Wallace Hall Academy

CfE Higher Physics

Unit 2 - Particles Notes

Name ___________________

Orders of Magnitude

Often, to help us grasp a sense of scale, newspapers compare things to everyday objects: heights are measured in double-decker buses, areas in football pitches etc. However, we do not experience the extremes of scale in everyday life so we use scientific notation to describe these. Powers of 10 are referred to as orders of magnitude, i.e. something a thousand times larger is three orders of magnitude bigger. As a starting point a range of lengths relating to the world in which we live are shown.

1 m	Human scale – the average British person is 1.69 m
10 m	The height of a house
100 m	The width of a city square
10^3 m	The length of an average street
10^4 m	The diameter of a small city like Perth
10^5 m	Approximate distance between Aberdeen and Dundee
10^6 m	Length of Great Britain
10^7 m	Diameter of Earth

The table above acts as a starting point for orders of magnitude but in Physics we must consider the Physics of the very small (atoms) and the Physics of the very big (space). There are two examples below to demonstrate the orders of magnitude involved in such calculations.

Example

If a proton is measured as having a radius of distance roughly 10^{-15} m, calculate how many of these protons would fit on the point of a pencil of width 1 mm.

Solution

Example

If a distant star is 6 x 10^{25} m away, calculate how long would it take light from the star to reach us.

Solution

In the following table some of the objects are missing. Complete the table from the list on the right hand side.

Order of magnitude (m)	Object
10^{-15}	
10^{-14}	
10^{-10}	Diameter of hydrogen atom
10^{-4}	
10^{0}	
10^{3}	
10^{7}	Diameter of Earth
10^{9}	
10^{13}	Diameter of Solar system
10^{21}	

Diameter of nucleus
Diameter of proton
Diameter of Sun
Distance to nearest galaxy
Height of Ben Nevis
Size of a dust particle
Your height

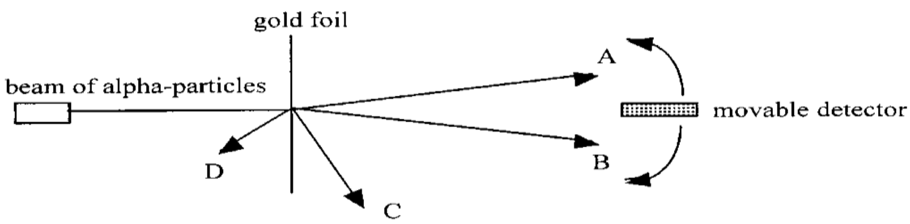
The Standard Model

The structure of atoms

At the start of modern physics at the beginning of the 20th century, atoms were treated as semi-solid spheres with charge spread throughout them. This was called the Thomson model after the physicist who discovered the electron. This model fitted in well with experiments that had been done by then, but a new experiment by Ernest Rutherford in 1909 would soon change this. This was the first scattering experiment – an experiment to probe the structure of objects smaller than we can actually see by firing something at them and seeing how they deflect or reflect.

The Rutherford alpha scattering experiment

Rutherford directed his students Hans Geiger and Ernest Marsden to fire alpha particles at a thin gold foil. This is done in a vacuum to avoid the alpha particles being absorbed by the air.



The main results of this experiment were:

- Most of the alpha particles passed straight through the foil, with little or no deflection, being detected between positions A and B.
- A few particles were deflected through large angles, e.g. to position C, and a very small number were even deflected backwards, e.g. to position D

Rutherford interpreted his results as follows:

- The fact that most (99.9%) of the particles passed straight through the foil, which was at least 100 atoms thick, suggested that **the atom must be mostly empty space**.
- In order to produce the large deflections at C and D, the positively charged alpha particles must be encountering **a nucleus of very large mass and a positive charge**.

Through a range of other experiments during the 20th Century we were able to show the existence of a range of other particles. Many of these discoveries came through the use of particle accelerators such as the one at CERN, which we will learn more about later. We were able to show that the protons and neutrons which make up the nucleus of an atom could be broken down into even smaller particles called quarks. The number of particles discovered increased so much that it was necessary to organise them into a table which summarises the Standard Model. This table acts like a periodic table for particles.

At present physicists believe that quarks are fundamental particles which cannot be broken down any further. There are 12 fundamental mass particles called **fermions** which are split into two groups: **leptons** and **quarks** There are also 4 force mediating particles called **bosons**. The table below shows the fundamental particles [at the moment!]

	fermions			bosons	
quarks	u up(⅔)	c charm (⅔)	t top (⅔)	γ photon	force carriers
	d down (- ⅓)	s strange (- ⅓)	b bottom (- ⅓)	g gluon	
leptons	ν_e electron neutrino (0)	ν_μ muon neutrino (0)	ν_τ tau neutrino (0)	Z Z boson	
	e electron (-1)	μ muon (-1)	τ tau (-1)	W W boson	

Columns 1 and 4 require the most attention as they are the most common and the most likely to be asked about in an exam!

Quarks

In 1964 Murray Gell-Mann proposed that protons and neutrons consisted of three smaller particles which he called '***quarks***' (pronounced kworks). There are two first generation quarks called ***up*** and ***down***. These make up neutrons and protons. There are two 2nd generation quarks called ***charm*** and ***strange***. Finally there are two 3rd generation quarks called ***top*** and ***bottom*.** Each quark has only a fraction (**⅓** or **⅔**) of the electron charge (1.6×10^{-19} C). These particles also have other properties, such as spin, colour, quantum number and even something called strangeness, which are not covered by this course.

Quarks have been observed by carrying out deep-inelastic scattering experiments which use high energy electrons to probe deep into the nucleus. However, they have never been observed on their own, only in twos or threes where they make up what are called ***hadrons*.**

Antiparticles

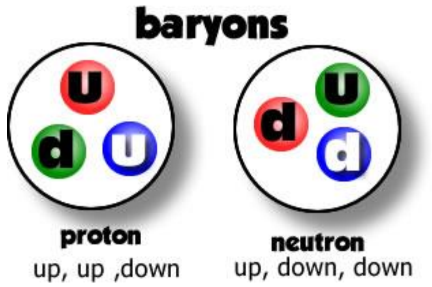
Most matter particles, including the ones shown above, also have corresponding antiparticles. These have the same rest mass as the particles but the opposite charge. With the exception of the antiparticle of the electron (e^-), which is the positron (e^+), **antiparticles are given the same symbol as the particle but with a bar over the top**. When a particle and its antiparticle meet, in most cases, they will annihilate each other and their mass is converted into energy. There are far more particles than antiparticles in the Universe, so annihilation is extremely rare.

Hadrons

Particles which are made up of quarks are called ***hadrons*** (the word hadron meant heavy particle). The Large Hadron Collider at CERN collides these particles. There are two different types of hadron, called ***baryons*** and ***mesons*** which depend on how many quarks make up the particle.

