A Level Physics Edexcel

8. Nuclear & Particle Physics

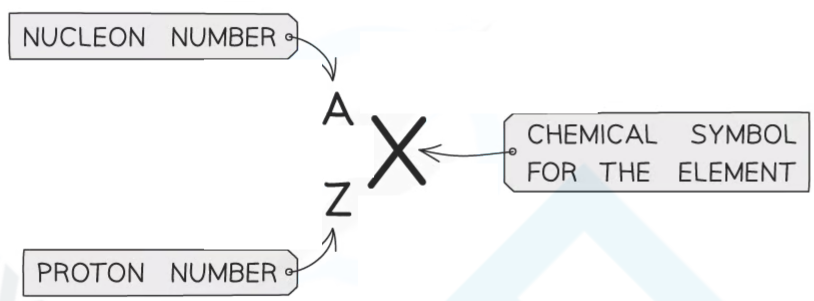
CONTENTS

Exploring the Structure of Matter

8.1 Nucleon & Proton Number

Nucleon & Proton Number

- Atomic symbols are written in a specific notation as shown below:



Atomic symbols show the proton number and nucleon number

- The top number A represents the **nucleon** number or the **mass** number
  - **Nucleon number (A)** = total number of **protons and neutrons** in the nucleus
- The lower number Z represents the **proton** or **atomic** number
  - **Proton number (Z)** = total number of **protons** in the nucleus
- Note: In Chemistry, the nucleon number is referred to as the mass number and the proton number as the atomic number. The periodic table is ordered by atomic number

Isotopes

- Although all atoms of the same element always have the same number of protons (and hence electrons), the number of neutrons can vary
- An isotope is an atom (of the same element) that has an equal number of protons but a **different number of neutrons**
  - For example, hydrogen has two isotopes: **deuterium** and **tritium**. Both isotopes have a proton number of 1
  - Deuterium has one neutron, so its nucleon number is 2
  - Tritium has two neutrons, so its nucleon number is 3

Particle Interactions & Conservation

8.11 The Standard Model

Baryons & Mesons

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

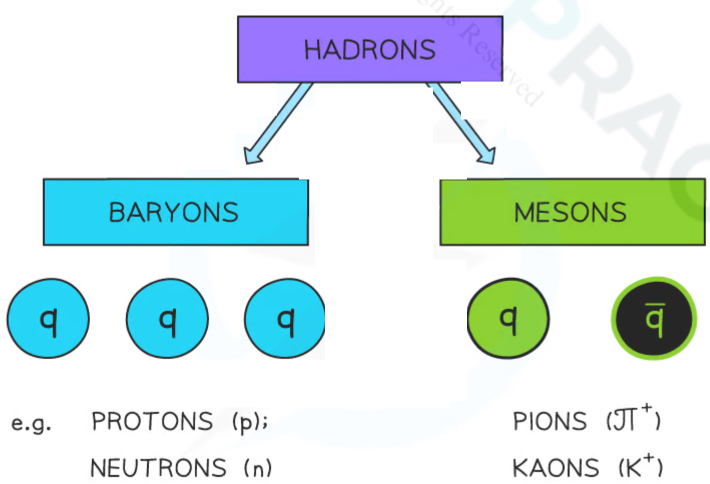
Generation	Quarks		Leptons	
I	u up $\left(+\frac{2}{3}e\right)$	d down $\left(-\frac{1}{3}e\right)$	e^- electron $(-1e)$	ν_e electron neutrino (0)
II	c charm $\left(+\frac{2}{3}e\right)$	s strange $\left(-\frac{1}{3}e\right)$	μ^- muon $(-1e)$	ν_μ muon neutrino (0)
III	t top $\left(+\frac{2}{3}e\right)$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

Increasing mass

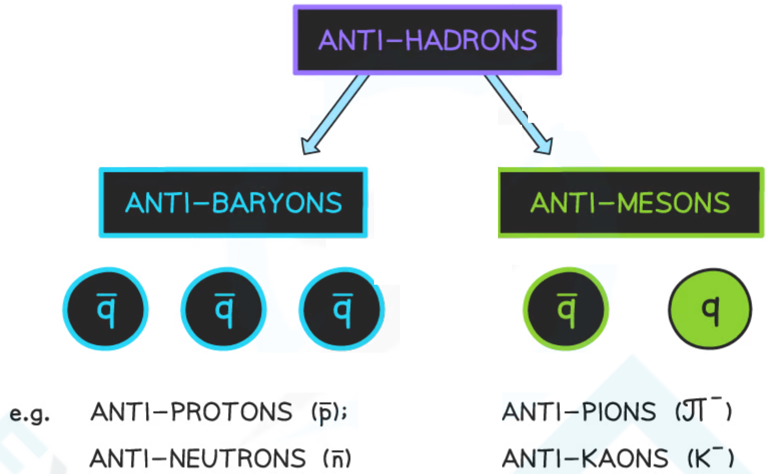
Quarks and leptons form the standard model of particle physics. The first generation of particles make up all ordinary matter

- **Hadrons** are made up of **quarks** and interact with the **strong nuclear force**
- **Baryons** and **mesons** are types of hadron
  - **Baryons** consist of **3 quarks**
  - **Mesons** consist of a **quark-antiquark pair**

- The most common baryons are protons and neutrons
- The most common mesons are pions and kaons



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



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

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

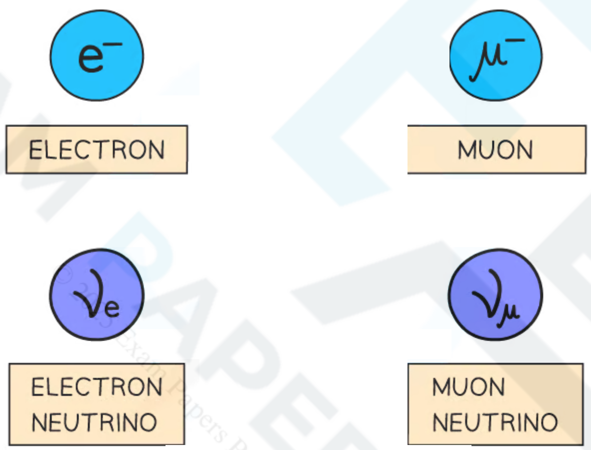
$\bar{u}ud$ WOULD NOT BE A QUARK COMBINATION THAT EXISTS

