HIGHER PHYSICS

UNIT 3 - RADIATION and MATTER

WAVES and LIGHT

1) REFLECTION, REFRACTION, DIFFRACTION and INTERFERENCE

You must be able to:

- Explain and use correctly the following terms - crest, trough, amplitude, wavelength, frequency, velocity, period, reflection, refraction, diffraction, interference, constructive interference, destructive interference, in phase, out of phase, coherent and monochromatic.
- State that the frequency of a wave is always equal to the frequency of the source producing the wave.
- State that the energy of a wave depends on its amplitude.
- State the period of a wave in terms of its frequency (and vice versa): $T = 1/f$ and $f = 1/T$.
- Solve problems using the wave equations: $T = 1/f$ or $f = 1/T$ and $v = f\lambda$.
- State that all types of waves show reflection, refraction, diffraction and interference.
- State that interference is the test for wave motion.
- Describe an experiment to demonstrate the effect of the path difference between two wave sources on the wave intensity detected at any point.
- State that the condition for maxima and minima in an interference pattern formed by two coherent wave sources is given by the equation path difference $= n\lambda$ for a maxima and $(n + 1/2)\lambda$ for a minima where n is an integer (whole number) and λ is the wavelength.
- Solve problems using this relationship.
- Describe and compare the effects produced by a prism and a diffraction grating on a beam of monochromatic light and a beam of white light.
- Describe an experiment to measure the wavelength of monochromatic light using a diffraction grating.
- Solve problems using the diffraction grating equation $n\lambda = d \sin \theta$.
- State approximate values for the wavelength of blue, green and red light.

WAVES - an Introduction

Waves carry **energy** from one place to another.

Waves can be classified as **mechanical** or **electromagnetic**.

Mechanical Waves

These are produced by a disturbance (such as a **vibrating object**) in a material and are transmitted by the particles of the material vibrating to and fro about a fixed point. These waves can often be seen or felt - For example, **water waves**, **waves on a spring** and **sound waves in various materials**.

Electromagnetic waves

These consist of a disturbance in the form of varying **electric** and **magnetic fields**. The waves travel through a vacuum (where there are no particles) with a velocity of **3 x 10^{8} m s^{-1}**.

The electromagnetic spectrum

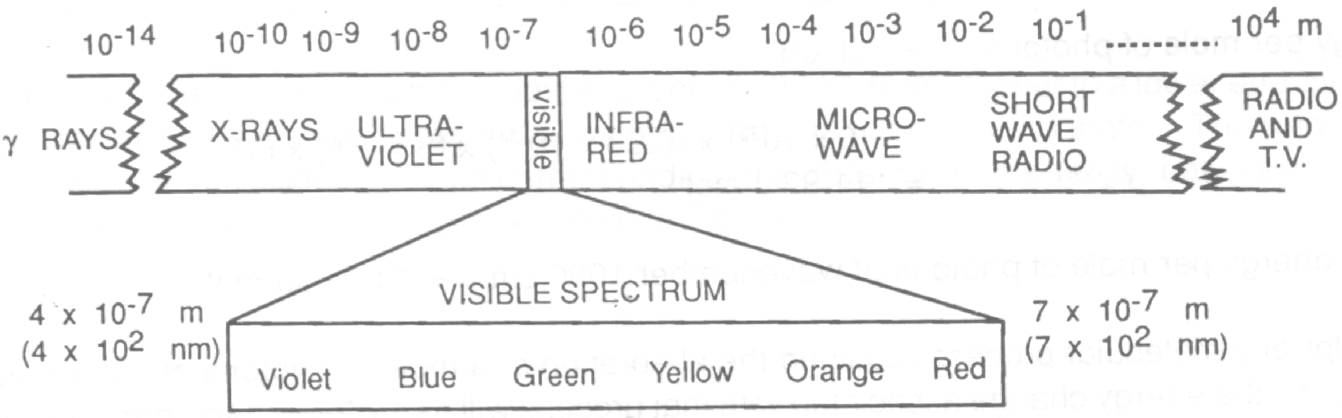
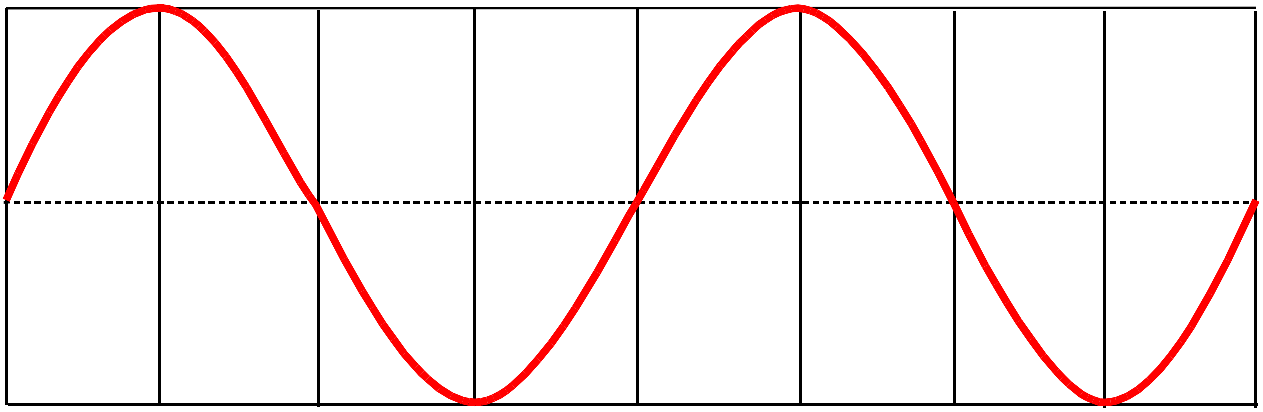


Diagram copyright Heriot-Watt University

Describing Waves

Various terms are used to describe waves:



On this wave diagram, mark a **crest**, a **trough**, the **amplitude** and the **wavelength**.

The **amplitude** of a wave is ____
____ Unit: metres (m).

The **energy** of a wave is shown by its **amplitude** - The __________ the **amplitude**, the ______________ the **energy** of the wave.

The **wavelength** (λ) of a wave is____
____ Unit: metres (m).

The **frequency** (**f**) of a wave is ____
____ Unit: hertz (Hz).

The **frequency** of a wave is always equal to the **frequency of the source producing the wave**
- A wave of frequency 10 Hz must be produced by a source vibrating at ____ Hz.

THE FREQUENCY OF A WAVE NEVER CHANGES AFTER THE WAVE LEAVES ITS SOURCE.

The **velocity** (**v**) of a wave is ____
______________________________________ Unit: metres per second ($m\ s^{-1}$).

The **period** (**T**) of a wave is ____
____ Unit: seconds (s).

Wave Equations

Three equations are commonly applied to waves:

displacement = velocity x time	velocity = frequency x wavelength	period (T) = $\frac{1}{\text{frequency(f)}}$
$s = v\,t$	$v = f\,\lambda$	or frequency (f) = $\frac{1}{\text{period(T)}}$
Calculate the displacement of a wave which travels to the right at 15 m s^{-1} for 3 s:	**Calculate the frequency of a wave which has a velocity of 2.5 m s^{-1} and a wavelength of 0.5 m:**	**Calculate the period of a wave whose source vibrates with a frequency of 4 Hz:**

Reflection, Refraction and Diffraction of Waves

All waves can be **reflected**, **refracted** and **diffracted**:

Reflection is ______________________________

____

____

During reflection:

Wave speed ____________________

Wavelength ____________________

Frequency ____________________

Complete the diagram:

NOTES:

Refraction is ______________________________

____

____

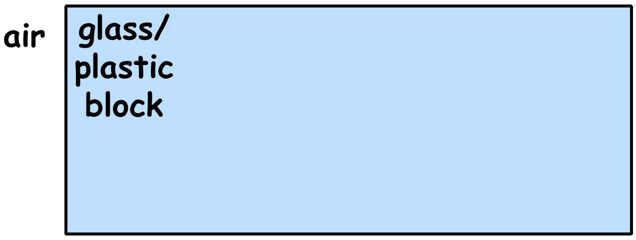
When light enters glass/plastic from air:

Wave speed ____________________

Wavelength ____________________

Frequency ____________________

Complete the diagram:



NOTES:

Diffraction is ______________________________

____

____

During diffraction:

Wave speed ____________________

Wavelength ____________________

Frequency ____________________

Complete the diagram:

NOTES:

Interference of Waves

When 2 waves meet, they overlap/combine - This is known as interference.

There are 2 types of **interference**:

Constructive Interference

When **2 wave crests** or **2 wave troughs** arrive at the same point at the same time, they are said to be **in phase**.

Constructive interference occurs:

Show this using a diagram:

Destructive Interference

When a **wave crest** and a **wave trough** arrive at the same point at the same time, they are said to be **out of phase**.

Destructive interference occurs:

Show this using a diagram:

Destructive Interference -The test for wave motion

Energy can be carried from one place to another by either particles or waves.

TO SHOW THAT THE ENERGY IS BEING CARRIED BY WAVES, IT IS NECESSARY TO DEMONSTRATE DESTRUCTIVE INTERFERENCE.

This is because____

____

____

____

____

Coherent Waves

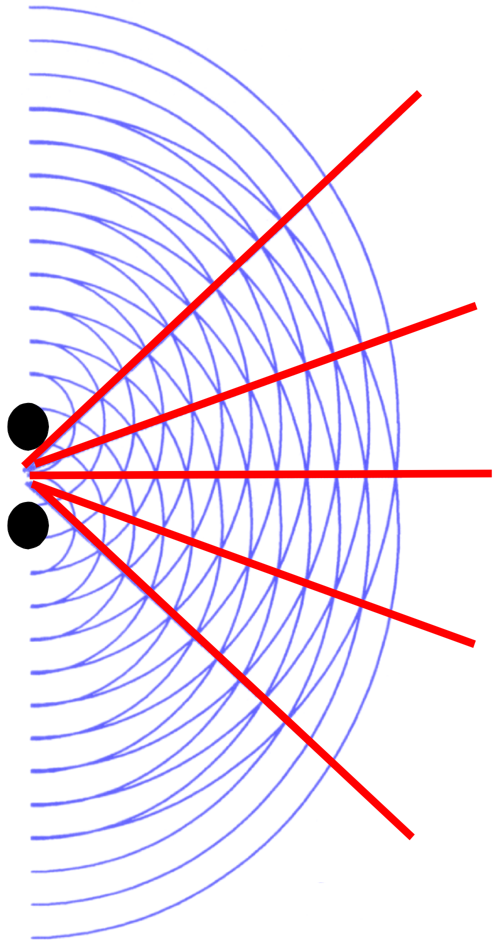
If 2 waves are **coherent**, they have the same **amplitude** and **frequency** and are always **exactly in phase**.

In order to achieve this, a **single source** must be used to produce the 2 waves.

This is illustrated on the next 2 pages.

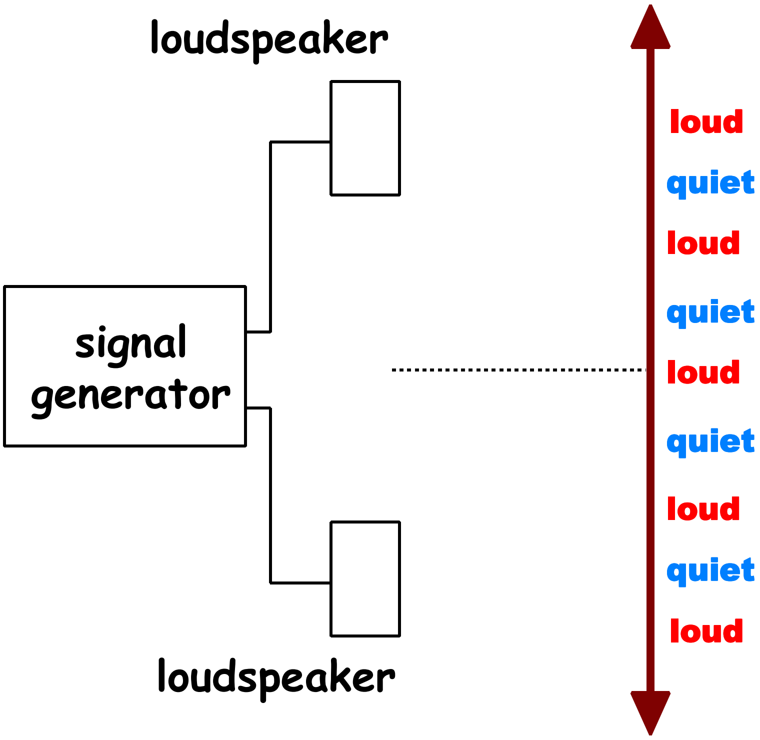
(a) Interference of water waves

Label the diagram and make notes:

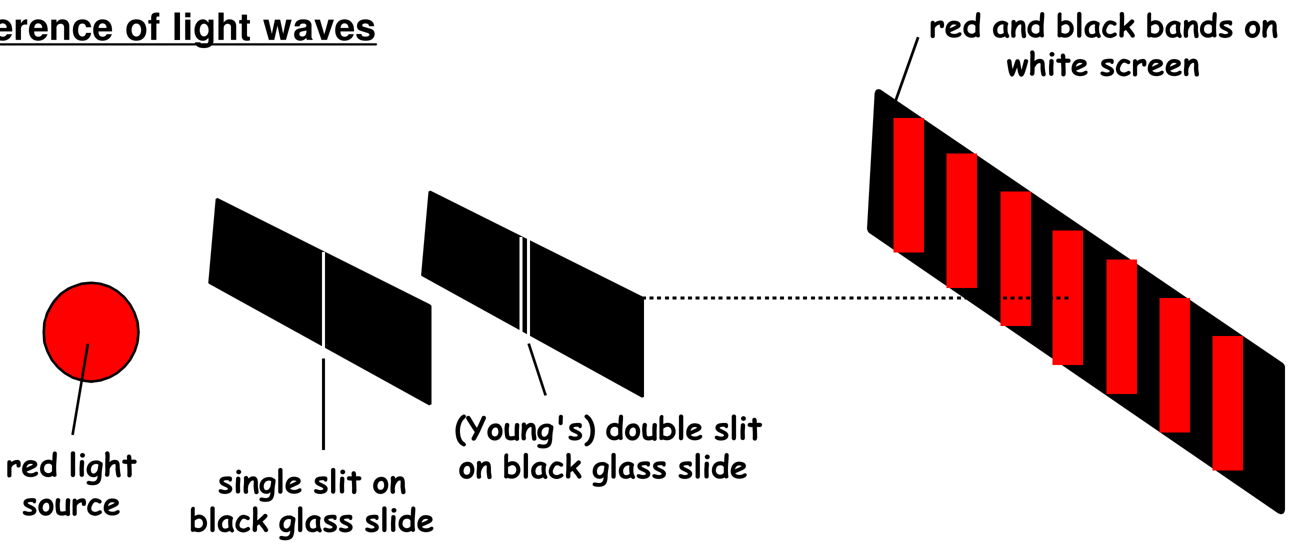


(b) Interference of sound waves

Label the diagram and make notes:



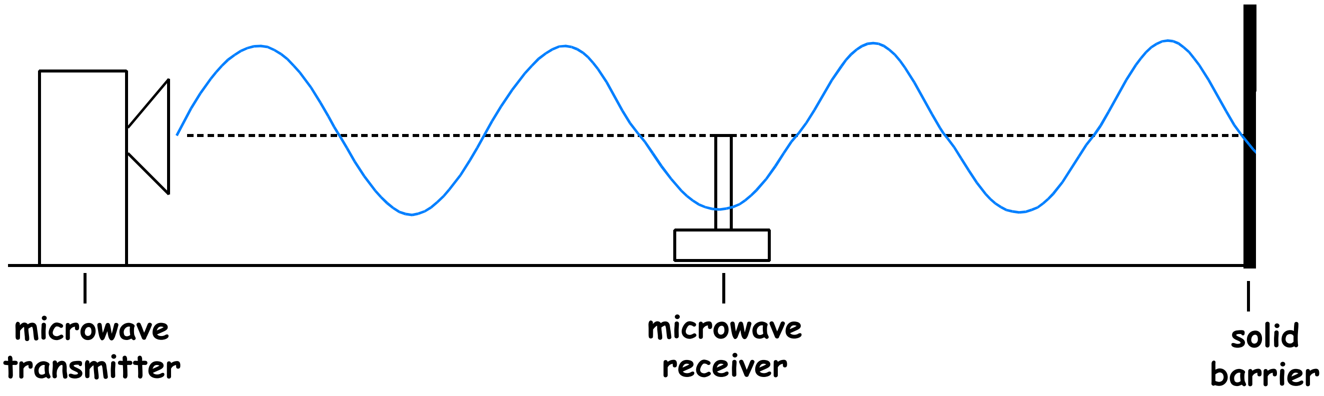
(c) Interference of light waves



Notes:

(d) Interference of microwaves

Complete the diagram to show what happens to the microwaves when they hit the solid barrier:



Notes:

Path Difference, Wavelength and Interference

The maxima in an interference pattern are numbered as shown.

To reach the central maximum, n = 0 (which is always the strongest), waves from both sources have to travel the same distance.

To reach other **maxima** or **minima**, waves from the 2 sources have to travel different distances - The **difference** between these 2 distances is known as the **path difference**.