Baryons are made up of *3* quarks. Examples include the proton and the neutron.

The charge of the proton (and the neutral charge of the neutron) arise out of the fractional charges of their inner quarks. This is worked out as follows:

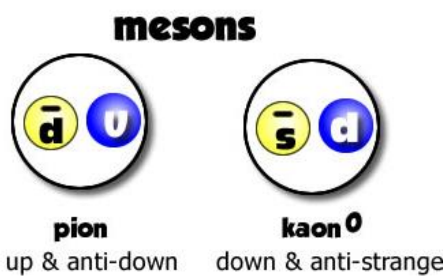


A **proton** consists of **2 up quarks and a down quark**.

A **neutron** is made up of **1 up quark and 2 down quarks**.

Mesons are made up of 2 quarks. They always consist of a quark and an anti-quark pair.

A **pion** consists of **1 up quark and 1 anti-down quark**.
Note that an anti-down quark is not an up quark



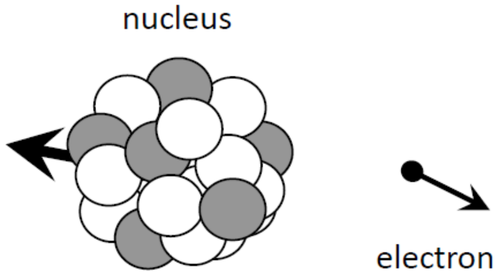
A **kaon^0** is made up of **1 down quark and 1 anti-strange quark**.

The Three Generations of leptons

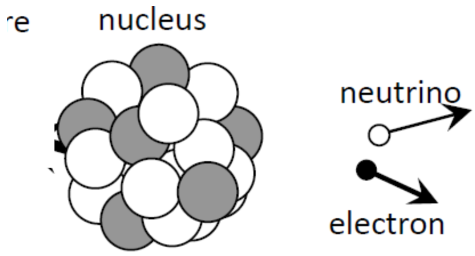
Leptons are a different type of particle which include the familiar ***electron*** which is a first generation particle. In addition, there is a second (middle) generation electron called the **muon** and a third (heaviest) generation electron called the ***tau*** particle. (The word lepton meant a light particle but the tau particle is actually heavier than the proton!)

Neutrinos

All 3 leptons have a "ghostly" partner associated with it called the ***neutrino***. This has no charge (its name means little neutral one). There is an electron neutrino, a muon neutrino and a tau neutrino.
Neutrinos were first discovered in radioactive beta decay experiments. In beta decay, a neutron in the atomic nucleus decays into a proton and an electron. When physicists were investigating beta decay they came up with a possible problem, the law of conservation of momentum appeared to be being violated.



To solve this problem, it was proposed that there must be another particle emitted in the decay which carried away with it the missing energy and momentum. Since this had not been detected, the experimenters concluded that it must be neutral and highly penetrating.

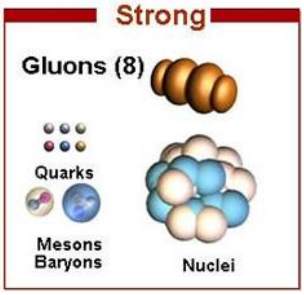


This was the first evidence for the existence of the neutrino. (In fact, in beta-decay an anti-neutrino is emitted along with the electron as lepton number is conserved in particle reactions).

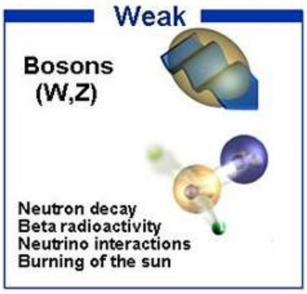
More than 50 trillion (50x 10^{12}) solar neutrinos pass through an average human body every second while having no measurable effect. They interact so rarely with matter that massive tanks of water, deep underground are required to detect them.

Forces and Bosons

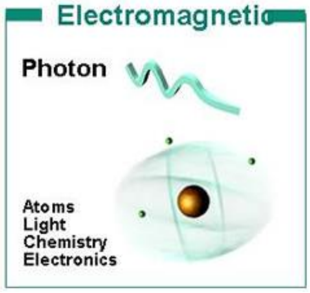
There are **4 fundamental forces**, 3 of which have bosons associated with them. The bosons are force mediating particles which pass between quarks to exert the 4 fundamental forces.



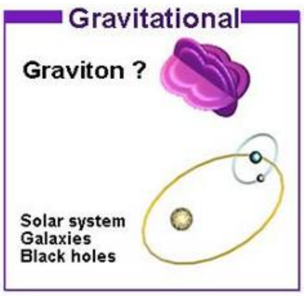
Strong nuclear force (force mediating particle - Gluon)
In the nucleus of every element other than hydrogen there is more than one proton. The charge on each proton is positive, so why don't the protons fly apart, breaking up the nucleus? This is because of the strong nuclear force which acts between quarks and the particle responsible for carrying the strong force is called the gluon. The strong nuclear force is obviously a force which only acts over a very small range.



Weak nuclear force (force mediating particle – W & Z bosons)
The weak nuclear force is involved in radioactive beta decay. It is called the weak nuclear force to distinguish it from the strong nuclear force, but it is not actually the weakest of all the fundamental forces. It is also an extremely short-range force.



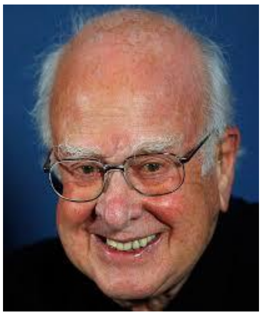
Electromagnetic force (force mediating particle - Photon)
The electromagnetic force stops the electron from flying out of the atom. This is the force which causes positive charges to attract negative charges. It is, however, weaker than the strong nuclear force so a nucleus can be held together. This force also acts over an extremely short range.



Gravitational force (Force mediating particle - undiscovered)
The final force is gravitational force. Although it is one of the most familiar forces to us it is also one of the least understood. It may appear surprising that gravity is, in fact, the weakest of all the fundamental forces when we are so aware of its effect on us in everyday life. However, if the electromagnetic and strong nuclear forces were not so strong then all matter would easily be broken apart and our universe would not exist in the form it does today. Gravitational force is obviously a very long range force.

