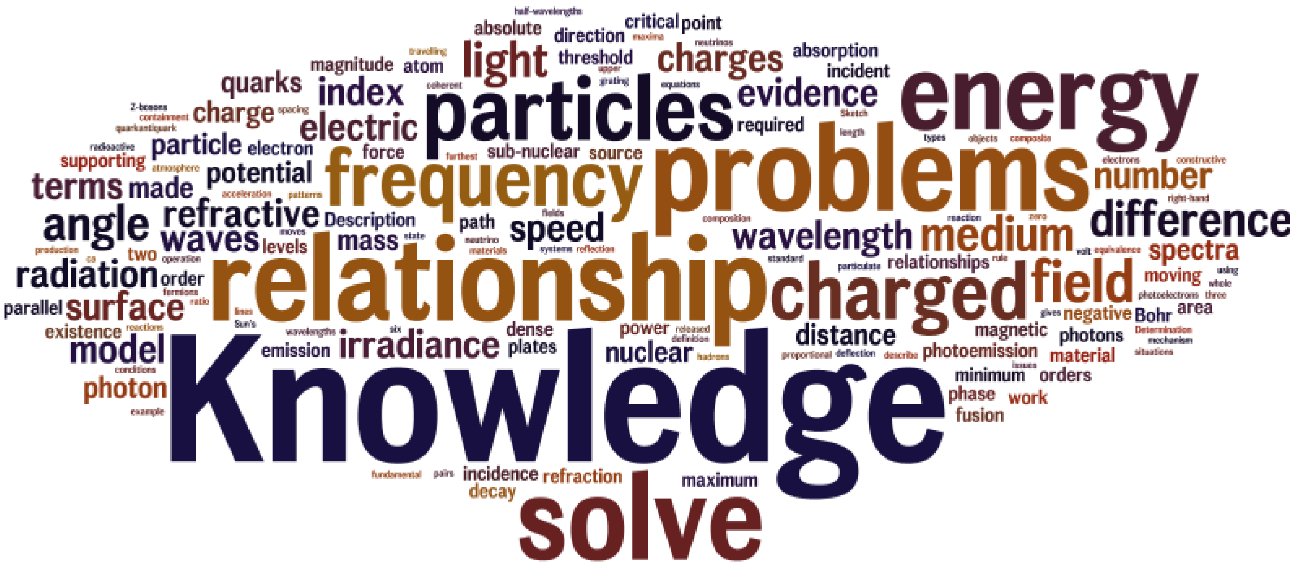
Higher Physics

Particles and Waves

Summary Notes



- The Standard Model
- Forces on charged particles
- Nuclear reactions
- Wave particle duality
- Interference and diffraction
- Refraction of light
- Spectra

The Standard Model

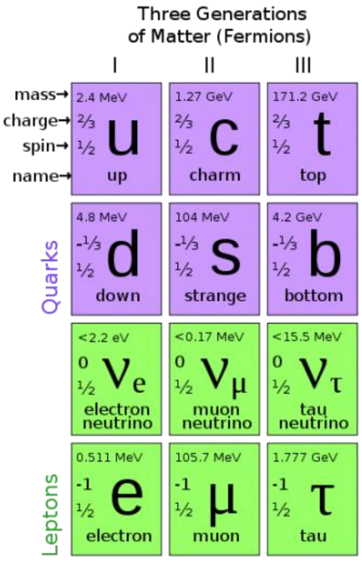
Physics involves studying matter at a range of scales; from the distance of the furthest known celestial objects (10^{26} m) to the diameter of an electron (10^{-18} m). The number of powers of 10 involved in describing the size of something is referred to as **orders of magnitude**. For example, the diameter of a hydrogen atom ($1{\cdot}2 \times 10^{-10}$ m) is five orders of magnitude greater than the diameter of its nucleus ($1{\cdot}75 \times 10^{-15}$ m).

Our current understanding of the fundamental nature of matter is described in what is known as the **Standard Model**.

Fundamental matter particles are divided into two groups; leptons and quarks.

There are six **leptons**; the electron, muon and tau, each paired with an associated neutrino (electron neutrino, muon neutrino and tau neutrino).

There are six types of **quark** which are arranged in three 'generations' (up and down, strange and charmed, top and bottom). Each generation of quarks is associated with a generation of leptons.



Three Generations of Matter (Fermions)

		I	II	III
Quarks	mass→ charge→ spin→ name→	2.4 MeV ⅔ ½ u up	1.27 GeV ⅔ ½ c charm	171.2 GeV ⅔ ½ t top
		4.8 MeV -⅓ ½ d down	104 MeV -⅓ ½ s strange	4.2 GeV -⅓ ½ b bottom
Leptons		<2.2 eV 0 ½ ν_e electron neutrino	<0.17 MeV 0 ½ ν_μ muon neutrino	<15.5 MeV 0 ½ ν_τ tau neutrino
		0.511 MeV -1 ½ e electron	105.7 MeV -1 ½ μ muon	1.777 GeV -1 ½ τ tau

Every fundamental particle also has an equivalent **antimatter** particle. Antimatter particles have the same mass, but opposite charge to their corresponding matter particle (e.g. the antiparticle of the electron is called a positron and has the same mass as an electron, but a charge of +1).

