REVISED HIGHER PHYSICS

REVISION BOOKLET

PARTICLES AND WAVES

Kinross High School

Orders of magnitude

You should know **that powers of 10 are referred to as orders of magnitude**. For example, something a million times larger is six orders of magnitude bigger. Examples of orders of magnitude are shown below.

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

Size	Powers of 10	Examples
	10^{-18} m	Size of an electron/quark?
1 fm (femto)	**10^{-15} m**	Size of a proton
	10^{-14} m	Atomic nucleus
1 pm (pico)	**10^{-12} m**	
1Å (Angstrom)	10^{-10} m	Atom
1 nm (nano)	**10^{-9} m**	Glucose molecule
	10^{-8} m	Size of DNA
	10^{-7} m	Wavelength of visible light. Size of a virus.
1 µm (micro)	**10^{-6} m**	Diameter of cell mitochondria
	10^{-5} m	Red blood cell
	10^{-4} m	Width of a human hair. Grain of salt
1 mm (milli)	**10^{-3} m**	Width of a credit card
1 cm (centi)	10^{-2} m	Diameter of a pencil. Width of a pinkie finger!
	10^{-1} m	Diameter of a DVD
1 m	10^0 m	Height of door handle
	10^1 m	Width of a classroom
	10^2 m	Length of a football pitch
1 km (kilo)	**10^3 m**	Central span of the Forth Road Bridge
	10^4 m	10km race distance. Cruising altitude of an aeroplane
	10^5 m	Height of the atmosphere
1 Mm (mega)	**10^6 m**	Length of Great Britain
	10^7 m	Diameter of Earth Coastline of Great Britain
1 Gm (giga)	**10^9 m**	Moon's orbit around the Earth, The farthest any person has travelled. The diameter of the Sun.
	10^{11} m	Orbit of Venus around the Sun
1 Tm (tera)	**10^{12} m**	Orbit of Jupiter around the Sun
	10^{13} m	The heliosphere, edge of our solar system?
	10^{16} m	Light year. Distance to nearest star Proxima Centauri,
	10^{21} m	Diameter of our galaxy
	10^{23} m	Distance to the Andromeda galaxy
	10^{29} m	Distance to the edge of the observable universe

The Standard Model of Particle Physics

Matter and anti-matter:

Almost everything we see in the universe appears to be made up of just ordinary protons, neutrons and electrons. **High energy collision experiments have revealed the existence of anti-matter**.

An **anti-matter** particle has exactly **the same mass but opposite charge as its counterpart atom**.

For example: an anti-proton has the same mass as a proton but it is negatively charged.
an electron has an anti-matter partner called a positron (e^+)

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

Matter and anti-matter **cannot co-exist** close to each other. If an electron and positron collide then they will annihilate each other and emit energy in the form of radiated photons. Often a pair of high energy photons (gamma rays) are produced, but other particles can be created from the conversion of energy into mass, using $E = mc^2$.

The electron:
Discovered by JJ Thomson, in 1897, it has a mass of 9.11×10^{-31} kg and a charge of 1.60×10^{-19} C. Thomson did not work out the charge of the electron, but the specific-charge, which is the ratio of mass over charge, e/m. He discovered that electrons are **negatively charged**.

Rutherford's alpha scattering experiment:
His research students were given the task of firing alpha particles at a thin gold foil. This was done in a vacuum so that the alpha particles were not absorbed by the air. His results showed that:
1. The atom must be mostly empty space
2. There is a very large mass with a positive charge in each atom.

The discovery of the neutron:
Physicists have postulated that there must be another particle, in the nucleus, to stop the positively charged protons from flying apart from each other. This particle is the neutron, which was discovered by Chadwick in 1932. This explained isotopes – elements with the same number of protons, but different number of neutrons.

Discovery of the positron:
Experimental proof of the positron came in the form of tracks left in a cloud chamber. It was observed that tracks of positrons were identical to those made by electrons, but curved in the opposite direction.

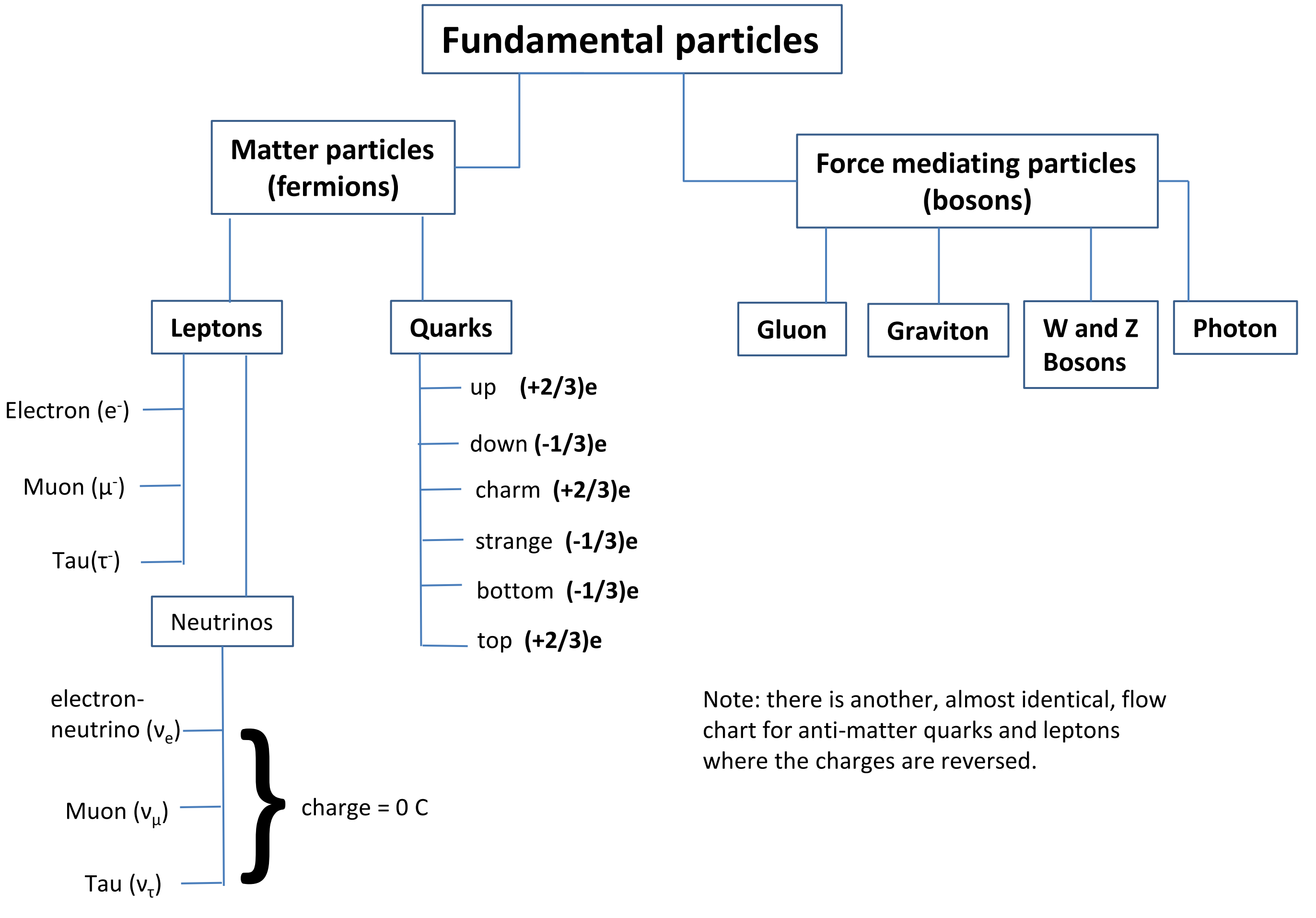
The Standard Model represents our understanding of the fundamental nature of matter.

It suggests that **fermions** (the matter particles) consist of quarks (six types) and leptons (six types: electron, muon and tau, together with their neutrinos), which are organised in three generations.

First generation includes the electron, neutrino and two different quarks – that make up protons and neutrons (i.e. normal matter of our universe)

Other generations are found in high-energy collisions in particle accelerators or in naturally occuring cosmic rays. Each has the charge of a fraction of the charge on an electron (1.60×10^{-19} C).

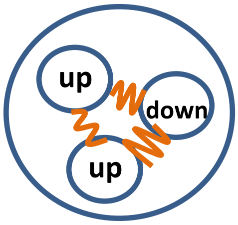
Leptons (Greek for 'light particle') are used to describe particles with similar properties to electrons and neutrinos.
The muon and tau are significantly heavier than the electron.