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

Leptons & Photons

Leptons

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



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

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

Photons

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

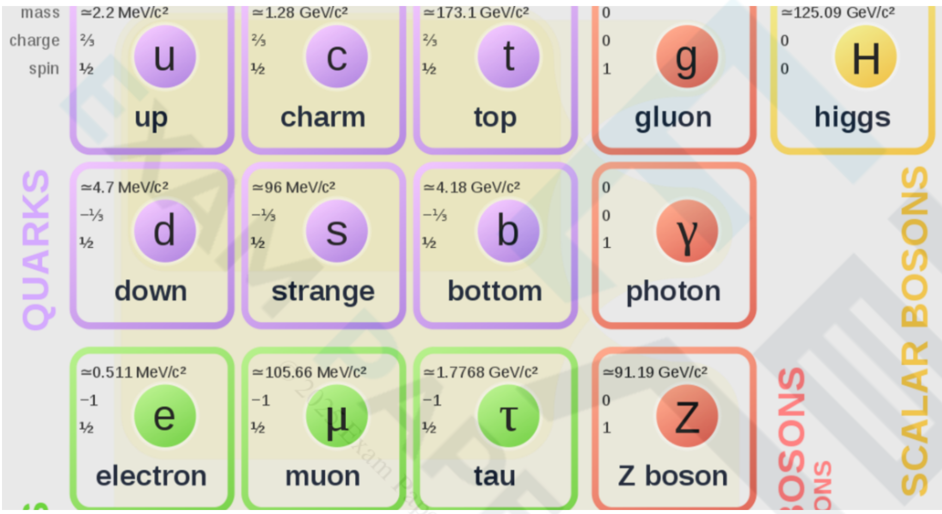
Exam Tip

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

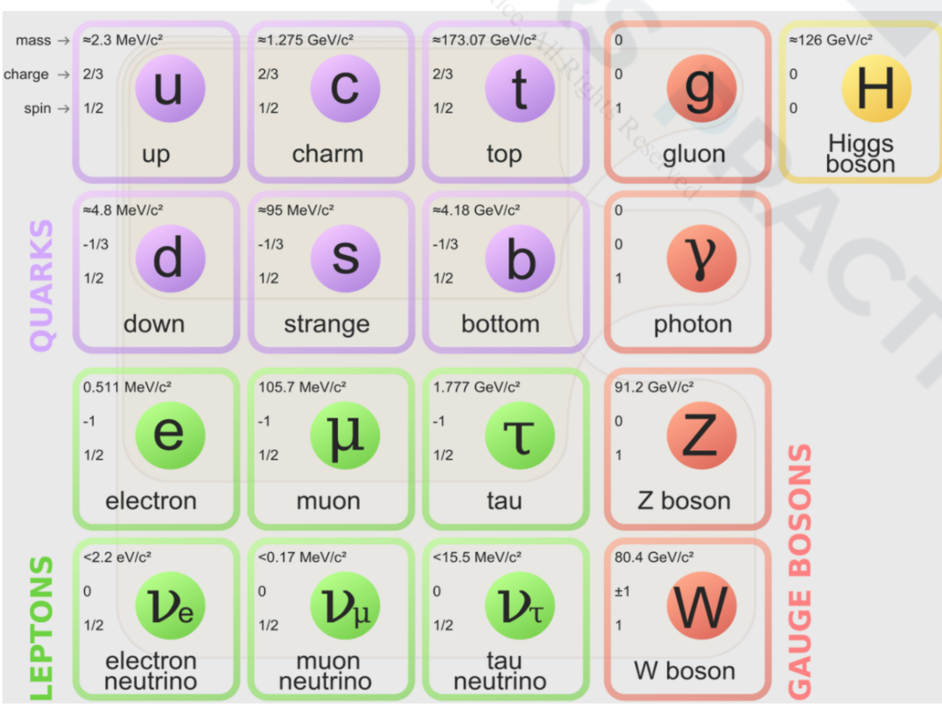
Symmetry of the Standard Model

- The first four quarks discovered were:
  - The up quark
  - The down quark
  - The strange quark
  - The charm quark

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



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



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

Exam Tip

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

8.12 Antimatter

Properties of Antimatter

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

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

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

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

Mass of Matter & Antimatter

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

Particle/Antiparticle	Mass (kg)	Rest Mass Energy (Me V)
Proton/Antiproton	$1.67(3) \times 10^{-27}$	938.257
Neutron/Antineutron	$1.67(5) \times 10^{-27}$	939.551
Electron/Positron	9.11×10^{-31}	0.510999
Neutrino/antineutrino	0	0

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

Exam Tip

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

Applying Conservation Laws

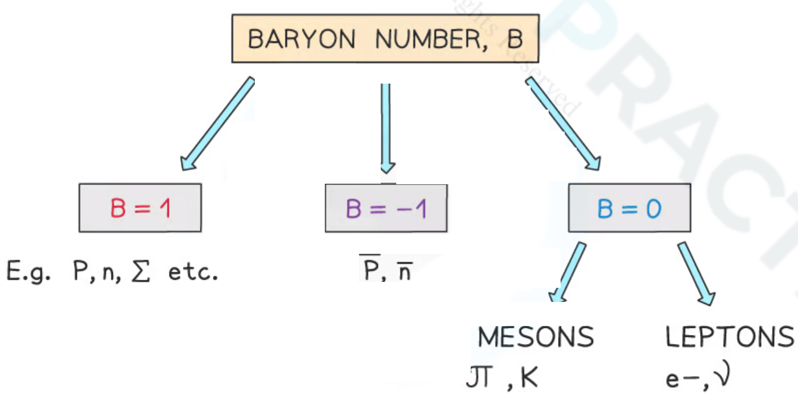
- When particles interact, they must obey a set of laws associated to the type of particles involved
  - These laws are governed by numbers called **quantum numbers**
- Quantum numbers that are **always conserved** (i.e., they are the same before and after an interaction) are:
  - Charge, Q
  - Baryon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

Conservation of Charge

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

Conservation of Baryon Number

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



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

- The up (u), down (d) and strange (s) quark have a baryon number of 1/3 each

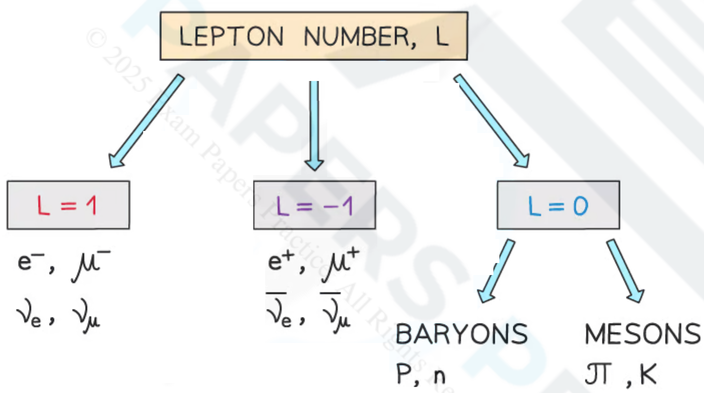
- This means that the anti-up, anti-down and anti-strange quarks have a baryon number of -1/3 each
- **Note:** The baryon number of each quark is provided on the datasheet

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

Conservation of Lepton Number

- Similar to baryon number, the lepton number, ***L*** is the number of leptons in an interaction
- ***L*** depends on whether the particle is a lepton, anti-lepton or neither
  - Leptons have a lepton number ***L*** = +1
  - Anti-leptons have a lepton number ***L*** = -1
  - Particles that are not leptons have a lepton number ***L*** = 0

- Lepton number is a quantum number and is conserved in all interactions
- This is helpful for knowing whether an interaction is able to happen



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

Worked Example

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

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

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

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

$$1 = 1 + 0 + 0$$

Step 3: Write a conclusion

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

Worked Example

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

$$n + \mu^+ \rightarrow p + \text{X}$$

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

- 0 + (–1) = 0 + X

Step 2: Identify the lepton number of X

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

Step 3: State the identity of particle X

- Particle X is an anti-neutrino

Exam Tip

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

Particle Interaction Equations

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

Worked Example

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

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

Determine whether this reaction is permitted.