Quarks never exist alone but combine to form **hadrons**. These combinations can only exist where the overall charge is a whole number.

Mesons are formed when two quarks combine (e.g. a π^+ meson is composed of an up quark and an antidown quark, $u\bar{d}$).

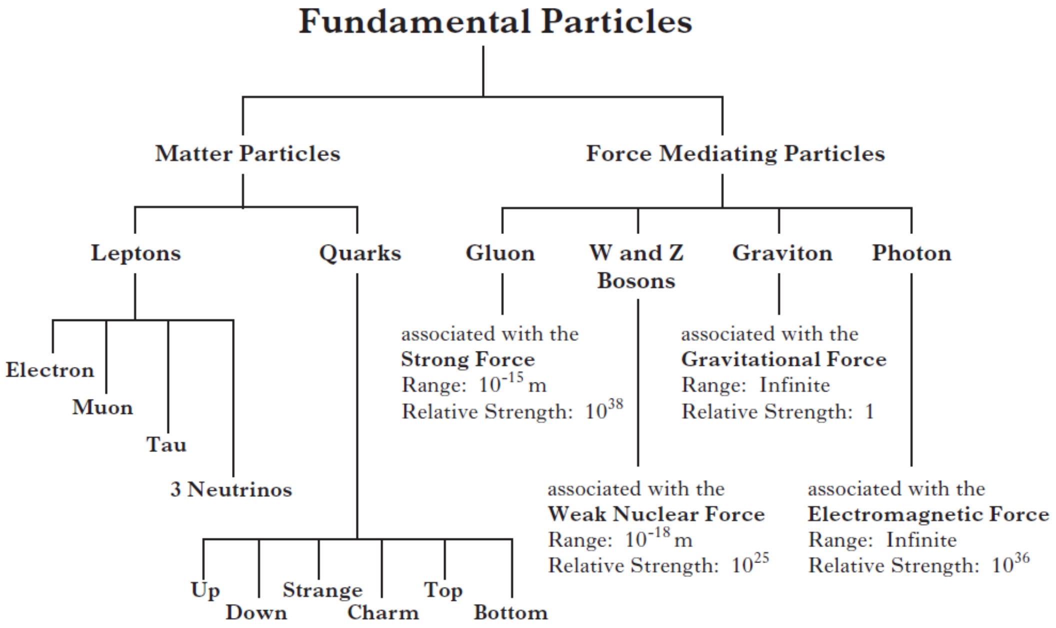
Baryons are formed when three quarks combine (e.g. protons are composed of two up and one down quark and neutrons are composed of one up and two down quarks).

There are four **fundamental forces** in the Universe (strong nuclear, weak nuclear, electromagnetic and gravitational). Each of these forces has a force-mediating particle (or particles) associated with it; known as gauge bosons. When matter particles interact they exchange gauge bosons and it is this exchange that leads to them experiencing a force.

- The **gravitational** force is the force of attraction between objects with mass. It is by far the weakest forces, but its range is infinite. The force mediating particle for the gravitational force is the graviton.
  (Note: the graviton has yet to be detected.)
- The **electromagnetic** force affects particles with charge and also acts over an infinite range. The force mediating particle for the electromagnetic force is the photon. Photons have no mass or charge.

- The **weak nuclear** force is associated with beta decay and only acts over distances on a nuclear scale. The force mediating particles for the weak nuclear force are the W and Z bosons.
- The **strong nuclear** force also acts only on a nuclear scale and is the force that holds quarks together to form particles such as protons and neutrons. The residual effect of the strong force holds these particles together to form nuclei. The force mediating particles for the strong nuclear force is the gluon.

The fundamental particles and forces can be summarised in the following diagram.



Note: Strictly speaking, the graviton is not part of the Standard Model, as there is no evidence (yet) of its existence.

The Standard Model also includes the Higgs boson. A particle theorised for many years to be involved in attributing the property of mass to other particles, but not experimentally identified until 2012.

There is a further classification of particles that relates to a property called spin. The matter particles are classified as **fermions** and include leptons and quarks as well as hadrons, whereas the force-mediating particles and mesons are classified as **bosons**.

Much of the evidence of the existence of fundamental particles and forces has been obtained from experiments involving particle accelerators and detectors (e.g. the Large Hadron Collider at CERN).

The first evidence for the neutrino came from the study of beta decay: it was noticed that during beta decay that the total and energy of the observed particles before and after decay did not match expectations. This led to the conclusion that another particle was involved in the decay; the neutrino.

