Gleniffer High School

S3

Waves and Radiation

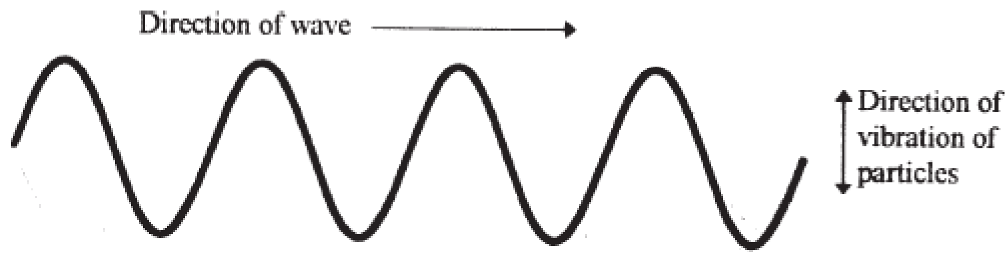
Summary Notes

WAVE PARAMETERS and BEHAVIOURS

Transverse Waves

A **water wave** is a transverse wave. The direction of vibration is at right angles to the direction of wave travel.

In this diagram the water particles move up and down but the wave travels from left to right.

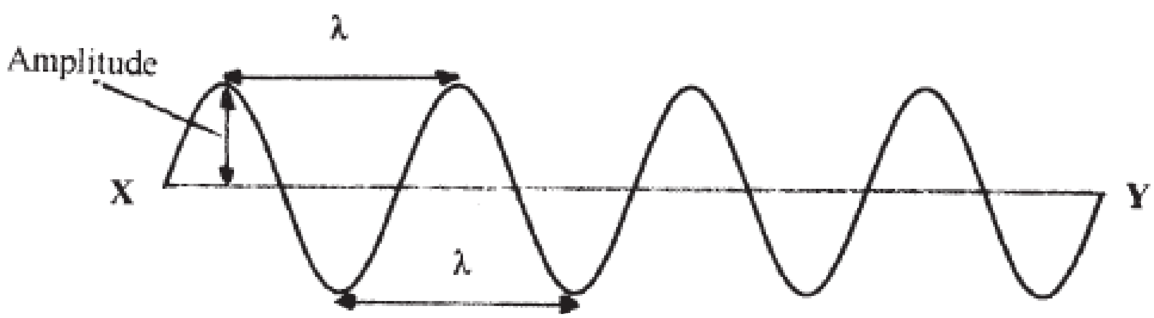


Longitudinal Waves

A **sound wave** is a longitudinal wave. The direction of vibration is in the same direction as the travel of the wave.

Wave Terms

A typical wave diagram is shown below: -



For this wave a number of terms can be measured or calculated.

The **wavelength (λ)** is the horizontal distance between any two corresponding points on adjacent waves.

The **amplitude** is the vertical distance measured from the middle of the wave to the top or to the bottom.

The **frequency (f)** of the wave is the number of waves that pass a point in one second and can be calculated using the following equation:

$$f = \frac{N}{t}$$

where,

f is the frequency of the wave measured in Hertz (Hz)

N is the number of waves

t is the time taken for the waves to pass a point measured in seconds (s)

The **period (T)** is the time taken for one complete wave and can be calculated using the equation:

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

where,

T is the period of the wave measured in seconds (s)

f is the frequency of the wave measured in Hertz (Hz)

The **wavespeed (v)** is the speed of the wave and can be calculated using the following equations:

$$v = \frac{d}{t}$$

where,

v is the wavespeed measured in metres per second (ms^{-1})

d is the distance travelled by the wave measured in metres (m)

t is the time taken by the wave measured in seconds (s)

OR

$$v = f\lambda$$

where,

v is the wavespeed measured in metres per second (ms^{-1})

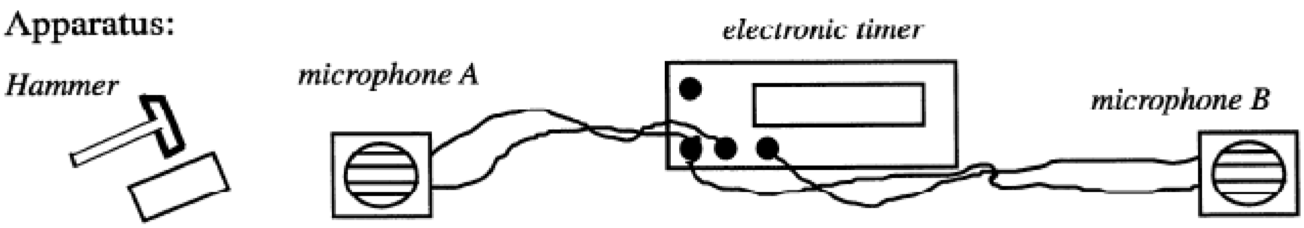
f is the frequency of the wave measured in Hertz (Hz)

λ is the wavelength of the wave measured in metres (m)

Calculating the speed of sound

In a laboratory the speed of sound can be calculated using the formula below.

$$v = \frac{d}{t}$$



A loud sound is made. As the sound reaches microphone A, the timer starts; when the sound waves reach microphone B, the timer stops. The distance between the microphones is measured with a metre stick.