Step 1: Determine conservation of charge Q

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

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

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

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

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

Step 3: Conclude whether this reaction is permitted

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

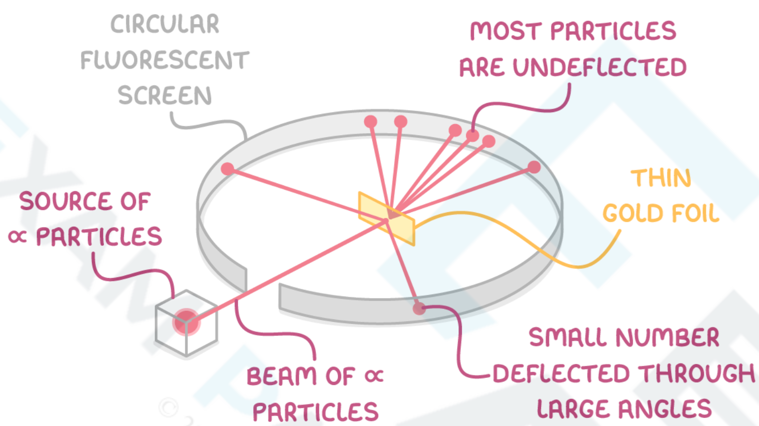
YOUR NOTES
⬇

Exploring the Structure of Matter

8.2 The Nuclear Model of the Atom

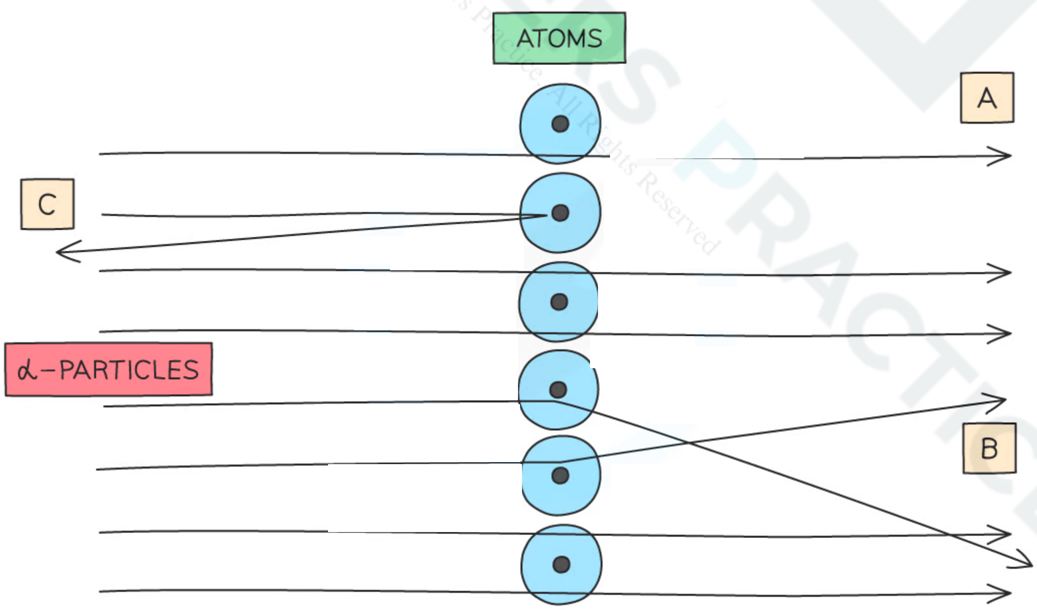
Alpha Particle Scattering

- Evidence for the structure of the atom was discovered by Ernest Rutherford in the beginning of the 20th century from the study of **alpha particle scattering**
  - This structure is commonly referred to as the 'nuclear model' of the atom
- The experimental setup consists of alpha particles fired at thin gold foil and a detector on the other side to detect how many particles deflected at different angles



Alpha particle scattering experiment set up

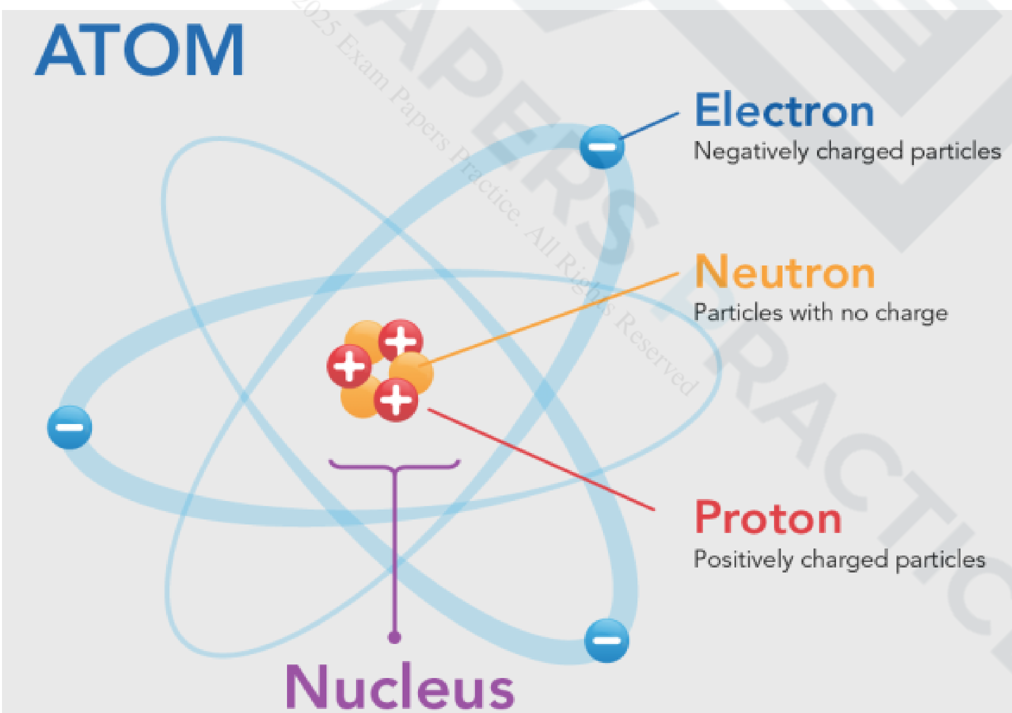
- α-particles are the nucleus of a helium atom and are positively charged



When α-particles are fired at thin gold foil, most of them go straight through but a small number bounce straight back

- The results from this experiment are summarised as follows:
- **The majority of α-particles went straight through the gold foil without deflection (A)**
  - This suggested the atom is mainly empty space
- **Some α-particles deflected through small angles of < 10° (B)**
  - This suggested there is a positive nucleus at the centre (since two positive charges would repel)
- **Only a small number of α-particles deflected straight back at angles of > 90° (C)**
  - This suggested the nucleus is extremely small and this is where the mass and charge of the atom is concentrated
  - It was therefore concluded that atoms consist of ***small dense positively charged nuclei***

- Since atoms were known to be neutral, the negative electrons were thought to be on a positive sphere of charge (plum pudding model) before the nucleus was theorised
- Now it is known that the negative electrons are orbiting the nucleus. Collectively, these make up the atom



An atom: a small, dense, positive nucleus, surrounded by negative electrons

Changing Models of Atomic Structure

- Our understanding of atomic structure has changed over time in the following ways:

John Dalton's Model (1803)

- Dalton imagined that all matter was made of tiny solid particles called atoms
- Dalton's model proposed:
  - Atoms are the smallest constituents of matter and cannot be broken down any further
  - Atoms of a given element are **identical** to each other and atoms of different elements are **different** from one another
  - When chemical reactions occur, the atoms rearrange to make different substances