Forces on charged particles

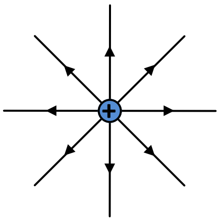
Electric charge Q is a physical property of matter and is measured in coulombs (C).

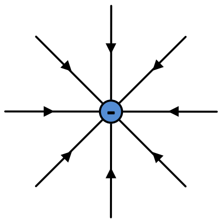
The charge on a proton is $+1{\cdot}6 \times 10^{-19}$ C and the charge on an electron is $-1{\cdot}6 \times 10^{-19}$ C (i.e. the same size, but opposite sign). Neutrons have no charge.

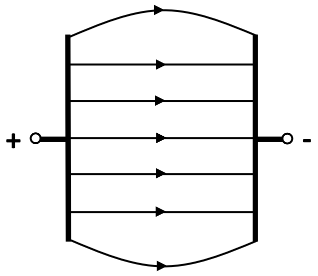
Opposite charges attract and similar charges repel. This interaction between charges can be explained by using the concept of an **electric field**.

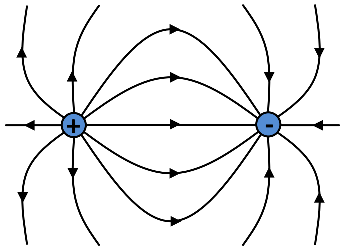
An electric field is a region of space around a charge where another charge will experience a force.

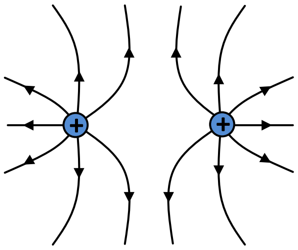
Electric fields around charges can be represented in a diagram showing field lines. By convention, the arrows on the field lines show the direction in which a positive charge experiences the force and the closer together the field lines, the stronger the force.











When a charge is moved through an electric field work W is done to the charge.

$$W = QV$$

When a charge is free to move in an electric field the work done by the field on the charge increases its kinetic energy.

Example:

An electron is accelerated from rest by a voltage of 2500 V between two metal plates. Calculate the speed of the electron as it reaches the positive plate.

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

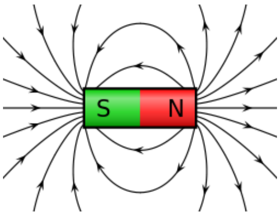
$$1{\cdot}6 \times 10^{-19} \times 2500 = \tfrac{1}{2} \times 9{\cdot}11 \times 10^{-31} \times v^2$$

$$v = 3{\cdot}0 \times 10^{7} \text{ m s}^{-1}$$

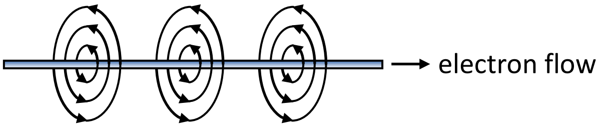
Magnets have two poles, north and south. Opposite poles attract and similar poles repel. This interaction between poles can be explained by using the concept of a **magnetic field**.

A magnetic field is a region of space around a pole where another pole will experience a force.

Magnetic fields around poles can be represented in a diagram showing field lines. By convention, the arrows on the field lines show the direction in which a north pole experiences the force and the closer together the field lines, the stronger the force

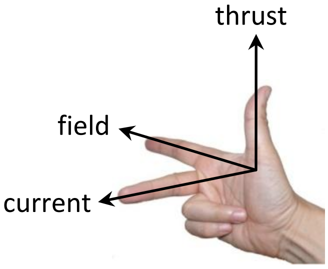


A magnetic field also exists round a current-carrying conductor.



When a current carrying conductor passes through a magnetic field it experiences a force due to the interaction between the magnetic field produced the conductor itself and the magnetic field it is passing through. The direction of this force is perpendicular to the direction of the current and perpendicular to the direction of the magnetic field.

The direction of this force can be determined by using Fleming's right hand rule.



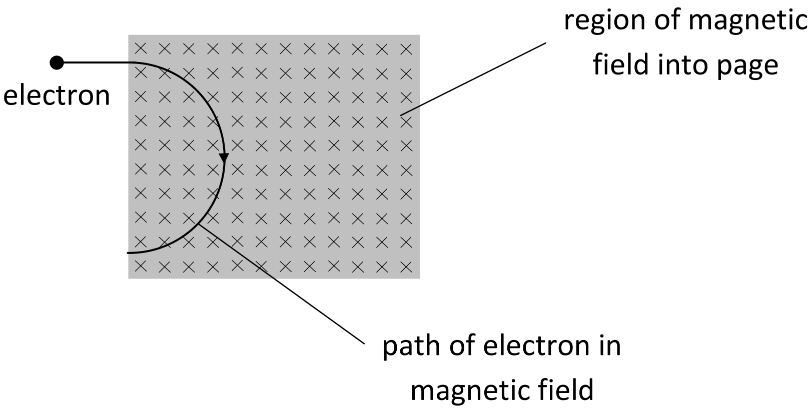
First finger – **F**ield (north to south)

se**C**ond finger – **C**urrent (electron flow)

