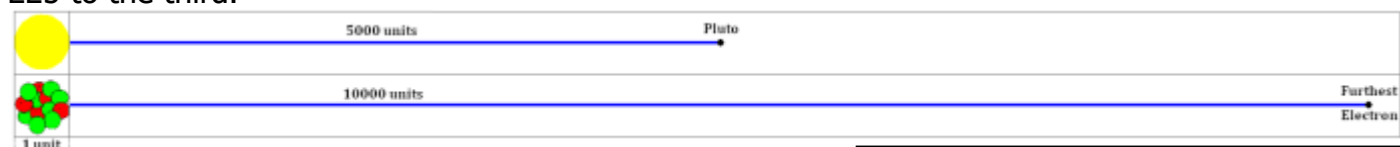
This is a topic found in a previous GCSE module - **Radioactivity**

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.



The electrons exist in energy levels (or orbitals) around the nucleus.

They do not orbit as shown in this picture.

In an orbital, an electron exists with a particular energy; it does not lose or gain energy when in the level.

The further away from the nucleus, the greater the energy the electron has.

Electrons can move between energy levels by either gaining (excitation) or losing energy (de-excitation).

Physics Tip

Electrons are considered fundamental.

This is a particle which cannot be split up into anything smaller.

Physics Tip

When calculating the mass of an atom or an ion, the mass of the electrons is very small compared to the mass of the nucleus.

So, you only need to use the mass of the nucleus when calculating the specific charge.

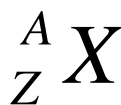


Notation

Prior Knowledge Link

This is a topic found in a previous GCSE module - **Radioactivity**

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

Prior Knowledge Link

This is a topic found in a previous GCSE module - **Radioactivity**

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.

Isotopes have different behaviour during nuclear decay however.

Chlorine

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

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

There are two stable isotopes of Chlorine, ${}^{35}_{17}\text{Cl}$ which accounts for $\sim 75\%$ and ${}^{37}_{17}\text{Cl}$ which accounts for $\sim 25\%$.

So, the average of a large amount of Chlorine atoms is ${}^{35.5}_{17}\text{Cl}$.

The nucleon number shown on the Periodic Table is an average value based on the different types of isotopes and their relative abundance on Earth.

Examination Hint

It is a common examination question to define an isotope.

An isotope has the same number of protons (1 mark) but a different number of neutrons (1 mark).

Isotopes exhibit similar chemical properties but different radioactive properties.



Specific Charge

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

Study Tip

You will be given the masses (in kg) of all particles and the charge (in C) in the data and formulae booklet.

Physics Tip

In physics, 'specific' mostly means 'per unit mass'.

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

Study Tip

You are **not** given this equation in the equation book.

$$\text{Specific Charge} = \text{Overall Charge (In C)} / \text{Mass (In kg)}$$

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 ⁻¹) or (C/kg)	
Proton	1.6×10^{-19}	1.673×10^{-27}	$1.6 \times 10^{-19} \div 1.673 \times 10^{-27}$	9.58×10^7
Neutron	0	1.675×10^{-27}	$0 \div 1.675 \times 10^{-27}$	0
Electron	$(-) 1.6 \times 10^{-19}$	9.1×10^{-31}	$1.6 \times 10^{-19} \div 9.11 \times 10^{-31}$	$(-) 1.76 \times 10^{11}$

We can see that the electron has the highest specific charge and the neutron has the lowest.

The larger the specific charge, the more particle is affected by the electric/magnetic field.

Examination 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.

Examination Tip

In an examination, you will be given the masses of all three particles in kilograms and the charge of an electron in coulombs in the data and formulae booklet in the exam.

You will be given their relative masses or charges though – so learn the numbers.

Examination Tip

When calculating specific charge, make sure the charge and the mass are in the right units.

**Ions****Prior Knowledge Link**

This is a topic found in a previous GCSE module - **Radioactivity**

An atom may gain or lose electrons. When this happens, the atoms become electrically charged (positively or negatively). We call this an ion.

Physics Tip

The charge should be always been given in Coulombs. Remember 1 charge unit at GCSE = $1.6 \times 10^{-19}\text{C}$

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. This happens when electrons are given enough energy to escape the positive attraction of the nucleus – the closer to the nucleus, the more energy is needed to be given.

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 **$+3.2 \times 10^{-19}\text{C}$** .

Physics Tip

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



VIDEO

To watch a video looking at this concept, please scan one of the following codes with your smartphone.



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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, β^- 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.	

Student Checklist

Have I.....	Yes or No?
Read through the notes of this section?	
Highlighted/underlined the key concepts of this section?	
Made my own notes based on the notes of this section?	
Brought the notes to be used in lesson?	



Fundamental Forces

There are 4 fundamental forces in the Universe; every other force is based off these. These are, in order of strength, strong, electromagnetic, weak and gravity.