J.J. Thomson's Model (1897)

- Thomson discovered the electron
- He then went on to propose the 'plum pudding' model of the atom
- In this model:
  - The atom consists of positive and negative charges in equal amounts so that it is neutral overall
  - They were modelled as spheres of positive charge with uniformly distributed charge and density. The negatively charged electrons were thought to be stuck to the sphere like currants in a plum pudding

Rutherford's Gold Foil Experiment (1909 – 1911)

- Hans Geiger and Ernest Marsden set out to test the plum pudding model
- They aimed beams of positively charged particles (alpha particles) at very thin gold foil
- According to the plum pudding model, these particles should have passed straight through, However, many of them were backscattered
- Ernest Rutherford explained these results in his 'planetary model of atom' which states:
  - Atoms have a central, positively charged nucleus containing the majority of the mass
  - Electrons orbit the nucleus, like planets around a star

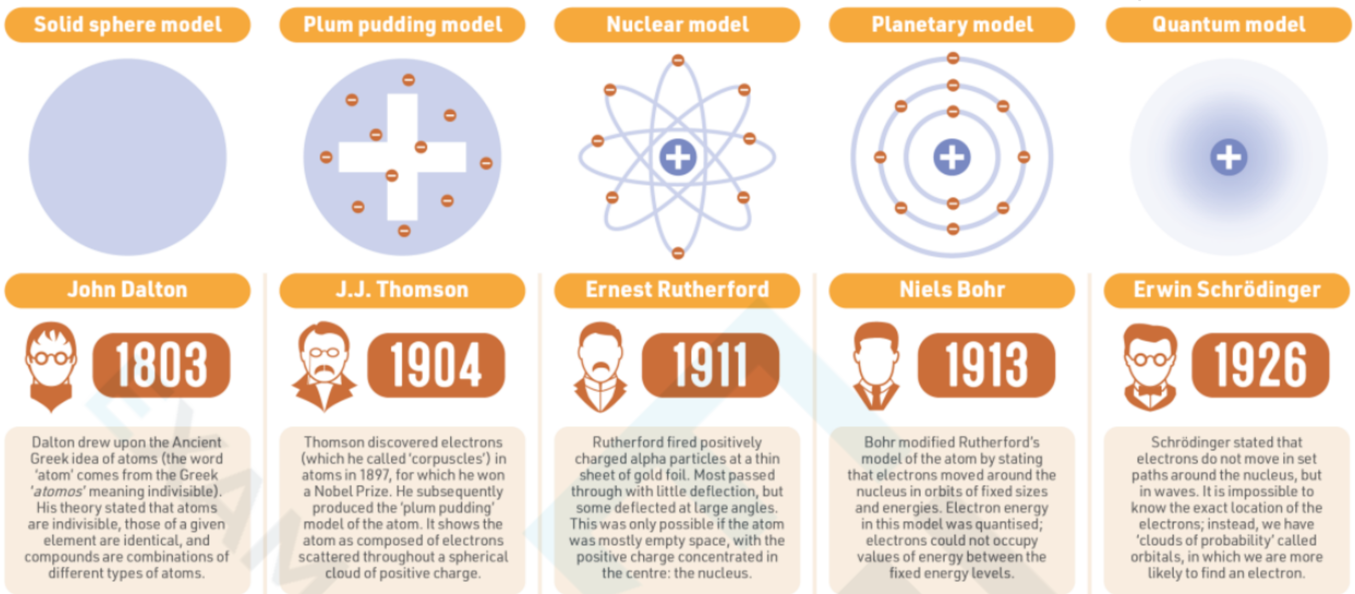
Neils Bohr's Model (1913)

- Bohr improved upon Rutherford's planetary model
- Using mathematical ideas, he showed that electrons occupy **shells** or **energy levels** around the nucleus
  - These are at particular distances from the nucleus

Quantum Mechanical Model (1926)

- Erwin Schrödinger took Bohr's model further and used equations to calculate the likelihood of finding an electron in a certain position
- This model can be portrayed as a nucleus surrounded by an electron cloud. Where the cloud is most dense, the probability of finding the electron is greatest and vice versa
- The atom was thought to only have a positively charged nucleus surrounded by negatively charged electrons. James Chadwick then discovered the neutron in 1932, which completes

the model of the atom we know today



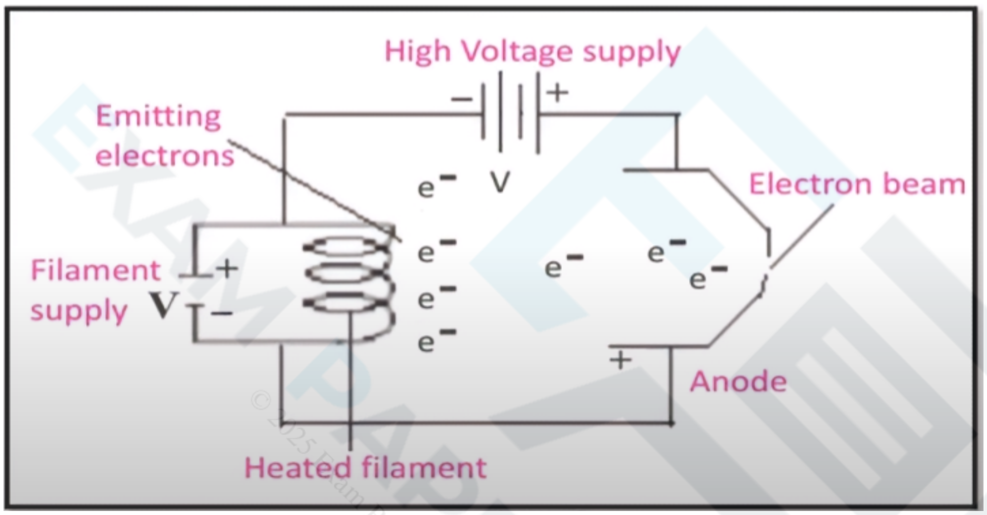
Timeline of the changing models of the atom

Exam Tip

Although you won't be expected to memorise specific dates or names of the scientists, it is good to know the rough order of the types of models and how they differ from each other.

Thermionic Emission

- When metals are **heated**, the conduction electrons within them gain **energy**
- If these electrons gain sufficient energy, they are able to leave the surface of the metal
  - This is known as **thermionic emission**
  - This is **similar** to the **photoelectric effect**, but the energy absorbed by electrons in this case is due to **thermal** energy, rather than the energy absorbed by incident **photons**
- Once electrons are released from a metal surface they may be accelerated by **electric** or **magnetic fields**



Electrons are emitted from the (negative) cathode and accelerated to the (positive) anode

Worked Example

Electron guns use electric fields to accelerate electrons to very high speeds.

Show that an electron accelerated from rest across a potential difference of 5.0 kV attains a speed of 4.2×10^7 m s^{-1}.