Thumb - **Th**rust

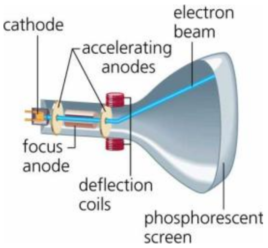
When applying this rule to a single charge moving through magnetic field this can result in the charge following a curved path.

e.g.



In **particle accelerators** charged particles are accelerated by electric fields and (if required) magnetic fields are used to change their path. The collisions of these charged particles with static targets or other charged particles can then be used to study the nature of matter and/or the fundamental forces.

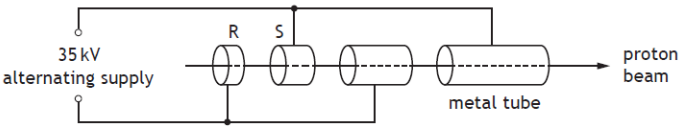
Electrostatic accelerators (e.g. cathode ray tube)



Charged particles are accelerated by the electric field produced by a large potential difference between two metal plates.

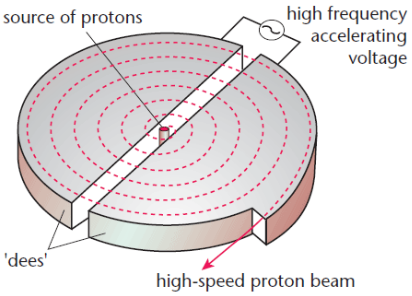
The path of the charged particles is changed by the magnetic field produced by deflection coils

Linear accelerators



Charged particles are accelerated by the electric field produced by a large potential difference between metal tubes. The process is repeated by alternating the voltage between increasing lengths of tube.

Cyclotrons



Charged particles are accelerated by the electric field produced by a large potential difference between two metal ‘dees’.

When in the dees the path of the charged particles is changed by a magnetic field.

The potential difference between the dees is alternated so that the charged particles are repeatedly accelerated as they cross the gap between the dees.

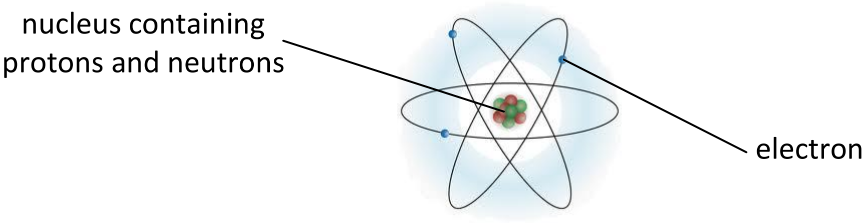
Synchrotrons

Charged particles are repeatedly accelerated as they pass through an electric field. Since the time taken for particles to complete a loop of the synchrotron decreases as their speed increases, the accelerating pulses must be synchronised.

As they go round the loop, the path of the charged particles is changed by magnetic fields.

Nuclear Reactions

The atom is the basic unit of matter. An atom is made up of a central nucleus with orbiting electrons.



The **nucleus** contains positively charged **protons** and uncharged (“neutral”) **neutrons**. Protons and neutrons have virtually identical masses. For convenience, the mass of a proton/neutron is usually given as 1 atomic mass unit (amu).

The **electrons** orbit the nucleus at high speed. Electrons are negatively charged and have much smaller mass than neutrons or protons.

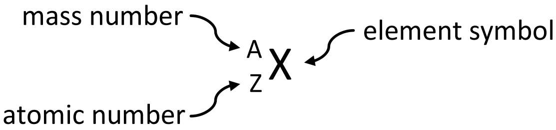
Particle	***Mass* (amu)**	***Charge***	***Symbol***
proton	1	+1	p
neutron	1	0	n
electron	$\frac{1}{1840}$	-1	e

An atom is normally electrically neutral as it has the same number of negative electrons orbiting the nucleus as positive protons in the nucleus. (The addition or removal of an electron from an uncharged atom is known as **ionisation**.)

Atoms of a particular **element** contain the same number of protons.

Isotopes are atoms of the same element with different numbers of neutrons in the nucleus.

A particular isotope can be identified by its mass number A (the total number of protons and neutrons) and atomic number Z (the number of protons).



(e.g. carbon-14, $^{14}_{6}C$, contains 6 protons and 8 neutrons)

Some isotopes are stable and some unstable. The nuclei of unstable isotopes undergo radioactive decay and emit **nuclear radiation**. The three main types of nuclear radiation are alpha, beta and gamma.

