Higher Physics

Unit 2

Particles and Waves Notes

Name ____

Key Area Notes Examples and Questions

Other Notes

Key Area: The Standard Model of Fundamental Particles.

Previous Knowledge

- Electrical charges

Success Criteria

1.1 I understand what is meant by "orders of magnitude".
1.2 I am aware of the range in orders of magnitude of sizes from sub-nuclear to celestial objects.
1.3 I understand that most matter is made from protons, neutrons and electrons.
1.4 I know that protons and neutrons are made from smaller particles and that there are many other sub-atomic particles.
1.5 I understand what is meant by the terms fermion, boson, quark, lepton.
1.6 I understand that for every matter particle in the standard model their exists an antimatter particle.
1.7 I can state the symbols used for quarks, leptons, electrons, protons, neutrons and their antiparticles.
1.8 I know what is meant by the terms for combinations of quarks: hadron, baryon and meson.
1.9 I can perform calculations involving the charges on quarks and the resultant charge of a baryon or meson.
1.10 I can state the four forces of nature, their associated bosons, their range and which type of particle affected by the force.
1.11 I can state that beta decay gave the first evidence for the neutrino.

1.1 I understand what is meant by "orders of magnitude".

Powers of 10 are referred to as orders of magnitude. Orders of magnitude are used as estimates of sizes where a precise value is not needed or not known. Any quantity can be rounded to its nearest power of ten to give an order of magnitude estimate.

<u>Examples</u>

- A human 1.78m tall has an order of magnitude estimate of $\times 10^0$m
- The distance from the earth to the Moon is 384,400km has an order of magnitude estimate $\times 10^5$km.
- $\times 10^8$ is two orders of magnitude bigger than $\times 10^6$.

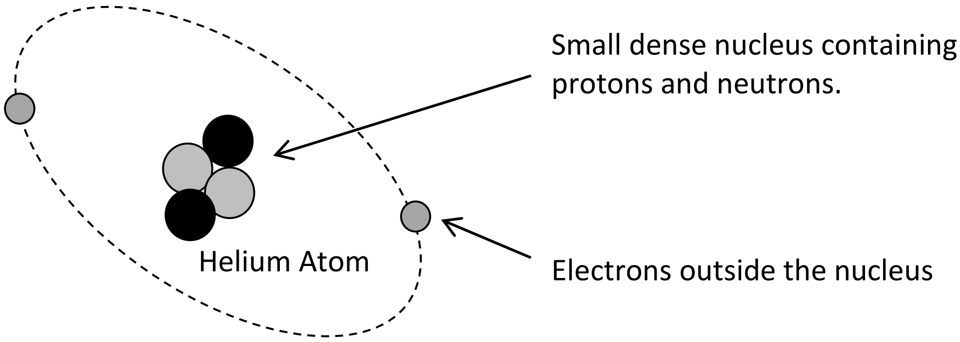
1.2 I am aware of the range in orders of magnitude of sizes from sub-nuclear to celestial objects.

The table below gives orders of magnitude dimensions for various objects.

Object	**Approximate Size in Metres**
Quark	10^{-18}
Proton	10^{-15}
Nucleus	10^{-14}
Atom	10^{-10}
Bacteria	10^{-5}
Human	10^{0}
Diameter of the Earth	10^{7}
Diameter of the Earth's Orbit	10^{11}
Diameter of the Solar system	10^{13}
Diameter of Milky Way Galaxy	10^{21}
Local Cluster of Galaxies	10^{23}
Observable Universe	10^{29}

Question book page 4 questions 2.

1.3 I understand that most matter is made from protons, neutrons and electrons.



Protons have an electrical charge of $1.6 \times 10^{-19}\mathrm{C}$

Electrons have and electrical charge of $-1.6 \times 10^{-19}\mathrm{C}$

Neutrons have zero charge.

“Normal” matter is made from protons, electron and neutrons.

1.4 I know that protons and neutrons are made from smaller particles and that there are many other sub-atomic particles.

Protons and neutrons are themselves made from smaller particles.

Many other particles can be created in radioactive decay and in collisions between particles. These together with protons, neutrons and electrons can be described using the standard model of fundamental particles.

1.5 I understand the standard model of particle physics and the grouping of all fundamental particles as fermions, bosons, quarks and leptons.

In the standard model there are three types of fundamental particles called quarks, leptons and some of the bosons. These are split into two groups which are determined by their spin (you do not need to know anything about spin in this course).

Fermions are a group consisting of all the leptons and some combinations of quarks.

Bosons are a group consisting of force carrying particles and some combinations of quarks.

Quarks and Leptons These occur in three generations each with increasing mass.

<u>Note about Electrical Charges</u>
The electrical charges of particles in the standard model are usually written as fractions or multiples of 1.6×10^{-19}C.

<u>Examples</u>
The charge on a proton is 1.6×10^{-19}C which will be written as +1 (or just 1) in the standard model.

The charge on a down quark is -1/3 of 1.6×10^{-19}C so is written as -1/3.

Quarks have a fractional electrical charge of either $+2/3$ or $-1/3$. Single quarks never occur. They are always combined with other quarks to produce particles (hadrons) with an integer value of electrical charge.

Leptons have an integer value of electrical charge. They never combine to produce other particles.

	First generation		**Second generation**		**Third generation**	
		Charge		**Charge**		**Charge**
Quarks	up	+⅔	charm	+⅔	top	+⅔
	down	−⅓	strange	−⅓	bottom	−⅓
Leptons	electron	−1	muon	−1	tau	−1
	(electron) neutrino	0	muon neutrino	0	tau neutrino	0

Increasing mass →

Note - an electron neutrino is often just referred to as a neutrino.

First generation quarks and leptons are the constituents of “normal” matter. The second and third generations are only found in cosmic rays or produced in particle accelerators. The reason why there are three generations of particles is currently not known.

<u>How to Remember Your Quarks</u>

All positive quarks have “positive” names Up, Charm and Top.

All negative quarks have “negative” names Down, Strange and Bottom.

Question book page 5 question 3.

1.6 I understand that for every matter particle in the standard model their exists an antimatter particle.

Anti-matter was first predicted from theory by Paul Dirac. Anti-electrons were first discovered when investigations into cosmic rays showed particles with the same properties as electrons but of opposite charge.

For each particle there also exists another anti-matter particle with opposite electrical charge. Neutrinos and other zero charge particles also have anti-particles but still with a charge of zero. Other properties of anti-matter particles (eg. mass) are identical to their matter particle versions.
<u>Examples</u>

An up quark has a charge of $+\frac{2}{3}$. An anti-up quark has an electrical charge of $-\frac{2}{3}$.

A muon has a charge of -1. An anti-muon has a change of +1.

A tau neutrino has a charge of 0. A tau anti-neutrino also has a charge of 0.

1.7 I can state the symbols used for quarks, leptons, electrons, protons, neutrons and their antiparticles.

The table below shows the symbol you need to know.

Examples

Particle	Symbol
neutron	n
Proton	p
electron	e
muon	μ
tau	τ
electron neutrino	υ
muon neutrino	ν_μ
tau neutrino	ν_τ
up quark	u
down quark	d
top quark	t
bottom quark	b
charm quark	c
strange quark	s

Most other particles are given Greek letters as symbols.

Anti-particles have the same symbol as matter particles but are drawn with a line over the symbol.

An electron is written as e and anti-electron (positron) is written as $\bar{e}$.

A muon neutrino is written as ν_μ and an anti-muon neutrino is written as $\overline{\nu_\mu}$.

Question book page 5 question 1

1.8 I know what is meant by the terms for combinations of quarks: hadron, baryon and meson.

Particles which are combinations of quarks or anti-quarks and are called **Hadrons**. They can be split into two groups.

Baryons which are made from three quarks (or anti-quarks). As these are made from an odd number of quarks they are classified as fermions.

Mesons which are made from one quark and one anti-quark. As these are made from and even number of quarks they are classified as bosons.

The only possible combinations of quarks are those which have integer values of charge.

Protons are the only stable type of hadron. All other hadrons are unstable and will decay into other more stable particles. The neutron is not stable on its own but can be stable when combined with protons in a nucleus.

1.9 I can perform calculations involving the charges on quarks and the resultant charge of a baryon or meson.

To the charge on a meson or baryon is the sum of the charges on their constituent quarks. All mesons and baryon have an integer value of charge. The only possible combinations of quarks are those which give integer values of charge.

Examples

A proton is a baryon consisting of two up quarks and a down quark.

The electrical charge on the proton can be obtained by adding up the charges of its constituent quarks.

$\mathrm{p} = \mathrm{u} + \mathrm{u} + \mathrm{d}$

$\mathrm{p} = \frac{2}{3} + \frac{2}{3} - \frac{1}{3}$

$\mathrm{p} = 1$

A neutron is a baryon consisting of one up quark and two down quarks.

$\mathrm{n} = \mathrm{u} + \mathrm{d} + \mathrm{d}$

$\mathrm{n} = \frac{2}{3} - \frac{1}{3} - \frac{1}{3}$

$\mathrm{n} = 0$

The kaon (K^{+}) is a meson consisting of and up quark and an anti-strange quark

$\mathrm{K}^{+} = \mathrm{u} + \bar{\mathrm{s}}$

$K^{+} = \frac{2}{3} + \frac{1}{3}$

$K^{+} = 1$

Question book page 6 questions 5 and 6.

1.10 I can state the four forces of nature, their associated bosons, their range and which type of particle affected by the force.

There are four forces in nature

- Electromagnetic
- Weak
- Strong
- Gravity

These forces are produced by the interaction of particles. In the standard model particles interact by exchanging particles called bosons.

Force	**Boson**	**Range (metres)**	**Which Particles the force affects**
Electromagnetic	photon	Infinite	Any particle with a charge
Weak	W± and Z	10^{-18}	Fermions
Strong	gluons	10^{-15}	Hadrons
Gravity	graviton	Infinite	All

Higgs Boson

This Boson interacts with particles to produce mass.

1.11 I can state that beta decay gave the first evidence for the neutrino.

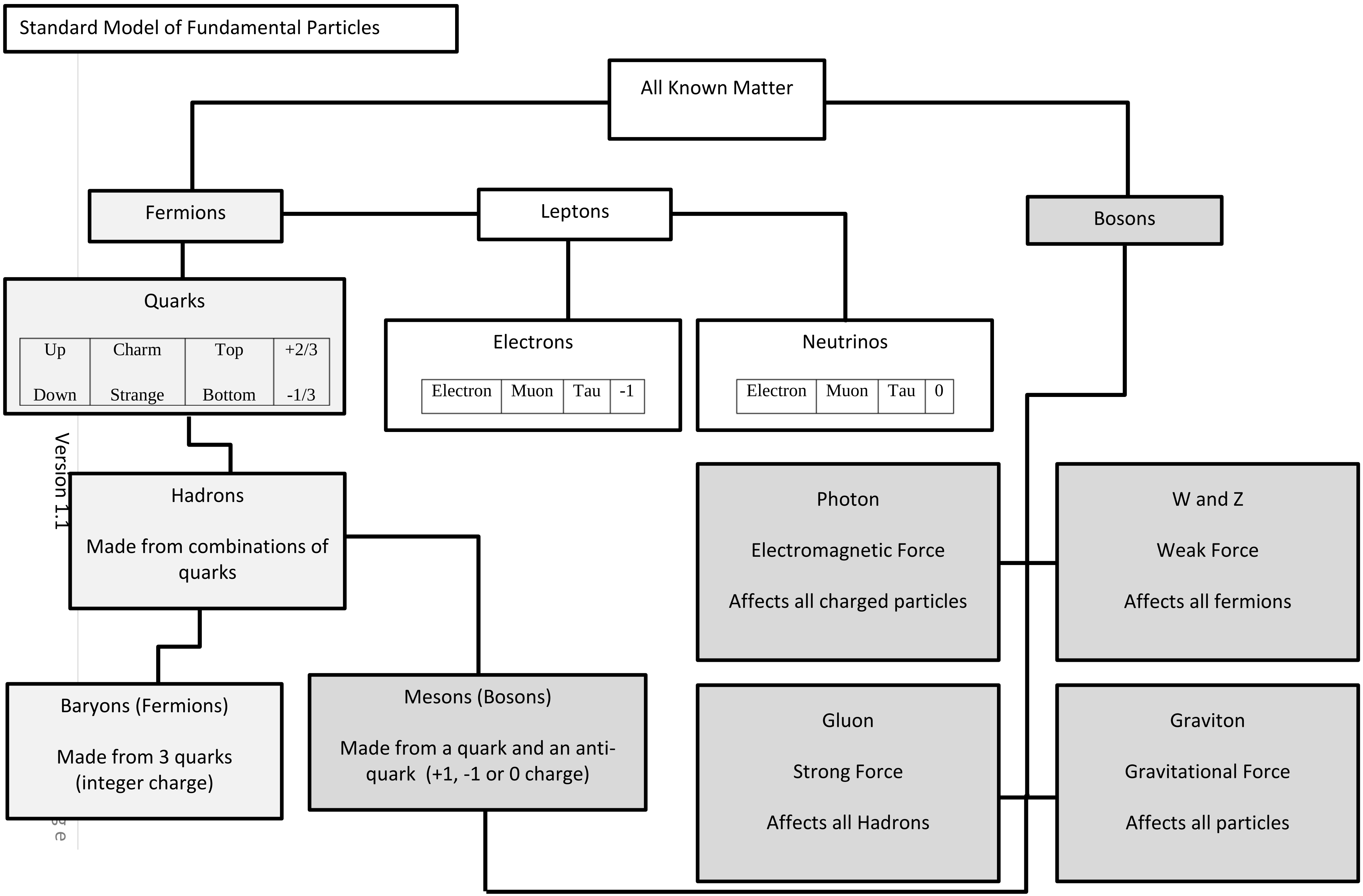
Evidence of Sub-nuclear Particles and Antimatter

Beta Decay as Evidence of Neutrinos

During beta decay the energy of the electron emitted was always smaller than the energy expected. This led to the proposal by Wolfgang Pauli that another particle with no charge and a low or zero mass was carrying away some of the energy. This particle is the anti-neutrino.   The weak force was proposed to explain beta decay.

Question book page 6 questions 4 and 7.

Homework The Standard Model



Standard Model of Fundamental Particles
All Known Matter
Fermions
Leptons
Bosons
Quarks
Up
Charm
Top
+2/3
Down
Strange
Bottom
-1/3
Electrons
Electron
Muon
Tau
-1
Neutrinos
Electron
Muon
Tau
0
Hadrons
Made from combinations of quarks
Photon
Electromagnetic Force
Affects all charged particles
W and Z
Weak Force
Affects all fermions
Baryons (Fermions)
Made from 3 quarks (integer charge)
Mesons (Bosons)
Made from a quark and an anti-quark (+1, -1 or 0 charge)
Gluon
Strong Force
Affects all Hadrons
Graviton
Gravitational Force
Affects all particles

Key Area: Forces on Charged Particles

Previous Knowledge

- Electrical charges.

Success Criteria

2.1 I know that electrical fields exist around charged particles and between charged parallel plates around them

2.2 I can sketch the electric field patterns for; single-point charges, a system of two-point charges and between parallel plates.

2.3 I know that a charged particle in an electric field will experience a force.

2.4 I can work out the direction of movement of a charged particle in an electric field.

2.5 I know the definition of the volt.

2.6 I can know that the work done on a charged particle in an electric field is given by the relationship $W = QV$

2.7 I know the definition of the Electron Volt (eV). This is not essential but is a commonly used unit to for small quantities of energy.

2.8 I can solve problems involving the charge, mass, speed, energy of a charged particle in an electric field and the potential difference through which it moves.

2.9 I can state that moving charges produce magnetic fields.

2.10 I can state that a magnetic field only produce a force on moving charged particles.

2.11 I understand the symbols used to represent magnetic fields in diagrams.

2.12 I can find the direction of the force on a charged particle moving in a magnetic field.

2.13 I can explain why charged particles in magnetic fields follow circular paths.

2.14 I am aware of the basic operation of particle accelerator in terms of acceleration, deflection and collision of charged particles.

2.1 I know that electrical fields exist around charged particles and between charged parallel plates.

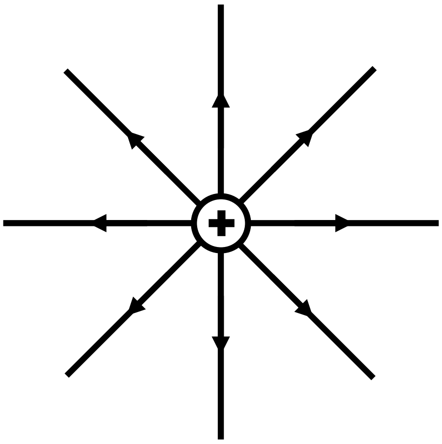
An electrical charge produces and electric field around it. These electric fields interact with other charged objects to a force on the objects.

2.2 I can sketch the electric field patterns for; single-point charges, a system of two-point charges and between parallel plates.

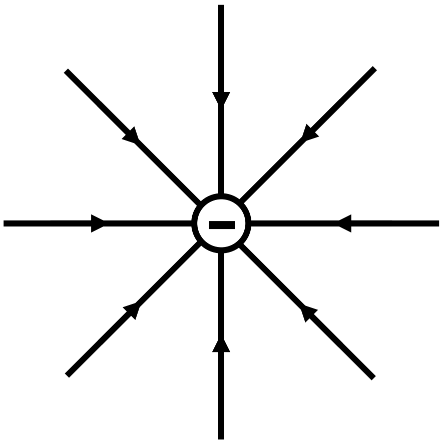
Electric fields can be drawn using field lines. They indicate the strength and direction of the electric field.

- Electric field lines start on positive charges and end on negative charges.
- Field lines are continuous.
- Field lines never cross.
- The arrow indicates the direction a positive charge would move.
- Field lines close together indicated a strong electric field. Field lines further apart indicated a weaker electric field.

Single-Point Charges

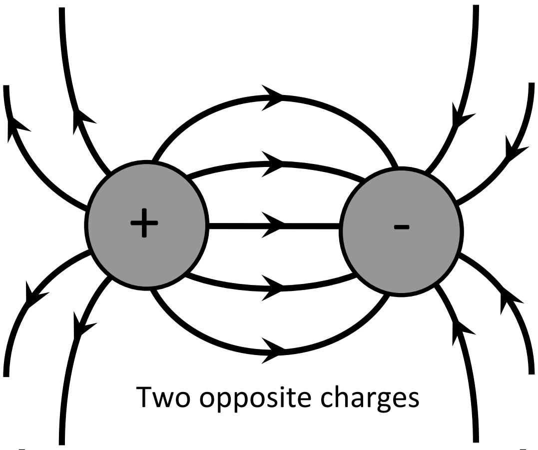


Single positive charge

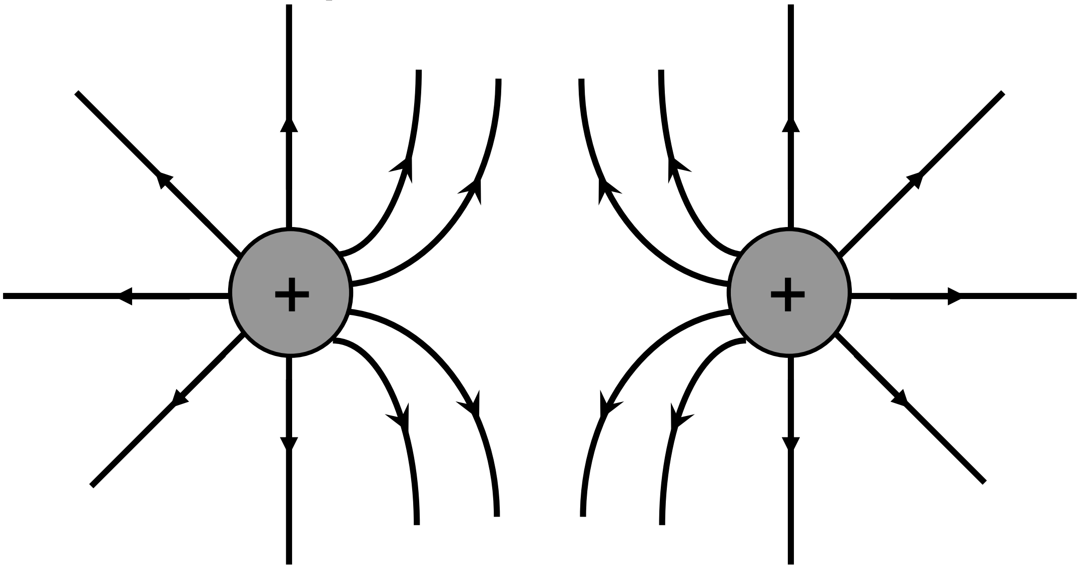


Single negative charge

Two-Point Charges

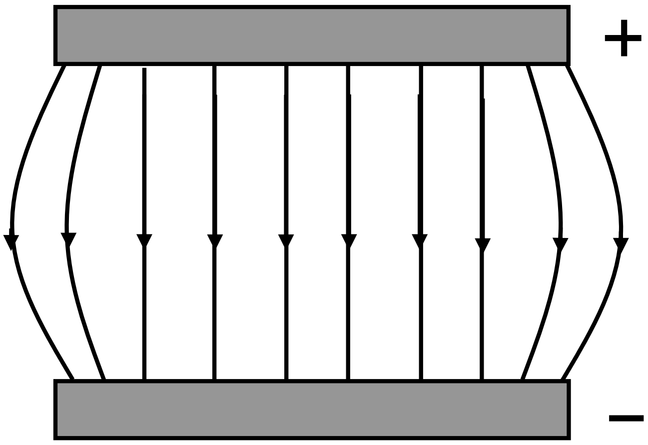


Two opposite charges



Two positive charges

Parallel Plates



Parallel plates produce a uniform field between the plates.
The curvature of the field lines at the edges of the plates is small and frequently not shown in diagrams.