Force	Exchange Particle	Range (m)	Relative strength	Approximate decay time (s)	Example effects
Strong nuclear	gluon	10^{-15}	10^{38}	10^{-23}	Holding protons in the nucleus
Weak nuclear	W and Z bosons	10^{-18}	10^{25}	10^{-10}	Beta decay; decay of unstable hadrons
Electromagnetic	photon	∞	10^{36}	10^{-20} – 10^{-16}	Holding electrons in atoms
Gravitational	graviton	∞	1	Undiscovered	Holding matter in planets, stars and galaxies

Higgs Boson

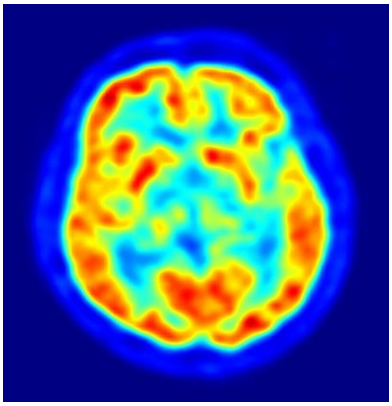


Many theories postulate the existence of a further boson, called the Higgs boson (sometimes referred to as the 'God particle'), which isn't involved in forces but is what gives particles mass. Attempts to verify its existence experimentally using the Large Hadron Collider at CERN and the Tevatron at Fermilab were rewarded on the 4th July 2012 when the announcement was made that the Higgs boson had been discovered

The Higgs boson plays a unique role in the Standard Model, by explaining why the other elementary particles, except the photon and gluon, are massive. In particular, the Higgs boson would explain why the photon has no mass, while the W and Z bosons are very heavy. The Higgs itself is incredibly massive with a mass equivalent to that of 133 protons (10^{-25} kg).

Practical Uses of Antimatter
Positron Emission Tomography (PET) Scanning

Positron emission tomography (PET) scanners use antimatter annihilation to obtain detailed 3-D scans of body function. Other imaging techniques called CT and MRI scans can give detailed pictures of the bone and tissue within the body but PET scans give a much clearer picture of how body processes are actually working.



A β^+ tracer with a short half-life is introduced into the body attached to compounds normally used by the body, such as glucose, water or oxygen. When this tracer emits a positron it will annihilate nearly instantaneously with an electron. This produces a pair of gamma-ray photons of specific frequency moving in approximately opposite directions to each other.

The gamma rays are detected by a ring of scintillators, each producing a burst of light that can be detected by photomultiplier tubes or photodiodes. Complex computer analysis traces tens of thousands of possible events each second and the positions of the original emissions are calculated. A 3-D image can then be constructed, often along with a CT or MRI scan to obtain a more accurate picture of the anatomy alongside the body function being investigated.

The detecting equipment in PET scanners has much in common with particle detectors and the latest developments in particle accelerators can be used to improve this field of medical physics.

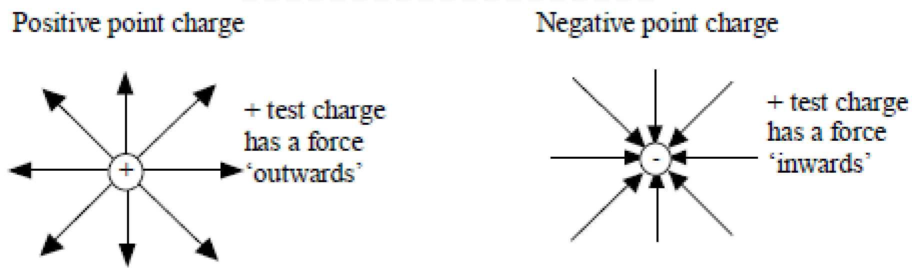
Forces on Charged Particles

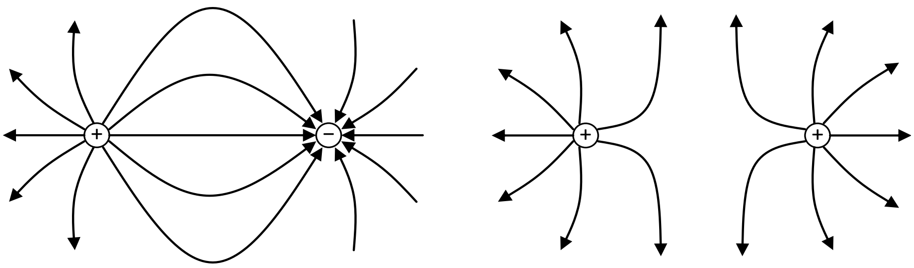
Charged Particles in Electric Fields

An electric field is a place where a charge experiences a force. We use lines of force to show the strength and direction of the force. The closer the field lines the stronger the force. Field lines are continuous they start on positive charge and finish on negative charge. The direction is taken as the same as the force on a ***positive*** "test" charge placed in the field.

Radial Fields

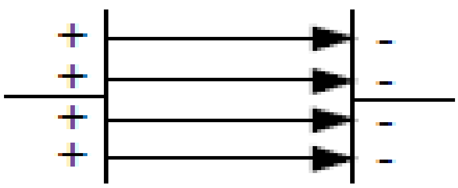
The strength of the field decreases as we move away from the charge.





Uniform Fields

The field lines are equally spaced between the parallel plates. This means the field strength is constant. This is called a ***uniform field***. All calculations you do in Higher Physics will involve uniform fields although you may be asked to sketch radial fields.



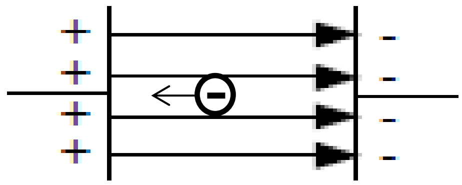
Electric fields have a number of applications and play an important role in everyday life. For example,

- the cathode ray tube (the basis for traditional television and monitor systems)
- paint spraying, e.g. for cars
- photocopying and laser printing

Stray electric fields can also cause problems, for example during lightning storms there is a risk of damage to microchips within electronic devices caused by static electricity.

Work Done

Consider a negative charge moved through a uniform electric field. The field will be doing work on the charge to move it and the charge will gain kinetic energy as a result.



The energy given to every Coulomb of charge moving through the uniform electric field is the potential difference.

$$E_W = QV$$

Where E_W is energy (work done) in joules (J), Q is the charge in coulombs (C) and V is the potential difference (p.d.) in volts (V). When work is done be an electric field on a charged particle the particle gains kinetic energy. All of the work done by the field is converted to kinetic energy of the particle.

$$E_W = E_K$$

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

Particle	Charge (C)	Mass (kg)
Electron	1.6×10^{-19}	9.11×10^{-31}
Proton	1.6×10^{-19}	1.673×10^{-27}
Neutron	0	1.675×10^{-27}

Example

An electron is placed in a uniform electric field created by a potential difference of 2.8 kV and accelerates towards the positive plate. ($m = 9.11 \times 10^{-31}$ kg, $Q = 1.6 \times 10^{-19}$ C)

a. Explain why the electron accelerates towards the positive plate.
b. Calculate how much work is done by the field moving the electron through it.
c. Calculate the final speed of the electron.