Einstein has theorised that gravity is not actual a force; however, this still an area of active research in Physics.

In particle physics, gravity is not considered as it is such a small effect.

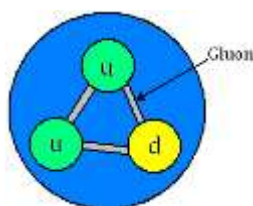
Strong		Strength 1	Range (m) 10^{-15} (diameter of a medium sized nucleus)	Particle gluons. π (nucleons)
Electro-magnetic		Strength $\frac{1}{137}$	Range (m) Infinite	Particle photon mass = 0 spin = 1
Weak		Strength 10^{-6}	Range (m) 10^{-18} (0.1% of the diameter of a proton)	Particle Intermediate vector bosons W^+ , W^- , Z_0 . mass > 80 GeV spin = 1
Gravity		Strength 6×10^{-39}	Range (m) Infinite	Particle graviton ? mass = 0 spin = 2

Study Tip

The gravitational attraction is so small compared to the other forces, it can be ignored.

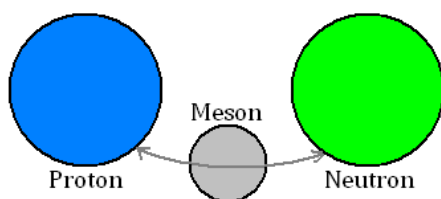
The Strong Interaction

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 (as the name suggests).

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.

For example, electromagnetism is infinite in range as the photon is infinite in range.

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



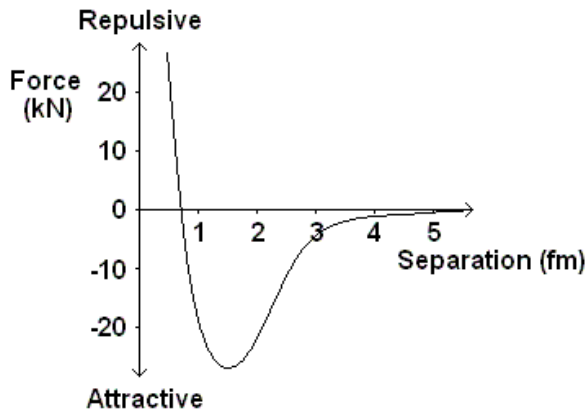
At this level, we say that a pion (π) is exchanged between the hadrons, this is the same as the gluon it is just named something else.

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 fm ($\times 10^{-15}$ m).

This prevents all the nucleons from crushing into each other. This allows protons and neutrons to exist.

Above this separation the force is strongly attractive with a peak around 1.3 fm. When the nucleons are separated by more than 5 fm they no longer experience the strong force. This allows the nucleus to form.

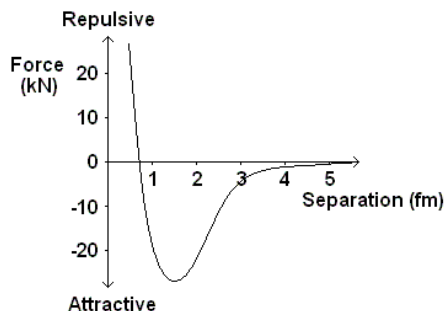
Study Tip

The range of the strong nuclear force is only a few femtometres. It struggles to hold together very large nuclei, which makes them unstable.



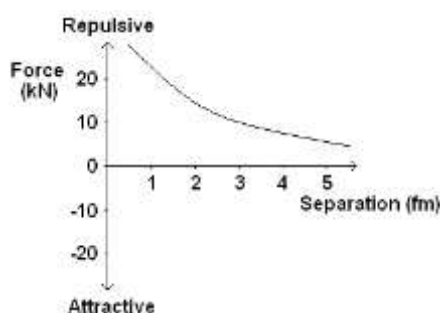
Proton-Proton

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



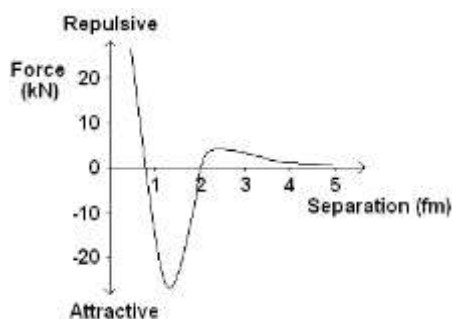
Graph A

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.

Physics Tip

The range of the strong nuclear force is only a few femtometres.

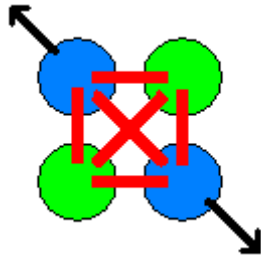
It struggles to hold together very large nuclei, this makes large nuclei unstable.



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.

