Gleniffer High School

# Higher

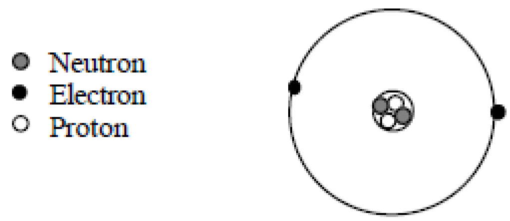
# Particles and Waves

# Summary Notes

**Name: ______________________________**

**<u>The Standard Model</u>**

Particle models of matter have existed from the early recorded history. At the start of the 20th century the model that was being developed consisted of a central nucleus surrounded by orbiting electrons.




The nucleus in this model consisted of nucleons called protons and neutrons. However, during the 20th century Physicists developed the idea of the **Standard Model** which led to the discovery of the fundamental particles which are found within protons and neutrons.

These fundamental particles are called **quarks**. Current theory suggests that there are six **flavours** of these fundamental particles. The flavours are known as – up, down, strange, charm, top and bottom. Most quarks only exist for a short period of time. The up and down quarks, which are the least massive, do exist for a longer period of time than the other flavours.

Quarks can combine with each other to form other particles called **hadrons** but they must obey the following rules:

- The electrical charge of the resultant particle must be an integer number.
- Only pairs or triplets of quarks can combine.
- **Pairs** form particles called **mesons**.
- **Triplets** form particles called **baryons**.

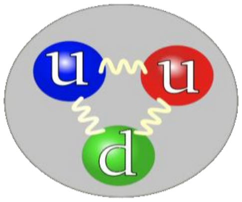
**Mesons** can only be made from matter/anti-matter combinations. This makes mesons

- Unstable
- Short lived

**Baryons** can be made from three matter quarks or from three anti-matter quarks. This makes baryons

- Stable
- Very long lived

Protons and neutrons are both in the baryon family of particles which helps ensure that we live in a world surrounded by stable, long-lived particles. Protons are made from a combination of two up quarks and one down quark. Neutrons are made from a combination of two down quarks and one up quark. A picture of the quark combination for a proton is shown below




Electrons on the other hand belong to a family of fundamental particles called **leptons**. There are also six members in this group - electrons, taus, muons, electron neutrinos, tau neutrinos and muon neutrinos.

A summary of the fundamental particles and their associated charges are shown in the following table.

| Name | Charge | Name | Charge | Name | Charge | Name | Charge |
|---|---|---|---|---|---|---|---|
| up | +2/3 | down | -1/3 | electron | -1 | electron neutrino | 0 |
| charm | +2/3 | strange | -1/3 | muon | -1 | muon neutrino | 0 |
| top | +2/3 | bottom | -1/3 | tau | -1 | tau neutrino | 0 |

As every matter particle also has an associated anti-matter particle. The anti-matter particles are identical in mass but opposite in charge to the matter particles. So the summary table for the anti-matter particles will be:

| Name | Charge | Name | Charge | Name | Charge | Name | Charge |
|---|---|---|---|---|---|---|---|
| anti-up | -2/3 | anti-down | +1/3 | anti-electron (positron) | +1 | anti-electron neutrino | 0 |
| anti-charm | -2/3 | anti-strange | +1/3 | anti-muon | +1 | anti-muon neutrino | 0 |
| anti-top | -2/3 | anti-bottom | +1/3 | anti-tau | +1 | anti- tau neutrino | 0 |

Within the Standard Model there are four fundamental forces of nature which are responsible for the attraction or repulsion of matter. In order of increasing strength these four fundamental forces of nature are:

Gravitation     Weak nuclear     Electromagnetism     Strong nuclear

Gravitation acts over an infinite range but is only significant when large masses are involved.
Weak nuclear is usually associated with beta decay and is only significant at an atomic range of approximately $10^{-18}$m.
Electromagnetism acts over an infinite range and is associated with charged particles.
Strong nuclear is the attractive force which holds atoms together and it acts over a range of approximately $10^{-14}$m.

These forces are transmitted by particles being exchanged between the objects involved. These force mediating particles belong to a large group of particles called **bosons**. Each of the four fundamental forces of nature has its own associated bosons, although all the force mediating particles belong to a group called **gauge-bosons.**

| Fundamental Force | Gauge-boson(s) |
|---|---|
| Strong nuclear | gluon |
| Electromagnetic | photon |
| Weak nuclear | $W^+$, $W^-$ and Z |
| Gravitation | graviton |

**The table below contains the details of the Past Paper examples for this area of the course. Past Papers, and their solutions, are free to download from the SQA website.**

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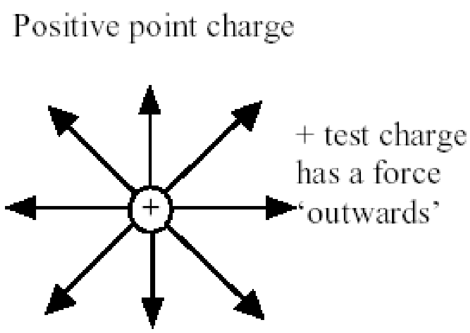
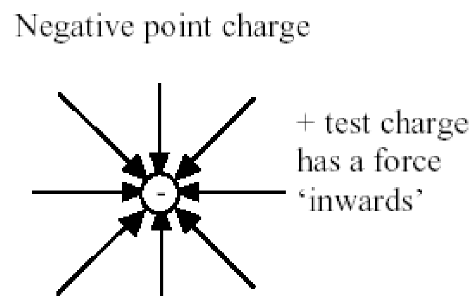
|---|---|---|
| 2015 | 9 | 6 |
| 2016 | 8 and 9 | No examples |
| 2017 | No examples | 7 |
| 2018 | 8 and 9 | No examples |
| 2019 | 13 | 7 a) b) c)i) and 14 d) |

**<u>Forces on Charged Particles</u>**

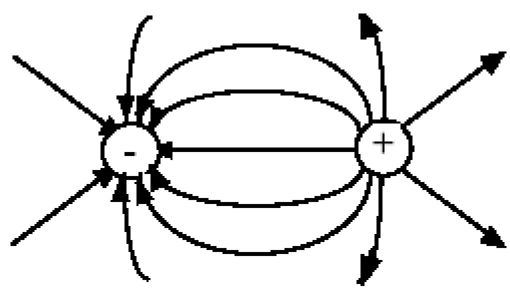
In an electric field, a charged particle will experience a force. Field lines are used to show the strength and direction of the force. The **closer** the field lines the **stronger** the force. The **arrows** on the field lines show the **direction** in which a **positive test charge** would move if placed in the field.



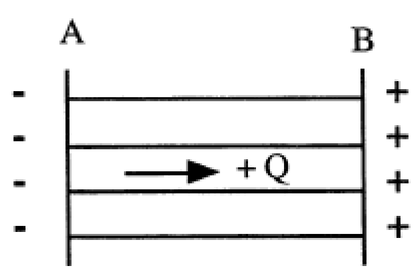




The electric fields shown above are known as radial fields. The strength of the field decreases (the field lines become more spread out) as the distance from the charge increases.

If two point charges are close to each other, the electric field surrounding the charges can also be represented by using electric field lines.




There is a uniform electric field between two charged parallel plates. This is represented by the evenly spaced field lines in the diagram below.



If a positive charge is moved from A to B as shown above, the work done in moving the charge will be stored as electrical potential energy.

If one joule of work is done in moving one coulomb of charge between the two points in an electric field, the potential difference (p.d.), between the points is one volt.