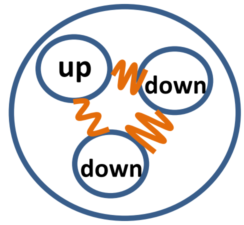
Note: there is another, almost identical, flow chart for anti-matter quarks and leptons where the charges are reversed.

Quarks:
Murray Gell-Mann proposed that protons and neutrons consisted of three smaller particles called quarks. There are also three generations of quarks with increasingly greater mass, in each generation. Lower mass (lower energy) quarks exist for a longer time compared with higher mass quarks.

Quark structure of protons and neutrons:



proton



neutron

The proton is a three-quark combination: Up, Up and Down.

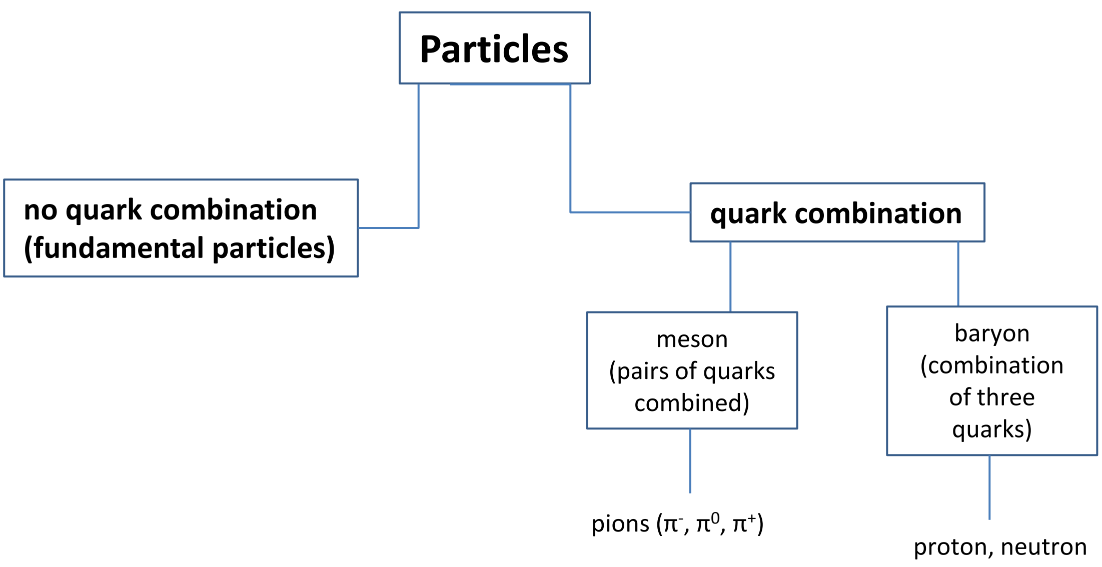
The Up quark has a charge of +(2/3)e; Down quark has a charge of –(1/3)e.

As a result, the overall charge of the proton is 2 x (+2/3)e + (-1/3)e = + e

The neutron is a three-quark combination: Up, Down and Down.

The Up quark has a charge of +(2/3)e; Down quark has a charge of –(1/3)e.

As a result, the overall charge of the proton is (+2/3)e + 2 x (-1/3)e = 0



Particles which are made up of quarks are called **hadrons**.

There are two **types of hadron**: **baryons and mesons**.

Baryons are made up of three quarks (e.g. proton and neutron).

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

Particles; such as electrons and muons, are **not made up of** smaller particles . They are known as **fundamental particles**.

Forces and bosons:

There are four fundamental, non-contact forces in the Standard Model, which may be used to explain how matter interacts. These forces are known as:

- **The nuclear weak force**
- **The nuclear strong force**
- **Electromagnetic force**
- **Gravitational force.**

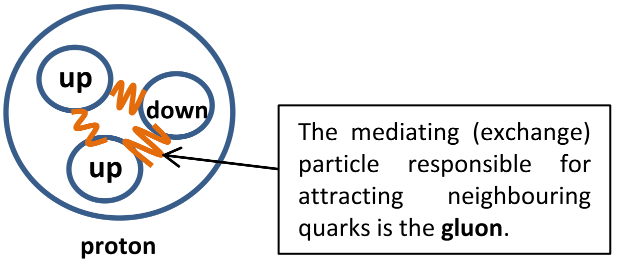
The range, strengths and examples of such forces are tabulated below:

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

In the Standard Model, the forces that attract or repel particles are explained in terms of 'force-mediating particles', called **bosons**. This means, the force acting on one object by another is due to a transfer of particles between other more massive particles.

Force	Exchange particle
Strong nuclear	Gluon
Weak nuclear	W and Z bosons
Electromagnetic	Photon
Gravitational	Graviton*

*Not yet verified experimentally.



The **strong nuclear force** is responsible for holding positively charged protons together. It is a **short range force** (less than 10^{-14} m) within a nucleus and it is **stronger than the electrostatic repulsion.**

The strong nuclear force is the **strongest** of the four fundamental forces. This type of force is also **experienced by quarks** and therefore by **the baryons and mesons that are made up from them**.

The weak nuclear force is involved in radioactive **beta decay**. It is called the weak nuclear force and is an extremely short-range force.

Beta decay:

Neutrinos were discovered in beta decay experiments.

In beta decay, a neutron (in the nucleus), decays into a proton **and** a high speed electron (beta particle). However, it was observed that momentum and energy is not conserved during this decay. Pauli proposed that there was another particle being emitted at the same time as the beta particle. This second particle had to be of a **very small mass**, **neutral charge** and **highly penetrating**. This particle is known as the **neutrino**.

Beta decay (β^- or β^+): For β^- decay, neutron -> proton + electron + anti-electron neutrino

$$ {}^{1}_{0}n \rightarrow {}^{1}_{1}p + e^{-} + \overline{\nu_e} $$

For β^+ decay, proton -> neutron + positron + electron-neutrino

$$ {}^{1}_{1}p \rightarrow {}^{1}_{0}n + e^{+} + \nu_e $$

Forces on charged particles.

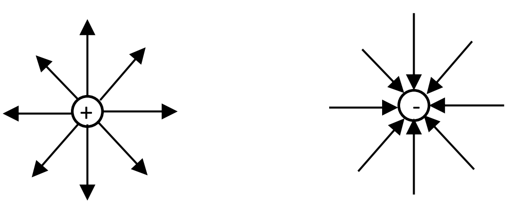
The region round an electric charge where it can affect another charge is said to have an electric field acting on it.

A charged particle will **experience a force** when it is in an electric field.

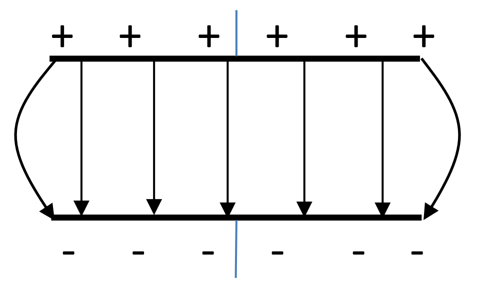
There are two types of charge: **positive** and **negative**.

Like charges repel; opposite charges attract. The direction of the force on the charge will depend on the **sign** of the charge.

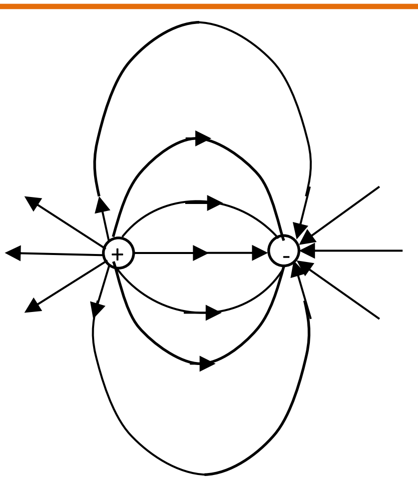
Radial field due to a point (isolated) charge.

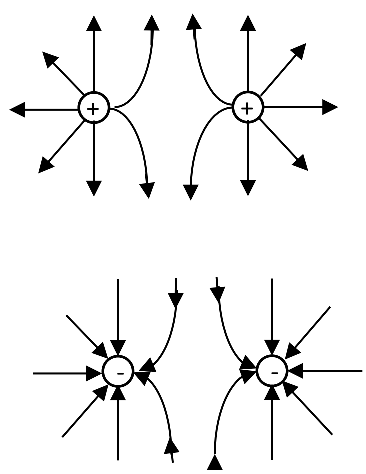


Uniform field between two parallel plates.



Electric field pattern for a system of two point charges.