Question Book Page 7 question 1

2.3 I know that a charged particle in an electric field will experience a force.

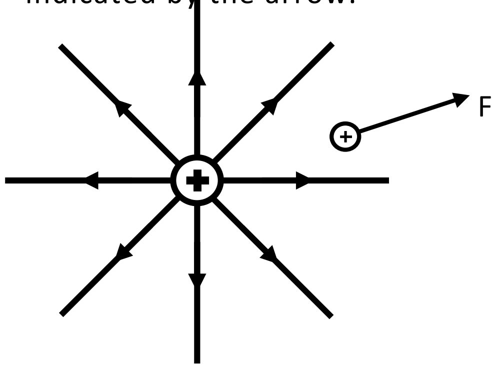
2.4 I can work out the direction of movement of a charged particle in an electric field.

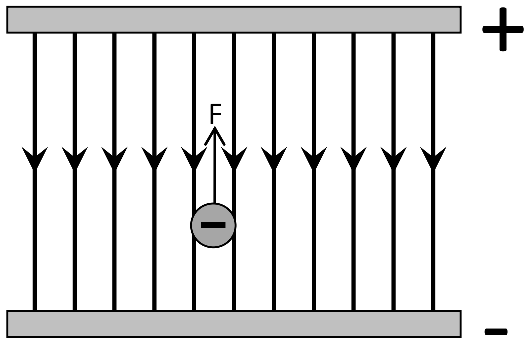
If a charge is placed in an electric field it will experience a force. A positive charge will experience a force in the same direction as the field lines. A negative charge will experience a force in the opposite direction to arrows on the field lines.
The force on a charged object in the field depends on;

- The strength of the electric field.
- The charge on the object.

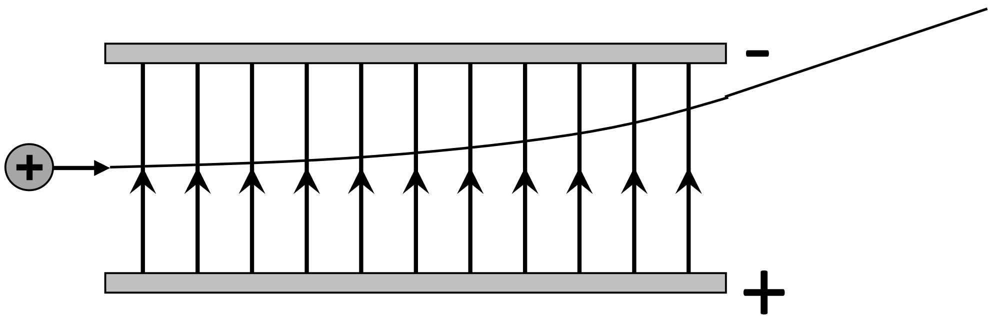
The direction of movement of a charged particle placed in an electric field depends on its charge. Positive charges will move in the same direction as the arrow on the field lines. Negative charges will move in the opposite direction.

Examples
In the diagrams below the direction of movement of the charges is indicated by the arrow.





Charges moving perpendicular to an electric field.
When a charge is moving perpendicular to an electric field its path is deflected. The component of its velocity perpendicular to the field is constant.



Question Book Page 7 question 2 and page 9 question 9

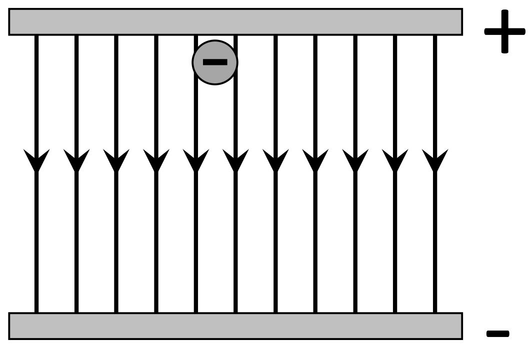
2.5 I know the definition of the volt.

If 1 joule of work is done by moving 1 coulomb of charge between two points in an electric field, the potential difference between the two points is 1 volt.

2.6 I can know that the work done on a charged particle in an electric field is given by the relationship $W = QV$

To move an electron (or another negative electrical charge) toward the negative plate requires work to be done on the electron.

The work done on or by the charge can be calculate using the relationship below.



Voltage between two points in an electric field in Volts (V).

$$W = QV$$

Work done moving the charge between two points in the electric field in Joules (J).

Charge (Coulombs,C)

2.7 I know the definition of the Electron Volt (eV). This is not essential but is a commonly used unit to for small quantities of energy.

The electron volt is a unit of energy not voltage. It is defined as the work done on an electron as it is moved between two points with potential difference of 1 volt. An electron volt is sometimes used in electrical problems when dealing with small energies.

Question Book page 7 questions 3 and 4.

2.8 I can solve problems involving the charge, mass, speed, energy of a charged particle in an electric field and the potential difference through which it moves.

When a charge is free to move in an electric field the unbalanced force exerted by the field will cause it to accelerate. The work done by the field on the charge will be converted to the kinetic energy of the charge.

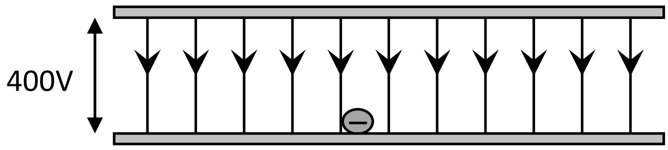
For a uniform field

$W = QV$ and $E = \frac{1}{2}mv^2$

Work done on the electron = Kinetic energy gain of the electron

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

Example
An electron of mass $9.1 \times 10^{-31}\text{kg}$ has a charge of $-1.6 \times 10^{-19}\text{C}$. The potential difference across the plates is 400V. If the electron is initially on the negative plate, calculate its speed when it hit the positive plate.



Work done on the electron = Kinetic energy gain by the electron

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

$$1.6 \times 10^{-19} \times 400 = \frac{1}{2} \times 9.1 \times 10^{-31} \times v^2$$

$$v = \sqrt{\frac{1.6 \times 10^{-19} \times 400}{\frac{1}{2} \times 9.1 \times 10^{-31}}}$$

$$v = 1.2 \times 10^7 \text{ms}^{-1}$$

Be careful to distinguish between.
V – potential difference (voltage).
v - speed.

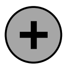
Question Book Page 8 Questions 5 to 8.

2.9 I can state that moving charges produce magnetic fields.

2.10 I can state that a magnetic field only produce a force on moving charged particles.

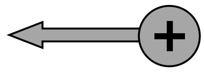
Electric fields are always produced by electric charges whether they are stationary or moving. Magnetic fields are **not** produced by electric charges when they are stationary. They are only produced when the charge is moving.

Magnetic fields like electric fields produce a force on electrical charges. However magnetic fields only produce a force when a there is component of the charge's velocity perpendicular to the magnetic field lines i.e. when a charged particle is moving along the field lines there is no force on the particle.



Stationary charge

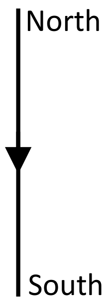
- Produces and electric field only.
- Affected by electric fields only.



Moving charge

- Produces and electric and magnetic field.
- Affected by electric fields and magnetic fields.

2.11 I understand the symbols used to represent magnetic fields in diagrams.



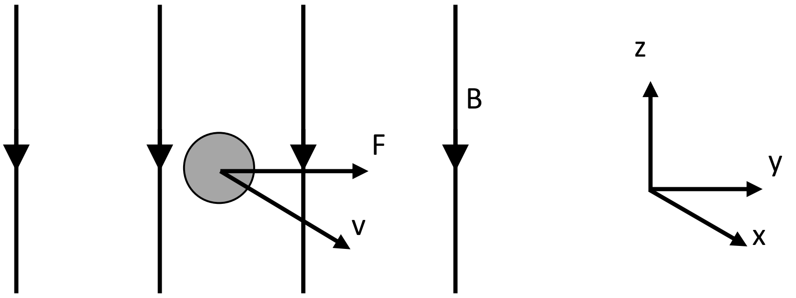
A magnetic field line along the plane of the paper

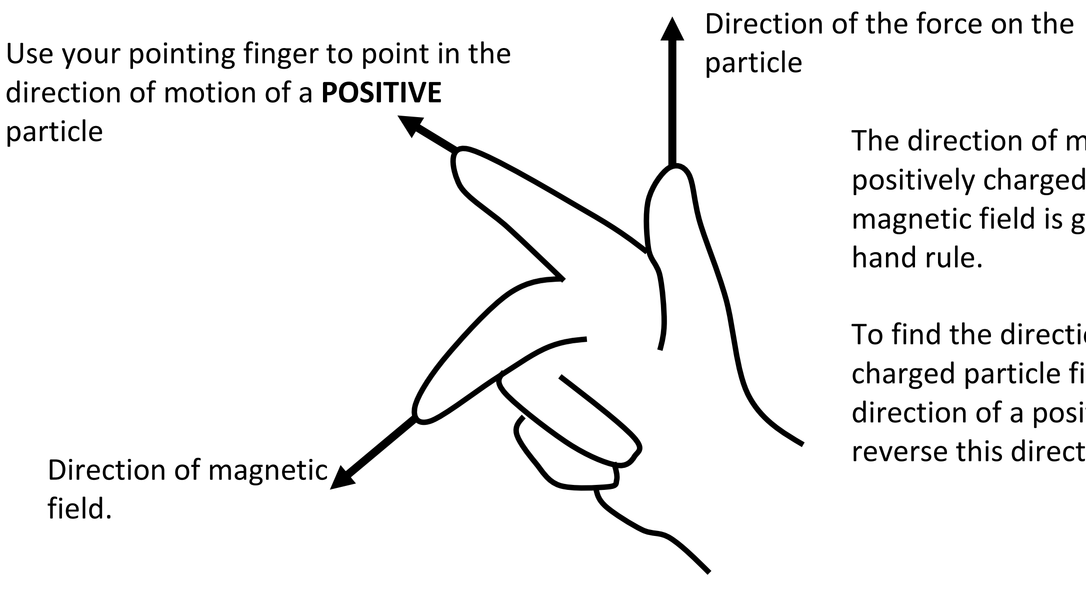
A magnetic field line going into the paper.

A magnetic field line coming out of the paper.

2.12 I can find the direction of the force on a charged particle moving in a magnetic field.

A charged particle moving in a magnetic field experiences a force which is perpendicular to both its velocity and the magnetic field lines.



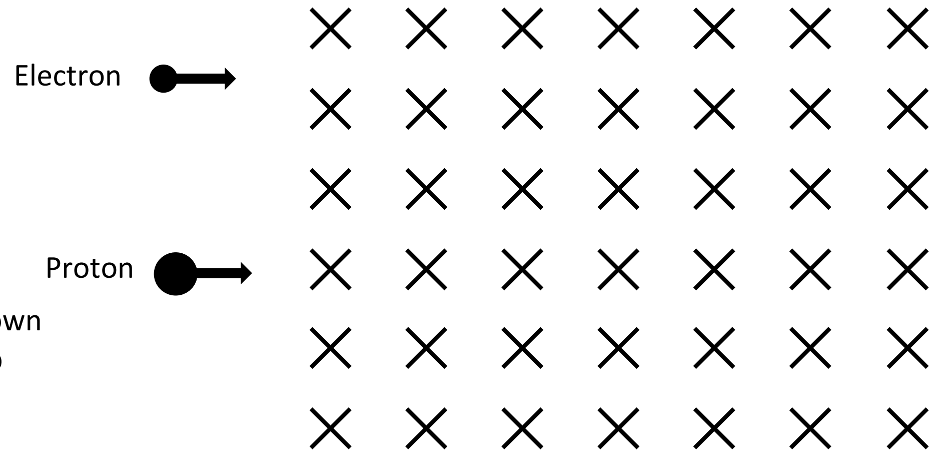


The direction of motion of a positively charged particle in a magnetic field is given by the right hand rule.

To find the direction of a negatively charged particle first find the direction of a positive particle then reverse this direction.

Example

State the direction of the force on (a) the electron and (b) the proton as it enters the region on constant magnetic field



(a) Down
(b) Up

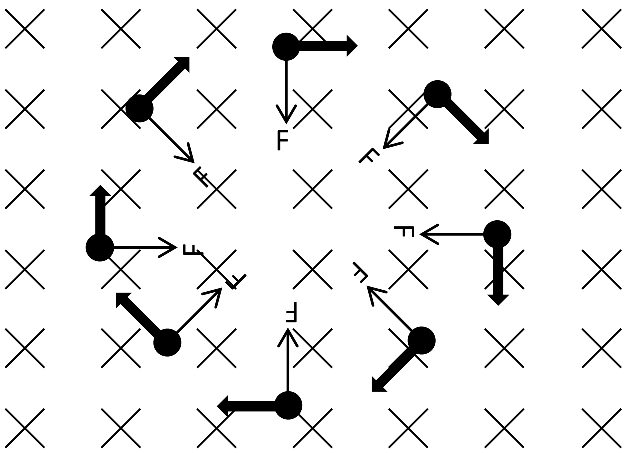
Question book pages 9 and 10 questions 2 to 3.

2.13 I can explain why charged particles in magnetic fields follow circular paths.

As the force on a charged particle is perpendicular to both the velocity and the magnetic field the path of a charged particle follows a circular path.

Example

Draw the path taken by and electron moving perpendicular to the field lines which are going into the page.



Question book page 13 questions 9 and 10.

2.14 I am aware of the basic operation of particle accelerator in terms of acceleration, deflection and collision of charged particles.

Particle accelerators are used to investigate the structure of matter in two different ways.

- They can be used to produce particles with a high velocity (high energy) which then collide with other particles. These collisions create new particles which can be studied in various types of detector. E.g. SLAC in the US and Large Hadron Collider at CERN in Europe.
- The electromagnetic radiation produced by synchrotron accelerators can be used to study the structure of matter. e.g. Diamond light source in the UK.

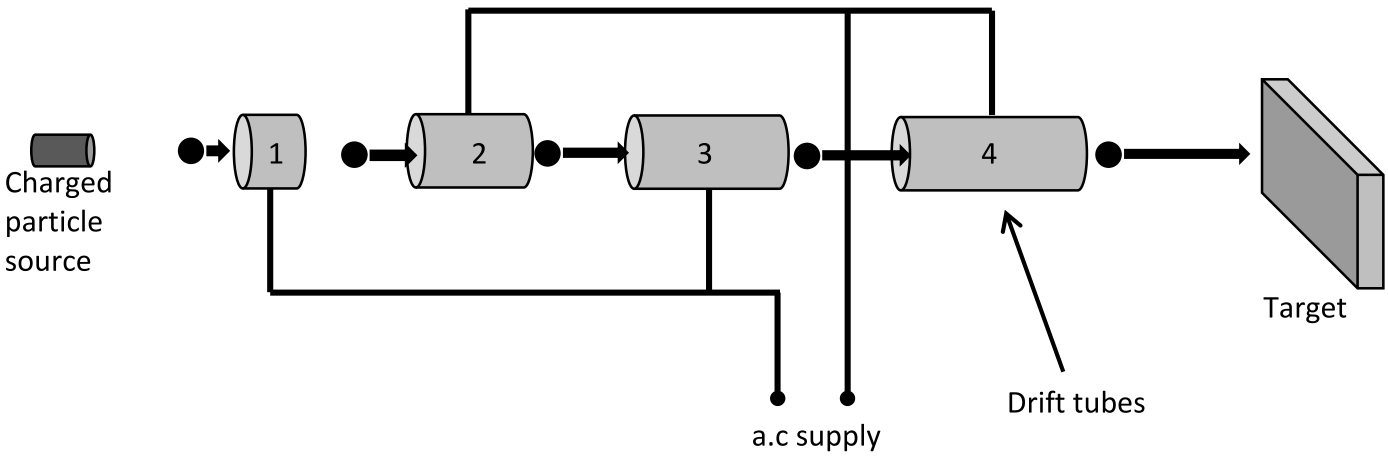
There are three main types of particle accelerator

- The linear accelerator
- Cyclotron
- Synchrotron

All three types of accelerator have the same basic parts

- A source of charged particles.
- A method of accelerating the charged particles.
- A method of deflecting and guiding the charged particles.
- A target.

Linear Accelerator



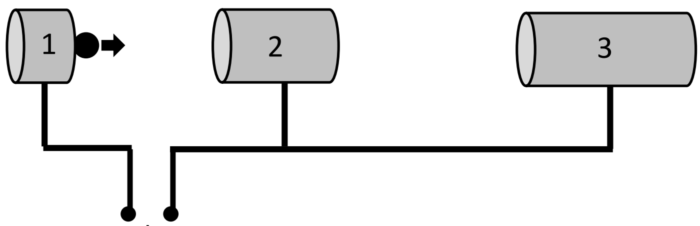
In this case we will consider electrons but a linear accelerator can be used to accelerate any charged particle.

- Electrons are produced by the particle source.
- They will accelerate towards drift tube 1 when it is in the positive part of the a.c. cycle.
- The electrons will travel at a constant speed through drift tube 1.
- As the electrons reach the end of tube 1 the a.c. supply will have changed so that tube 1 is negative and tube 2 is positive. The electrons will then be accelerated across the gap between the tubes.
- This will continue with the a.c supply switching the polarity of the tubes so that the electrons are always accelerated across the gaps between the tubes.
- The electrons strike the target (fixed target experiment).

The drift tubes need to increase in length as the speed of the electrons increases in order to keep in time with the polarity changes produced by the a.c. supply.

Example

In a linear accelerator, as an electron leaves drift tube 1, it is moving at $3.0 \times 10^{7}\mathrm{ms}^{-1}$ and is accelerated across the gap to drift tube 2 by a potential difference of 3.0kV.



a. Calculate the work done on the electron as it travels between drift tubes 1 and 2.
b. Calculate the speed of the electron as it enters drift tube 2.
c. Why is drift tube 2 longer than drift tube 1?
d. What effect would increasing the distance between drift tube 1 and drift tube 2 have on the speed of the electron?

Charge on an electron is $-1.6 \times 10^{-19}\mathrm{C}$

Mass of an electron is $9.1 \times 10^{-31}\mathrm{kg}$

a. $\mathrm{W} = \mathrm{QV}$
$\mathrm{W} = 1.6 \times 10^{-19} \times 3000$
$\mathrm{W} = 4.80 \times 10^{-16}\mathrm{J}$

b. Original kinetic energy
$\mathrm{E_k} = \frac{1}{2}\mathrm{mv}^2$

$$\mathrm{E_k} = \frac{1}{2} \times 9.1 \times 10^{-31} \times (3.0 \times 10^{7})^2$$

$$\mathrm{E_k} = 4.10 \times 10^{-16}\mathrm{J}$$

New Kinetic energy

$$\mathrm{E_k} = \text{Original Kinetic Energy} + \text{Work done}$$

$$\mathrm{E_k} = 4.10 \times 10^{-16} + 4.80 \times 10^{-16} = 8.90 \times 10^{-16}\mathrm{J}$$

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

$$8.90 \times 10^{-16} = \frac{1}{2} \times 9.1 \times 10^{-31} \times v^2$$

$$v = \sqrt{\frac{2 \times 8.90 \times 10^{-16}}{9.1 \times 10^{-31}}}$$

$$v = 4.4 \times 10^7 \mathrm{ms}^{-1}$$

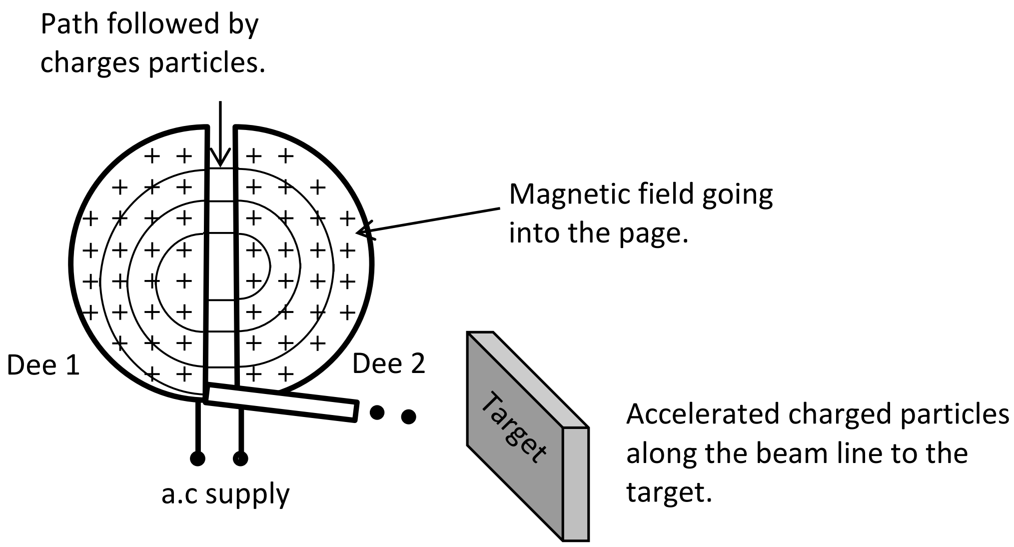
c. The electrons travel further in a given time as they increase in speed so tube 2 must be longer to keep synchronised with the a.c. supply.
d. No effect as the work done on the electron only depends on the potential difference and the charge of the electron. $W = QV$

Cyclotron

Cyclotrons work in a similar way to linear accelerators in that charge particles are accelerated across a gap.