This definition of the volt can be expressed in the following equation:

$$\text{Work done} = \text{charge} \times \text{potential difference}$$

$$E_w = Q \times V$$

where,
$E_w$ is the work done in Joules
Q is the charge in Coulombs
V is the potential difference in Volts

If the charge is released from plate B, the stored electrical potential energy, which is equal to the work done, will be converted to kinetic energy.

$$\text{Work done on the charge} = \text{Kinetic energy}$$

In equation form this is written as,

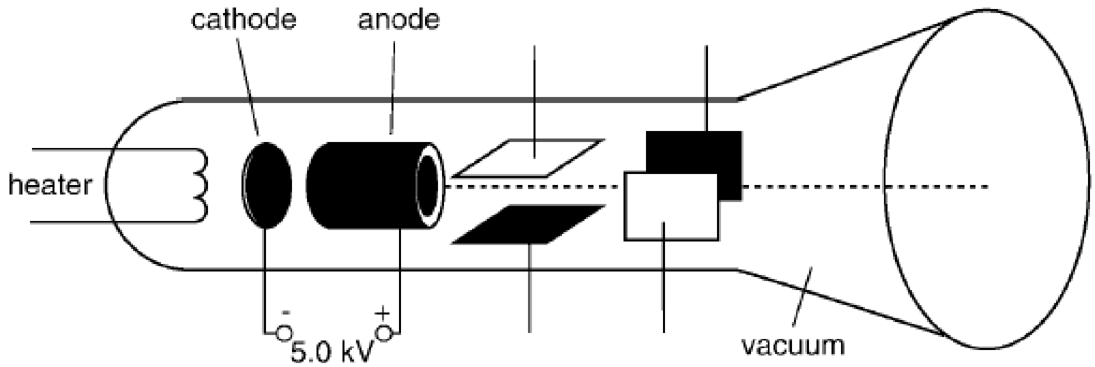
$$E_w = E_k$$

or

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

The theory behind charged particles, electric fields and movement in electric fields has many applications. These include photocopiers, ink jet and laser printers, CROs and electrostatic spray cans. Although a thorough knowledge of these applications is not needed for the course, it is likely that an exam question will be set in the context of one of these applications.

**Example**
The diagram below shows the cathode ray tube from an oscilloscope.




Electrons are accelerated between the cathode and the anode by the potential difference of 5.0kV.

a) Calculate the work done on an electron when it is accelerated between the cathode and the anode.
b) Calculate the speed of the electrons when the reach the anode.

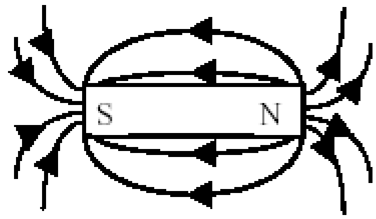
a)
$E_w$ = ?
Q = $1.6 \times 10^{-19}$C
(from data sheet)
V = 5.0kV
V = $5.0 \times 10^{3}$V

$E_w = QV$
$E_w = 1.6 \times 10^{-19} \times 5.0 \times 10^{3}$
$E_w = 8.0 \times 10^{-16}$J

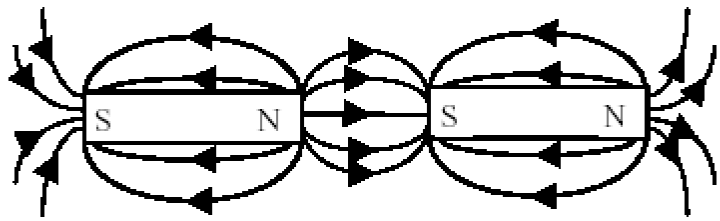
b)
$E_k = E_w = 8.0 \times 10^{-16}$J
m= $9.11 \times 10^{-31}$kg
(from data sheet)
v = ?

$E_k = ½mv^2$
$8.0 \times 10^{-16} = 0.5 \times 9.11 \times 10^{-31} \times v^2$
$v^2 = 1.756 \times 10^{15}$
$v = 4.2 \times 10^{7}$ ms$^{-1}$

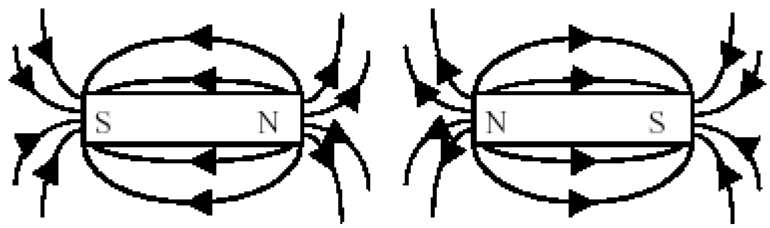
A charged particle will also experience a force when moving across a magnetic field. Some common magnetic field patterns for permanent magnets are shown below.




isolated bar magnet




opposite poles adjacent




like poles adjacent

Note that in all diagrams the magnetic field lines point towards the South Pole and that the strongest magnetic fields are shown by the field lines being closer together.

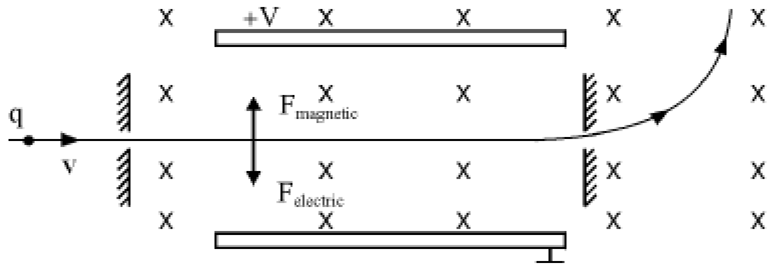
A moving charge will also have a magnetic around it. This means that when a current carrying is placed in a magnetic field, the magnetic field around the current carrying wire will interact with the magnetic field.

Assuming the moving charge in the current carrying wire is **negative** the following rule can be used to predict the direction of movement of the wire.

Using the right hand, hold the thumb and first two fingers at right angles to each other. Point the first finger – the **f**ore finger- in the direction of the magnetic **f**ield. Point the second finger-the **c**entre finger- in the direction in which the negative **c**harge flows. The thumb should now point in the direction in which the wire will move. This is known as the **right-hand rule**.

If the moving charge is positive then the same rules can be applied but the **left hand** must be used instead of the right.

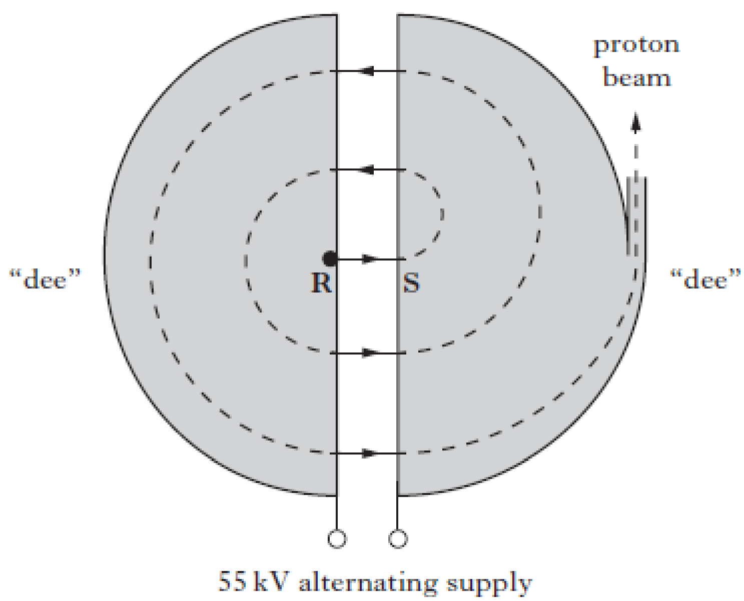
**Example**
The following diagram shows a simplified part of a mass spectrometer.




When the charged particle, q, enters the region where there is only a magnetic field it moves in an upwards direction. If the magnetic field is acting into the page, what is the charge on the particle?

**Solution**
Apply the right-hand rule.
This implies that a negative charge would flow in the opposite direction to the arrows in the diagram. Therefore, the charge on the particle must be positive.