Type	Description	Mass (amu)	Speed	Charge
alpha α	helium nucleus	4	~0·1c	+2
beta β	fast moving electron	$\frac{1}{1840}$	~0·9c	-1
gamma γ	electromagnetic radiation	0	c	0

In **alpha decay** the nucleus loses two protons and two neutrons (a helium nucleus). The daughter nucleus is that of a different element.

e.g. $^{241}_{95}\text{Am} \rightarrow\, ^{237}_{93}\text{Np} +\, ^{4}_{2}\alpha$

During **beta decay** a neutron decays into a proton and an electron (and an anti-neutrino). Again, the daughter nucleus is that of a different element.

e.g. $^{90}_{38}\text{Sr} \rightarrow\, ^{90}_{39}\text{Y} +\, ^{0}_{-1}\beta$

In **gamma decay** there is no change in the mass number or atomic number (i.e. the daughter nucleus is the same), but energy is released in the form of electromagnetic radiation.

In a nuclear **fission** reaction, a large nucleus is split into smaller nuclei. This is either **spontaneous**:

e.g. $^{239}_{94}\text{Pu} \rightarrow\, ^{112}_{46}\text{Pd} +\, ^{124}_{48}\text{Cd} + 3\,^{1}_{0}\text{n}$

or, is **induced**, when bombarded by a neutron.

e.g. $^{235}_{92}\text{U} +\, ^{1}_{0}\text{n} \rightarrow\, ^{90}_{37}\text{Rb} +\, ^{143}_{55}\text{Cs} + 3\,^{1}_{0}\text{n}$

When measured accurately, the sum of the masses of the particles produced by the reaction is actually slightly less than the sum of masses of the particles before the reaction. This ‘lost mass’ is turned into energy according to Einstein’s mass-energy equivalence principle:

$$E = mc^2$$

In a nuclear **fusion** reaction, small nuclei are joined together.

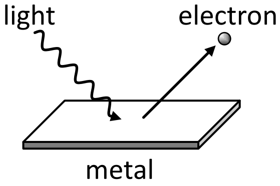
e.g. $^{2}_{1}\text{H} +\, ^{3}_{1}\text{H} \rightarrow\, ^{4}_{2}\text{He} +\, ^{1}_{0}\text{n}$

Again, when measured accurately, the sum of the masses of the particles produced by the reaction is actually slightly less than the sum of masses of the particles before the reaction and this ‘lost mass’ is turned into energy according to Einstein’s mass-energy equivalence principle ($E=mc^2$).

Nuclear fusion requires extremely high temperatures to create the plasma (a state of matter where electrons have sufficient energy to be ionised from their atoms) in which the reactions can take place. This poses difficulties in finding a suitable **coolant**, to extract useful energy from the heat produced by the reaction, and in **containment**, to prevent the high temperatures melting the container the plasma is in.

Wave-Particle Duality

The **photoelectric effect** is evidence of light behaving like a particle.



In the photoelectric effect, electrons (**photoelectrons**) are ejected from the surface of a metal due to the action of light in a process called **photoemission**. Photoemission only takes place when the frequency of the incident light is above a specific frequency, no matter the intensity of the light. This frequency is different for different metals.

In order to explain the photoelectric effect it is necessary to think of light as consisting of particles, known as **photons**.

Each photon has a specific amount of energy (a quantum of energy). The energy of a photon is proportional to its 'frequency' according to the relationship:

$$E = hf$$

where h is Planck's constant

$$h = 6 \cdot 63 \times 10^{-34} \text{ Js}$$

In the photoelectric effect, an electron only absorbs the energy of a single photon, so only when an incident photon has sufficient energy is it able to eject an electron from the metal surface.

Note: If light is considered to be a continuous wave, then even a bright, low-frequency wave would be able to build up enough energy for an electron to be ejected.

The minimum energy required for photoemission to occur from a metal is known as its **work function**, ϕ. The minimum frequency of light that causes photoemission is known as the **threshold frequency**, f_0.

$$\phi = hf_0$$

If the energy of the incident photon is greater than the work function is greater than the work function of the metal than the excess energy supplied the electron with kinetic energy, E_k.

$$E_k = hf - hf_0$$

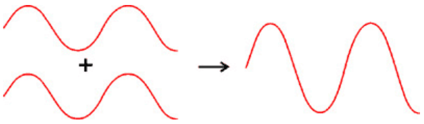
or

$$E = hf - \phi$$

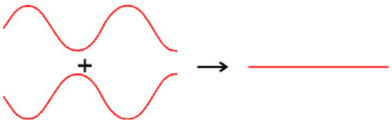
The fact that light behaves like a particle in the photoelectric effect seems to contradict the fact that light behaves like a wave in other situations (e.g. during interference). Our current understanding is that photons (and all elementary particles) exhibit both wave and particle properties. This concept is known as **wave-particle duality**.