In this case charged particles are accelerated multiple times across a single gap between two “dees”. A magnetic field is used to bring the charged particles back to the gap for each acceleration. This makes cyclotrons more compact than linear accelerators.

- Charge particles are inserted into the centre of the cyclotron.
- They are accelerated across the gap between the dees by an electric field.
- When the charged particle enters a dee it follows a circular path around the dee and back to the gap again.
- When the particles reach the gap again the polarity of the dees are changed by the a.c supply so they are accelerated again.
- With each acceleration the radius followed by the charged particle increases.
- Accelerated particles are ejected along the beam line when the reach the outer edge of the dees



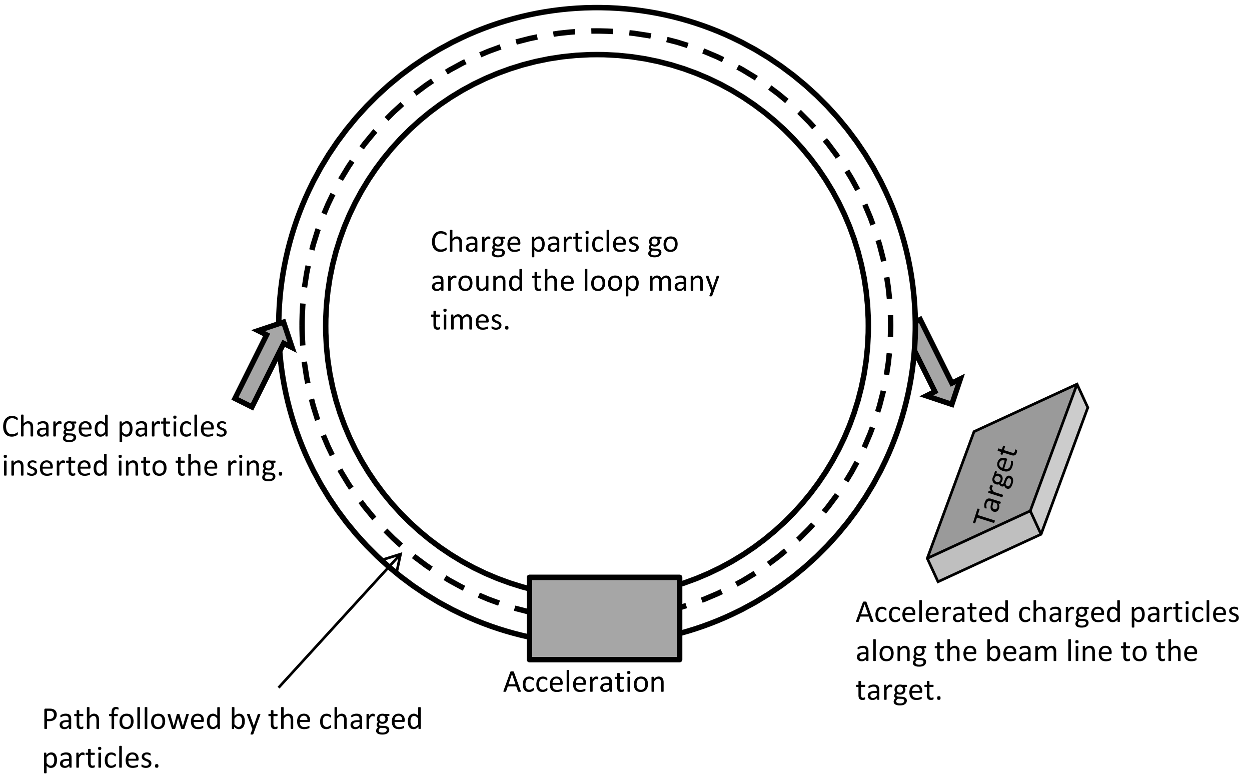
Synchrotrons

Synchrotrons, like cyclotrons, deflect charged particles around circular paths.

Charged particles are inserted into the ring and follow a circular path due to the presence of a magnetic field (not shown on the diagram).

They are accelerated each time they go around the ring. The radius of the path followed by the charged particles is kept constant by increasing the strength of the magnetic field after each acceleration. When particles of opposite charge are inserted into the ring they will travel in opposite directions. These particles can then be caused to collide with each other doubling the energy of the collision (colliding-beam experiment).

Synchrotrons as Light Sources



Synchrotrons used as light sources are not usually circular but polygons where intense beams of electromagnetic radiation are emitted as electrons change direction at the vertices. The advantages synchrotrons have over other sources is the high intensity of the radiation produced and that the frequency range of radiation emitted is easily altered from infrared to x-rays.

Question book pages 11 and 12 question 1 to 8, page 14 question 11
Homework Charged Particles

Key Area: Nuclear Reactions

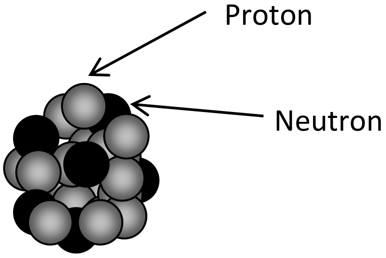
Previous Knowledge

- Electrical charges.

Success Criteria

3.1 I understand the following terms; element, atomic number and mass number.
3.2 I understand the symbols used in nuclear equations
3.3 I understand what is meant by the term isotope.
3.4 I can use nuclear equations to describe nuclear decay, fission and fusion reactions.
3.5 I know that the energy released from nuclear reactions results from the loss of mass in the reaction products.
3.6 I can use the relationship $E = mc^2$ to solve problems involving the mass loss and energy released by a nuclear reaction.
3.7 I understand how energy is produced from nuclear fission and fusion reactions.
3.8 I understand some of the coolant and containment issues with nuclear fusion.

3.1 I understand the following terms; element, atomic number and mass number.



Nucleus of an atom

An atom can be classified by the number of protons and neutrons in its nucleus.

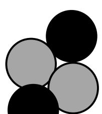
- **Atomic number, Z,** is the number of protons in the nucleus of an atom.
- Each **element** has its own specific the atomic number.
- **Mass number, A,** is the total number of protons and neutrons in the nucleus.
- In a neutral atom the number of protons equals the number of electrons.

3.2 I understand the symbols used in nuclear equations.

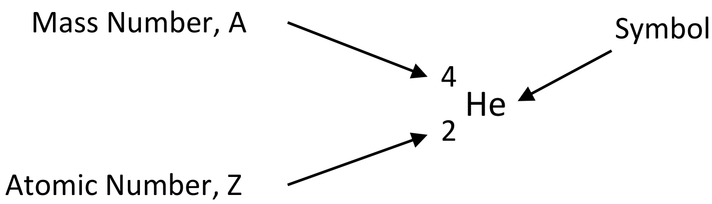
Terms in nuclear equations contain information about the nucleus of the atoms and information about other the particles involved in the nuclear reaction. This information consists of the symbol for the element or particle, its mass number and its atomic number.

Example

A Helium 4 nucleus (alpha particle) consists of two protons and two neutrons.



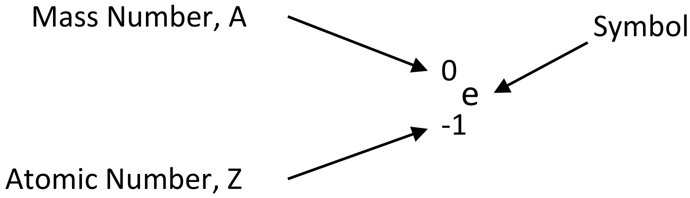
Helium Nucleus



Example

An electron (beta particle).

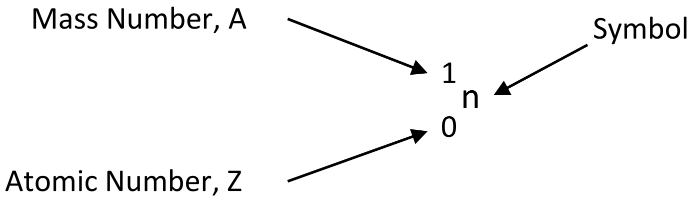
Electron (beta particle)



Example

A neutron

Neutron



3.3 I understand what is meant by the term isotope.

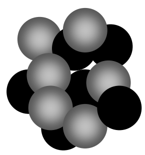
Each element in the periodic table has a different atomic number Z.

Elements can have differing numbers of neutrons in their nucleus. These are called **isotopes**. Isotopes of an element have the same atomic number but different mass numbers.

Example

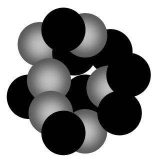
Carbon 12 and Carbon 14 are both isotopes of carbon.

Carbon 12 has 6 protons and 6 neutrons in its nucleus



$^{12}_{6}C$

Carbon 14 has 6 protons and 8 neutrons in its nucleus.



$^{14}_{6}C$

Problem book page 16 question 1 and 2

3.4 I can use nuclear equations to describe nuclear decay, fission and fusion reactions.

Some isotopes of some elements are unstable and can decay to a more stable state by emitting radiation. These are known as radioisotopes or radionuclides. The isotopes of all elements with atomic number greater than 82 are radionuclides.

Example

Carbon 12 is a stable isotope of carbon however Carbon 14 is unstable and will decay to give a stable isotope of Nitrogen.

The three common ways in which radionuclides can decay and the radiation they produce are called alpha, beta (minus) and gamma.

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

For all types of decay 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 new nucleus produced after decay is called the **daughter product** (which may still be unstable and decay further).

Alpha decay

Alpha decay occurs when a radionuclide emits an alpha particle consisting of two protons and two neutrons. This is the same as a Helium-4 nucleus, ${}^{4}_{2}\mathrm{He}$.

Alpha decay usually occurs in heavy nuclei such as uranium or plutonium. An alpha particle is relatively more massive than other forms of radiation. It can be stopped by a sheet of paper and cannot penetrate human skin. An alpha particle can only travel a few centimetres through the air.

Although the range of an alpha particle is short, it is very ionising so if an alpha decaying element is ingested, the alpha particles can do considerable damage to the surrounding tissue. This is why plutonium, with a long half-life, is extremely hazardous if ingested.

<u>Example</u>

Plutonium can decay to Uranium emitting and alpha particle.

$$^{239}_{94}\mathrm{Pu} \xrightarrow{24{,}000\mathrm{years}} {}^{235}_{92}\mathrm{U} + {}^{4}_{2}\mathrm{He}$$

Before Decay	After Decay
Atomic Number = 94	Atomic Number = 92 + 2 = 94
Mass Number = 239	Mass Number = 235 + 4 =239

The mass numbers and atomic numbers are conserved.

Beta decay

There are two types of beta decay

- Beta minus β^{-}
  A neutron is converted into a proton which stays in the nucleus with an electron and anti-electron neutrino which are emitted. This is the more common type of beta decay.

- Beta plus β^{+}
  A proton is converted into a neutron which stays in the nucleus with an anti-electron (positron) and electron neutrino are emitted.

When emitted, beta particles travel at almost the speed of light. A typical particle will travel about 3m through the air, and can be stopped by 4-6 cm of wood. Beta particles cause less ionisation than alpha.

In nuclear equations electrons are given an atomic number of -1 and positrons +1. The mass number of both is zero.
ie. An electron has the symbol ${}^{0}_{-1}\mathrm{e}$
A positron has the symbol ${}^{0}_{1}\mathrm{e}$

<u>Example</u>
Tritium (a radionuclide of hydrogen) decays to Helium-3 through beta minus decay

$$^{3}_{1}\mathrm{H} \xrightarrow{12.3\mathrm{years}} {}^{3}_{2}\mathrm{He} + {}^{0}_{-1}\mathrm{e} + {}^{0}_{0}\bar{\upsilon}$$

Before Decay	After Decay
Atomic Number = 1	Atomic Number = 2 - 1 = 1
Mass Number = 3	Mass Number = 3 + 0 + 0 = 3

Gamma decay

Gamma rays are a type of electromagnetic radiation that results from a redistribution of particles within a nucleus. Gamma rays are more penetrating than either alpha or beta radiation, but less ionising. The emission of a gamma ray does not change the mass or atomic numbers of a nucleus.

Fission

Spontaneous Fission

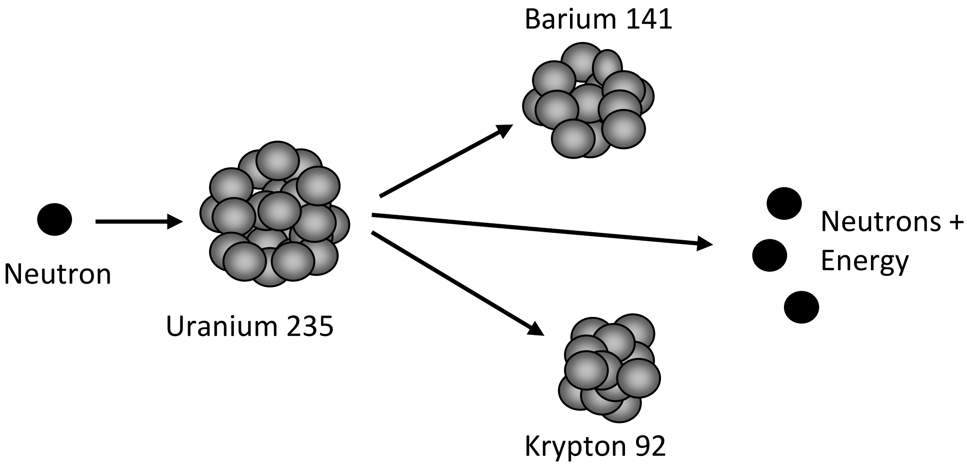
Fission occurs when a heavy nucleus decays to two nuclei with smaller mass numbers. This decay can happen spontaneously. The nucleus will split into two nearly equal nuclei and several free neutrons. A large amount of energy is also released. Elements do not spontaneously fission unless their mass number is greater than 230.

Induced Fission

Induced fission occurs when a nucleus absorbs a neutron (neutron bombardment). This neutron usually will come from a spontaneous fission or another induced fission.

Example

When a Uranium 235 nucleus absorbs a neutron it frequently splits into a Barium 141 nucleus and a Krypton 92 nucleus. This also releases more neutrons and large amounts of energy.



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

Before Decay	After Decay
Atomic Number = 92 + 0 = 92	Atomic Number = 36 + 56 + (3x0) = 92
Mass Number = 235 + 1 = 236	Mass Number = 92 + 141 + (3x1) = 236

Problem book pages 16 and 17 questions 3 and 4.

3.5 I know that the energy released from nuclear reactions results from the loss of mass in the reaction products.

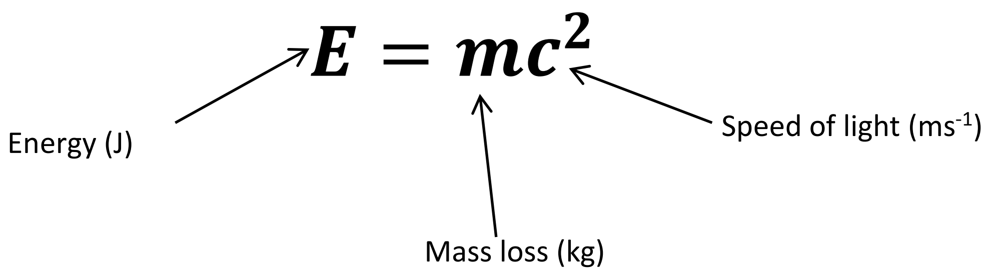
Energy can be released from nuclear reactions by fission or by fusion. When nuclei with atomic number less than iron are fused energy is released. When nuclei with atomic number greater than iron undergo fission energy is released.

Mass number and atomic number are both conserved during fission and fusion reactions. However, when measured precisely, the total mass after a nuclear fission or fusion will be different from the total mass before. This lost mass is converted into energy

3.6 I can use the relationship $E = mc^2$ to solve problems involving the mass loss and energy released by a nuclear reaction.

The mass lost is related to the energy released by the equation

$$E = mc^2$$



The energy produced in nuclear reactions is in the form of kinetic energy of the reaction products.

Example

Calculate

a. The mass lost in this fission reaction.
b. The energy released by the reaction.

$^{235}_{92}\text{U}$	+ $^{1}_{0}\text{n}$	$\longrightarrow$ $^{134}_{52}\text{Te}$	+ $^{98}_{40}\text{Zr}$	+ $4\,^{1}_{0}\text{n}$
$3.901 \times 10^{-25}\text{kg}$	$0.01700 \times 10^{-25}\text{kg}$	$2.221 \times 10^{-25}\text{kg}$	$1.626 \times 10^{-25}\text{kg}$	$4(0.01700 \times 10^{-25}\text{kg})$

Calculate the total masses on the left and right hand sides of the nuclear equation.

Left Side	Right Side
$\text{m} = 3.901 \times 10^{-25} + 0.01700 \times 10^{-25}$	$\text{m} = 2.221 \times 10^{-25} + 1.626 \times 10^{-25} + 4 \times 0.01700 \times 10^{-25}$
$\text{m} = 3.918 \times 10^{-25}\text{kg}$	$\text{m} = 3.915 \times 10^{-25}\text{kg}$

$$\text{Mass loss} = 3.918 \times 10^{-25} - 3.915 \times 10^{-25} = 3.0 \times 10^{-28}\text{kg}$$

a. Energy released

$$E = mc^2$$

$$E = 3.0 \times 10^{-28} \times (3.0 \times 10^{8})^2$$

$$E = 2.7 \times 10^{-11}\text{J}$$

Question book page 17 and 18 question 6 to 8.

3.7 I understand how energy is produced from nuclear fission and fusion reactions.

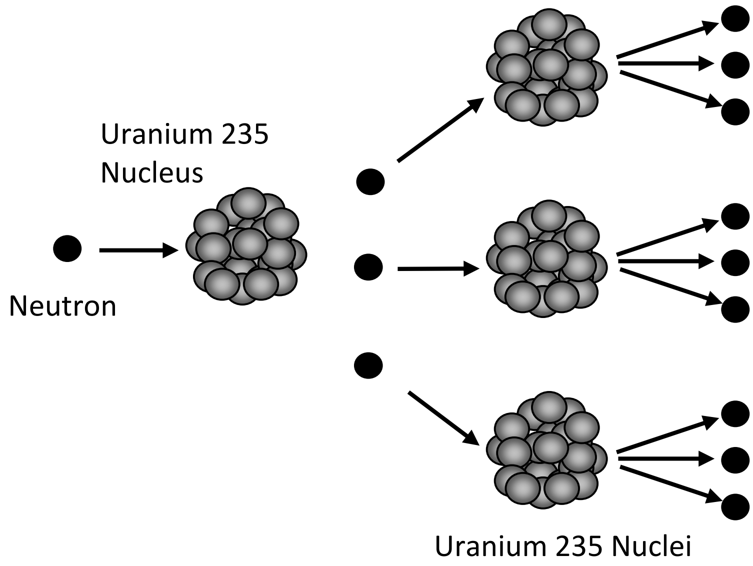
Energy from Fission Reactions

Using fission to produce energy is achieved by the exploiting the chain reaction described below.

In a fissionable material a neutron released from induced fission can go on to induce fission in other nuclei. This can cause a rapid release of energy in a material which contains large proportion of fissionable atoms. In nuclear power stations a chain reaction in either uranium or plutonium is used to produce energy. Materials which slow down or absorb neutrons are used to control the chain reaction.

<u>Example</u>

The neutrons released when a Uranium 235 nucleus fissions can go on to induce fission in other Uranium 235 nuclei.

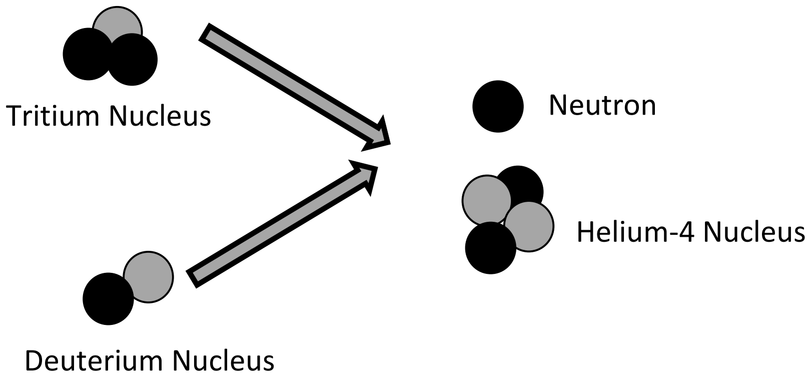


Energy from Fusion Reactions

Fusion occurs when two smaller nuclei are forced together to produce a larger nucleus. This is the process which produces energy in the Sun and other stars. In main sequence stars hydrogen nuclei are fused to form helium nuclei mainly via the proton-proton chain. In other stars, helium and other heavier elements are fused to form larger nuclei up to iron. Elements with atomic number greater than iron are produced by fusion during supernovae explosions.

