St Ninian's High School

Higher Physics

Particles & Waves
Pupil Notes

2.1 The Standard Model

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. It would be useful to get an idea of scale to better understand how sub-nuclear and astronomical dimensions compare with those in our everyday life. When we get into the world of the very small or very large it is difficult to get a picture of scale in our minds. Below is a table giving some examples of scale in our world;

10^{-15}m	Diameter of a proton
10^{-12}m	Diameter of the atom
10^{-4}m	Dust particle
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
10^{9}m	Diameter of the Sun
10^{21}m	Distance to the nearest galaxy

Historical Background

The ancient Greeks believed the world was made of 4 **elements** (fire, air, earth and water). Democritus used the term 'atom', which means "indivisible" (cannot be divided) to describe the basic building blocks of life. Other cultures including the Chinese and the Indians had similar concepts.

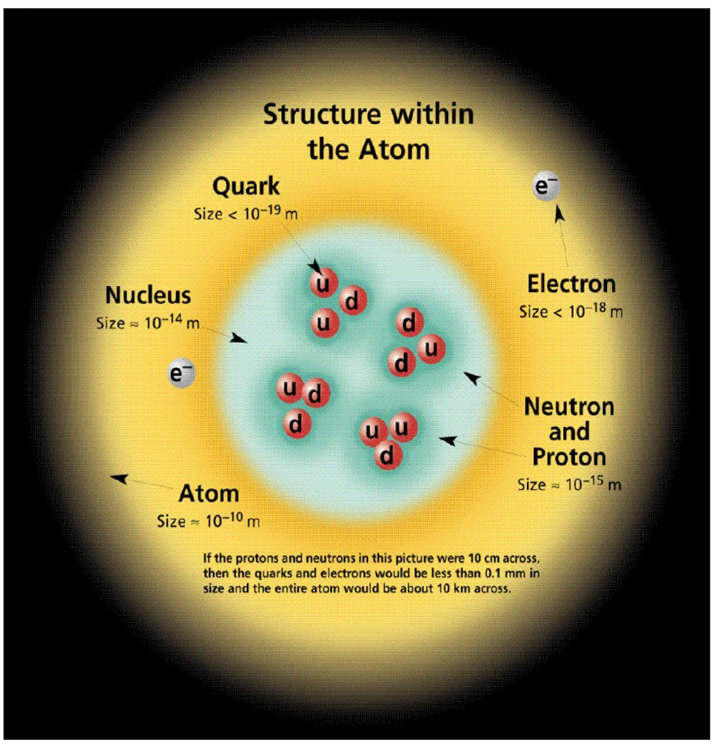
1789 - Lavoisier discovers that mass stays the same (is conserved) in chemical reactions and defines the element as a material that cannot be broken down further by chemical means.

1803 - Dalton discovers that the proportion of elements in various materials and reactions always occurs in small integer multiples. This is considered the start of modern atomic theory.

1869 - Mendeleev notices that certain properties of chemical elements repeat themselves periodically and he organised them into the first periodic table.

1897 - J.J. Thomson discovered the electron and the concept of the atom as a single unit ended. This marked the birth of particle physics.

Today we know that atoms do not represent the smallest unit of matter. Atoms are made up of a positively charged nucleus containing protons and neutrons with negatively charged electrons orbiting it. The standard model attempts to explain everything in the universe in terms of fundamental particles. **A fundamental particle is one which cannot be broken into anything else.** These fundamental particles are the building blocks of matter and the things which hold matter together.



The Structure of Atoms

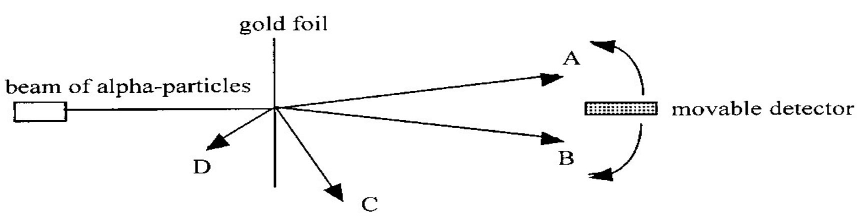
We cannot see atoms using light as it has too large a wavelength, but we can create an image of one using an electron microscope. This fires a beam of electrons at the target. By measuring the reflections and shadows, an image of individual atoms can be formed.

Similarly the structure of atoms can be determined by firing other particles at them and seeing how they deflect or reflect. These are called scattering experiments.

The Rutherford Alpha Scattering Experiment

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.

In 1909 Ernest Rutherford directed his students Hans Geiger and Ernest Marsden to fire alpha particles at a thin gold foil. This was done in a vacuum to avoid the alpha particles being absorbed by the air.



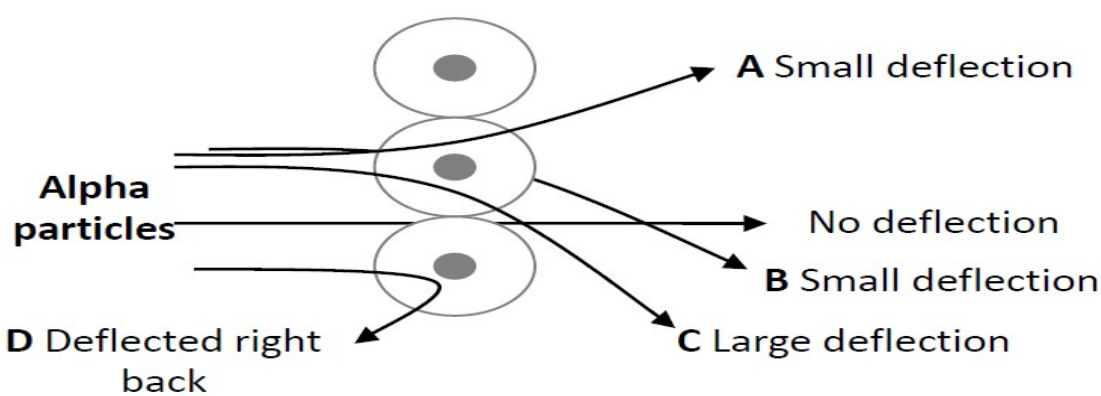
The main **results** of this experiment were:

- **Most of the alpha particles passed straight through the foil.**
- **A few particles were deflected through large angles, e.g. to position C.**
- **A very small number were even deflected backwards, e.g. to position D**

From these results Rutherford concluded that

- **Atoms are mostly empty space!**
- **The centre of the atom has a very large mass and a positive charge**

The diagram below shows the path of the alpha particles as they encounter the atoms in the gold foil.



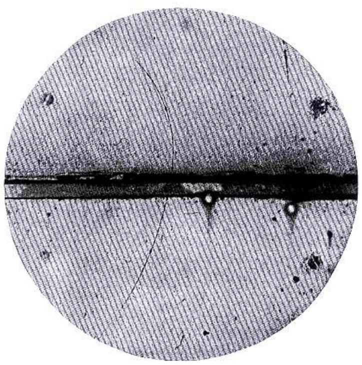
Matter and Antimatter

Almost everything we see in the universe appears to be made up of protons, neutrons and electrons. However high-energy collisions of particles have revealed the existence of antimatter. **Antimatter consists of particles that are identical to their counterparts in every way apart from charge**, e.g. an antiproton has the same mass as a proton but a negative charge.

Antiparticles are given the same symbol as the particle but with a bar over the top e.g. $\overline{p}$ is the symbol for the antiproton.

It is believed that every particle of matter has a corresponding antiparticle.

In 1928, Paul Dirac proposed the theoretical existence of antimatter in electron interactions. The positive electron was named the positron, and experimental proof of its existence came just four years later in 1932 (the positron is the only antiparticle with its own name).



The experimental proof for the positron came in the form of tracks left in a cloud chamber (particle detector).

The rather faint photograph on the right shows the first positron ever identified. The tracks of positrons are identical to those made by electrons but curve in the opposite direction.

Annihilation

Annihilation occurs when a matter particle meets an anti-matter particle and energy is released, usually as a pair of high energy photons (gamma rays). Other particles can be created from the conversion of energy into mass (using $E = mc^2$).

There are far more particles than antiparticles in the Universe, so annihilation is extremely rare.

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.

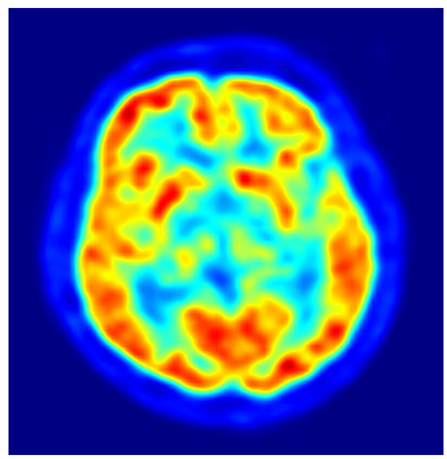
The detecting equipment in PET scanners has much in common with particle detectors and the latest developments in particle accelerators can be used to improve this field of medical physics.

Additional Reading – How PET scanners work

This additional information on PET scanners is for interest only.
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 reason it is only an approximately opposite direction is that the positron and electron are moving before the annihilation event takes place.)

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.

Tracing the use of glucose in the body can be used in oncology (the treatment of cancer) since cancer cells take up more glucose than healthy ones. This means that tumours appear bright on the PET image. Glucose is also extremely important in brain cells, which makes PET scans very useful for investigation into Alzheimer's and other neurological disorders. If oxygen is used as the tracking molecule, PET scans can be used to look at blood flow in the heart to detect coronary heart disease and other heart problems.



The Particle Zoo

The discovery of anti-matter was only the beginning. From the 1930s onwards the technology of particle accelerators greatly improved and nearly 200 more particles were discovered. This was known as the particle zoo, with more and more new particle 'species' being discovered each year.

The Standard Model

The Standard Model was developed in the early 1970's in an attempt to tidy up the number of particles being discovered and the phenomena that physicists were observing.

In a particle accelerator, very small particles e.g. electrons, can be accelerated by electric and magnetic fields to high speeds. Speeds near to the speed of light may be achieved. When these particles collide with a stationary target, or other fast-moving particles, a substantial amount of energy is released in a small space. Some of this energy may be converted into mass ($E = mc^2$), producing showers of nuclear particles.

We can pass these particles through a magnetic field and by observing deflections their mass and charge can be measured. For example, particles with low mass will be more easily deflected than heavier ones and a positive particle will be deflected in the opposite direction to a negative particle.

At present physicists believe that 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	

Quarks

In 1964 Murray Gell-Mann proposed that protons and neutrons were made up of three smaller fundamental particles which he called '***quarks***'.
There are six types of quark (3 pairs) named:

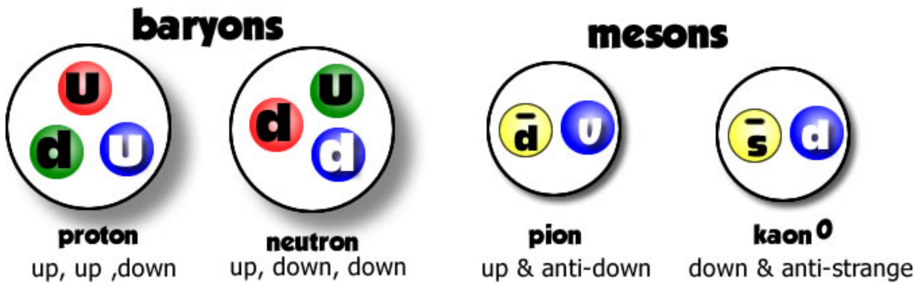
Up	**Down**	(these combine to make up protons and neutrons)
Top	**Bottom**	
Strange	**Charm**	

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. They are usually only ever observed in twos or threes where they make up what are called **hadrons.** However, the observation of a single top quark was confirmed by scientists at Fermilab in 2009.

Hadrons

Hadrons are particles made up of quarks (the word hadron means 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) arises out of the fractional charges of their quarks. This is worked out as follows:

A **proton** consists of **2 up quarks and a down quark**. Total charge = +1 ($\frac{2}{3}+\frac{2}{3}-\frac{1}{3}$ **= 1)**.

A **neutron** is made up of **1 up quark and 2 down quarks**. Total charge = 0 ($\frac{2}{3}-\frac{1}{3}-\frac{1}{3}$ **= 0**).

Mesons are made up of 2 quarks.

They always consist of a quark and an anti-quark pair.

An example of a meson is a negative pion ($\pi^- = \bar{u}\, d$).

A **pion** consists of **1 anti-up quark and 1 down quark**. Total charge = -1 **($-\frac{2}{3}-\frac{1}{3}$ = -1)**.

Note: A bar above a quark represents an antiquark e.g. $\bar{u}$ is the anti-up quark and is **not** the same as the down quark. The negative pion only has a lifetime of around 2.6×10^{-8} s**.**

Leptons

Leptons are a different type of fundamental.
The 3 types of lepton are named:

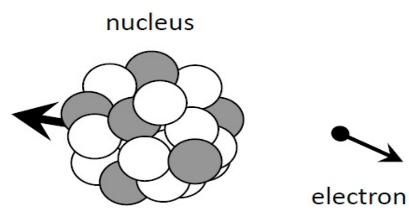
electron
muon
tau (much heavier than the other two)

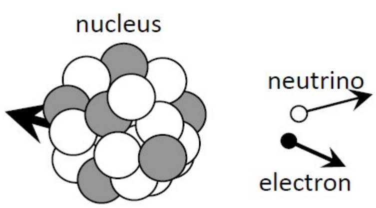
(The word lepton means a light particle but the tau particle is actually heavier than the proton!)

Neutrinos

All 3 leptons have a "ghostly" partner 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.**

The first evidence for the existence of Neutrinos was 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.

(In fact, in beta-decay an anti-neutrino is emitted along with the electron as lepton number is conserved in particle reactions).

Interesting fact
More than 50 trillion (50×10^{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.

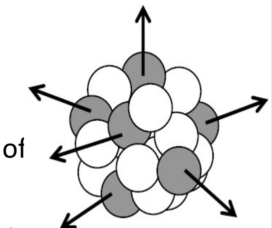
Fundamental particles

The 6 quarks and 6 leptons are all believed to be fundamental particles. That is physicists believe that they are not made out of even smaller particles. It is possible that future experiments may prove this statement to be wrong (just as early 20th Century scientists thought that the proton was a fundamental particle.)

The Four Fundamental Forces

Strong (Nuclear) Force

In the nucleus of every element other than hydrogen there is more than one proton. The charge on each proton is positive. They should repel one another, but **the strong force**, a short range force that holds particles of the same charge together, is stronger than the electrostatic repulsion that tries to force the particles apart and prevents the nucleus from breaking up.



This force acts over an extremely short range [approx 10^{-15} m], of the order of nucleus. Outside of this range the strong force has no effect whatsoever.
If a proton was placed close to a nucleus it would be repelled and forced away.

Weak (Nuclear) Force

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

The **electromagnetic force** stops the electron from flying out of the atom. It causes particles of opposite charge to be attracted to one another. The theory of the electromagnetic force and electromagnetic waves was created by the Scottish Physicist James Clerk Maxwell in the 19th Century.