Interference

When waves meet they are able to pass through each other and their energies can add up **constructively** or **destructively**.



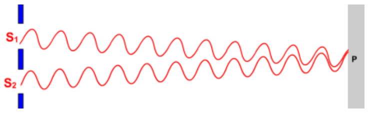
When waves meet **in phase** with each other (i.e. a peak meets a peak and a trough meets a trough) they interfere constructively.



When waves meet **out of phase** with each other (i.e. a peak meets a trough and vice versa) they interfere destructively.

Interference patterns can be observed when **coherent** waves interfere. Coherent waves have the same frequency, wavelength and velocity, i.e. they are either in phase or have a constant phase difference.

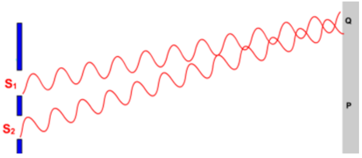
Interference patterns arise from the fact that waves from different coherent sources travel different distances. This difference is known as the **path difference**.



When the path difference between the waves is equal to a whole number of wavelengths the waves will meet in phase and interfere constructively.

path difference $= m\lambda$

where $m = 0, 1, 2 \ldots$



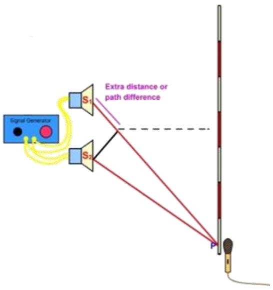
When the path difference between the waves is equal to an odd number of half-wavelengths the waves will meet out of phase and interfere destructively.

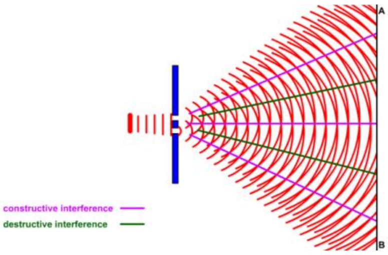
path difference $= \left(m + \frac{1}{2}\right)\lambda$

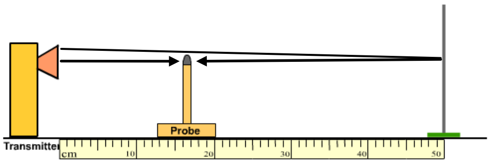
where $m = 0, 1, 2 \ldots$

Interference patterns can occur when:

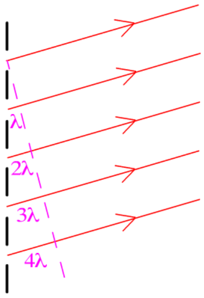
- waves are produced by two separate coherent sources (e.g. sound waves from two loudspeakers connected to the same signal generator)
- waves from a single source pass through a double slit (e.g. microwaves or light waves) – the coherent waves diffracting through the slits interfere with each other
- a direct wave from a source interferes with a reflected wave from a nearby surface (e.g. radio waves in built up areas)







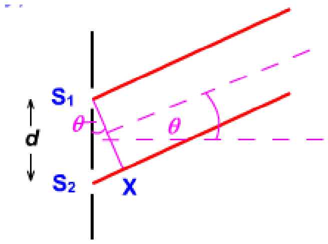
A **diffraction grating** is piece of transparent material with many, parallel, closely spaced lines etched into it. Waves diffracting through each of the slits interfere with waves from neighbouring slits to produce a pattern of distinct points of maximum intensity (maxima), separated by areas of minimum intensity. Maxima are formed when waves from adjacent slits arriving at that point have a path difference equal to a whole number of wavelengths.



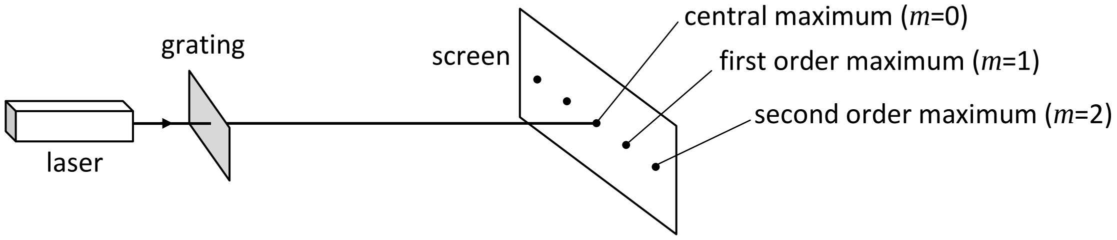
It can be shown that maxima occur when:

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

d = grating spacing
θ = angle to the maximum
m = 0, 1, 2 . . . (order of maximum)
λ = wavelength of the light



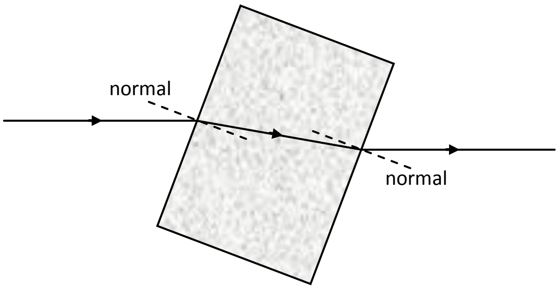
A grating can be used to produce interference patterns with distinct maxima which are widely spaced.