The experiment was repeated five times and the results are shown below.

Distance from microphone A to microphone B = 1 m.

Experiment	1	2	3	4	5
Time (s)	0.0030	0.0029	0.0031	0.0027	0.0029

Average time = 0.0029 s

The speed of sound can be calculated as follows:

v = ?	v = d / t
d = 1 m	v = 1 / 0.0029
t = 0.0029 s	v = 345 ms^{-1}

The **speed of sound in air** is normally quoted as **340 ms^{-1}** and will appear on your data sheet for assessments.

Wave Calculations

For wave calculations it is important to write down all the information from the question before selecting the appropriate method for solving the problem.

Example One

A water wave takes 0.2 seconds to travel 1.6 metres. Calculate the speed of the water wave.

t = 0.2 s

d = 1.6 m

v = ?

v = d / t

v = 1.6 / 0.2

v = 8 ms^{-1}

Example Two

A sound wave traveling at 340 ms^{-1}, has a frequency of 2720 Hz. Calculate the wavelength of the wave.

v = 340 ms^{-1}

f = 2720 Hz

λ = ?

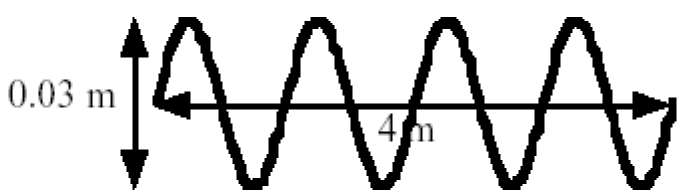
v = f x λ

340 = 2720 x λ

λ = 0.125 m

Example Three

The diagram below represents a wave 0.2 s after it has started.



a) State the amplitude of the wave.
b) State the wavelength of the wave.
c) Calculate the frequency of the wave.
d) Calculate the speed of the wave.

a) Amplitude is defined as the distance from the centre line to the top of the wave. In this case 0.03 / 2 = 0.015 m

b) In this diagram the four complete waves, cover a distance of 4 m. This means that each wavelength must be 4 / 4 = 1 m c)

f = ?	f = N / t
N = 4	f = 4 / 0.2
t = 0.2 s	f = 20 Hz

d)

d = 4 m	d = v x t
t = 0.2 s	4 = v x 0.2
v = ?	v = 4 / 0.2
	v = 20 ms^{-1}

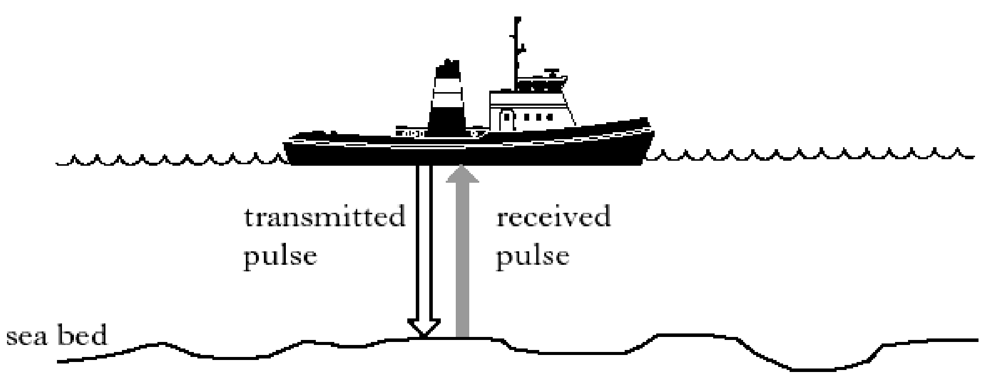
OR

v = ?	v = f x λ
f = 20Hz	v = 20 x 1
λ = 1 m	v = 20 ms^{-1}

Example Four

A ship is carrying out a survey of the seabed using ultrasound waves, which travel at a speed of 1500 ms^{-1} in sea water.

When stationary, the ship transmits and receives pulses of ultrasound waves with a frequency of 30 kHz.



a) Calculate the period of the ultrasound waves.

f = 30 kHz

f = 30 000 Hz or 30 x 10^3 Hz

T = ?

T = 1 / f

T = 1 / 30 000

T = 3.3 x 10^{-5} s

b) Calculate the wavelength of the ultrasound waves.

v = 1500 ms^{-1}

f = 30 kHz = 30,000 Hz

λ = ?

v = f x λ

1500 = 30,000 x λ

λ = 1500 / 30,000

λ = 0.05 m

c) At one point, each ultrasound pulse is received back at the ship 0.36 s after it has been transmitted. Calculate the distance to the seabed.

d = ?

v = 1500 ms^{-1}

t = 0.36 s

d = v x t

d = 1500 x 0.36

d = 540 m

This is the total distance travelled by the pulse.