The ability to move charged particles by using magnetic fields has many applications. These include a variety of particle accelerators including the cyclotron (shown below) and synchrotron. Further details on pages 109 and 110 of your textbook.




Magnetic fields are also instrumental in the collision and detection of charged particles. This has allowed the discovery of sub-atomic particles in Large Hadron Collider (LHC) at CERN.

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|---|---|---|
| 2015 | 10 and 11 | No examples |
| 2016 | No examples | 7 and 8d) |
| 2017 | No examples | 8 |
| 2018 | 10 | 6 |
| 2019 | 11 and 12 | No examples |

**Nuclear Reactions**

It is often very convenient to explain nuclear reactions by using nuclear notation for all the particles involved in the reaction.

Elements in the periodic table can be identified by their **atomic number**. However, it is possible to have different versions of the same element. Each different version is known as an **isotope**. Each isotope of an element has the same atomic number but a different **mass number**. This can be shown using the following notation.

Carbon-12 $^{12}_{6}C$

Carbon-14 $^{14}_{6}C$

The atomic number (the bottom number) is the same for both isotopes. This indicates that there are 6 protons in the nucleus of each isotope. However, the mass number (the top number) is different for both isotopes. This indicates that there are 6 neutrons (12 – 6) in the nucleus of Carbon-12 and that there are 8 neutrons (14 - 6) in the nucleus of Carbon-14.

Most isotopes of most elements are stable because they contain the correct numbers of protons and neutrons. However, some isotopes of elements can be unstable because they contain too many or too few neutrons. These isotopes will decay by the emission of nuclear particles to form more stable isotopes of other elements.

Two common types of particle that are emitted by unstable isotopes are alpha particles and beta particles.

In alpha decay, the unstable isotope emits 2 protons and 2 neutrons. This is equivalent to emitting a Helium nucleus. This type of nuclear decay can be written as follows.

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

In this case an unstable isotope Uranium-238 has been changed to Thorium-234 by the emission of the alpha particle (Helium nucleus).

In beta decay, inside the unstable isotope a neutron in the nucleus is changed into a proton and an electron. The electron is the emitted beta particle. This type of nuclear decay can be written as follows.

$${}^{210}_{82}Pb \rightarrow {}^{210}_{83}Bi + {}^{0}_{-1}e$$

In this case the unstable isotope Lead-210 has been changed to Bismuth-210 by the emission of a beta particle (an electron).

**Example**
The isotope of Americium-241 that is often used in smoke alarms is shown below.

$${}^{241}_{95}Am$$

This isotope decays inside the smoke alarm by the emission of alpha particles.

a) State the number of protons and neutrons in the nucleus of this isotope of Americium.
b) State the atomic number and the mass number of the isotope produced when Americium-241 undergoes an alpha decay.

**Solution**
a)
Number of protons = atomic number = 95
Number of neutrons = mass number – atomic number = 241 – 95 = 146
b)
Atomic number will decrease by 2 due to alpha decay. Answer 93
Mass number will decrease by 4 due to alpha decay. Answer 237

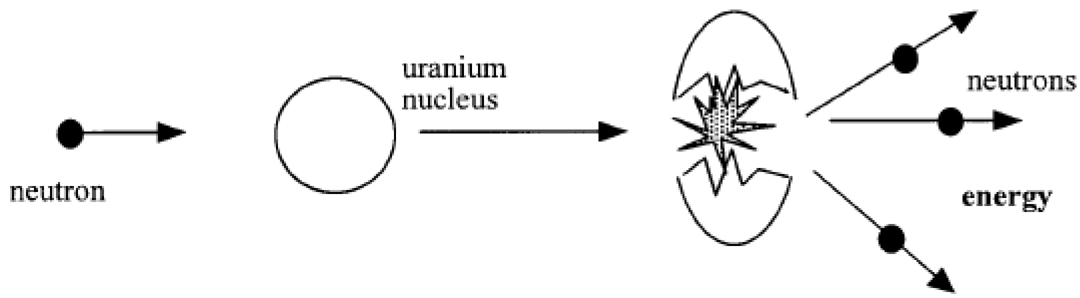
**Nuclear Fission**

Nuclear fission occurs when heavy elements (those with a significantly greater mass than iron) disintegrate to form two elements with smaller masses.

$${}^{238}_{92}U \rightarrow {}^{92}_{36}Kr + {}^{141}_{56}Ba$$

This **spontaneous fission** reaction would also produce 5 neutrons and release energy.

The unstable isotopes that undergo spontaneous fission are rarely found on Earth but it is possible to split a stable heavy nucleus by using neutron bombardment.

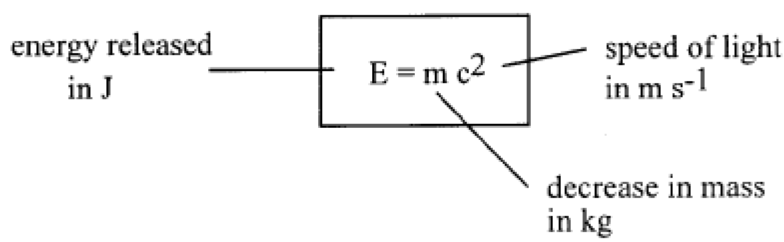



An equation for this **induced fission** process is shown below.

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

The nuclear equation shows that the atomic number and mass number before the reaction are the same as the atomic number and mass number after the reaction. However a detailed analysis of the total mass before and after the reaction reveals that the mass before is greater than the mass after.

Einstein suggested that the mass difference was equivalent to the value of energy produced from the reaction. Einstein summed up this relationship in his famous equation.



**Example**
Calculate the energy released during this induced fission reaction.

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

**Solution**
The mass difference has to be calculated before the energy can be worked out. The data needed to find the mass difference would be given to you in a table or in the data sheet.

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

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

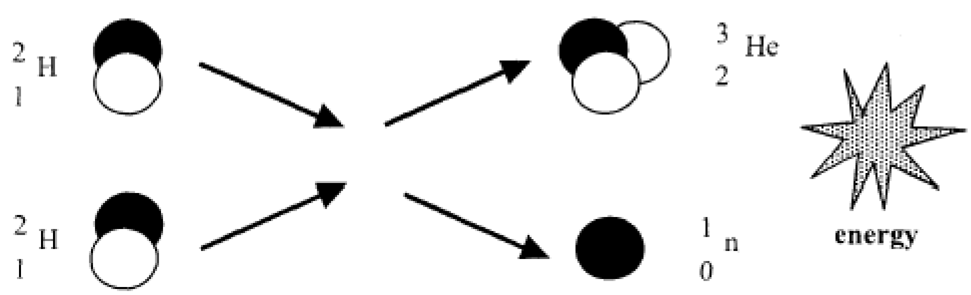
The energy can now be calculated using Einstein's famous equation.

$E = mc^2$
$E = 0.325 \times 10^{-27} \times (3 \times 10^8)^2$
$E = 2.9 \times 10^{-11}$ J

This may seem like a very small value of energy. However, this is just from one nucleus and this type of reaction would take place in a **nuclear reactor** where millions of such reactions would take place in a **controlled chain reaction**.

**Nuclear Fusion**

Nuclear fusion occurs when two low mass nuclei fuse together to form a more massive nuclei.



The equation for this **nuclear fusion** process is shown below.

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

The nuclear equation shows that the atomic number and mass number before the reaction are the same as the atomic number and mass number after the reaction. However a detailed analysis of the total mass before and after the reaction reveals that the mass before is greater than the mass after.

So Einstein's famous equation can be used for nuclear fusion reactions as well.

Nuclear fusion is the process that takes place in **stars** and it is very difficult to recreate the conditions for this type of reaction on Earth. The temperatures involved are so high that they would melt a normal containment vessel. However, it is possible to contain the particles involved in nuclear fusion by using a **strong magnetic field**. This type of containment vessel was first designed by the Russians in the 1950s and is known as a **TOKAMAK** reactor.