When white light is passed through a grating a series of spectra are observed on either side of a central white maximum. (At the central point the path difference of light from adjacent slits is zero, so all wavelengths interfere constructively at this point and, for the spectra, since red light has a longer wavelength than blue light, the maximum for red light will occur at a slightly greater angle that for the blue light).

Refraction

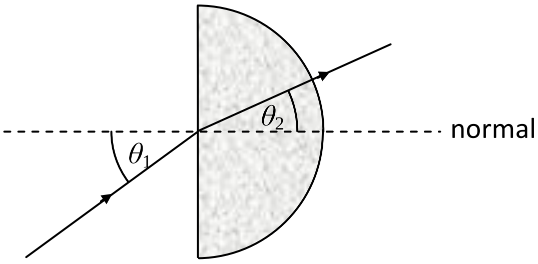
Refraction is the change in speed of light as it travels from one medium into another. This change in speed can lead to a change in direction. When light travels from a less dense medium to a more dense material it tends to change direction towards the normal, and when it travels from a more dense to a less dense medium it tends to change direction away from the normal.



The absolute refractive index *n* of a medium is defined as the ratio of the speed of light in a vacuum to the speed of light in the medium. In practice, the speed of light in air is virtually identical to the speed of light in a vacuum.

$$n = \frac{v_1}{v_2} \quad \text{or} \quad n = \frac{v_{air}}{v_{medium}}$$

The absolute refractive index of a medium is also equal to the ratio of the sine of the angle of the light to the normal in a vacuum/air to the sine of the angle of the light to the normal in the medium.

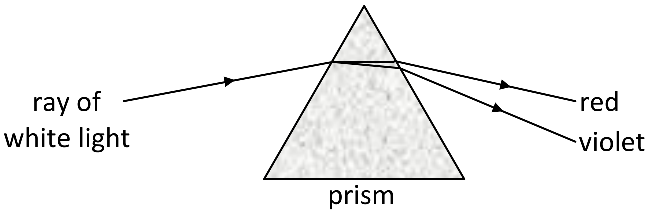


The relationship between the angles is given by Snell's Law:

$$n = \frac{\sin\theta_1}{\sin\theta_2} \quad \text{or} \quad n = \frac{\sin\theta_{air}}{\sin\theta_{medium}}$$

When a wave travels from one medium into another it also changes wavelength.

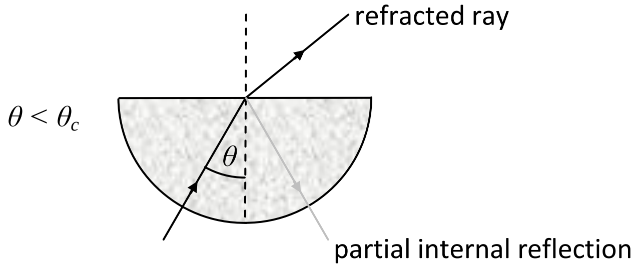
$$n = \frac{\lambda_1}{\lambda_2} \quad \text{or} \quad n = \frac{\lambda_{air}}{\lambda_{medium}}$$



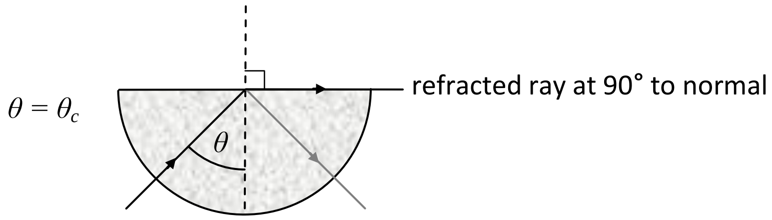
The refractive index of a material varies slightly with frequency. The refractive index of a medium for violet light is slightly greater than the refractive index of the medium for red light. Therefore, when white light is passed through a prism a spectrum a spectrum is produced.

When light is incident at a boundary between a slow medium and a fast medium:

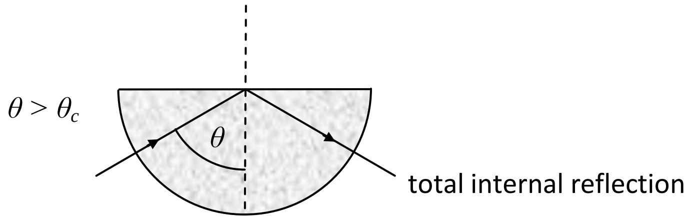
① At small angles of incidence most of the light is refracted away from the normal in the fast medium, but some of the light is also reflected back inside the slow medium (partial internal reflection).