Work is currently being done to use fusion to produce energy. The main method being explored is by fusing deuterium ${}^{2}_{1}\mathrm{H}$ and tritium ${}^{3}_{1}\mathrm{H}$ to form helium given by the nuclear equation

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



The deuterium and tritium nuclei will only fuse when they are within the range of the strong force $\sim 10^{-15}\mathrm{m}$. As both nuclei are positively charged there is a large repulsive force which keeps them apart. This can be overcome by increasing the temperature to around 100million Kelvin so that the nuclei have sufficient kinetic energy to overcome the repulsive force.

3.8 I understand some of the coolant and containment issues with nuclear fusion.

The main issue around the production of energy from nuclear fusion is the containment of the very hot plasma required for the nuclear reactions to occur.

There are several approaches to producing nuclear fusion. The two main ones are

- Magnetic confinement
- Inertial confinement

Magnetic Confinement

The hot plasma is confined by magnetic fields within a torus shaped container. The magnetic field keeps the hot plasma from touching the sides of the torus which would cool the plasma and stop the fusion reactions. The plasma within the torus is heated by induction to the required high temperature.

Inertial Confinement

Small pellets containing around 10milligrams of deuterium and tritium and compressed and heated by lasers to achieve fusion temperatures. The time for the fusion reaction is so short that the inertia of the deuterium and tritium keeps them sufficiently close together for fusion to occur.

Homework Nuclear Reactions questions 1 and 2

Key Area: Spectra

Previous Knowledge

- Frequency
- Wavelength.
- What is meant by directly and inversely proportional.
- Calculate areas.

Success Criteria

4.1 I know that irradiance is the power per unit area incident on a surface.

4.2 I can solve problems involving irradiance, power and area.

4.3 I understand what is meant by the term “point source”.

4.4 I know that irradiance is inversely proportional to the square of the distance from a point source.

4.5 I can use and appropriate relationship to solve problems involving irradiance and distance from a point source.

4.6 I know what is meant by the terms of line emission spectra, continuous emission spectra and absorption spectra.

4.7 I am aware that the absorption lines in the spectrum of sunlight provide evidence for the composition of the Sun’s upper atmosphere.

4.8 I have knowledge of the Bohr Model of the Atom and the terms *ground state, energy levels, ionization* and *zero potential energy* which are used in this model.

4.9 I know the mechanism of production of line emission spectra, continuous emission spectra and absorption spectra in terms of electron energy level transitions.

4.10 I can solve problems involving energy levels and the frequency of the radiation emitted or absorbed

4.1 I know that irradiance is the power per unit area incident on a surface.

Irradiance is the total power incident on a surface per unit area.

Power (W)

Irradiance (Wm^{-2})

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

Area (m^2)

4.2 I can solve problems involving irradiance, power and area.

<u>Example</u>

A 200W projector projects and image onto a screen 1.5m by 1.5m. Calculate the irradiance at the screen.

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

$$I = \frac{200}{1.5 \times 1.5}$$

$$I = 89\text{Wm}^{-2}$$

Problem Book page 32 question 1

4.3 I understand what is meant by the term "point source".

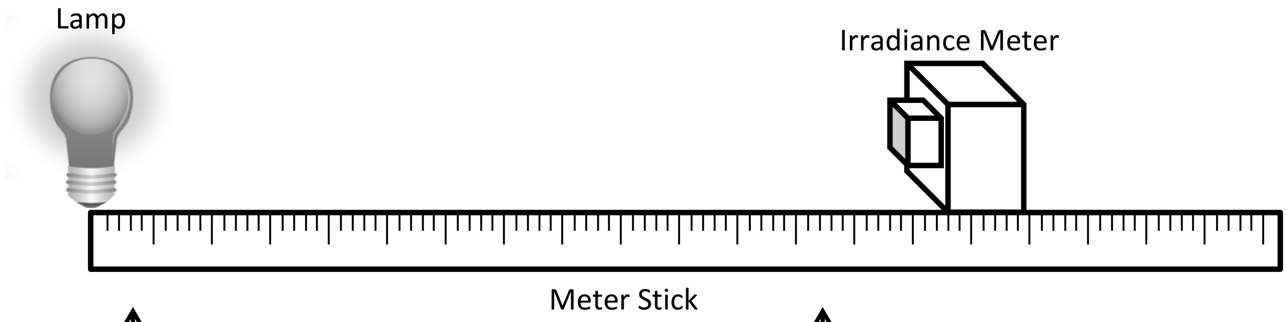
A point source is

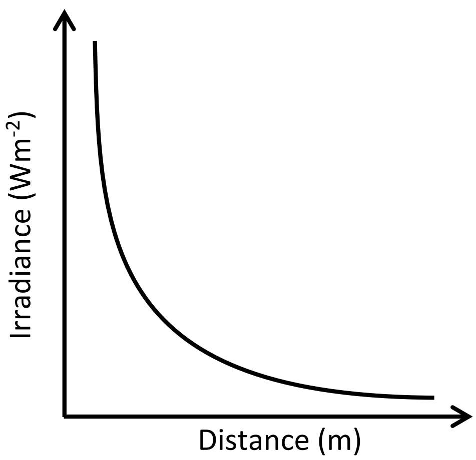
- where the source of light has negligible dimensions relative to the other dimensions of the situation being considered.
- where light radiates equally in all directions (Isotropic).

There are no true point sources of radiation. However, the concept is useful as many sources of light can be approximated to a point source.

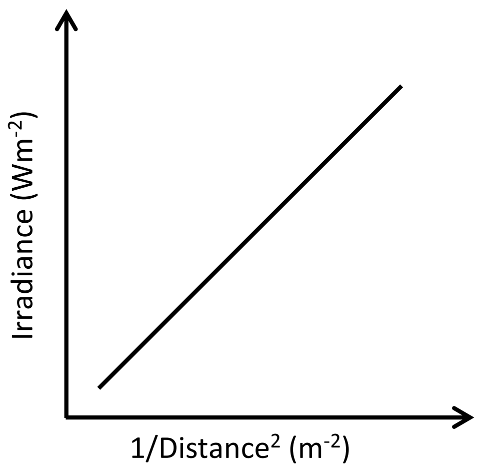
4.4 I know that irradiance is inversely proportional to the square of the distance from a point source.

The setup below can be used show the relationship between irradiance and distance for a point source. Irradiance is measured at various distances from the lamp and plotted on the left hand graph.





Graph shows that there is not a straight line relationship between distance and irradiance.



Re-plotting the data shows that there is a straight line relationship between $1/\text{Distance}^2$ and irradiance and that the line passes through the origin.

The right hand graph shows that $\textbf{Irradiance} \propto \frac{1}{\text{Distance}^2}$. This is known as an inverse square law as the irradiance is proportional to the inverse of the distance squared.

4.5 I can use and appropriate relationship to solve problems involving irradiance and distance from a point source.

As $\text{Irradiance} \propto \frac{1}{\text{Distance}^2}$ then

Irradiance (Wm^{-2})

$$I = \frac{k}{d^2}$$

k is a constant which depends on the brightness of the source.

Distance (m)

Inverse Square Law

A useful form of the inverse square law which gives the relationship between irradiance at two different distances from a point source is

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

This form of the relationship is not given on your relationship sheet.

> **Note** The inverse square law only applies when the light source is a point source.
>
> The inverse square law cannot be used with light from sources such as torches, led lamps, lasers and fluorescent lamps. Although they are small these sources do not emit light equally in all directions.
>
> The inverse square law can be used with the sun and stars. They can be considered as point sources when considered on the scale of the solar system or larger scales and they emit light equally in all directions.

Example

In a darkened room the irradiance from a filament lamp is $60Wm^{-2}$ at 1.2m. Find the irradiance at 2.0m

$d_1 = 1.2\text{m}$ $\qquad$ $I_1 = 60\text{Wm}^{-2}$

$d_2 = 2.0\text{m}$ $\qquad$ $I_2 = ?$

$I_1 d_1^2 = I_2 d_2^2$

$60 \times 1.2^2 = I_2 \times 2.0^2$

$$I_2 = \frac{60 \times 1.2^2}{2.0^2}$$

$$I_2 = \frac{60 \times 1.2^2}{2.0^2}$$

$$I_2 = 22\text{Wm}^{-2}$$

Example

At a distance, d, from a lamp the irradiance is I. Find an expression for the irradiance at $\frac{1}{2}d$.

Solution

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

From the question $d_2 = \frac{1}{2}d_1$

$$I_1 d_1^2 = I_2 \left(\frac{1}{2}d_1\right)^2$$

The d_1 terms cancel to give

$$I_1 = I_2 \left(\frac{1}{2}\right)^2$$

$$I_1 = \frac{1}{4}I_2$$

$$I_2 = 4I_1$$

Problem book pages 32 and 33 questions 2 to 5.

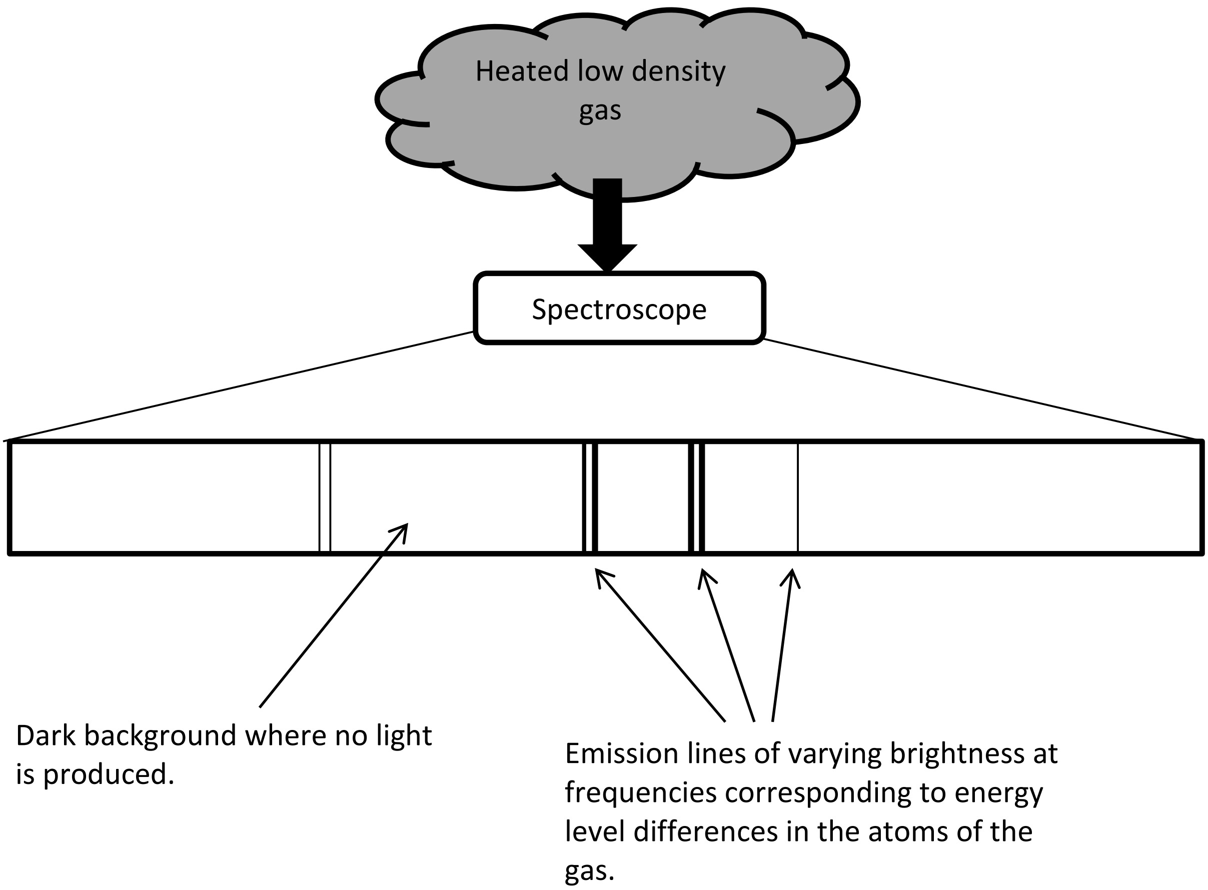
4.6 I know what is meant by the terms of line emission spectra, continuous emission spectra and absorption spectra.

Note
When referring to spectra "light" refers to any electromagnetic radiation not only visible light.

When light is passed through a spectroscope a spectrum is produced showing the different frequencies of light present.

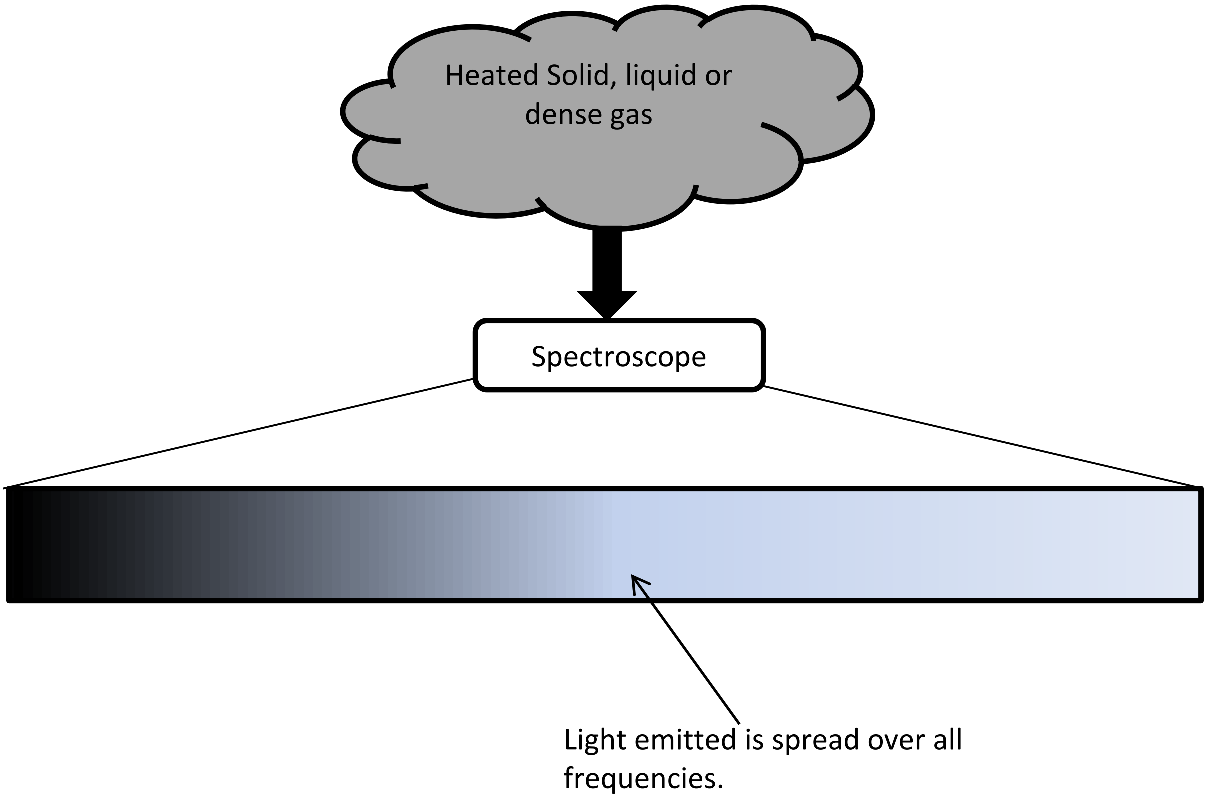
Line Emission Spectra

These are usually produced by heated low pressure gases. The frequencies of light produced correspond to the energy level differences present in the atoms of the gas. The pattern of lines is unique to each element. This type of spectrum can be used to identify the composition of gases.



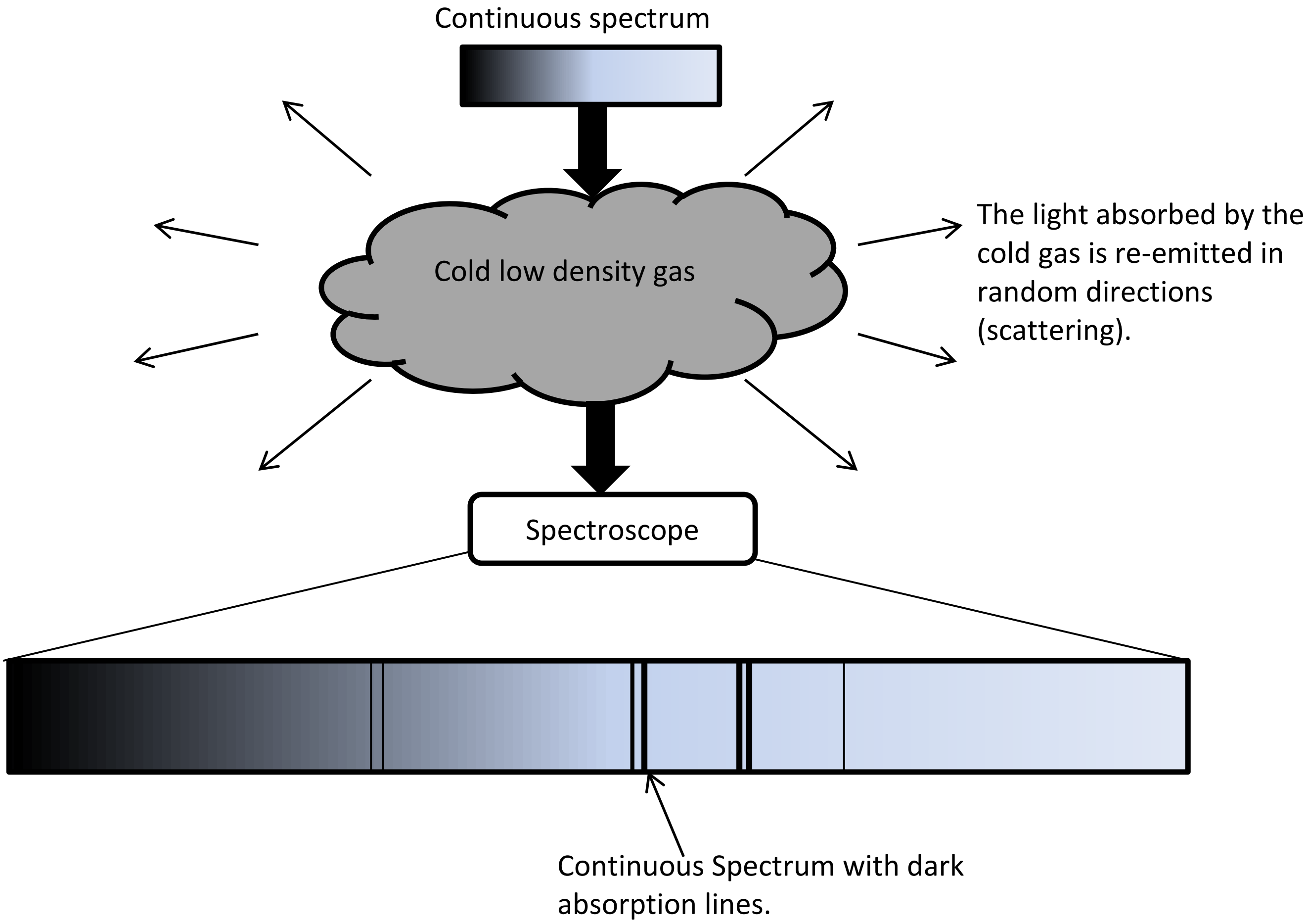
Continuous Emission Spectra

In heated solids, liquids and gases the light is emitted at all frequencies.



Absorption Spectra

When light of a continuous spectrum passes through a cold gas the frequencies corresponding to the energy level differences of the gas atoms are absorbed. These frequencies are then re-emitted but in random directions. This produces a continuous spectrum with dark bands.



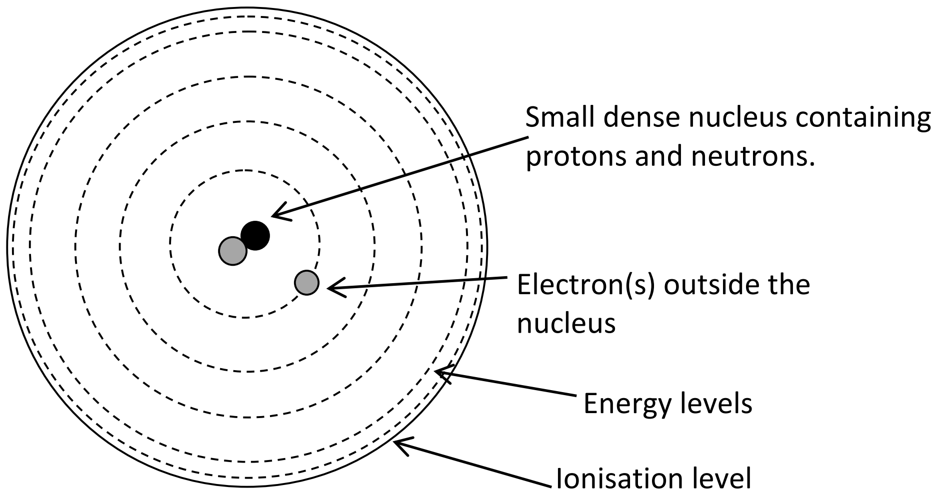
4.7 I am aware that the absorption lines in the spectrum of sunlight provide evidence for the composition of the Sun's upper atmosphere.