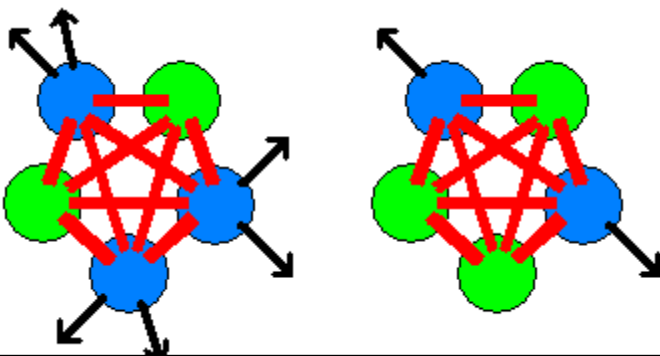


A stable nucleus contains particles which exert a much greater strong force attraction than electromagnetic repulsion.

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.



As neutrons only interact via the strong force, they increase the stability of the nucleus.

However, **extremely neutron-rich nuclei do not exist in the Universe**, since other quantum mechanical effects mean too many neutrons would cause the nucleus to fission or simply decay via the beta decay process.

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.

Increasing the neutrons increases stability as it increases the presence of the strong force (which is stronger than the electromagnetic force) and does not increase the presence of the electromagnetic force.



Examination Tip

It is a common examination question to be asked to 'Describe the interaction that is responsible for keeping protons and neutrons together in a stable nucleus.'

the strong interaction (1 mark)

has short range OR mention range (less than 5 fm) (1 mark)

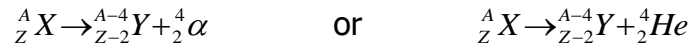
attraction up to 5 fm (1 mark)

repulsive (any distance below 1fm) (1 mark)

is zero/negligible beyond 5 fm (1 mark)

**Alpha Decay****Prior Knowledge Link**This is a topic found in a previous GCSE module - **Radioactivity**

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.

Physics Tip

An alpha particle is a fast-moving helium nucleus emitted from the nucleus of another atom.

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.

Examination Tip

It is a common examination question to ask why alpha decay does not occur via the weak interaction.

Alpha decay occurs via the strong interaction (1 mark)

This is because no leptons are involved in alpha decay (1 mark).

No particle flavour/ neutrino is produced (1 mark)

This means the decay happens quickly and produces particles of identical energy (1 mark).



Beta Decay and the Neutrino

Prior Knowledge Link

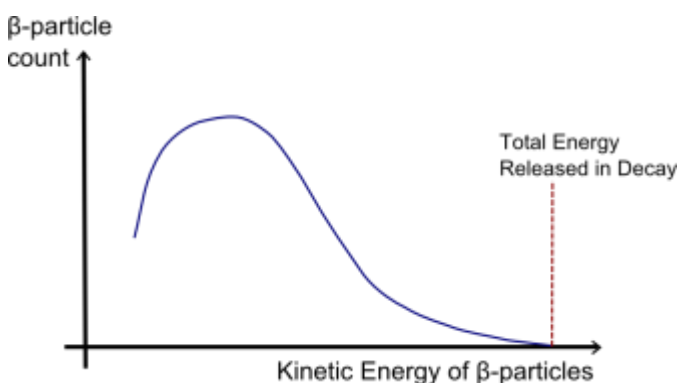
This is a topic found in a previous GCSE module - **Radioactivity**

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

Physics Tip

A beta minus particle is a fast-moving electron emitted from the nucleus of another atom.

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 seems to disappear.



This graph shows that different beta particles are produced with a different range of kinetic energies.

This would violate the energy-mass conservation law if it was the only particle produced in the decay.

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.

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.

Study Tip

Make sure you do not forget the anti-neutrino in the beta minus decay and the neutrino in the beta plus decay. It can be easily missed as it does not change the nucleon or proton number.

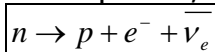


In fact, there are two types of beta decay.

The beta decay covered at GCSE, it actually called the beta minus decay.

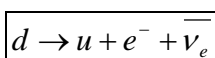
Beta Minus (β^-) Decay

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

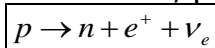
In terms of quarks beta minus decay looks like this: $dud \rightarrow uud + e^- + \bar{\nu}_e$ which simplifies to:



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

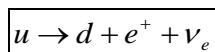
Beta Plus (β^+) Decay

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

Physics Tip

A beta plus particle is a fast-moving positron emitted from the nucleus of another atom.

Physics Tip

Make sure you do not forget the anti-neutrino (or neutrino) in the beta decay equations.

It can be easily missed because it does not change the nucleon or the proton numbers.



Examination Tip

It is a common examination question to ask which fundamental force is responsible for beta decay...

It is the weak interaction/weak nuclear force (1 mark).