Force of Gravity

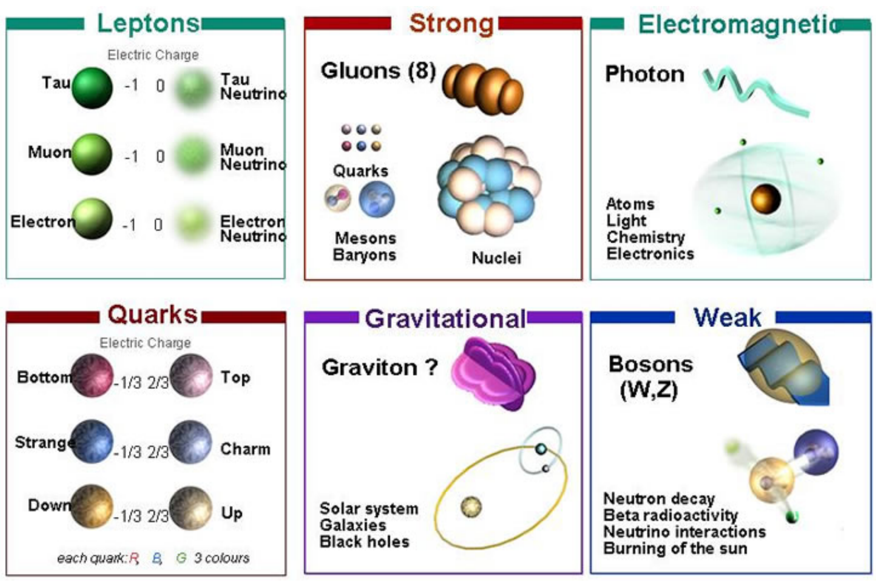
The final force is **gravity**. Although it is one of the most familiar forces, it is also one of the least understood.
It may appear surprising that gravity is the weakest of all the fundamental forces, when we are so aware of its affect on us in everyday life. However, if the electromagnetic and strong 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.

Force Particles – The Bosons

Bosons are the particles associated with each force that transmit the effects of that force. The table below summarizes the current understanding of the fundamental forces.

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

At a microscopic level **we explain the action of forces using 'exchange particles' or bosons.**



The Higgs Boson

This was proposed by many theories and 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 (have mass). In particular, the Higgs boson explains 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).

2.2 Forces on Charged Particles

Force Fields

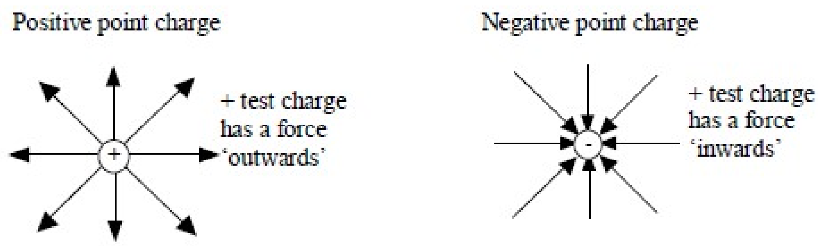
In Physics, a **force field is a region where an object experiences a force without being touched**.

For example, there is a gravitational field around the Earth. This attracts anything that has mass towards the Earth's centre.

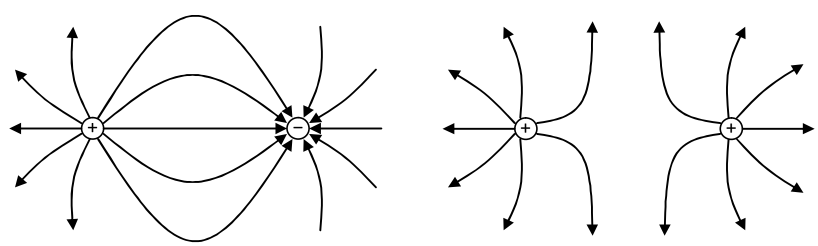
Electric Fields

An electric field is the area around a stationary charged particle where other charges experience a force.

We use **field lines** to show the strength and direction of the force. The closer the field lines the stronger the force.



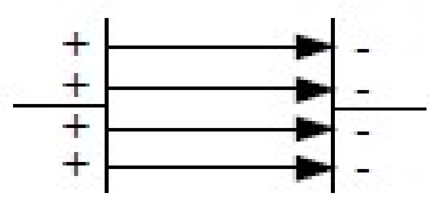
Notice that the field lines start from the surface of the charge and point in the direction a positive charge in the field would take.
These are called radial fields. The lines are like the radii of a circle. The strength of the field decreases as we move away from the charge.



Lines point away from positive charges and towards negative charges.

Parallel Plates

When charges line up along the surface of a conductor, the electric field pattern looks like this:



The field lines are equally spaced between the parallel plates. This means the field strength is constant. This is called a **uniform field**.
Note: If an electric field is applied to a conductor it w move .

Applications of Electric Fields

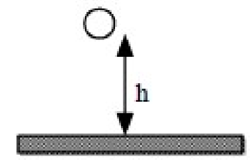
Electric fields have a number of applications and play an important role in everyday life. For example,

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

Stray electric fields can also cause problems, for example there is a risk of damage to microchips within electronic devices, caused by static electricity, when we handle them.

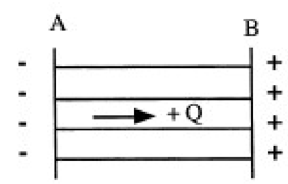
Work Done

Electric fields are similar to gravitational fields in some ways.
Consider the following:
If a mass is lifted or dropped through a height then work is done i.e. energy is changed.
If the mass is dropped then the energy will change to kinetic energy.
If the mass is lifted again then the energy will change to gravitational potential energy.



Change in gravitational potential energy = work done

Now consider a negative charge moved through a distance in an electric field
If the charge moves in the direction of the electric force, the energy will appear as kinetic energy. If a positive charge is moved against the direction of the force, as shown in the diagram, the energy will be stored as electric potential energy



Definition of Potential Difference and the Volt
Potential difference (p.d.) is defined to be a measure of the work done in moving one coulomb of charge between two points in an electric field. Potential difference (p.d.) is often called voltage. This gives the definition of the volt.
There is a potential difference of 1 volt between two points if 1 joule of energy is required to move 1 coulomb of charge between the two points, 1 V = 1 J C^{-1}

This relationship can be written mathematically:

$$E_W = QV$$

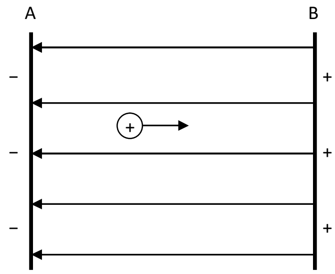
Where E_W is energy (work done) in joules (J), Q is the charge in coulombs (C) and V is the potential difference (p.d.) in volts (V). If the small positive charge above is released, the electrical potential energy is changed to kinetic energy and the charge moves. C

Conservation of energy means that; $E_W = E_K$ for charges moving in an electric field

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

Example:

A positive charge of 3.0 µC is moved from A to B.
The potential difference between A and B is 2.0 kV.



(a) Calculate the electric potential energy gained by the charge–field system.

(b) The charge is released. Describe the motion of the charge.

(c) Determine the kinetic energy when the charge is at point A.

(d) The mass of the charge is 5.0 mg. Calculate the speed of the charge.

Solution:

(a) $Q = 3.0\ \mu C = 3.0 \times 10^{-6}$ C

$V = 2.0$ kV $= 2.0 \times 10^{3}$ V

$E_W = ?$

$E_W = QV$

$E_W = 3.0 \times 10^{-6} \times 2.0 \times 10^{3}$

$E_W = 6.0 \times 10^{-3}$ J

(b) The electric field is uniform so the charge experiences a constant unbalanced force. The charge accelerates uniformly towards the negative plate A.

(c) By conservation of energy, $E_K = E_W = 6.0 \times 10^{-3}$ J

(d) $m = 5.0$ mg $= 5.0 \times 10^{-6}$ kg

$E_K = 6.0 \times 10^{-3}$ J

$v = ?$

$E_K = ½mv^2$

$6.0 \times 10^{-3} = 0.5 \times 5.0 \times 10^{-6} \times v^2$

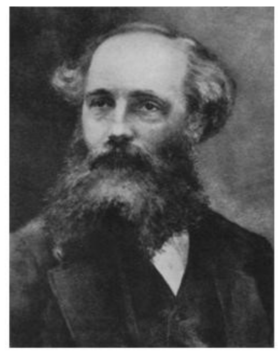
$v^2 = 2.4 \times 10^{-3}$

$v = 49$ m s^{-1}

Charged Particles in Magnetic Fields

The discovery of the interaction between electricity and magnetism, and the resultant ability to produce movement, must rank as one of the most significant developments in physics in terms of the impact on everyday life.

This work was first carried out by Michael Faraday whose work on electromagnetic rotation in 1821 gave us the electric motor. He was also involved in the work which brought electricity into everyday life, with the discovery of the principle of the transformer and generator in 1831. The Scottish physicist, James Clark Maxwell (1831–1879), built upon the work of Faraday and wrote down mathematical equations describing the interaction between electric and magnetic fields, creating a single electromagnetic theory. The computing revolution of the 20th century could not have happened without an understanding of electromagnetism.



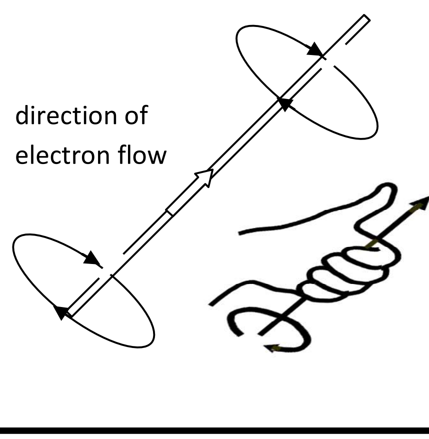
Michael Faraday James Maxwell

Magnetic Field Around A Current Carrying Wire

In 1820 the Danish physicist Oersted, discovered that a magnetic compass was deflected when an electrical current flowed through a nearby wire. This was explained by saying that **when a charged particle moves a magnetic field is generated**.
So static (stationary) charges create electric fields and moving charges create magnetic fields.

A wire with a current flowing through it creates a magnetic field.

The magnetic field around a current carrying wire is circular. The direction of the field can be found using **the left hand grip rule.**



Moving Charges in Magnetic Fields

A magnetic field surrounds a magnet. When two magnets interact, they attract or repel each other due to the interaction between the magnetic fields surrounding each magnet.

A moving electric charge behaves like a mini-magnet as it creates its own magnetic field. This means it experiences a force if it moves through an external magnetic field.

Simple rules can be used to determine the direction of force on a charged particle in a magnetic field.

Movement of a negative charge in a magnetic field – The Right-Hand Motor Rule

Use your thumb to show the direction the

magnetic field will force the particle to move in.

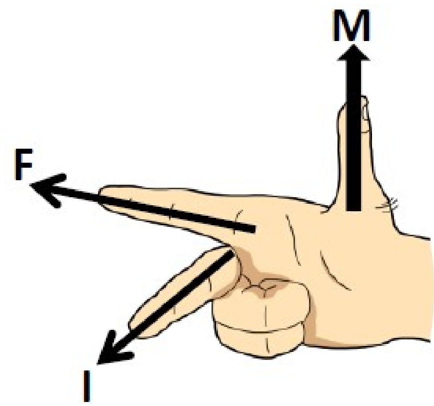
This is the direction of Motion (M).

The fore finger points in the direction of the field (F)

and the middle finger in the direction of the current (I)

(or original direction of the charge).

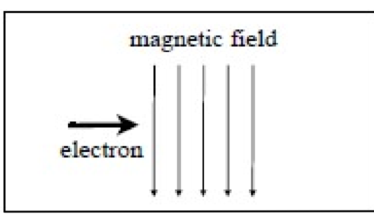
Your fingers should point at right angles to one other.



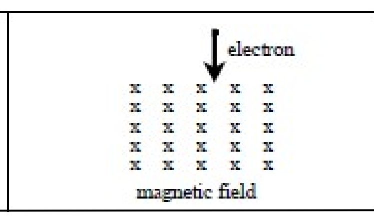
Movement of a positive charge in a magnetic field

For a positive charge, the direction of movement is opposite to the direction worked out above. It is easiest to work out which way a negative charge would move using the right hand rule and then simply reverse this.

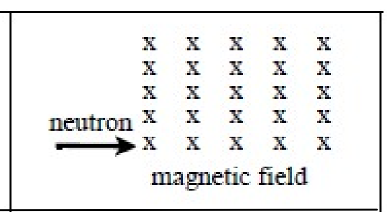
If a charge travels parallel to the magnetic field, it will not experience any additional force.



Electron curves out of page



Electron curves to the left



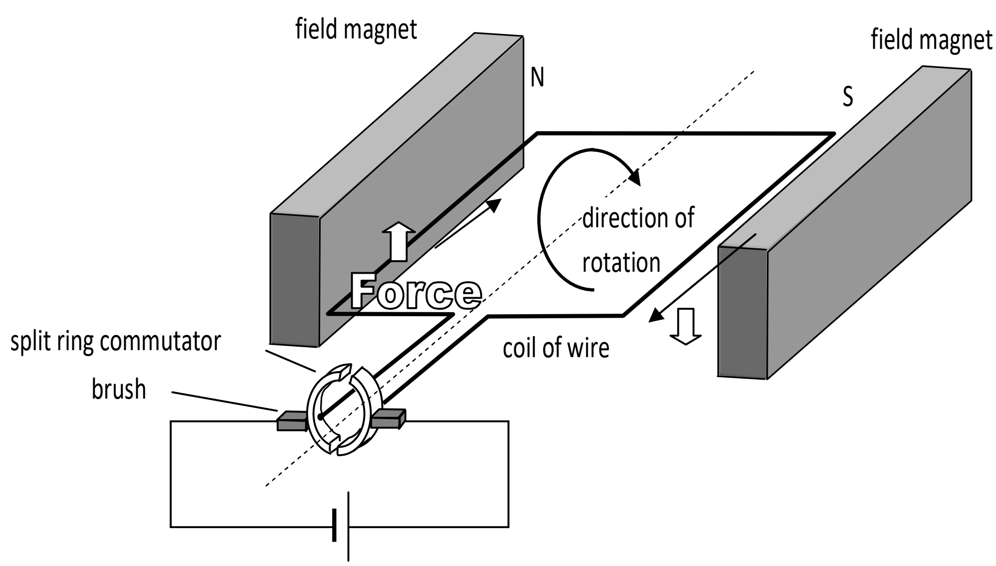
No change in direction (no charge)

The Electric Motor

When a current-carrying wire is placed between the poles of a permanent magnet, it experiences a force. The direction of the force is at right-angles to:

- the direction of the current in the wire;
- the direction of the magnetic field of the permanent magnet

We can utilize this principle in the electric motor;



An electric motor must spin continuously in the same direction. Whichever side of the coil is nearest the north pole of the field magnets above must always experience an upwards force if the coil is to turn clockwise.

That side of the coil must therefore always be connected to the negative terminal of the power supply. Once the coil reaches the vertical position the ends of the coil must be connected to the opposite terminals of the power supply to keep the coil turning. This is done by split ring commutator. **The commutator reverses the direction of current every half turn.**

In order for the coil to spin freely there cannot be permanent fixed connections between the supply and the split ring commutator. **Brushes** rub against the split ring commutator to **ensure that a good conducting path exists between the power supply and the coil regardless of the position of the coil.**

Particle Accelerators

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. Particle accelerators are also used to produce a range of electromagnetic radiations which can be used in many other experiments.

There are three main types of particle accelerators:

- linear accelerators
- cyclotrons
- synchrotrons

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

- **Particle Source** (these may come from another accelerator)
  Accelerators using electrons use thermionic emission in the same way as a cathode ray tube.

  The Large Hadron Collider (LHC) at CERN uses a bottle of Hydrogen gas as the source of particles. Electrons are stripped from the hydrogen atoms leaving positively charged protons. These are then passed through several smaller accelerator rings before they reach the main beam pipe of the LHC.

- **Beam Pipes** (also called the **vacuum chamber)**
  The particles are moved through a **vacuum** to ensure that the particles do not collide with other atoms such as air molecules. They are contained inside pipes as they accelerate.

- **Accelerating Structures** (a method of accelerating the particles)
  Electric fields are used to accelerate the charged particles. At the LHC, as protons approach the accelerating region, the electric field is negative and the protons accelerate towards it. As they move through the accelerator, the electric field becomes positive and the protons are repelled. The protons increase their kinetic energy and are accelerated to almost the speed of light.