Use the following data:

- Mass of an electron $m_e = 9.11 \times 10^{-31}$ kg
- Electron charge e = 1.6×10^{-19} C

Step 1: List the known quantities

- Potential difference = 5 kV = 5000 V
- Mass of an electron, $m_e = 9.11 \times 10^{-31}$ kg
- Electron charge e = 1.6×10^{-19} C

Step 2: Equate the kinetic energy gained by the electron to the energy transferred across the potential difference

- Potential difference V is the energy transferred W per unit of charge Q, or $V = \frac{W}{Q}$
- Since the charge in this case is an electron, $Q = e$ and so $W = eV$
- Therefore, the kinetic energy gained is equal to eV so we can write:

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

Step 3: Make speed *v* the subject of the equation

- Rearranging this equation for v gives:

$$mv^2 = 2eV$$

$$v^2 = \frac{2eV}{m}$$

$$v = \sqrt{\frac{2eV}{m}}$$

Step 4: Substitute quantities and calculate the speed *v*

- Substituting known quantities gives:

$$v = \sqrt{\frac{2 \times (1.6 \times 10^{-19}) \times 5000}{(9.11 \times 10^{-31})}} = 41\,908\,313... = 4.2 \times 10^7 \text{ m s}^{-1}$$

Exam Tip

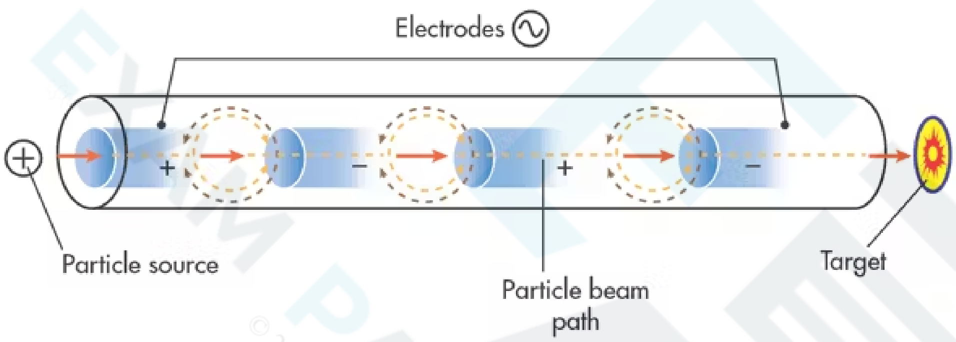
Examiners commonly test if candidates can equate the energy gained across a potential difference with the kinetic energy of a particle, as we did here. Make sure you can combine the equations for kinetic energy and potential energy in order to calculate speed like we did here!

Particle Accelerators & Detectors

Linear Accelerators

- A linear accelerator (LINAC) is a type of particle accelerator that accelerates ions (charged particles) to very high speeds in **straight lines**
- LINACs use **electric fields** within and between metallic tubes which act as oppositely charged **electrodes**
- The high-energy ions produced are used in collider experiments
  - These experiments enable the internal structure of atoms and subatomic particles to be investigated

- LINACs are comprised of a series of hollow cylindrical tubes



Linacs accelerate ions through progressively longer tubes, connected to an alternating power supply. This ensures they are always accelerating from one tube to the next

- An **AC power supply** is connected across each tube to ensure ions are always **accelerated** from one to the next
  - The ions will be **attracted** to the **midpoint** of a tube
  - At this point, the AC supply will **switch** such that the ions are **repelled** to the exit, and attracted to the next tube
  - This process continues in a **straight line** all the way to the end of the accelerator

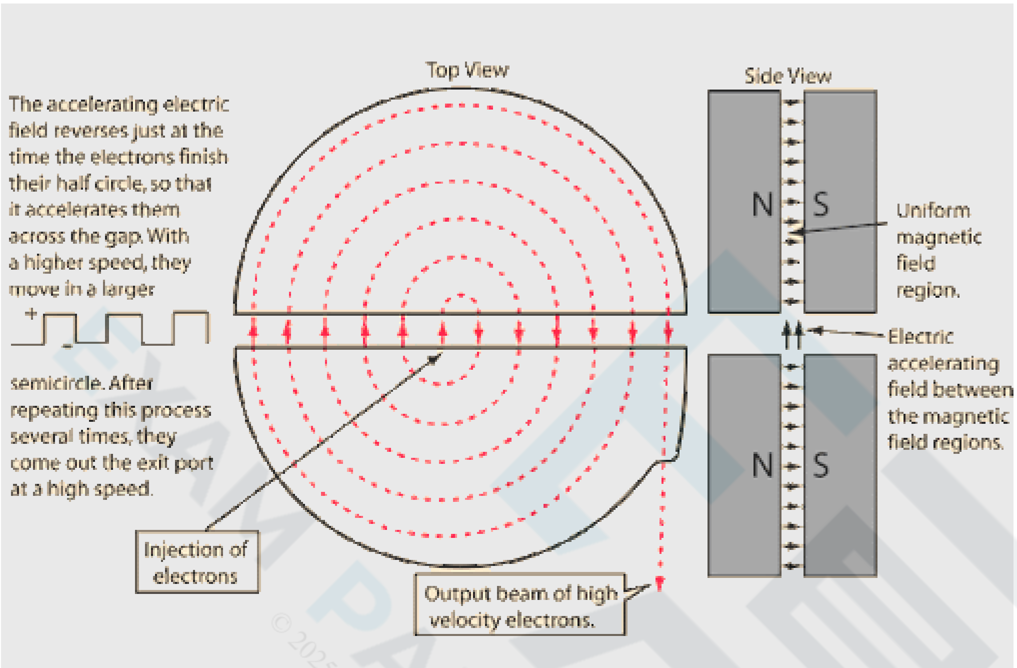
- The **frequency** of the AC supply is fixed
  - This means the polarity (positive or negative charge) of each tube switches at a **constant rate**

- Therefore, each tube must be built **successively longer**
  - This is because the ions are **speeding up**
  - Hence, this ensures ions spend the same amount of **time** under acceleration in each tube

Cyclotrons

- A cyclotron is a type of particle accelerator that accelerates ions from a central entry point around a **spiral** path
- They are used for medical research such as:
  - Producing medical isotopes (**tracers**)
  - Creating high-energy beams of radiation for **radiotherapy**

- Cyclotrons are comprised of:
  - Two hollow semicircular electrodes called '**dees**'
  - A uniform **magnetic field** applied **perpendicular** to the electrodes
  - An **AC power supply** applied across each dee, which creates an **electric field** in the **gap** between them



A cyclotron uses magnetic fields and electric fields to accelerate charged particles, like protons. The magnetic fields keep protons in a circular path, and the electric field increases their speed

- The process of accelerating an ion in a cyclotron is:
  - A source of charged particles is placed at the **centre** of the cyclotron and they are fired into one of the dees
  - The magnetic field in the electrode makes them follow a **circular path**, since it is perpendicular to their motion until they eventually leave the electrode
  - The potential difference applied between the electrode **accelerates** the ions across the gap to the next dee (since there is an **electric field** in the gap)
  - In the next dee, the ions continue moving in a circular path within the magnetic field
  - The potential difference is then reversed so the ions again accelerate across the gap
  - This process is repeated as the particles spiral outwards and eventually have a speed large enough to exit the cyclotron

- The alternating potential difference is needed to accelerate the particles across the gap between opposite electrodes
  - Otherwise, the ions would only speed up in one direction