Fraunhofer lines are the absorption lines seen in the spectrum of the Sun. The Sun produces a continuous spectrum. This then passes through the Sun's colder outer atmosphere which produces the absorption lines seen. As each element and molecule as its own unique pattern of absorption this allows the composition of the Sun's atmosphere to be determined.

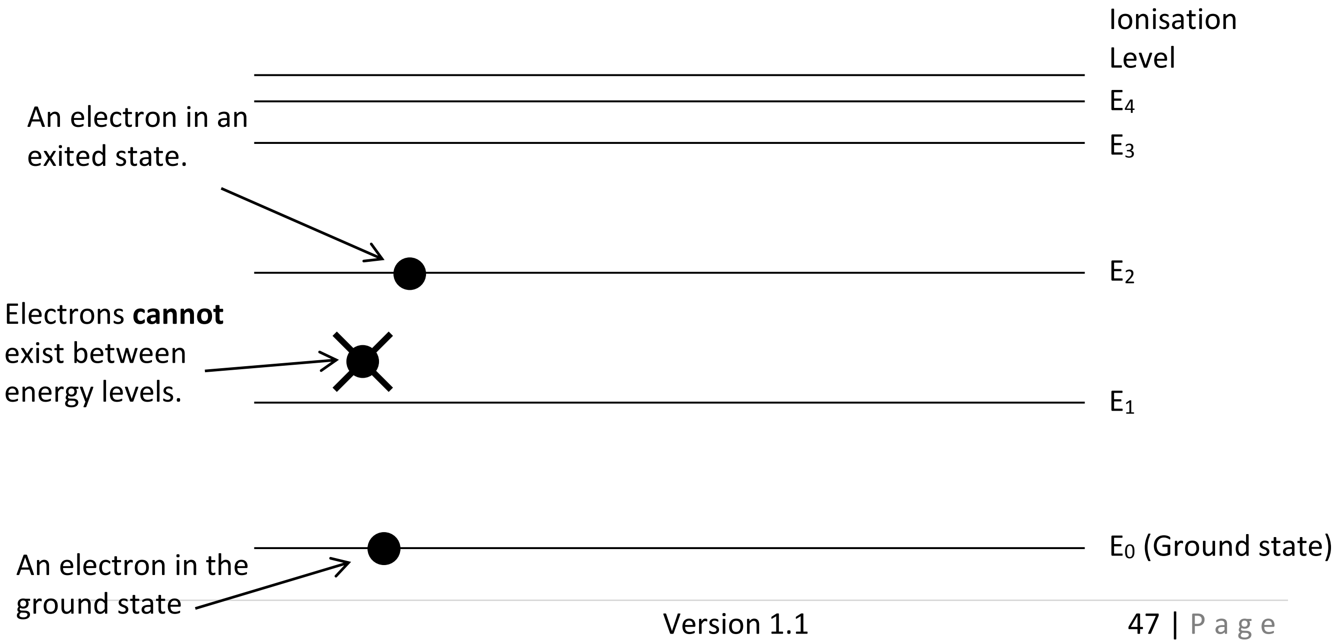
Question book page 35 question 6.

4.8 I have knowledge of the Bohr Model of the Atom and the terms *ground state, energy levels, ionization* and *zero potential energy* which are used in this model.

In Bohr model of the atom there is a central nucleus containing protons and neutrons. Around the nucleus there are electrons which occupy different energy levels. The lowest energy level is referred to as the ground state. At higher energy levels the electron is in an exited state but is still bound to the atom. The highest level is called the ionisation level. This is where the electron has sufficient energy to leave the atom leaving a positively charged ion.

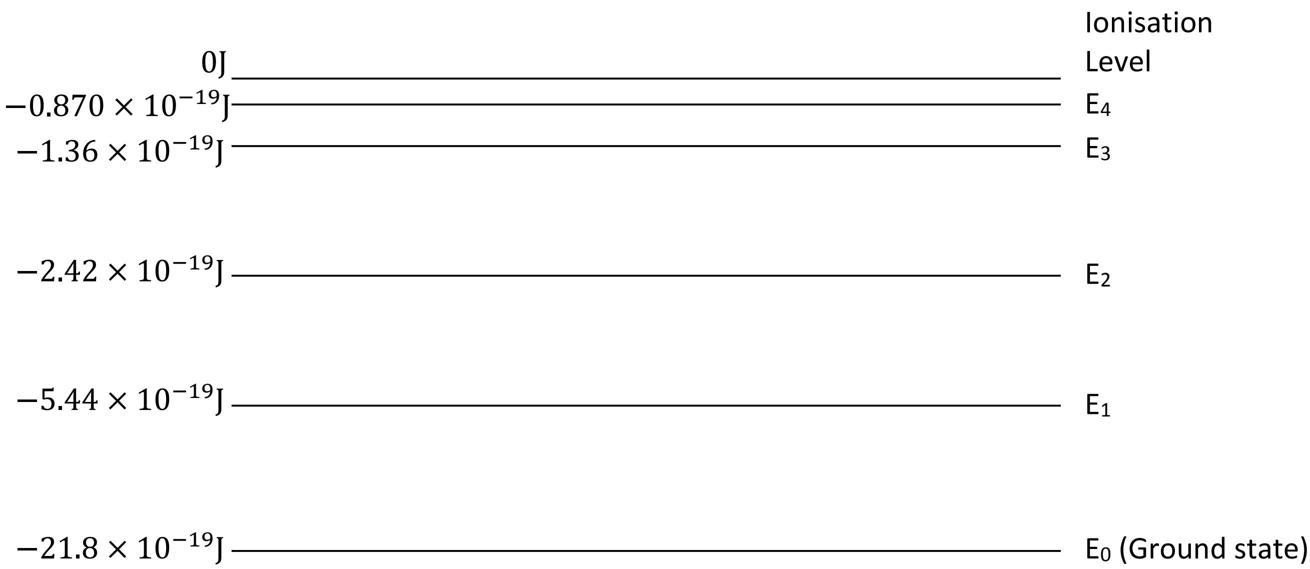


The energy levels are usually drawn as straight lines with the ground state at the bottom. These are labelled E_0, E_1, E_2 . . . The energy levels become closer together as they approach the ionisation level.



Energy level values are usually given in electron volts (eV) but in this course the SI unit of Joules will be used. Below are some of the energy levels in a hydrogen atom. There are many more levels between the E4 level and the ionisation level which are not shown on the diagram.

The negative sign indicates that energy is lost by the electron as it moves into a lower energy state. E.g. if and electron moves from E_2 to E_1 it loses energy. An electron which is at reaches the ionisation level has zero potential energy at which point it has escaped from the atom.



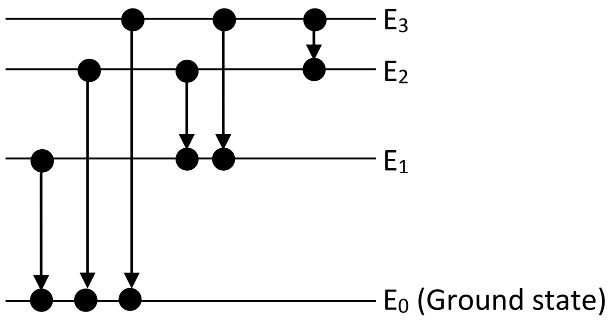
4.9 I know the mechanism of production of line emission spectra, continuous emission spectra and absorption spectra in terms of electron energy level transitions.

Emission and Absorption of Photons

Electrons are not stable in energy levels above the ground state. Electrons in a higher energy level will move to a lower energy level emitting energy in the form of photon.

Electrons are moved from lower energy levels to higher energy levels by the absorption of a photon. This photon can come from incident radiation, the interaction of the electron with electrons in an electrical current, or from interaction with electrons in other atoms in heated materials.

The energy of this photon absorbed or emitted will be equal to the energy difference between the energy levels.



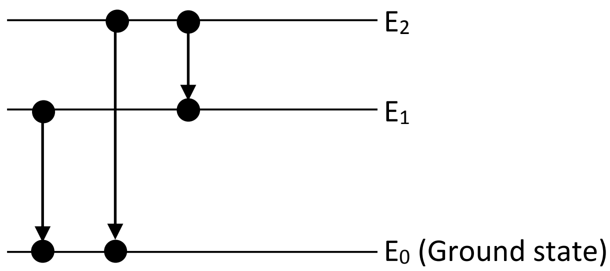
There are many possible transitions from one energy level to another in an atom. Each transition corresponds to a line in a line spectrum produced by the atom.

In an absorption spectrum each transition corresponds to a line in the absorption spectrum.

<u>Example</u>

The diagram below shows the energy levels in an atom. How many lines would appear in the line spectrum produced by this atom.

Solution



There are three possible transitions between energy levels so there will be three lines in the emission spectrum.

Question book page 33 question 2.

4.10 I can solve problems involving energy levels and the frequency of the radiation emitted or absorbed

From the section on the photoelectric effect you know $\mathrm{E} = \mathrm{hf}$ so the frequency of light emitted or absorbed can be calculated.

$$\Delta \mathrm{E} = \mathrm{hf}$$

Difference between Energy levels (J)

Plank's constant (Js)

$= 6.63 \times 10^{-34}\mathrm{Js}$

Frequency (Hz)

Example

In a hydrogen atom an electron moves from the E_2 level to the E_1 level emitting a photon. Calculate the frequency of this photon.

$$E_1 = -5.44 \times 10^{-19}\mathrm{J}$$

$$E_2 = -2.42 \times 10^{-19}\mathrm{J}$$

$$\Delta E = E_1 - E_2 = 5.44 \times 10^{-19} - 2.42 \times 10^{-19}$$

You can ignore the negative signs

$$\Delta E = 3.02 \times 10^{-19}\mathrm{J}$$

$$\Delta E = hf$$

$$3.02 \times 10^{-19} = 6.63 \times 10^{-34} \times f$$

$$f = \frac{3.02 \times 10^{-19}}{6.63 \times 10^{-34}}$$

$$f = 4.56 \times 10^{14}\mathrm{Hz}$$

Problem book pages 33 to 35 questions 1 to 8.

Homework Spectra.

Key Area: Wave Particle Duality

Previous Knowledge

- Frequency
- Wavelength.
- $E = hf$.

Success Criteria

5.1 I am aware that there is a wave model of light and a particle model of light.
5.2 I know the photoelectric effect occurs when photons of sufficient energy eject electrons from the surface of materials.
5.3 I know that the threshold frequency is the minimum frequency of a photon required for photoemission.
5.4 I know that the work function of the material is the minimum energy required to cause photoemission.
5.5 I can use an appropriate relationship to solve problems involving the maximum kinetic energy of photoelectrons, the threshold frequency of the material and the frequency of the photon
5.5 I understand and can sketch graphs of current against frequency involving the photoelectric effect.
5.7 I am aware of the photoelectric effect as evidence supporting the particulate model of light.

5.1 I am aware that there is a wave model of light and a particle model of light.

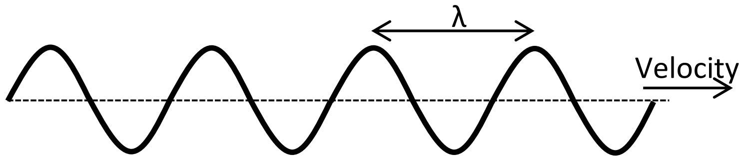
The properties and behaviour of light can be described as a wave or as a particle.

<u>Light as Waves</u>

Light (and other electromagnetic waves) can be described as continuous waves. They can be reflected, refracted, diffracted and produce interference.

A continuous electromagnetic wave has

- Speed (v) of 3.0×10^8 ms^{-1} in a vacuum.
- Frequency (f) measured in hertz.
- Wavelength (λ) measured in metres.



The equation $v = f\lambda$ gives the relationship between these three properties of a wave.

Period and frequency are related by the equation

Period (s)

$$T = \frac{1}{f}$$

Frequency (Hz)

Example

A red light source has a wavelength of 650nm.

a. Calculate its frequency.
b. Calculate its period.

Solution

a. $v = f\lambda$

$f = \frac{v}{\lambda}$

$f = \frac{3.0 \times 10^8}{650 \times 10^{-9}}$

$f = 4.6 \times 10^{14}\text{Hz}$

b. $T = \frac{1}{f}$

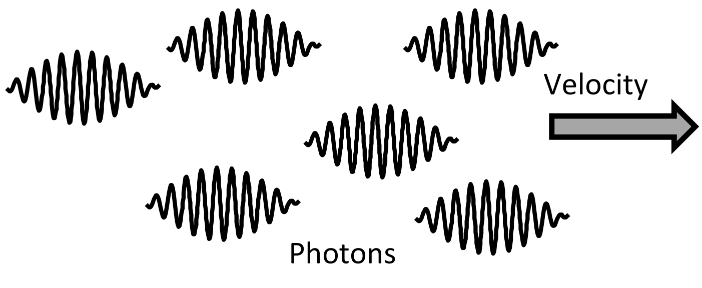
$T = \frac{1}{4.6 \times 10^{14}}$

$T = 2.2 \times 10^{-15}\text{s}$

Question book page 19 questions 1, 2 and 3.

Light as Particles

Light is represented as a stream of energy moving in discrete packets (quanta) called photons.



The energy of each of these photons is given by

$$E = hf$$

Energy (J) — Plank's constant (Js) — Frequency (Hz)

$= 6.63 \times 10^{-34}$Js

<u>Example</u>

A red light source has a frequency 2.2×10^{15}Hz. Calculate the energy of each photon.

$E = hf$

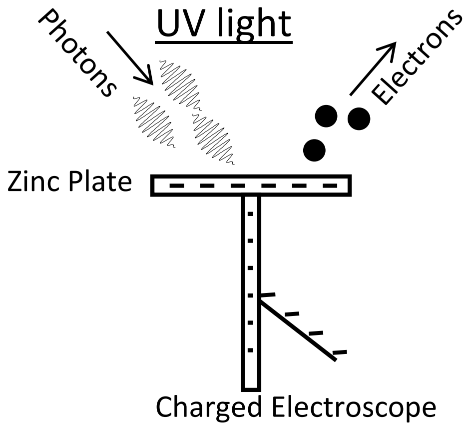
$E = 6.63 \times 10^{-34} \times 2.2 \times 10^{15}$

$E = 1.5 \times 10^{-18}$J

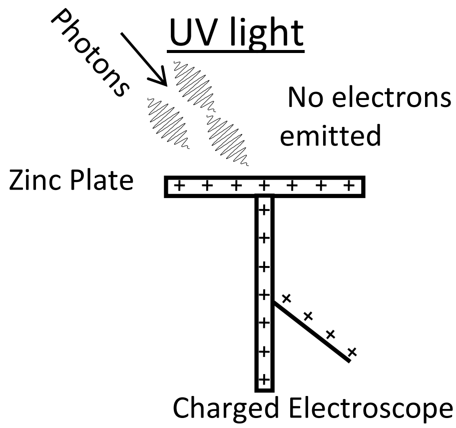
Question book page 19 questions 4 to 6.

5.2 I know the photoelectric effect occurs when photons of sufficient energy eject electrons from the surface of materials.

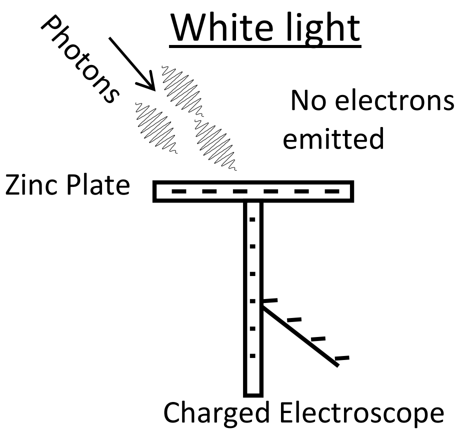
The experiment shown below shows what occurs when both white light and UV light are shone on to a metal zinc plate.



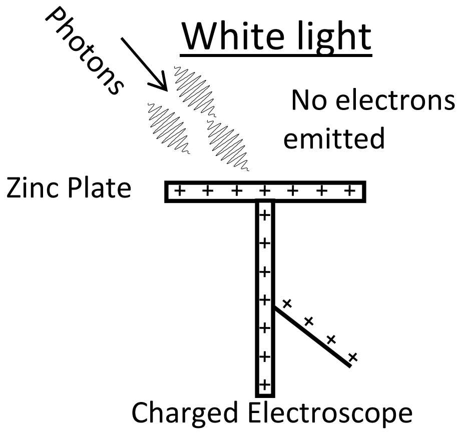
(Negative)



(Positive)



(Negative)



(Positive)

Only the combination of UV light and a negatively charged plate gives the emission of electrons from the surface of the zinc.

- White light will not cause the emission of electrons from the surface of the zinc.
- The zinc plate must be negatively charged for electrons to be emitted.

Electrons are bound in the metal by attractive forces. Energy is requried to overcome these forces and remove the electrons from the surface. Each photon which strikes the metal causes one electron to be emitted. This only occurs if the energy of the photon is equal to or greater than the work function of the metal. Electrons are not emitted from the positively charge plate as any electron emitted is immediately attracted back onto the plate by the positive charge.

5.3 I know that the threshold frequency is the minimum frequency of a photon required for photoemission.

The minimum frequency required to eject electrons is called the threshold frequency (f_0). Below the threshold frequency no electrons are emitted. Above the threshold frequency electrons are emitted. The threshold frequency is related to the work function of the material.

5.4 I know that the work function of the material is the minimum energy required to cause photoemission.

Work function is the **minimum** energy required to remove an electron from the metal. As one photon will eject one electron then

$$\text{Work Function} = hf_0$$

Plank's Constant   Threshold frequency

Each metal has its own value for work function eg zinc 6.88×10^{-19}J and copper

7.52×10^{-19}J

<u>Example</u>

Calculate the threshold frequency of copper.

<u>Solution</u>

Work function = h f_0

$$f_0 = \frac{\text{Work Function}}{h}$$

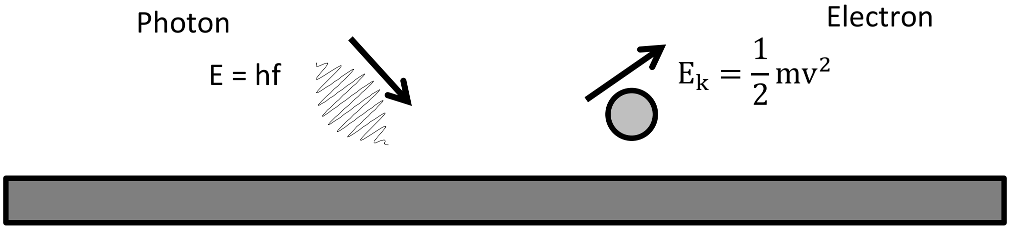
$$f_0 = \frac{7.52 \times 10^{-19}}{6.63 \times 10^{-34}}$$

$$f_0 = 1.13 \times 10^{15}\text{Hz}$$

Problem book page 20 question 7.

5.5 I can use an appropriate relationship to solve problems involving the maximum kinetic energy of photoelectrons, the threshold frequency of the material and the frequency of the photon

EINSTEIN'S PHOTOELECTRIC EQUATION



Metal work function $= hf_0$

In the photoelectric effect energy is transferred from an incident photon to an electron. Some of the energy of the photon (hf) absorbed by the metal is used to remove the electron from the metal (work function $= hf_0$) any remaining energy appears as kinetic energy of the electron $E_k = \frac{1}{2}mv^2$.

$$\text{Energy of the photon} = \text{work function} + \text{Maximum Kinetic energy of the electron}$$

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

As the work function is the minimum energy required to remove an electron Einstein's equation will give the maximum kinetic energy of the electron.

<u>Example</u>

Light of frequency 2.00×10^{15} Hz is shone onto a negatively charged plate of zinc. Calculate the maximum speed of the electrons emitted.