② At the **critical angle** θ_c the angle of refraction in the fast medium is equal to 90°.



③ At angles of incidence above the critical angle, all the light is reflected inside the slow medium. This is called **total internal reflection**.



The critical angle of the medium can be calculated using the relationship:

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

Spectra

Irradiance I is defined as the power per unit area of electromagnetic radiation incident on a surface:

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

Irradiance is inversely proportional to the square of the distance from a point source. (A **point source** is a small, compact source that emits radiation uniformly all directions.)

$$I = \frac{k}{d^2}$$ where k is a constant

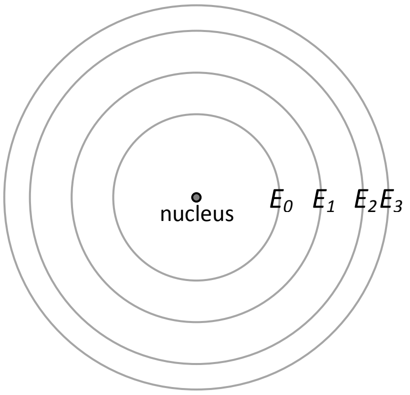
For calculation purposes this can expressed by the relationship

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

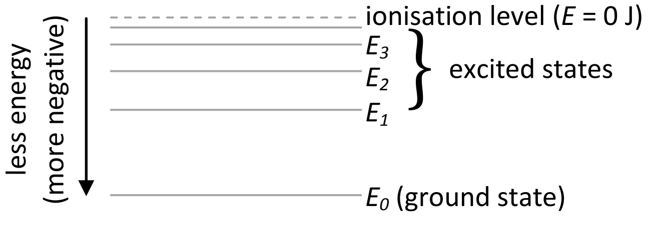
Bohr's atomic model describes the arrangement of electrons within an atom. According to the model:

- electrons are in circular orbits around the nucleus
- these orbits correspond to energy levels
- electrons can only occupy certain energy levels (i.e. the orbits/energy levels are quantised)
- electrons in the lowest energy orbit are said to be in the **ground state**
- electrons may gain energy to move to higher energy levels (**excited states**), or lose energy to drop down energy levels.
- when an electron is completely removed from at atom it is said to be **ionised**
- an electron in the ionised state is defined as having zero potential energy – the consequence of this is that all energy levels within an atom have negative values.

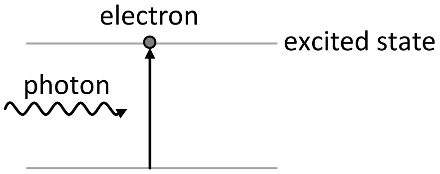
This can be represented diagrammatically as:



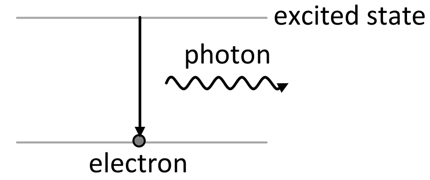
or



Electrons can move between energy levels by absorbing or emitting photons of electromagnetic radiation.



An electron moves to a higher energy level when it absorbs the energy of a photon. Only photons with energies exactly matched to the difference between two energy levels can be absorbed.



When an electron moves from higher energy level to a lower energy level a photon is emitted. Again, only photons with energies exactly matched to the difference between two energy levels can be emitted.

The energy of the photons absorbed or emitted can be determined using the relationship:

$$E_2 - E_1 = hf$$

Continuous spectra are produced when energy is supplied to solids, liquids and high-pressure gases. In these materials, the interactions between atoms cause the energy levels to interact with each other and become grouped into bands (see Band Theory in the Electricity unit). This means that an infinite number of transitions are possible and so an infinite number of frequencies of are produced.

Line emission spectra are produced when energy is supplied low-pressure gases. In low-pressure gases the atoms are free and the electrons can only occupy specific energy levels. Each element has a unique line emission spectrum with lines corresponding to the frequencies of the photons emitted when electrons move down between these specific energy levels. The number of lines in the spectrum corresponds to the number of possible transitions. When more electrons make a certain transition the corresponding line is brighter.

Absorption spectra (black lines on a continuous spectrum) are formed when light with a continuous spectrum passes through a low-pressure gas. The lines are formed when electrons in the gas absorb photons to move up between energy levels. The position of the absorption lines for a particular element is identical to the position of the bright lines in the element's emission spectrum.

Absorption lines in the spectrum of sunlight (**Fraunhofer lines**) provide evidence for the composition of the Sun's upper atmosphere. The core of the Sun produces a continuous spectrum, but different elements in the Sun's atmosphere absorb particular frequencies of photons.