Particle Detectors

- When charged particles move through any medium, such as a **gas**, they transfer **energy** to it
- This is usually through the process of **ionisation**
    - High-energy ions transfer some of their energy to surrounding atoms, removing electrons
    - The ions and electrons produced are then **accelerated** by applied **electric fields**
    - Once these are **discharged** they form pulses of electric **current**
- Each pulse of electricity is **counted** by electronic counters connected by electrodes
    - 'Counts' are then interpreted as detection of individual particles
- Ionisation is the principle by which many particle detectors operate, such as in:
    - Geiger-Muller tubes
    - Spark chambers
    - Gas and cloud chambers
- The particles are sometimes **deflected** meaning they are also scattered
    - This can cause multiple scattering of the particle in the material

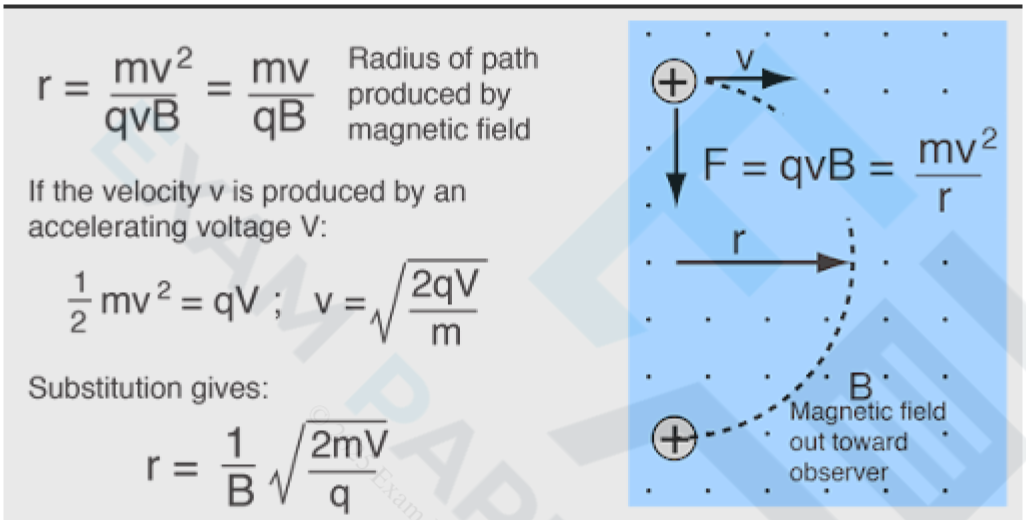
Exam Tip

Make sure you can distinguish between the two types of particle accelerator: remember, LINACs **only** use electric fields (to accelerate ions in straight lines) whereas **cyclotrons** use both electric fields and magnetic fields.

In particle detectors, you only need to describe the two key principles which allow scientists to detect particles: **ionisation** and **deflection** (by applied electric fields).

Radius of a Charged Particle in a Magnetic Field

- A charged particle in uniform **magnetic field** which is perpendicular to its direction of motion travels in a **circular** path
- This is because the **magnetic force** *F* is always perpendicular to its velocity *v*
  - *F* will always be directed towards the centre of orbit



A charged particle travels in a circular path in a magnetic field

- The magnetic force *F* provides the **centripetal force** on the particle
- The equation for centripetal force is:

$$F = \frac{mv^2}{r}$$

- Where:
  - *F* = centripetal force (N)
  - *m* = mass of the particle (kg)
  - *v* = linear velocity of the particle (m s^{-1})
  - *r* = radius of orbit (m)

- Equating this to the magnetic force on a moving charged particle gives the equation:

$$\frac{mv^2}{r} = Bqv$$

- Rearranging for the radius *r* obtains the equation for the radius of the orbit of a charged particle in a perpendicular magnetic field:

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

- The product of mass *m* and velocity *v* is momentum *p*
  - Therefore, the radius of the charged particle in a magnetic field can also be written as:

$$r = \frac{p}{Bq}$$

- Where:
  - r = radius of orbit (m)
  - p = momentum of charged particle (kg m s^{-1})
  - B = magnetic field strength (T)
  - q = charge of particle (C)
- This equation shows that:
  - Particles with a larger momentum (either larger mass *m* or speed *v*) move in larger circles, since $r \propto p$
  - Particles with greater charge *q* move in smaller circles: $r \propto 1 / q$
  - Particles moving in a strong magnetic field *B* move in smaller circles: $r \propto 1 / B$

Worked Example

An electron with charge-to-mass ratio of 1.8×10^{11} C kg^{-1} is travelling at right angles to a uniform magnetic field of flux density 6.2 mT. The speed of the electron is 3.0×10^6 m s^{-1}.

Calculate the radius of the circular path travelled by the electron.

Step 1: Write down the known quantities

Charge-to-mass ratio = $\frac{q}{m}$ = 1.8×10^{11} C kg^{-1}

Magnetic flux density, B = 6.2 mT

Electron speed, v = 3.0×10^{6} m s^{-1}

Step 2: Write down the equation for the radius of a charged particle in a perpendicular magnetic field

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

Step 3: Substitute in values

$$\frac{m}{q} = \frac{1}{1.8 \times 10^{11}}$$

$$r = \frac{(3.0 \times 10^{6})}{(1.8 \times 10^{11}) \times (6.2 \times 10^{-3})} = 2.688 \times 10^{-3} \text{ m} = \mathbf{2.7 \text{ mm (2 s.f.)}}$$

Exam Tip

Make sure you're comfortable with deriving the equation for the radius of the path of a charged particle travelling in a magnetic field, as this is a common exam question.

Crucially, the **magnetic force** is **always** perpendicular to the velocity of a charged particle. Hence, it is a **centripetal** force and the equations for circular motion can be applied.

Interpreting Particle Tracks

- Particle detectors that count particles, like Geiger-Muller tubes, are useful but they cannot distinguish different types of particle
- Modern detectors can show the **paths** of charged particles, from which physicists are able to interpret the characteristics of the particle

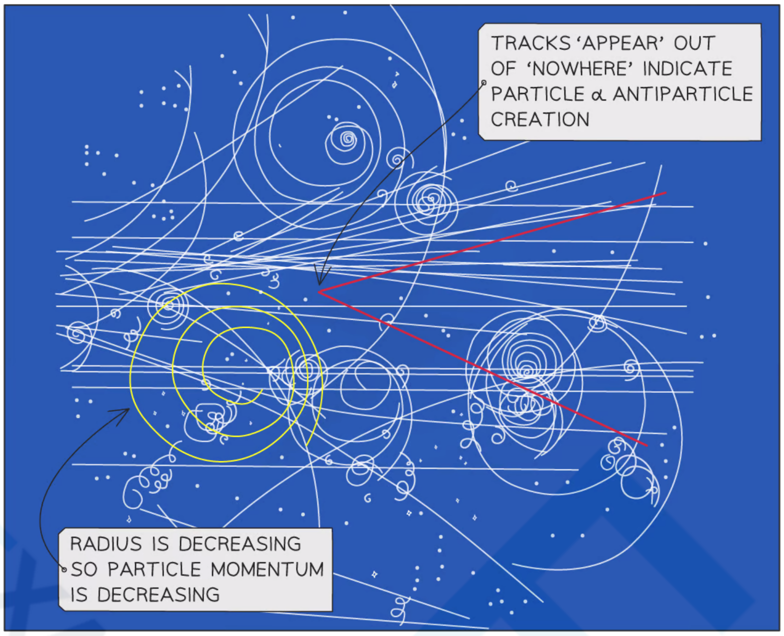
- The **curvature** of the particle tracks gives an indication of its momentum
  - A **smaller radius** means the particle has a **smaller momentum**
  - A **larger radius** means the particle has a **larger momentum**