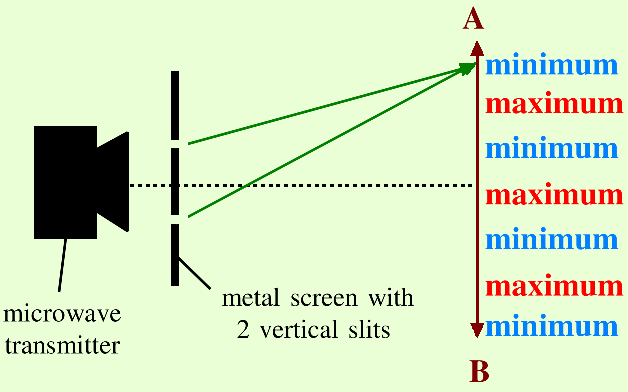
For any maximum, path difference = $n\lambda$

For any minimum, path difference = $(n + 1/2)\lambda$

		Path difference to point
	X second order maximum, n = 2	2λ
	X minimum	$1\ 1/2\ \lambda$
	X first order maximum, n = 1	1λ
source 1	X minimum	$1/2\ \lambda$
--	X central maximum, n = 0	0
source 2	X minimum	$1/2\ \lambda$
	X first order maximum, n = 1	1λ
	X minimum	$1\ 1/2\ \lambda$
	X second order maximum, n = 2	2λ

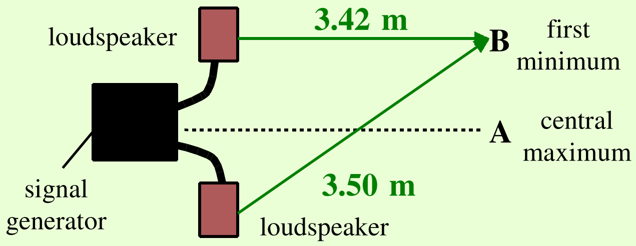
Richard pointed a microwave transmitter at a metal screen with 2 vertical slits in it. When Richard moved a microwave receiver along the line AB, a meter connected to the receiver displayed the readings shown.

If the microwaves had a wavelength of 3 cm, what was the path difference between the 2 slits and the minimum shown?



Kris connected 2 loudspeakers to a signal generator, then moved a sound level meter from the central maximum at A to the first minimum at B.

What was the wavelength of the sound coming from the 2 loudspeakers?



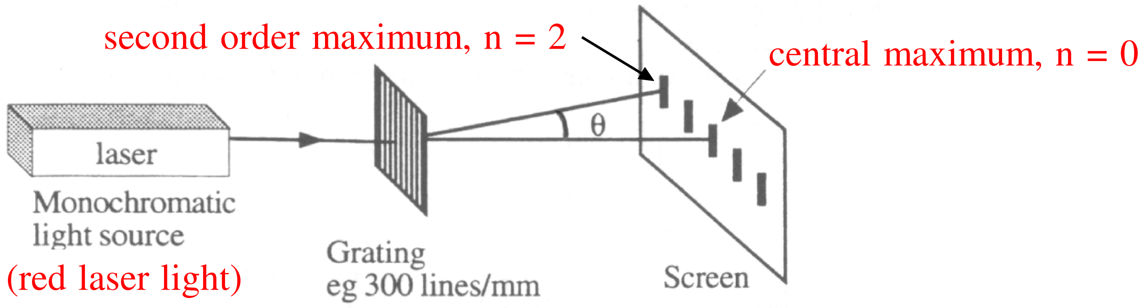
Diffraction Grating for the Interference of Light

To produce a ***bright*** and ***sharp*** **interference pattern** for **light**, a **diffraction grating** is used in preference to a Young's double slit.

A **diffraction grating** consists of many equally-spaced slits placed extremely close together, e.g., 300 lines per millimetre.

Light is diffracted through each slit, causing **constructive** and **destructive interference**.

Monochromatic light (light of a single colour, and hence one frequency/wavelength) or **white light** can be used.



This equation (the **grating equation**) applies:

$$n\lambda = d \sin \theta$$

n = order of maximum

λ = wavelength of light (in metres)

d = distance between slits on diffraction grating (in metres)

θ = angle between central maximum and maximum of order n (in degrees)

EXAMPLE - Experimental determination of the wavelength of red light

Matthew used the apparatus shown above to measure the wavelength of red laser light. With a protractor, Matthew measured the angle between the central maximum and second order maximum to be 25°.

$n = 2.$

$\lambda = ?$

$d = 3.33 \times 10^{-6}\text{m}$

$\sin \theta = \sin 25^\circ = 0.423$

To determine value for d in metres:

Grating has 300 slits (lines) per mm

$= 300 \times 1\ 000 = 300\ 000$ slits per m

distance between slits (d) = $\dfrac{1}{300\ 000}$

$= (3.33 \times 10^{-6})\ \text{m}$

$$n\lambda = d \sin \theta$$

$$2\lambda = (3.33 \times 10^{-6}) \times 0.423$$

$$2\lambda = 1.41 \times 10^{-6}$$

$$\lambda = \frac{1.41 \times 10^{-6}}{2}$$

$$= \underline{7.05 \times 10^{-7}\ \text{m}} \quad (705\ \text{nm})$$

Changing the distance between maxima

The grating equation can be rearranged to give $\sin \theta = \frac{n\lambda}{d}$

θ gives an indication of the separation of the maxima on the interference pattern.

To make the maxima further apart, you could:

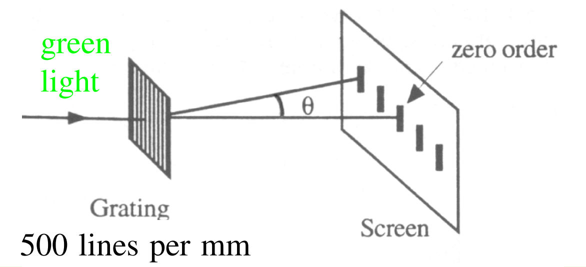
1) **Use light of a longer wavelength - towards the red end of the visible spectrum;**
2) **Decrease the slit separation - have more lines per mm.**

You could also:

3) **Move the screen further away from the diffraction grating.**

EXAMPLE

Emma sets up this apparatus to measure the wavelength of green light. She measures the angle θ between the central (zero order) maximum and second order maximum with a protractor and finds it to be 33°. Calculate the wavelength value Emma will obtain:

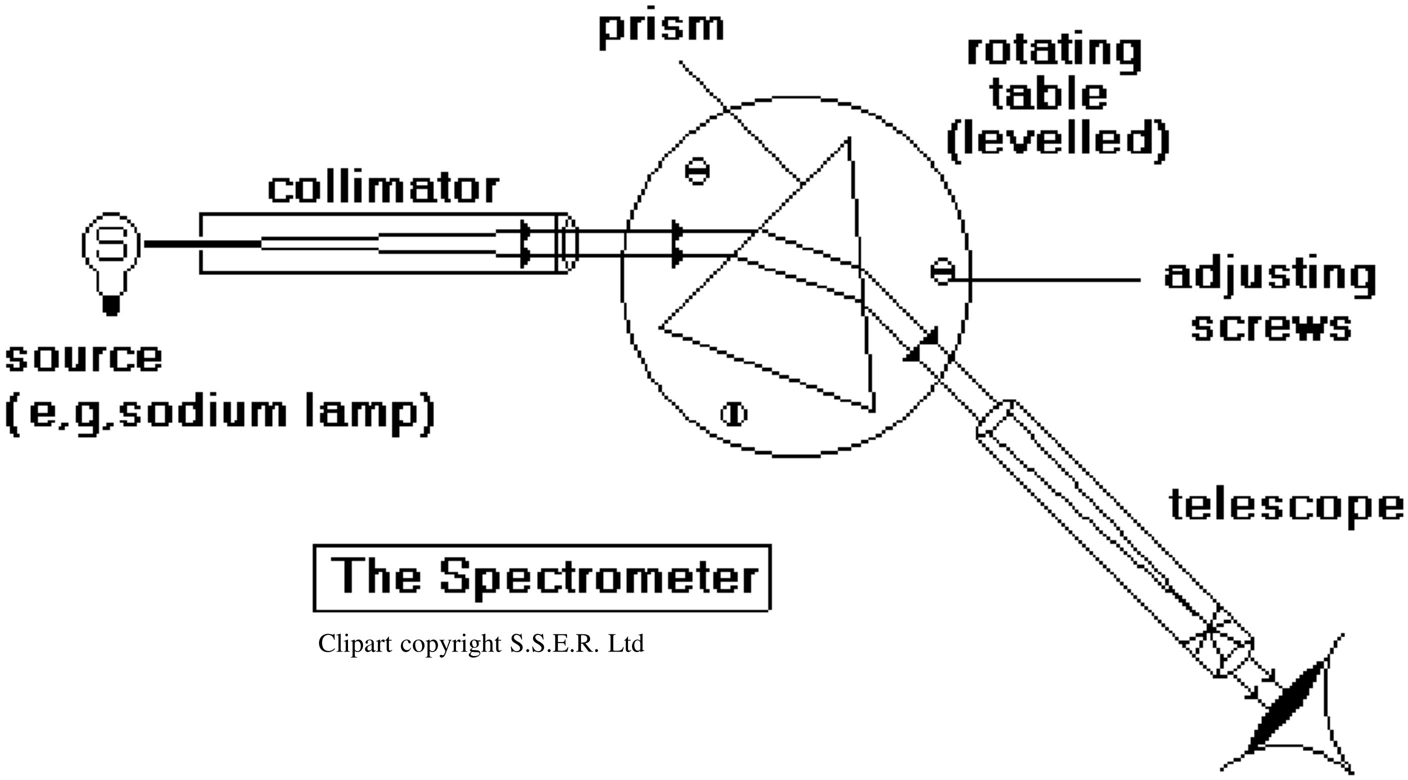


500 lines per mm

What affect will there be on the separation of the maxima on the screen if Emma :

Uses red light (wavelength 7 x 10^{-7} m);	Uses a diffraction grating with 700 lines per mm;	Increases the distance between the diffraction grating and screen?

Use of SPECTROMETER to measure angles between maxima



Clipart copyright S.S.E.R. Ltd

In order to obtain an extremely accurate value for the angle between maxima in a light interference pattern, a device called a **spectrometer** is often used.

A diffraction grating or prism are positioned on a level turntable which can be turned through very small angles. These angles can be measured from a very fine scale on the turntable.

The collimator ensures light coming from the source is parallel.

The telescope is used to obtain the exact position of each maxima, so the angle from the central maximum can be measured accurately.

Approximate Wavelength of blue, green and red light

You must be able to quote an approximate value for the wavelength of blue, green and red light.

Wavelength of blue light = 4.9×10^{-7} m = 490 nm

Wavelength of green light = 5.4×10^{-7} m = 540 nm

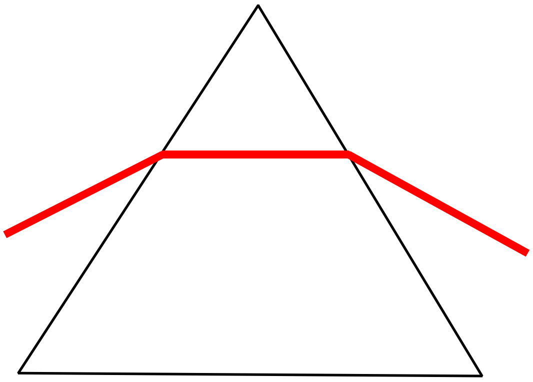
Wavelength of red light = 7.0×10^{-7} m = 700 nm

*** 1 nanometer (nm) = 1×10^{-9} m**

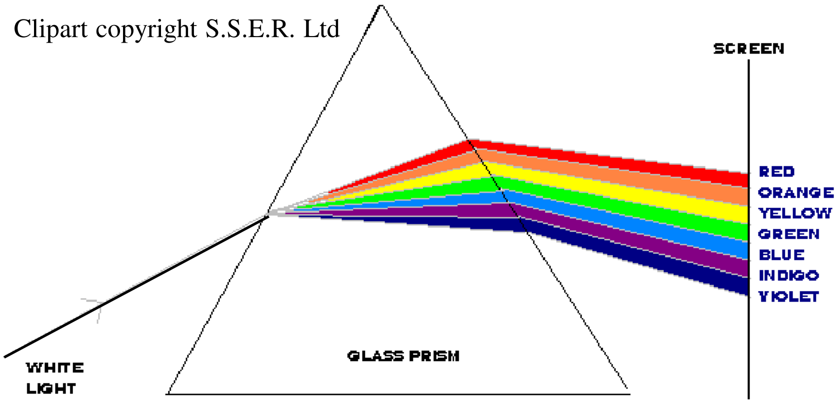
If you can't remember these values, similar values will be quoted in the data sheet you receive with your final exam paper - The data on this sheet refers to the wavelength of the red, green and blue spectral lines of the element cadmium.

Comparing White Light Spectra from Prisms and Gratings

When a ray of **monochromatic** (e.g., **red**) light is passed through a glass prism, the ray is **refracted**:



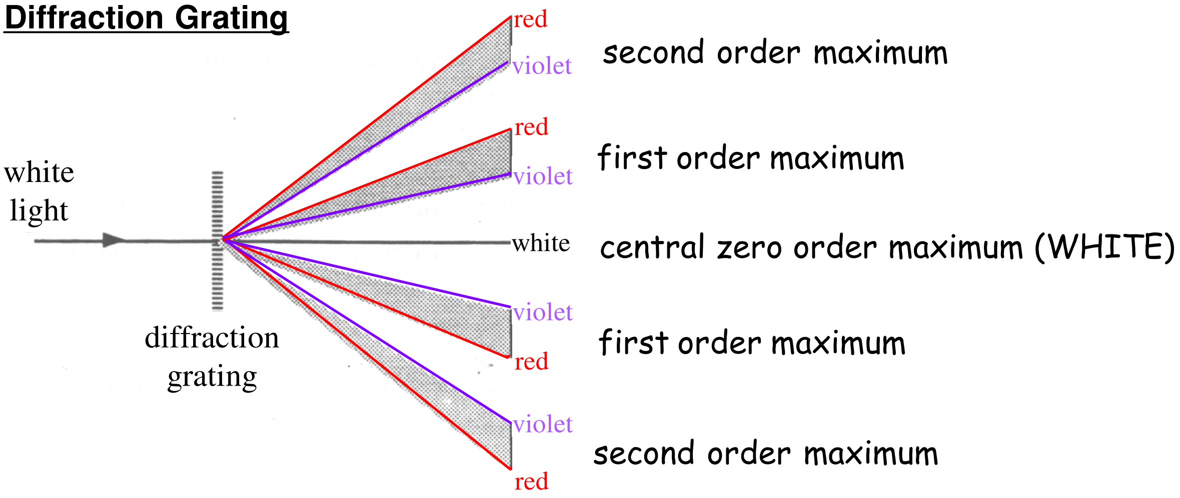
When a ray of **white** light is passed through a glass prism, a **visible spectrum** is produced:



Clipart copyright S.S.E.R. Ltd

DISPERSION OF WHITE LIGHT BY A PRISM

Diffraction Grating



PRISM	DIFFRACTION GRATING
Only one spectrum is produced (by refraction).	Many spectra are produced (by interference), symmetrically about a central white maximum. At central white maximum, path difference is zero, so all wavelengths (colours) of the visible spectra arrive in phase - They recombine to give white light.
Red light is deviated least. Violet light is deviated most.	Red light is deviated most. Violet light is deviated least. Red light has the longer wavelength, so is deviated most according to the **grating equation**: $\sin\theta = \frac{n\lambda}{d}$
Spectrum is brighter.	Spectra are less bright. The energy is divided between several spectra.
Colours in spectrum are close together.	Colours in spectra are more spread out.

HIGHER PHYSICS

UNIT 3 - RADIATION and MATTER

WAVES and LIGHT

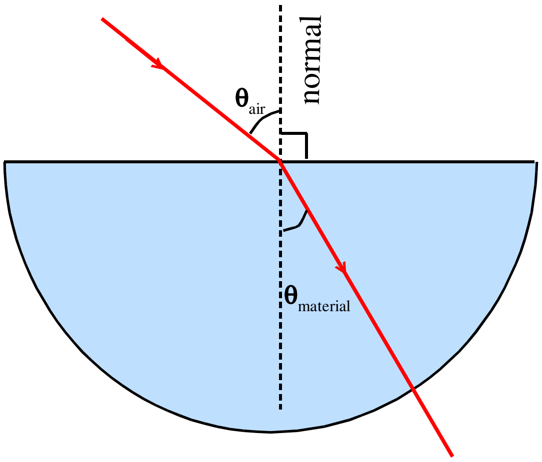
2) REFRACTIVE INDEX, CRITICAL ANGLE and TOTAL INTERNAL REFLECTION

You must be able to:

- Describe an experiment to show that when monochromatic light passes between air and a material of different density at an angle other than 90° (or vice versa), the ratio $\sin\theta_{air}/\sin\theta_{material}$ is a constant value n (the refractive index of the material).
- Understand that if air is replaced by a vacuum, the ratio $\sin\theta_{vacuum}/\sin\theta_{material}$ is called the absolute refractive index of the material.
- Solve problems using the above relationships.
- State that the refractive index of a material depends on the frequency of the light hitting the material. (The frequency does not change when light passes from one material into another).
- State the relationship: $n = \dfrac{\sin\theta_{air}}{\sin\theta_{material}} = \dfrac{v_{air}}{v_{material}} = \dfrac{\lambda_{air}}{\lambda_{material}}$
- Explain what is meant by total internal reflection and critical angle.
- Describe an experiment to show total internal reflection/measure the critical angle for a material.
- Derive the relationship $\sin\theta_c = 1/n$, where θ_c is the critical angle for a material of refractive index n.
- Solve problems using the above relationship.