When an electric field is applied to a conductor, the free negative charges in the conductor move.

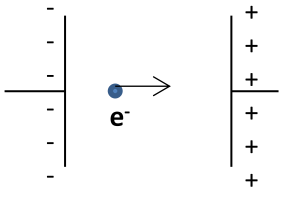
When a charge, Q, moves in an electric field, work is done by the electric field on that charged particle.

The work done is given by: **W = Q V**

The **potential difference**, V, between two points is a measure of **the work done in moving one coulomb of charge between the two points**.

The definition of one volt: If one joule of work is done in moving one coulomb of charge between two points. **One volt is one joule per coulomb**.

An electron moving parallel to the electric field, as shown, will be accelerated by the force due to the electric field. The electron will **gain kinetic energy equal to the work done**.



When the electron reaches the anode, **its original electrical potential energy is transferred into kinetic energy**.

The final speed of the electron, as it reaches the anode, is deduced from the expression:

$$\frac{1}{2} mv^2 = Q V$$

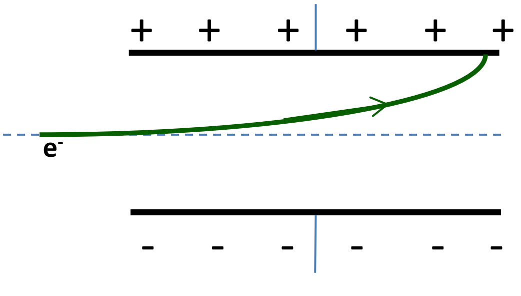
Q

An electron is accelerated by a 1kV potential.
Calculate the electron's final speed.

[Note: charge of an electron = 1.6×10^{-19} C
mass of electron = 9.11×10^{-31} kg]

Answer: 1.9×10^{7} ***ms***$^{-1}$

If an electron is moving horizontally, at right angles to the electric field, the electron will experience an **upward electrical force towards the positive plate**.
The electron will **accelerate upwards**, while its horizontal speed is constant. The electron follows a **parabolic path**.



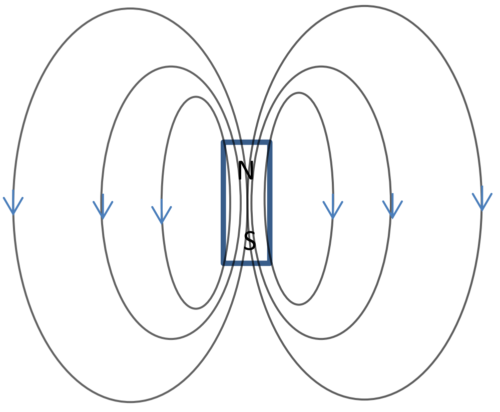
A **moving electric** charge **produces a magnetic field**.

A **moving charge** will experience a force when it is in a magnetic field.

There are two types of polarities: **north** and **south**.

Like poles repel; opposite poles attract.

The magnetic field lines are loops. The closer the field lines, the stronger the magnetic field.

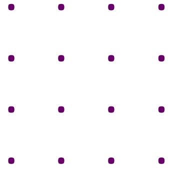


Direction of magnetic fields:

Magnetic field lines pointing 'into paper' are represented as crosses.

X X X X
X X X X
X X X X
X X X X

Magnetic fields lines pointing 'out-of-paper' are represented as dots.

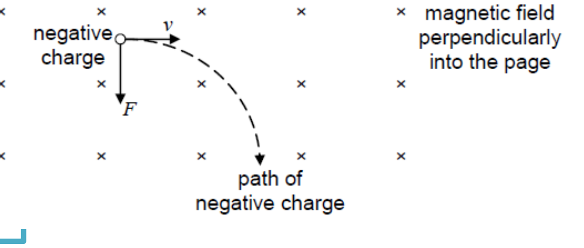


The direction of the magnetic force, on a moving charged particle, can be worked out using the hand rules.

CAUTION!

Some have been taught that the left hand is for negative charges; right hand for positive charges. This is fine, so long as …
1. the thumb represents the direction of magnetic force
2. the middle finger represents the direction of magnetic field
3. the fore-finger represents the direction of moving charge.

Traditionally, the left hand is for positive charges; right hand is for negative charges. Again, this is fine, so long as…
1. the thumb represents the direction of magnetic force, BUT
2. the middle-finger **represents the direction of moving charge**, AND
3. the fore-finger **represents the direction of magnetic field**.



Particle accelerator:

There are three types of particle accelerators: **linear accelerators**, **cyclotrons** and **synchrotrons.**

There are basic parts of a particle accelerator: a source of particles, beam pipes (vacuum chamber), accelerating structures, a system of magnets and a target/collisions.

- The **beam pipes** must be evacuated so that the charged particles do not collide with other particles (e.g. air)
- **Accelerating structures** are regions where there is a rapidly changing electric field. At the Large Hadron Collider, protons approach a region where the electric field is negative (causing the protons to accelerate towards it). As it moves through the accelerator, the electric field becomes positive and protons are repelled away from it. The protons have increased their kinetic energy and accelerated to bigger speeds.
- The **system of magnets** bend and focus the beam of charged particles, in the accelerator.

- Two particles can be **collided** or smashed together. Either a fixed target can be used or it can move into another beam of moving particles.
- **Detectors** are placed at points where collisions take place. Detectors use electric and magnetic fields to follow the trace of the results of the collision.

Particle accelerator:

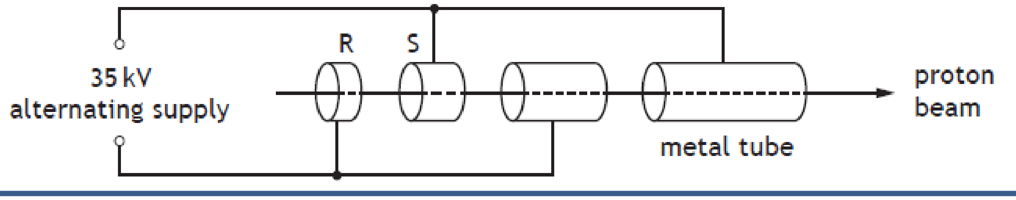
There are three types of particle accelerators:

1. Linear accelerators
2. Cyclotrons
3. Synchrotrons.

Linear accelerator (linacs):

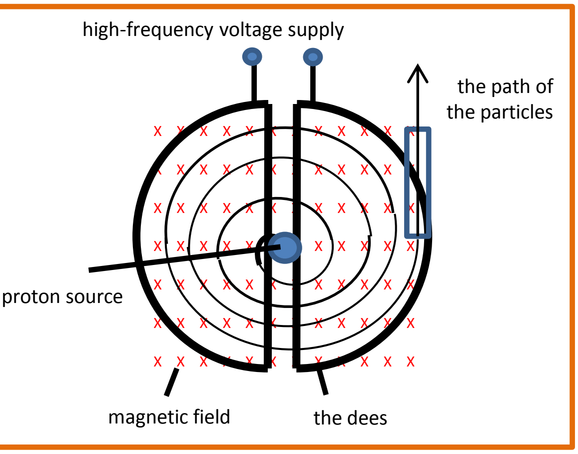
In a linear accelerator, bunches of charged particles are accelerated by a series of charged cylindrical conductors with alternating electric fields. The charges gain kinetic energy between the tubes, not inside the tubes. The final energy of the particles is limited by the length of the accelerator. This type of accelerator is used in fixed target experiments.

The problem with linacs is that they are straight and both the tunnel and accelerator, in it, must be long.



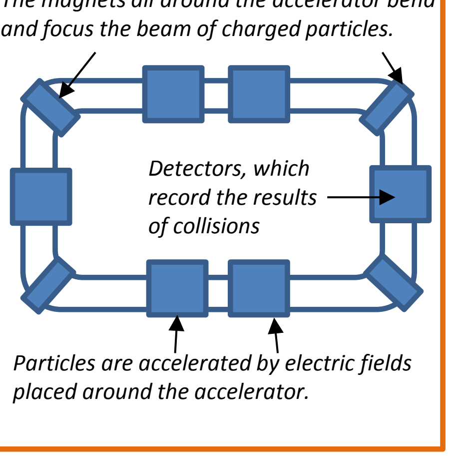
Cylcotron:

In a cyclotron, the charged particles are accelerated by alternating electric fields. The particles travel in a spiral of increasing radius as a result of a constant magnetic field, which is perpendicular to the spiral. The diameter of the cyclotron is limited by the strength of the magnet. The resultant energy of the particles is limited by the diameter of the cyclotron and by relativistic effects. This type of accelerator is used in fixed-target experiments.