Solution

Charged Particles in Magnetic Fields

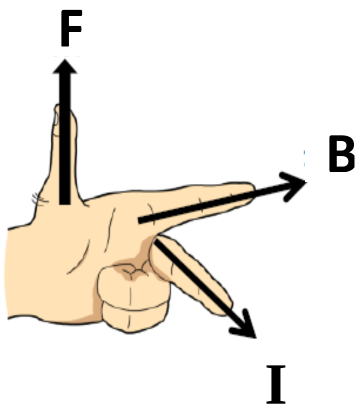
A magnetic field is a place where a moving charge experiences a force. We are aware that when permanent magnets are near each other they will either attract or repel each other. A moving charge or a current carrying wire also generates a magnetic field around itself. This magnetic field a moving charge generates will also interact with nearby permanent magnets and cause the moving electric charge to alter its path. The direction that charged particles would take when travelling at 90^0 to a magnetic field can be described by the following rules.

F – direction of Force (which direction will the particle be forced)

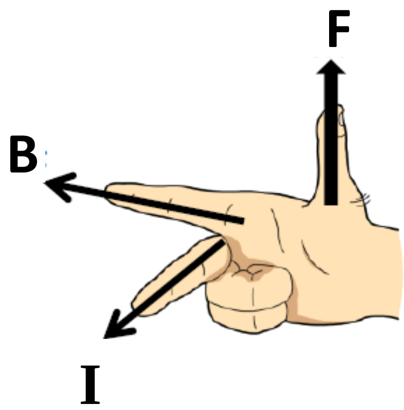
B – direction of magnetic field

I – direction of particle flow

For positive charges use your left hand.



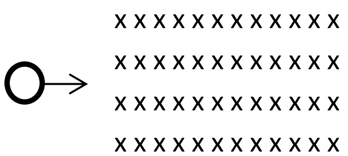
For negative charges use your right hand.



Traditionally when drawing magnetic fields they are drawn into or out of the page.
When drawn into the page they are represented by a cross and when drawn out of the page they are represented by a dot.

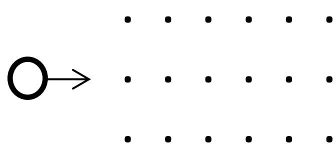
Describe the direction the particles would be forced in the following examples.

Electron



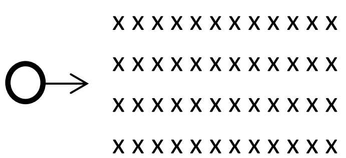
Would move ________________

Electron



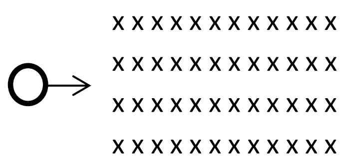
Would move ________________

Proton



Would move ________________

Neutron



Would move ________________

Particle Accelerators

Particle accelerators use a series of electric and magnetic fields to accelerate charged particles. Particle accelerators are used to probe matter. They have been used to determine the structure of matter and investigate the conditions soon after the Big Bang.

There are three main types of particle accelerators:

- **linear accelerators**
- **cyclotrons**
- **synchrotrons**

Regardless of whether the particle accelerator is linear or circular, the 5 basic parts are the same:

- **a source of particles**

The particles which are to be accelerated are created in a variety of ways and are often provided by another accelerator so they are already travelling at great speed by the time they enter the particle accelerator.

- **beam pipes**

Beam pipes are special pipes which the particles travel through while being accelerated. There is a **vacuum** inside the pipes which ensures that the beam particles do not collide with other atoms such as air molecules.

- **accelerating structures**

As the particles speed around the beam pipes they enter special accelerating regions where they are accelerated by electric fields.

- **a system of magnets**

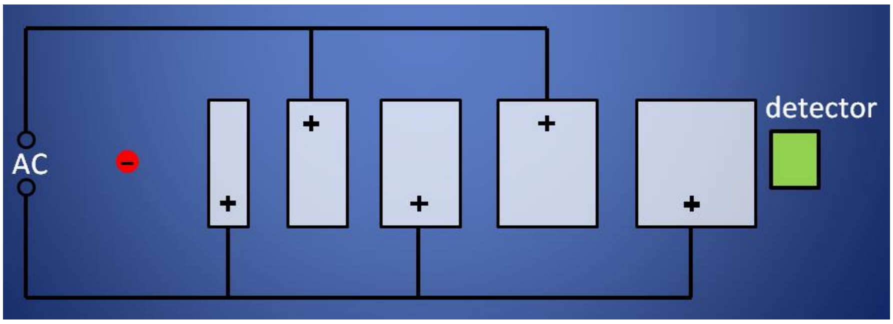
Magnetic fields are used to keep the particles away from the walls of the particle accelerator as the particles need to be very hot but will cool down as soon as they touch the walls.

- **a target**

The target could be some form of detector or other particles depending on the experiment being conducted.

Linear accelerators

A linear accelerator uses alternating electric fields to accelerate particles in a line by attracting and repelling them with electric fields.



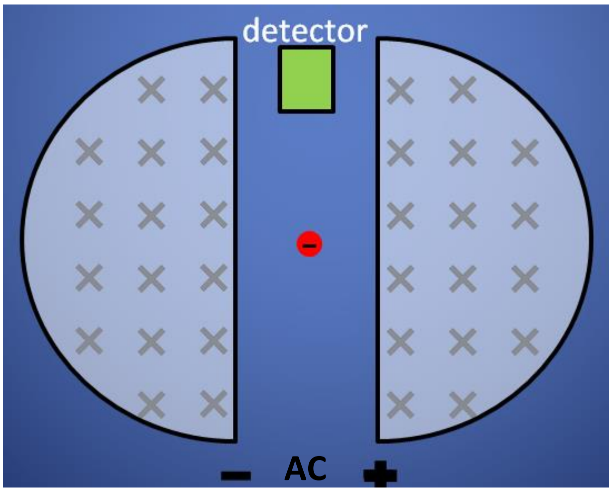
<u>Example</u>

A proton is accelerated through a linear accelerator with a potential difference of 3.5 kV between each section. It is moving at 4×10^6 ms^{-1} when it enters the linear accelerator. (m = 1.673×10^{-27} kg, Q = 1.6×10^{-19} C)

a. Calculate how much kinetic energy the protons gain after passing through 5 sections.
b. Calculate the kinetic energy of the proton at the end of the linear accelerator.