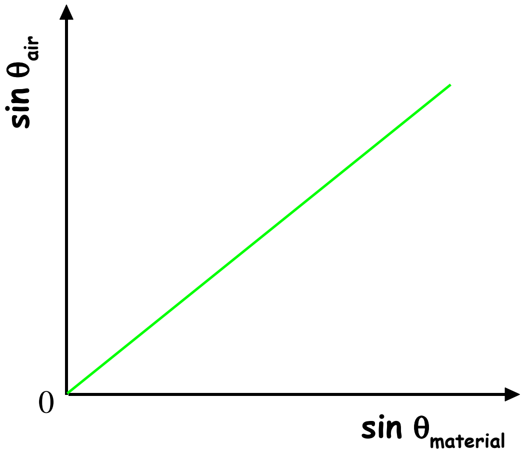
1) REFRACTIVE INDEX (n) OF A MATERIAL

When a ray of **light** is shone from air onto the flat face of a semi-circular block of transparent material which is denser than air, at any angle other than 90°, the ray changes **direction** on entering the material (due to a change in **velocity**) - The ray is **refracted**:



On entering the material, the light ray bends **towards the normal** line - The angle $\theta_{material}$ is always less than the angle θ_{air}.

If you change θ_{air} several times, measure θ_{air} and $\theta_{material}$ each time, then calculate values for $\sin\theta_{air}$ and $\sin\theta_{material}$, you can plot a graph of $\sin\theta_{air}$ against $\sin\theta_{material}$. The graph you obtain is a straight line passing through the origin:



The graph shows that:

$$\sin\theta_{air} \propto \sin\theta_{material}$$

or

$$\frac{\sin\theta_{air}}{\sin\theta_{material}} = \text{constant}$$

The constant is known as the **refractive index** of the material. It is given the symbol **n**. It does not have a unit :

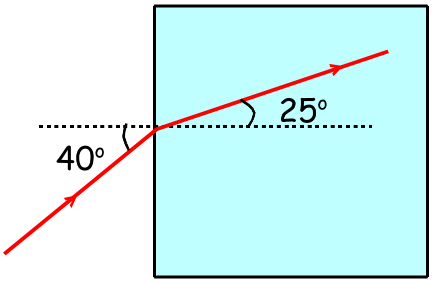
$$\text{refractive index (n)} = \frac{\sin\theta_{air}}{\sin\theta_{material}}$$

Note

- This equation applies to any material that light can pass through, e.g., glass, plastic, water.
- Each material has its own distinct value of refractive index (which is always equal to or greater than 1).
- The greater the refractive index, the greater the change in direction of the light ray.
- The refractive index of a material is the same whether light moves from air into the material or vice versa.
- The term **absolute refractive index** is used when air is replaced by a vacuum. (The values obtained using air and a vacuum are almost identical).

Example

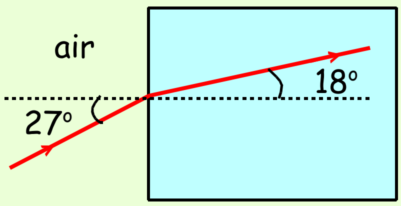
Calculate the refractive index of the glass block shown:



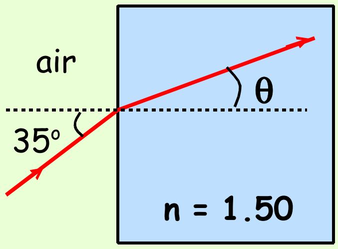
$$n = \frac{\sin\theta_{air}}{\sin\theta_{material}} = \frac{\sin 40°}{\sin 25°} = \frac{0.643}{0.423}$$

$$= \underline{1.52}$$

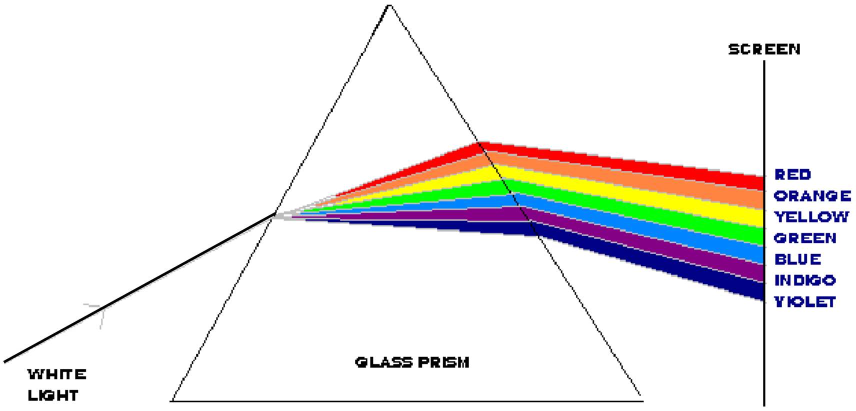
Calculate the refractive index of the material this block is made from:



Calculate the value of the unknown angle θ :



Refractive Index and Frequency of Light



Dispersion of white light by a prism

Clipart copyright S.S.E.R. Ltd

The **refractive index** of a material depends on the **frequency** (colour) of the light hitting it.

When **white light** passes through a glass prism, a **visible spectrum** is produced because each component colour of **white light** has a different **frequency**, so is **refracted** by a **different amount.**

Violet is refracted more than **red**, so **the refractive index for violet light must be greater than the refractive index for red light.**

Refractive Index, Angles, Velocity and Wavelength of Light

When light passes from **air** into a **denser material** such as **glass**:

Its velocity decreases. Its wavelength decreases. Its frequency remains constant.

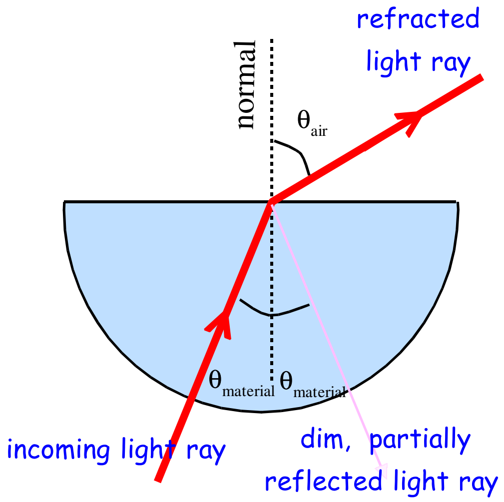
This equation shows the relationship between **refractive index**, **angles**, **velocity of light** and **wavelength of light** in air and a material:

$$\text{refractive index (n)} = \frac{\sin\theta_{air}}{\sin\theta_{material}} = \frac{\text{velocity (v)}_{air}}{\text{velocity (v)}_{material}} = \frac{\text{wavelength }(\lambda)_{air}}{\text{wavelength }(\lambda)_{material}}$$

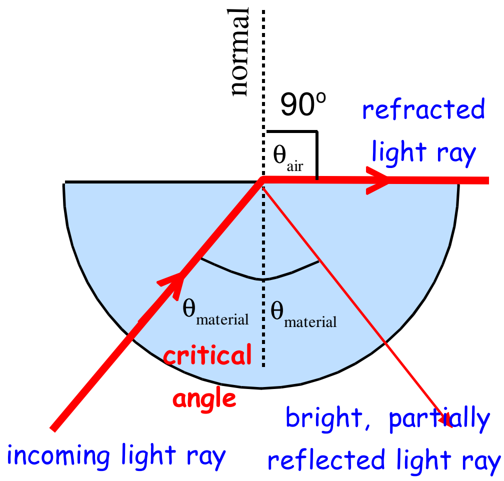
Calculate the velocity of light in a glass block which has a refractive index of 1.50. (Velocity of light in air = 3 x 10^8 ms^{-1}):

Red light (wavelength 700 nm in air) is passed into a plastic material of refractive index 1.47. Calculate the wavelength of the light in the plastic:

2) CRITICAL ANGLE and TOTAL INTERNAL REFLECTION

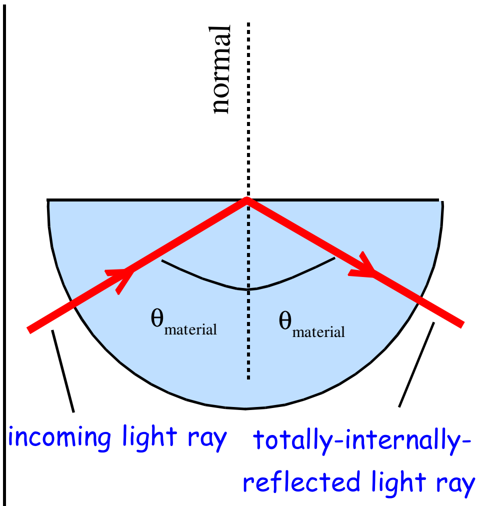


When a monochromatic light ray is passed from air into a semi-circular **crown glass** block at an angle of incidence close to the normal line, most of the light ray is **refracted** into the air at the flat surface. A small amount of the light is **reflected** back into the glass by the flat surface - the dim, partially reflected light ray.



If the angle of incidence between the incoming light ray and the normal line is increased to **42°**, most of the light ray is **refracted** along the flat surface into the air (at 90° to the normal line). A much larger amount of the light is **reflected** back into the glass by the flat surface - the partially reflected light ray is **much brighter**.

We call the angle of incidence at which this happens the **CRITICAL ANGLE** for the material.

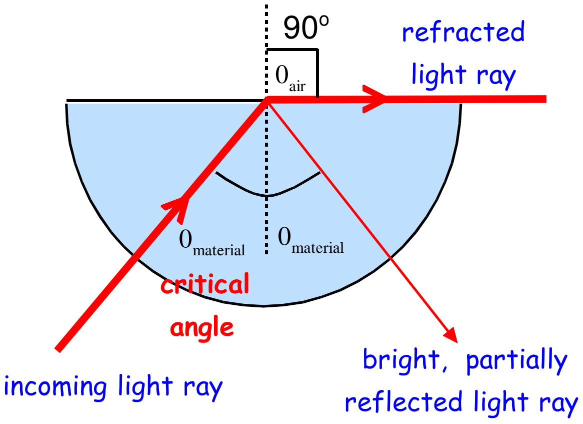


If the angle of incidence between the incoming light ray and the normal line is increased **above** the **critical angle** (**42°**), **all** of the light ray is **reflected** back into the glass by the flat surface.

This is called **TOTAL INTERNAL REFLECTION**.

Total internal reflection occurs when the angle of incidence at which a light ray strikes the inside surface of a material is greater than the material's critical angle.

Relationship Between Critical Angle and Refractive Index



At the **critical angle** (θ_c), $\theta_{air} = 90°$.

$$\text{refractive index (n)} = \frac{\sin\theta_{air}}{\sin\theta_{material}} = \frac{\sin 90°}{\sin\theta_c}$$

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

Adam performed an experiment to find the critical angle and refractive index of a plastic material which had been shaped into a semi-circular block.

Adam typed up and saved his report on a PC - but when he opened the file next day, he found that the PC had not saved some words, a calculation and the labels and arrows on his diagrams (as shown below):

Help Adam by fully-labelling his diagrams, filling in the missing words and completing his refractive index calculation:

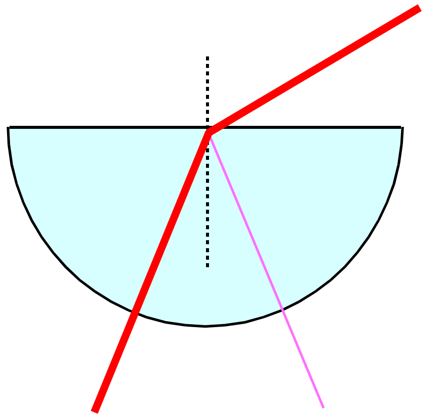
Experiment to Find the Critical Angle and Refractive Index of a Semi-Circular Plastic Block

I passed a ray of red light into the plastic block. The angle of incidence between the ray and the normal line was small. Most of the light ray ______________

____

but a ______ amount of the light was ____________

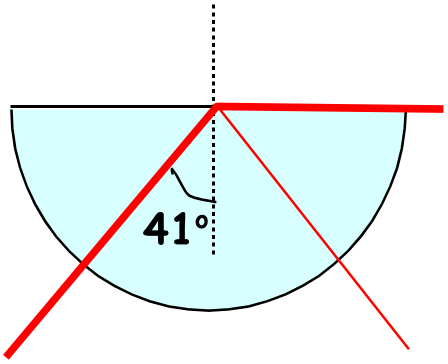
____



I increased the angle of __________ between the incoming light ray and the normal line until most of the ray was __________ along the flat surface of the block (at ___ to the normal line). A much larger amount of light was ____________________________

____

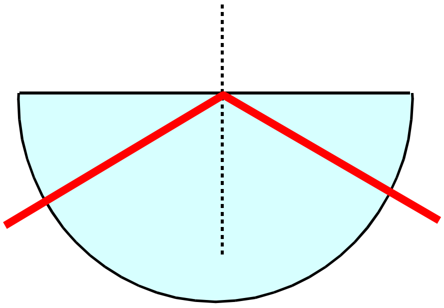
The angle of incidence at which this happened is called the ___________ ______ for the material. Its value was ____.



When I increased the angle of _________ between the incoming light ray and the normal a little bit further (above the ________ angle) ____________

____

- This is known as _______ _________ _________.

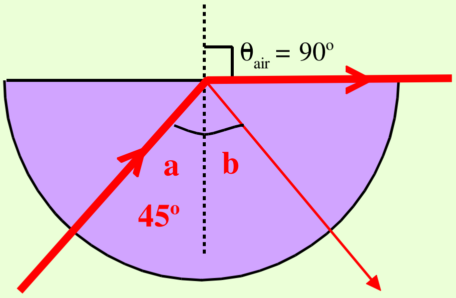


Here is how I derived the relationship between the refractive index and critical angle of the plastic:

Here is how I calculated the refractive index of the plastic:

1) Jane used a ray of red light to determine the refractive index of special glass X (in the form of a semi-circular block).

Jane adjusted her apparatus until she observed the following:



(a) **How does the size of angle a compare with the size of angle b?** ______________________________

(b) **State the value of angle b:** ____________

(c) **What name is given to angle a when the light rays are as shown?** ______________________________

(d) **Use the diagram to derive an equation which links the refractive index of special glass X to its critical angle:**

(e) **Calculate the refractive index of special glass X:**

(f) **Describe what will happen when angle a is increased above 45°. Include the name of this process:** ______________________________

____

____

---

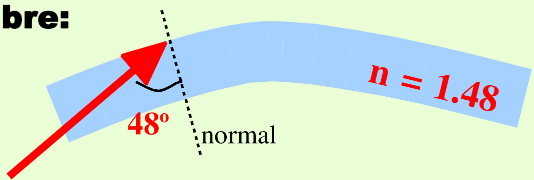
2)(a) **Explain how you know whether a ray of light which strikes the inside surface of a material will be totally internally reflected:** ______________________________

____

____

____

(b) **Determine whether this light ray will be totally internally reflected by the optic fibre:**



---

3) Calculate the critical angle for a material with a refractive index of 1.55.

4) Calculate the refractive index of a substance which has a critical angle of 42.5°.

HIGHER PHYSICS

UNIT 3 - RADIATION and MATTER

OPTO-ELECTRONICS

1) IRRADIANCE OF RADIATION

You must be able to:

- State that the irradiance (I) of radiation striking a surface is the power (P) of the radiation per unit area (A) of the surface: $I = P/A$. Unit of irradiance: watts per square metre ($W\ m^{-2}$).
- Solve problems using the above relationship.
- State the relationship $I \ \alpha \ k/d^2$ for the irradiance (I) of radiation at a distance (d) from a point source, where k is a constant. Use the relationship in the form $I_1d_1^2 = I_2d_2^2$.
- Describe a method to verify the above relationship.
- Solve problems using the above relationship.