Work function of zinc $= 6.88 \times 10^{-19}$ J

Mass of an electron $= 9.11 \times 10^{-31}$ kg

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

$$6.63 \times 10^{-34} \times 2.00 \times 10^{15} = 6.88 \times 10^{-19} + \frac{1}{2} \times 9.11 \times 10^{-31} \times \mathrm{v}^2$$

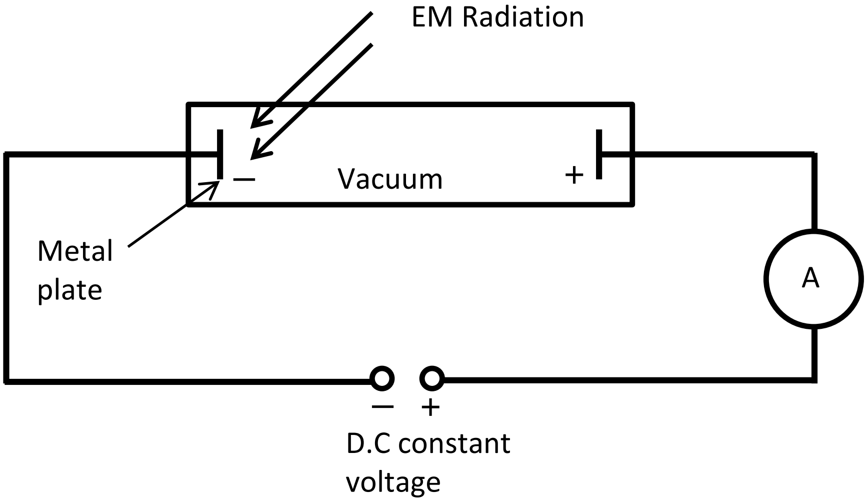
$$\mathrm{v} = \sqrt{\frac{(6.63 \times 10^{-34} \times 2.00 \times 10^{15}) - 6.88 \times 10^{-19}}{\frac{1}{2} \times 9.11 \times 10^{-31}}}$$

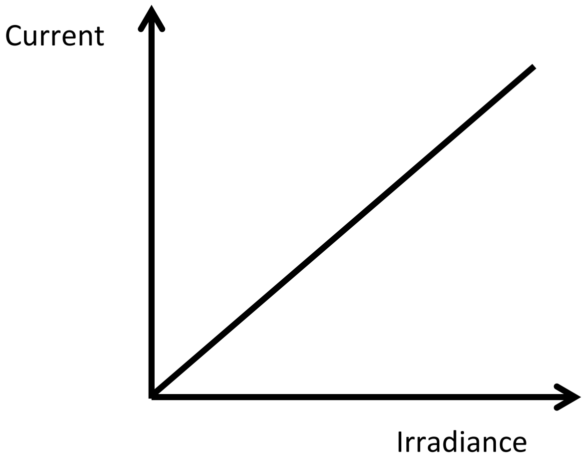
$$\mathrm{v} = 1.2 \times 10^{6} \mathrm{ms}^{-1}$$

Problem book page 21 questions 9 to 12

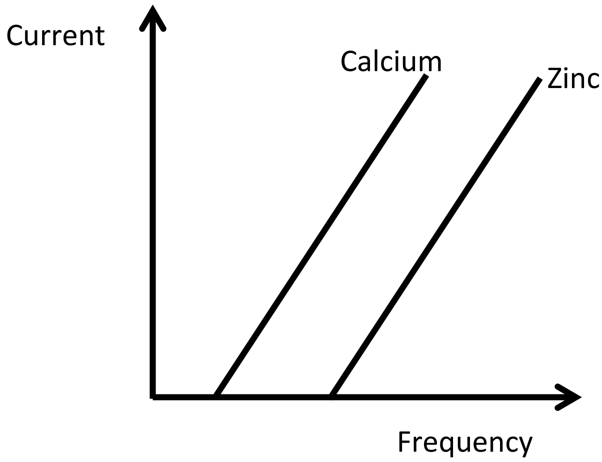
5.6 I understand and can sketch graphs of current against frequency involving the photoelectric effect.

The equipment below can be used to measure the number of electrons produced by the photoelectric effect. Electromagnetic radiation of frequency above the threshold frequency is shone onto the negative metal plate in the vacuum tube. The emitted electrons are attracted to the positively charged plate. This produces an electric current called the photoelectric current which can be measured with a picoammeter. This current will be proportional to the number of electrons emitted.





For a constant frequency above the threshold frequency the current is proportional to irradiance.



For a constant irradiance there exists a threshold frequency for each metal.

Problem book page 20 question 8, page 22 question 13 and 14.

5.7 I am aware of the photoelectric effect as evidence supporting the particulate model of light.

The table below gives a summary of the predictions of the wave and particle models of light. It clearly shows that in the photoelectric effect light is behaving as a particle. However in the following section on interference evidence will be presented showing light behaving as a wave.

Light as a Wave	Light as a Particle	Evidence from the photoelectric effect
Energy is proportional to amplitude squared so any frequency of light should emit electrons given sufficient irradiance.	Energy is given by E = hf. Only frequencies above the threshold frequency should emit electrons.	Threshold frequency exists.
Energy delivered as a continuous wave so it should take time for sufficient energy to be acquired by the electrons	Energy delivered in discrete packets so electrons should be emitted immediately.	Electrons emitted immediately.
Increased irradiance should give greater energy to the electrons so their kinetic energy should depend on irradiance.	Energy delivered in discrete packets so the kinetic energy of each electron should not depend on irradiance.	Kinetic energy of the electrons does not depend on irradiance.
Energy delivered depends on irradiance not frequency so the kinetic energy of the electrons should not depend of frequency.	Energy delivered depends on frequency so the kinetic energy of the electrons should depend on frequency.	Kinetic energy of the electrons depends on frequency.

Homework Wave Particle Duality questions 3 to 5.

Key Area: Interference and Diffraction

Previous Knowledge

- Frequency
- Wavelength.

Success Criteria

6.1 I know the meaning of the terms; crest, trough, amplitude, wavelength, frequency and period.

6.2 I know that coherent waves have a constant phase relationship and have the same frequency, wavelength and velocity.

6.3 I can describe the conditions for constructive and destructive interference in terms of the phase difference between two waves.

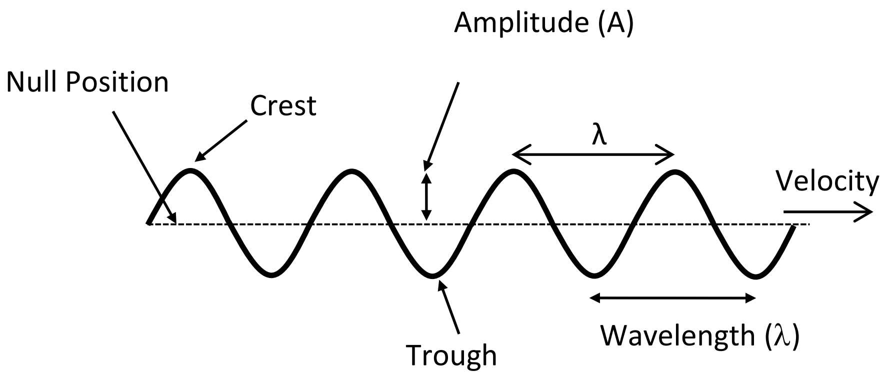
6.4 I know that maxima and minima are produced when the path difference between waves is a whole number of wavelengths or an odd number of half-wavelengths respectively.

6.5 Use of an appropriate relationship to solve problems involving the path difference between waves, wavelength and order number.

6.6 Use of an appropriate relationship to solve problems involving grating spacing, wavelength, order number and angle to the maximum.

6.7 I can describe and explain the spectrum produced when white light passes through a diffraction Gratings.

6.1 I know the meaning of the terms; crest, trough, amplitude, wavelength, frequency and period.



Amplitude (A): Height of a wave from the null position. (metres - m)

Wavelength (λ): Length over which a wave repeats itself. (metres - m)

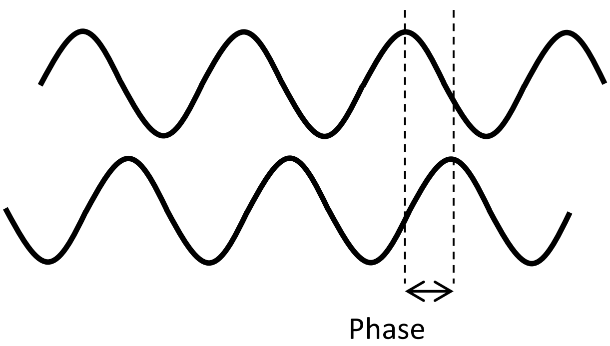
Frequency (f): Number of waves per second (Hertz - Hz).

Velocity (v): The distance the wave moves per second (metres per second – ms^{-1})

Period (T): The time taken for one wave to pass (seconds - s).

6.2 I know that coherent waves have a constant phase relationship and have the same frequency, wavelength and velocity.

If 2 waves are coherent when they have the same frequency, wavelength, velocity and a constant phase relationship.



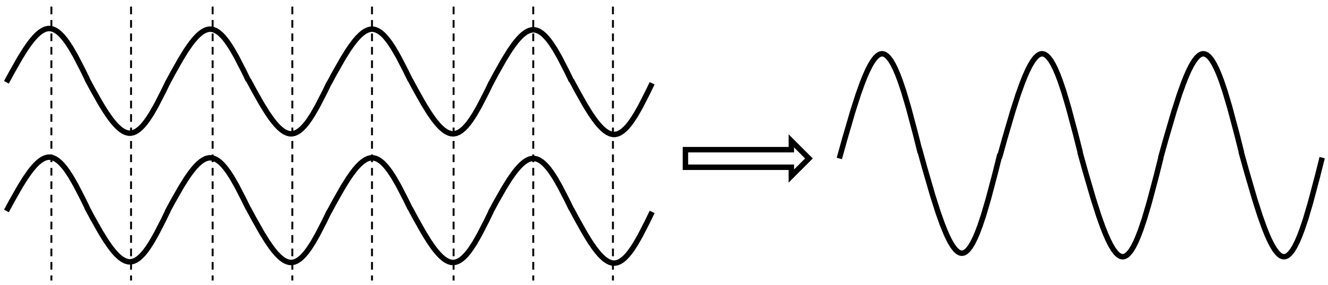
A constant phase relationship is when the difference in position between wave crests (phase difference) does not change.

6.3 I can describe the conditions for constructive and destructive interference in terms of the phase difference between two waves.

6.4 I know that maxima and minima are produced when the path difference between waves is a whole number of wavelengths or an odd number of half-wavelengths respectively.

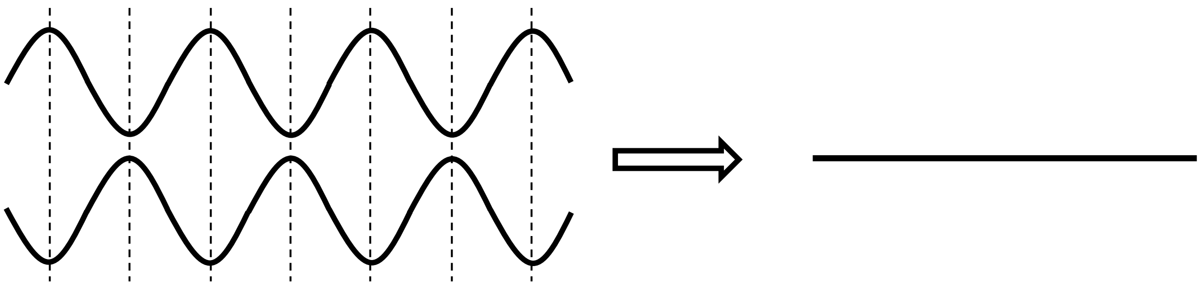
Constructive Interference

When two waves cross and their crests and troughs line up a larger amplitude wave is produced. Constructive interference is at a maximum when the phase difference is zero or a multiple of whole wavelengths.



Destructive Interference

When two waves cross and their crests line up with troughs the waves cancel each other. Destructive interference is at a maximum when the phase difference is half a wavelength or an odd multiple of half wavelengths.

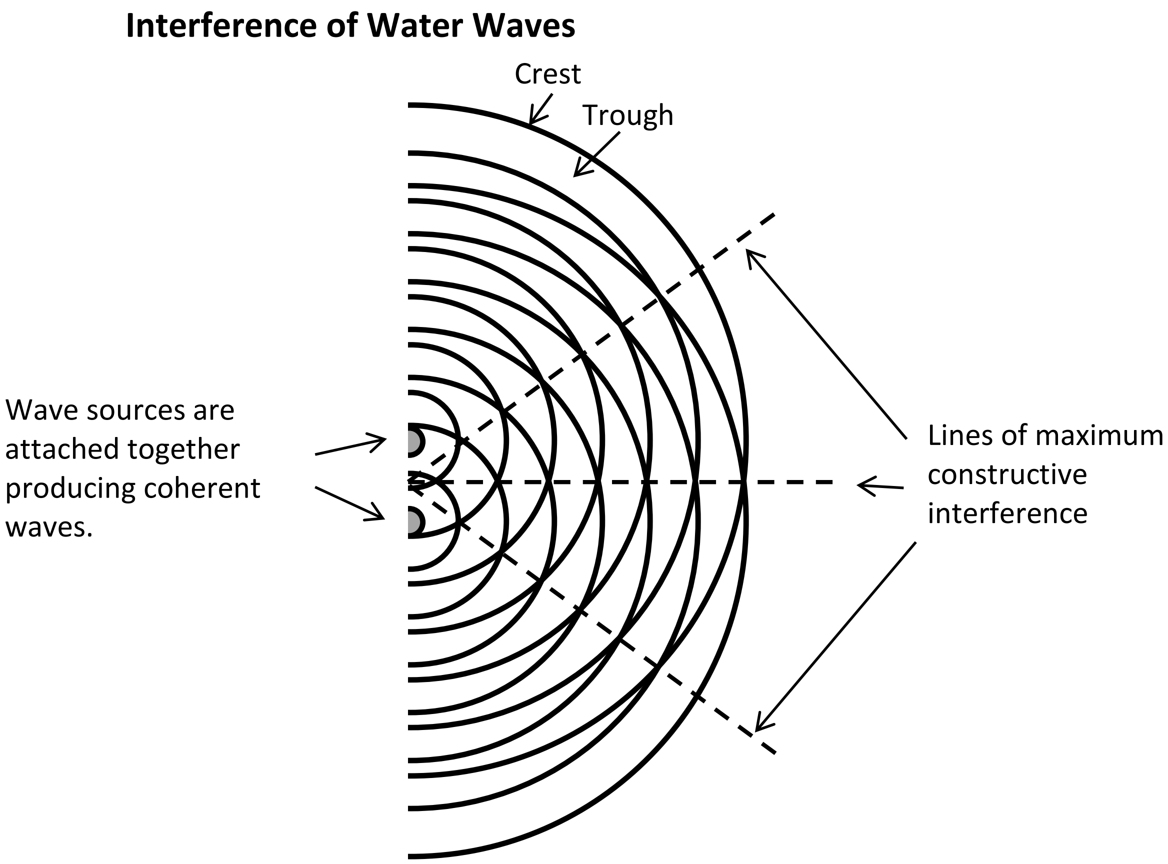


Interference occurs between all waves. However, if the waves are not coherent the changing phase relationship between them cancels out the constructive and destructive interference. Interference effects are usually only apparent when interference occurs between waves from coherent sources.

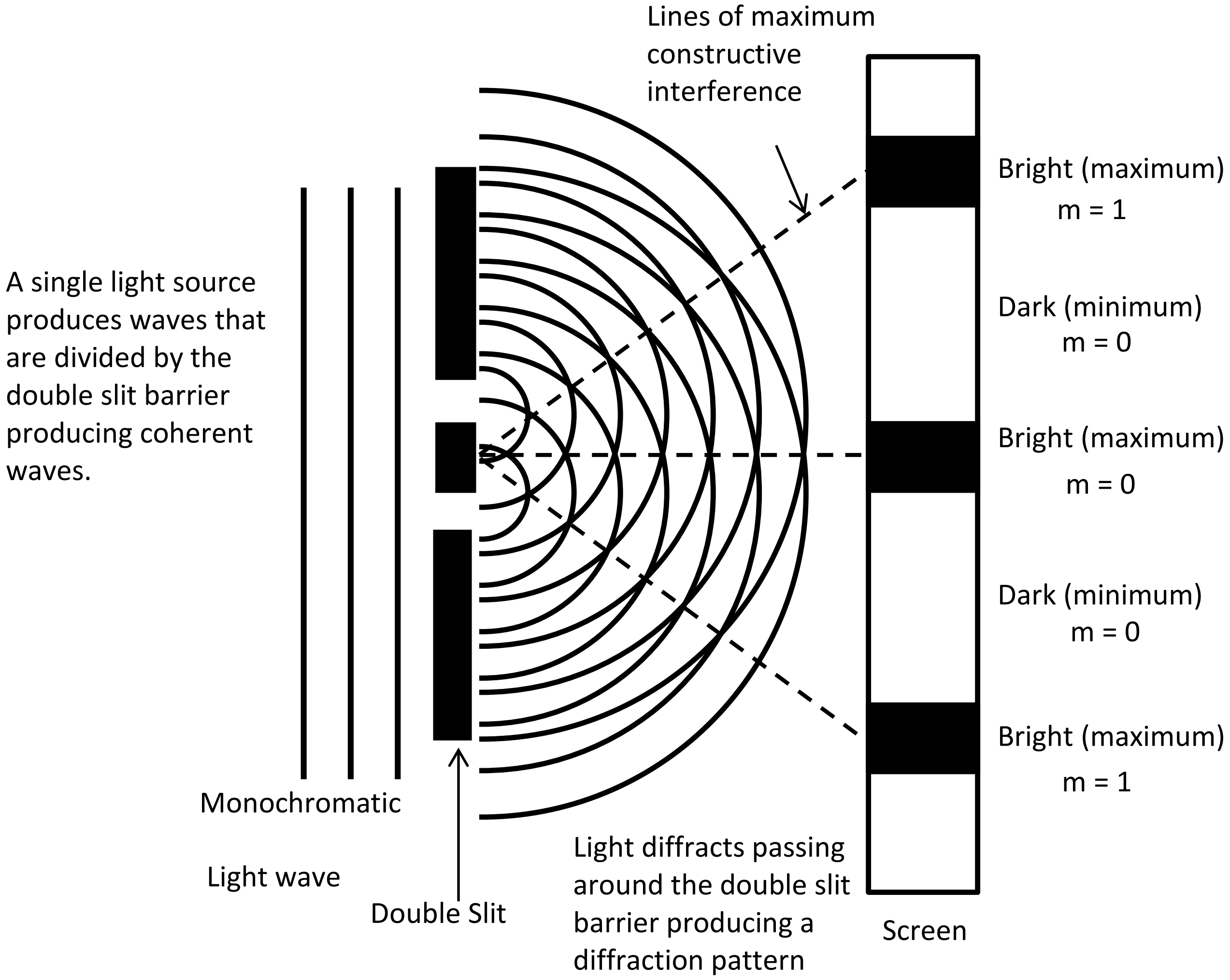
Destructive Interference and Light

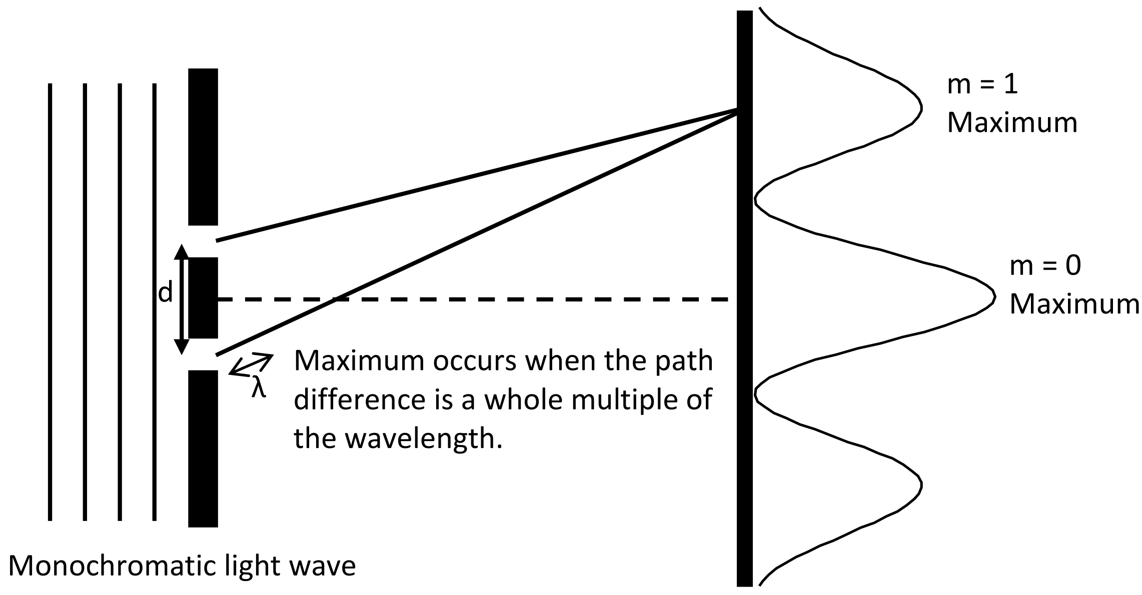
Interference is a property of waves. Waves combine through destructive interference to cancel each other out. This is not possible with particles as particles will not cancel. Interference of light shows that it behaves like a wave. Note that the photoelectric effect shows that light can also behave like a particle.