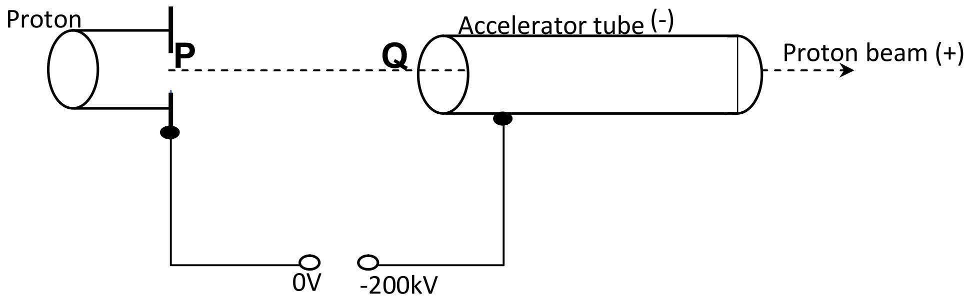
- **Magnetic Field**
  Magnetic Fields are used to cause circular motion of the charged particles.
  This is produced by electromagnets or superconducting magnets as in the LHC. There are over 9000 superconducting magnets at the LHC in CERN.
  These operate at temperatures very close to zero Kelvin and so the whole machine needs to be cooled down. If superconducting magnets were not used, the beam could not be steered and focused within such a tight circle and the energies of the protons would be much lower.

- **A Target**
  This can be a stationary target, such as a metal block and much of the beam energy is simply transferred to the block instead of creating new particles. In the LHC, the target is an identical bunch of particles travelling in the opposite direction. The two beams are brought together at four special points on the ring where massive detectors are used to analyse the collisions

Linear Accelerator Example

The diagram below shows the basic features of a proton accelerator. It is enclosed in an evacuated container.

Protons released from the proton source start at rest from P. A potential difference of 200kV is maintained between P & Q.



a) Calculate the Work Done on the proton as it accelerates from P to Q

b) Calculate the speed of the proton as it reaches Q

c) If the distance between P and Q is halved, what effect does this have on the speed of the proton?

Solution:

a) $E_W = Q V$

$= 1.6 \times 10^{-19} \times 200 \times 10^{3}$

$= 3.2 \times 10^{-14}$ J

b) Work Done = Kinetic Energy at Q

$E_W = E_k = \frac{1}{2} mv^2$

$3.2 \times 10^{-14} = \frac{1}{2} \times 1.673 \times 10^{-27} \times v^2$

$v^2 = \frac{3.2 \times 10^{-14} \times 2}{1.673 \times 10^{-27}}$

$v^2 = 3.825 \times 10^{13}$

$v = 619 \times 10^{4}\ ms^{-1}$

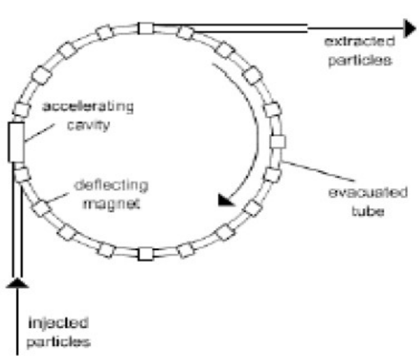
c) No effect.

Speed depends on Work Done, which depends on Q and V

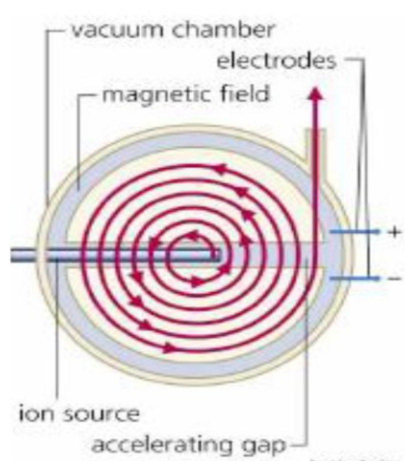
Q and V are constant, so speed is constant

Other Accelerator Types

Synchrotron



Cyclotron



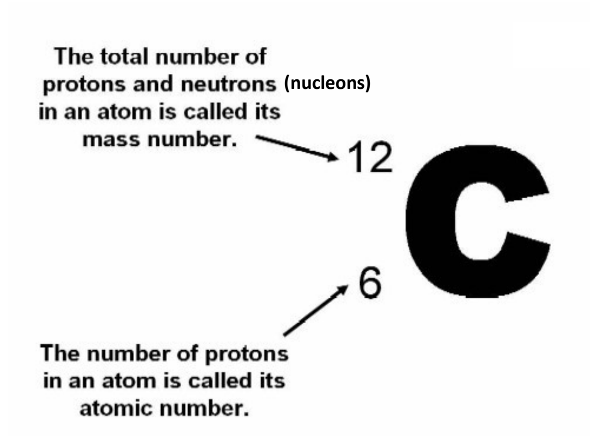
2.3 Nuclear Reactions

To examine nuclear reactions it is necessary to define a number of terms used to describe a nucleus.

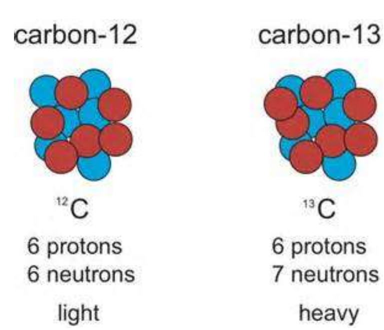
Nucleon **a particle in a nucleus**, i.e. either a proton or a neutron.

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

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



Isotopes 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.



Radioactive Decay

Radioactive decay is the breakdown of a nucleus to release energy and matter. The release of energy and/or matter allows unstable nuclei to achieve stability. **Unstable nuclei** are called **radioisotopes** or **radionuclides**.

The following types of radiation are emitted during radioactive decay.

Radiation	Nature	Symbol
Alpha particle	Helium nucleus	$^{4}_{2}He$ α
Beta particle	Fast electron	$^{0}_{-1}e$ β
Gamma ray	High frequency electromagnetic wave	γ

Representation of decay by symbols and equations
In the following equations, both mass number and atomic number are conserved, i.e. the totals are the same before and after the decay. The original radionuclide is called the parent and the radionuclide produced after decay is called the daughter product

Alpha decay
Uranium 238 decays by alpha emission to give Thorium 234

$$^{238}_{92}U \rightarrow \, ^{234}_{90}Th + \, ^{4}_{2}He$$

Mass number decreases by 4, atomic number decreases by 2 (due to the loss of 2 protons and 2 neutrons).

Properties of Alpha Radiation
Alpha decay usually occurs in heavy nuclei such as uranium or plutonium, and is a major part of the radioactive fallout from a nuclear explosion. Since an alpha particle is more massive than other forms of radioactive decay, it can be stopped by a sheet of paper and cannot penetrate human skin. A 4 MeV alpha particle can only travel a few centimetres through the air. Although the range of an alpha particle is short, if an alpha decaying element is ingested (swallowed), the alpha particle can do considerable damage to the surrounding tissue. This is why, plutonium with a long half-life, is extremely hazardous if ingested.

Beta decay
Atoms emit beta particles through a process known as beta decay. Beta decay occurs when an atom has too many protons or neutrons in its nucleus. Two types of beta decay can occur. One type (positive beta decay) releases a positively charged beta particle, called a positron, and a neutrino; the other type (negative beta decay) releases a negatively charged beta particle, called an electron, and an antineutrino. The neutrino and the antineutrino are high-energy elementary particles with little or no mass and are released to conserve energy during the decay process. Negative beta decay is far more common than positive beta decay.
Lead 210 decays by beta emission to give Bismuth 210.

Properties of Beta Radiation
The high speed beta particles are very light and so are less ionising than alpha. They can travel a few metres in air and can be absorbed by a few millimetres of Aluminium.

Gamma decay
Gamma rays are a type of electromagnetic radiation that results from a redistribution of electric charge within a nucleus. Gamma rays are like X – rays but have higher energy and while X rays are emitted during atomic processes involving energetic electrons, Gamma radiation is emitted by excited nuclei or other processes involving subatomic particles; it often accompanies alpha or beta radiation, as a nucleus emitting those particles may be left in an excited (higher-energy) state.

Properties of Gamm Radiation
Gamma rays are more penetrating than either alpha or beta radiation, but less ionising. Gamma rays from nuclear fallout would probably cause the largest number of casualties in the event of the use of nuclear weapons in a nuclear war. They produce damage similar to that caused by X-rays, such as burns, cancer and genetic mutations. Several centimetres of lead is required to absorb gamma rays and they travel at the speed of light, like all Electromagnetic radiation.

Examples of Radioactive Decay:

The incomplete statements below illustrate four nuclear reactions.

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

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

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

Solutions:

A: Thorium 230 decays into Radium.

Difference in Atomic number 90 – 88 = 2 A is an alpha particle.

B: Radon 220 decays into atom B plus and alpha particle.

Difference in Atomic number 86 – 2 = 84 B has atomic number 84 which is Polonium.

Difference in Mass number is 220 – 4 = 216 so B is Polonium 216

C: Lead 211 decays to Bismuth 211.

Difference in Atomic number 82 – 83 = -1 C is a Beta particle.

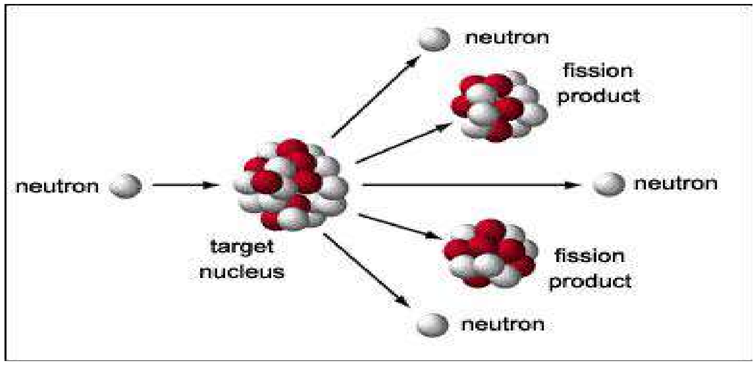
D: Radioisotope D decays to Radon 219 plus an alpha particle.

Atomic number of D = 86 + 2 = 88 so D is Radium.

Mass number is 219 + 4 = 223. D is Radium 223

Nuclear Fission

Fission is the decay of a large nucleus into two or more nuclei of smaller mass number. In spontaneous fission, the decay occurs randomly and the nucleus will split into two nearly equal fragments and several free neutrons. A large amount of energy is also released.
Most elements do not decay in this manner unless their mass number is greater than 230.
Fission can also be induced (persuaded to happen) by neutron bombardment.



This is what happens in a nuclear reactor and is given by the equation;

$$^{235}_{92}\text{U} + {}^{1}_{0}\text{n} \rightarrow {}^{92}_{36}\text{Kr} + {}^{141}_{56}\text{Ba} + 3\ {}^{1}_{0}\text{n} + \text{energy}$$

We know this is induced fission because of the neutron on the left hand side.

Mass number and atomic number are both conserved during this reaction. However, even though the mass number is conserved, when the masses before and after the fission are compared accurately, there is a mass difference. **The mass difference is the difference in mass between the mass before fission and the total mass of the products.**
Einstein suggested that mass was a form of energy, and that when there was a decrease in mass, an equivalent amount of energy was produced.

$$E = mc^2$$

In fission reactions, the energy released is carried away as ***kinetic energy*** of the fission products.

Example:

Calculate the energy released during this fission reaction

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

Solution:

Mass before fission (kg)		Mass after fission (kg)	
U	390.2×10^{-27}	Ba	227.3×10^{-27}
n	1.675×10^{-27}	Mo	160.9×10^{-27}
		2n	3.350×10^{-27}
391.875×10^{-27}		391.550×10^{-27}	

Decrease in mass = $(391.875 - 391.550) \times 10^{-27} = 0.325 \times 10^{-27}$ kg

Energy released during this fission reaction, using $E = mc^2$

$E = 3.25 \times 10^{-28} \times (3 \times 10^8)^2 = 2.9 \times 10^{-11}$ J

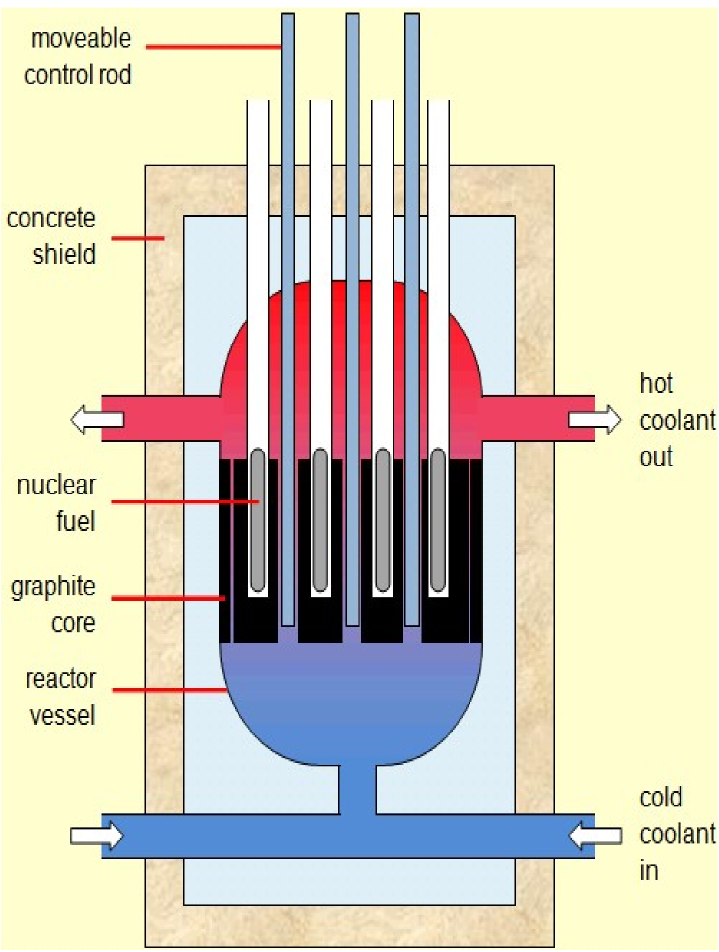
This is the energy released by fission of a single nucleus

Chain Reaction

A chain reaction refers to a process in which neutrons released in fission produce an additional fission in at least one further nucleus.

This nucleus in turn produces neutrons, and the process repeats. The process may be controlled (nuclear power) or uncontrolled (nuclear weapons).

Nuclear Fission in Nuclear Reactors



Controlled fission reactions take place in nuclear reactors. The neutrons released are fast moving.

A **moderator**, e.g. graphite is used to slow them down and increase the chance of further fissions occurring.

These **slow (thermal) neutrons** cause a chain reaction so that more fissions occur.

Control rods, e.g. boron, absorb some of the slow neutrons and keep the chain reaction under control.

The energy of the moving fission products is transferred as heat in the reactor core, turning water to steam which drives the turbines to generate electricity.

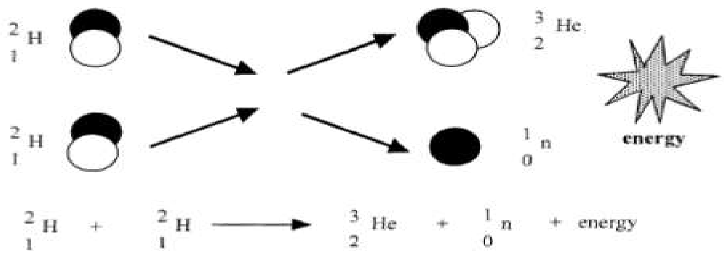
A **coolant** fluid (liquid or gas) is required to avoid the core overheating and in addition it can act as a moderator.

Fission reactors require containment within reinforced concrete and lead-lined containers to reduce contamination

Nuclear Fusion

Nuclear fusion is the combination of small light nuclei to form a heavier nucleus releasing energy.