- This is due to the equation for the radius of a charged particle in a magnetic field:

$$r = \frac{mv}{BQ} = \frac{p}{BQ}$$

- Where:
  - r = orbital radius of charged particle (m)
  - p = momentum of charged particle (kg m s^{-1})
  - B = magnetic field strength (T)
  - Q = charge of particle (C)
  - m = mass of the particle (kg)
  - v = velocity of the particle (m s^{-1})

- If the **radius** of a track is decreasing (i.e., it is spiralling closer inwards)
  - This means the particle's momentum is **decreasing**
  - This is because $r \propto p$
  - Therefore, the **velocity** of the particle is **decreasing**
  - Hence, the **kinetic energy** of the particle is also decreasing, due to **ionising** other particles in its path



The radius and direction of particle tracks is used to determine momentum and charge. Creation and annihilation is also observable

- The **direction** of a track's curvature gives an indication of the particle's **charge**
  - **Fleming's Left Hand Rule** can be used to determine the sign of the particle's charge
- Sometimes, particle tracks appear to start out of 'nowhere'
  - This indicates particle-antiparticle **creation**
  - These paths are in **opposite directions** because the particle-antiparticle pair is **oppositely charged**
  - Therefore, the magnetic force on them is **oppositely directed**
  - However they have the same **radius** because they each have the same **mass** (and hence, **momentum**)
- Therefore charge, energy and momentum are always conserved in interactions between particles

High Energy Particle Collisions

The Diameter of a Nucleon

- High energy electron beams can be used to analyse **nucleons**, e.g.
  - Protons
  - Neutrons

- When electrons are accelerated to very high energies, they can **collide** with nucleon targets
- The **scattering pattern** is used to analyse the size and structure of nucleons
- To **resolve** detail, like the nucleon diameter, the **de Broglie wavelength** of the electron must be comparable to the **size of the nucleon**
  - The de Broglie wavelength, and hence an approximation to nucleon diameter, is given by:

$$\lambda = \frac{h}{mv} \approx \textbf{nucleon diameter}$$

- Where:
  - λ = de Broglie wavelength (m)
  - h = Planck's constant (J s)
  - m = mass (kg)
  - v = velocity (m s^{-1})
- Note that electrons do not experience the **strong nuclear force**
  - Therefore, they are able to get extremely close to the nucleons without interacting
  - This allows them to build up a better idea about the size of the nucleus than **alpha particles**, which are comprised of protons and neutrons

Inside the Nucleon

- If electrons are accelerated to even **higher** energies, their de Broglie wavelength becomes even **smaller**
  - This is because $\lambda \propto \frac{1}{v}$ therefore the **faster** the electrons, the **smaller** their de Broglie wavelength
- Hence, the electron wavelength becomes small enough to be used to resolve **internal** structure of the nucleon
  - Such an electron beam would be able to resolve individual **quarks** inside the nucleon

Worked Example

The diameter of a proton is of the order of 10^{-15} m.

Explain why electrons must be accelerated to very high energies if they are to be used to probe the internal structure of a proton.

Step 1: Refer to the de Broglie wavelength

- The proton diameter ~ 10^{-15} m so the **de Broglie wavelength** of the electrons must be **at most** this size in order to resolve the internal structure of the proton

Step 2: Refer to the proportionality between wavelength and momentum

- Since the de Broglie wavelength is **inversely proportional** to the momentum of the electrons, then they must be accelerated to very high velocity (and hence, energy) in order to obtain very short wavelengths

Exam Tip

Remember to use words like 'proportional' and 'inversely proportional' when explaining how two quantities relate to each other, using an equation.

In the case of particle physics, it is likely that you will be asked to explain effects based on the de Broglie wavelength λ, which you should remember is given by:

$$\lambda = \frac{h}{p} = \frac{h}{mv}$$

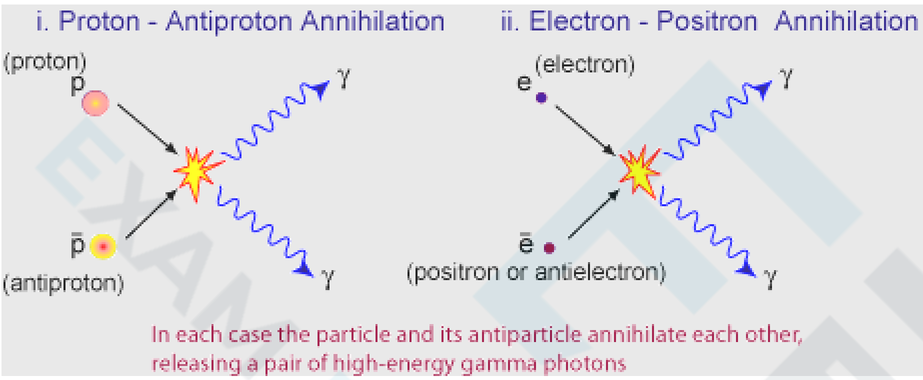
Therefore, the de Broglie wavelength λ is **inversely proportional** to particle momentum p and velocity v.

Annihilation of Matter & Antimatter

Annihilation

- When a particle meets its antiparticle partner, the two will **annihilate**
- Annihilation is:

> **When a particle meets its equivalent anti–particle they both are destroyed and their mass is converted into energy in the form of two gamma ray photons**



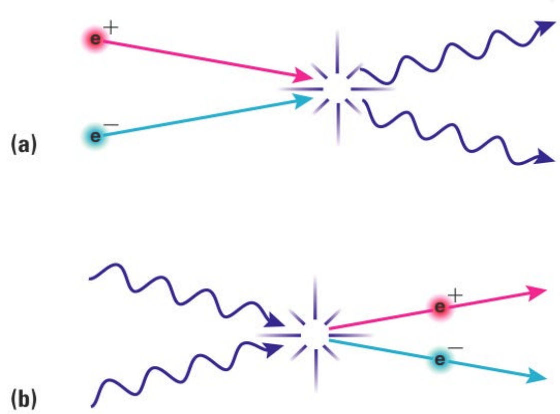
When an electron and positron collide, their mass is converted into energy in the form of two photons emitted in opposite directions

Pair Production

- Pair production is the opposite of annihilation
- Pair production is:

> **When a photon interacts with a nucleus or atom and the energy of the photon is used to create a particle–antiparticle pair**

- The presence of a nearby neutron is essential in pair production so that the process conserves both energy and momentum
- A single photon alone cannot produce a particle–anti-particle pair or the conservation laws would be broken
- Pair creation is a case of energy being converted into matter



When a photon with enough energy interacts with a nucleus it can produce an electron-positron pair

- This means the energy of the photon must be above a certain value to provide the **total rest mass energy** of the particle–antiparticle pair
- Einstein's famous mass-energy relation showed that **energy** can be converted into **mass**, and vice versa
- It is given by:

$$\Delta E = c^2 \Delta m$$

- Where:
  - Δm = rest mass of the particle (kg)
  - c = speed of light (m s^{-1})
  - ΔE = rest mass energy of the particle (J)

- Therefore, in order to create a particle & anti-particle pair, the energy carried by a single photon must be **at least** twice the rest-mass energy required, i.e.

$$\mathbf{2\Delta E = 2(c^2 \Delta m)}$$

- This also means if a particle meets its anti-particle and annihilates, the energy carried away by **each** of the two photons E_{photon} is given by:

$$\mathbf{E_{photon} = hf = \frac{hc}{\lambda} = c^2 \Delta m}$$

Worked Example

Calculate the maximum wavelength of one of the photons produced when a proton and antiproton annihilate each other.