Because it involves leptons and hadrons/ because quark (1 mark).

Whilst the character/flavour/identity/type is changed (1 mark).

Examination Tip

It is a common examination question to ask how we can identify that a beta decay is occurring...

Electron released (from nucleus) which is observed in a cloud chamber. (1 mark)

Antineutrino/neutrino released (1 mark)

No photon released (no energy is given out) (1 mark)

Examination Tip

It is a common examination question to recognise and state the beta decay.

Do not forget the corresponding neutrino or anti-neutrino depending on the beta decay.

Examination Tip

It is a common examination question to be asked to 'State two differences between the parent nucleus and the daughter nucleus after electron capture'.

The daughter nucleus has 1 more neutron than the parent nucleus (1 mark).

The parent nucleus has 1 less proton than the daughter nucleus (1 mark).



Examination Tip

It is a common examination question to be asked look at beta decay.

When scientists studied beta decay they observed that

- the beta particle and the daughter nucleus did not travel in opposite directions
- beta particles from the decay of a particular nuclide had a range of energies.

'Explain how these observations led to the prediction of a previously undiscovered particle.'

This can be answered as following....

Conservation of momentum or energy discussed (1 mark)

Third particle carries some energy or momentum (1 mark)

Each decay (of a given nuclide) has the same energy (1 mark)

Mention of components of momentum (perpendicular to direction of recoil) (1 mark)



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 ± 1 .

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

Physics Tip

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.

Physics Tip

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.

Examination Tip

Strange particles are produced with the strong force as the strong force conserves strangeness.

Strange particles (tend to) decay with the weak force as the weak force does not need to conserve strangeness.

Examination Tip

It is a common examination question to recognise decays with strange particles.

Remember if the decay is via the weak interaction, strangeness does not need to be conserved.

Study Tip

A strange particle is always made up of smaller particles called quarks, one of these must be a strange quark.



Examination Tip

It is a common examination question to ask 'Explain how baryon number is conserved in alpha and beta decay'.

This would be answered the following way...

In alpha decay number of nucleons/protons and neutrons is unchanged OR baryons in parent nucleus equals the total number of baryons in daughter nucleus and the alpha particle (1 mark)

In beta decay a neutron changes into a proton (and both have same baryon number) (1 mark)

Beta (-) particle and antineutrino have zero baryon number/beta (+) and neutrino have zero baryon number (1 mark).



Internal Conversion

You must also be aware of the process of internal conversion in an atom. This is a nuclear process like beta decay or alpha decay.

Internal conversion is a process in which a nucleus in an excited state can release its excess energy.

In internal conversion all of the excess energy is transferred from the nucleus to an orbital electron through the electromagnetic force. This orbital electron is ejected from the atom.

Examination Tip

It is a common examination question to be asked to 'discuss three differences between internal conversion and beta (β^-) decay'.

Difference 1

internal conversion: only electron released;

beta-decay: (electron and) anti-neutrino released; (1 mark)

Difference 2

(both statements required for mark) internal conversion: all electrons released will have similar/discrete energies/momenta

beta-decay: electrons will have a range of energies/momenta (1 mark)

Difference 3

Internal conversion: no change in constituents of nucleus/element does not change

beta-decay: neutron converted to proton (allow in terms of quarks)/element changes (to one with (one) more p, different Z, different proton number/different atomic number)) (1 mark)

Difference 4

Internal conversion: orbital electron lost

beta-decay: electron comes from nucleus / no change in orbital electrons (1 mark)

Difference 5

(both statements required for mark) internal conversion: mediated by electromagnetic force / virtual photons

beta-decay: mediated by weak interaction / W^- (1 mark)



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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.	

Student Checklist

Have I.....	Yes or No?
Read through the notes of this section?	
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Brought the notes to be used in lesson?	



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*.

Physics Tip

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.

The symbol for an anti-particle is the particle symbol with a hat over the top. E.g. \bar{p}

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

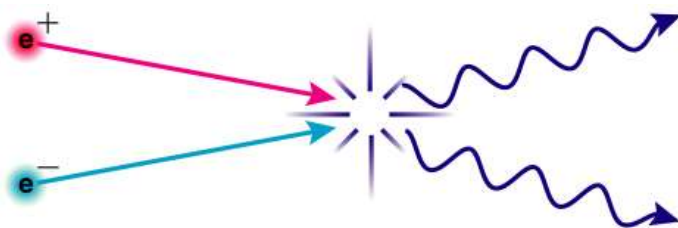
Examination Note

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** in opposite directions are produced – not one.

This is why....

$E = hf$ for annihilation

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:

$$E = mc^2$$

Study Tip

This equation is found in the data booklet.

Learn the key terms of each part of the equation.



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.

Physics Tip

Annihilation produces two photons of equal energy.

Physics Tip

If electrons are being annihilated, the rest energy of an electron is 0.511MeV.