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|---|---|---|
| 2015 | 12 | No examples |
| 2016 | 10 | 8 not d) |
| 2017 | 8 | 9 |
| 2018 | 11 | No examples |
| 2019 | 14 | 7 d) and 8 |

## Interference

The following list explains some simple wave terminology.

**Crest** – the positive peak of a wave.
**Trough** – the negative peak of a wave.
**Amplitude** – the distance from the centre to the peak of a wave.
**Period** – the length of time for a single cycle of a wave.
**Frequency** – the number of cycles that pass a point in a second.

You should also be familiar with the wave equation… $v = f\lambda$

Also, all waves exhibit the following properties:-

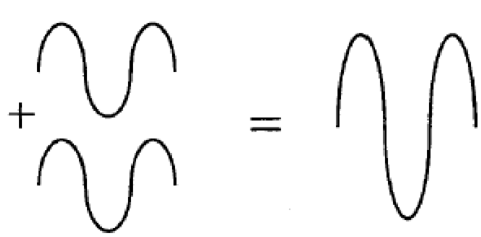
- Reflection
- Refraction
- Diffraction
- Interference

When two sets of waves meet they combine to form a new pattern. Waves can combine in one of two ways shown below.

***Constructive interference***

Two sets of waves meet in **phase**.

Two crests meet or two troughs meet to produce a larger crest or trough.

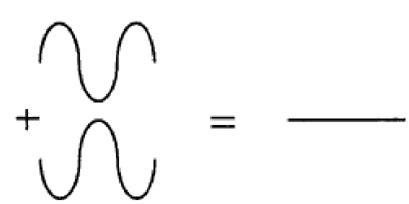



***Destructive interference***

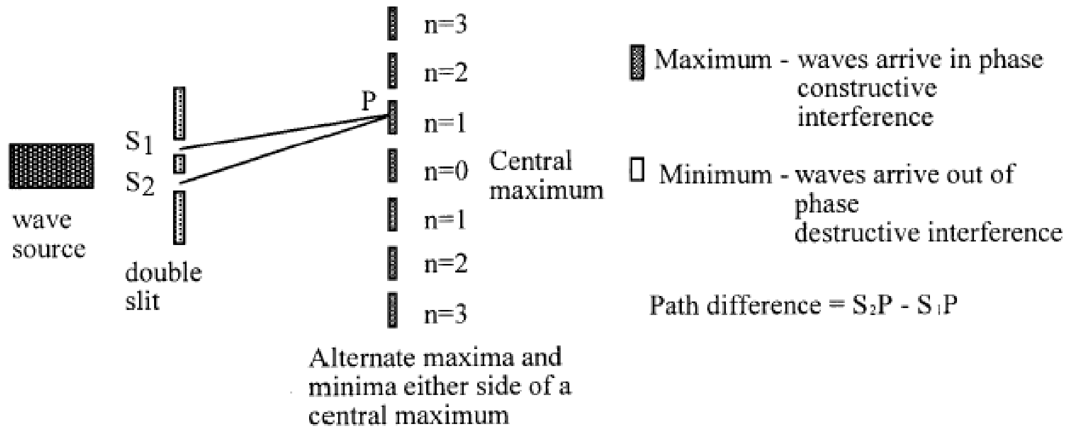
Two sets of waves meet completely out of phase, i.e. 180° out of phase.

A crest meets a trough and combine to cancel each other out and produce no wave at that point.

If the waves are not of equal amplitude, then complete cancelling out does not occur.



Interference patterns can be demonstrated by water waves in a ripple tank but they are easier to explain using the concept of **path difference**.
Consider an interference pattern produced by two coherent wave sources as shown below. (Coherent waves have a constant phase difference and the same frequency.)
This experimental design will produce an interference pattern because the gap between the slits is of a similar order to the wavelength of the wave being produced by the wave source.




Take the point P in the interference pattern shown.
As you move from the central maximum towards point P there is a minimum and then there is a maximum at P. This first maximum occurs when the path difference to point P is 1λ. In other words, the waves from source $S_2$ have travelled 1λ more to reach P than the waves from source $S_1$.
This pattern of minimum followed by maximum keeps repeating itself, with all the maxima occurring when the path difference is a whole number of wavelengths. The rule for **maxima** can be summarised in the following equation:-

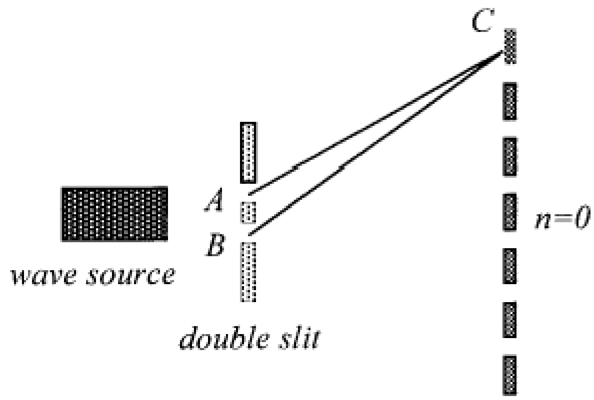
$$\text{Path difference} = n\lambda$$

The rules for minima are slightly more complicated. For a minimum to occur the waves need to arrive at a point completely out of phase. This happens when the path difference between the two waves is an odd number of half wavelengths. The rule for **minima** can be summarised in the following equation:-

$$\text{Path difference} = (n + \tfrac{1}{2})\lambda$$

ALWAYS REMEMBER THAT THE FIRST MINIMUM WILL OCCUR WHEN n = 0.

**Example**
a) If the distance AC and BC are 51cm and 63cm respectively, and point C is third maximum from the central maximum, calculate the wavelength of the source.




Path difference = nλ
(63 -51) = 3 x λ
12 = 3 x λ
λ = 12 / 3
λ = 4cm

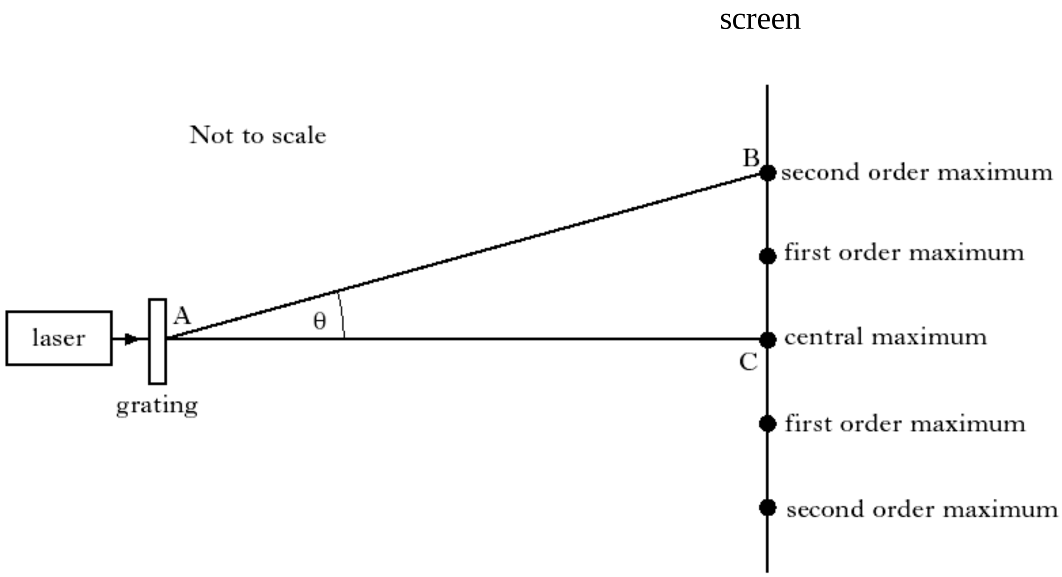
b) A wave source with a wavelength of 8cm replaces the one in part a). Show that the second minimum from the central maximum will now occur at point C.