1) IRRADIANCE OF RADIATION

The **irradiance** of radiation striking a surface is the **power** of the radiation per **unit area** of the surface:

watts (W)

$$\text{Irradiance (I)} = \frac{\text{Power (P)}}{\text{Area (A)}}$$

watts per square metre ($W\ m^{-2}$)

square metres (m^2)

Example

A 100 W light bulb shines on a table top of area 2 m^2. If no light is lost, calculate the irradiance of the light hitting the table:

$$\text{Irradiance (I)} = \frac{\text{Power (P)}}{\text{Area (A)}} = \frac{100\ W}{2\ m^2} = 50\ W\ m^{-2}$$

An overhead projector uses a 300 W light bulb to project light onto a screen which measures 2 m x 3 m. Assuming no light is lost, calculate the light irradiance on the screen:

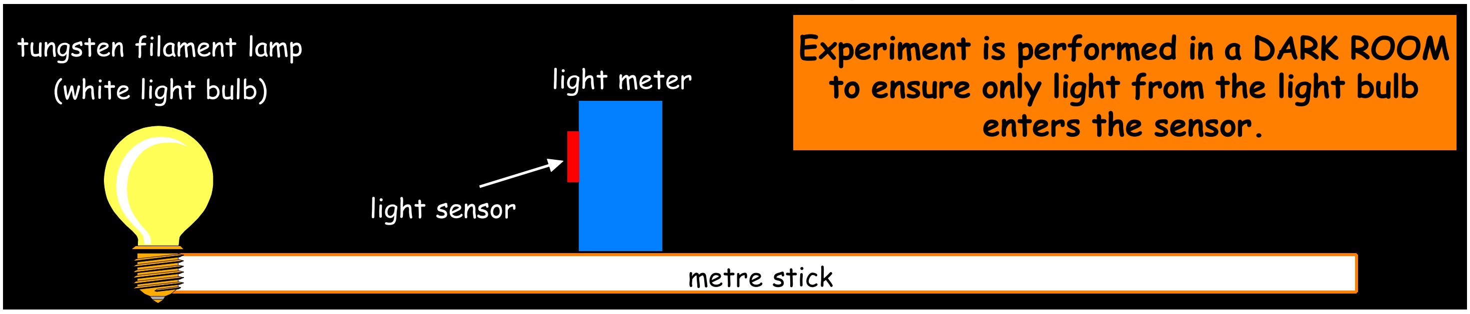
A cinema projector uses a 3 kW lamp. It projects a film onto a flat screen measuring 10 m x 6 m. What is the light irradiance on the screen (assuming no light loss)?:

A 60 W table lamp reflects all of its light onto the table it sits on. If the light irradiance at the table top is 200 W m^{-2}, what area of the table is illuminated?

Calculate the power of a car head lamp which produces light of irradiance 12.5 W m^{-2} on an area of 8 m^2:

2) Light Irradiance and Distance From a Point Source

The apparatus shown can be used to investigate the relationship between the **light irradiance** at different **distances** from a **point source**:



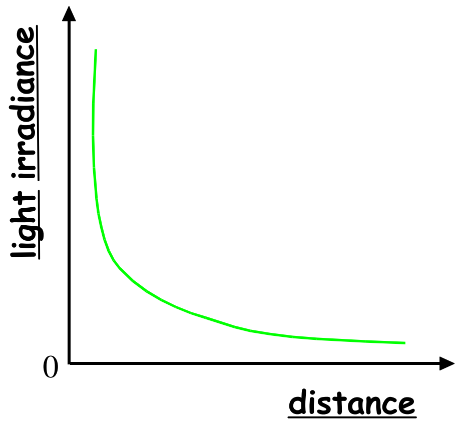
Experiment is performed in a DARK ROOM to ensure only light from the light bulb enters the sensor.

The light bulb acts as a **point source** - a source that radiates its energy equally in all directions.

The light sensor detects the light irradiance and converts it to a voltage which is displayed on the light meter - The light irradiance is directly proportional to the voltage.

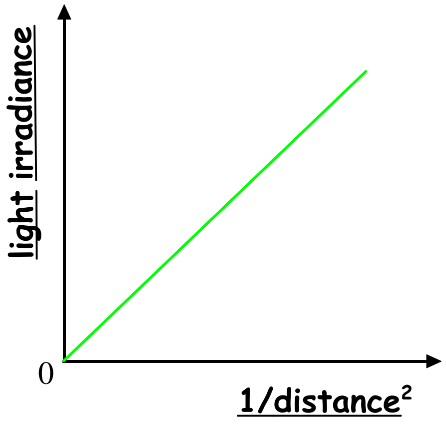
The light sensor is moved to different distances from the light bulb (measured with the metre stick). At each distance, the light irradiance is read from the light meter.

Graph of light irradiance against distance



The graph indicates some form of **inverse proportion relationship** between **light irradiance** and **distance**.

Graph of light irradiance against 1/distance^2



The graph is a straight line passing through the origin. This shows that:

$$\text{light irradiance} \propto \frac{1}{\text{distance}^2}$$

This is a form of the inverse square law - **The light irradiance is inversely proportional to the square of the distance from the point source.**

$\text{light irradiance} \propto \frac{1}{\text{distance}^2}$ or $\text{light irradiance} = \frac{\text{constant}}{\text{distance}^2}$ or light irradiance x distance^2 = constant

$$\boxed{I_1 d_1^{\,2} = I_2 d_2^{\,2}}$$

light irradiance at distance d_1

light irradiance at distance d_2

Example

In a dark room, Steven measured the light irradiance at 0.5 m from a light bulb and found it to be 50 W m^{-2}. What would be the light irradiance at a distance of 0.7 m from the light bulb?

$$I_1 d_1^2 = I_2 d_2^2$$
$$50 \times 0.5^2 = I_2 \times 0.7^2$$
$$12.5 = 0.49\ I_2$$
$$I_2 = \frac{12.5}{0.49} = 25.5\ \text{W m}^{-2}$$

What is meant by a point source?

When Leanne placed a light meter 1 m away from a light bulb in a dark room, the meter indicated a light irradiance of 75 W m^{-2}. Calculate the light irradiance reading Leanne should obtain on the meter at a distance of 1.5 m from the light bulb:

Russell's experiment in a dark room produced these results:

Distance from lamp = 80 cm.

Light irradiance = 12 W m^{-2}.

What light irradiance should Russell have obtained at a distance of 20 cm from the lamp?:

A light meter shows a light irradiance reading of 4 W m^{-2} when it is held 2 m from a point source. How far away from the point source should the meter be held if it is to show a light irradiance reading of 0.25 W m^{-2}?:

A solar cell is placed 20 cm from a light source in an otherwise dark room, giving an output voltage of 800 mV. When the solar cell is moved further away from the light source, the output voltage drops to 100 mV.

(a) What is the relationship between the output voltage and light irradiance?:

(b) Calculate the new distance between the light source and solar cell:

HIGHER PHYSICS

UNIT 3 - RADIATION and MATTER

OPTO-ELECTRONICS

2) QUANTUM THEORY and THE PHOTOELECTRIC EFFECT

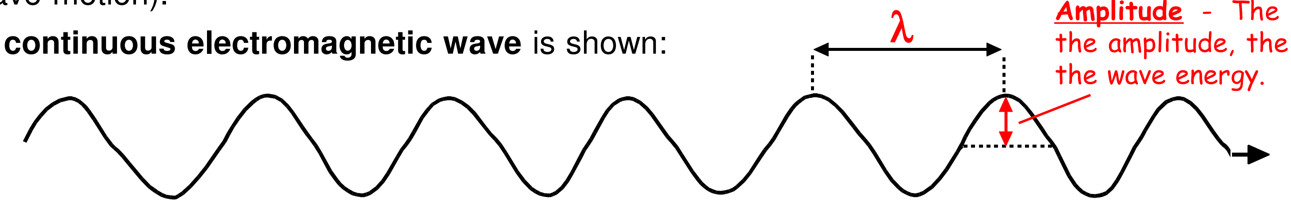
You must be able to:

- State that electromagnetic radiation can be regarded as a stream of tiny, individual "wave packets" called photons.
- State that each photon of electromagnetic radiation has an energy $E = hf$ where h is Planck's constant and f is the frequency of the radiation.
- Solve problems involving the above relationship.
- State that the irradiance (I) of electromagnetic radiation falling on a surface is given by the equation $I = Nhf$ where N is the number of photons per second falling on every square metre of the surface, h is Planck's constant and f is the frequency of the radiation.
- Solve problems involving the above relationship.
- Explain the photoelectric effect in terms of photons and emitted electrons.
- Describe an experiment to show that photoelectric emission occurs when the frequency of the incident electromagnetic radiation is sufficiently high and that increasing the irradiance of the incident electromagnetic radiation increases the photoelectric emission.
- Describe the energy conversion taking place in the photoelectric effect in terms of the equation $hf = hf_o + 1/2mv^2$ where hf is the energy of the incident photon, hf_o is the work function of the metal and $1/2mv^2$ is the maximum kinetic energy of the emitted electron.
- Solve problems involving the above relationship.

1) CLASSICAL WAVE THEORY

We have seen that **electromagnetic energy** (such as **light**) behaves as a **continuous wave** - It can be **reflected**, **refracted** and **diffracted**. More importantly, it can produce **interference** (which is the test for wave motion).

A **continuous electromagnetic wave** is shown:



Amplitude - The greater the amplitude, the greater the wave energy.

Such a **continuous electromagnetic wave** has a **velocity** (**v**) of 3 x 10^8 m s^{-1} in air, a **frequency** (**f**) measured in **hertz** and **wavelength** (**λ**) measured in **metres**.

The equation $v = f \lambda$ applies to the wave.

Max Planck

Clipart copyright S.S.E.R. Ltd

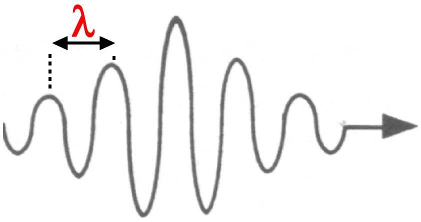
2) QUANTUM THEORY

In the early years of the 20 th century (about 100 years ago), scientists **Max Planck** and **Albert Einstein** proposed an alternative theory for **electromagnetic energy** - The **quantum theory**:

Albert Einstein

Clipart copyright S.S.E.R. Ltd

Electromagnetic energy is a stream of tiny, individual "**wave packets**" called **quanta** or **photons**:



A photon of electromagnetic energy

As with **classical wave theory**, each **photon** has a **velocity** (**v**) **of** 3 x 10^8 m s^{-1} in air, a **frequency** (**f**) measured in **hertz** and **wavelength** (**λ**) measured in **metres**.

The equation $v = f \lambda$ applies to each **photon**.

However, the energy of a photon does not depend on amplitude.

The **energy** (**E**) of a **photon** is directly proportional to its **frequency** (**f**):

$E \alpha f$ or $E = \text{constant} \times f$

The constant is named after Max Planck (**Planck's constant**) and is given the symbol **h**:

energy of photon ↔ $E = h f$ ↔ frequency of photon

(unit: J) (unit: Hz)

Planck's constant = 6.63 x 10^{-34} J s

Example

In air, a photon of **yellow** light has a wavelength of 589 nm (i.e., 589 x 10^{-9} m).

Calculate: (a) the **frequency** of the photon; (b) the **energy** of the photon.

(a) $v = f\lambda$, so $f = \frac{v}{\lambda} = \frac{3 \times 10^{8}}{589 \times 10^{-9}} = \underline{\underline{5.09 \times 10^{14}\ \text{Hz.}}}$

(b) $E = hf = (6.63 \times 10^{-34}) \times (5.09 \times 10^{14})$
$= \underline{\underline{3.37 \times 10^{-19}\ \text{J.}}}$

1) In air, a photon of blue light has a wavelength of 480 nm (i.e., 480 x 10^{-9} m).

Calculate:

(a) the frequency of the photon; **(b) the energy of the photon.**

2) (a)Calculate the energy, in air, of a photon of:

(i) red light; **(wavelength 700 nm)**

(ii) green light; **(wavelength 540 nm)**

(iii) violet light. **(wavelength 400 nm)**

(b) In the visible spectrum, which colour of light has the highest energy?

3) A photon of ultraviolet radiation has a frequency of 7.69 x 10^{14} Hz in air. Calculate the energy of this photon in air:

4) In air, a photon of infra-red radiation has an energy of 1.99 x 10^{-20} J. Calculate the frequency of this photon in air:

Irradiance of Electromagnetic Radiation

The **irradiance** (I) of electromagnetic radiation falling on any surface is given by the equation:

$$I = N h f$$

I: irradiance of radiation (unit: $W\ m^{-2}$)

f: frequency of radiation (unit: Hz)

N: number of photons per second falling on every square metre of surface

h: Planck's constant = 6.63×10^{-34} J s

1) Every second, 2×10^{19} photons of light with a frequency of 7.5×10^{14} Hz fall on each square metre of a floor. Calculate the irradiance of the light on the floor.

2) How many photons per second fall on 1 m^2 of a table that is being illuminated by a lamp producing light of irradiance 8 $W\ m^{-2}$ and frequency 4.5×10^{14} Hz?

3) THE PHOTOELECTRIC EFFECT

WORK FUNCTION

On the surface of metals, there are tiny particles called electrons.
The electrons are held on the metal surface by attractive forces.

If an electron is to escape from the metal surface, it must overcome these attractive forces.

The work function of a metal is the energy which must be supplied to enable an electron to escape from the metal surface.

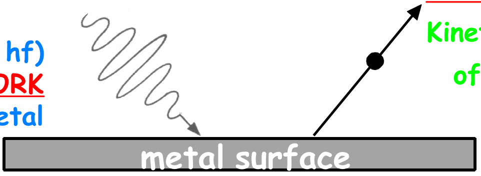
PHOTOELECTRIC EFFECT / PHOTOELECTRIC EMISSION

If one photon of electromagnetic energy (**E = hf**) strikes a metal surface, it causes one electron to be emitted from the metal surface if the photon's energy (**hf**) is equal to or greater than the **work function** of the metal, part of the photon's energy being used to enable the electron to escape. The rest of the photon's energy is given to the emitted electron as **kinetic energy**. The photon then no longer exists - This is known as the **photoelectric effect** and the emission of the electron is known as **photoelectric emission** or **photoemission**.

THRESHOLD FREQUENCY (f_o)

A photon must have a minimum energy equal to the **work function** of a metal and hence a **minimum frequency** (f_o) to emit an electron from the metal surface. This **minimum frequency** (f_o) is called the **threshold frequency** for the metal. Each metal has its own unique value of **threshold frequency** (f_o).

ONE photon with energy (E = hf) equal to or greater than WORK FUNCTION of metal strikes metal surface.



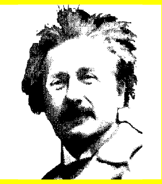
ONE electron emitted from metal surface.

Kinetic energy of electron = energy of photon - work function of metal

Work function = h f_o

Photoelectric emission is described by

EINSTEIN'S PHOTOELECTRIC EQUATION:



Energy of photon striking metal surface = Energy needed to eject electron from metal surface (work function of metal) + Kinetic energy given to emitted electron

$$h\,f = h\,f_o + 1/2\,m\,v^2$$

h – Planck's constant = 6.63×10^{-34} J s

f – frequency of photon

h – Planck's constant = 6.63×10^{-34} J s

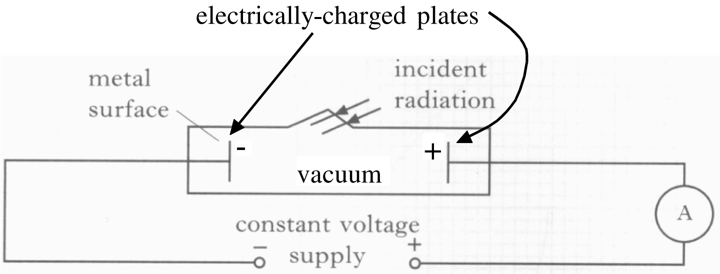
f_o – threshold frequency (minimum frequency photon must have to eject electron)

m – mass of electron = 9.11×10^{-31} kg

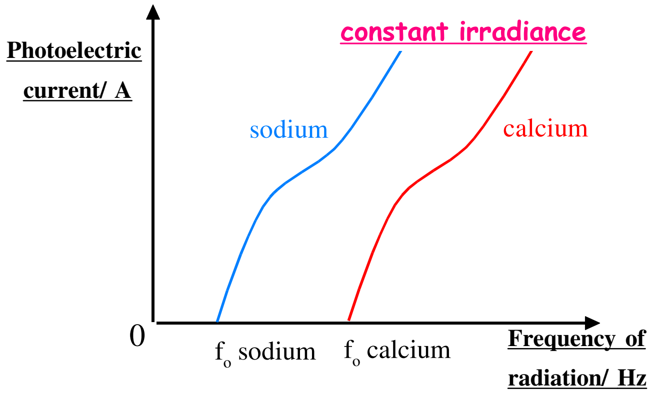
v – maximum velocity of electron

This apparatus is used to investigate the **photoelectric effect**:

When electromagnetic radiation of sufficient energy/frequency strikes the metal surface, electrons are emitted from the metal surface (1 electron per photon). The emitted electrons are attracted to the positively-charged plate through the vacuum (there are no air molecules to stop them) - An electric current (known as a **photoelectric current**) is thus created in the circuit, so the ammeter displays a current reading. [The constant voltage supply is used to give the plates inside the vacuum their - and + electric charge].



Changing Frequency of Electromagnetic Radiation

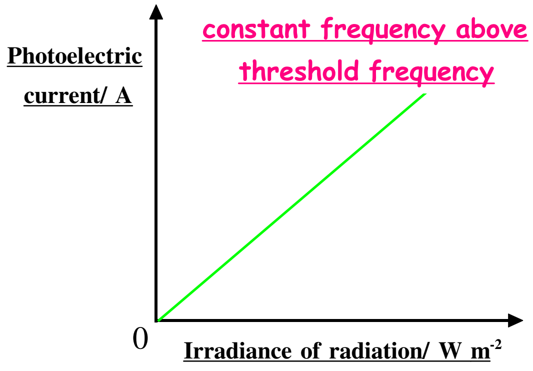


Below a certain frequency [the **threshold frequency** (f_o)], no electrons are emitted from the metal surface - There is no photoelectric current.