Step 1: Write down the known quantities

Rest mass energy of a proton (and antiproton) = 938.257 MeV

$$1 \text{ MeV} = 1.60 \times 10^{-13} \text{ J}$$

Step 2: Write the equation for the minimum photon energy

$$E_{min} = hf_{min} = E$$

Step 3: Write energy in terms of wavelength

$$f_{min} = \frac{c}{\lambda_{max}}$$

$$E_{min} = \frac{hc}{\lambda_{max}} = E$$

Step 4: Rearrange for wavelength

$$\lambda_{max} = \frac{hc}{E}$$

Step 5: Substitute in values

$$\lambda_{max} = \frac{\left(6.63 \times 10^{-34}\right) \times (3.0 \times 10^{8})}{938.257 \times \left(1.60 \times 10^{-13}\right)} = 1.32 \times 10^{-15} \text{ m}$$

Exam Tip

Since the Planck constant is in Joules (J s) remember to always convert the rest mass-energy from MeV to J.

Remember that the equation $E = hf$ is only relevant for **photons**, not for all particles!

Unit Conversions for Energy & Mass

Units of Energy

- The electronvolt is a unit of **energy**
- It is equivalent to the amount of energy transferred to an electron accelerated across a potential difference of 1 V:

$$1\ \text{eV} = 1.6 \times 10^{-19}\ \text{J}$$

- In order to convert between electronvolts and joules:
  - **Multiply** electronvolts by 1.6×10^{-19} to get the equivalent energy in joules
  - **Divide** joules by 1.6×10^{-19} to get the equivalent energy in electronvolts

Convert joules to electronvolts

$$\text{eV} = \text{joule} \times 6.242\text{E}{+}18$$

Converting between electronvolts and joules

- Sometimes, units of MeV or GeV are used
  - These are given by:

$$1\ \text{MeV} = 1 \times 10^{6}\ \text{eV} = 1.6 \times 10^{-13}\ \text{J}$$

$$1\ \text{GeV} = 1 \times 10^{9}\ \text{eV} = 1.6 \times 10^{-10}\ \text{J}$$

Units of Mass

- Energy and mass are related by Einstein's energy-mass relation

$$\Delta E = c^2 \Delta m$$

$$\Delta m = \frac{\Delta E}{c^2}$$

- Therefore, units of **mass** can be related to units of energy by **division** of c^2
  - This provides particle physicists convenient units of calculation to work with
  - This is especially useful in experiments involving particle collisions, where **annihilation** and **creation** is common

- Possible units of mass are therefore:

$$\frac{MeV}{c^2}, \text{ or, } \frac{GeV}{c^2}$$

- The following conversions are used to convert into S.I. units:

$$1\frac{MeV}{c^2} = 1.67 \times 10^{-30} \text{ kg}$$

$$1\frac{GeV}{c^2} = 1.67 \times 10^{-27} \text{ kg}$$

Worked Example

Show that the rest mass of a proton, 1.67×10^{-27} kg, is roughly equivalent to 1 GeV/c^2.

Step 1: Write the known quantities

- Rest mass of a proton, $m_p = 1.67 \times 10^{-27}$ kg
- Speed of light $c = 3 \times 10^8$ m s^{-1}

Step 2: Substitute quantities into Einstein's energy-mass relation

$$E = m_p c^2$$

$$E = (1.67 \times 10^{-27}) \times (3 \times 10^8)^2 = 1.50 \times 10^{-10} \text{ J}$$

Step 3: Convert joules to electronvolts

- To convert a quantity of energy in joules to electronvolts, divide by 1.6×10^{-19}

$$\frac{1.50 \times 10^{-10}}{1.6 \times 10^{-19}} = 9.4 \times 10^8 \text{ eV} = 0.94 \text{ GeV}$$

Step 4: Convert electronvolts to GeV/c^2

- 0.94 GeV is equivalent to a mass of 0.94 GeV/c^2, which is roughly 1 GeV/c^2

Exam Tip

In this worked example, we could have used the direct conversion between GeV/c^2 and kg, because 1 GeV/c^2 = 1.8×10^{-27} kg, but you should be super comfortable with using Einstein's energy-mass relation to find quantities of mass/energy in standard units, and converting to eV and eV/c^2 the 'long way round'. Exam questions may require you to do this when the conversions are not so straightforward.

Relativistic Situations

- Accelerated particles often reach speeds that are very close to the **speed of light**
- At such high velocities and energies, **relativistic effects** begin to become important
- These are effects such as:
  - Time dilation
  - Length contraction

Time Dilation

- Clocks run slower for moving particles
  - This means that unstable particles, with a **short lifetime**, actually survive for **much longer** in a laboratory if they are moving very quickly
  - This is useful because they will leave **longer tracks** in particle detectors (making detection easier)

- For example, muons created high up in the atmosphere, have a lifetime of about 2 μs
  - The time required to travel to sea-level is **too great** to survive the journey
  - However, they are detected at sea-level in large numbers
  - This is because they are travelling at **relativistic speeds** (e.g. 0.98c) so **time dilation** means their lifetime is dilated to times much longer than 2 μs

Length Contraction

- Moving rulers are shorter than stationary rulers
  - This means that particles moving at very high velocities travel much further through detectors than expected
  - Unstable particles with very short lifetimes would not travel for appreciable distances without **relativistic** effects like length contraction

- For example, if exotic particles produced in particle accelerators decayed within the particle chamber before escaping it, none would be detectable
  - In fact, **many** types of exotic particles are detected
  - This is evidence of length contraction

Worked Example

Muons, which normally have a lifetime of 2.2×10^{-6} s, are created in the upper atmosphere at a height of about 10 km above sea level.

a) Calculate the distance a muon would travel towards the ground if it was moving at 0.99 c.

b) Comment on the relativistic effects necessary if muons are to be detected at sea level.

Part (a)

Step 1: Write the known quantities

- Muon lifetime, $t = 2.2 \times 10^{-6}$ s
- Speed of light, $c = 3 \times 10^8$ m s^{-1}
- Speed of muons, $v = 0.99\,c = 0.99 \times (3 \times 10^8) = 2.97 \times 10^8$ m s^{-1}

Step 2: Calculate distance travelled

- Speed v = distance d ÷ time t
- Therefore, the distance travelled by muons travelling at 0.99 c is given by:

$$d = vt = (2.97 \times 10^8) \times (2.2 \times 10^{-6}) = 653.4 \text{ m}$$

Part (b)

Step 1: Compare the distance calculated to the distance required

- The distance a muon travels with a lifetime of 2.2×10^{-6} s is only 653.4 m
  - This is much less than the 10 km required to sea level

Step 2: Conclude that relativistic effects must be at play

- Therefore, time dilation must be allowing the muons to last much longer than 2.2×10^{-6} s
  - This is because they are detected in large numbers at sea level

Exam Tip

For your exam, you are only required to understand the situations in which a **relativistic increase** particle lifetime would be significant. As seen in the worked example, this is a combination of time dilation and length contraction. This is when, as we have seen, particles are moving **very close** to the speed of light. This is normally at velocities greater than 90% the speed of light.