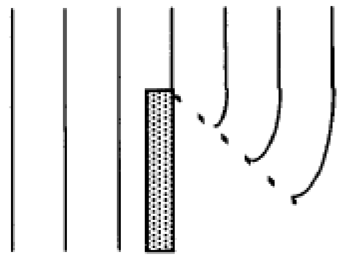
The distance to the seabed must be 270 m. (540 / 2)

Diffraction

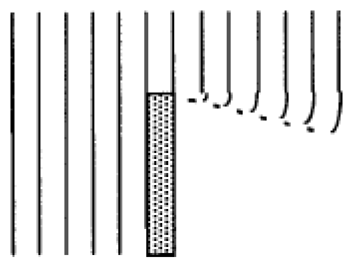
The ability of a wave to bend around an object is known as diffraction.

Waves which have a longer wavelength produce more diffraction than waves with a shorter wavelength.

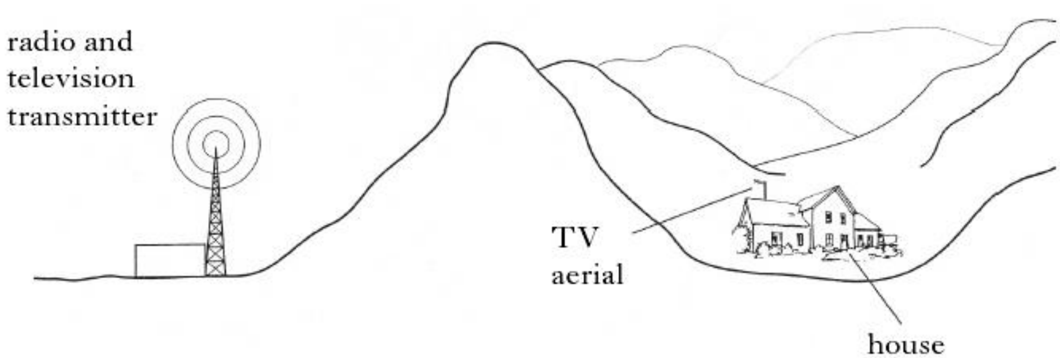
Long wavelength diffraction



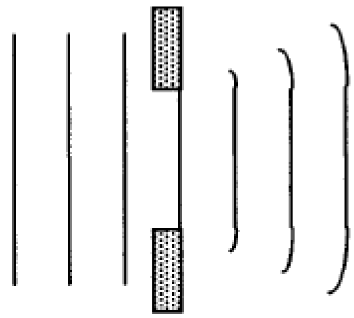
Short wavelength diffraction



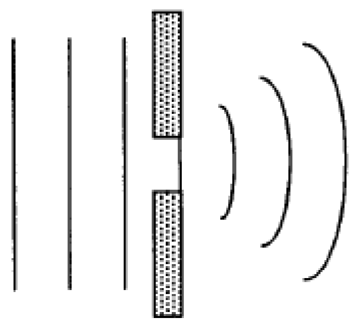
This property of waves has many applications. For example, in telecommunications it is easier to receive a longer wavelength radio wave behind a hill than a shorter wavelength TV wave. The house in the following diagram would have a good quality radio signal but a poor quality TV signal from the transmitter.



Diffraction can also happen when waves travel between objects.



In this diagram the gap between the objects is much bigger than the wavelength of the waves. But if a gap size is chosen that is very similar to the wavelength of the waves it is possible create circular waves.



THE ELECTROMAGNETIC SPECTRUM

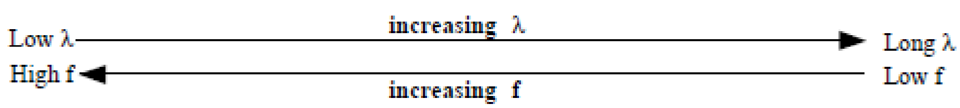
The electromagnetic (EM) spectrum is a family of waves. Like all families the members have lots in common. But each family member is also unique.

The names of the members of the **EM Spectrum** are:-

- Radio
- Microwave
- Infrared
- Visible
- Ultraviolet
- X-ray
- Gamma Ray

All members of the EM Spectrum share two very important characteristics. They travel at the same **speed 3×10^8 ms^{-1}**. (300 million metres per second) They are **transverse waves.**

Although only the visible part can be viewed, all parts can be identified by their frequency or wavelength.



Gamma Ray	X-ray	Ultraviolet	Visible	Infrared	Microwave	Radio

The EM spectrum has many **industrial and medical** applications.

A summary table is shown below.

EM Wave	Detector	Source	Application
Radio	Telescope	Transmitter	Radar
Microwave	Aerial	Transmitter	Mobile phones
Infrared	Photodiode	Lamp	TV remote
Visible light	Eyes	Various	Fibre optics
Ultraviolet	Fluorescent pigments	The Sun	Reduce acne
X-ray	Photographic film	Particle accelerators	Crystallography
Gamma ray	GM Tube	Radioactive nuclei	Tracers

As the frequency of the waves in the EM spectrum increases so does their energy. This makes gamma rays the most dangerous for living cells and radio waves the safest. However, the high energy associated with gamma rays can be used in medical applications such as sterilising surgical instruments.

Example

The diagram below represents the electro-magnetic spectrum.

gamma	X-rays	P	Visible light	Q	microwaves	Radio and TV

Electromagnetic spectrum

a) Name the radiations represented by P and Q.