This is given in your data and formulae booklet.

Physics Tip

PET scanners work by placing a positron emitting isotope into the bloodstream, and the gamma ray photons produced by the electron-positron annihilation that occurs.

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:

$$E = hf$$

Physics Tip

You will be given a data and formulae booklet that has these equations and Planck's constant in it.

You must be able to use these equations correctly.

Physics Tip

These equations can only be used for wave-like phenomena such as electromagnetic radiation.

Physics Tip

Remember if you are using the correct base units these equations should give answers in terms of Joules.

Remember to put units in your answer.

Physics Tip

Planck's constant is a proportionality constant linking photon energy with the frequency of the photon.

**Study Tip**

This equation can only be used to find the energy of a photon – a discrete packet of energy.

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

Since $c = f\lambda$ we can also write this as:

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

Study Tip

This equation is found in the data booklet.

Learn the key terms of each part of the equation.

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.

Study Tip

Do not forget, the units of energy are joules.

Make sure you remember to put your units in your answer.

Examination Tip

It is a common examination question to be asked to 'define an anti-particle'.

Particle with equal (rest) mass/energy (1 mark)

but opposite charge/baryon number/lepton number (1 mark)

Physics Tip

The existence of the photon explained the behaviour of radiation in the photoelectric effect and the ultraviolet catastrophe.

It is proof that light, and all radiation, must have particle like properties.



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....

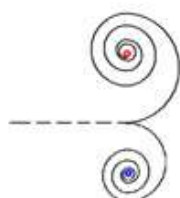
$2E = hf$ for pair production

There are two particles 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 be made and the photon had 16 bits the particle-antiparticle pair is made and the left over (6 bits) 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.

Any energy above the minimum energy goes into kinetic energy of the particles.

Examination Tip

It is a common examination question to state why pair production needs a minimum energy...

energy of photon needs to provide (1 mark) at least the rest masses (1 mark) of particle and antiparticle (1 mark)

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.

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.

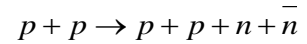
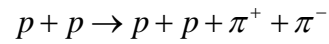
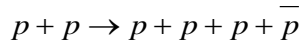
Study Tip

Energy is always conserved – it cannot be created or destroyed, only turned into other forms.



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.

Physics Tip

Protons repel each other, so it takes a lot of energy to make them collide.

The energy supplied is released when they collide, so proton-proton collisions release a lot of energy.

Physics Tip

Only gamma ray photons have enough energy to produce an electron-positron pair.

From the equation, $E = hf$; the higher the frequency, the higher the energy contained in the photon.

Gamma rays are high frequency/energy photons.

Physics Tip

It is common to express energies in annihilation and pair production in MeV.

To change MeV into J, you need to multiply the number by 10^6 (to change MeV into eV), and then multiply your answer by 1.60×10^{-19} (to change eV into J).

Examination Tip

It is a common examination question to be asked to 'Describe annihilation. Include the circumstances under which it can occur and its outcome.'

This can be answered as following....

A particle and its (corresponding) antiparticle (or particle-antiparticle pair) (1 mark)

Cease to exist/are destroyed OWTTE (1 mark)

Two (gamma) photons are produced (1 mark)

The photons have the same total energy as the mass-energy of the particles or momentum is conserved (1 mark)



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TOPIC: 3.2.1.4: Particle Interactions

SPEC CHECK

Specification	Completed?
Four fundamental interactions: gravity, electromagnetic, weak nuclear, strong nuclear. (The strong nuclear force may be referred to as the strong interaction.)	
The concept of exchange particles to explain forces between elementary particles.	
The electromagnetic force; virtual photons as the exchange particle.	
The weak interaction limited to β^- and β^+ decay, electron capture and electron-proton collisions; W^+ and W^- as the exchange particles.	
Simple diagrams to represent the above reactions or interactions in terms of incoming and outgoing particles and exchange particles.	

Student Checklist

Have I.....	Yes or No?
Read through the notes of this section?	
Highlighted/underlined the key concepts of this section?	
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Which Particle for What Force

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

Interaction/Force	Exchange Particle			What it 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

When you are discussing quarks, it is best to say the exchange particle is the gluon. When discussing protons and neutrons, it is best to say the exchange particle is the pion. It is the same particle, just called different names.

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 ΔE could exist for a time Δt 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.

Study Tip

The fourth fundamental interaction is gravity. Particle physicists never bother about gravity because it is so incredibly feeble compared with the other types of interaction. Gravity only matters when you have big masses like stars and planets.

It is not known for certain what the exchange particle of gravity is, but it is believed to be the graviton (which has not been observed yet).



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.

Study Tip

When drawing particle interaction diagrams, the incoming particles start from the bottom and move upwards.