Synchrotron:

In a synchrotron bunches of charged particles travel in a circular path of fixed radius as a result of C-shaped magnets whose strength can be varied. The particles are accelerated by alternating magnetic fields. As the energy of the particles increases the strength of the magnetic field is increased to maintain the radius of the path of the particles. In synchrotron accelerators, the particles can have, in theory, an unlimited series of accelerators as the particles can transit indefinitely around the ring. There will be a limit caused by relativistic effects. In this type of accelerator, particles with the same mass and opposite charge can circulate in opposite directions at the same time before colliding. This increases the energy of impact. This type of accelerator is used in colliding-beam experiments.



Nuclear reactions.

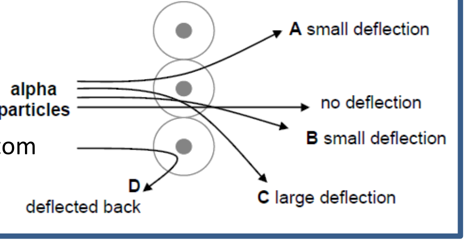
Rutherford's experiment confirmed the view that the atom consists of a central nucleus with a relatively small diameter containing most of the mass. It involved firing alpha particles at a gold foil in a vacuum.

The main results were:

1. Most of the alpha particles passed straight through the foil with little or no deviation
2. A few were deviated through fairly large angles, up to 90^0.
3. A very few were deviated through angles of more than 90^0, i.e. they bounced back.

Rutherford concluded that:

1. Most of the atom, in the gold foil, must be empty space since so many alpha particles passed through the 'gap' between neighbouring atoms.
2. Since some alpha particles bounce back, most of the mass and all the positive charge must be concentrated in a very small volume; this is the nucleus.



This gave Rutherford's model of the atom:

1. The nucleus has a small diameter, compared with that of the atom
2. The charge of the nucleus is positive
3. Most of the mass of the atom is concentrated in the nucleus.

Structure of the nucleus:
The atomic number is the number of protons in the nucleus.
For an electrically neutral charged atom, this number is equal to the number of electrons orbiting the nucleus.
The mass number is the number of protons and neutrons in the nucleus.

The chemical symbol for an element is normally written as

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

where X is the chemical symbol for the element; A is the mass number and Z is the atomic number.

For example: $^{14}_{6}C$ is a carbon atom with 6 protons and 8 neutrons.

Nuclei with the same atomic number but different mass numbers are called isotopes. For example:

$$^{14}_{6}C \text{ and } ^{12}_{6}C$$

The relative masses and charges of the proton, neutron and electron are:

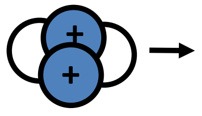
Particle	Mass	Charge	Symbol
proton	1	+1	$^{1}_{1}p$
neutron	1	0	$^{1}_{0}n$
electron	1/1840 (is often taken as zero)	-1	$^{0}_{-1}e$

Alpha, beta and gamma radiations all emit from the nucleus of an atom.

A **radionuclide** (or **radioisotope**) is an isotope which decays radioactively.

An **alpha particle** is a slow moving **helium nucleus**. It has **two protons** and **two neutrons**. It has an overall charge of **+2** and can be **deflected in a magnetic or electric field**.

$^{4}_{2}\mathrm{He}$



Example of alpha decay:

$$^{235}_{92}\mathrm{U} \rightarrow {}^{231}_{90}\mathrm{Th} + {}^{4}_{2}\mathrm{He}$$

Remember: the total atomic number and total mass number on either side of the nuclear equation is conserved.

A **beta particle** is a high energy (fast moving) **electron from a nucleus**. It is created when a neutron decays into an electron and a proton. It has an overall charge of **-1** and can be **deflected in a magnetic or electric field**.

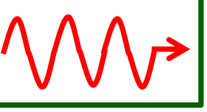
$^{0}_{-1}\mathrm{e}$

Example of beta decay:

$$^{231}_{90}\mathrm{Th} \rightarrow {}^{231}_{91}\mathrm{Pa} + {}^{0}_{-1}\mathrm{e}$$

Remember: the total atomic number and total mass number on either side of the nuclear equation is conserved.

In gamma decay, there is no change in the isotope. The nucleus just loses energy in the form of electromagnetic radiation.
Gamma rays have no mass or charge.



In both alpha and beta decay, there may be gamma radiation given off as well.

Fission:

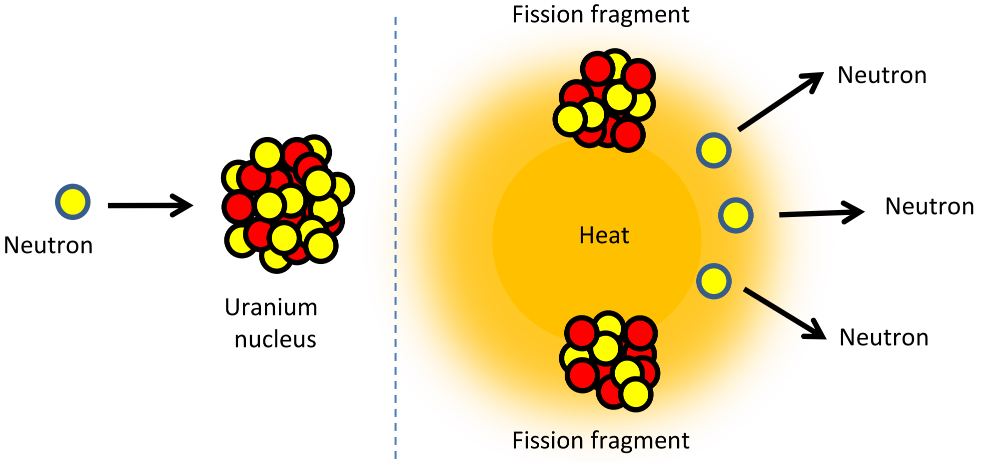
Fission is the **splitting of a large nucleus**. In fission, a **large nucleus splits into two nuclei of smaller mass with the release of several neutrons and energy**.

Spontaneous fission: This occurs at random with a fixed half-life.
An example of a reaction is

$$^{256}_{100}\mathrm{Fm} \rightarrow {}^{140}_{54}\mathrm{Xe} + {}^{112}_{46}\mathrm{Pd} + 4\,{}^{1}_{0}\mathrm{n} + \text{energy}$$

Stimulated fission: The nucleus is bombarded by an incident neutron causing it to undergo fission.
An example of a reaction is

$$^{235}_{92}\mathrm{U} + {}^{1}_{0}\mathrm{n} \rightarrow {}^{138}_{55}\mathrm{Cs} + {}^{92}_{39}\mathrm{Rb} + 2\,{}^{1}_{0}\mathrm{n} + \text{energy}$$



Fusion:

Fusion is the **joining of nuclei**. In fusion, **two nuclei combine to form a nucleus of larger mass number**. The nuclei that fuse together are usually very small.
An example of this reaction is: $^{2}_{1}H + ^{3}_{1}H \rightarrow ^{4}_{2}He + ^{1}_{0}n$ + energy

A large amount of energy is released and no radioactive waste is produced in the reaction.

If the mass before the fusion reaction and after the fusion reaction are accurately measured, there is always some missing mass.

During fission and fusion reactions, **the total mass of the individual particles before and after the reaction is not the same.** The mass of the products is always less than the mass of the starting materials. The missing mass is called the **lost mass**.

This lost mass is converted into energy according to Einstein's equation: **$E = mc^2$**
The products of fission and fusion acquire large amounts of kinetic energy.

Q

A uranium isotope decays as shown.

$$^{235}_{92}U + ^{1}_{0}n \rightarrow ^{138}_{55}Cs + ^{92}_{39}Rb + 2^{1}_{0}n$$

Calculate the (a) total mass before the reaction
(b) total mass after the reaction
(c) the lost mass
(d) energy released
(e) energy released in 1 kg of uranium.