As the frequency (and hence energy) of the radiation is increased **above** the **threshold frequency** (f_o), more electrons are emitted - the photoelectric current increases.

Different metals produce different curves - Each metal has its own unique value of **threshold frequency** (f_o).

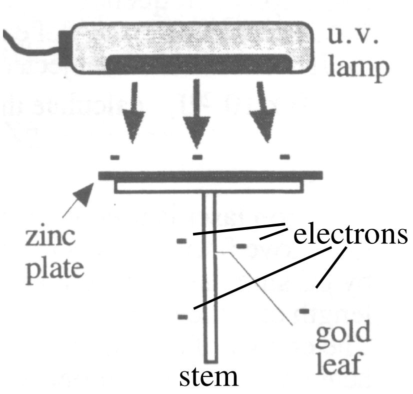
Changing Irradiance of Electromagnetic Radiation



If the frequency of the radiation is high enough to cause emission of electrons from the metal surface, **more electrons are emitted as the irradiance of the radiation is increased**

- **The photoelectric current is directly proportional to the irradiance of the radiation**.

Laboratory Demonstration of the Photoelectric Effect



A gold leaf electroscope (with a zinc plate on top) is negatively-charged - The zinc plate, stem and gold leaf are all covered with negatively-charged electrons, so the gold leaf is repelled (pushed away) by the stem.

When photons of ultra-violet radiation are shone onto the zinc plate, the photons have sufficient energy to eject electrons from the surface of the zinc - The photons have energy higher than the **work function** of zinc.

The electrons on the zinc surface escape into the air and are replaced by the electrons from the stem and gold leaf - The gold leaf is no longer repelled by the stem, so it falls.

If the irradiance of the ultra-violet radiation is increased, the gold leaf falls faster because more ultra-violet photons strike the zinc plate, so electrons are emitted from the zinc faster.

If white light (which contains photons of all 7 colours of the visible spectrum - red, orange, yellow, green, blue, indigo and violet) is shone onto the zinc plate, the gold leaf does not fall. Photons of these colours of light do not have high enough energy to eject electrons from the zinc surface - The photons of these colours of light have energy **lower** than the **work function** of zinc.

If the zinc plate is replaced with a tin plate, and photons of ultra-violet or white radiation are shone onto the tin, the gold leaf does not fall - Photons of ultra-violet or white radiation have a **lower** energy than the **work function** of tin, so no electrons are emitted from the tin.

If the gold leaf electroscope is positively-charged, the gold leaf does not fall when the metal plate is illuminated by electromagnetic radiation of high enough energy/frequency because the stem and gold leaf lack electrons, so cannot replace the electrons emitted from the metal plate.

1) Explain the following terms:

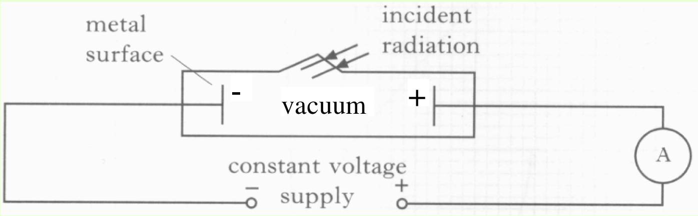
(a) work function of a metal:

(b) photoelectric emission - INCLUDE A LABELLED DIAGRAM:

(c) threshold frequency:

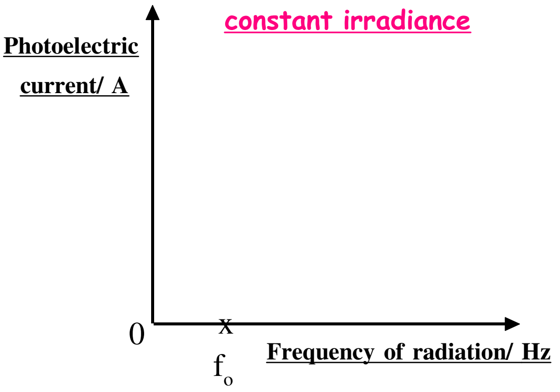
2) This apparatus is used to investigate the photoelectric effect.

The metal used is caesium, which emits electrons when electromagnetic radiation of a frequency equal to or above 4.59 x 10^{14} Hz strikes it.

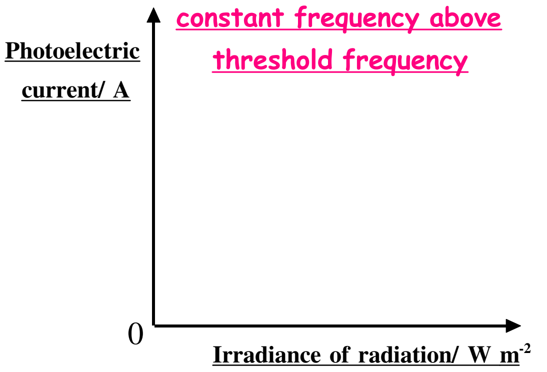


(a) Complete the following graphs:

Changing Frequency of Electromagnetic Radiation



Changing Irradiance of Electromagnetic Radiation



(b) Why are no electrons emitted from the caesium metal when photons of frequency below f_o strike its surface?______________________________

____

____

(c) Explain why increasing the irradiance of the electromagnetic radiation increases the number of electrons emitted from the caesium surface:

____

____

____

(d) Calculate the work function of the caesium metal:

3) What frequency of photon is required to just release an electron from the surface of a metal that has a work function of 4.5 x 10^{-19}J?

4) A metal has a work function of 2.16 x 10^{-19} J. Calculate the minimum frequency a photon must have in order to emit an electron from the metal surface.

5) Write down EINSTEIN'S PHOTOELECTRIC EQUATION in words and symbols:

6) When a photon of electromagnetic radiation of frequency 7.5 x 10^{14} Hz strikes a metal surface, an electron is ejected from the metal surface with a maximum kinetic energy of 1.6 x 10^{-19} J.
Calculate the work function of this metal.

7) The work function of metal X is 1.5 x 10^{-20} J.

(a) A photon of frequency 3.0 x 10^{13} Hz strikes the surface of metal X, causing one electron to be emitted from the metal surface.
Determine the maximum kinetic energy of this emitted electron.

(b) Calculate the maximum velocity of the emitted electron.

UNIT 3 - RADIATION and MATTER

OPTO-ELECTRONICS

3) EMISSION and ABSORPTION SPECTRA

You must be able to:

- Use the following terms correctly: photon, work function, photoelectric emission (photoemission) and threshold frequency.
- Describe experiments to display emission and absorption spectra.
- Use the following terms correctly - ground state, excited state, ionisation level, electron transition, emission spectrum and absorption spectrum.
- State that electrons in free atoms occupy discrete energy levels.
- Draw a diagram to represent the energy levels for a hydrogen atom.
- Describe spontaneous emission of radiation as a random process analogous to that of radioactive decay.
- Explain an emission line spectrum in terms of electron transitions from higher to lower energy levels and explain why some emission lines are brighter than others.
- State that a photon of light emitted from an atom has an energy (hf) equal to the difference in energy (ΔE) between the 2 energy levels involved in the electron transition responsible for creating the photon. $\Delta E = h f$.
- Explain an absorption line spectrum in terms of electrons in lower energy levels absorbing photons of correct energy (hf) and making transitions of energy difference (ΔE) to higher energy levels.
- Solve problems involving the equation $\Delta E = h f$.
- Explain the presence of absorption lines in the spectrum of sunlight.

RUTHERFORD-BOHR MODEL OF THE ATOM

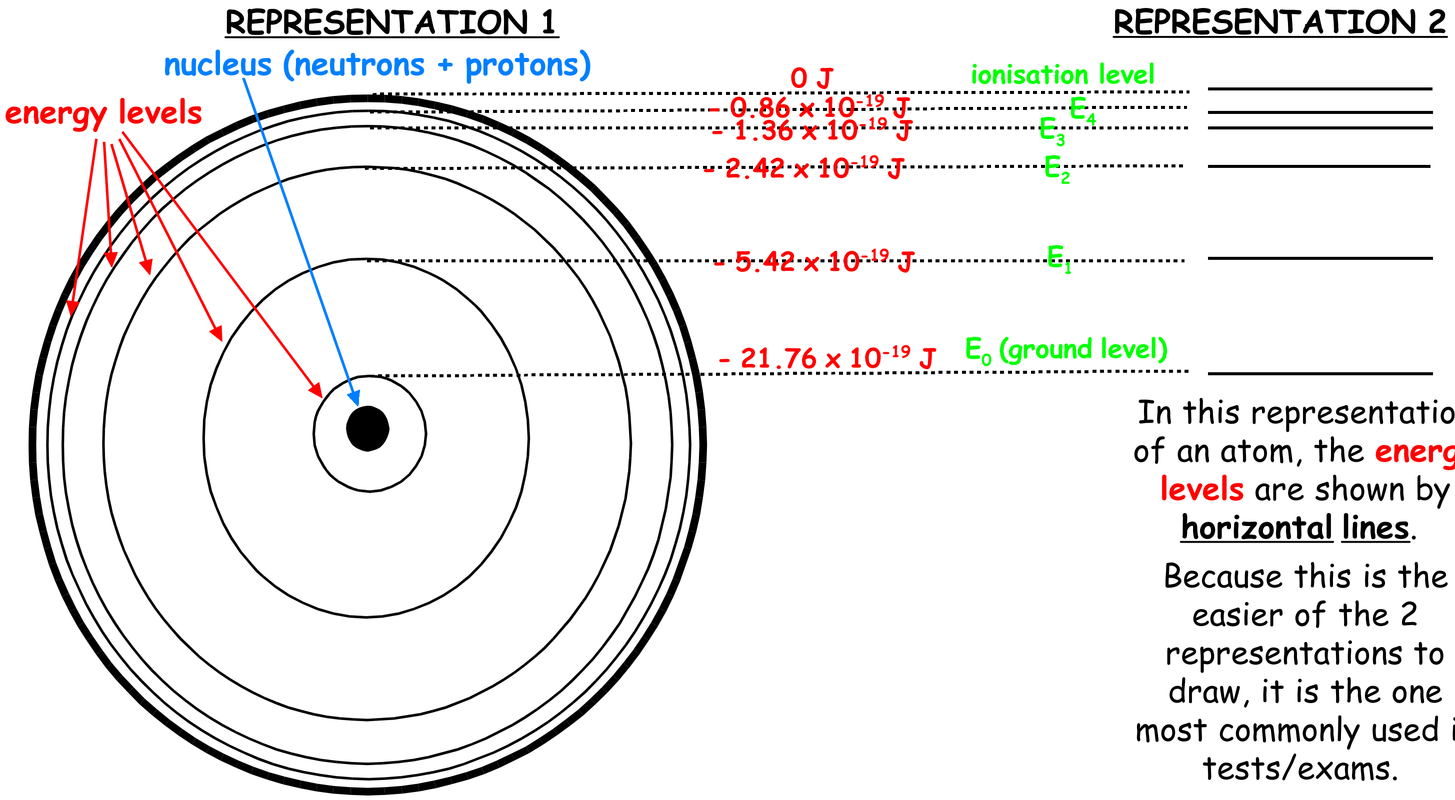
Free (unreacted) atoms consist of a tiny, central **nucleus** (containing particles called **neutrons** and **protons**) surrounded by particles called **electrons**.

The **electrons** circle around the **nucleus** at fixed distances from it. Electrons at each distance have a **fixed energy value** - so each distance is known as an **energy level**.

Electrons can move from one **energy level** to another **energy level**, but cannot stop **between** the **energy levels**.

As an **electron** gets closer to the **nucleus**, the **electron** loses energy - so the **energy levels** closer to the nucleus have **more negative** energy values.

two representations of some of the energy levels in a hydrogen atom



In this representation of an atom, the **energy levels** are shown by **horizontal lines**.

Because this is the easier of the 2 representations to draw, it is the one most commonly used in tests/exams.

A hydrogen atom has only 1 electron, but this can move to any of the possible energy levels.

The **energy level** closest to the **nucleus** (the level with lowest energy) is called the **ground level** (E_0) - An **electron** in this **energy level** is said to be in its **ground state**.

The **energy levels** further from the **nucleus** (E_1, E_2, E_3, etc) are called **excited energy levels** - An **electron** in any of these **energy levels** is said to be in an **excited state**.

An **electron** can reach a distance so far away from the **nucleus** that the **electron** can escape from the atom - We say the **electron** has reached the **ionisation level** (where it has **0 Joules of energy**). When this happens, the **atom** is said to be in an **ionisation state**.

ATOMIC SPECTRA

Under certain circumstances, free (unreacted) atoms can **give out** (**emit**) or **take in** (**absorb**) **photons** of **electromagnetic energy**, including **photons** of **different coloured light**. REMEMBER - The **colour** of light depends on its **frequency**/**wavelength**.

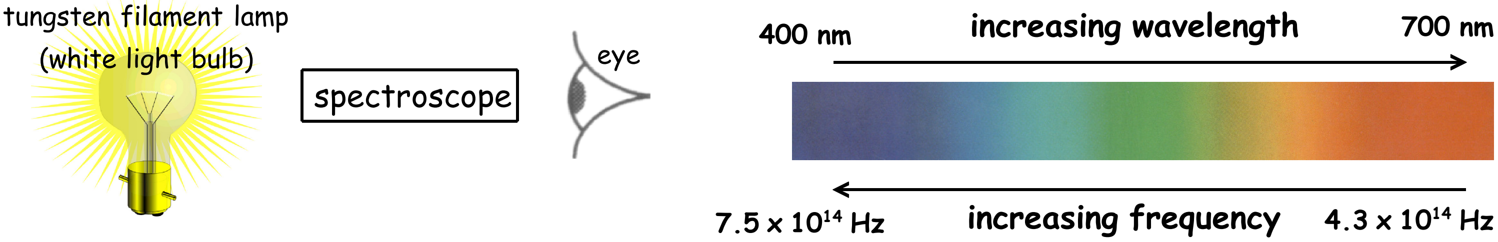
When the light is passed through a **prism**, **diffraction grating** or **spectroscope**, an **atomic spectrum** is produced.

Different atoms produce different atomic spectra (e.g., mercury atoms produce a different **spectrum** from sodium atoms.) As a result, an atom can be identified by observing its **spectrum**.

1) EMISSION SPECTRA

(a) Continuous Spectra

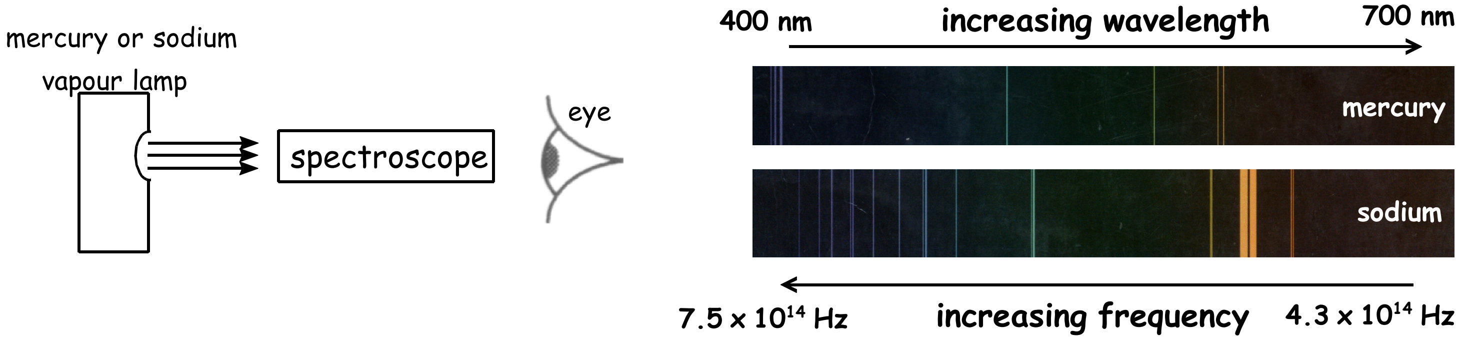
A tungsten filament lamp (a normal light bulb) emits **white light**. When the **white light** is passed through a spectroscope, a **continuous spectrum** is obtained. This contains all 7 colours of the **visible spectrum:**



(b) Line Spectra

A **mercury vapour lamp** or **sodium vapour lamp** emits different photons of **specific frequency/wavelength** (and hence **colour**). When the light is passed through a spectroscope, a series of **different coloured lines** on a **black background** is obtained. Each line occupies an exact position corresponding to its **exact frequency/wavelength**.