Interference Between Coherent Sources

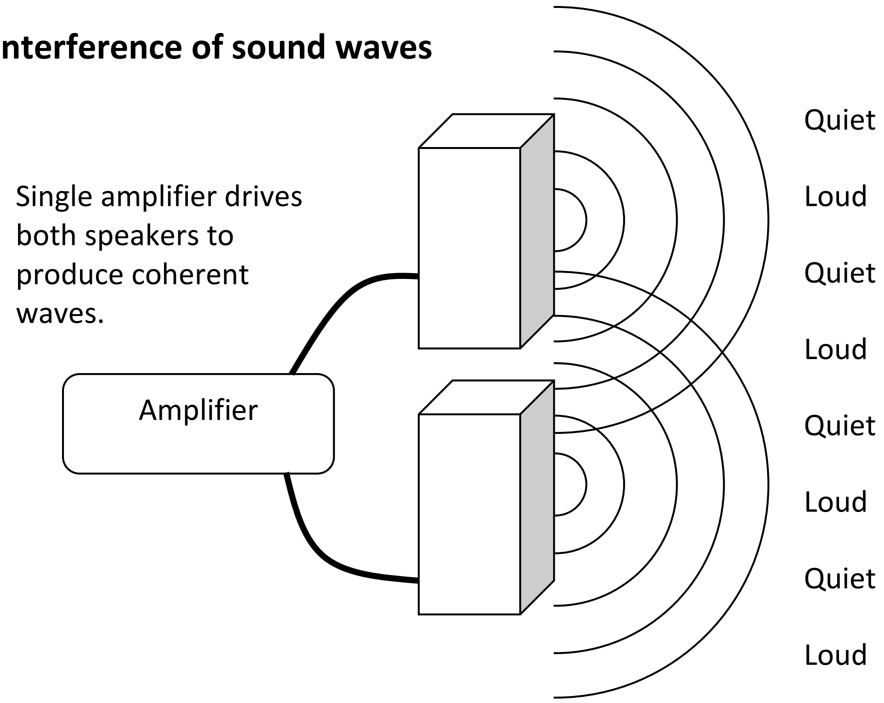


Interference of Light Using a Double Slit





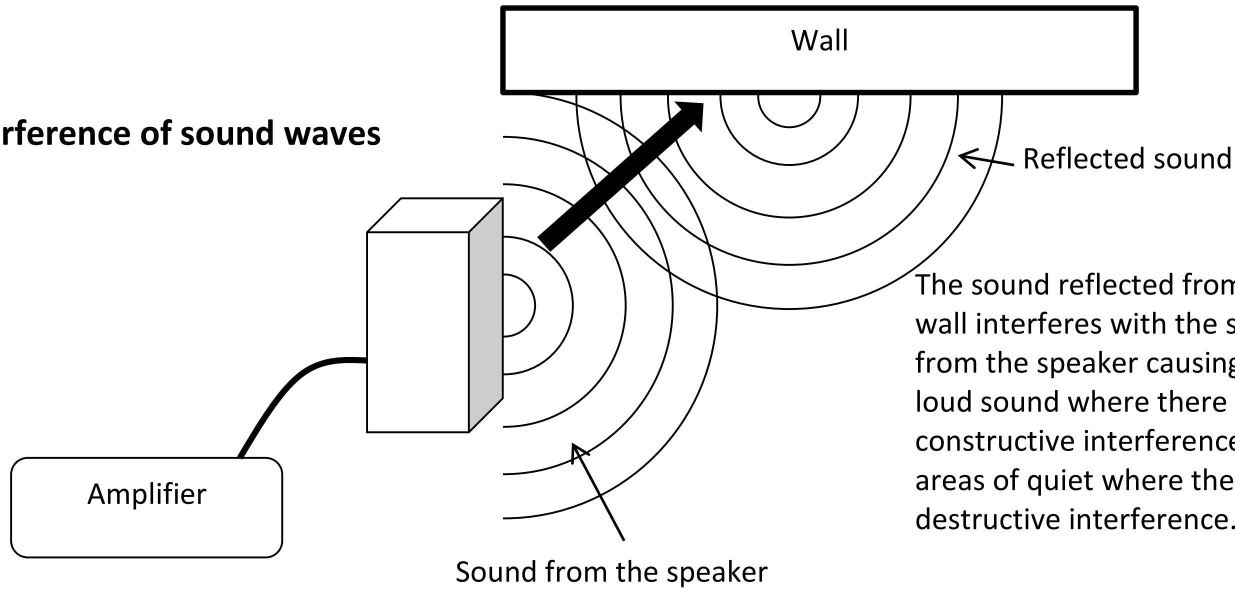
Interference of sound waves



Areas of loud sound where there is constructive interference and areas of quiet where there is destructive interference.

Interference from reflections

Interference of sound waves



The sound reflected from the wall interferes with the sound from the speaker causing areas of loud sound where there is constructive interference and areas of quiet where there is destructive interference.

Problem book page 24 question 1

6.5 I can use an appropriate relationship to solve problems involving the path difference between waves, wavelength and order number.

Constructive interference (i.e. a maximum)

For constructive interference the difference in path length must be a multiple of whole wavelengths.

Wavelength (λ)

$$\text{Path difference} = \text{m}\lambda$$

Order, m = 0, 1, 2 . . .

m = 0 for the central maximum, m = 1 for the next maximum, . . .

Destructive Interference (i.e. a minimum)

For destructive interference the difference in path length must be an odd multiple of half wavelengths.

Wavelength (λ)

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

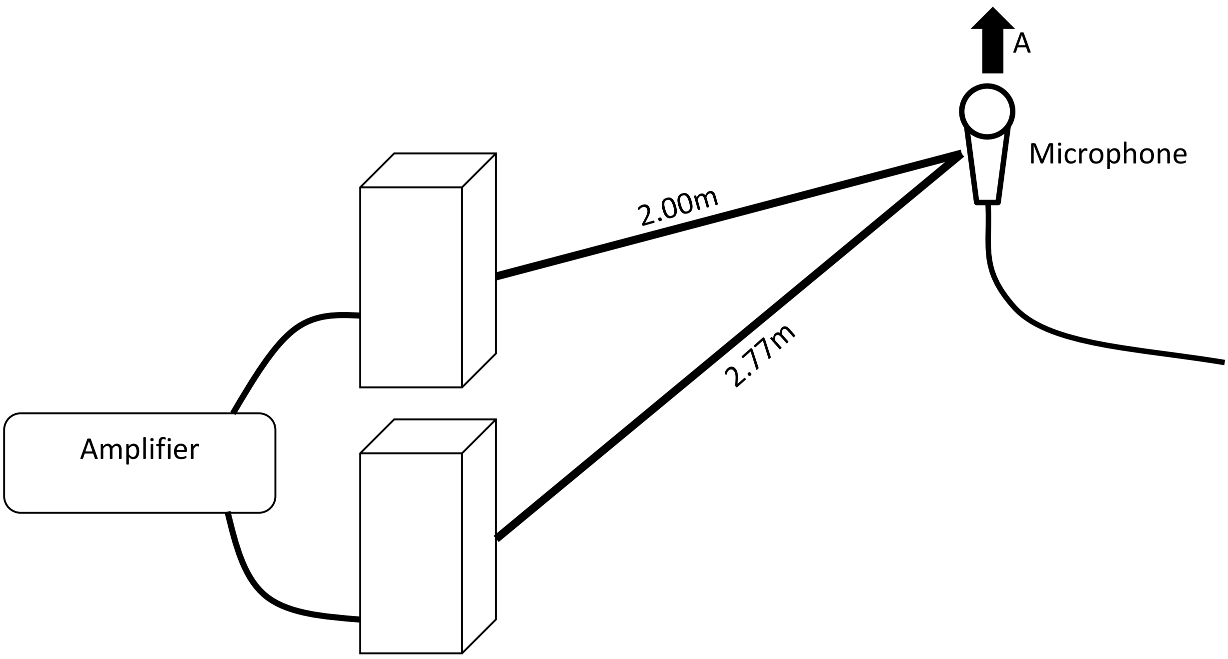
Order, m = 0, 1, 2 . . .

m = 0 for the first minimum, m = 1 for the next minimum . . . Note that this is different from constructive interference.

Example

A pair of loud speakers produces a sound at 440Hz. The path lengths to a microphone are shown on the diagram.

a. Show by calculation that there will be constructive interference at the microphone.
b. State and explain what would happen to the volume of the sound picked up by the microphone as it is moved in the direction indicated by arrow A.



Solution

a. Path difference $= 2.77 - 2.00 = 0.77\text{m}$

$$v = f\lambda$$

$$\lambda = \frac{v}{f} = \frac{340}{440} = 0.77\text{m}$$

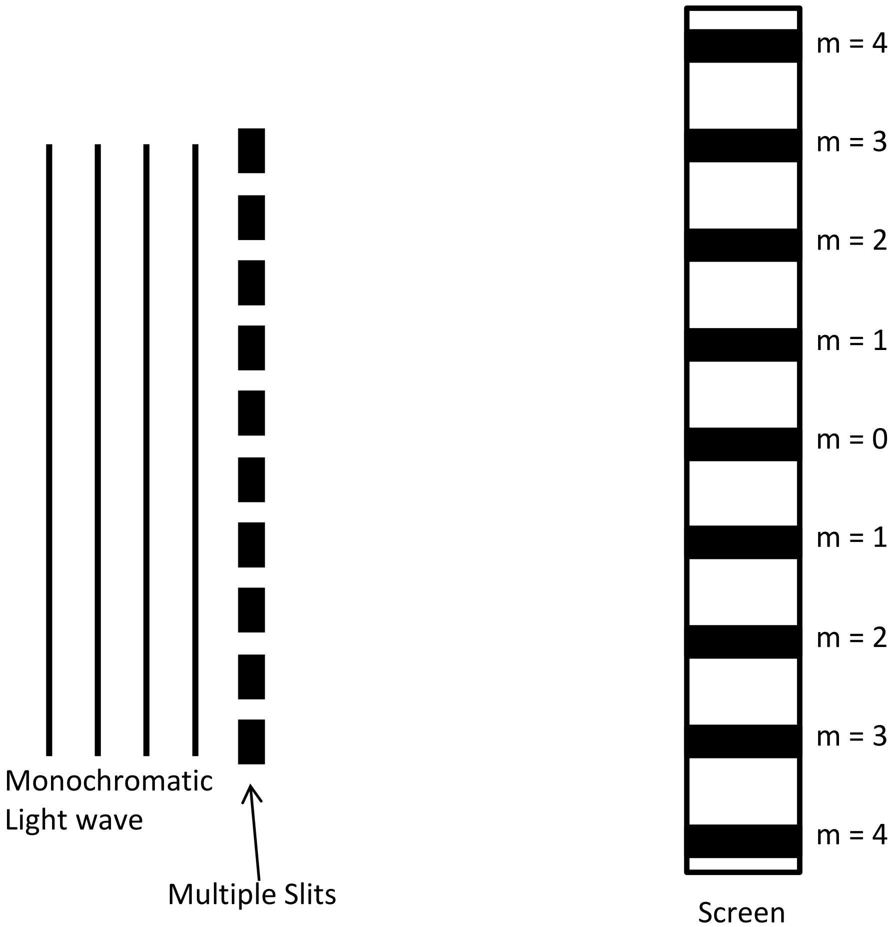
The path difference is one wavelength so there will be constructive interference.

b. The volume will decrease then increase as it moves from a maximum to a minimum then back to a maximum. This is due to alternating areas of constructive and destructive interference.

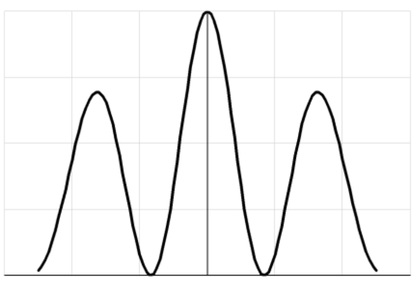
Problem book pages 24 and 25 question 2 to 4, Page 26 question 6

6.6 I can use an appropriate relationship to solve problems involving grating spacing, wavelength, order number and angle to the maximum.

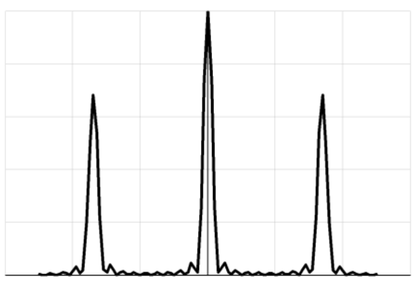
Interference of Light Using a Diffraction Grating



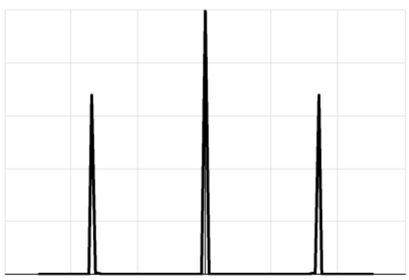
A diffraction grating consists of many slits. This produces a much sharper diffraction pattern than the double slits.



2 Slits



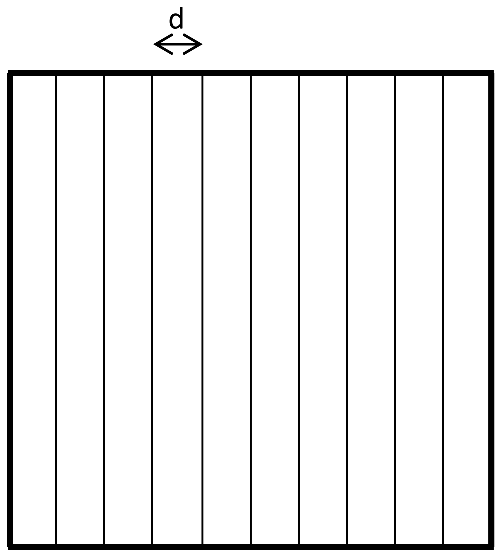
10 Slits



100 Slits

The Diffraction Grating

Diffraction gratings consist of a piece of glass with many lines scored on it creating multiple slits. The specification of a diffraction pattern usually tells you the number of lines per millimetre there are on the glass e.g. 400 lines/mm.
Calculations frequently require the slit spacing of the diffraction grating.



Example -Converting lines/mm to slit spacing (d)

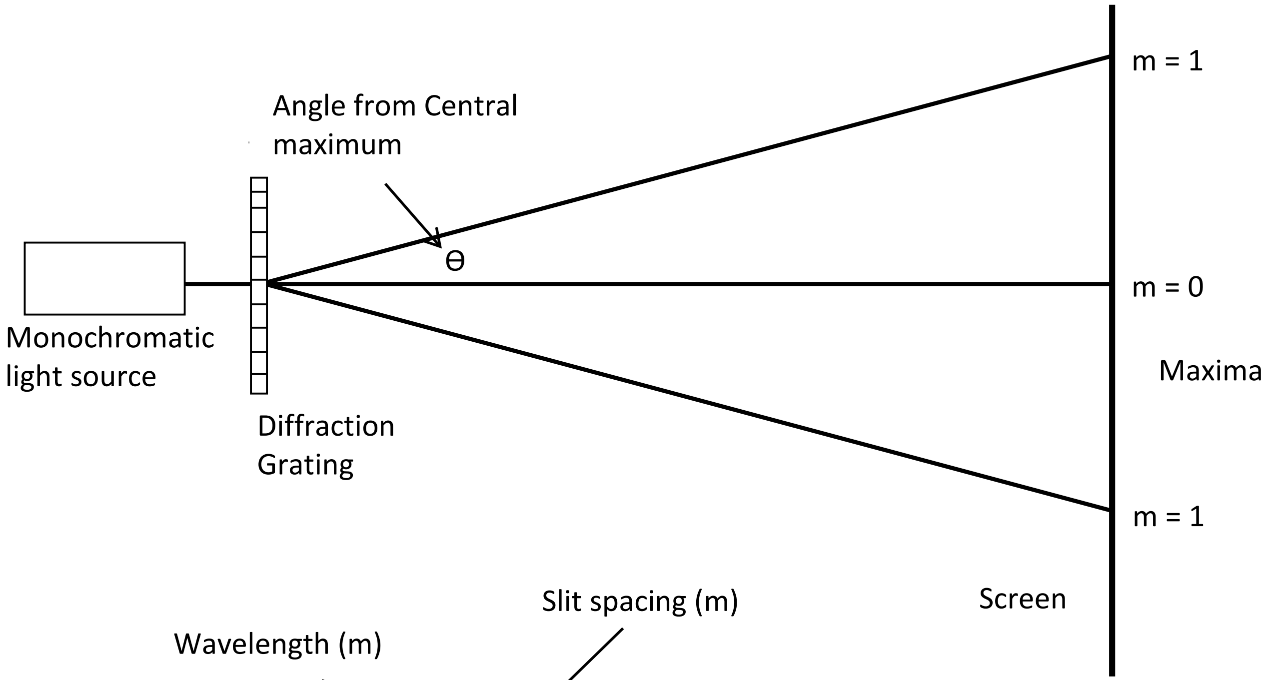
What is the slit spacing of a grating of 400lines/mm?

Solution

400 lines/mm = 400x1000 = 400,000 lines/m

$$d = \frac{1}{400,000} = 2.5 \times 10^{-6}\text{m}$$

The Grating Equation



Wavelength (m)

Slit spacing (m)

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

Order

Angle from central maximum (degrees)

Example 1

Light from laser is shone through a 1000lines/mm grating. The distance from the central maxima to the first order maxima is 39.3^{O}.

a. Show that the wavelength of the laser is 633nm.
b. Would you be able to see a second order maximum? Justify your answer using a calculation.

Solution 1

a. $d = \frac{1}{1000\times1000} = 1.00 \times 10^{-6}\text{m}$

$m = 1$

$\theta = 39.3^{O}$

$m\lambda = d\sin\theta$

As m = 1

$\lambda = d\sin\theta$

$\lambda = 1.00 \times 10^{-6} \times \sin39.3^{O}$

$\lambda = 6.33 \times 10^{-7}\text{m} = 633\text{nm}$

b. When m = 2

$\sin\theta = \frac{m\lambda}{d}$

$\sin\theta = \frac{2 \times 6.33 \times 10^{-7}}{1.00 \times 10^{-6}}$

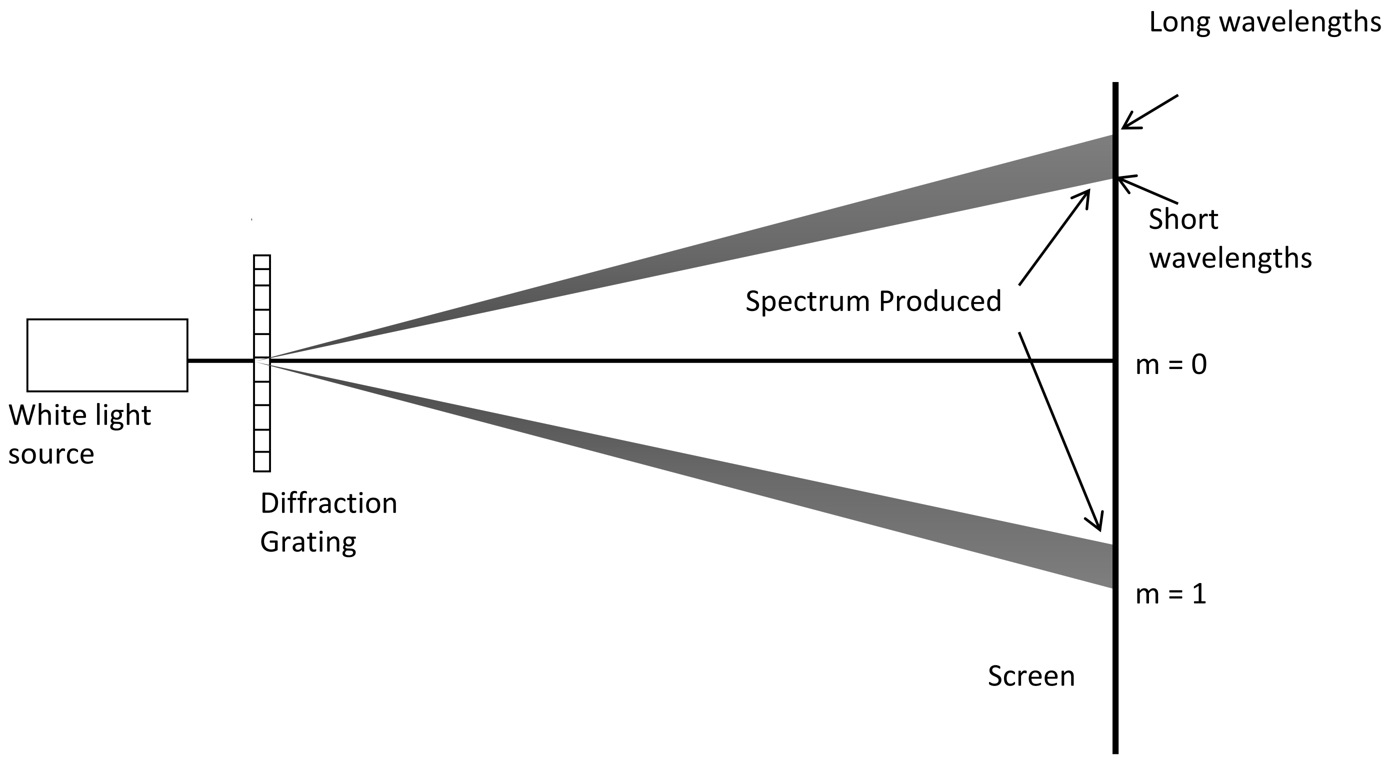
$\sin\theta = 1.27$

As $\sin\theta$ has a maximum of 1 the 2^{nd} order maximum will not be visible.

Problem book page 26 and 27 questions 8 to question 11.

6.7 I can describe and explain the spectrum produced when white light passes through a diffraction Gratings.

For the first order maximum the grating equation shows a direct relationship between wavelength and $\sin\theta$. Larger wavelengths will occur at larger angles and smaller wavelengths at smaller angles forming a spectrum.



Problem book page 27 questions 12 and 13.