P – ultraviolet

Q – infrared

b) Which of the two radiations, P or Q, has the greater energy? Explain your answer.

P has the greater energy because it is nearer the gamma end of the spectrum and this is the end with the highest frequency. When a radiation has a high frequency it will correspond to a high energy value.

c) Name a non-medical use for radiation P.

P could be used for detecting counterfeit bank notes.

d) Name a medical use for radiation Q.

Q could be used for treating muscle injuries.

e) Which of the two radiations, P or Q has the greater wavelength?

Q has the greater wavelength.

f) If the wavelength of Q is 6×10^{-9} m, calculate the frequency of this radiation.

$v = 3 \times 10^{8}\ ms^{-1}$

$f = ?$

$\lambda = 6 \times 10^{-9}$ m

$v = f \times \lambda$

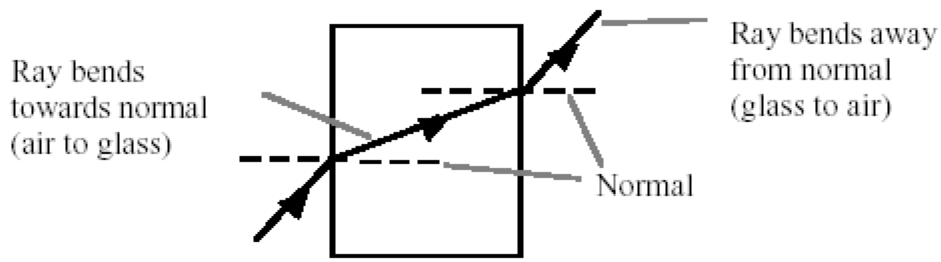
$3 \times 10^{8} = f \times 6 \times 10^{-9}$

$f = 3 \times 10^{8} / 6 \times 10^{-9}$

$f = 5 \times 10^{16}$ Hz

REFRACTION of LIGHT

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



glass block

Refraction is the **change in speed** of a wave that happens when the wave changes from one material to another.

As the above diagram shows, the ray of light has undergone a change in speed when it has changed the material that it is travelling through which has caused also caused a change in direction of the ray of light. The following points should be noted for refraction of light.

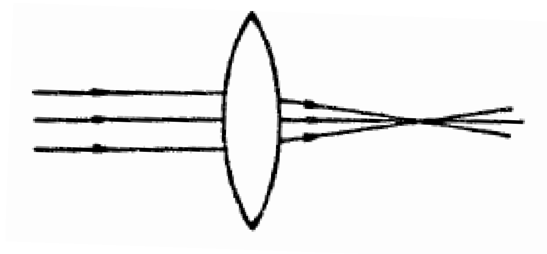
- Light slows down when it enters a denser material e.g. when it travels for air into glass.
- The refracted and incident angles are always measured from the normal line.
- The wavelength of the light will decrease when it enters a denser material, e.g. when it travels from air into glass.
- Frequency does not change when a light passes into a new material.

Knowledge of the physics of refraction can be used in different contexts, e.g. lenses and fibre optic communication.

Lenses

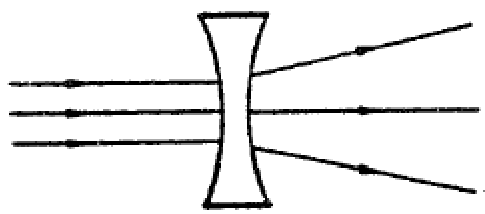
Refraction of light is used in lenses.

When parallel light rays enter a convex (converging) lens the refraction that takes place brings the rays of light to a focus or focal point.



Converging Lens

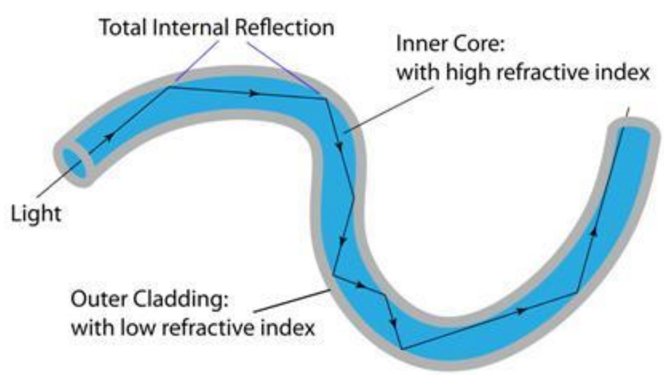
When parallel light rays enter a concave (diverging) lens the refraction that takes place spreads the rays of light out as shown below.



Diverging Lens

Optical Fibres

Optical fibres are long, thin, flexible pieces of glass that carry rays of light. The are manufactured in a way that ensures the rays of light do not escape, helping to ensure the message being sent gets communicated successfully from sender to receiver.