Examples

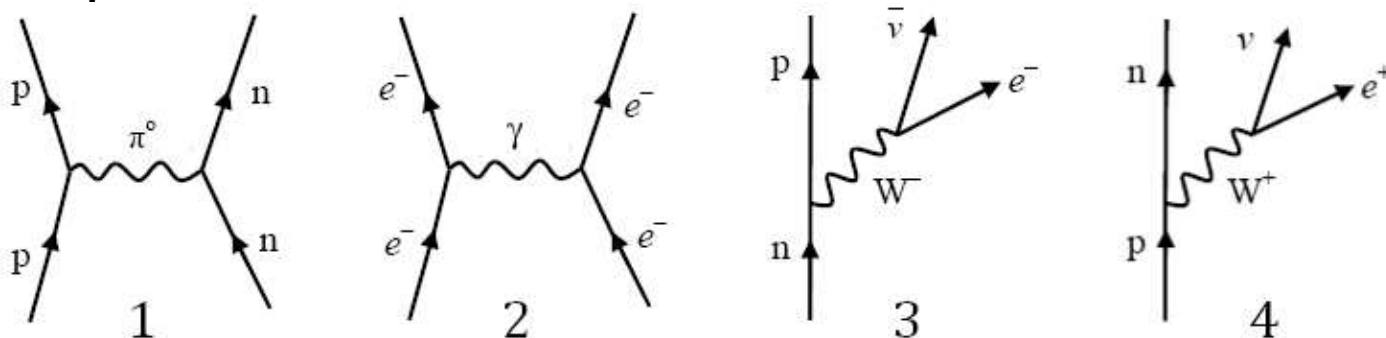


Diagram 1 represents the strong interaction. A proton and neutron are attracted together by the exchange of a neutral pion.

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.

**Study Tip**

Electron capture and electron-proton collisions are confusingly similar. They have different particle interaction diagrams and use different W bosons because the boson comes from the particle that is 'acting'.

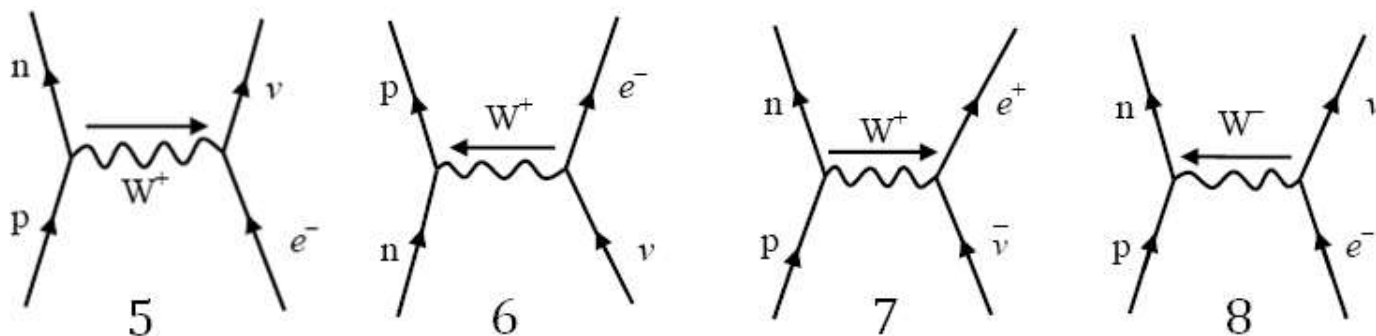


Diagram 5 represents electron capture. A proton captures an electron and becomes a neutron and an electron neutrino.

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 neutral, 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.

Examination Tip

Feynman diagrams can be drawn in terms of particles or quarks.

It is more common that the examination question will show a Feynman diagram in terms of quarks.

Examination questions then ask you to identify particles based on quark composition.



Examination Tip

It is a common examination question to be asked to 'describe how the variation of the strong nuclear force with distance contributes to the stability of the nucleus'.

Short-range) attraction up to about 3 fm (1 mark)

(Very short-range) repulsion closer than 0.5 fm (1 mark)

Prevent proton and neutron moving closer or further apart (1 mark)



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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"> • baryons (proton, neutron) and antibaryons (antiproton and antineutron) • mesons (pion, kaon). 	
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.	



Student Checklist

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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	$+2/3$	$+1/3$	0
u	$+2/3$	$+1/3$	0
d	$-1/3$	$+1/3$	0
p	+1	+1	0

Neutron	Charge (Q)	Baryon Number (B)	Strangeness (S)
d	$-1/3$	$+1/3$	0
u	$+2/3$	$+1/3$	0
d	$-1/3$	$+1/3$	0
n	0	+1	0

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.

Examination Tip

You need to know the baryon numbers of all particles in the exam, make sure you know these rules.