<u>Solution</u>

Cyclotrons



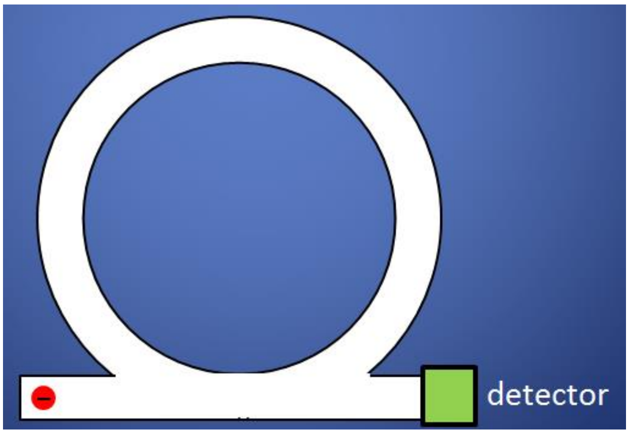
A cyclotron uses electric fields to accelerate particles across a gap several times. To do this it uses an AC source to alternate the polarity as the particles go in both directions across the gap. It also uses magnetic fields to move the particles in a half circle to keep them within the accelerator. **Electric fields accelerate particles, magnetic fields deflect particles.**

Example

An electron enters the electric field of a cyclotron moving at 4.2×10^7 ms^{-1}. It is accelerated across the gap using a potential difference of 6 kV. Calculate what the velocity of the electron will be after passing across the electric field once. ($m = 9.11 \times 10^{-31}$ kg, $Q = 1.6 \times 10^{-19}$ C)

Solution

Synchrotrons



A synchrotron often uses a linear accelerator to feed particles into it. The particles are then accelerated around a very large ring (many km's across) where they are kept apart from the walls using magnetic fields. An example of a synchrotron is at CERN. A particle will usually go round the ring many, many times before colliding with a detector or other particles. **Electric fields accelerate particles, magnetic fields deflect particles.**

Nuclear Reactions

Nuclear reactions describe reactions which involve radiation being emitted from a nucleus, a nucleus splitting to form smaller nuclei (fission) or nuclei joining to create one larger nuclei (fusion). To examine nuclear reactions it is necessary to define a number of terms used to describe a nucleus.

Nucleon

A nucleon is a particle in a nucleus, i.e. either a proton or a neutron.

$$^{A}_{Z}X$$

Atomic Number

The atomic number, Z, equals the number of protons in the nucleus. In a chemical symbol for an element it is written as a **subscript** either before or after the element symbol

Mass Number

The mass number, A, is the number of nucleons in a nucleus. In a chemical symbol for an element it is written as a **superscript** before or after the element symbol.

Example

A description of a Uranium nucleus is shown.

$$^{235}_{92}U$$

a. Calculate how many nucleons it contains.
b. Calculate how many protons it contains.
c. Calculate how many neutrons it contains.

Solution

Each element in the periodic table has a different atomic number and is identified by that number. It is possible to have different versions of the same element, called isotopes. An isotope of an atom has the same number of protons but a different number of neutrons, i.e. the same atomic number but a different mass number. An isotope is identified by specifying its chemical symbol along with its atomic and mass numbers. For example:

C^{12}_{6}

nucleons

protons

neutrons

C^{14}_{6}

nucleons

protons

neutrons

Radioactive Decay

Radioactive decay is the breakdown of a nucleus to release energy and matter from the nucleus. There are a number of different particles which can be released from the nucleus as shown below.

Name of particle	Composition of particle	Representation
Proton		
Alpha particle		
Electron or Beta particle		
Neutron		

You can perform calculations when a nucleus emits these particles to determine what new nucleus is created. This is done by adding all the mass numbers and adding all the atomic numbers.

Example
A description of a Uranium nucleus is shown.

Calculate what nucleus is created if the Uranium nucleus emits an alpha particle. $^{235}_{92}U$

Solution

The incomplete statements below illustrate four nuclear reactions.

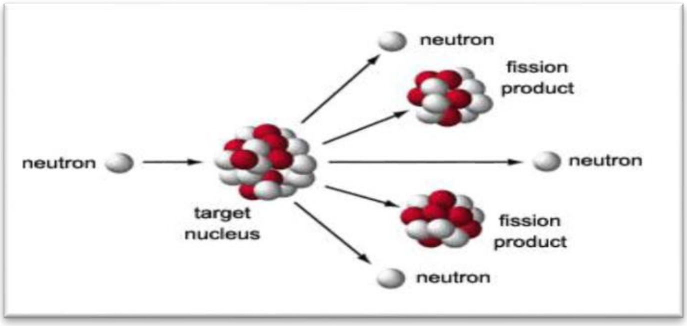
$^{228}_{90}\text{Th} \rightarrow {}^{224}_{88}\text{Ra} + \text{A}$ $\qquad$ $^{220}_{86}\text{Rn} \rightarrow {}^{4}_{2}\text{He} + \text{B}$

$^{211}_{82}\text{Pb} \rightarrow {}^{211}_{83}\text{Bi} + \text{C}$ $\qquad$ $\text{D} \rightarrow {}^{219}_{86}\text{Rn} + {}^{4}_{2}\text{He}$

Identify the missing particles or nuclides represented by the letters A, B, C and D.

Nuclear Fission

Nuclear fission occurs when a large nuclei splits to create 2 smaller nuclei, extra neutrons and energy. The reaction is spontaneous if no neutron causes the reaction and it is induced if a neutron does cause the reaction.



In a nuclear fission reaction the total mass numbers and total atomic numbers are equal before and after the reaction. The total mass of the particles at the end is, however, always less than the total mass of the particles at the start. **In a fission reaction the lost mass is converted into energy according to the following equation.**

$$E = mc^2$$

Where E is energy (J), m is mass lost (kg) and c is the speed of light (3×10^8 ms^{-1}).

Example:
Calculate the energy released in the following fission reaction.

$$^{235}_{92}U + ^{1}_{0}n \rightarrow ^{137}_{56}Ba + ^{97}_{42}Mo + 2\ ^{1}_{0}n + \text{energy}$$

Particle	Mass (kg)
U 235	3.902×10^{-25}
Ba 137	2.273×10^{-25}
Mo 97	1.609×10^{-25}
neutron	1.675×10^{-27}

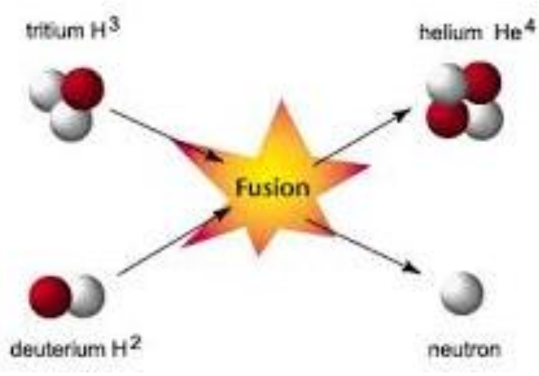
Solution:

Nuclear fission in nuclear reactors

While individual fission reaction create only a tiny amount of energy the extra neutrons created in a fission reaction can go on to create further fission reactions in a process called a chain reaction. The particles created have lots of kinetic energy and when they bombard into the coolant their kinetic energy is transferred into heat energy in the coolant. The hot coolant is then removed from the reactor to boil water into steam and turn turbines to generate electricity.