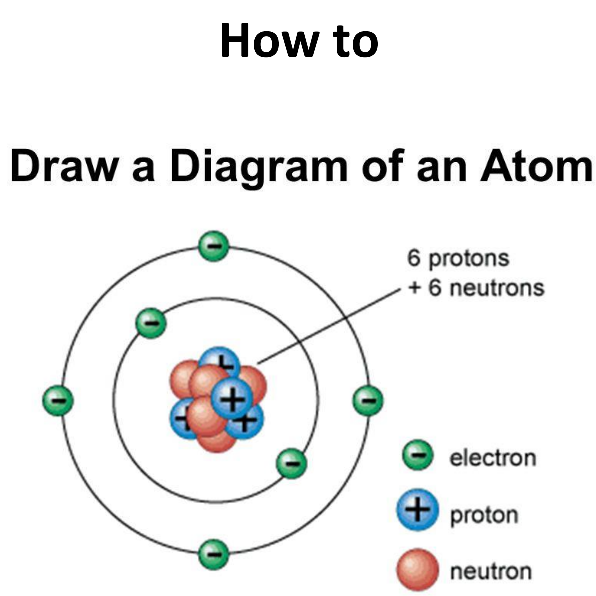


<u>NUCLEAR RADIATION</u>

<u>Atoms</u>

Every substance is made up from atoms.

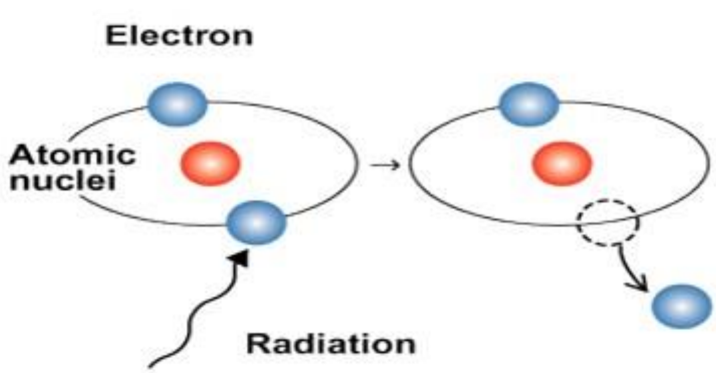
The nucleus is the central part of an atom. The nucleus contains **protons**, which are positively charged, and **neutrons** which have no charge. Orbiting the nucleus are negatively charged **electrons**.



Ionisation is the process in which an atom gains or loses an electron to form an ion.

When an atom **gains** an electron it becomes a **negative ion**.

When an atom **loses** an electron it becomes a **positive ion** as shown below.



In most atoms the numbers of neutrons and protons in the nucleus makes the substance very stable.

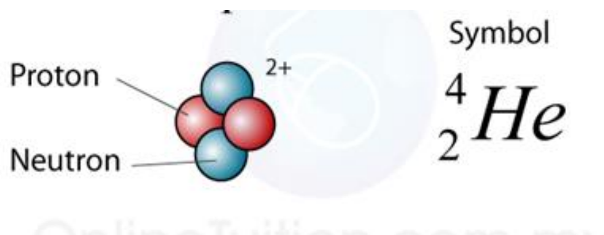
There are some substances where the number of protons and neutrons make the atoms become radioactive. This means they can emit **nuclear radiation**.

Three nuclear radiation are…**alpha (α)**, **beta (β) and gamma (γ).**

<u>Alpha Radiation (α)</u>

Alpha **particles** are positively charged and cause lots of ionisation.

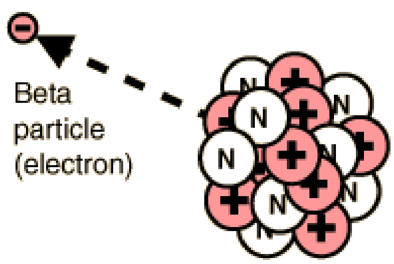
They can move a few cm through air.



<u>Beta Radiation (β)</u>

Beta **particles** are negatively charged and can cause some ionisation.

They can move tens of cm through air.



<u>Gamma Radiation (γ)</u>

Gamma **rays** have no charge as they are a high energy EM wave, which rarely causes ionisation.

They travel many km through air.

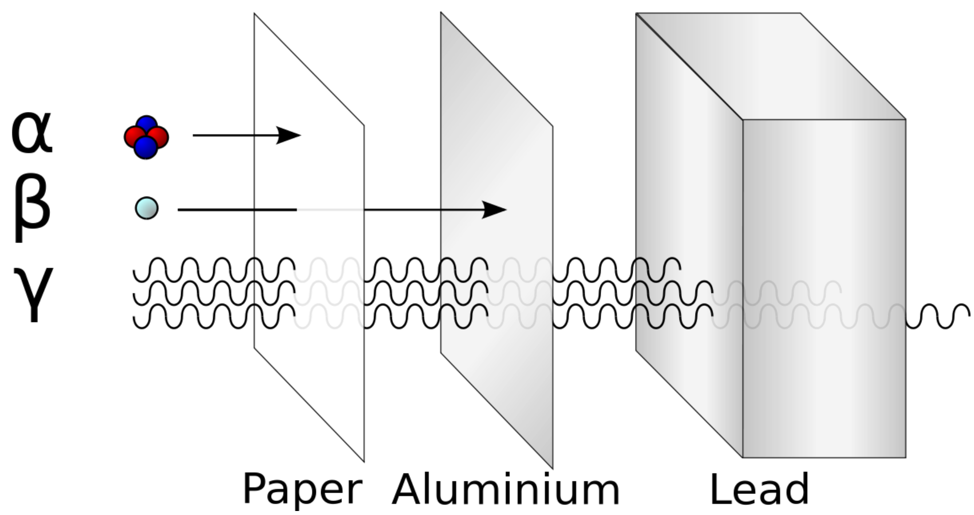
Properties of Radiation

Alpha particles will travel a few centimetres through air before they are fully absorbed. They will be stopped by a sheet of paper. Alpha particles produce a much greater ionisation density than beta particles or gamma rays.