For the second minimum n = 1

Path difference = (n + ½) λ
(63 – 51) = (1 + ½)8
12 = (1.5) x 8
12 = 12

The effects of interference can be seen in everyday life. The colours observed when an oil layer forms on water or when soap bubbles float around in the air. The colours represent areas where constructive interference has taken place.

Interference patterns can also be observed using monochromatic (one frequency) light and a diffraction grating. (A grating is usually consists of a glass slide that has many equally spaced slits placed extremely close together e.g. 300 slits per mm.)




This experimental design will produce an interference pattern because the slit separation is of a similar order to the wavelength of the light that is being shone through the grating.

The relationship between the variables in this experiment can be summarised in the following equation.

$$m\lambda = d\sin\Theta$$

where,
m – is the order(number) of the maxima
λ – is the wavelength of the monochromatic light
d – is the separation of the slits
Θ - is the angle from the zero order (central) maximum to the mth order maximum

Note that by carrying out any of the following the interference pattern would become more spread out. You can verify this both mathematically and experimental.

- Increase the wavelength of the monochromatic light source.
- Increase the number of slits per mm.
- Increase the distance between the screen and the grating.

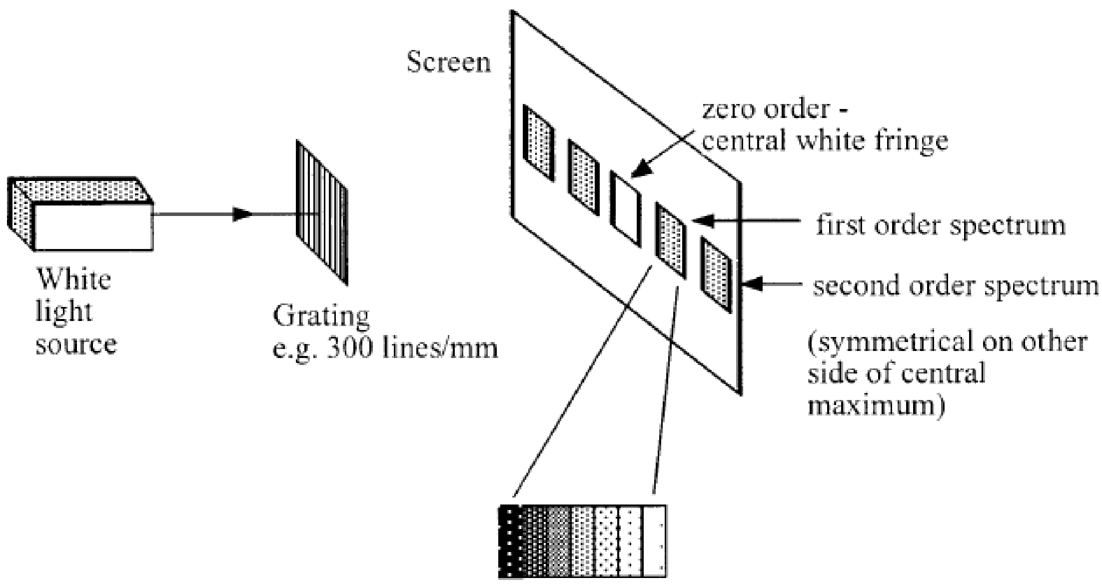
**Example**
A diffraction grating with 300 lines per mm is used to produce an interference pattern. The second order maximum is obtained at an angle of $19^0$ from the central maximum. Calculate the wavelength of the light.

**Solution**
Before using the grating equation you need to work out the slit separation. If there are 300 lines per mm, there would be 300,000 lines per m. And the gap between each line (slit) would be $3.33 \times 10^{-6}$m. (1 / 300,000)

$m\lambda = d\sin\Theta$
$2 \times \lambda = 3.33 \times 10^{-6} \times \sin 19$
$2 \times \lambda = 1.1 \times 10^{-6}$
$\lambda = 1.1 \times 10^{-6} / 2$
$\lambda = 5.5 \times 10^{-7}$m or 550 nm

You can self check these wavelength calculations as the spectrum of visible light has wavelengths in the approximate range 400nm (violet end) to 700nm (red end).

It is also possible to shine white light, which consists of all the colours of the visible spectrum, through a diffraction grating to produce an interference pattern.



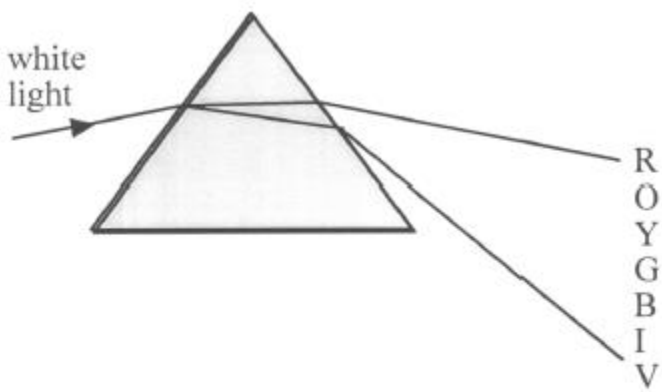
Each fringe appears as a visible spectrum, apart from the central white fringe. Red is deviated the most, violet is deviated the least.

The above interference pattern can be explained as follows.
The central fringe (maximum) is white because at that position, the path difference for all wavelengths present will be zero. This means that all the wavelengths arrive in phase and the central fringe (maximum) will be the same colour as the source, in this case, white.

The first maximum occurs when the path difference is one wavelength. Since violet light has a shorter wavelength than red light, the path difference will be smaller, so the violet maximum will appear closer to the central maximum than any other colour. As each colour has its own unique wavelength they will all appear at a slightly different position and so will spread out to form a spectrum.

As the order of the maxima increases they become more spread out and the higher order maxima will overlap each other.

It is also possible to produce a visible spectrum using white light and a prism.




In this case there is only one spectrum produced. This spectrum shows red being deviated the least and violet being deviated the most. The spectrum produced by a prism is usually less spread out than that produced by a diffraction grating.

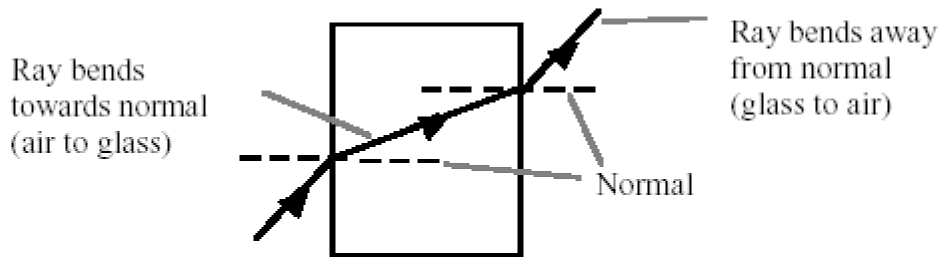
To help explain these differences it should be remembered that the **prism** is allowing the light to undergo **refraction**.

**The table below contains the details of the Past Paper examples for this area of the course. Past Papers, and their solutions, are free to download from the SQA website.**

| Year | Section/Paper One | Section/Paper Two |
|---|---|---|
| 2015 | 13 | No examples |
| 2016 | 13 | 9 |
| 2017 | 11 | 10 |
| 2018 | 13 | 8 |
| 2019 | 17 | 10 |

**Refraction of Light**

Refraction of light can take place whenever light enters a new material.



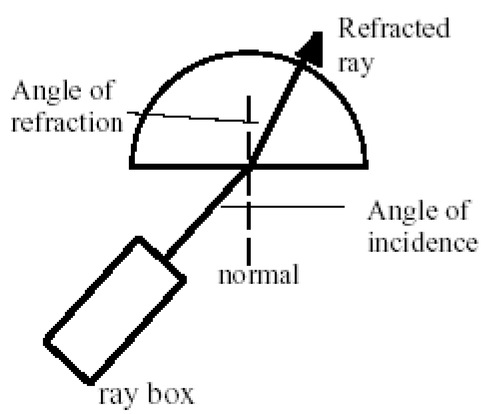

glass block

As the above diagram shows, the ray of light has changed direction when it has change the material that it is travelling through. This is known as refraction. The following points should be noted for refraction of light.