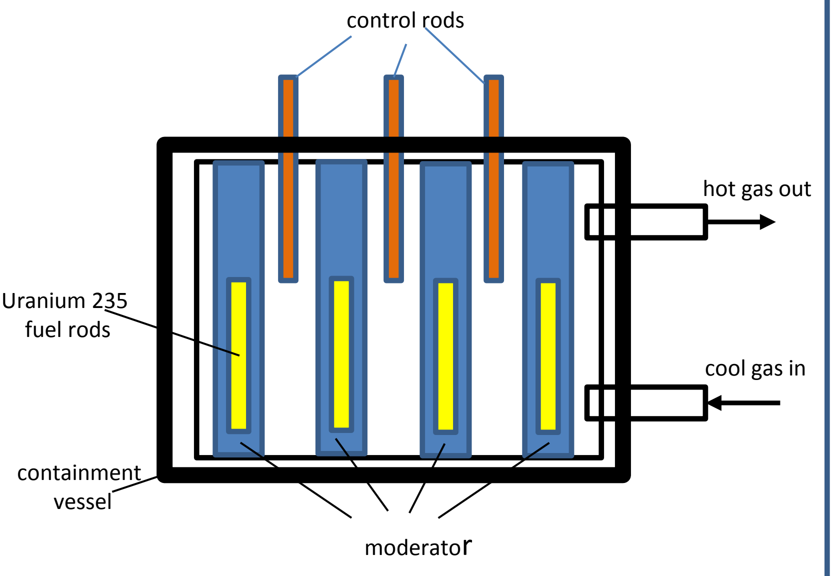
(Never round-up your calculations)

symbol	mass (kg)
$^{235}_{92}U$	3.9014×10^{-25}
$^{138}_{55}Cs$	2.2895×10^{-25}
$^{92}_{39}Rb$	1.5925×10^{-25}
$^{1}_{0}n$	1.6750×10^{-27}

Answer: 3.91815×10^{-25} kg, 3.9155×10^{-25} kg, 2.65×10^{-28} kg, 2.38×10^{-11} J, 6.11×10^{13} J

Fission reactors:

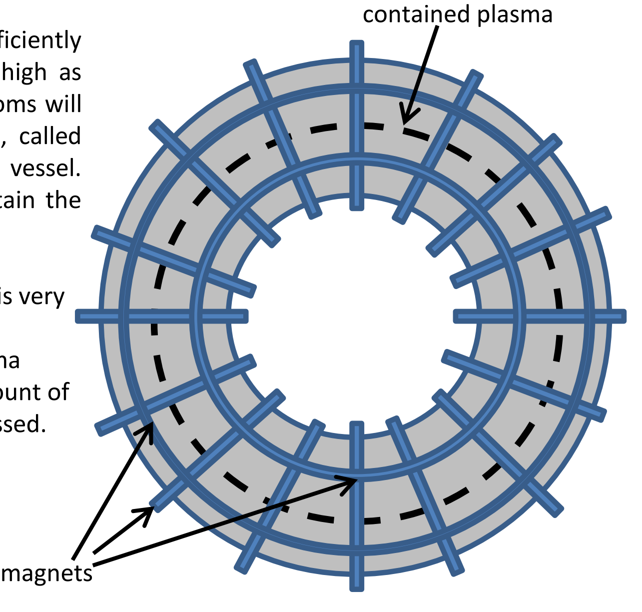
- **Containment vessel:** This absorbs the gamma radiation produced and also withstand the heat and the pressure.
- **Coolant:** This takes away the heat from the core.
- **Moderator:** This slows down the neutrons.
- **Control rods:** This controls the rate of the reaction.
- **Fuel rods:** This is the nuclear fuel in the reactor.



Fusion reactors:

For fusion to take place, the atoms must have sufficiently **high kinetic energy**. This means temperatures, as high as 10^7 ^{0}C, are required for fusion to take place. The atoms will lose electrons and become positively charged ions, called plasma. The plasma is too hot to be contained in a vessel. This means strong magnetic fields are used to contain the plasma.

The power required to ignite and sustain the plasma is very high. There are complex issues, such as, building the magnetic field cage, extracting energy from the plasma (during the reaction) and achieving a sustainable amount of delivery output power. All of these need to be addressed.



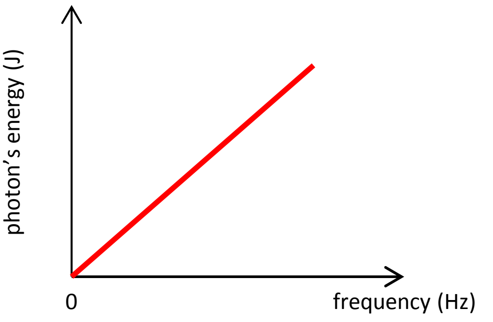
Wave particle duality

Max Planck first showed that energy was dependent on wavelength or frequency. Einstein added that light is **described as discrete light particles**, called **photons** (or quanta). Light is **quantised**.

The energy of each quantum of light, or photon, is $\mathbf{E = hf}$

where E is in joules, h – Planck's constant (6.63×10^{-34} Js) and f – frequency (Hz).

The greater the photon's frequency, the greater its energy.



Q Calculate the energy of a photon of wavelength 100 nm.

Answer: 1.989×10^{-18} J

Photoelectric effect

In the photoelectric effect, electrons are 'knocked off' a metal surface by photons. The liberated electrons can form a photoelectric current. This is true if the **frequency of the incident photons is greater than the metal's threshold frequency**.

All metals have a **work function**. This is the **minimum energy** needed to knock an electron off a particular metal surface.

The work function, $\mathbf{W = hf_0}$ where f_0 is the threshold frequency.

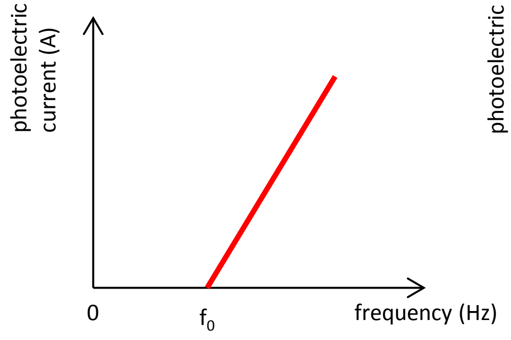
The work function and threshold frequency are different for different metals. So…

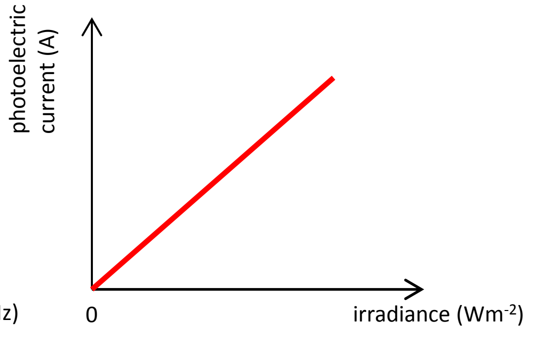
- If the photon's frequency is less than the metal's threshold frequency (i.e. $\mathbf{f_{photon} < f_0}$), then there is no photoelectric effect. Even if you increase the number of photons, with frequencies less than f_0, it will not make any difference.
- If $\mathbf{f_{photon} = f_0}$, then the electron will be knocked off the metal plate and the electron will have zero kinetic energy.
- If $\mathbf{f_{photon} > f_0}$, then the electron will be knocked off and the extra energy is the electron's kinetic energy.
- When the photon's frequency is above f_0, there is a photoelectric current. The bigger the irradiance, the bigger the photoelectric current.

Just to recap again,

when $\mathbf{f_{photon} < f_0}$, the photoelectric does not take place.
when $\mathbf{f_{photon} = f_0}$, the electron will be knocked off with $\mathbf{E_k = 0\ J}$.
when $\mathbf{f_{photon} > f_0}$, the electron will be knocked off with $\mathbf{E_k = hf - hf_0}$ $\mathbf{(E_k = hf - W)}$

The graph shows that photoelectric current exists when $\mathbf{f_{photon} > f_0}$. The graph on the right shows that the photoelectric current is directly proportional to irradiance when $\mathbf{f_{photon} > f_0}$.





Remember: A bright light source produces more photons per second causing more electrons to be ejected, but only if the frequency is greater than the metal's threshold frequency.

The irradiance of a beam of photons I, is **I = Nhf**, where N is the number of photons incident on a square metre surface every second.

Q

The work function of a metal is 6.4×10^{-19} J.

(a) Calculate: (i) the metal's threshold frequency

(ii) the kinetic energy of electrons emitted when radiation of frequency 2.6×10^{15} Hz is incident on the metal surface

(b) State whether the photoelectric effect will occur with light of wavelength 400 nm.

Answer: (a)(i) 9.65×10^{14} Hz (ii) 1.08×10^{-18}J (b) no

If the ejected electrons are captured and stopped by an electric field, their velocity can be found from $\mathbf{qV = \frac{1}{2} mv^2}$. The term, V, is known as the **stopping potential**.

Wave-particle duality

Interference experiments suggest a wave nature of light, but the photoelectric effect suggests a particle nature of light. Both natures exist, and this is called **wave-particle duality**.