Nuclear Fusion

Nuclear fusion occurs when 2 small nuclei fuse together to create a larger nucleus, a neutron and energy.



In a nuclear fusion reaction the total mass numbers and total atomic numbers are equal before and after the reaction. The total mass of the particles at the end is, however, always less than the total mass of the particles at the start. **In a fusion reaction the lost mass is converted into energy according to the following equation.**

$$E = mc^2$$

Where E is energy (J), m is mass lost (kg) and c is the speed of light (3×10^8 ms^{-1}).

<u>Example:</u>
Calculate the energy released in the following fusion reaction.

$${}^{2}_{1}H \quad + \quad {}^{3}_{1}H \quad \rightarrow \quad {}^{4}_{2}He \quad + \quad {}^{1}_{0}n \quad + \quad \text{energy}$$

Particle	Mass (kg)
H 2 (deuterium)	3.345×10^{-27}
H 3 (tritium)	5.008×10^{-27}
He 4	6.647×10^{-27}
neutron	1.675×10^{-27}

<u>Solution:</u>

Nuclear fusion in fusion reactors

Nuclear fusion is the process by which stars (including our own Sun) produce their energy. It is more complex to reproduce on Earth due to the high temperatures required for it to occur. It is, however, possible. Just like in particle accelerators magnetic fields are used to keep the particles away from the walls of the reactor to keep them hot as they cool down and the reaction stops as soon as they touch the walls. This method of energy generation is not yet efficient enough for commercial use but could provide a viable and less dangerous alternative to nuclear fission in the future.

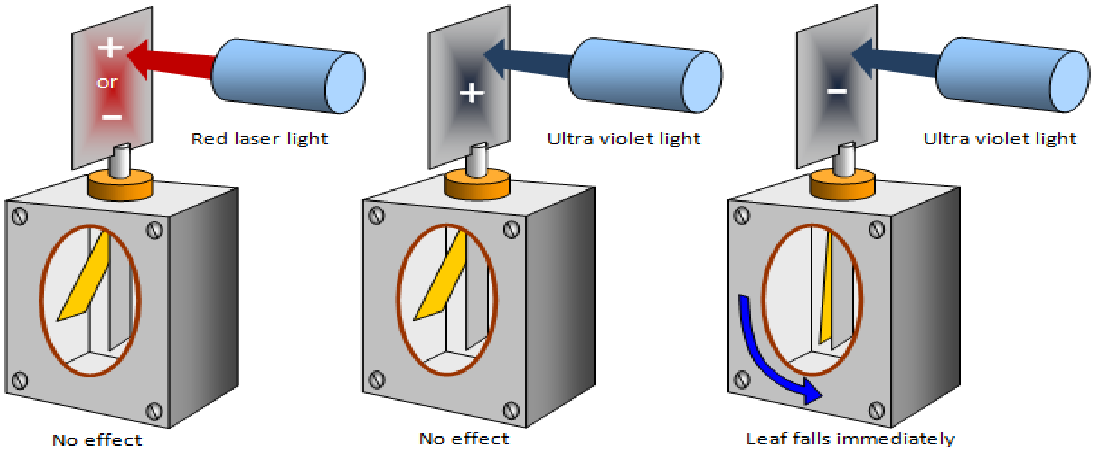
Wave-Particle Duality

The Photoelectric Effect

Up until now we have always thought of light behaving as a wave. It can, however, be thought of as a particle called a **photon**. One of the most famous experiments for demonstrating that light behaves as a particle is the photoelectric effect. Although he didn't do all of the work Einstein was awarded the Nobel prize in 1921 for his work on the photoelectric effect.

The photoelectric effect shows that light can cause electrons to be ejected from the surface of a metal. The light gives energy to the electrons to allow them to be released from the metal. There are a number of conditions which need to be met for photoelectric emission to occur.

- The light (photons) must have high frequency and energy, usually UV
- The metal must be negatively charged due to an excess of electrons
- The metal must have a small work function meaning it doesn't cling on to the electrons too tightly



The key thing to notice is that no matter how bright or intense the source of light is, if it does not have a high enough frequency then photoelectric emission will not occur. Conversely a very dim but high frequency source of light will easily eject electrons as it is individual particles of light (photons) which provide the energy and not a bright wave of light.

Photon energy

The energy of a photon is proportional to its frequency and is described by the following equation.

$$E = hf$$

Where E is photon energy (J), h is Planck's constant (6.63 x 10^{-34} Js) and f is photon frequency (Hz).

<u>Example:</u> Calculate the energy of a photon with a UV wavelength of 220 nm.

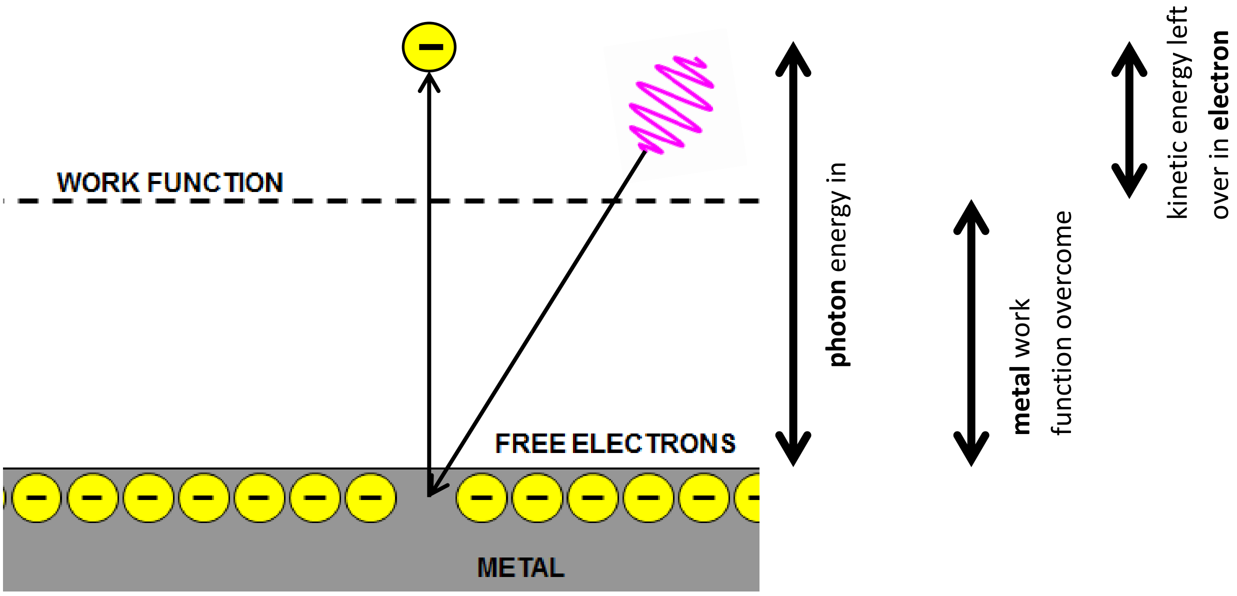
<u>Solution:</u>

Threshold frequency and work function

The threshold frequency is the minimum frequency of photon required to eject an electron from the surface of a metal.