Mesons Made from a quark and an antiquark

Pion Plus	Charge (Q)	Baryon Number (B)	Strangeness (S)
u	$+2/3$	$+1/3$	0
\bar{d}	$+1/3$	$-1/3$	0
π^+	+1	0	0

Pion Minus	Charge (Q)	Baryon Number (B)	Strangeness (S)
\bar{u}	$-2/3$	$-1/3$	0
d	$-1/3$	$+1/3$	0
π^-	-1	0	0

Pion Zero	Charge (Q)	Baryon Number (B)	Strangeness (S)
u	$+2/3$	$+1/3$	0
\bar{u}	$-2/3$	$-1/3$	0
π^0	0	0	0

Pion Zero	Charge (Q)	Baryon Number (B)	Strangeness (S)
d	$-1/3$	$+1/3$	0
\bar{d}	$+1/3$	$-1/3$	0
π^0	0	0	0

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

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



Kaon Zero	Charge (Q)	Baryon Number (B)	Strangeness (S)
d	$-\frac{1}{3}$	$+\frac{1}{3}$	0
\bar{s}	$+\frac{1}{3}$	$-\frac{1}{3}$	+1
K⁰	0	0	+1

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

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.

Examination Tip

It is a common examination question to ask you to identify substructure of a Kaon particle (this could be K zero, K plus or K minus).

Remember all Kaons contain at least one strange or anti-strange quark.

This means that in decays, strangeness does not have to be conserved in the weak interaction – this makes it much more likely to happen in the Universe by this method.

Remember, if a particle takes a long time to decay it decays via the weak interaction (this means it is likely strangeness has not been conserved).

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 π^+ and a π^- are particle and antiparticle of each other.

Anti-Proton	Charge (Q)	Baryon Number (B)	Strangeness (S)
\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
\bar{p}	-1	-1	0

Anti Neutron	Charge (Q)	Baryon Number (B)	Strangeness (S)
\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
\bar{n}	0	-1	0

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.

Study Tip

The superscript in a particle's symbol tells you its charge – e.g. μ^+ has a charge of +1.



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 chargeless, 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)
Electron	e^-	-1	+1
Electron Neutrino	ν_e	0	+1
Muon	μ^-	-1	+1
Muon Neutrino	ν_μ	0	+1
Tau	τ^-	-1	+1
Tau Neutrino	ν_τ	0	+1

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

Examination Tip

If a muon or tau decays – it will decay into the most stable lepton – the electron.

Along with this, in the decay, an electron anti-neutrino and the muon (or tau) neutrino is also produced.

The opposing particles are produced if an anti-muon or anti-tau decays.

Physics Tip

Anti-neutrinos are always released in beta minus decay.

Neutrinos are always released in beta plus decay.

Physics Tip

Leptons are not affected by the strong interaction – only the weak and electromagnetic interactions.



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.

Study Tip

You will not be expected to know all the particles you encounter in your examination. You might be given in a particle you have never seen before, so you will need to be familiar with working with different particles.

If this does happen, all information you will need will be given in the examination.



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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.	

Student Checklist

Have I.....	Yes or No?
Read through the notes of this section?	
Highlighted/underlined the key concepts of this section?	
Made my own notes based on the notes of this section?	
Brought the notes to be used in lesson?	



NOTES

Rutherford Scattering

Prior Knowledge Link

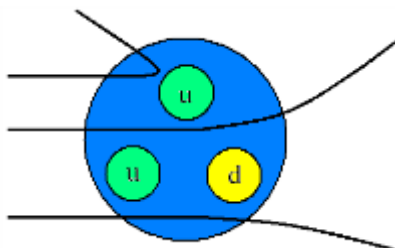
This is a topic found in a previous GCSE module - **Radioactivity**

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.

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.

Study Tip

In addition to this, patterns in data allowed Murray Gell-Mann to predict the existence of quarks and particles like the omega minus.



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

Physics Tip

Patterns of particles constructed from the properties of quarks allowed Murray Gell-Mann to predict the existence of omega minus two years before it was observed.

Physics Tip

Remember that anti-quarks have the opposite properties of the quarks stated above.

Examination Tip

Remember that quark properties are given in the formula and data booklet in the exam.

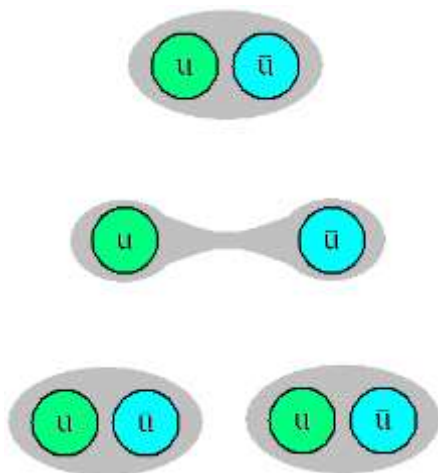
Study Tip

Remember -antiprotons and antineutrons are both types of anti-baryons.