A beam of radiation can be regarded as a stream of individual energy bundles called photons, each having an energy dependent on the frequency of the radiation.

Light **can behave as a wave or as a particle**.

Interference and diffraction.

Recap on waves
Waves is a **movement of energy** and are created by **vibrating sources**.

You should be able to identify parts of the wave; define what is meant by amplitude, period, frequency and wavelength.

The energy (E_p and E_k) of a wave depends on its **amplitude**.

The wave equation is given as **$v = f\lambda$.**

The period of the wave is worked out from $p = \frac{1}{f}$

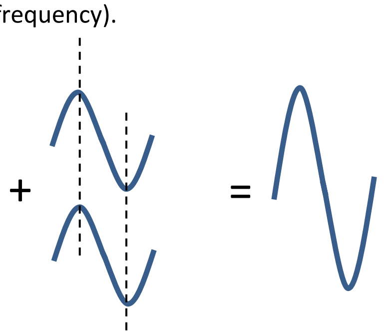
All radiations in the electromagnetic spectrum travel at 3×10^8 ms^{-1}. In the spectrum, gamma rays have the shortest wavelength (highest frequency) and radio waves have the longest wavelength (smallest frequency). Blue light has wavelength of 400nm; red light – 650 nm.

Sound waves travel at 340 ms^{-1}in air.

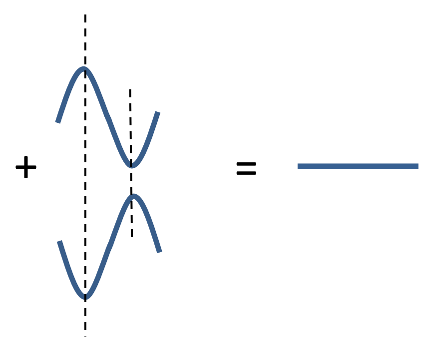
Reflection, refraction, diffraction and **interference** are characteristic behaviours of all types of waves.

Interference
If sound waves (or some other type of wave) were produced by two sources and have the same wavelength, frequency and speed and are in-phase, then the two sources are **coherent**.

Constructive interference: This occurs when two waves meet up **in-phase (peak-to-peak and trough-to-trough)** and have the same amplitude and produce a wave of double the amplitude (with the same wavelength and frequency).



Destructive interference: This occurs when two waves meet **up out-of-phase (peak-to-trough and trough-to-peak)** and have the same amplitude and cancel each other out.



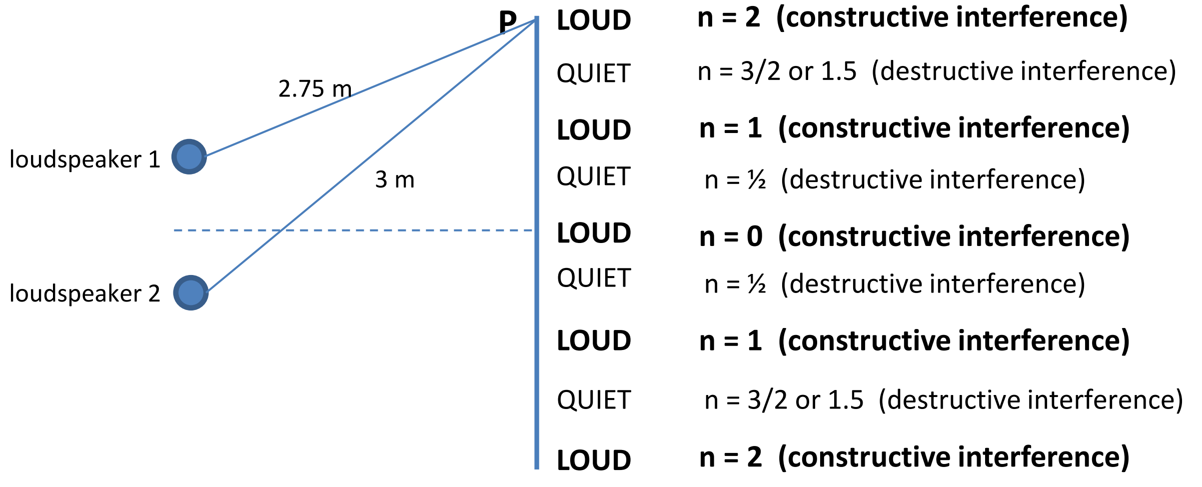
Interference is the **test for wave motion**. In order to prove that any form of energy travels as a wave an interference pattern must be shown. This was done for light by Young with the double slit experiment and proved that light is a wave motion.

When two wave trains from coherent sources overlap, an interference pattern is produced. Constructive interference takes place when the two waves (light or sound) are in-phase. The general condition for a maximum in the interference pattern is:

path difference = n λ, **n = 0, 1, 2, 3, ...**

The general condition for a minimum in the interference pattern is:

path difference = ½ λ, 3λ/2, 5λ/2 ...



An example of using the above formula:
(a) Calculate the path difference at point **P**.

(b) Calculate the wavelength of the sound wave emitted from both loudspeakers.

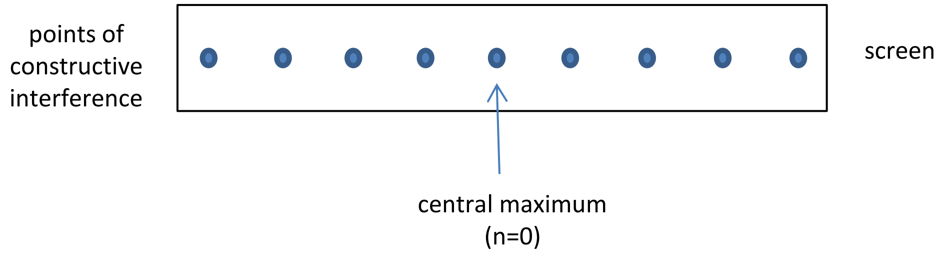
(a) path difference = 3 – 2.75 = 0.25 m

(b) path difference = n λ

2 λ = 0.25

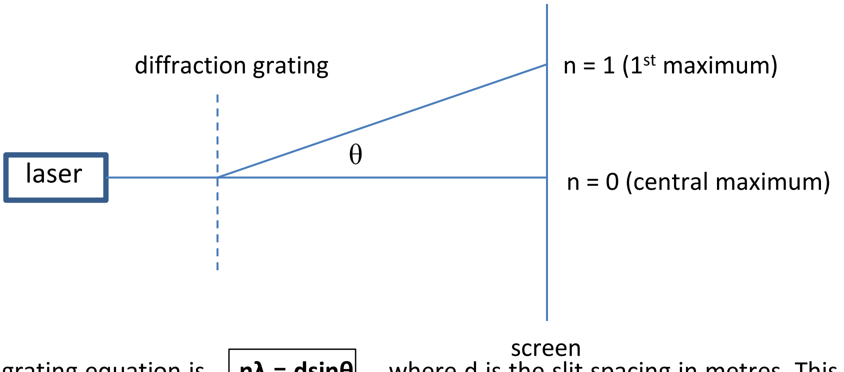
λ = 0.125 m

A diffraction grating consists of a small piece of glass into which many thousands of tiny parallel lines have been etched. After light goes through the parallel lines, an interference pattern is produced.



A laser produces a monochromatic beam of light. It can be used with a diffraction grating to produce the interference pattern for light. If the laser is red light, the lines of constructive interference are red.

Diffraction grating equation:
From the set-up shown:



the diffraction grating equation is **$n\lambda = d\sin\theta$**, where d is the slit spacing in metres. This is the same equation for Young's slits.

If you were told the number of lines per mm e.g. 100 lines per mm, then the slit spacing, d, is worked out as

100 lines per mm = 100 x 1000 lines per mm = 100000 lines per m

$$d = \frac{1}{100000}$$

$d = 1 \times 10^{-5}$ m

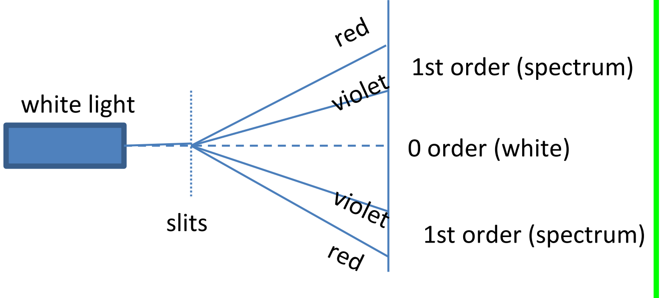
Longer wavelengths diffract more than shorter wavelengths. Since the wavelength of red light is greater than the wavelength of blue light, then red light diffracts more than blue light. As a result, the points of constructive interference for red light are more further apart than blue light.