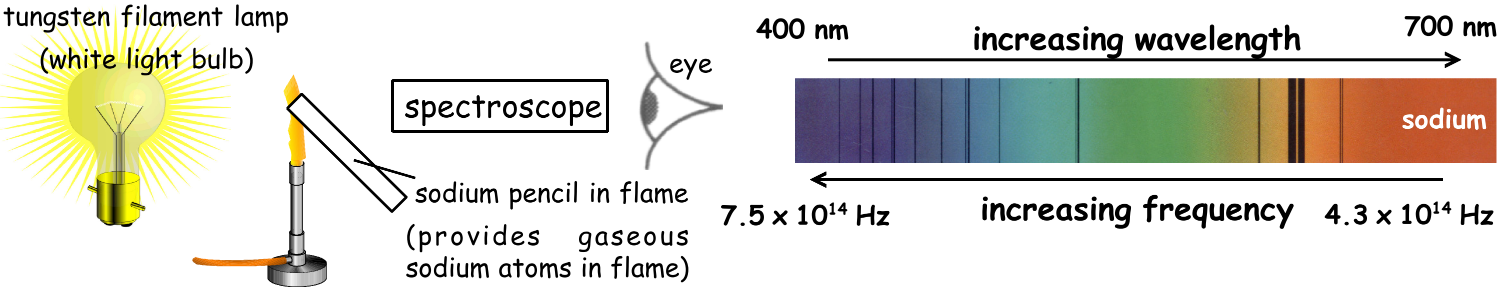
Notice the different colours and positions of the emission lines for mercury and sodium.



2) ABSORPTION SPECTRA

When **white light** (containing photons of all 7 different colours of the visible spectrum) is passed through atoms of an element like sodium which are in the **gaseous state**, the **gaseous atoms** absorb photons from the **white light** of **specific frequency/wavelength** (and hence **colour**). When the light is passed through a spectroscope, a **continuous spectrum** with a **series of black absorption lines** is obtained. Each **black absorption line** occupies an exact position corresponding to the exact **frequency/wavelength** of the photons from the white light that have been **absorbed** by the gaseous atoms.

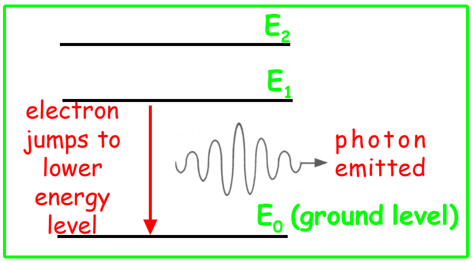
[COMPARE THE LINE **EMISSION** AND **ABSORPTION** SPECTRA OF **SODIUM**].



HOW EMISSION LINE SPECTRA ARE CREATED

At **any time**, an **electron** in an **excited** (**higher**) **energy level** of an atom can make a **transition** (**jump**) to a **less excited** (**lower**) **energy level** in the same atom (including the **ground level, E_o**). This process is **random** - We cannot predict when it will happen (just like we cannot predict when the radioactive decay of an atomic nucleus will take place.)

When an **electron** makes such a **transition** (**jump**), **one photon of electromagnetic energy is emitted from the atom**. **The energy of this photon is exactly equal to the difference in energy between the 2 energy levels involved.**



This equation applies:

$$\Delta E = h\,f$$

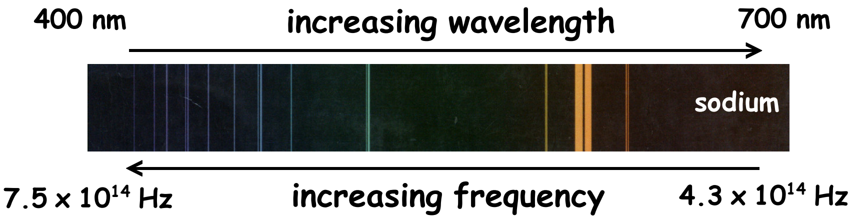
difference in energy between the 2 energy levels involved in electron transition

Planck's constant = 6.63×10^{-34} J s

frequency of photon emitted from atom

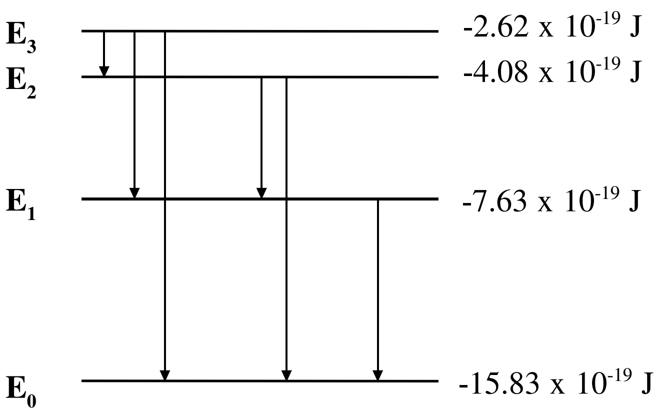
The emitted photon often has a frequency within the visible spectrum, so produces a coloured emission line in the atom's emission line spectrum. The photon may also have a frequency outwith the visible spectrum - in the infra-red or ultra-violet.

Various such electron transitions (jumps) of **different energy** (and hence different **frequency/wavelength**) are possible - so an emission line spectrum may consist of several emission lines of different **frequency/wavelength**, e.g., the **sodium line emission spectrum** shown below:



For example:

Atom **X** has 4 possible energy levels, as shown:



There are **6** possible downward electron transitions (jumps) - as shown by the **6** downward arrows. Each happens without outside influence - they are **spontaneous**.

Each downward electron transition (jump) will produce **one** emission line in the atom's emission spectrum (one photon being emitted per jump) - so the spectrum will have **6** emission lines.

The position of each emission line on the emission spectrum will depend on the **frequency/wavelength** of each emitted photon, which depends on the **difference in energy** (**ΔE**) between the 2 energy levels involved in the electron transition.

PROBLEM

Calculate the **energy** and **frequency** of the photon emitted when an electron jumps from energy level **E_2** to energy level **E_1**.

$$\Delta E = (7.63 \times 10^{-19})\text{J} - (4.08 \times 10^{-19})\text{J}$$

$$= (3.55 \times 10^{-19})\text{J}$$

So, energy of emitted photon

$$= (3.55 \times 10^{-19})\text{J}$$

Since we are calculating the change in energy, there is no need to use the - signs in front of the numbers.

$$f = \Delta E/h$$

$$= (3.55 \times 10^{-19})\text{J}/(6.63 \times 10^{-34})\text{J s}$$

$$= 5.35 \times 10^{14}\ \text{Hz}$$

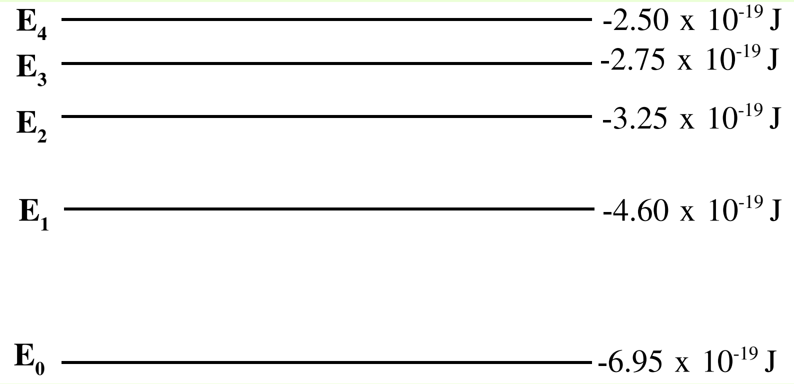
Brightness of Emission Lines

Emission spectra are usually obtained by observing a **vapour lamp** through a **spectroscope**. The **vapour lamp** contains millions of atoms, each giving out photons - so many photons are emitted.

Some emission lines in an emission spectrum are brighter than others (see the 2 very bright orange lines in the sodium emission spectrum) - The brighter lines are caused by a larger number of electrons (from the same and other identical atoms) making the same energy transition (jump) - so more photons of light with the same frequency/wavelength are produced.

1) Explain, with the help of a labelled diagram, how an atom can emit a photon of electromagnetic energy:

2) All the possible energy levels of atom A are shown:



(a) Show, using downward arrows, all the possible downward electron transitions

(b) All the photons emitted from the atom can be detected easily.

How many emission lines will be present in the atom's emission spectrum?__________

(c) Why will some emission lines be brighter than others?__________________________

____

____

____

(d) Explain whether we can predict the exact moment when an electron will make a downward transition:____

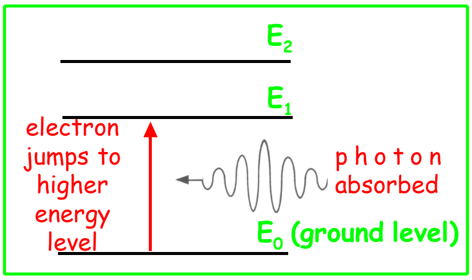
____

(e) Calculate the energy and frequency of the photon emitted from the atom when an electron makes a transition from energy level E_4 to E_0:

HOW ABSORPTION LINE SPECTRA ARE CREATED

An **atom** can **absorb** a photon of **electromagnetic energy**. **The atom can only do so if the energy of the photon is exactly equal to the difference in energy (ΔE) between any 2 energy levels in the atom.**

When a **photon** is absorbed, **one electron** makes a **transition** (**jump**) between **the 2 energy levels with exact energy difference ΔE**, from the **less excited** (**lower**) **energy level** to the **more excited** (**higher**) **energy level**.



This equation applies: $\Delta E = h f$

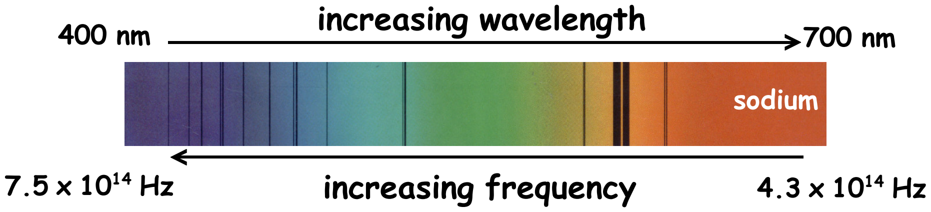
ΔE: difference in energy between the 2 energy levels involved in electron transition

f: frequency of photon absorbed by atom

h: Planck's constant = 6.63×10^{-34} J s

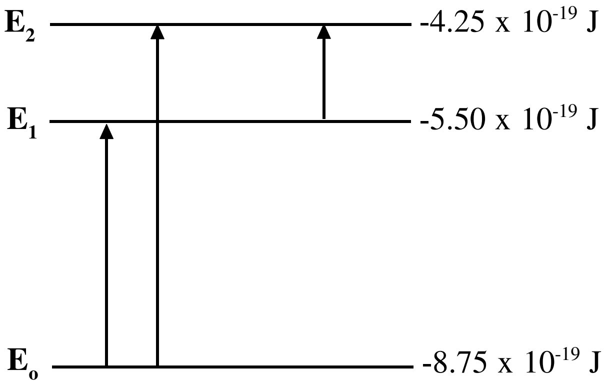
Various such electron transitions (jumps) of **different energy** are possible, provided **photons of suitable energy** are present to be **absorbed**.

The **absorbed photons** are **removed** from the incident electromagnetic radiation, so **black absorption lines** are produced on the atom's absorption line spectrum against a **coloured visible spectrum background** where **no photons** are being absorbed, e.g., the sodium line absorption spectrum shown below:



For example:

Atom **Y** has 3 possible energy levels, as shown:



There are **3** possible upward electron transitions (jumps) - as shown by the **3** upward arrows.

Each upward electron transition (jump) will produce **one** absorption line in the atom's absorption spectrum (one photon being absorbed per jump) - so the spectrum will have **3** absorption lines.

The position of each absorption line on the absorption spectrum will depend on the **frequency/wavelength** of each absorbed photon, which depends on the **difference in energy** (**ΔE**) between the 2 energy levels involved in the electron transition.

PROBLEM

Calculate the **energy** and **frequency** of the photon **absorbed** when an electron jumps from energy level $\mathbf{E_0}$ to energy level $\mathbf{E_2}$.

$$\Delta E = (8.75 \times 10^{-19})\text{J} - (4.25 \times 10^{-19})\text{J}$$
$$= (4.50 \times 10^{-19})\text{J}$$

So, energy of absorbed photon $= (4.50 \times 10^{-19})$J

Since we are calculating the change in energy, there is no need to use the - signs in front of the numbers.

$$f = \Delta E/h$$
$$= (4.50 \times 10^{-19})\text{J}/(6.63 \times 10^{-34})\text{J s}$$
$$= 6.79 \times 10^{14} \text{ Hz}$$

Fraunhofer Lines - Absorption Lines in Sunlight

YOU MUST NEVER OBSERVE SUNLIGHT DIRECTLY

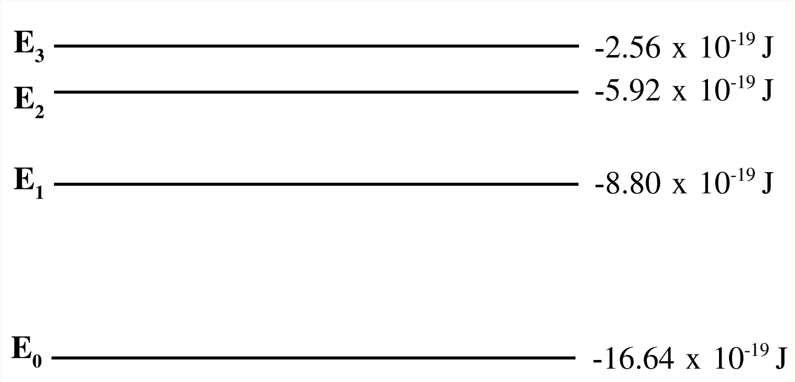
When **sunlight** is passed through a **spectroscope**, black absorption lines are observed in its **visible spectrum**.

These **absorption lines** are due to **photons** of **certain energies** from the sun's **hot core** being absorbed by **gaseous atoms** in the sun's **cooler outer layer**.

The **absorption lines** correspond to those produced by **hydrogen**, **helium**, **sodium** and **other atoms** - **So these must be present in the sun's atmosphere**.

1) Explain, with the help of a labelled diagram, how an atom can absorb a photon of electromagnetic energy:

2) All the possible energy levels of an atom are shown:



(a) Show, using upward arrows, all the possible upward electron transitions.

(b) All the photons absorbed by the atom can be detected easily.

How many absorption lines will be present in the atom's absorption spectrum?________

(c) An electron in this atom makes a transition from energy level E_0 to level E_1. What must be the (a) energy and (b) frequency of the photon absorbed?

(d) A photon of energy 6.24×10^{-19} J is absorbed by this atom, causing one electron to make a transition from a lower to a higher energy level.

(i) Between which 2 energy levels does the electron jump? ____________________

(ii) Calculate the absorbed photon's frequency and wavelength.

3) Explain why the visible spectrum of sunlight contains black absorption lines.

4) What name is given to these absorption lines in the sun's visible spectrum?

5) What do these absorption lines tell us about the sun's atmosphere?

Notes

HIGHER PHYSICS

UNIT 3 - RADIATION and MATTER

OPTO-ELECTRONICS

4) LASERS

You must be able to:

- State that an incoming photon (with energy equal to the difference in energy between levels E_1 and E_0 of an atom) stimulates an "excited" electron to jump from energy level E_1 to E_0 (ground level) of the atom, causing another identical photon to be emitted.

- State that both photons are in phase and now travel in the same direction.

- State that the term LASER stands for Light Amplification by the Stimulated Emission of Radiation.

- Explain the function of the two mirrors in a laser.

- State that laser light is monochromatic, coherent, parallel and has a very high irradiance.

- Compare laser light to light from a filament lamp.

- Explain why a beam of laser light with a power of 0.1 mW can cause eye damage.

SPONTANEOUS and STIMULATED EMISSION

The transition of an electron in an atom from a higher energy level to a lower energy level with the emission of a photon can be either:

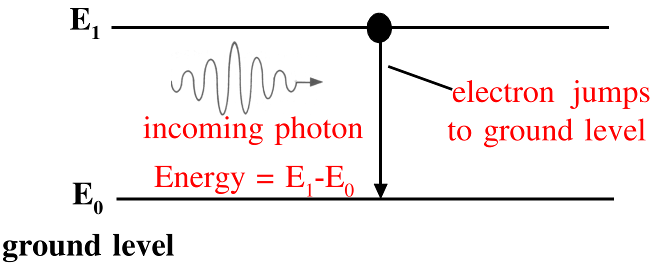
(a) Spontaneous

This is what happens during the production of the **line emission spectra** you have just studied. The process is **random** - We cannot predict when an electron will jump to a lower energy level, causing a photon to be emitted.

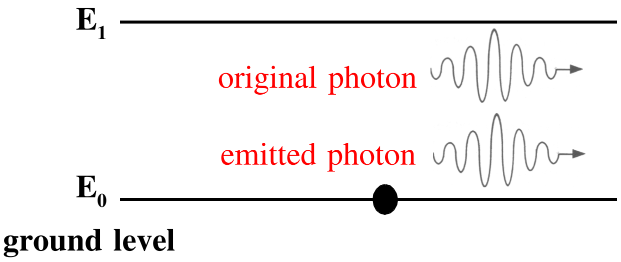
(b) Stimulated

This happens in a **laser**.

An **incoming photon** (with energy equal to the difference in energy between levels E_1 and E_0 of an atom) **stimulates** an **"excited" electron** to jump from energy level E_1 to E_0 (**ground level**) of the atom.