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.



Physics Tip

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.

Examination Tip

You must be able to recognise the neutron and proton from its quark sub-structure.

Remember – the most stable baryon is a proton.

This is a common bit of key knowledge which is tested.

All free baryons decay into protons.

If a baryon is in the nucleus, it is not free, it will not decay – this is due to the strong force in the nucleus.

Examination Tip

It is a common examination question to ask you to identify the mechanism by how a neutron decays into a proton.

The process can be either electron capture or beta plus decay. (1 mark).

This process occurs via the weak interaction (as leptons are involved) (1 mark).



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TOPIC: 3.2.1.7 Applications of Conservation Laws

SPEC CHECK

Specification	Completed?
Change of quark character in β^- and in β^+ 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.	

Student Checklist

Have I.....	Yes or No?
Read through the notes of this section?	
Highlighted/underlined the key concepts of this section?	
Made my own notes based on the notes of this section?	
Brought the notes to be used in lesson?	



Conservation Laws

Key Topic Warning

This topic is a very common question on previous A-Level Papers.

For a particle interaction to occur the following laws must be obeyed, if either is violated the 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 EM and Strong Interaction. Doesn't have to be conserved in Weak Interaction

Examination Tip: Nearly every year, a conservation law question is found on the A-Level Physics papers.

Examples

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

	γ	\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 from GCSE Physics.

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.

Study Tip

If any of the properties (apart from strangeness) are not conserved on each side of an equation, the equation does not represent a possible interaction.



Examination Tip

It is a common examination question to be told that 'there have been considerable advances in our understanding of particle physics over the past 100 years. Explain why it is necessary for many teams of scientists and engineers to collaborate in order for these advances to be made.'

This can be by the following...

Results of experiments must be independently checked/validated/peer reviewed before they are accepted/can be confirmed (1 mark).

Particle accelerators are very expensive, and collaboration helps to spread the cost of building them (1 mark).

Many skills and disciplines are required (which one team are unlikely to have) (1 mark).

lots of data to process (so more teams needed) (1 mark).



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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 β^- 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"/>



Specification reference	Checklist questions	
3.2.1.3	Can you compare particle and antiparticle mass, charge, and rest energy in MeV?	<input type="checkbox"/>
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 β^- and β^+ 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 β^- and β^+ 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	3.00×10^8	m s^{-1}
permeability of free space	μ_0	$4\pi \times 10^{-7}$	H m^{-1}
permittivity of free space	ϵ_0	8.85×10^{-12}	F m^{-1}
magnitude of the charge of electron	e	1.60×10^{-19}	C
the Planck constant	h	6.63×10^{-34}	J s
gravitational constant	G	6.67×10^{-11}	$\text{N m}^2 \text{kg}^{-2}$
the Avogadro constant	N_A	6.02×10^{23}	mol^{-1}
molar gas constant	R	8.31	$\text{J K}^{-1} \text{mol}^{-1}$
the Boltzmann constant	k	1.38×10^{-23}	J K^{-1}
the Stefan constant	σ	5.67×10^{-8}	$\text{W m}^{-2} \text{K}^{-4}$
the Wien constant	α	2.90×10^{-3}	m K
electron rest mass (equivalent to 5.5×10^{-4} u)	m_e	9.11×10^{-31}	kg
electron charge/mass ratio	$\frac{e}{m_e}$	1.76×10^{11}	C kg^{-1}
proton rest mass (equivalent to 1.00728 u)	m_p	$1.67(3) \times 10^{-27}$	kg
proton charge/mass ratio	$\frac{e}{m_p}$	9.58×10^7	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	N kg^{-1}
acceleration due to gravity	g	9.81	m s^{-2}
atomic mass unit (1u is equivalent to 931.5 MeV)	u	1.661×10^{-27}	kg

ALGEBRAIC EQUATION

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

ASTRONOMICAL DATA

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

GEOMETRICAL EQUATIONS

arc length = $r\theta$

circumference of circle = $2\pi r$

area of circle = πr^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	γ	0
lepton	neutrino	ν_e	0
		ν_μ	0
	electron	e^\pm	0.510999
	muon	μ^\pm	105.659
mesons	π meson	π^\pm	139.576
		π^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
u	$+\frac{2}{3}e$	$+\frac{1}{3}$	0
d	$-\frac{1}{3}e$	$+\frac{1}{3}$	0
s	$-\frac{1}{3}e$	$+\frac{1}{3}$	-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 $I = \frac{\Delta Q}{\Delta t}$ $V = \frac{W}{Q}$ $R = \frac{V}{I}$

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

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 γ 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 $v \ll c$</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>	$\frac{1}{T_B} = \frac{1}{T_1} + \frac{1}{T_2}$



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 = $2(\Delta f + f_M)$



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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.