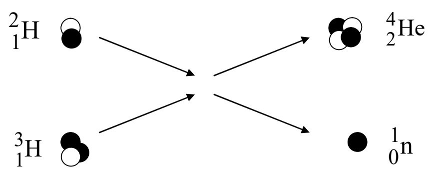
For example, in a hydrogen bomb, two isotopes of hydrogen, deuterium and tritium are fused to form a nucleus of helium and a neutron.



Unlike nuclear fission, there is no limit on the amount of the fusion that can occur. An example is the immense energy produced by our Sun. Very high temperatures in the Sun (2.3 × 10^7 Kelvin) supply sufficient energy for nuclei to overcome repulsive forces and fuse together.

When nuclei fuse, the final mass is less than the initial mass, ie there is a mass difference or mass defect.

Fusion Example



The nuclear reaction can be represented by:

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

deuterium + tritium ⟶ α-particle + neutron + energy

Once again it is found that the total mass after the reaction is less than the total mass before. This reduction in mass appears as an increase in the kinetic energy of the particles.

Mass before fusion (m_1):	deuterium	$3{\cdot}345 \times 10^{-27}$ kg
	tritium	$5{\cdot}008 \times 10^{-27}$ kg
	total	**$8{\cdot}353 \times 10^{-27}$ kg**
Mass after fusion (m_2):	α-particle	$6{\cdot}647 \times 10^{-27}$ kg
	neutron	$1{\cdot}675 \times 10^{-27}$ kg
	total	**$8{\cdot}322 \times 10^{-27}$ kg**
Loss of mass (m_1 - m_2):	**Δm**	**$0{\cdot}031 \times 10^{-27}$ kg**

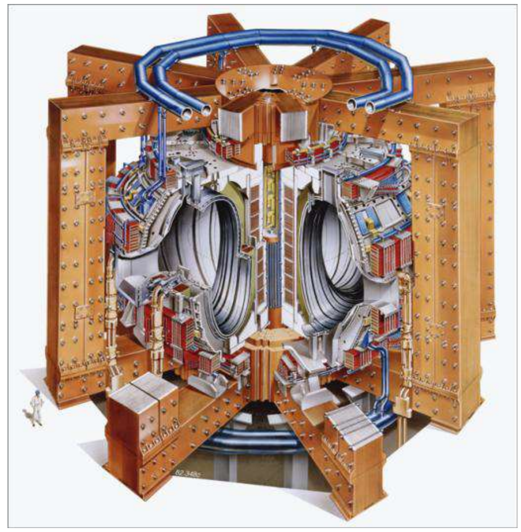
Energy released

$$E = mc^2$$
$$= 0{\cdot}031 \times 10^{-27} \times (3{\cdot}0 \times 10^8)^2$$
$$= 2{\cdot}8 \times 10^{-12} \text{ J}$$

A Fusion Reactor

Fusion has been successfully achieved with the hydrogen bomb. However, this was an uncontrolled fusion reaction and the key to using fusion as an energy source is control.

The Joint European Torus (JET), in Oxfordshire, is Europe's largest fusion device. In this device, deuterium–tritium fusion reactions occur at over 100 million kelvin. Even higher temperatures are required for deuterium–deuterium and deuterium–helium 3 reactions



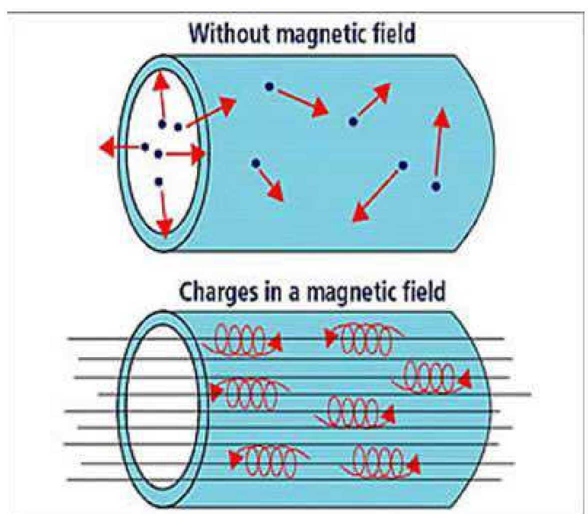
To sustain fusion, 3 conditions must be met at the same time.

- Extremely high plasma temperature (*T*): 100–200 million K
- A stable reaction lasting at least 5 seconds. This is called the **energy confinement time (*t*)**
- A precise plasma density of around 10^{20} particles/m^3
  (This is one thousandth of a gram/m^3 = one millionth the density of air).

One type of fusion reactor is called a Tokomak. In this design the plasma is heated in a torus or "doughnut-shaped" vessel.

The hot plasma is kept away from the vessel walls by applied magnetic fields. This is shown in the diagram on the right.

One of the main requirements for fusion is to heat the plasma particles to very high temperatures or energies. The methods on the following page are typically used to heat the plasma – all of them are employed on JET.



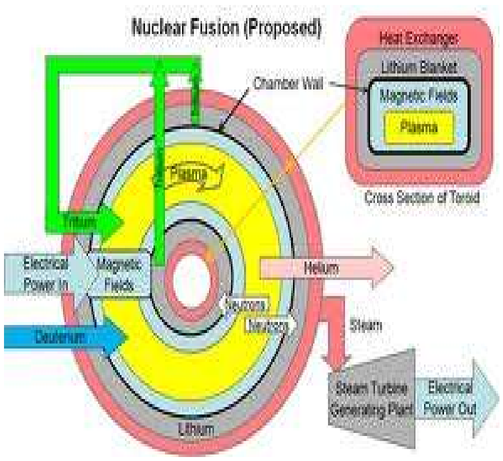
Induced current
The main plasma current is **induced** in the plasma by the action of a large **transformer**. A changing current in the primary coil induces a powerful current (up to 5 million amperes on JET) in the plasma, which acts as the transformer secondary circuit.

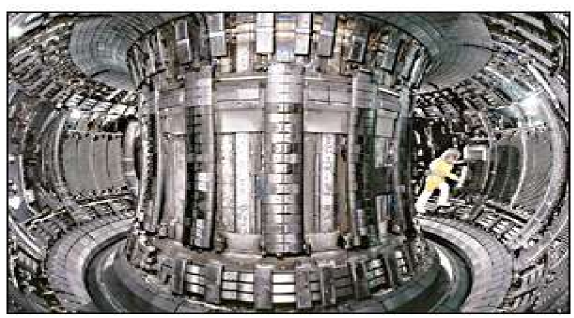
Neutral beam heating
Beams of high energy, (neutral) deuterium or tritium atoms, are injected into the plasma, transferring their energy to the plasma via collisions with the ions.

Radio-frequency heating
Electromagnetic waves of a frequency matched to the ions or electrons are able to energise the plasma particles. This is similar to the accelerating structures in a particle accelerator.

Self-heating of plasma
The helium ions (or so-called alpha-particles) produced when deuterium and tritium fuse remain within the plasma's magnetic trap for a time, before they are pumped away through the diverter. The neutrons (being neutral) escape the magnetic field and their capture in a future fusion power plant will be the source of fusion power to produce electricity.

Breakeven and Ignition
When fusion power out just equals the power required to heat and sustain plasma then ***breakeven*** is achieved. However, only the fusion energy contained within the helium ions heats the deuterium and tritium fuel ions (by collisions) to keep the fusion reaction going. When this self-heating mechanism is sufficient to maintain the plasma temperature required for fusion the reaction becomes self-sustaining (ie no external plasma heating is required). This condition is referred to as ***ignition***. In magnetic plasma confinement of the D–T fusion reaction, the condition for ignition is approximately six times more demanding (in confinement time or in plasma density) than the condition for breakeven.

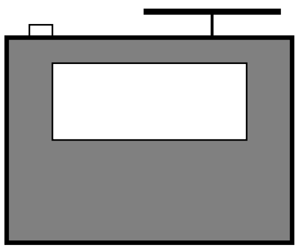




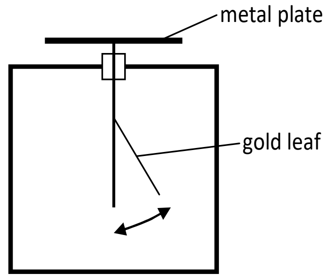
2.4 Wave-Particle Duality

The Photoelectric Effect

Under certain situations an electrically charged object can be made to discharge by shining electromagnetic radiation at it. This can be best demonstrated by charging a device on which the charge stored can be measured, either a digital coulombmeter or a gold leaf electroscope.



digital coulombmeter



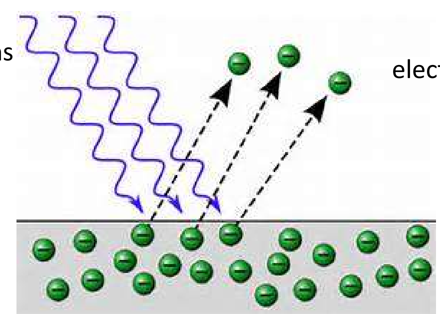
gold leaf electroscope

As charge is added to a gold leaf electroscope the thin piece of gold leaf is repelled by the vertical rod as they both have the same charge. This causes it to rise at an angle.

To observe the effect a zinc plate is placed on the electroscope or coulombmeter and it must be **negatively charged.** If an ultraviolet light is shone on the metal plate it discharges.

The effect can only be explained if we consider that electromagnetic radiation (the light) does not always behave like a wave - a smooth continuous stream of energy being delivered to a point. The effect can be explained if the radiation is behaving like packets of energy being delivered one by one. We call these packets of energy ***quanta*** or ***photons***.

The idea that light could be delivered as packets of energy, was initially put forward by Max Planck. Albert Einstein applied this theory to the photoelectric effect. It is for this work that he obtained the Nobel prize in 1921. Modern physics now takes the view that light can act both like a wave and like a particle without contradiction. This is known as ***wave-particle duality.***



The photoelectric effect is the emission of electrons from a metal surface when light is shone on it.

Photon Energy

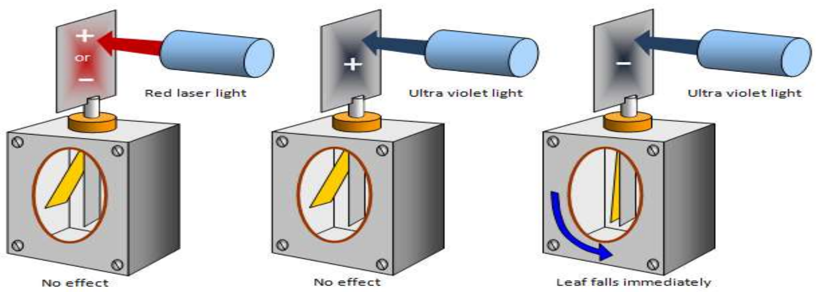
The energy of each photon can be determined by the equation

$$E = hf$$

Where;
E = energy of the photon (J)
f = frequency of the photon (Hz)
h = Planck's constant 6.63 x 10^{-34} Js

Different frequencies of electromagnetic radiation can be directed at different types of charged metals.

As shown below, the electroscope will only discharge if the light has a high enough frequency and the metal is negatively charged.



We can explain the **photoelectric effect** in terms of electrons within the metal being given sufficient energy to come to the surface and be released from the metal. The negative charge on the plate ensures that the electrons are then repelled away from the electroscope.

The minimum frequency needed to eject electrons from the surface of a metal is called the **threshold frequency (f_o)** and is different for each metal.

Increasing frequency above the threshold has no effect on photoemission.

Each photon ejects one electron. Photons with higher energy produce electrons with more kinetic energy.

Increasing Irradiance increases photoemission.

A higher irradiance (brighter source for visible light) produces more photons each second to eject more electrons each second.

Note

Each metal requires a different frequency because it's electron arrangement is different. For some e.g. copper, the value of f_o is higher than UV frequencies. For others e.g.selenium and cadmium**,** photoemission can occur in the visible light region of the spectrum. They have a very low value of f_o.

One reason for these different values of f_o is that some metals hold on to their electrons more strongly than others (their electron arrangements are different).

Threshold Frequency and Work Function

The **minimum energy** required to release an electron from a metal surface is called the **work function, E_o**.

$$E_o = hf_o$$

Where f_o is the threshold frequency
and h is Planck's constant

If E_{photon} is less than E_o there is no photoemission.
If E_{photon} is the same as E_o electrons will be ejected but will have no kinetic energy .
If E_{photon} is greater than E_o the electrons will have kinetic energy given by

$$E_k = E_{photon} - E_o$$

And so

$$E_{photon} = E_k + hf_o$$

Example:

The work function of sodium metal is 3.6×10^{-19}J . A photon of frequency 5.5×10^{14} Hz is incident on the metal.

(a) Calculate the minimum frequency of light needed to eject an electron from Sodium.
(b) Is an electron is ejected by this photon?
(c) What speed will it be travelling at?

Solution:

(a) $E_o = 3.6 \times 10^{-19}$ ms $^{-1}$ $E_o = hf_o$

$$3.6 \times 10^{-19} = 6.63 \times 10^{-34} \times f_o$$

$$f_o = 5.43 \times 10^{14} \text{ Hz}$$

(b) Photon frequency 5.5×10^{14} Hz is greater than f_o, so **<u>yes, an electron will be released.</u>**

(c) We can find it's kinetic energy from

$$E = E_o + E_k$$

$$hf = E_o + E_k$$

$$6.63 \times 10^{-34} \times 5.5 \times 10^{14} = 3.6 \times 10^{-19} + E_k$$

$$E_k = 3.645 \times 10^{-19} - 3.6 \times 10^{-19} = 0.045 \times 10^{-19} \text{ J}$$

To find the speed of the electron

$$E_k = \tfrac{1}{2}mv^2$$

$$0.045 \times 10^{-19} = \tfrac{1}{2} \times 9.11 \times 10^{-31} \times v^2$$

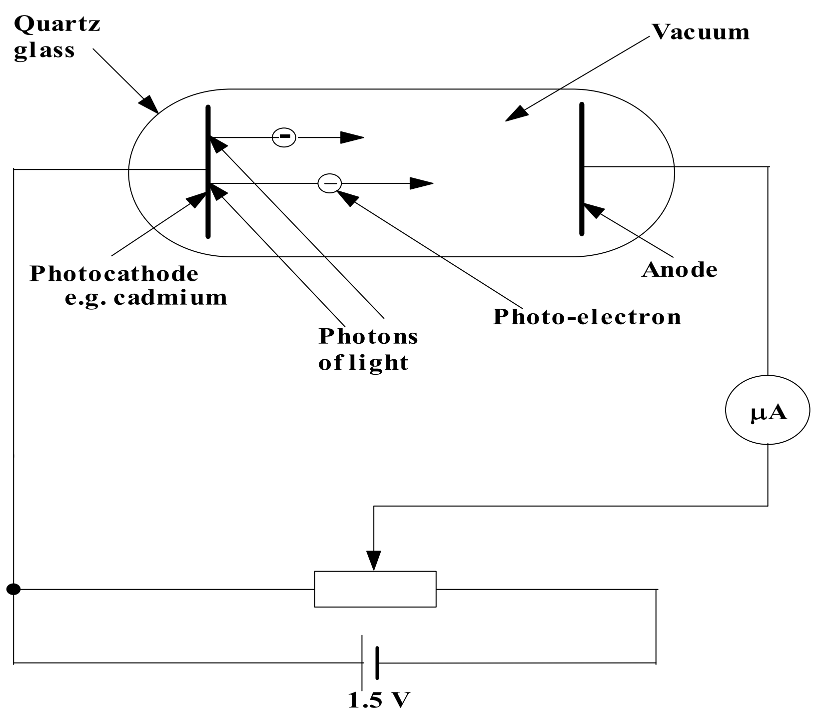
$$\frac{0.090 \times 10^{-19}}{9.11 \times 10^{-31}} = v^2$$

$$v = \sqrt{0.989 \times 10^{10}}$$

$$\underline{\underline{v = 9.9 \times 10^{4} \text{ ms}^{-1}}}$$

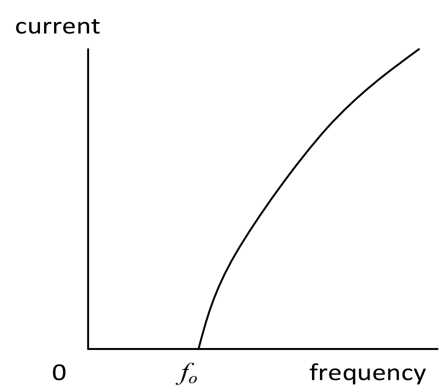
Measuring Photocurrent – Finding Planck's Constant

For photon energies greater than the work function, electrons are freed at the surface and have kinetic energy allowing them to travel. Using the equipment shown, ejected electrons are then attracted to the positively charged anode and electrons flow in the circuit producing a photocurrent.