The 'dots' of constructive interference can be brought together by: moving the screen towards the grating, replacing a laser with smaller wavelength and a diffraction grating with a larger slit spacing.

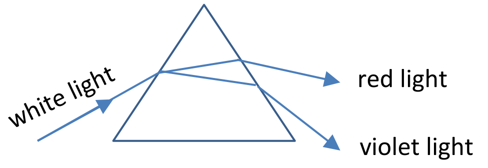
The wavelength of monochromatic light (e.g. from a sodium lamp or red laser) can be measured using a diffraction grating of known spacing on a spectrometer. The angle for the first line of constructive interference on each side of the centre is measured. θ is equal to the average of these two angles. Then λ can be found using **$n\lambda = d\sin\theta$.**

Q Monochromatic light is used with a diffraction grating with 600 lines per mm, to produce an interference pattern. The first order line of constructive interference is at 17.8^0.
Show that the wavelength of light is 510 nm.

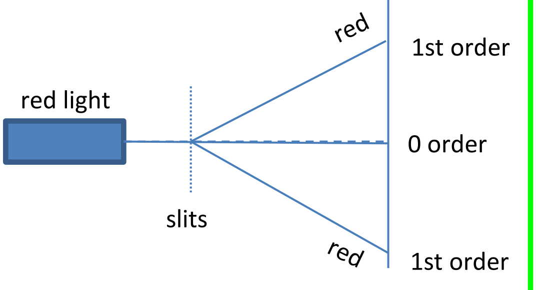
White light:
A diffraction grating would produce: (i) a white central maximum, (ii) several coloured spectra on either side of the central maximum and (iii) red light diffracts more than violet light since red light has the longest wavelength.



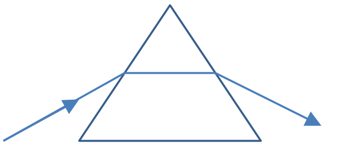
A prism produces one spectrum only, by refraction, and violet light refracts more than red light.



Monochromatic light:
A diffraction grating would produce points of constructive interference of one colour only.

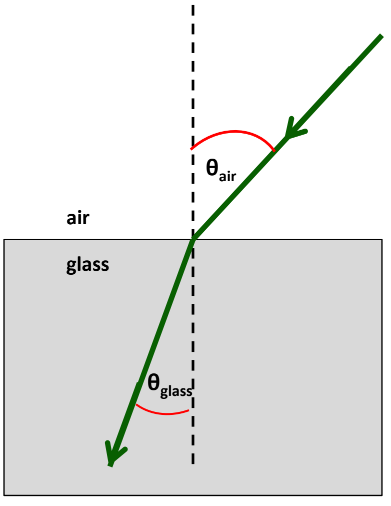


A prism refracts light of the same colour.

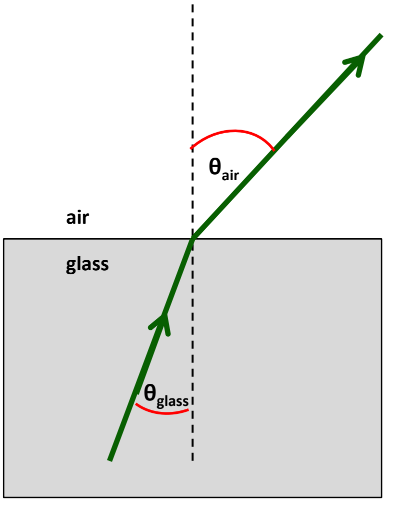


Refraction of light.

Refraction occurs when **light changes its velocity as it enters from one transparent medium to another** (as shown below).



When light travels from a less dense (air) to a more dense (glass) material, it slows down and refracts towards the normal.



When light travels from a more dense (glass) to a less dense (air) material, it speeds up and refracts away from the normal.

The amount light refracts depends on the type of materials used. Each material has its **own refractive index**. The refractive index of a material, with light coming from a vacuum (not air) is known as the **absolute refractive index** of that material.

The ratio of $\sin\theta_{air}$ and $\sin\theta_{medium}$ defines the refractive index of the glass, n. The refractive index has no units.

In practice, we can use:

$$n = \frac{\sin\theta_{air}}{\sin\theta_{medium}}$$

but the formula sheet has $n = \frac{\sin\theta_1}{\sin\theta_2}$ (This is Snell's Law)

When calculating the refractive index, of a material, quote it to three significant figures. (e.g. water: 1.33; air: 1.00)

Q Glass has a refractive index of 1.40. Calculate the incident angle, in air, if the angle of refraction in glass is 35^0.

Answer: 53.4^0

Refractive index and velocity

When a wave passes from one medium to another, there is a change in wave speed.
The ratio of wave speeds can be used to work out the refractive index of a material.
We use: $n = \frac{v_1}{v_2}$

Refractive index and wavelength

When a wave passes from one medium to another, there is a change in wavelength.
The ratio of wavelengths can be used to work out the refractive index of a material.
We use: $n = \frac{\lambda_1}{\lambda_2}$

Refractive index and frequency

The refractive index depends on the frequency of the incident light (i.e. red light and blue light have different frequencies and so have different refractive indices.) Therefore, a beam of white light is split into a spectrum when passing through a prism. The refractive index of a material may vary depending on the colour/frequency of light in use. Remember: during refraction of white light - the higher frequency blue light refracts more than the lower frequency red light.

The frequency of light does not change when it refracts from one medium to another. For example, the frequency of red light is the same in water and in air.

Q

A wave of frequency 6×10^{14} Hz enters a block at an angle of 50^0, and the angle in the block is 36^0.
Calculate: (a) the speed
(b) the wavelength of the light in the block.

Answers: (a) 2.3 x 10^8 ms^{-1} (b) 3.8 x 10^{-7} m

Remember: Snell's law simplifies to:

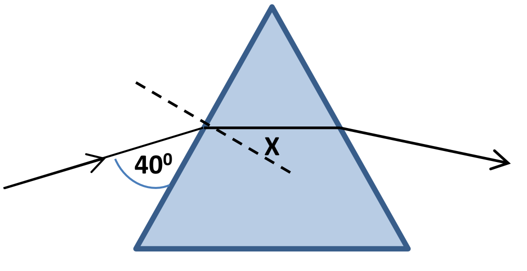
$$n = \frac{\sin\theta_1}{\sin\theta_2} = \frac{v_1}{v_2} = \frac{\lambda_1}{\lambda_2}$$

Q

Red light of wavelength 6.5 x 10^{-7}m refracts from air into glass as shown. The refractive index of the glass (for red light) is 1.52.

(a) Calculate (i) angle X
(ii) the wavelength of the light in the glass.

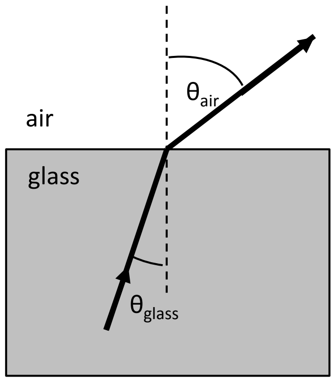
(b) When blue light enters the prism, at the same angle of incidence, angle X is found to be 29.6^0. Calculate the refractive index of the glass for blue light.



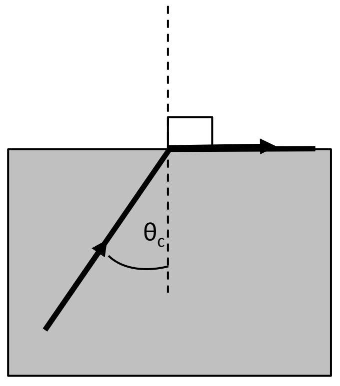
Answers: (a) 30.3^0 4.28 x 10^{-7} m (b) 1.55

Critical angle and total internal reflection.

- Total internal reflection occurs when the angle of incidence in the ‘denser’ medium (e.g. water, glass) is greater than the critical angle, θ_C.
- The critical angle is reached when the angle of refraction is 90^0.
- The diagrams below show what happens as the angle θ in the glass is increased.



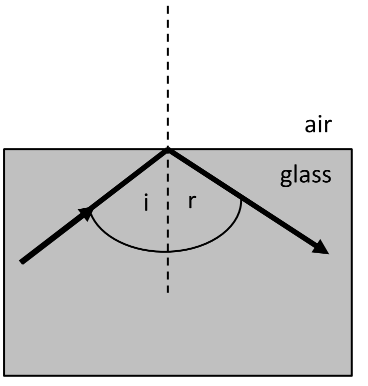
When θ_{glass} < critical angle, then the ray of light will refract from glass into air.