- Light slows done when it enters a denser material e.g. when it travels for air into glass.
- The frequency of the light does not change when it changes material.
- The wavelength of the light will decrease when it enters a denser material, e.g. when it travels from air into glass.

The measure of the refractive effect that a material has on light is known as its **refractive index.** The greater the refractive index the greater the effect on the ray of light**.**

To find the refractive index of a glass block the following experiment was set up. The angle of incidence was varied and the corresponding angle of refraction was noted.

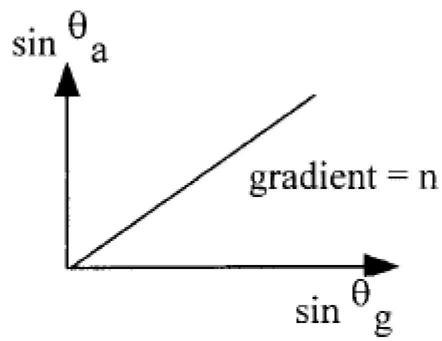


The results of the experiment were analysed and the following relationship was found.

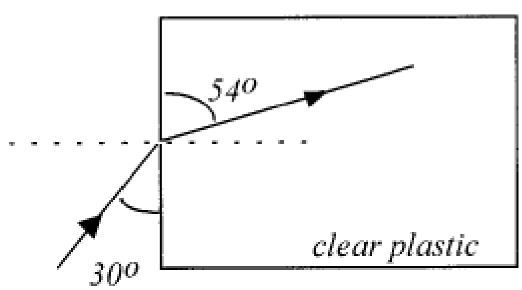
$$\frac{\sin\theta_a}{\sin\theta_g} = n$$

where,
$\Theta_a$ – is the angle between the **normal line** and the incident ray of light
$\Theta_g$ – is the angle between the **normal line** and the refracted ray of light
n– is the refractive index of the material doing the refraction

This relationship is known as **Snell's Law** and it is sometimes expressed in graphical form as:




**Example**
Calculate the refractive index of the clear plastic used in the following diagram.




**Solution**

$\Theta_a = (90 – 30) = 60^0$
$\Theta_b = (90 – 54) = 36^0$
n = ?

n = $\sin\Theta_a / \sin\Theta_b$
n = sin60 / sin 36
n = 1.47

The refractive index can also be calculated by using the change in speed or the change in wavelength experienced by a ray of light when it passes from one material to another.

This leads to the following general equation for calculating refractive index.

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

where,
$v_1$ = the speed of light in air
$v_2$ = the speed of light in the refracting material
$\lambda_1$ = the wavelength in air
$\lambda_2$ = the wavelength in the refracting material

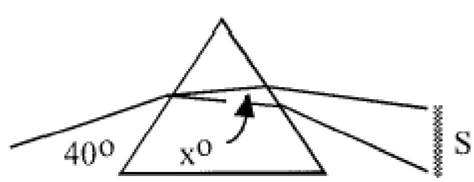
**Example**
Calculate the speed of red light in plastic which has a refractive index of 1.47.

**Solution**
$v_1 = 3 \times 10^8 ms^{-1}$
$v_2$ = ?
n = 1.47

$n = v_1 / v_2$
$1.47 = 3 \times 10^8 / v_2$
$v_2 = 2.04 \times 10^8 ms^{-1}$

Each colour of light will have its own frequency and will therefore have its own refractive index as it passes through a prism. As violet refracts more than red, the refractive index for violet will be greater than the refractive index for red.

**Example**
A ray of white light is dispersed to form a spectrum by passing it through a prism. The angle, x, between the red end and the violet end is $0.9^0$.




Calculate the refractive index for violet light, if the refractive index for red light is 1.52.

**Solution**

For red light

$n = 1.52$

$\Theta_1 = (90 – 40) = 50^0$

$\Theta_2 = ?$

$n = \sin\Theta_1 / \sin\Theta_2$

$1.52 = \sin 50 / \sin\Theta 2$

$\Theta 2 = 30.3^0$

For violet light

$n = ?$

$\Theta_1 = (90 – 40) = 50^0$

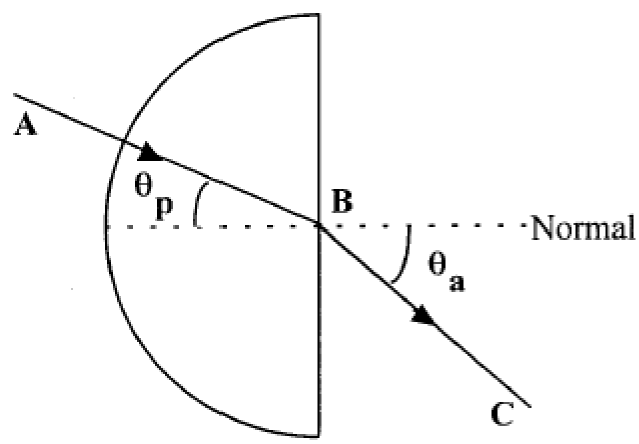
$\Theta_2 = (30.3 – 0.9) = 29.4^0$

$n = \sin\Theta_1 / \sin\Theta_2$

$n = \sin 50 / \sin 29.4$

$n = 1.56$

To find the **critical angle** for a perspex semicircular block the following experiment was set up.

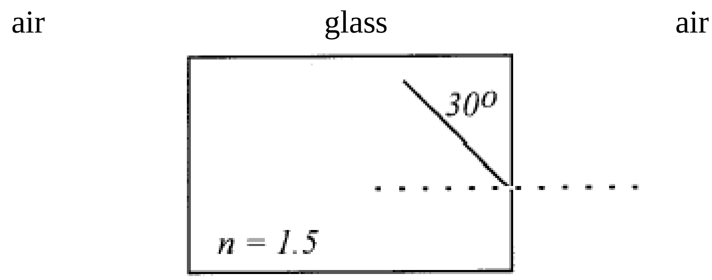



The incident angle, $\Theta_p$, was gradually increased until the refracted angle, $\Theta_a$, was $90^0$. At this point the incident angle is known as the **critical angle, $\Theta_c$**. At all angles greater than the critical angle the ray of light will obey the Law of Reflection and no light will be refracted out of the block.

The critical angle for a material can also be used to find the refractive index of the material and vice versa. The equation that lets you do this is shown below.

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

**Example**
A ray of light strikes the boundary between the glass and the air in the following diagram.




Describe what happens to the ray of light at this boundary.

**Solution**

| | |
|---|---|
| $n = 1.5$ | $n = 1 / \sin \Theta c$ |
| $\Theta_c = ?$ | $1.5 = 1 / \sin \Theta_c$ |
| | $\sin \Theta_c = 1 / 1.5$ |
| | $\Theta_c = 41.8^0$ |

At the boundary the incident angle is $(90 – 30) = 60^0$. This is greater than the critical angle. The ray of light will **reflect** off the glass/air boundary at an angle of $60^0$.

**The table below contains the details of the Past Paper examples for this area of the course. Past Papers, and their solutions, are free to download from the SQA website.**

| Year | Section/Paper One | Section/Paper Two |
|---|---|---|
| 2015 | 15 | 9a) |
| 2016 | 14 | 10 |
| 2017 | 12 and 13 | No examples |
| 2018 | 14 | 9 |
| 2019 | 18 | 11 |

## Inverse Square Law

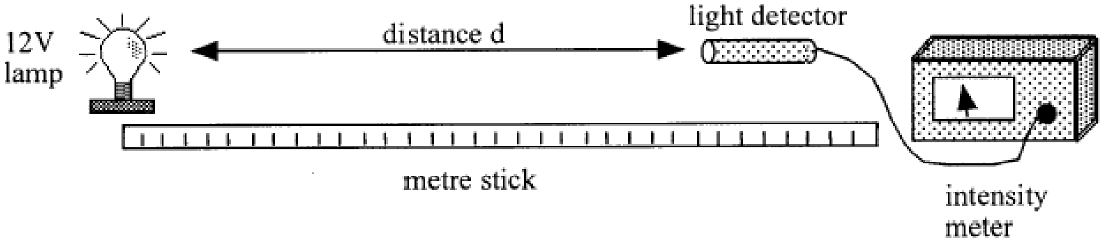
Irradiance is defined using the following equation.