Beta particles can travel tens of centimetres through air and will be stopped by a thin sheet (few millimetres in thickness) of aluminium. Beta particles have a much lower ionisation density than alpha particles.

Gamma rays can only be stopped by a very thick piece (tens of centimetres in thickness) of lead or concrete. Gamma rays travel at the speed of light and have the lowest ionisation density.

These properties can be seen in the following diagram.



A summary table for alpha, beta and gamma is shown below.

Name	Description	Distance Travels In Air	Absorbed by	Possible Use
Alpha	Slow moving nucleus	A few cm	Paper	Smoke Alarms
Beta	Fast moving electron	Tens of cm	Thin Aluminium	Medical Tracers
Gamma	High energy wave	Many km	Thick Lead	Cancer Treatment

Background radiation

Background radiation is the name given to radiation that is always present in our atmosphere. Everyone is exposed to this radiation. Background radiation can come from **natural sources** and from **man-made sources**. A list of sources and their contributions to background radiation is given below.

- Radon gas
- Soil and rocks
- Cosmic rays
- Nuclear power
- Nuclear weapons
- Medical uses
- Food and drink

Natural	Annual dose (mSv)	Man-made	Annual dose (mSv)
Radon	0.8	Medical	0.25
Soil and rocks	0.4	Nuclear weapons	0.01
Food and drink	0.37	Nuclear power	0.002
Cosmic rays	0.3		

This shows that natural sources make a significantly greater contribution than man-made sources to background radiation.

Radiation Calculations

The following equations can be used to measure exposure to radiation:

$$A = \frac{N}{t}$$

$$D = \frac{E}{m}$$

$$H = Dw_r$$

Activity

The Activity (A) of a radioactive source is the number of disintegrations (decays) per second and is measured in Becquerels (Bq).

Example One

In a radioactive source 24000 nuclei disintegrate in one minute. Calculate the activity of the source.

A = ?	A = N / t
N = 24000	A = 24000/60
t = 1 x 60 = 60 s	A = 400 Bq

Example Two

A radioactive source produces 7 200 000 disintegrations, resulting in an activity of 8 kBq. Calculate the over which these disintegations took place.

A = 8 kBq = 8 x 10^3 Bq	A = N / t
N = 7 200 000	8 x 10^3 = 7 200 000 / t
t = ?	t = 7 200 000 / 8 x10^3
	t = 900 s

Example Three

It is possible to determine the age of pre-historic relics that contain carbon-14. The activity of a piece of wood from a pre-historic boat is 1.5 mBq.

Calculate the number of disintegrations in one hour.

A = 1.5 mBq = 1.5 x 10^{-3} Bq	A = N / t
N = ?	1.5 x 10^{-3} = N / 3600
t = 1 hour = (60 x 60) = 3600 s	N = 1.5 x 10^{-3} x 3600
	N = 5.4

Absorbed dose

When radiation reaches the body or our tissues it is absorbed. This is called the Adorbed Dose (D). The aborbed dose is measured in Grays (Gy) where one Gray is equal to one joule of energy absorbed by one kilogram of tissue.

Example One

A part of the body of mass 0.5 kg is exposed to radiation. The energy absorbed is 0.3 J. Calculate the absorbed dose received by this part of the body.

D = ?	D = E/m
E = 0.3 J	D = 0.3 / 0.5
m = 0.5 kg	D = 0.6 Gy

Example Two

An airport worker receives 7200 µJ of energy and an absorbed dose of 90 µGy from an X-ray machine. Calculate the mass of the airport worker. As both units have the same prefix "µ" the solution will be:

D = 90 µGy	D = E / m
E = 7200 µJ	90 = 7200 / m
m = ?	m = 7200 / 90
	m = 80 kg

Example Three

During a scan of a patient's brain, the absorbed dose is measured as 1.5 mGy. The mass of the brain is 1.4 kg.

Calculate the energy absorbed by the brain during the scan.

D = 1.5 mGy = 1.5×10^{-3} Gy	D = E / m
E = ?	1.5×10^{-3} = E / 1.4
m = 1.4 kg	E = $1.5 \times 10^{-3} \times 1.4$
	E = 2.1×10^{-3} J

Equivalent Dose

All ionising radiation can cause damage to the body. The risk of biological harm from an exposure to radiation depends on:

- the absorbed dose, D, which is the energy absorbed per unit mass
- the type of radiation
- the body organs or tissues exposed

This means that two different organs exposed to the same absorbed dose of alpha or gamma will experience a different biological effect. To solve this problem a radiation weighting factor, w_r, is given to each type of radiation. Some examples are given below.