When $\theta_{air} = 90^0$, then the angle of incidence is known as the **critical angle**.

The light’s critical angle is related to the refractive index, n by

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



When θ_{glass} > critical angle, then the ray of light will reflect back into the glass. Here, the **angle of incidence = angle of reflection**. This is the principle behind total internal reflection in an optic fibre.

Q Calculate the critical angle for each of the following: (a) glass with n = 1.60 (b) diamond with n = 2.4.

Answer: (a) 38.7^0 (b) 24.6^0

Q A glass block has a refractive index of 1.50. Complete the ray path through the block. You should justify your answer with calculations.

Answer: light should reflect back into the glass and refract from the normal (other side of glass block) at 45^0.

Irradiance.

Irradiance is the **power incident per unit surface area**.
Irradiance is measured in **Wm^{-2}**.

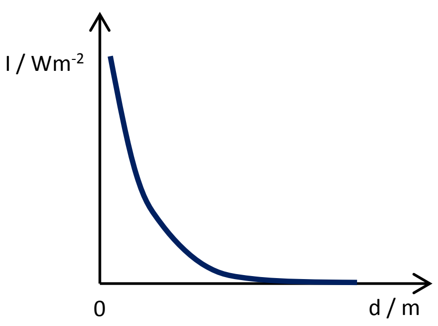
The equation for irradiance is given as $I = \frac{P}{A}$

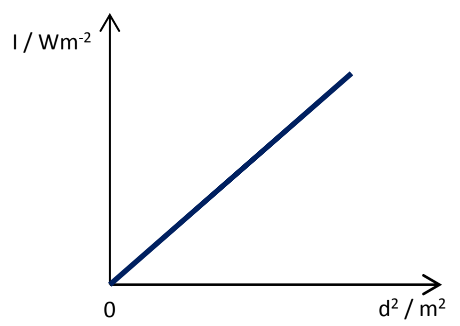
Irradiance decreases as you **move further away** from a point source. The relationship between irradiance and distance can be investigated using a metre-stick and photo-diode (or light sensor) connected to a computer.
Remember*: a point source emits rays equally in all directions.*

Irradiance follows the **inverse square law**: $I = \frac{k}{d^2}$ and $I_1 {d_1}^2 = I_2 {d_2}^2$

If a point source radiates uniformly in all directions and there is no absorption, then the irradiance decreases in proportion to the square of the distance from the object, since the power is constant and it is spread over an area that increases with the square of the distance.

The graphs are true for point sources. The Sun is an example of a point source as it emits radiation in all directions. A laser is **not** a point source since it gives a parallel beam of light.





Q A point source of light produces an irradiance of 5 Wm^{-2} at a distance of 50 cm.
Calculate the irradiance at 2.5 m.

Answer: 0.2 Wm^{-2}

Q A 100 W lamp illuminates a screen whose area is 4 m^2. Calculate the irradiance on the screen.

Answer: 25 Wm^{-2}

Atomic spectra.

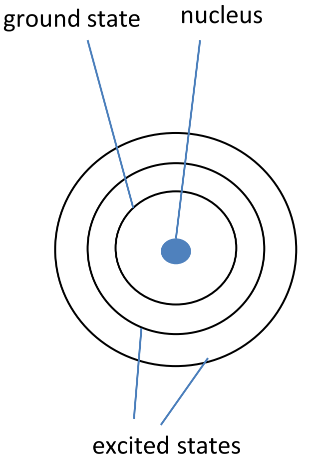
In an atom, the electrons orbit the nucleus. Only certain orbits are allowed and this means that the energy of the electron can only have certain allowed energy level.

In the smallest orbit, nearest the nucleus, the electron has the least energy and is said to be in the **ground state**. The ground level energy is a measure of the energy needed to unbind the electron from the atom.

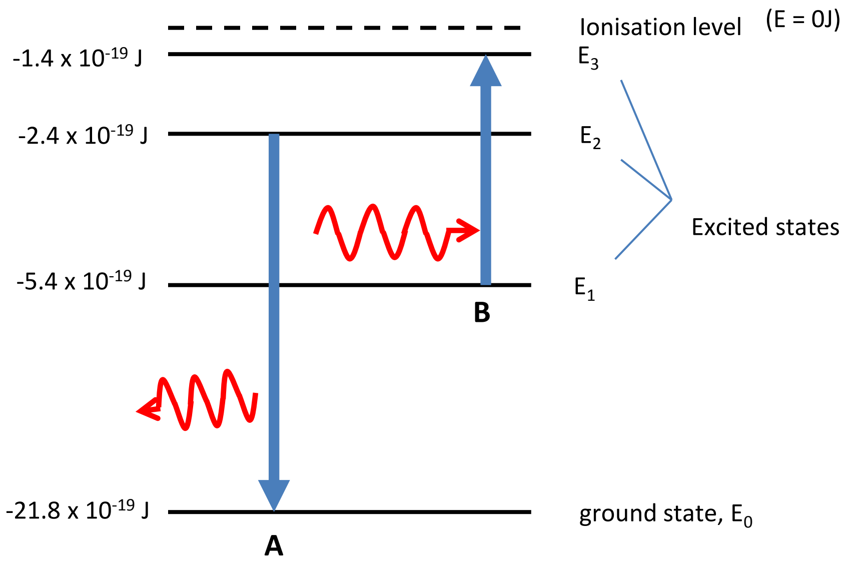
When an electron gains energy, from any outside source, it may be able to move into a higher energy level and is said to be **excited**.

The electron can only absorb energy if it is the right amount to take the electron to another allowed energy level.

If the electron gains enough energy, then it can reach the top level, which is equivalent to leaving the atom altogether. This is called the **ionisation level**.



An example of energy levels is shown:



The frequency of the absorbed or emitted photon can be found from:

$$f = \frac{\Delta E}{h}$$

Note – the negative sign can be ignored if you wish, as long as you subtract the size of the two numbers to get the change in energy.

- The ionisation level corresponds to an electron having zero energy. This means the electron is free from the atom (but it is not moving away from it, otherwise the electron would have positive energy). From the diagram, there are six possible (upward and downward) transitions (excluding the ionisation level).

- When an electron follows transition A (i.e. dropping from E_2 to E_0), a photon is emitted with energy $\mathbf{\Delta E = (E_2 - E_0)}$. The frequency of that photon is worked from the formula: $\Delta E = hf$.

- When an electron follows transition B (i.e. jumping from E_1 to E_3), a photon is absorbed with energy $\mathbf{\Delta E = (E_3 - E_1)}$. The frequency of that absorbed photon is worked from the formula: $\Delta E = hf$.

Remember:

- An emission line spectrum is produced when electrons move from an excited energy level, E_2, to a lower energy level, E_1. The energy of the emitted photon is $\boxed{E_2 - E_1 = hf}$. If you are observing from a spectroscope, you would see coloured lines on a black background.

- An absorption line spectrum is produced when electrons in energy level E_1 absorbs radiation of energy, hf, and moves to excited energy level E_2. This means the energy, E_2, is equal to $E_2 = E_1 + hf$. If you are observing from a spectroscope, you would see dark lines on a continuous spectrum background.

Remember:

The spectrum from a light source can be displayed using a prism or a diffraction grating.

Emission spectra are produced when light is given out, by electrons moving down in energy level (i.e. from an excited energy level to a lower energy level). The emission line spectrum **will appear brighter if more electrons make that particular transition**.

Absorption spectra are produced when the electrons absorb energy and move up in energy level (i.e. from lower energy level and excited to higher energy level). The absorption spectrum of an element consists of black lines on a continuous spectrum, in exactly the same positions as the bright lines of the emission spectrum.

Continuous spectra are produced by solid, liquid and high pressure gases.

Line spectra are produced by low pressure gases.

An electron will only absorb a photon where the photon's energy is an **exact match for the difference in energy levels**.

Fraunhofer lines

Absorption lines occur in the Sun's spectrum because gases in the outer part of the Sun absorb light of particular frequencies. The white light is produced in the centre of the Sun but after passing through the gas layer, certain frequencies are missing. This gives dark lines which correspond to the frequencies which have been absorbed by the gases in the Sun's atmosphere. This allows elements which make up the Sun to be determined. The dark lines are called **Fraunhofer lines**.

Q

The energy levels for hydrogen are shown in the last page.

(a) Calculate the highest frequency line produced.

(b) Will light of wavelength 663 nm be absorbed? Justify your answer.

Answers: (a) 2.93 x 10^{15} Hz (b) yes, from E_2 to E_3.