The supply is set to 0 V. The graph shows that no electrons are ejected until we reach the threshold frequency. The photocurrent is 0A.

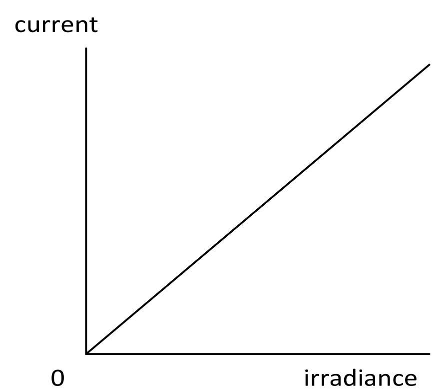
Then, in each case a small current is observed on the microammeter.



If the irradiance of the light is increased, the photocurrent increases (more photons each second eject more electrons each second).

The graph of photocurrent against irradiance is a straight line through the origin

The photocurrent is directly proportional to the irradiance of the incident light.



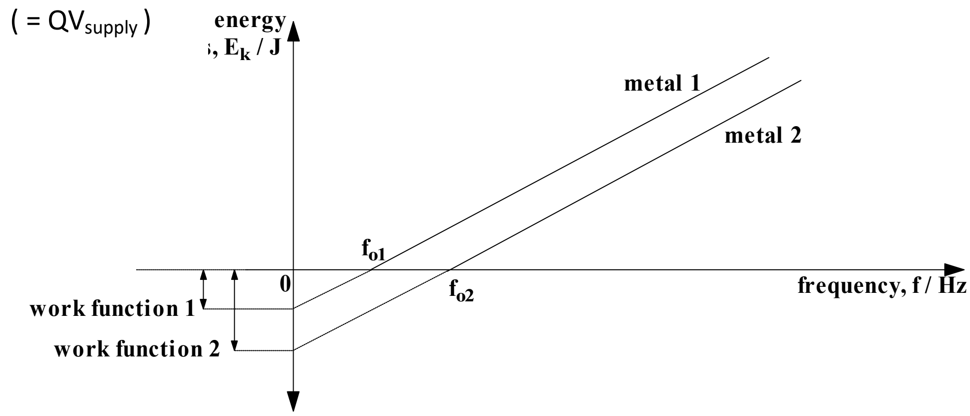
Finding the Value of Planck's Constant

If we increase the potential difference of the supply in this experiment, the electric field created across the gap opposes the flow of electrons. We can stop the electrons when their kinetic energy is equal to the work done crossing the electric field between the plates.

This is called the **stopping potential**.

Starting with red light we find the stopping potential for red. If we keep the p.d. of the supply constant, but change to violet light, the same metal will now produce a photocurrent. This demonstrates that electrons ejected by higher frequency photons have greater kinetic energy.

If the experiment is repeated with different metal cathodes and using a range of different frequencies of light, graphs of maximum energy of photoelectrons against frequency of light can be plotted, as follows:



All metals give straight line graphs which **do not** pass through the origin.
From the straight line graph it can be seen that:

$$y = mx + c$$

$$E_k = mf + c$$

$$E_k = hf - E_o$$

The gradient of each line is the same. **This gradient is Planck's constant *h*.**
The work function of the metal is the intercept on the energy axis.
Hence:

$$hf = E_o + E_k \qquad \text{or} \qquad hf = hf_o + E_k$$

(energy of absorbed photon = work function + kinetic energy of emitted electron)

Irradiance of photons

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

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

The irradiance, *I*, on a surface is the power per square metre.

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

$$\boxed{I = Nhf}$$

Where; I = irradiance in W m^{-2}
h = Planck's constant in J s
f = frequency in Hz
N = no of photons.

Note

The energy transferred to the electrons depends ***only*** on the frequency of the photons. Higher irradiance radiation does not increase the velocity of the electrons; it produces ***more*** electrons of the same velocity.

Example:

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 μJ

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.

Solution:

a) $E = hf = 6.63 \times 10^{-34} \times 9.0 \times 10^{14} = \underline{5.967 \times 10^{-19} J}$

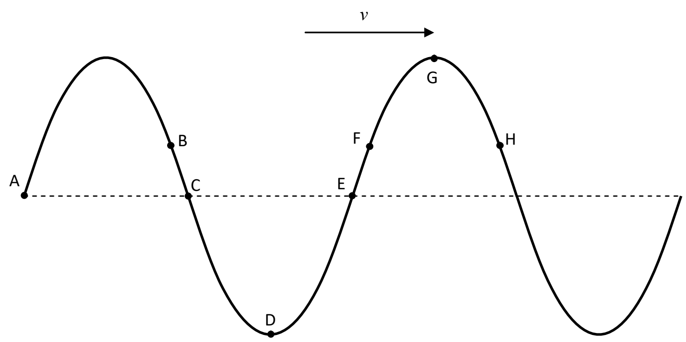
b) Energy of radiation needed to erase the information, E_{total} = 40.5 μJ

$$E_{total} = N(hf)$$
$$40.5 \times 10^{-6} = N \times 5.967 \times 10^{-19}$$
$$N = 40.5 \times 10^{-6} / 5.967 \times 10^{-19}$$
$$\underline{N = 6.79 \times 10^{13}}$$

2.5 Interference & Diffraction

Phase and Coherence

Two points on a wave that are vibrating in exactly the same way, at the same time, are said to be **in phase**, e.g. two crests, or two troughs.
Two points that are vibrating in exactly the opposite way, at the same time, are said to be **exactly out of phase**, or **180° out of phase**, e.g. a crest and a trough



Points _A_ & _E_ or _B_ & _H_ are in phase.

Points _A_ & _C_ or _C_ & _E_ or _D_ & _G_ are exactly out of phase.

Points _C_ & _D_ or _D_ & _E_ or _E_ & _G_ are 90° out of phase.

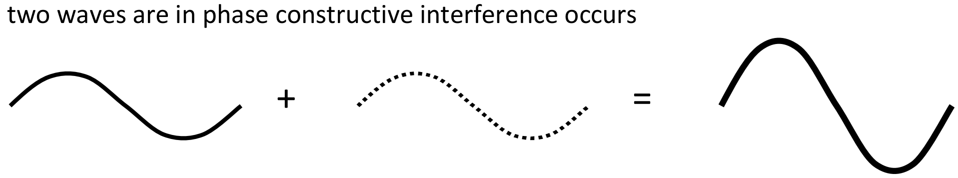
Coherent Sources

Two sources are said to be **coherent** if they are oscillating with **a constant phase relationship**. This means the two sources also have the same frequency.

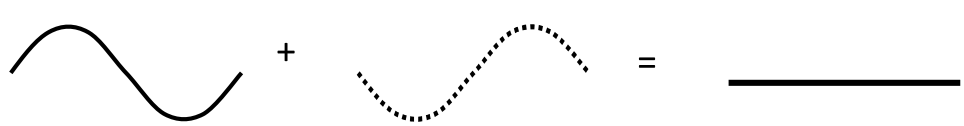
Interference

The addition of two or more waves to form a single waveform is called **superposition**.

Constructive Interference
When the two waves are in phase constructive interference occurs



Destructive Interference
When the two waves are exactly out of phase destructive interference occurs



Only waves show this property of interference. So, **interference is the test for a wave**.

Interference of Water Waves

If two point sources produce two sets of circular waves, they will overlap and combine to produce an **interference pattern**. The semicircular lines represent crests; the troughs are between the crests. Using a barrier with two small gaps can achieve this.

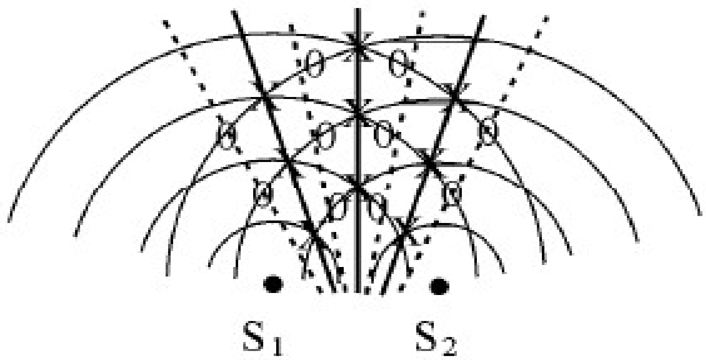
S1 and S2 are coherent point sources, ie the waves are produced by the same vibration.

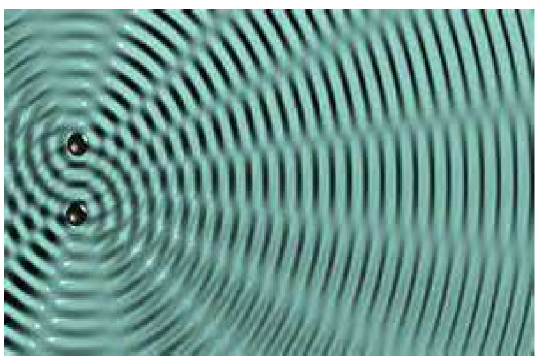
X point of constructive interference.

O point of destructive interference.

line of constructive interference.

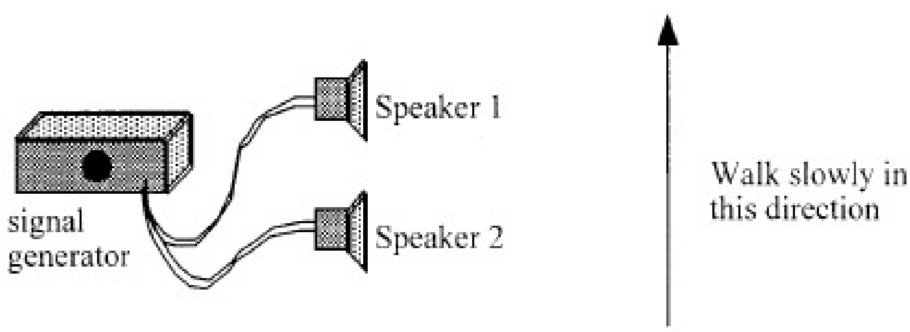
line of destructive interference.





The points of constructive interference form waves with larger amplitude and the points of destructive interference produce calm water. The positions of constructive interference and destructive interference form alternate lines which spread out from between the sources. As you move across a line parallel to the sources, you will therefore encounter alternate large waves and calm water.

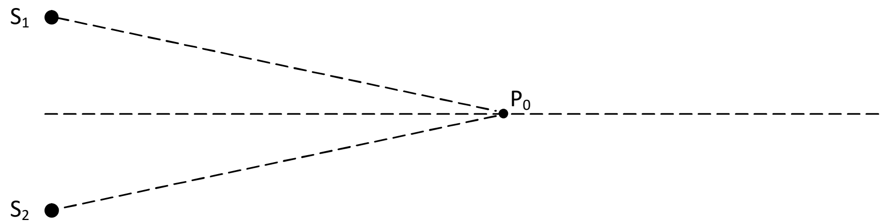
Interference of Sound Waves



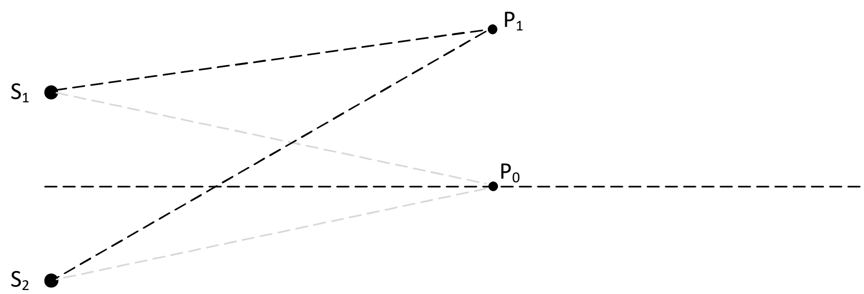
If we set up the apparatus as shown and walk slowly across the 'pattern' as shown above. We should be able to listen to the effect on the ***loudness*** of the sound heard. The effect heard happens as there will be points where the sound is louder [constructive interference] and points where the sound is quieter [destructive interference]. The waves that meet at your ear will have travelled different distances from each loudspeaker. The difference in distance is known as the ***path difference***.

Interference and Path Difference
Constructive Interference

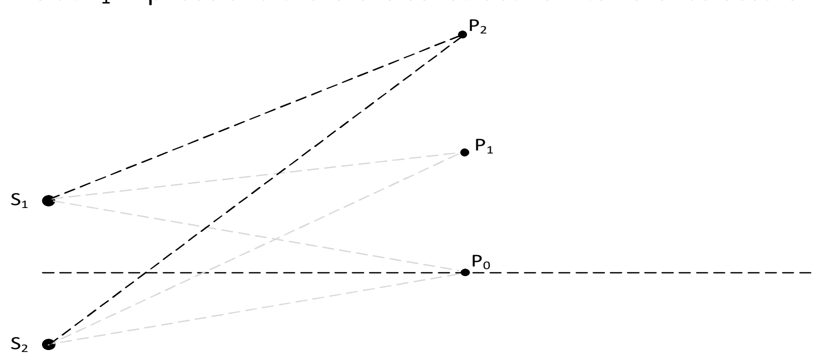
Two sources S_1 and S_2 in phase and 3 cm apart, wavelength 1 cm



- P_0 is a point on the centre line of the interference pattern.
- P_0 is the same distance from S_1 as it is from S_2.
- The path difference between S_1P_0 and $S_2P_0 = 0$
- Waves arrive at P_0 in phase and therefore constructive interference occurs



- P_1 is a point on the first line of constructive interference out from the centre line.
- P_1 is one wavelength further from S_2 than it is from S_1.
- The path difference between S_1P_1 and $S_2P_1 = 1 \times \lambda$
- Waves arrive at P_1 in phase and therefore constructive interference occurs

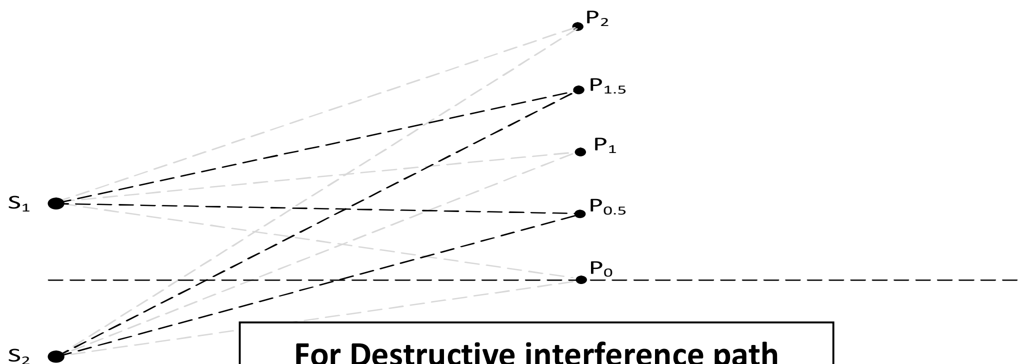


- P_2 is a point on the second line of constructive interference out from the centre line.
- P_2 is two wavelengths further from S_2 than it is from S_1.
- The path difference between S_1P_2 and $S_2P_2 = 2 \times \lambda$
- Waves arrive at P_2 in phase and therefore constructive interference occurs.