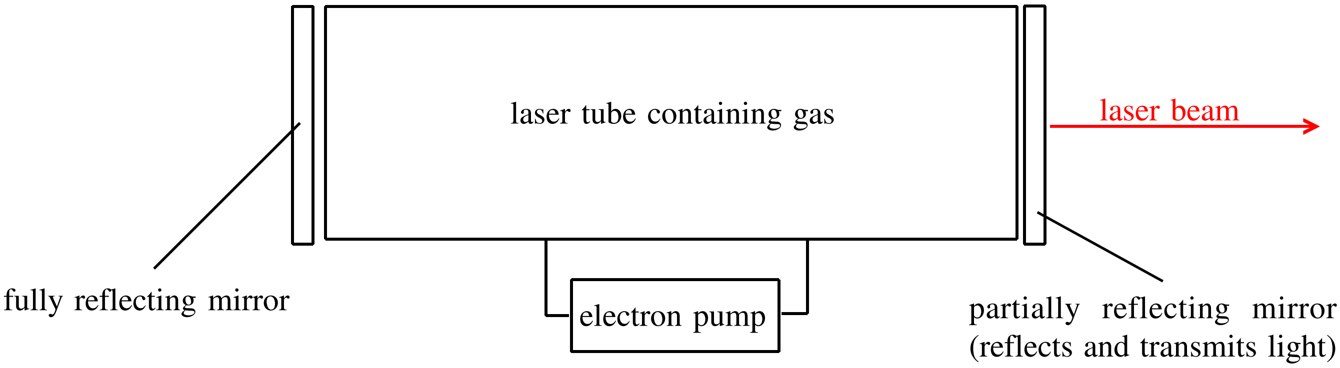


Another **identical photon** (**same frequency and energy**) is emitted as a result. Both photons are **in phase** and **travel in the same direction**.



LASERS

The term **laser** stands for **L**ight **A**mplification by the **S**timulated **E**mission of **R**adiation.



In a **laser**, a gas is contained in a tube with a **fully-reflecting silver mirror** at one end and a **partially-reflecting silver mirror** at the other end.

Photons produced by **stimulated emission** travel through the gas, **reflecting between the two mirrors**. The photons **stimulate more electrons** to **jump from from excited energy level E_1 to the ground level E_0 of the gas atoms, producing more identical photons**.

Some of the **photons** created **escape through the partially reflecting mirror into the air**, creating a **laser beam**.

The **electron pump** provides energy to the atoms in the gas, to raise their electrons back to energy level E_1 , so the stimulated emission process can carry on.

Comparing Laser Light and Light from a Filament Lamp

Filament lamp (light bulb)	**Laser**
Emits photons of **all frequencies** in the visible spectrum.	Laser light is **monochromatic** - all the photons have the **same frequency**.
Light is **not coherent** (the emitted photons are **not in phase**).	Laser light is **coherent** - all the photons are **in phase**.
Light spreads out in all directions - so has a **low irradiance**.	Laser light does not spread out - It is **parallel**. It has a **very high irradiance** - all the photons are concentrated in a very small area. THE LASER BEAM HAS A **CIRCULAR CROSS-SECTION**.

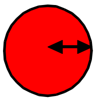
Laser Light and Eye Damage

Because a **laser beam** is **parallel** and has a **high irradiance**, it can cause serious damage to the human eye. For example:

Calculate the irradiance of a laser beam with typical power 0.1 mW (0.0001 W) which has a radius 0.5 mm (0.0005 m).

$$\text{Irradiance (I)} = \frac{\text{Power (P)}}{\text{Area (A)}} = \frac{0.0001\ \text{W}}{\pi \times \text{radius}^2} = \frac{0.0001}{3.14 \times 0.0005^2}$$

$$= \underline{127\ \text{W m}^{-2}}$$



Cross-section of laser beam.
Radius = 0.0005 m.

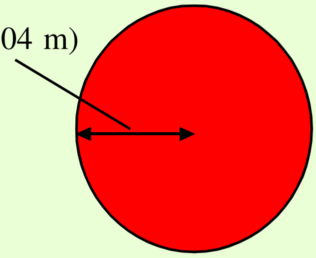
An irradiance of 127 W m^{-2} is sufficiently high to cause severe eye damage.

It is far higher than the irradiance of light produced by a filament lamp (light bulb).

1)(a) Calculate the irradiance of this laser beam:

power = 0.1 mW (0.0001 W)

radius = 0.4 mm (0.0004 m)



(b) Explain whether the laser beam will be capable of causing eye damage:

2) With the aid of a labelled diagram, describe stimulated emission:

3) What does the term LASER stand for?

4) Describe laser light:

5) Describe the purpose of the 2 mirrors in a laser:

HIGHER PHYSICS

UNIT 3 - RADIATION and MATTER

RADIOACTIVITY

1) The ATOM and NUCLEAR REACTIONS

You must be able to:

- Describe how Rutherford showed that:

(a) Compared to the atom, the nucleus has a very small diameter;
(b) Most of the mass of the atom is concentrated in the nucleus.

- State that a nucleus contains protons and neutrons and has a net positive charge.

- Explain what is meant by alpha, beta and gamma decay using appropriate symbols and identify these processes in given nuclear equations.

- Define the average activity A of a quantity of radioactive substance by the equation $A = N/t$ where N is the number of nuclei decaying in time t.

- Solve problems using the above equation.

- State that the becquerel is the unit of activity and that 1 becquerel is 1 decay per second.

- Describe fission as the process whereby a nucleus of large mass splits into 2 nuclei of smaller mass number along with several neutrons.

- State that fission may be spontaneous or induced by neutron bombardment.

- Describe fusion as the process whereby 2 nuclei combine together to form a nucleus of larger mass number.

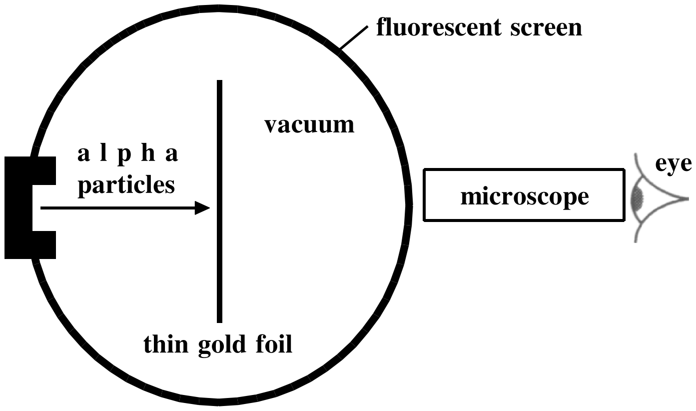
- Explain using the equation $E = mc^2$ how the products of a fission or fusion reaction gain large amounts of kinetic energy.

- Solve problems using $E = mc^2$ for fission and fusion reactions.

RUTHERFORD'S SCATTERING EXPERIMENT

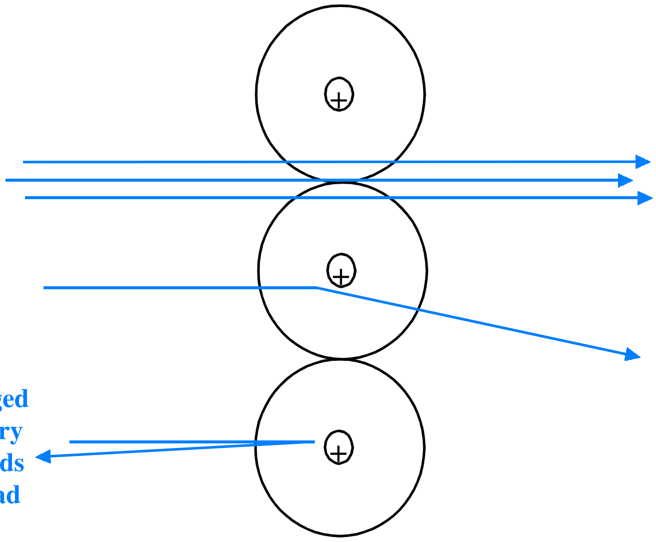
At the start of the 20th century, Ernest Rutherford devised an experiment to investigate the structure of atoms.

Positively-charged alpha particles were fired at a very thin piece of gold foil in the apparatus shown below. Because of the vacuum, the alpha particles were able to travel freely.



Every time an alpha particle hit the fluorescent screen, the screen glowed for a short time.

The microscope was moved all around the outside of the circular fluorescent screen, so that the number of alpha particles hitting the screen at every position could be observed.

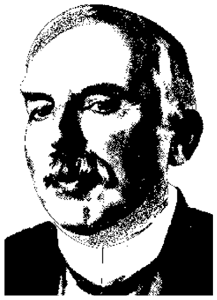


gold atoms in thin gold foil

Most of the positively-charged alpha particles (99%) passed straight through the gold foil.

A few of the positively-charged alpha particles were deflected slightly

Very, very few positively-charged alpha particles (about 1 in every 8 000) were deflected backwards in almost the direction they had come from.



Ernest Rutherford

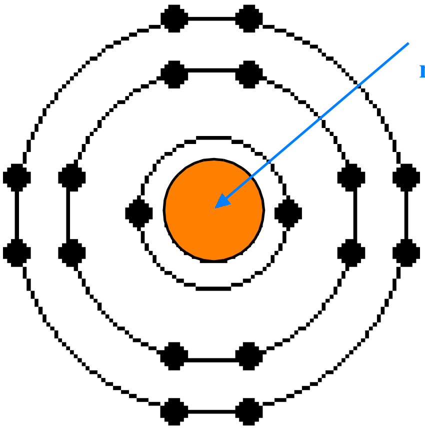
FROM THE RESULTS OF THIS EXPERIMENT, RUTHERFORD MADE THESE DEDUCTIONS ABOUT THE STRUCTURE OF ATOMS:

1) Because most of the positively-charged alpha particles passed straight through the gold atoms in the foil, **most of the atom must be empty space**.

2) Because only very, very few positively-charged alpha particles were deflected backwards in almost the direction they had come from, **most of the mass of the atom must be concentrated in a very small central area (which we call the nucleus)**.

3) Because some of the positively-charged alpha particles were deflected by the **nucleus**, the **nucleus** must be **positively-charged**.

OUR PRESENT DAY MODEL OF THE ATOM



Nucleus. Contains protons (+ charge) and neutrons (0 charge), so has overall + charge.

electrons (- charge) circle around nucleus

The symbol for an atom is often written in this form:

$${}^{235}_{92}\mathrm{U}$$

mass number (represents the total number of protons plus neutrons in the nucleus)

chemical symbol

atomic number (represents the number of protons in the nucleus)

To find the number of **neutrons** in an atom, we subtract the **atomic number** from the **mass number**, e.g., for the atom above: **Number of neutrons = mass number - atomic number**

= 235 - 92 = 143.

1) What is the number of protons and the number of neutrons in these atoms?

${}^{23}_{11}\mathrm{Na}$	${}^{64}_{30}\mathrm{Zn}$	${}^{141}_{56}\mathrm{Ba}$	${}^{140}_{54}\mathrm{Xe}$

Atoms which have the same **atomic number** but different **mass numbers** are known as **isotopes**, e.g., uranium has isotopes:

${}^{235}_{92}\mathrm{U}$ **and** ${}^{238}_{92}\mathrm{U}$

2)(a) How many protons and neutrons are present in each uranium isotope?

(b) Does each uranium isotope have:

(i) the same number of protons?____ (ii) the same number of neutrons?____

RADIOACTIVE DECAY

From Standard Grade Physics, you know that three types of radioactivity is emitted from atoms during radioactive decay - **alpha particles**, **beta particles** and **gamma rays**.

Complete this table:

Type of radiation	Symbol	What it is	What stops it	Amount of ionisation
alpha				
beta				
gamma				

alpha decay

Alpha decay takes place when an **alpha** particle (consisting of **2 protons plus 2 neutrons**) is ejected from an atom's nucleus.

An alpha particle is represented by the symbol:

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

A different atom is created as a result:

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

original (parent) atom

new (daughter) atom

emitted alpha particle

The mass number of the new (daughter) atom is _____ ___________ than the original (parent) atom and the atomic number is _____ _____________.

TOTAL OF MASS NUMBERS ON LEFT OF ARROW = __________

TOTAL OF ATOMIC NUMBERS ON LEFT OF ARROW = ________

beta decay

Beta decay takes place when a **neutron** in the **nucleus** splits up into a **proton** and an **electron**. The **proton** stays in the **nucleus** (so the atomic number increases by 1) while the **electron** is ejected from the atom's **nucleus** as a **beta particle**.

A beta particle is represented by the symbol:

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

A different atom is created as a result:

$$^{234}_{91}\mathrm{Pa} \rightarrow {}^{234}_{92}\mathrm{U} + {}^{0}_{-1}\mathrm{e}$$

original (parent) atom

new (daughter) atom

emitted beta particle

The mass number of the new (daughter) atom is _____ _________ _____ the original (parent) atom and the atomic number is _____ _____________.

TOTAL OF MASS NUMBERS ON LEFT OF ARROW = ________

TOTAL OF ATOMIC NUMBERS ON LEFT OF ARROW = ______

gamma decay

Gamma rays are **electromagnetic energy** - They are not **particles**. When **gamma rays** are ejected from an atom's nucleus (along with alpha and beta particles), this does not change the mass number or atomic number of the atom.

1) Identify the particle emitted in each of these radioactive decays:

(a) ${}^{212}_{83}\mathrm{Bi} \rightarrow {}^{208}_{81}\mathrm{Tl} + \_\_\_\_\_$ **(b)** ${}^{218}_{84}\mathrm{Po} \rightarrow {}^{218}_{85}\mathrm{At} + \_\_\_\_\_$ **(c)** ${}^{234}_{90}\mathrm{Th} \rightarrow {}^{234}_{91}\mathrm{Pa} + \_\_\_\_\_$

(d) ${}^{234}_{92}\mathrm{U} \rightarrow {}^{230}_{90}\mathrm{Th} + \_\_\_\_\_$ **(e)** ${}^{226}_{88}\mathrm{Ra} \rightarrow {}^{222}_{86}\mathrm{Rn} + \_\_\_\_\_$ **(f)** ${}^{234}_{91}\mathrm{Pa} \rightarrow {}^{234}_{92}\mathrm{U} + \_\_\_\_\_$

(g) ${}^{210}_{82}\mathrm{Pb} \rightarrow {}^{210}_{83}\mathrm{Bi} + \_\_\_\_\_$ **(h)** ${}^{230}_{90}\mathrm{Th} \rightarrow {}^{226}_{88}\mathrm{Ra} + \_\_\_\_\_$ **(i)** ${}^{228}_{88}\mathrm{Ra} \rightarrow {}^{228}_{89}\mathrm{Ac} + \_\_\_\_\_$

2) A radioactive decay chain is shown below.
Above each arrow, write the type of particle emitted for that stage:

$${}^{238}_{92}\mathrm{U} \longrightarrow {}^{234}_{90}\mathrm{Th} \longrightarrow {}^{234}_{91}\mathrm{Pa} \longrightarrow {}^{234}_{92}\mathrm{U}$$

3) Fill in the 4 missing numbers in this radioactive decay chain:

$${}^{\_\_}_{\_\_}\mathrm{Bi} \xrightarrow{{}^{0}_{-1}e} {}^{\_\_}_{\_\_}\mathrm{Po} \xrightarrow{{}^{4}_{2}\mathrm{He}} {}^{208}_{82}\mathrm{Pb}$$

4) Explain why the above radioactive decay equations do not give a complete picture of the radioactivity emitted from an atom's nucleus:

ACTIVITY

A radioactive source contains many atoms.

The activity (A) of a radioactive source is the number of atoms (nuclei), (N) in the source which decay in a given time time (t).

If the time is in seconds, the activity of the radioactive source is measured in becquerels (Bq) - 1 becquerel (Bq) is 1 decay per second.

activity in Bq

number of atoms (nuclei) which decay

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

time in s

Example

500 atoms (nuclei) in a radioactive source decay in a time of 2 minutes (120 seconds).

Calculate the **activity** of the source.

$A = N/t = 500$ atoms$/120$ s $=$ 4.2 Bq

1) In a sample of uranium, 720 000 atoms (nuclei) decay in 1 minute.

Calculate the activity of the uranium source:

2) A radioactive source has an activity of 5 kBq (5 000 Bq).

How many atoms (nuclei) decay every minute?

3) A radioactive substance has an activity of 8 MBq (8 x 10^{6} Bq).

What time will it take 12 million atoms in the source to decay?

NUCLEAR FISSION

In **nuclear fission**, a large **atomic nucleus** splits into **2 smaller nuclei** and **several neutrons**.
The **smaller nuclei** and **neutrons** produced gain **large amounts of kinetic energy.**

Fission may be either:

(a) Spontaneous

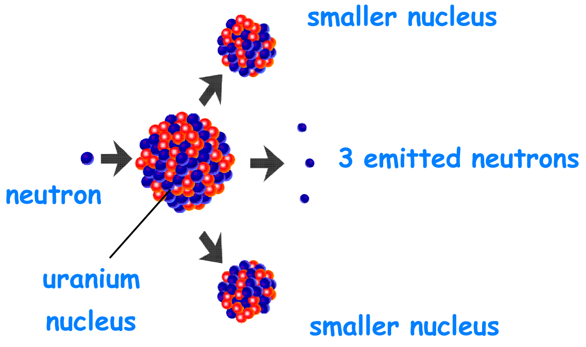
The large **atomic nucleus** splits up by itself at random - There is no **"outside influence"**.