Radiation Weighting Factor w_r	Type of Radiation
1	Beta particles
1	Gamma rays
10	Fast neutrons
10	Protons
20	Alpha particles

When Physicists calculate the effect on our bodies the absorbed dose and the radiation weighting factor are combined in the following equation to give the dose equivalent.

Dose equivalent = absorbed dose x radiation weighting factor

$$H = D \times w_r$$

where,

H – the dose equivalent is measured in Sieverts(Sv)

D – the absorbed dose is measured in Grays (Gy)

w_r – the radiation weighting factor is just a number and has no units

Example

A worker in the nuclear industry receives the following absorbed doses.

- 30 mGy from gamma rays
- 300 µGy from fast neutrons

Calculate their equivalent dose.

For gamma

$H = ?$

$D = 30$ mGy $= 30 \times 10^{-3}$ Gy

$w_r = 1$

$H = D \times w_r$

$H = 30 \times 10^{-3} \times 1$

$H = 30 \times 10^{-3}$ Sv

$H = 30$ mSv

For fast neutrons

$H = ?$

$D = 300$ µGy $= 300 \times 10^{-6}$ Gy

$w_r = 10$

$H = D \times w_r$

$H = 300 \times 10^{-6} \times 10$

$H = 3000 \times 10^{-6}$ Sv

$H = 3$ mSv

Their equivalent dose is (30 + 3) mSv = 33 mSv

Applications

Nuclear radiations have a wide variety of applications including nuclear power stations, car manufacturing and many medical uses.

In nuclear power stations the reactors are fuelled by a **nuclear chain reaction**. Car manufacturers use nuclear radiation for quality control on the thickness of car body parts. In medicine radioactive iodine is used in the **treatment of thyroid cancers** and gamma rays can be used to sterilise surgical instruments.

However, you must remember that over exposure to nuclear radiations can damage living cells.

Half-life

The Activity (A) of a radioactive source is the number of disintegrations (decays) per second and is measured in Becquerels (Bq).

However, radioactive decay is a random process. This means that for a radioactive source, it can never be predicted when an atom is about to decay. In any radioactive source, the activity decreases with time because the number of unstable atoms gradually decreases leaving fewer atoms to decay.

The half-life of a radioactive source is the time for the activity to fall to half its original value.

Example One

The activity of a source falls from 80 MBq to 5 MBq in 8 days. Calculate its half-life.

Solution

$$80 \rightarrow 40 \rightarrow 20 \rightarrow 10 \rightarrow 5$$

Each arrow represents one half-life. There are four arrows, so in 8 days there are four half-lives.

The half-life will be 8 / 4 = 2 days.

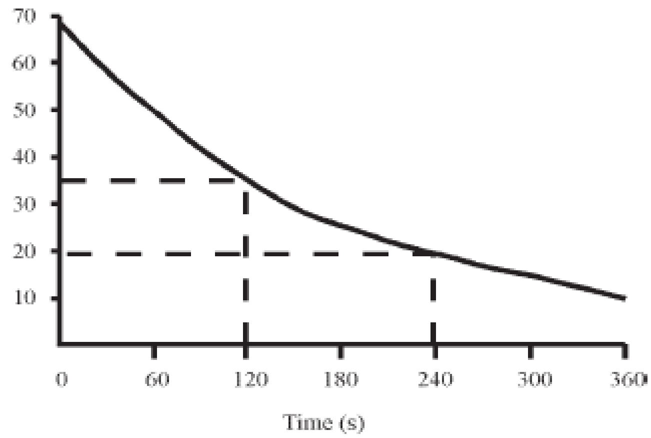
Example Two

A Geiger-Muller tube and a ratemeter were used to measure the half-life of Caesium-140. The count rate was noted every 60 seconds. The results are shown in the table:

Time (s)	0	60	120	180	240	300	360
Count rate (counts per minute)	70	50	35	25	20	15	10

By plotting a suitable graph, find the half-life of Caesium-140.

Counts per minute



In graph type examples a number of results should be taken from the graph before the half-life is stated.

For the above graph the time taken for the count rate to half from 70 counts per minute (0 s) to 35 counts per minute (120 s) is 120 s. Also the time taken for the count rate to half from 35 counts per minute to 17.5 counts per minute is also approximately 120 s.

When enough examples have been taken from the graph we can state that the half-life for the Caesium -140 will be 120 s.