For Constructive Interference

Path difference = $m\lambda$ where m is an integer

Destructive Interference

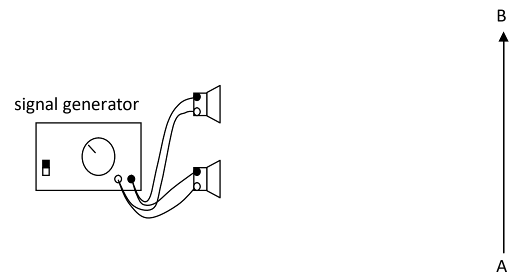


For Destructive interference path difference = (m + ½) λ

where m is an integer

Example:

A student sets up two loudspeakers a distance of 1·0 m apart in a large room. The loudspeakers are connected in parallel to the same signal generator so that they vibrate at the same frequency and in phase.



The student walks from A and B in front of the loudspeakers and hears a series of loud and quiet sounds.

a) Explain why the student hears the series of loud and quiet sounds.
b) The signal generator is set at a frequency of 500 Hz. The speed of sound in the room is 340 m s^{-1}. Calculate the wavelength of the sound waves from the loudspeakers.
c) The student stands at a point 4·76 m from loudspeaker and 5·78 m from the other loudspeaker. State the loudness of the sound heard by the student at that point. Justify your answer.
d) Explain why it is better to conduct this experiment in a large room rather than a small room

Solution:

a) The student hears a series of loud and quiet sounds due to interference of the two sets of sound waves from the loudspeakers. When the two waves are in phase there is constructive interference and when the two waves are exactly out of phase there is destructive interference.

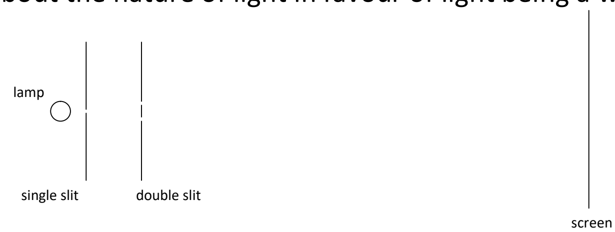
b)
$$v = f\lambda$$
$$340 = 500 \times \lambda$$
$$\lambda = \underline{0{\cdot}68 \text{ m}}$$

c) Path difference = 5·78 – 4·76 = 1·02 m
Number of wavelengths = 1·02/0·68 = 1·5λ
A path difference of 1·5λ means the waves are exactly out of phase. The student hears a quiet sound.

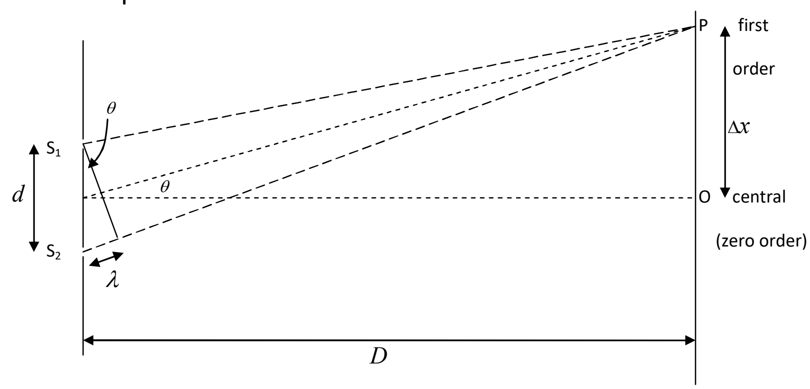
d) In a small room, sound waves will reflect off the walls and therefore other sound waves will also interfere with the waves coming directly from the loudspeakers.

Young's Double Slit Experiment

When Thomas Young showed that an interference pattern could be produced using light, this settled the long running debate about the nature of light in favour of light being a wave.



Passing light from the lamp through the single slit ensures the light passing through the double slit is coherent. An interference pattern is observed on the screen.



The path difference between S_1P and S_2P is one wavelength.

As the wavelength of light λ is very small the slits separation d must be very small and much smaller than the slits to screen distance D. Angle θ between the central axis and the direction to the first order maximum is therefore very small. For small angles sinθ is approximately equal to tanθ, and the angle θ itself is measured in radians.

Hence from the two similar triangles:

From triangle BAN: $\theta = \frac{\lambda}{d}$ also from triangle PMO: $\theta = \frac{\Delta x}{D}$

Thus $\frac{\Delta x}{D} = \frac{\lambda}{d}$ or $\Delta x = \frac{\lambda D}{d}$

Giving the fringe separation between adjacent fringes Δx

$$\Delta x = \frac{\lambda D}{d}$$

To produce a widely spaced fringe pattern:

(a) Very closely separated slits should be used since $\Delta x \propto 1/d$.

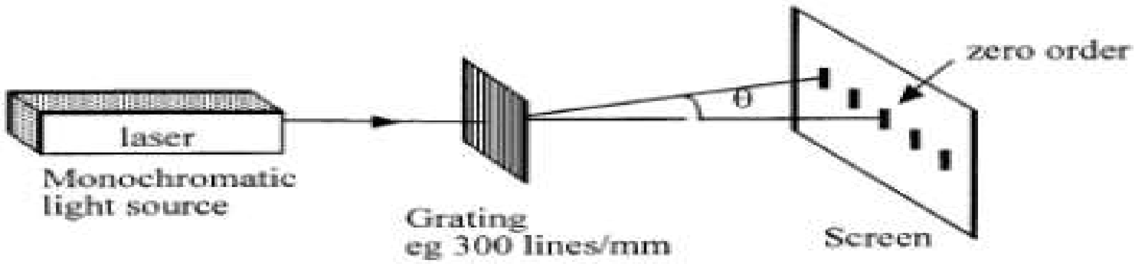
(b) A long wavelength light should be used, i.e. red, since $\Delta x \propto \lambda$.

(The wavelength of red light ≈ $7{\cdot}0 \times 10^{-7}$ m, green light ≈ $5{\cdot}5 \times 10^{-7}$ m and blue light ≈ $4{\cdot}5 \times 10^{-7}$ m.)

(c) A large slit to screen distance should be used since $\Delta x \propto D$.

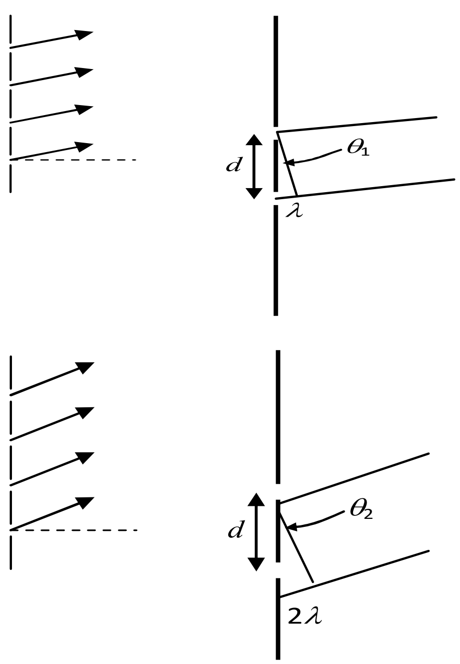
The Grating

A grating consists of many equally spaced slits positioned extremely close together. Light is diffracted through each slit and interference takes place in a similar fashion to the double slit we used when we investigated the interference of light. The advantage of the grating is that it has many more slits (up to 7500 per mm in our school set) so much more light is transmitted through and a clearer interference pattern is seen.



Gratings

A double slit gives a very dim interference pattern since very little light can pass through the two narrow slits. Using more slits allows more



As in Young's Double Slit Experiment the first order bright fringe is obtained when the path difference between adjacent slits is one wavelength λ.

Therefore:

$$\sin\theta_1 = \lambda/d \quad \text{and} \quad \lambda = d\sin\theta_1$$

The second order bright fringe is obtained when the path difference between adjacent slits is two wavelengths 2λ.

Therefore:

$$\sin\theta_2 = 2\lambda/d \quad \text{and} \quad 2\lambda = d\sin\theta_2$$

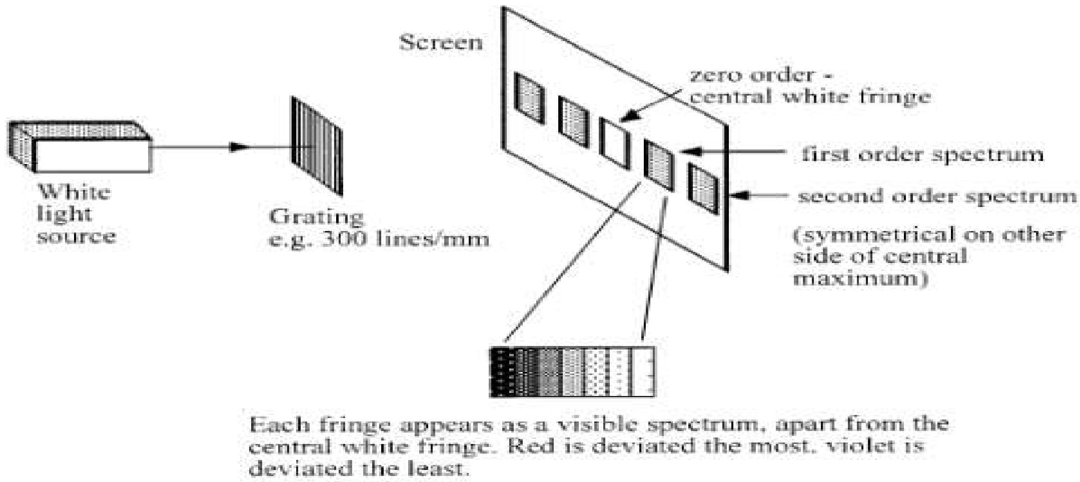
The general formula for the m^{th} order spectrum is:

$$m\lambda = d\sin\theta$$

Where;
m = order of the maximum
λ = wavelength of light
d = separation of slits
θ = angle from zero order to m^{th} maximum.

Gratings and White Light

It is possible to use a grating to observe the interference pattern obtained from a white light source.

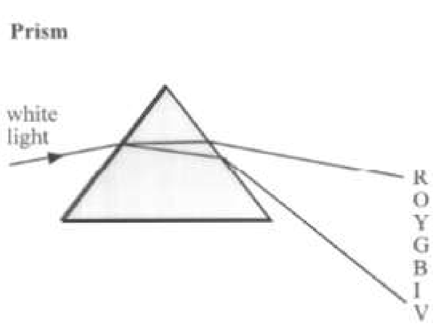


The central fringe is white because at that position, the ***path difference*** for all wavelengths is ***zero*** and all wavelengths arrive in phase. The central fringe is the same colour as the source.

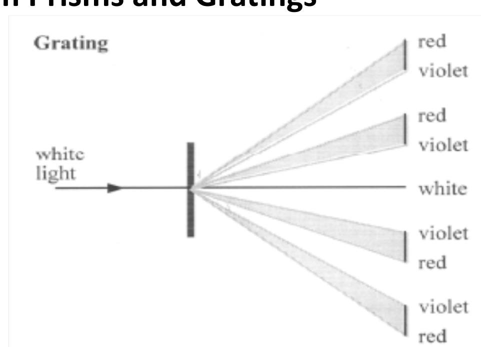
The first maximum occurs when the ***path difference*** is 1 x λ. Blue light has a shorter wavelength than red, so the path difference is smaller and the blue maximum is closer to the centre. Each colour produces a maximum in a slightly different position and so the colours spread out into a ***spectrum***.

These effects can also be explained using the formula $m\lambda = d\sin\theta$. If d and m are fixed, the angle θ depends on the wavelength. As wavelength increases, θ increases. The red fringe will be at a greater angle than the blue. The higher order spectra overlap.

Comparing Spectra from Prisms and Gratings



Only one spectrum is produced.
Red is deviated least, violet the most.
Bright images.
Usually less widely spaced (dispersed).

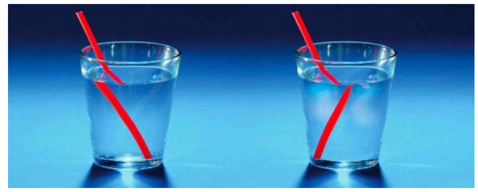


Many spectra are produced, symmetrical about the central maximum.
Red is deviated most, violet the least.
Less intense – energy divided between spectra.
Usually more spread out.
The Central image is always the same colour as the source.

2.6 Refraction

Background

Light, and other forms of electromagnetic radiation, do not require a medium through which to travel. Light travels at its greatest speed in a vacuum ($3{\cdot}00 \times 10^8$ m s^{-1}). Light also travels at almost this speed in gases such as air.



Whenever light passes from a vacuum to any other medium its speed decreases. Media such as glass, perspex, water and diamond are more optically dense than a vacuum. Air is only slightly more dense than a vacuum when considering its optical properties.

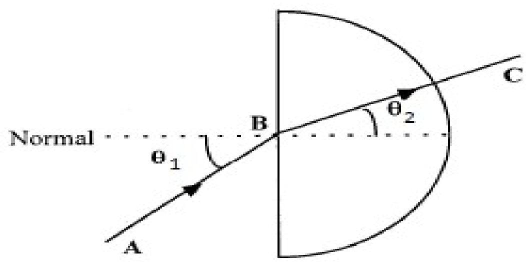
Refraction is the change in speed and wavelength of light as it moves from one material to another.

This then also results in a change in direction, unless light is travelling perpendicular (90^0) or 'normal' to the boundary between the media.

The absolute refractive index, n, of a medium is the ratio of the speed of light in a vacuum to the speed of light in the medium.

Refractive Index – Snell's Law

If we carry out the experiment below varying the incident angle θ_1 and measuring the refracted angle θ_2



A graph of sin θ_1 against sin θ_2 gives a straight line. This shows that sin θ_1 / sin θ_2 = k (a constant)
This constant is known as the ***refractive index*** and is given the symbol **n**

$$\frac{\sin \theta_1}{\sin \theta_2} = n$$

This is known as Snell's Law

The **absolute refractive index** of a medium, *n*, is the refractive index of the medium divided by that of a vacuum. The absolute refractive index of a vacuum (and therefore also air) is 1·0.

For refraction between any media (e.g. water to glass)

$$n_1 \sin \theta_1 = n_2 \sin \theta_2$$

which when rearranged gives; $\frac{\text{Sin}\theta_1}{\text{Sin}\theta_2} = \frac{n_1}{n_2}$

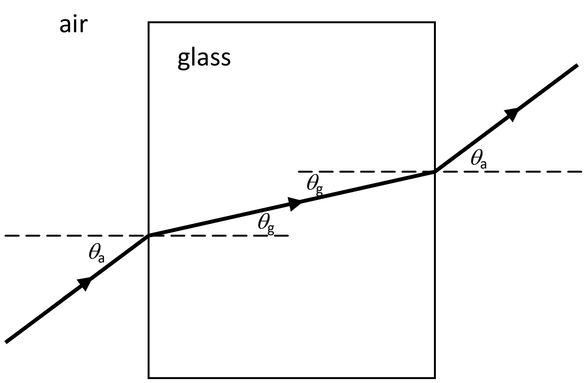
Where medium 1 is a vacuum or air, and therefore n_1 = 1·0, this simplifies to:

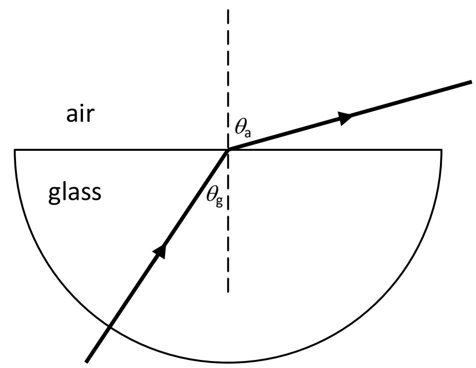
$$\sin \theta_1 = n_2 \sin \theta_2$$

or $n_2 = \frac{\text{Sin}\theta_1}{\text{Sin}\theta_2}$

Measuring the Refractive Index of Glass

The refractive index of glass can be measured by directing a ray of light through optical blocks and measuring the appropriate angles in the glass and the surrounding air.