The work function is the minimum energy of photon required to eject an electron from the surface of a metal.

All metals have different work functions. A good way to think about the work function is that it is a wall that the electron needs to overcome to escape from the surface of the metal. If the photon gives the electron enough energy then it will clear the wall but if there is not enough energy then the electron will not be ejected. Any spare energy is kept by the electron as kinetic energy.



The equation used to calculate the kinetic energy of the ejected electrons is shown below.

$$\frac{1}{2} mv^2 = hf - hf_0$$

Where m is the mass of the ejected electron (9.11×10^{-31} kg), v is the velocity of the ejected electron (ms^{-1}), h is Planck's constant (6.63×10^{-34} Js), f is the frequency of the incident photon (Hz), f_0 is the threshold frequency of the metal (Hz), and hf_0 is the work function of the metal (J).

$\frac{1}{2} mv^2$ **is the energy (kinetic) of the**

hf **is the energy of the**

hf_0 **is the energy (work function) of the**

It is often easier to understand the photoelectric effect when simple numbers are applied. If a 10 J photon is incident on a metal surface with a work function of 7 J then the ejected electron will have an energy of 3 J.

The ejected electrons are also sometimes called photoelectrons.

Example:

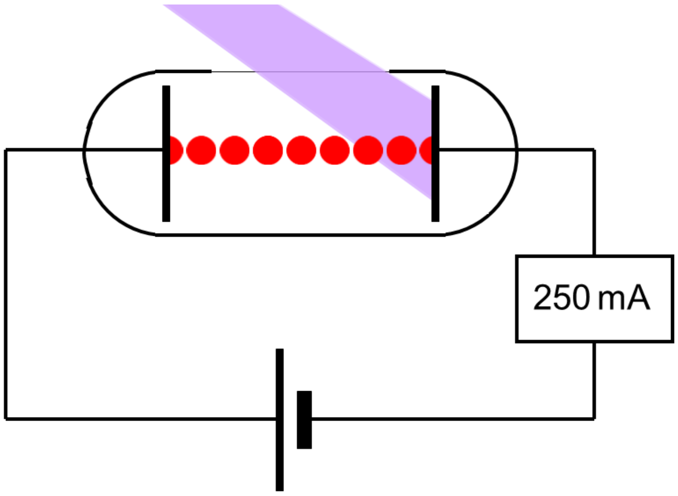
A 230 nm photon is incident on a metal with a work function of 6.2×10^{-19} J.

a. i. Calculate the energy of the incident photon.
   ii. Calculate the energy of the ejected electron.
   iii. Calculate the speed of the ejected electron.
b. The frequency of the photons is increased, explain how this affects the energy of the ejected electrons.
c. The frequency of the photons is increased, explain how this affects the number of the ejected electrons.
d. The wavelength of the photons is increased, explain how this affects the energy of the ejected electrons.
e. The wavelength of the photons is increased, explain how this affects the number of the ejected electrons.
f. The number of photons is increased, explain how this affects the energy of the ejected electrons.
g. The number of photons is increased, explain how this affects the number of the ejected electrons.

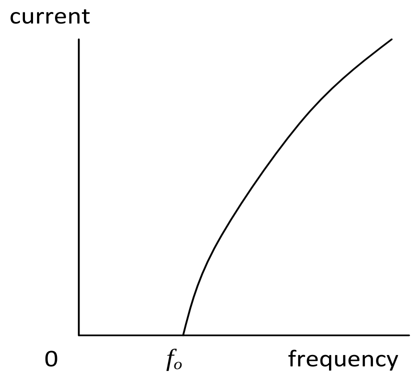
Solution:

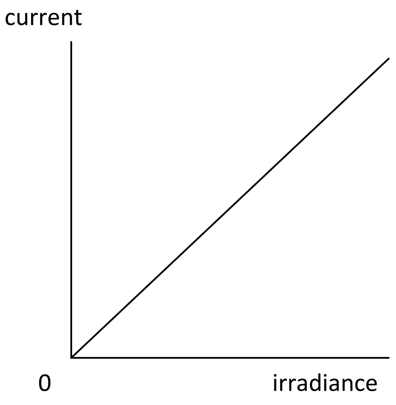
Photoelectric current

A photoelectric current can be created if two metal plates are held in an evacuated chamber which has a window on it. The two metal plates can be attached to a power supply and an ammeter as shown below. The gap between the metal plates means that initially no current will flow. If UV light is shone through the window on the evacuated chamber it will cause electrons to be emitted from the negatively charged plate and will give them enough energy to cross the gap to the second plate. This completes the circuit and allows a current (photoelectric current) to flow.



The photoelectric current will only flow if the incident photons of light are greater than the work function of the metal as shown in the graph to the right.





The size of the photoelectric current is proportional to the irradiance of the incident photons as shown in the graph to the left. Essentially more photons in means more electrons out. If we put 3 photons in we would expect 3 electrons out and if we put 5734 photons in we would expect 5734 electrons out.

Irradiance of photons

If N photons of frequency f are incident each second on each one square metre of a surface, then the energy per second (power) absorbed by the surface is:

$$P = \frac{E}{t} = \frac{\text{no of photons x energy of each photon}}{\text{time}} = \frac{N \;\; \text{x} \;\; hf}{1} = Nhf$$

The irradiance, I, at the surface is given by the power per square metre.

$$I = \frac{P}{A} = \frac{N \text{ x } hf}{1} = Nhf$$

Where I is irradiance (Wm^{-2}), h is Planck's constant (6.63×10^{-34} Js), f is photon frequency(Hz) and N is number of photons.

<u>Example:</u>
A semiconductor chip is used to store information. The information can only be erased by exposing the chip to UV radiation for a period of time. The following data is provided.
Frequency of UV used = 9.0×10^{14} Hz
Minimum irradiance of UV radiation required at the chip = 25 Wm^{-2}
Area of the chip exposed to radiation = 1.8×10^{-9} m^2
Energy of radiation needed to erase the information = 40.5 mJ

a) Calculate the energy of a photon of the UV radiation used.
b) Calculate the number of photons of the UV radiation required to erase the information.

<u>Solution:</u>

Particles

Explain why bosons and fermions are known as fundamental particles.

They cannot be broken down into smaller particles

State the name given to the 12 fundamental mass particles.

Fermions

State the names of the two types of fermions.

Quarks and leptons

State the names of the 4 force mediating particles.