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

$I$ — $W\,m^{-2}$; $P$ — watts; $A$ — $m^2$

This equation implies that for the same power of light, a beam with a smaller cross-sectional area will have a larger irradiance.

The relationship between irradiance and distance which can be found by using the following experimental approach:




By varying the distance between the light source and the light detector the following **inverse square** relationship can be shown.

$$I \propto \frac{1}{d^2}$$

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

where,
$I_1$ is the irradiance at distance $d_1$
$I_2$ is the irradiance at distance $d_2$

**Example**
A lamp shines on a screen of area $2.5m^2$, which is 1.5m away. The irradiance at the screen is $4.0Wm^{-2}$.
a) Calculate the power of the incident beam.
b) Calculate the irradiance on the screen if it moved to a distance of 3m from the lamp.

**Solution**
a)
$I = 4.0Wm^{-2}$
$A = 2.5m^2$
P = ?

I = P / A
4.0 = P / 2.5
P = 4.0 x 2.5
P = 10W

b)

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

$4.0 \times (1.5)^2 = I_2 \times (3)^2$

$9 = I_2 \times 9$

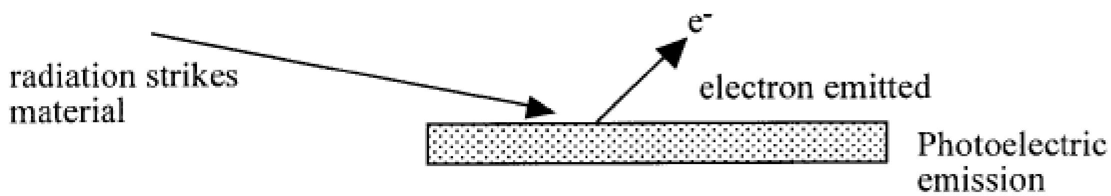
$I_2 = 1.0 Wm^{-2}$

**The table below contains the details of the Past Paper examples for this area of the course. Past Papers, and their solutions, are free to download from the SQA website.**

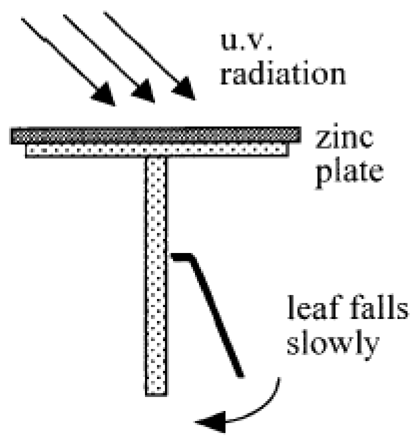
| Year | Section/Paper One | Section/Paper Two |
|---|---|---|
| 2015 | No examples | 8 |
| 2016 | 15 | No examples |
| 2017 | 15 | No examples |
| 2018 | 12 | No examples |
| 2019 | No examples | 9 a)ii) and 9 b) |

## **Wave Particle Duality**

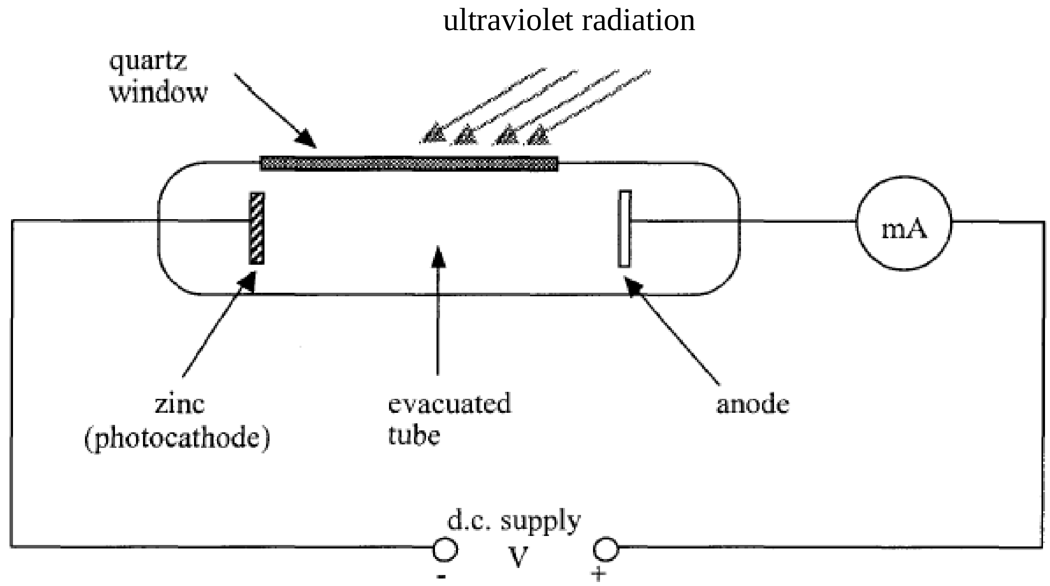
Sometimes when electromagnetic radiation above a certain frequency strikes a surface, electrons are emitted from the surface. This is known as **photoelectric emission** and the electrons emitted are known as photoelectrons.



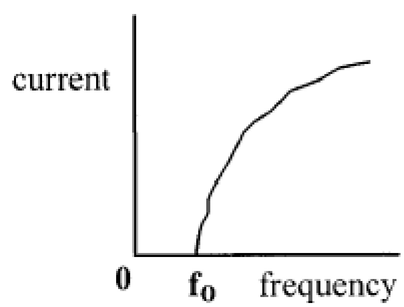

Photoelectric emission can be demonstrated by using a negatively charged electroscope. When the zinc plate is irradiated with white light the gold leaf is not affected because the frequency of the radiation is not high enough. However, when ultraviolet light is used the gold leaf falls because the frequency of the radiation is above the minimum frequency.



To study photoelectric emission in greater detail an experiment similar to the following would be necessary:




The ultraviolet radiation passes through the quartz window and strikes the zinc plate. This causes photoelectrons to be emitted. As the anode is positive, the negatively charged photoelectrons will be attracted towards the anode. This in turn will produce a current which will be registered on the milliammeter. A current produced in this manner is known as a photoelectric current.
The relationship between the current and the frequency causing it is shown in the following graph.




The minimum frequency, $f_0$, needed for photoelectric emission to take place is known as the **threshold frequency**.

The wave theory of light is unable to explain the photoelectric effect. However, the photoelectric effect can be explained if light is considered to be of a **particle nature**. These particles of light are called **photons**. Each photon has a particular energy that depends on its frequency.

The relationship between photon energy and frequency is shown in the Einstein-Planck equation.

$$E = hf$$

where,
E is the energy of the photon measured in Joules
h is Planck's constant 6.63 x $10^{-34}$Js
f is the frequency of the photon measured in Hertz

It follows that if there is a minimum frequency required for the photoelectric effect to take place, there must also be an associated **minimum energy**. This minimum energy is known as the **work function.** So the Einstein-Planck equation can be written as:

$$E_o = hf_o$$

where,
$E_0$ is the work function measured in Joules
h is Planck's constant 6.63 x $10^{-34}$Js
$f_0$ is the threshold frequency measured in Hertz

If the surface is irradiated with more than the minimum energy, then the extra energy will appear as the kinetic energy of the emitted photoelectron.

$$E_{in} = E_0 + E_k$$

where,
$E_{in}$ is the energy of the incident radiation
$E_0$ is the work function
$E_k$ is the kinetic energy of the photoelectron

**Example**
The work function of a particular metal is 5.1 x $10^{-19}$J.
a) Calculate the minimum frequency required to eject photoelectrons from the surface of the metal.
b) If radiation of frequency 8.45 x $10^{14}$Hz is incident on this metal, calculate the kinetic energy of the ejected photoelectrons.