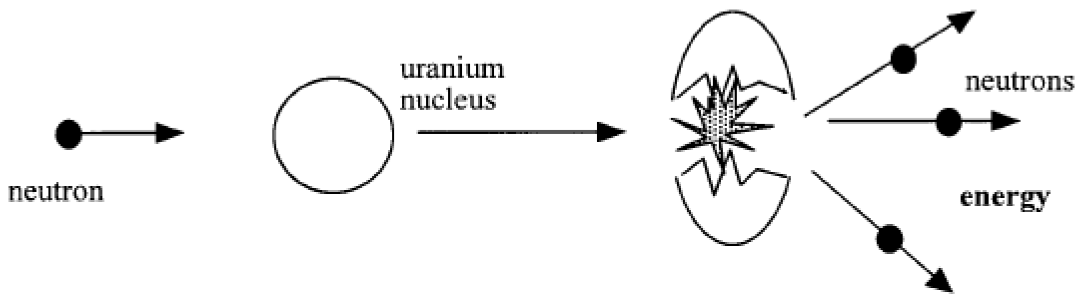
Nuclear Fission

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

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

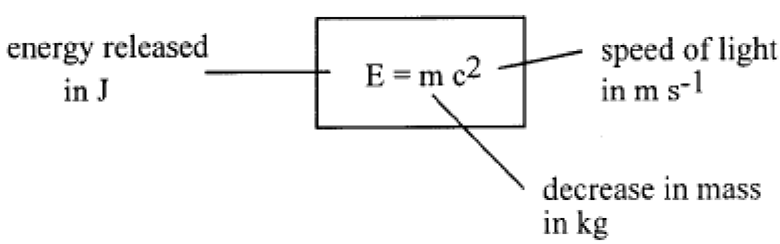
This **spontaneous fission** reaction would also produce 5 neutrons and release energy.

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.



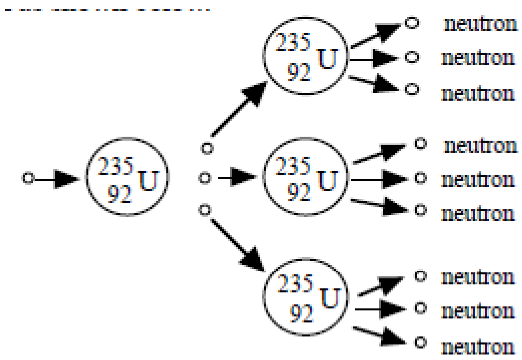
A detailed analysis of the total mass before and after the reaction reveals that the mass before is greater than the mass after.

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.



One fission reaction would typically release 1.6 x 10^{-13} 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**.

Once a nucleus has divided by fission, the neutrons that are emitted can strike other neighbouring nuclei and cause them to split releasing energy each time. This results in what is called a chain reaction, as shown below.

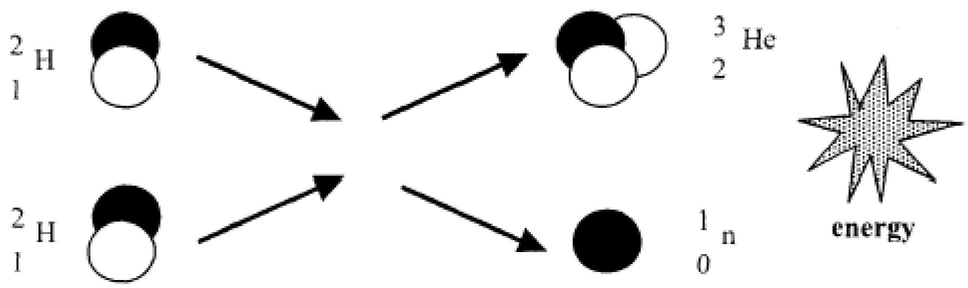


In a controlled chain reaction, on average only one neutron from each fission will strike another nucleus and cause it to divide. This is what happens in a **nuclear power station**.

In an **uncontrolled chain reaction** all the neutrons from each fission strike other nuclei producing a large surge of energy. This occurs in **nuclear bombs**.

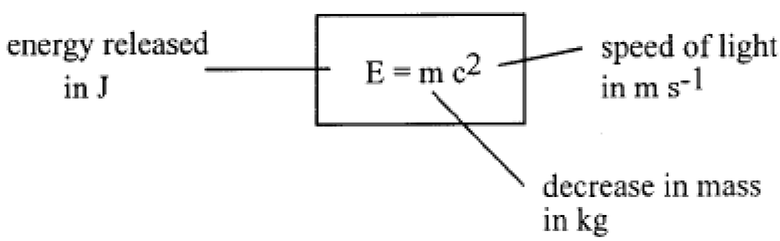
Nuclear Fusion

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



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** but is not currently used in nuclear power stations.

Although we have a natural source for fusion – hydrogen atoms in water – the extreme temperatures needed for hydrogen atoms to "fuse" are so high (150 million °C) that hydrogen becomes a **plasma**.

The technology needed for the **containment** of this plasma is extremely complex and is still under development.

$E_p = mgh$

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

$Q = It$

$V = IR$

$R_T = R_1 + R_2 + \ldots$

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

$V_2 = \left(\frac{R_2}{R_1 + R_2}\right)V_s$

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

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

$P = IV$

$P = I^2 R$

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

$E_h = cm\Delta T$

$p = \frac{F}{A}$

$\frac{pV}{T} = \text{constant}$

$p_1V_1 = p_2V_2$

$\frac{p_1}{T_1} = \frac{p_2}{T_2}$

$\frac{V_1}{T_1} = \frac{V_2}{T_2}$

$d = vt$

$v = f\lambda$

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

$A = \frac{N}{t}$

$D = \frac{E}{m}$

$H = Dw_R$

$\dot{H} = \frac{H}{t}$

$s = vt$

$d = \bar{v}t$

$s = \bar{v}t$

$a = \frac{v-u}{t}$

$W = mg$

$F = ma$

$E_w = Fd$

$E_h = ml$