For example:

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

large atomic nucleus — 2 smaller nuclei — 4 neutrons

or (b) Stimulated by Neutron Bombardment



Clipart copyright S.S.E.R. Ltd

For example:

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

neutron — uranium nucleus — 2 smaller nuclei — 3 neutrons

A neutron is "fired" at a uranium nucleus, causing the uranium nucleus to split up.

NUCLEAR FUSION

In **nuclear fusion**, **2 small atomic nuclei** combine to form a **larger nucleus**.
Other small particles (such as **neutrons**) may also be formed.

For example:

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

2 small atomic nuclei — larger nucleus — neutron

The **larger nucleus** and **other particles** produced gain **large amounts of kinetic energy**.

Nuclear fusion takes place in **stars**, like the **sun**.

LOST MASS and E = mc^2

In both **nuclear fission** and **nuclear fusion** reactions, the **mass** of the **products** formed is **always less than** the **mass** of the **starting species** - **Mass is lost during the reaction.**

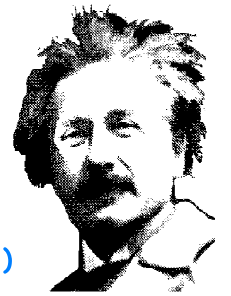
The **"lost mass"** is converted into **kinetic energy** of the **products**, in accordance with Albert Einstein's famous equation:

$$E = mc^2$$

kinetic energy of products (J)

speed of light (3×10^8 m s^{-1})

mass lost in reaction (kg)



Albert Einstein

Clipart copyright S.S.E.R. Ltd

This is an example of a nuclear fission reaction:

$$^{235}_{92}\text{U} + \,^{1}_{0}\text{n} \longrightarrow \,^{134}_{52}\text{Te} + \,^{98}_{40}\text{Zr} + 4\,^{1}_{0}\text{n}$$

3.901×10^{-25} kg	0.017×10^{-25} kg	2.221×10^{-25} kg	1.626×10^{-25} kg	0.017×10^{-25} kg

The mass of each species taking part in the reaction is shown in blue.

(a) Describe what happens in a nuclear fission reaction:

(b) Explain whether the above nuclear fission reaction is "spontaneous" or "induced":

(c) Calculate the total mass of the species on the left of the arrow (the reactants):

(d) Calculate the total mass of the species on the right of the arrow (the products):

(e) Calculate the lost mass when this nuclear fission reaction happens once:

(f) Calculate the kinetic energy gained by the products when this nuclear fission reaction happens once:

This is an example of a nuclear fusion reaction:

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

3.342×10^{-27} kg 3.342×10^{-27} kg 5.004×10^{-27} kg 1.674×10^{-27} kg

The mass of each species taking part in the reaction is shown in blue.

(a) Describe what happens in a nuclear fusion reaction:

(b) State where nuclear fusion reactions take place:

(c) Calculate the total mass of the species on the left of the arrow (the reactants):

(d) Calculate the total mass of the species on the right of the arrow (the products):

(e) Calculate the lost mass when this nuclear fusion reaction happens once:

(f) Calculate the kinetic energy gained by the products when this nuclear fusion reaction happens once:

HIGHER PHYSICS

UNIT 3 - RADIATION and MATTER

RADIOACTIVITY

You must be able to:

- Define the absorbed dose (D) as the energy absorbed per unit mass of absorbing material.

- State that the gray (Gy) is the unit of absorbed dose and that 1 gray is 1 joule per kilogram.

- State that the risk of biological harm from radiation depends on:
  (a) the type of radiation;
  (b) the absorbed dose (D);
  (c) the body organ/tissue absorbing the radiation.

- Explain the use of the radiation weighting factor (w_R) of each type of radiation as a measure of its biological effect.

- Define the equivalent dose (H) using the relationship $H = D\ w_R$ and solve problems using this relationship.

- State that the unit of equivalent dose (H) is the sievert (Sv).

- State that the effective dose is used to take account of the different susceptibilities to harm of any tissue exposed to radiation and is used to indicate the level of health risk from exposure to radiation.

- Define equivalent dose rate using the relationship $\dot{H} = H/t$ and solve problems using this relationship.

ABSORBED DOSE

When **radiation** (**alpha**, **beta**, **gamma** or **other type**) strikes the human body, the **energy** of the **radiation** is **absorbed** by the body.

The **absorbed dose** (**D**) is the **energy absorbed** (**E**) per **unit mass** (**m**) of material.

If the **energy** is in **joules** and the **mass** is in **kilograms**, the **absorbed dose** is measured in **grays** (**Gy**) - **1 gray is equivalent to 1 joule of energy absorbed by 1 kg of body tissue**.

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

energy absorbed in J

mass of absorbing tissue in kg

absorbed dose in Gy

Example

25 joules of energy are absorbed by 2 kg of body tissue.

Calculate the **absorbed dose.**

D = E/m = 25 J/2 kg = 12.5 Gy.

1) **12 J of energy are absorbed by 2.5 kg of body tissue.**

Calculate the absorbed dose:

2) **Calculate the energy absorbed by 0.3 kg of body tissue which receives an absorbed dose of 6 Gy:**

3) **300 Gy absorbed dose is received by a cancer tumour which absorbs 15 J of energy.**

Calculate the mass of the tumour:

EQUIVALENT DOSE

The risk of **biological harm** from **radiation** depends on:

(a) the **type of radiation**;

(b) the **absorbed dose** (**D**);

(c) the **type of body tissue absorbing the radiation**.

To take account of the **type of radiation**, a **radiation weighting factor** (*w_R*) is applied to the **absorbed dose** (**D**) - This gives a new quantity: **equivalent dose** (**H**).

$$H = D\,W_R$$

absorbed dose in grays (Gy)

equivalent dose in sieverts (Sv)

radiation weighting factor (no unit)

Radiation weighting factors for different types of radiation

Type of radiation	Radiation Weighting Factor (w_R)
alpha particles	20
beta particles	1
gamma rays	1
X-rays	1
slow neutrons	2.3
fast neutrons	10

Example

When **alpha particles** hit a body, they cause an **absorbed dose** of 100 μG (100 x 10^{-6} Gy).

Calculate the **equivalent dose.**

$$H = D\ W_R = (100 \times 10^{-6})\ Gy \times 20 = \underline{0.002\ Sv} \quad \text{or} \quad \underline{2\ mSv}$$

1) When alpha particles hit a body, they cause an absorbed dose of 250 μGy (250 x 10^{-6} Gy).

Calculate the equivalent dose:

2) When beta particles hit a body, they cause an absorbed dose of 120 μGy (120 x 10^{-6} Gy).

Calculate the equivalent dose:

3) When slow neutrons hit a body, they cause an absorbed dose of 300 μGy (300 x 10^{-6} Gy).

Calculate the equivalent dose:

EFFECTIVE DOSE

The risk of biological harm from radiation depends on the type of body tissue (lungs, heart, skin, etc) absorbing the radiation.

By adding the contributions from each type of body tissue, an effective dose for the whole body can be determined.

4) A sample of human tissue receives an absorbed dose of 25 mGy of alpha particles and 8 mGy of gamma rays.

Calculate the effective dose received by the sample (in mSv):

5) A sample of body tissue receives an absorbed dose of 35 mGy of alpha particles and 20 mGy of slow neutrons.

Calculate the effective dose received by the sample (in mSv):

EQUIVALENT DOSE RATE

The **equivalent dose rate** ($\dot{H}$) indicates the **rate** at which radiation is absorbed - It is the **equivalent dose** per **unit time**.

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

equivalent dose in sieverts (Sv)

equivalent dose rate in Sv h^{-1}, Sv $year^{-1}$, etc

time in h, years, etc

Example

A worker in a nuclear power station receives an equivalent dose of 10 mSv over a time of 8 hours.

Calculate the **equivalent dose rate**.

$\dot{H}$ = H/t = 10 mSv/8 hours = 1.25 mSv h^{-1}

1) A doctor receives an equivalent dose of 120 mSv over a 3 year period.

Calculate the equivalent dose rate:

2) Over a 5 year period, a nurse receives an equivalent dose of 2 500 mSv.

Calculate the equivalent dose rate:

3) A workman receives an equivalent dose of 2 mSv over an 8 hour shift.

Calculate the equivalent dose rate:

4) A research worker receives 10 µGy of gamma radiation and 50 µGy of fast neutrons during an experiment lasting 8 hours.

Calculate: (a) her effective dose in µSv;

(b) the equivalent dose rate in µSv h^{-1}.

5) A laboratory technician receives an absorbed dose of 15 mGy of alpha radiation and 25 mGy of beta radiation over 7 days (168 hours).

Calculate: (a) his effective dose in mSv;

(b) the equivalent dose rate in mSv h^{-1}.

HIGHER PHYSICS

UNIT 3 - RADIATION and MATTER

RADIOACTIVITY

3) SAFETY and HALF-VALUE THICKNESS

You must be able to:

- Give examples of factors affecting background radiation levels.

- State that the annual effective dose that a person in the UK receives from natural sources (background radiation) is approximately 2 mSv yr^{-1}.

- State that annual effective dose limits have been set for exposure to radiation for the general public (5 mSv yr^{-1}) and higher limits have been set for workers in certain occupations (50 mSv yr^{-1}) - in addition to natural sources (background radiation).

- Describe an experiment to show how the intensity of a beam of gamma radiation varies with the thickness of an absorbing material and how the results are used to calculate the half-value thickness for the absorbing material.

- Sketch a line graph to show the variation of intensity of a beam of gamma radiation with thickness of an absorbing material.

- Solve problems involving half-value thickness.

- State that equivalent dose rate is reduced by:
  (a) shielding;
  (b) increasing the distance from the source of radiation.

BACKGROUND RADIATION

Radioactivity is always present in the air around us - This **background radiation** has many different sources.

The table shows some common sources of **background radiation** and lists some factors affecting our exposure to each source:

Source of background radiation	Factors affecting exposure
Radon gas, thoron gas and gamma rays from the ground, rocks and buildings.	In certain parts of the country, the ground, rocks and buildings made from the rocks emit significant amounts of radioactivity - For example, granite rocks in Aberdeen.
X-rays and radio-isotopes used in hospitals.	The more X-rays a patient has, the higher their level of exposure to radiation.
Cosmic rays from outer space.	The greater the time a person spends flying, the greater their exposure to cosmic rays.
Leaks from nuclear power stations and nuclear weapons tests.	People living near nuclear power stations or nuclear weapons test areas are likely to receive higher exposure to radiation.

In the UK, the average **annual effective dose** for a person receives from **natural sources** (**background radiation**) is approximately **2 mSv yr^{-1}**.

Annual effective dose limits have been set for exposure to radiation for **members of the public**: **5 mSv yr^{-1}** (**in addition to natural sources/background radiation**).

Higher limits are set for **workers in certain occupations**, e.g., **nuclear power station workers**: **50 mSv yr^{-1}** (**in addition to natural sources/background radiation**).

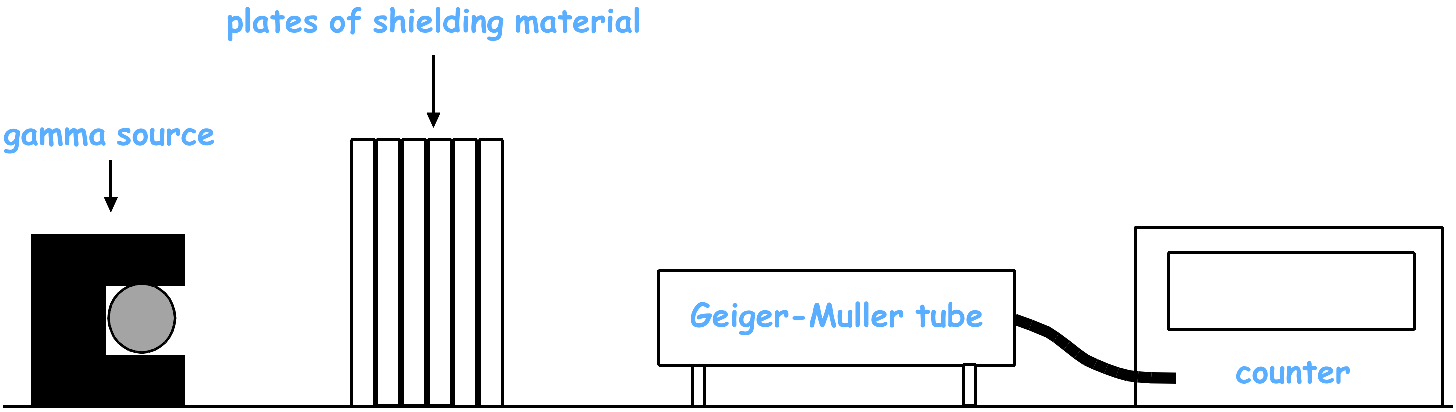
To reduce the dose equivalent rate, we can:

(a) shield the absorber with suitable material;

(b) increase the distance between the source and the absorber.

SHIELDING and HALF-VALUE THICKNESS

This apparatus can be used to investigate the effect of placing different thicknesses of absorbing material between a source of gamma radiation and a detector:



Method

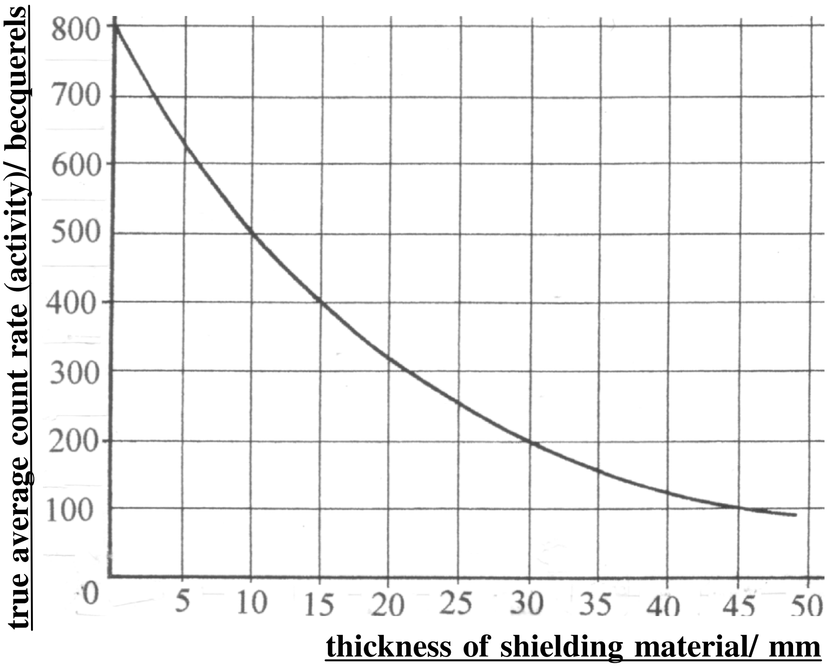
1) With **no radioactive source present**, determine the average background count rate.
2) Set up the apparatus, as shown.
3) Place a known thickness of shielding material between the gamma source and the Geiger-Muller tube. Determine the average count rate for this thickness of material, then **subtract the average background count rate to obtain the true average count rate for this thickness**.
4) Repeat for different thicknesses of shielding material.
5) Plot a graph of true average count rate versus thickness of shielding material.

The graph obtained is similar to the **half-life** graphs studied in Standard Grade Physics.

The thickness of shielding material which halves the true average count rate can be obtained from the graph - This thickness of shielding material is known as the **"half-value thickness"**.

From graph, half-value thickness =

____



A typical half-value thickness problem

A source of gamma radiation is placed close to a Geiger-Muller tube with counter.
The true average count rate is found to be 1 000 Bq.

Metal X (half-value thickness = 15 mm) is placed between the source and Geiger-Muller tube.

What thickness of metal X will be required to reduce the true average count rate detected to 125 Bq?

$$1\,000\text{ Bq} \xrightarrow{\text{half-value thickness}} 500\text{ Bq} \xrightarrow{\text{half-value thickness}} 250\text{ Bq} \xrightarrow{\text{half-value thickness}} 125\text{ Bq}$$

To reduce the average count rate from 1 000 Bq to 125 Bq requires
3 half-value thicknesses of metal X.

3 x 15 mm = 45 mm of metal X.

1) When a solid block of metal Y (half-value thickness = 12 mm) is placed between a gamma radiation source and a detector, the true average count rate falls from 2 000 Bq to 125 Bq.

Calculate the thickness of the block of metal Y:

2) Material M has a half-value thickness of 1.5 cm.

What thickness of M would be required to reduce an equivalent dose from 4 000 mSv to 125 mSv?

3) At a certain point in a laboratory, the equivalent dose rate for the human body is 400 mSv h^{-1}.

If 15 mm of metal Z (half-value thickness = 5 mm) is placed around the point, what will be the new equivalent dose rate?

4) Lead has a half-value thickness of 40 mm for gamma rays.

What thickness of lead would reduce the absorbed dose in a body to 1/16 of its current value?

5) The equivalent dose rate due to gamma radiation from a nuclear reactor is 800 mSv h^{-1}, as detected by a gamma ray detector.

Calculate the new equivalent dose rate when 75 cm of material W (half-value thickness = 15 cm) is placed between the nuclear reactor and gamma ray detector.