**Solution**

a)

$E_0 = 5.1 \times 10^{-19}J$
$h = 6.63 \times 10^{-34}Js$
$f_0 = ?$

$E_0 = hf_0$
$5.1 \times 10^{-19} = 6.63 \times 10^{-34} \times f_0$
$f_0 = 5.1 \times 10^{-19} / 6.63 \times 10^{-34}$
$f_0 = 7.69 \times 10^{14}Hz$

b)

$E_{in} = ?$
$h = 6.63 \times 10^{-34}Js$
$f = 8.45 \times 10^{14}Hz$

$E_{in} = hf$
$E_{in} = 6.63 \times 10^{-34} \times 8.45 \times 10^{14}$
$E_{in} = 5.6 \times 10^{-19}J$

$E_{in} = E_0 + E_k$
$5.6 \times 10^{-19} = 5.1 \times 10^{-19} + E_k$
$E_k = 5.0 \times 10^{-20}J$

**The table below contains the details of the Past Paper examples for this area of the course. Past Papers, and their solutions, are free to download from the SQA website.**

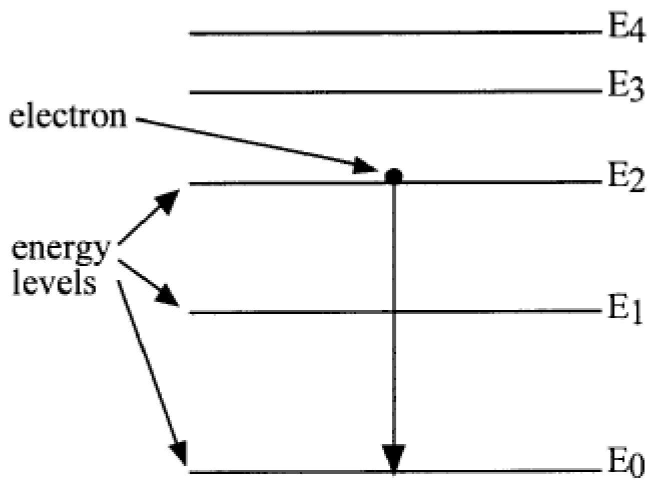
| Year | Section/Paper One | Section/Paper Two |
|---|---|---|
| 2015 | No examples | No examples |
| 2016 | 13 | 9 |
| 2017 | 11 | 10 |
| 2018 | 13 | 8 |
| 2019 | 15 and 16 | No examples |

**Spectra**

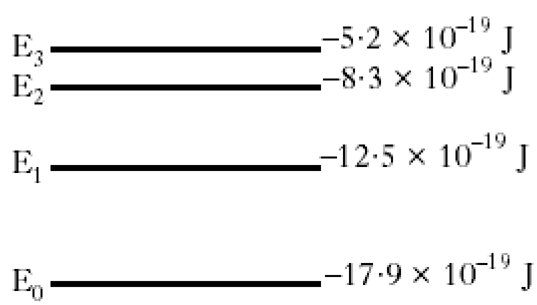
In the early 20th century a number of scientists were developing the model of the atom. One of these scientists, Bohr, proposed the following:

- Electrons have different energies in different orbits.
- There is a minimum number of electrons for each orbit.
- Electrons tend to occupy the lowest available energy levels, which are closest to the nucleus.
- Electrons can move between levels, but cannot stop between them.

This proposal can be further explained by using an **energy level diagram**.




The lowest energy level, $\mathbf{E_0}$, is called the **ground state**. Electrons in the other energy levels are said to be in an excited state. The most **excited state** is called the **ionisation level.**
Electrons in the ionisation level have an energy value of **0J**. As this is the highest energy level possible, all the other energy levels must have a **negative value.**




When an excited electron moves to a lower energy level, e.g. $E_3$ to $E_1$, this will result in the release of a **photon of energy**. The energy of the emitted photon will be equal to the difference in energy between the two levels. For $E_3$ to $E_1$ this will be $7.3 \times 10^{-19}$J.

By using the Einstein-Planck equation, E = hf, the frequency of the emitted radiation can be worked out.

**Example**
For the previous energy level diagram, calculate the frequency of the radiation released when an electron moves from $E_2$ to $E_1$.

**Solution**
Energy difference = $4.2 \times 10^{-19}$J
h = $6.63 \times 10^{-34}$Js
f = ?

E = hf
$4.2 \times 10^{-19} = 6.63 \times 10^{-34} \times f$
$f = 4.2 \times 10^{-19} / 6.63 \times 10^{-34}$
$f = 6.33 \times 10^{14}$Hz

This frequency has a corresponding wavelength of 474nm, which means the downward transition of the electron has released a photon of visible light. This is how the lines in **emission spectra** are produced.

It should be noted that not all downward transitions produce radiations that are part of the visible spectrum. Infrared and ultraviolet radiations are also commonly produced. This can be checked by carrying out a similar analysis of all six possible downward transitions in the previous energy level diagram.
(Coloured pictures of emission spectra can be seen on pages 153 and 154 of your textbook.)

When light is passed through a medium containing a gas, any photons of light which have the same frequency as the photons emitted to produce the line emission spectrum of the gas, are absorbed by the gas. This is because the energy of the photons of light (hf) is the same as the energy difference required to cause an electron to be moved from the lower energy level to the higher energy level. The energy is then absorbed by the electron and that photon is removed from the incident light.

The absorption of energy by gases is a useful technique for analysing the composition of stars. The atmosphere of the Sun contains sodium gas, therefore the spectrum of sunlight contains black absorption lines corresponding to the absorbed frequencies as described in the previous paragraph. So the spectrum of sunlight is an **absorption spectrum**.
(Coloured pictures of absorption spectra can be seen on page 153 of the textbook.)

**The table below contains the details of the Past Paper examples for this area of the course. Past Papers, and their solutions, are free to download from the SQA website.**

| Year | Section/Paper One | Section/Paper Two |
|---|---|---|
| 2015 | 16 | 4a) and 9b) |
| 2016 | 16 | 12b)ii |
| 2017 | No examples | 6 |
| 2018 | No examples | 10a) and b) |
| 2019 | 19 | 9 a)i) |

## 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* | *Element* | *Wavelength/nm* | *Colour* |
|---|---|---|---|---|---|
| Hydrogen | 656 | Red | Cadmium | 644 | Red |
| | 486 | Blue-green | | 509 | Green |
| | 434 | Blue-violet | | 480 | Blue |
| | 410 | Violet | Lasers | | |
| | 397 | Ultraviolet | *Element* | *Wavelength/nm* | *Colour* |
| | 389 | Ultraviolet | Carbon dioxide | 9550 } 10590 } | Infrared |
| Sodium | 589 | Yellow | 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.

$d = \bar{v}t$

$s = \bar{v}t$

$v = u + at$

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

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

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

$W = mg$

$F = ma$

$E_W = Fd$

$E_P = mgh$

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

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

$p = mv$

$Ft = mv - mu$

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

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

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

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

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

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

$v = H_0 d$

$E_W = QV$

$E = mc^2$

$E = hf$

$E_K = hf - hf_0$

$E_2 - E_1 = hf$

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

$v = f\lambda$

$d\sin\theta = m\lambda$

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

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

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

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

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

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

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

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

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

$Q = It$

$V = IR$

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

$R_T = R_1 + R_2 + ....$

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

$E = V + Ir$

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

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

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

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