Bosons

State the name of the fundamental particles which make up hadrons.

Quarks

State the names of the two types of hadron.

Baryons and Mesons

Describe the difference between baryons and mesons.

Baryons are made up of 3 quarks, mesons are made up of 2 quarks

State two examples of baryons.

Protons and neutrons

Describe the combination of quarks which make up a proton.

Up, Up, Down (+2/3, +2/3, -1/3)

Describe the combination of quarks which make up a neutron.

Up, Down, Down (+2/3, -1/3, -1/3)

State what type of particle an electron is.

An electron is a mass particle so it is a **fermion**. It is also belongs to the **lepton** group of fermions.

Describe what antiparticles are.

A complete set of particles exist (antiparticles) that are identical to the matter particles except for charge.

Describe why it is so difficult to observe antiparticles.

When particles and antiparticles come into contact they annihilate each other and create energy.

Describe the 3 things Rutherford's alpha scattering experiment told us about the structure of the atom.

1. The nucleus is much smaller than the atom as so few alpha particles are deflected.
2. The nucleus is positively charged as it is able to reflect positively charged alpha particles.
3. The nucleus is massive as alpha particles were not able to dislodge any gold nuclei.

State the name of the 4 fundamental forces.

Gravitational force, strong nuclear force, weak nuclear force, electromagnetic force

State the name of the boson related to the electromagnetic force.

Photon

State the name of the boson related to the strong nuclear force.

Gluon

State the name of the bosons related to the weak nuclear force.

W and Z bosons

State the name of the fundamental force which binds protons and neutrons together in a nucleus.

Strong nuclear force

State the name of the fundamental force which is related to beta decay.

Weak nuclear force

State the name of the fundamental force which allows planets to orbit round stars.

Gravitational force

State the name of the fundamental force which binds electrons to atoms.

Electromagnetic force

State the name of the radioactive process which provides evidence for the neutrino.

Beta decay

Explain what the separation of the field lines in an electric field diagram tell us about the electric field.

The closer the field lines, the stronger the electric field.

Explain what the arrows on the field lines in an electric field diagram tell us about the electric field.

The arrows tell us the direction a positively charged particle would move in the field.

Describe which type of particles experience a force in an electric field.

Charged particles

Describe what a charged particle will do if placed in an electric field.

It will **accelerate** towards the plate of opposite charge to its own

Describe which particles will experience a force in a magnetic field.

Moving charged particles

Describe what is meant by the 'potential difference across an electric field'.

Potential difference is the energy gained per Coulomb of charge by a particle crossing the electric field

State what is meant by a potential difference of 3.4 kV across an electric field?

3.4 kJ of energy is gained by every Coulomb of charge crossing the electric field

Describe how charges attract or repel each other depending on their charge.

Like charges repel (eg + and + or - and -), opposite charges attract (+ and -)

When moving in an electric field work is done by the field on the charge. State what this work is converted into.

Kinetic energy in the particle

The distance between 2 plates creating an electric field is halved, explain what effect this will have on the kinetic energy gained by a particle moving between them.

No effect as distance between plates is not involved in the equations $E_w=QV=1/2mv^2$

The potential difference between 2 plates creating an electric field is halved, explain what effect this will have on the kinetic energy gained by a particle moving between them.

It will be halved as if V is halved, E_w is halved so E_k is halved

Describe how the direction of force (F), direction of the magnetic field (B) and the direction of charge flow (I) are related for a moving **negative** particle in a magnetic field.

They are at right angles to each other and can be determined using the **right hand** rule and FBI

Describe how the direction of force (F), direction of the magnetic field (B) and the direction of charge flow (I) are related for a moving **positive** particle in a magnetic field.

They are at right angles to each other and can be determined using the **left hand** rule and FBI

A proton and an electron are fired into a magnetic field. Describe one similarity and describe two difference in their motion.

They will both move in a circle. They will move in opposite directions (one clockwise and one anti-clockwise) due to their different charges and they will have different radii of orbit due to different masses.

State the names of the 3 types of particle accelerator.

Linear accelerator, cyclotron and synchrotron

State the name of the 5 things that all particle accelerators need.

1. A source of particles
2. Beam pipes for particles to travel in
3. A method of accelerating particles
4. A series of magnets to guide particles
5. A target to detect particles

Describe how cyclotrons and synchrotrons accelerate and deflect charged particles.

Electric fields are used to accelerate particles and magnetic fields are used to deflect particles.

Explain why an alternating voltage is required in a cyclotron.

This alternates the direction of the electric field across the gap. This is needed because the direction of particle flow across the gap also alternates.

State what type of particle accelerator is used at CERN.

Synchrotron

Describe a nuclear fusion reaction.

Two small particles join together to create a larger particle. The mass that is lost during the reaction is converted to energy according to $E=mc^2$.

Describe a nuclear fission reaction.

One large particle splits to create two smaller particles, extra neutrons and energy. The mass that is lost during the reaction is converted to energy according to $E=mc^2$.

Explain how you can tell if a fission or fusion reaction is induced or spontaneous.

An induced reaction has a neutron on the left hand side of the equation to cause the reaction, a spontaneous reaction does not.

Describe a practical example where nuclear fission is used.

To generate nuclear power in a nuclear power station

Describe an example of where nuclear fusion takes place.

The sun generates its energy through nuclear fusion reactions in its core.

Explain why is it difficult to create nuclear fusion reactions.

Very high temperatures are required and the plasma must be kept away from the container walls to avoid it cooling which is very difficult to do.

Describe what the photoelectric effect tell us about the nature of light.

Light can behave as particles called photons

State what is meant by the term ‘threshold frequency’.

The minimum frequency of photon required to eject an electron from the surface of a metal.

State what is meant by the term ‘work function’.

The minimum energy of photon required to eject an electron from the surface of a metal.

Describe what happens to the excess energy if a high energy photon ejects an electron from the surface of a metal.

It is converted into kinetic energy in the ejected electron.

The energy of the incident photons is increased, describe how this affects the number of electrons ejected from the surface of a metal.

It has no effect as the number of incident photons remains constant.

The energy of the incident photons is increased, describe how this affects the energy of electrons ejected from the surface of a metal.

It increases the energy of the ejected electrons as there is more energy left over.

The number of incident photons is increased, describe how this affects the number of electrons ejected from the surface of a metal.

It increases the number of ejected electrons as the number of incident photons increases (1 photon in, 1 electron out. 34 photons in, 34 electrons out)

The number of incident photons is increased, describe how this affects the energy of electrons ejected from the surface of a metal.

It has no effect as the energy of the individual incident photons has not changed.

Light is shone on a metal but no photoelectric emission occurs. Describe what must be done to the light in order to cause photoelectric emission.

Energy or frequency needs to be increased or wavelength needs to be decreased.