Using the relationship above $\dfrac{\sin \theta_{air}}{\sin \theta_{glass}} = n_{glass}$

Refractive Index and Frequency

The frequency of a wave is determined by the source that makes it. It must remain unchanged as it moves through different materials, i.e. the same number of peaks and troughs, otherwise it would no longer be the same wave.
However, we know that the speed of the wave changes so, given the relationship $v = f\lambda$, the wavelength of the wave must be changing. If we consider a wave moving from air to glass then

frequency in air = frequency in glass.

Since f = v/λ we can write $\dfrac{v_1}{\lambda_1} = \dfrac{v_2}{\lambda_2}$

rearranging gives $\dfrac{v_1}{v_2} = \dfrac{\lambda_1}{\lambda_2}$

The ratio of the speeds is the absolute refractive index so;

$$\frac{n_2}{n_1} = \frac{\text{Sin}\theta_1}{\text{Sin}\theta_2} = \frac{\lambda_1}{\lambda_2} = \frac{v_1}{v_2}$$

Example:
Calculate the speed of light in glass of refractive index 1.50

Solution:

$$\frac{v_1}{v_2} = \frac{n_1}{n_2}$$

$$\frac{3 \times 10^8}{v_2} = \frac{1.5}{1}$$

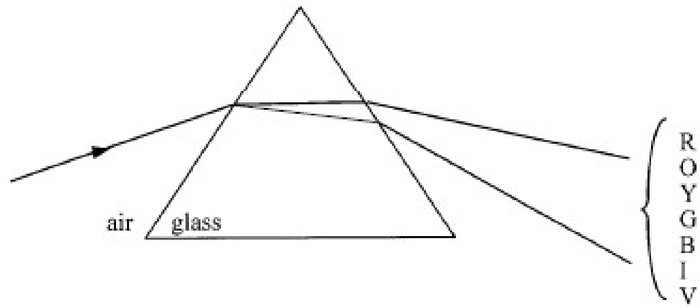
$$v_2 = \frac{3 \times 10^8}{1.5} = 2 \times 10^8 \text{ ms}^{-1}$$

Dependence of Refraction on Frequency

The refractive index of a medium depends upon the frequency (colour) of the incident light.
We saw in the last topic that when light enters a glass prism, it separates into its component colours and produces a spectrum. This happens because each frequency (colour) is refracted by a different amount.

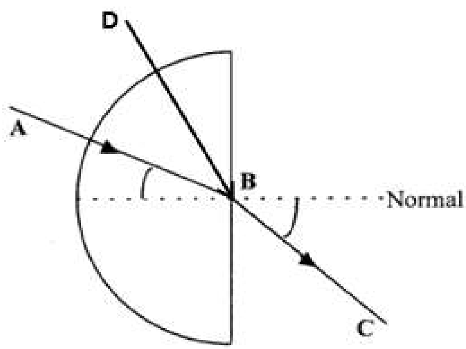
Since violet is refracted more than red it follows that the refractive index for violet light must be greater than the refractive index for red light.

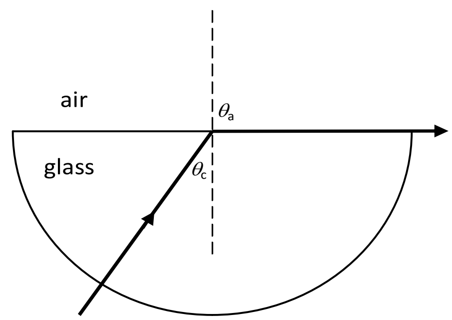
This means that the speed of light n the prism is greater for violet light than red light.



Critical Angle and Total Internal Reflection

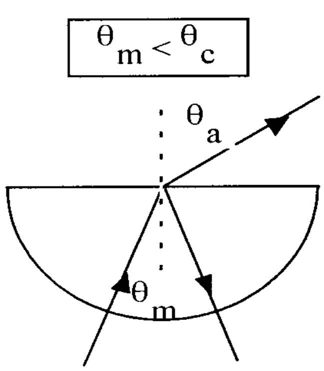
When light travels from a medium of high refractive index to one of lower refractive index (e.g. glass into air), it bends away from the normal. If the angle within the medium θ_i is increased, a point is reached where the refracted angle, θ_r, becomes 90^o.



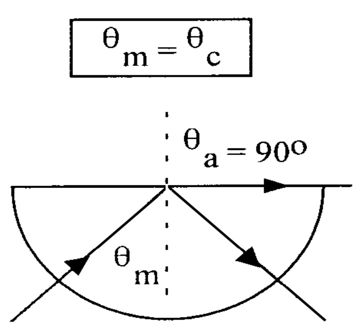


The angle in the medium resulting in an angle of refraction in air of 90^o is called the critical angle, θc. The critical angle can also be defined as the minimum angle at which total internal reflection occurs.

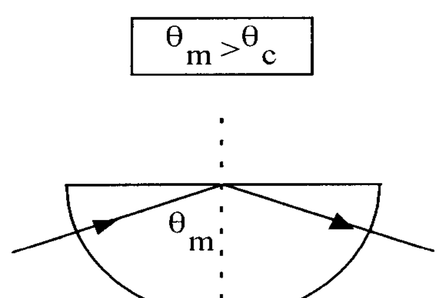
If the angle in the medium is greater than the critical angle, then no light is refracted and **Total Internal Reflection** takes place within the medium.



Most of incident light refracted into air.
Weak, partially reflected ray.



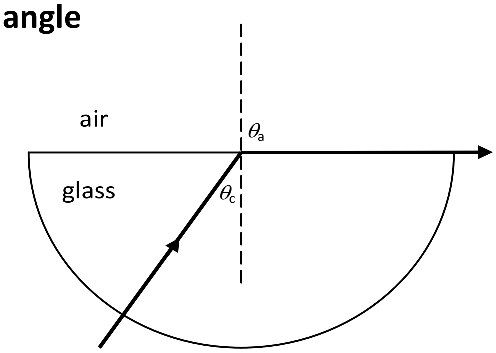
Light refracted into air at 90^o
Partially reflected ray stronger.



No light refracted into air.
All light reflected back into medium.

Deriving the critical angle

At the critical angle $\theta_m = \theta_c$ and $\theta_a = 90^o$



$$\frac{\sin\theta_a}{\sin\theta_m} = \frac{\sin 90^\circ}{\sin\theta_c} = \frac{1}{\sin\theta_c}$$

$$n = \frac{1}{\sin\theta_c}$$

Note

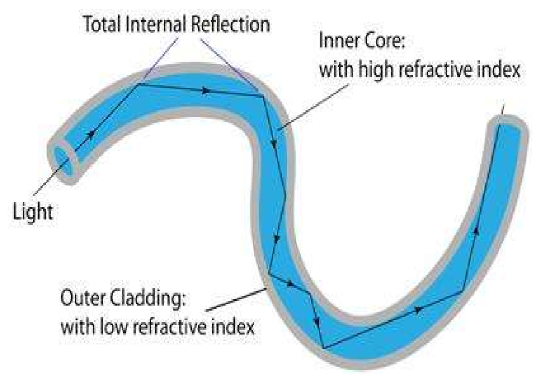
For angles of incidence less than the critical angle some reflection and some refraction occur. The energy of the light is split along two paths.

For angles of incidence greater than the critical angle only reflection occurs, i.e. total internal reflection, and all of the energy of the light is reflected inside the material.

Applications of Total Internal Reflection

Fibre Optics

Total internal reflection allows light signals to be sent large distances through optical fibres. Very pure, high quality glass absorbs very little of the energy of the light making fibre optic transmission very efficient. In an optical fibre rays of light always strike the internal surface of the glass at an angle greater than the critical angle. A commercial optical fibre has a fibre core of high refractive index surrounded by a thin, outer cladding of glass with lower refractive index than the core. This ensures that total internal reflection takes place.

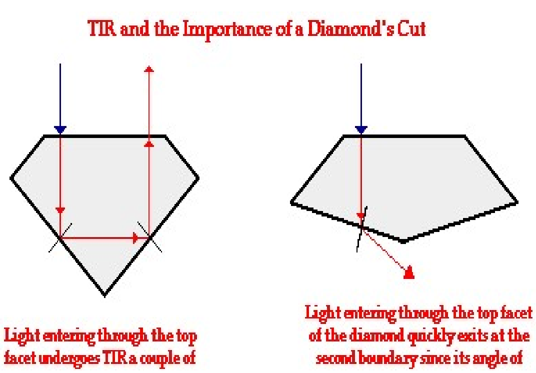


Diamonds

The critical angle from glass to air is about 42° but the material with the smallest critical angle, 24.4°, is diamond. That is why they sparkle so much!

As most rays of light will strike the diamond at an angle greater than its critical angle, rays of light can easily be made to totally internally reflect by careful cutting of the stone.

The refraction at the surfaces then splits the light into a spectrum of colours.



2.7 Spectra

Irradiance and the Inverse Square Law

The irradiance of light *I* is defined as the amount of light energy incident on every square metre of a surface per second. The equation for irradiance is therefore:

$$I = \frac{E}{A \times t}$$

This can be reduced to:

$$I = \frac{P}{A}$$

Where: I = Irradiance in Wm^{-2}
P = power in Watts
A = Area in m^2

Example:
A light bulb of power 100 W illuminates an area of 12 m^2 . What is the irradiance of light hitting the area?

Solution:

I = P/A
I = 100 / 12
I = 8.3 Wm^{-2}

Irradiance of Laser Light

Light from a laser

- is monochromatic (one frequency)
- is coherent
- forms a parallel beam.

Because the beam is intense and parallel, it is a potential hazard to the eye (even if the laser appears to be of low power).
A laser of power 0.1 mW forming a beam of radius 0.5 mm produces a light intensity given by

I = P/A
$I = 0.1 \times 10^{-3} / \pi r^2$
$I = 0.1 \times 10^{-3} / 7.85 \times 10^{-7}$
I = 127 Wm^{-2}

An irradiance of this size is high enough to cause severe eye damage. It is far higher than the irradiance of light produced by a filament lamp (calculated in the earlier example).

Why does irradiance matter?

An understanding of irradiance is relevant to a range of applications. For example, NASA monitors solar irradiance to understand the activity of the Sun and climate scientists use it to research the impact of solar activity on the Earth's climate.
Interactions between solar radiation and the atmosphere of the Earth can impact on air quality and an understanding of irradiance can allow investigation of the composition of the Earth's atmosphere.

Excessive exposure to sunlight has been linked to the development of a range of skin cancers.

The performance of solar cells, an increasingly common use of solar radiation as an energy resource, requires an understanding of irradiance.

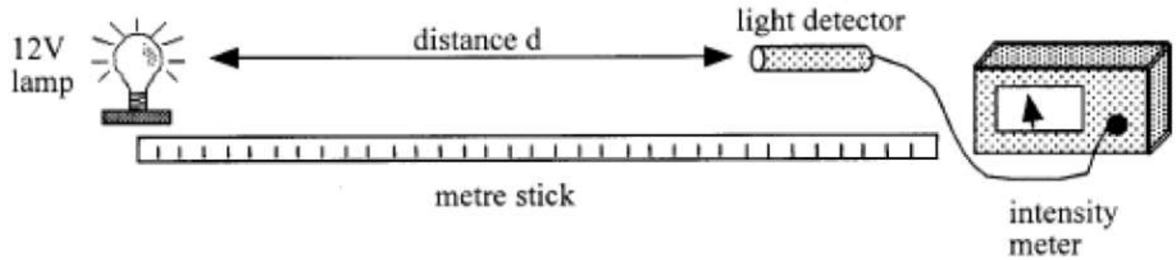
Investigating Irradiance

The relationship between irradiance of a point source and the distance from that source can be investigated using a simple experimental set up.

Activity

Aim: To investigate the variation of irradiance with distance from a point source of light.

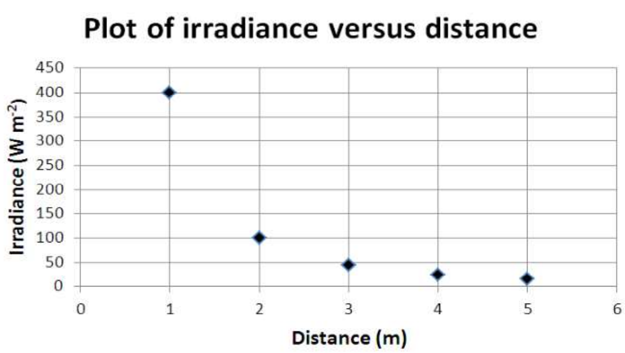
Apparatus: 12 V power supply, 12 V lamp, light detector and meter, metre stick.

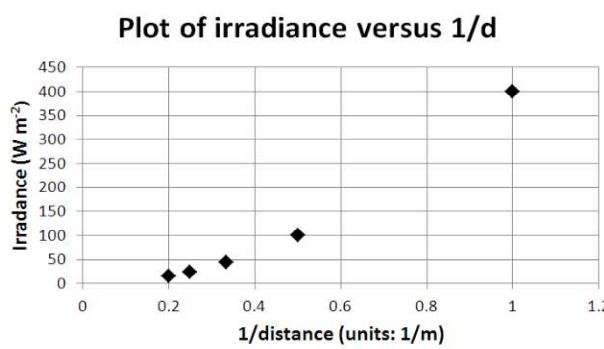


Instructions

1. Darken the room. Place the light detector a distance from the lamp.
2. Measure the distance from the detector to the lamp and the irradiance of the light at this distance.
3. Repeat these measurements for different distances between detector and lamp.
4. Plot a graph of light irradiance against distance from the lamp.
5. Consider this graph and your readings and use an appropriate format to find the relationship between the light irradiance and distance from the lamp.

Plotting the results



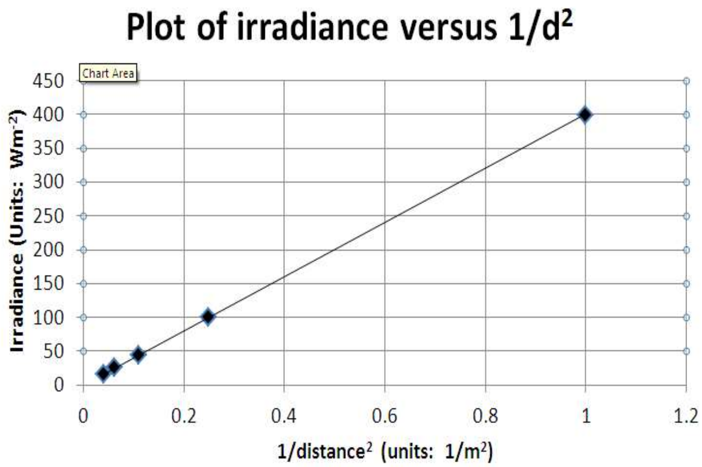


The graph of a typical set of results from the experiment is shown:
It is clear from this graph that the relationship between irradiance and distance is not a linear one.

A plot of irradiance (in Wm^{-2}) against 1/distance is not a straight line.

Analysis

However, the graph of average irradiance against $1/d^2$ ***is*** a straight line.
This demonstrates an inverse square relationship between irradiance and distance.