Homework Interference and Diffraction.

Key Area: Refraction

Previous Knowledge

Frequency
Wavelength

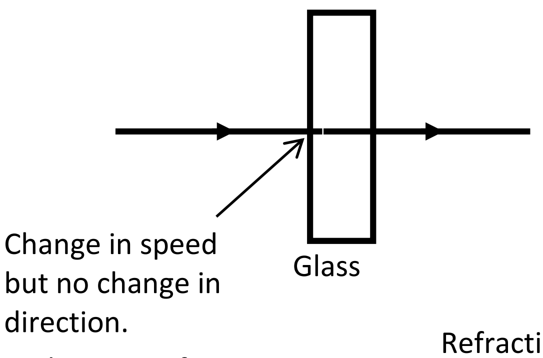
Success Criteria

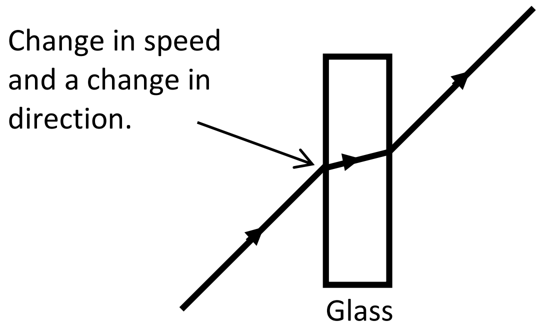
7.1 I can explain what is meant by the term refraction and explain where it occurs.
7.2 I can define absolute refractive index of a medium as the ratio of the speed of light in a vacuum to the speed of light in the medium.
7.3 I can use of an appropriate relationship to solve problems involving the angles of incidence and refraction, the wavelength of radiation in each medium and the speed of the radiation in each medium.
7.4 I am aware of the variation of refractive index with frequency.
7.5 I understand the terms critical angle and total internal reflection.
7.6 I can use an appropriate relationship to solved problems involving critical angle and refractive index.

7.1 I can explain what is meant by the term refraction and explain where it occurs.

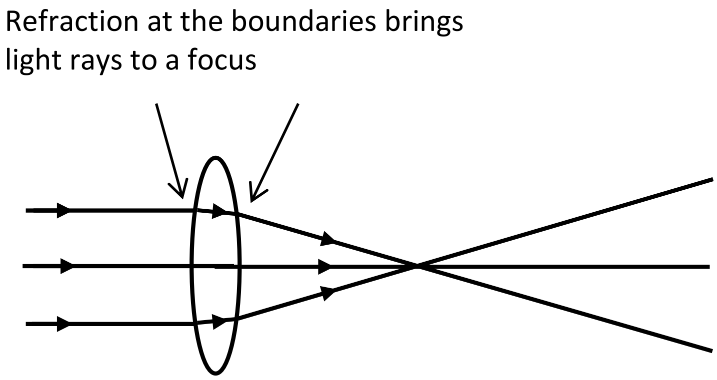
Refraction at a Boundary due to Changing Materials

Light travels at $3.0 \times 10^{8} \mathrm{ms}^{-1}$ when traveling through a vacuum. It travels at a lower speed when moving through other materials. This change in speed causes light to change direction except where light strikes perpendicular to the surface.





Example Lens Refraction

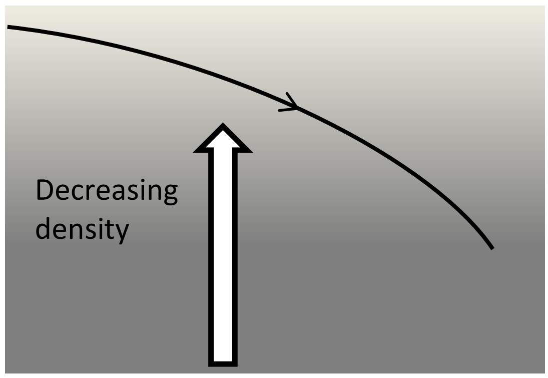


Refraction due to Changing Density

When light travels through a material where the density changes, the change in the speed of light will cause refraction. Increasing density reduces the speed of light

Example

In the earth's atmosphere the density decreases with height. This causes light to be refracted towards the ground.



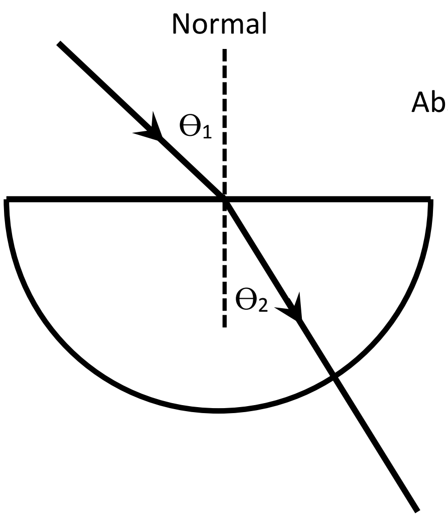
7.2 I can define absolute refractive index of a medium as the ratio of the speed of light in a vacuum to the speed of light in the medium.

The absolute refractive index of a medium is defined as the ratio of the speed of light in a vacuum to the speed of light in the medium. Absolute refractive index is written without units.

The absolute refractive index of air is very close to that of a vacuum. When measuring absolute refractive index, the ratio of the speed of light in air to the speed of light in the medium is used.

7.3 I can use of an appropriate relationship to solve problems involving the angles of incidence and refraction, the wavelength of radiation in each medium and the speed of the radiation in each medium.

Rather than measuring the speed of light the measurement of the absolute refractive index of a material is obtained from the ratio of the angle of incidence to the angle of refraction of a material. This is called Snell's Law.



Snell's Law

Absolute Refractive Index

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

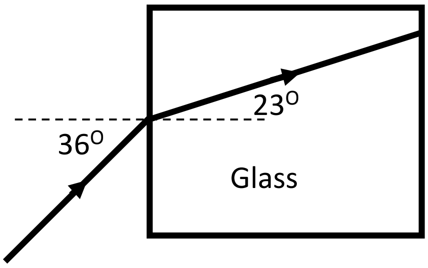
Angle between the ray in air (or a vacuum) and the normal line.

Angle between the ray in the material and the normal line.

Example

Calculate the refractive index of the glass block.

$$n = \frac{\sin\theta_1}{\sin\theta_2} = \frac{\sin 36}{\sin 23} = 1.5$$



Problem book page 28 questions 1 and 2.

Refractive index can also be calculated from the ratio of the wavelengths of light.

Wavelength in air (m)

Speed in air (ms^{-1})

Refractive Index

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

Speed in the material (ms^{-1})

Wavelength in the material (m)

> **Note**
>
> Frequency will not change during refraction.

<u>Example</u>

For a light of 633nm entering glass where n = 1.5. Calculate

a. The speed of light in the glass.
b. The wavelength in the glass.

a. $n = \frac{v_1}{v_2}$

$$1.5 = \frac{3.0 \times 10^8}{v_2}$$

$$v_2 = \frac{3.0 \times 10^8}{1.5}$$

$$v_2 = 2.0 \times 10^8 ms^{-1}$$

b. $n = \frac{\lambda_1}{\lambda_2}$

$$1.5 = \frac{633 \times 10^{-9}}{\lambda_2}$$

$$\lambda_2 = \frac{633 \times 10^{-9}}{1.5}$$

$$\lambda_2 = \frac{633 \times 10^{-9}}{1.5}$$

$$\lambda_2 = 422 \times 10^{-9} m$$

Problem book pages 28 and 29 questions 3 to 5.

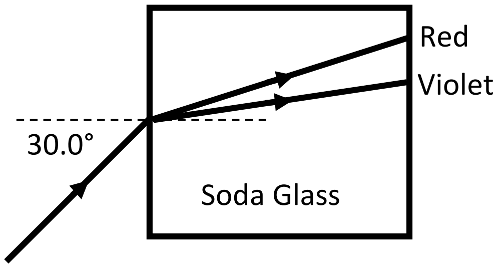
7.4 I am aware of the variation of refractive index with frequency.

Refractive index changes for different frequencies of light. This means that different colours of light will be refracted through different angles. This is called dispersion. This occurs in glass and other materials to produce a spectrum.

Example

White light is shone at an angle of 30.0° into a glass block. Using the data in the table, calculate the angle between the red and violet rays in the spectrum produced.

Soda Glass		
Colour	Wavelength (nm)	Refractive index
Violet	400	1.537
Red	700	1.520



Violet

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

$$1.537 = \frac{\sin 30^O}{\sin\theta_2}$$

$$\sin\theta_2 = \frac{\sin 30^O}{1.537}$$

$$\theta_2 = \sin^{-1}\left(\frac{0.500}{1.537}\right)$$

$$\theta_2 = 18.98^O$$

Red

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

$$1.520 = \frac{\sin 30^O}{\sin\theta_2}$$

$$\sin\theta_2 = \frac{\sin 30^O}{1.520}$$

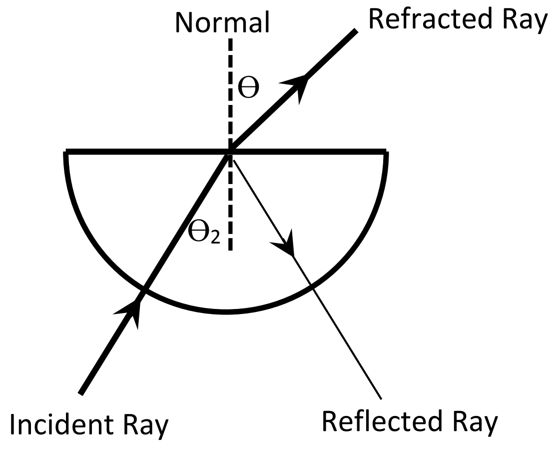
$$\theta_2 = \sin^{-1}\left(\frac{0.500}{1.520}\right)$$

$$\theta_2 = 19.20^O$$

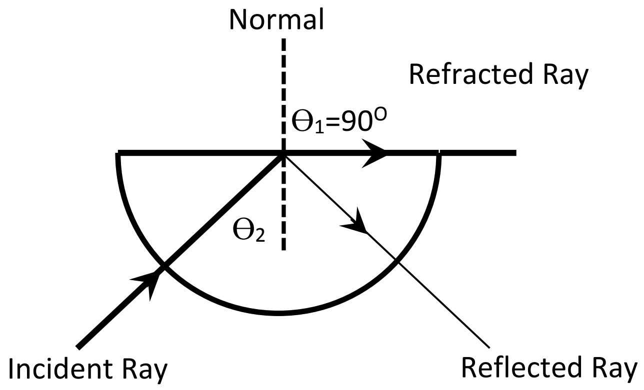
$$\theta_{Red/violet} = 19.20^O - 18.98^O = 0.220^O$$

Problem book pages 29 and 30 questions 6 and 7.

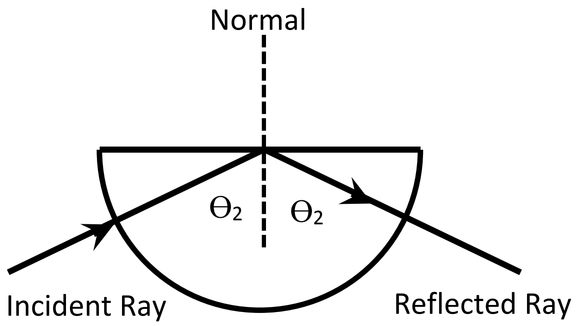
7.5 I understand the terms critical angle and total internal reflection.



When the angle of incidence (Θ_2) in the block is small there is a refracted ray and a weak partially reflected ray.



When the angle of incidence is such that the angle of refraction (Θ_1) is 90^O there is a refracted ray which lies along the surface of the block and a partially reflected ray. The incident angle at which this occurs is called the **critical angle**.



When the angle of incidence is greater than the critical angle there is no refracted ray. All the light is reflected. This is called **total internal reflection.**

7.6 I can use an appropriate relationship to solve problems involving critical angle and refractive index.

At the critical angle $\theta_1 = \theta_c$ and $\theta_2 = 90^O$

$$n = \frac{\sin 90^O}{\sin\theta_c} = \frac{1}{\sin\theta_c}$$

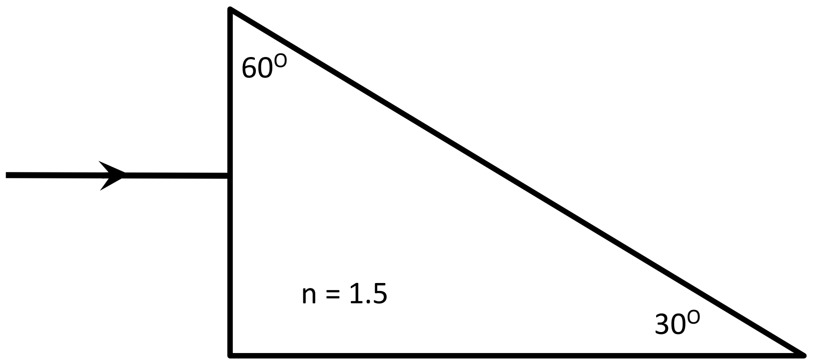
Critical Angle (Degrees)

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

Refractive Index

Example

A monochromatic light ray is incident on a glass prism with a refractive index of 1.5 as shown in the diagram. Complete the diagram showing the path of the ray through the prism.



Solution

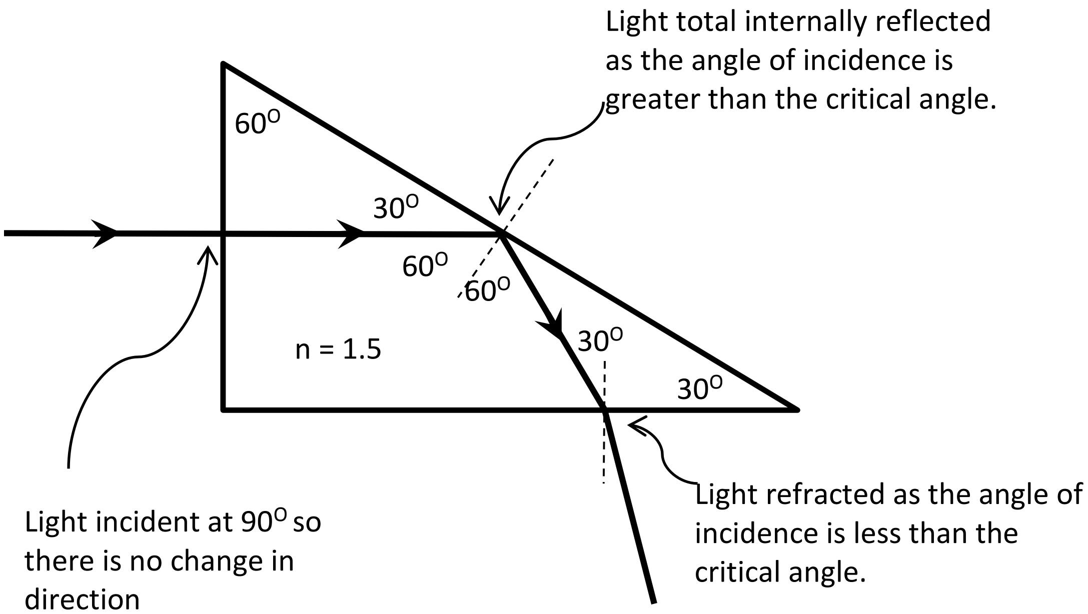
$$n = \frac{1}{\sin\theta_c}$$

$$1.5 = \frac{1}{\sin\theta_c}$$

$$\theta_c = \sin^{-1}\left(\frac{1}{1.5}\right)$$

$$\theta_c = \sin^{-1}\left(\frac{1}{1.5}\right)$$

$$c = 41.8^{o}$$



Problem book pages 30 and 31 questions 8 to 11.
Homework Refraction.

Quantities, Units and Multiplication Factors

Quantity	Quantity Symbol	Unit	Unit Abbreviation
Frequency	f	Hertz	Hz
Wavelength	λ	Metres	m
Period	T	Seconds	s
Refractive Index	n	No units	-
Critical Angle	θ_c	Degree	°
Velocity/speed	v	Metres per Second	ms^{-1}
Energy	E	Joules	J
Charge	Q	Coulombs	C
Voltage	V	Volts	V
Work done	W	Joules	J
Mass	m	Kilogram	kg

Prefix Name	Prefix Symbol	Multiplication Factor
Pico	p	$\times 10^{-12}$
Nano	n	$\times 10^{-9}$
Micro	µ	$\times 10^{-6}$
Milli	m	$\times 10^{-3}$
Kilo	k	$\times 10^{3}$
Mega	M	$\times 10^{6}$
Giga	G	$\times 10^{9}$
Tera	T	$\times 10^{12}$

Relationships required for Physics Higher

$d = \bar{v}t$

$s = \bar{v}t$

$v = u + at$

$s = ut + \frac{1}{2}at^2$

$v^2 = u^2 + 2as$

$s = \frac{1}{2}(u + v)t$

$W = mg$

$F = ma$

$E_W = Fd$

$E_p = mgh$

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

$P = \frac{E}{t}$

$p = mv$

$Ft = mv - mu$

$F = G\frac{m_1 m_2}{r^2}$

$t' = \frac{t}{\sqrt{1 - \left(\frac{v}{c}\right)^2}}$

$l' = l\sqrt{1 - \left(\frac{v}{c}\right)^2}$

$f_o = f_s\left(\frac{v}{v \pm v_s}\right)$

$z = \frac{\lambda_{observed} - \lambda_{rest}}{\lambda_{rest}}$

$z = \frac{v}{c}$

$v = H_0 d$

$W = QV$

$E = mc^2$

$E = hf$

$E_k = hf - hf_0$

$E_2 - E_1 = hf$

$T = \frac{1}{f}$

$v = f\lambda$

$d\sin\theta = m\lambda$

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

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

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

$I = \frac{k}{d^2}$

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

path difference $= m\lambda$ or $\left(m + \frac{1}{2}\right)\lambda$ where $m = 0, 1, 2 \ldots$

random uncertainty $= \frac{\text{max. value} - \text{min. value}}{\text{number of values}}$

$V_{peak} = \sqrt{2}V_{rms}$

$I_{peak} = \sqrt{2}I_{rms}$

$Q = It$

$V = IR$

$P = IV = I^2R = \frac{V^2}{R}$

$R_T = R_1 + R_2 + \ldots$

$\frac{1}{R_T} = \frac{1}{R_1} + \frac{1}{R_2} + \ldots$

$E = V + Ir$

$V_1 = \left(\frac{R_1}{R_1 + R_2}\right)V_s$

$\frac{V_1}{V_2} = \frac{R_1}{R_2}$

$C = \frac{Q}{V}$

$E = \frac{1}{2}QV = \frac{1}{2}CV^2 = \frac{1}{2}\frac{Q^2}{C}$

DATA SHEET

COMMON PHYSICAL QUANTITIES

Quantity	*Symbol*	*Value*	*Quantity*	*Symbol*	*Value*
Speed of light in vacuum	c	$3{\cdot}00 \times 10^{8}$ m s^{-1}	Planck's constant	h	$6{\cdot}63 \times 10^{-34}$ J s
Magnitude of the charge on an electron	e	$1{\cdot}60 \times 10^{-19}$ C	Mass of electron	m_e	$9{\cdot}11 \times 10^{-31}$ kg
Universal Constant of Gravitation	G	$6{\cdot}67 \times 10^{-11}$ m^{3} kg^{-1} s^{-2}	Mass of neutron	m_n	$1{\cdot}675 \times 10^{-27}$ kg
Gravitational acceleration on Earth	g	$9{\cdot}8$ m s^{-2}	Mass of proton	m_p	$1{\cdot}673 \times 10^{-27}$ kg
Hubble's constant	H_0	$2{\cdot}3 \times 10^{-18}$ s^{-1}			

REFRACTIVE INDICES

The refractive indices refer to sodium light of wavelength 589 nm and to substances at a temperature of 273 K.

Substance	*Refractive index*	*Substance*	*Refractive index*
Diamond	2·42	Water	1·33
Crown glass	1·50	Air	1·00

SPECTRAL LINES

Element	*Wavelength*/nm	*Colour*
Hydrogen	656	Red
	486	Blue-green
	434	Blue-violet
	410	Violet
	397	Ultraviolet
	389	Ultraviolet
Sodium	589	Yellow

Element	*Wavelength*/nm	*Colour*
Cadmium	644	Red
	509	Green
	480	Blue

Lasers		
Element	*Wavelength*/nm	*Colour*
Carbon dioxide	9550 } 10590 }	Infrared
Helium-neon	633	Red

PROPERTIES OF SELECTED MATERIALS

Substance	*Density*/kg m^{-3}	*Melting Point*/K	*Boiling Point*/K
Aluminium	$2{\cdot}70 \times 10^{3}$	933	2623
Copper	$8{\cdot}96 \times 10^{3}$	1357	2853
Ice	$9{\cdot}20 \times 10^{2}$	273	. . . .
Sea Water	$1{\cdot}02 \times 10^{3}$	264	377
Water	$1{\cdot}00 \times 10^{3}$	273	373
Air	1·29	. . . .	. . . .
Hydrogen	$9{\cdot}0 \times 10^{-2}$	14	20

The gas densities refer to a temperature of 273 K and a pressure of $1{\cdot}01 \times 10^{5}$ Pa.