This is described as an inverse square law

From the graph: $I \propto 1/d^2$

$Id^2 =$ a constant

$$I_1 d_1^2 = I_2 d_2^2$$

I = irradiance in Wm^{-2}

d = the distance from a point source in m

Example:

A lamp illuminates a screen of area $2.0m^2$ which is 4.0m away. The irradiance at the screen is 0.02 Wm^{-2}.

a) Calculate the power of the beam
b) If the screen is moved to a distance of 3.0m, what would the new irradiance be?

Solution:

a) $I = 0.02\ Wm^{-2}$
$A = 2.0\ m^2$

$I = P/A$
$P = 0.02 * 2.0$
$\underline{P = 0.04\ W}$

b) $I_1 = 0.02\ Wm^{-2}$
$d_1 = 4.0m$
$d_2 = 3.0m$

$I_1 d_1^2 = I_2 d_2^2$
$0.02 \times 4^2 = I_2 \times 3^2$
$I_2 = \frac{0.02 \times 4^2}{3^2}$
$\underline{I_2 = 0.036\ Wm^{-2}}$

Point Sources

A point source is one which irradiates equally in all directions, i.e. the volume that will be irradiated will be a sphere. The surface area of a sphere can be calculated using $A = 4\pi r^2$, i.e. the area which will be irradiated is proportional to r^2 (or d^2).

Examples of point sources are the Sun or a filament lamp.

A laser is not a point source and its irradiance doesn't follow the inverse square law.

Introduction to Emission Spectra

An emission spectrum is the range of colours given out (emitted) by a light source. There are two kinds of emission spectra: continuous spectra and line spectra. To view spectra produced by various sources, a spectroscope or spectrometer can be used.

Spectrometer

Spectroscope

Continuous spectra

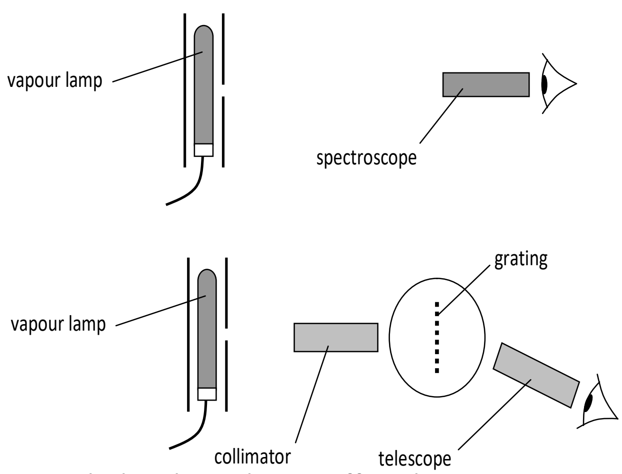
In a continuous spectrum all frequencies of radiation (colours) are present in the spectrum. The continuous spectrum colours are red, orange, yellow, green, blue, indigo, violet.

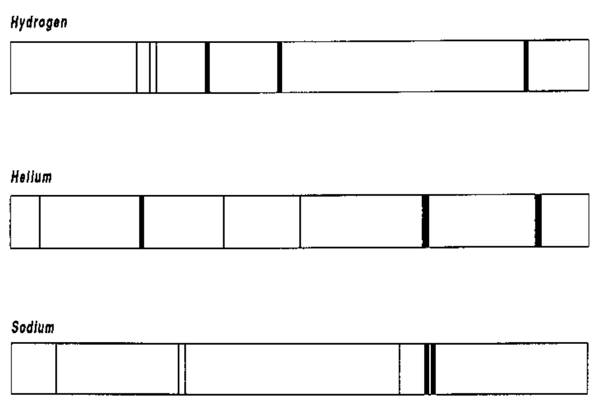
Line spectra

Some sources of light do not produce continuous spectra when viewed through a spectroscope. They produce line spectra – coloured lines spaced out by different amounts. Only specific, well-defined frequencies of radiation (colours) are observed.

A line spectrum is emitted by excited atoms in a low pressure gas. Each element emits its own unique line spectrum that can be used to identify that element. The spectrum of helium was first observed in light from the sun (Greek - helios), and only then was helium searched for and identified on Earth.

A grating or prism is used with the spectroscope or spectrometer to observe spectrum.



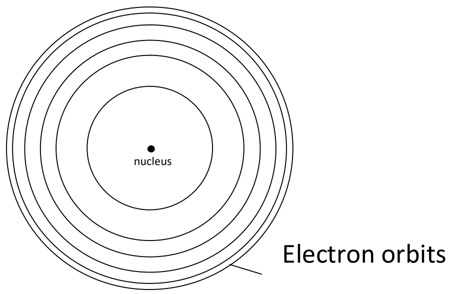


As with the photoelectric effect, line emission spectra cannot be explained by the wave theory of light. In 1913, Neils Bohr, a Danish physicist, first explained the production of line emission spectra. This explanation depends on the behaviour of the electrons in atoms and requires light to be emitted as photons or quanta.

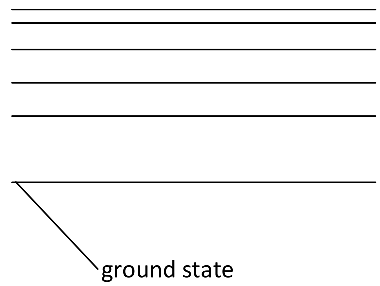
Line Emission Spectra, The Bohr Model & Energy Levels

The electrons in a *free* atom are restricted to particular radii of orbits. A free atom does not experience forces due to other surrounding atoms. Each orbit has a discrete energy associated with it and as a result they are often referred to as energy levels.

Bohr model of the atom



Energy level diagram



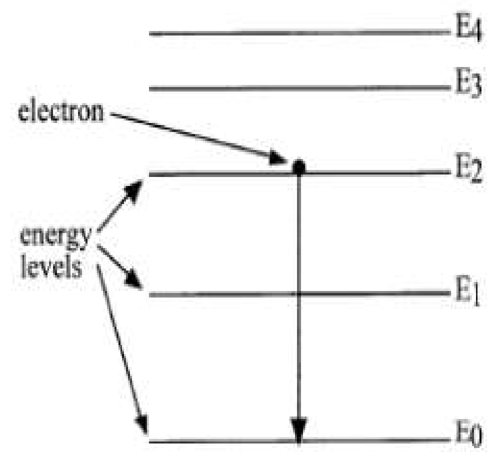
The Bohr model is able to explain emission spectra in the following way;

- electrons exist only in allowed orbits and they do not radiate energy if they stay in this orbit.
- electrons tend to occupy the lowest available energy level, i.e. the level closest to the nucleus.
- electrons in different orbits have different energies.
- electrons can only jump between allowed orbits. If an electron absorbs a photon of exactly the right energy, it moves up to a higher energy level.
- if an electron drops down from a high to a low energy state it emits a photon which carries away the energy, i.e. light is emitted when electrons drop from high energy levels to low energy levels. The allowed orbits of electrons can be represented in an energy level diagram.

The orbit closest to the nucleus is called the ***ground state***, E_0, (shown as the dashed line at the bottom).

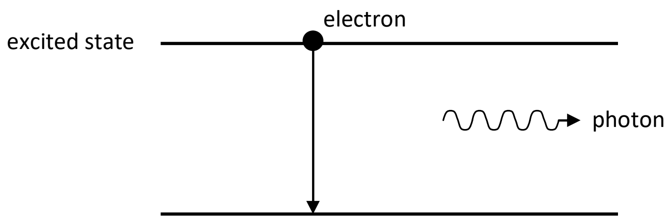
E_1– E_4 are ***excited states***,. These correspond to orbits further away from the nucleus.

An electron which has gained just enough energy to leave the atom has 0 J of kinetic energy. This is the ***ionisation level*** and is the highest energy level. This means that an electron which is trapped in the atom has less energy and so it has a ***negative energy*** level.



The lines on an emission spectrum are made by electrons making the transition from high energy levels (excited states) to lower energy levels (less excited states).
The number of lines on an emission spectrum is equal to the number of possible transitions.

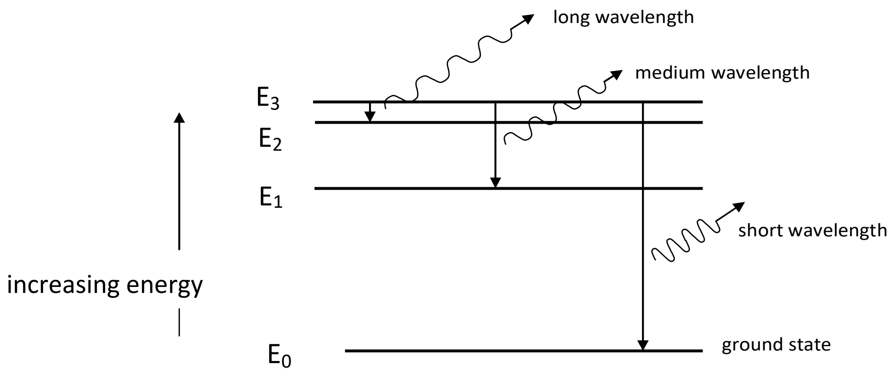
Energy level diagram



When the electron drops the energy is released in the form of a photon where its energy and frequency are related by the energy difference between the two levels. For example take an electron dropping from level two to one;

$$E_2 - E_1 = \Delta E = hf$$

From this calculation, we can go on and work out the frequency of the emitted photon.



As we can see there are many different combination of gap between energy levels and as such there are numerous frequencies that can be emitted from one type of atom. From this we can say;

- The photons emitted may not all be in the visible wavelength.
- Only certain frequencies of light can be emitted from specific atoms.
- The larger the number of excited electrons that make a particular transition, the more photons are emitted and the brighter the line in the spectrum.

Example:

What type of photon is emitted when an electron falls from the E_2 energy level of -2.416×10^{-19} J to the E_1 energy level of -5.424×10^{-19} J in a Hydrogen atom?

Solution:

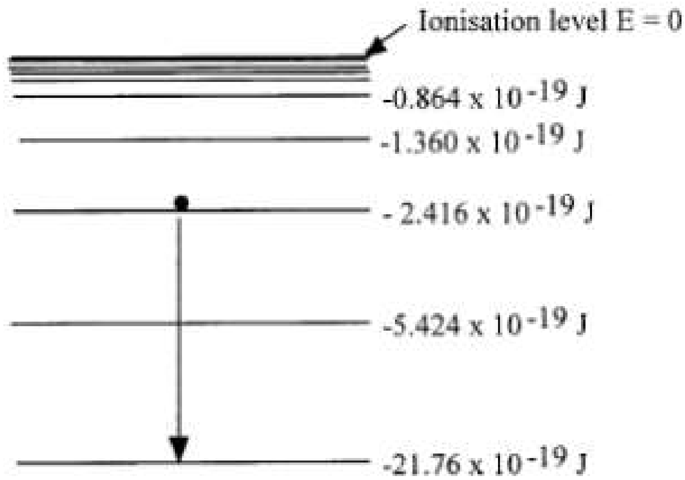
Difference in energy $\Delta E = E_2 - E_1 = -2.416 \times 10^{-19} - (-5.424 \times 10^{-19}) = 3.008 \times 10^{-19}$ J

$$E = hf$$

$$f = \frac{3.008 \times 10^{-19}}{6.63 \times 10^{-34}} = 4.537 \times 10^{14} \text{ Hz}$$

$$\lambda = v/f = 3 \times 10^{8} / 4.537 \times 10^{14} = 661 \times 10^{-9} \text{ m}$$

An example of the energy levels in a Hydrogen Atom



A hydrogen atom has only one electron. If the electron is given enough energy, it can escape completely from the atom. The atom is then said to be in an ***ionisation state***.

More about Spectra

Because each element has a different atomic structure, each element will produce a different line spectrum unique to that element. The line spectrum is a good way of identifying an element, a kind of 'atomic fingerprint'. Astronomers use this idea to identify elements in the spectrum of stars.

Most spectra contain bright lines and faint lines. This is because electrons sometimes favour particular energy levels. The transitions involving these energy levels will happen more often and hence lead to brighter lines in the emission spectrum, since more photons with that particular energy and frequency will be produced. How bright the line is depends on the number of photons emitted.

The energy to raise the electrons to the 'excited' higher levels can be provided in various ways:

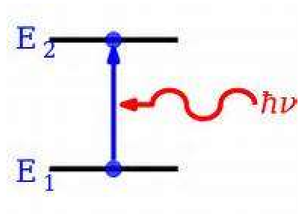
- a high voltage, as in discharge tubes
- heat, as in filament lamps
- nuclear fusion, as in stars

The Continuous Spectrum & Energy levels

A continuous visible spectrum consists of all wavelengths of light from violet (~400 nm) to red (~700 nm). Such spectra are emitted by glowing solids (a tungsten filament in a lamp), glowing liquids or gases under high pressure (stars). In these materials the electrons are not *free*. The electrons are shared between atoms resulting in a large number of possible energy levels and transitions.

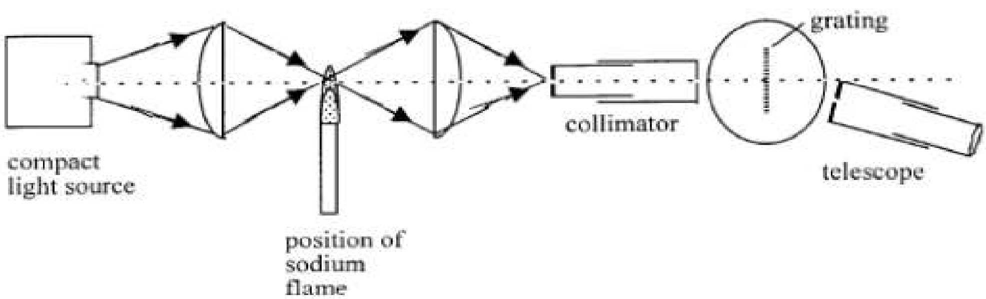
Absorption Spectra

When light is passed through a medium containing a gas, the atoms of the gas can absorb photons. This happens if the energy of the photons (*hf)* is the same as the energy difference needed to move an electron between energy levels. The energy is absorbed by the electron and that photon is 'removed' from the incident light.



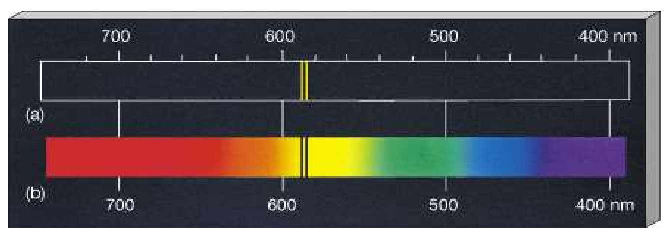
$E_2 = E_1 + hv$

In practice, it may be difficult to produce a line absorption spectrum. The apparatus below shows how to produce an absorption spectrum for a sodium flame.



White light from the compact light source is passed through a large lens and brought to a focus within a sodium flame. The light then passes through another lens and is brought to focus on the slit of a spectrometer.

Viewing the spectrum produced through the spectrometer reveals a continuous spectrum with two black lines in the yellow region.



This is the absorption spectrum of sodium. The black lines correspond to the position of the sodium D lines in the sodium emission spectrum. These lines correspond to the frequencies of the photons absorbed by the electrons within the sodium flame.

The energy absorbed by the electrons within the sodium flame will be emitted again. The emitted photon will have the same energy and frequency as the one absorbed, but can be emitted in any direction. Therefore, the spectrum viewed through the spectrometer will show black absorption lines corresponding to the absorbed frequency of radiation.

Absorption Lines in Sunlight

The white light produced in the centre of the Sun passes through the relatively cooler gases in the outer layer of the Sun's atmosphere. After passing through these layers, certain frequencies of light are missing. Fraunhofer lines are the dark lines that correspond to the frequencies that have been absorbed.

The lines correspond to the bright emission lines in the spectra of certain gases. This allows the elements that make up the Sun to be identified.