

Unit 2 - Particles and Waves - Part 2

WAVE-PARTICLE DUALITY

8. The photoelectric effect and wave particle duality
 - Photoelectric effect as evidence for the particulate nature of light.
 - Photons of sufficient energy can eject electrons from the surface of materials.
 - The threshold frequency is the minimum frequency of a photon required for photoemission.
 - The work function is the minimum energy required to cause photoemission.
 - The maximum kinetic energy of photoelectrons can be determined.

INTERFERENCE AND DIFFRACTION

9. Conditions for constructive and destructive interference
 - Coherent waves have a constant phase relationship and have the same frequency, wavelength and velocity.
 - Constructive and destructive interference in terms of phase between two waves.
10. Interference of waves using two coherent sources
 - Maxima and minima are produced when the path difference between waves is a whole number of wavelengths or an odd number of half wavelengths respectively.
 - Investigations which lead to the relationship between the wavelength, distance between the sources, distance from the sources and the spacing between maxima or minima.
11. Gratings
 - Monochromatic light can be used with a grating to investigate the relationship between the grating spacing, wavelength and angle to the maxima.
 - A white light source may be used with a grating to produce spectra.
 - Comparing the spectra produced by gratings with prisms.

REFRACTION OF LIGHT

12. Refraction
 - Refractive index of a material as the ratio of the sine of angle of incidence in a vacuum (air) to the sine of angle of refraction in the material.
 - Refractive index of air is treated as the same as that of a vacuum.
 - Situations where light travels from a more dense to less dense substance.
 - Refractive index as the ratio of speed of light in a vacuum (air) to the speed in the material, also as the ratio of the wavelengths.
 - Variation of refractive index with frequency.
13. Critical angle and total internal reflection
 - Investigating total internal reflection, including critical angle and its relationship with refractive index.

SPECTRA

14. Irradiance and the inverse square law

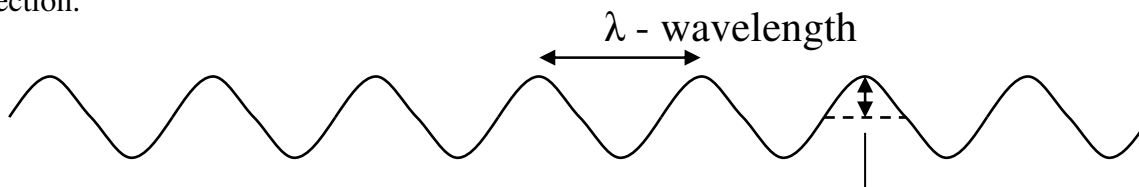
- Investigating irradiance as a function of distance from a point light source
- Irradiance as power per unit area.

15. Line and continuous emission spectra, absorption spectra and energy level transitions

- The Bohr model of the atom.
- Electrons can be excited to higher energy levels by an input of energy.
- Ionisation level is the level at which an electron is free from the atom.
- Zero potential energy is defined as equal to that of the ionisation level, implying that other energy levels have negative values.
- The lowest energy level is the ground state.
- A photon is emitted when an electron moves to a lower energy level and its frequency depends on the difference in energy levels.
- Planck's constant is the constant of proportionality.
- Absorption line in the spectrum of sunlight as evidence for the composition of the Sun's upper atmosphere.

CLASSICAL WAVE THEORY

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). These properties of a wave will be described later in this section.



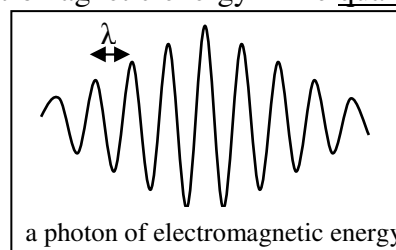
Such a continuous electromagnetic wave has a **velocity** (v) of $3 \times 10^8 \text{ ms}^{-1}$ in air, a **frequency** (f) measured in **hertz** and **wavelength** (λ) measured in **metres**.
The equation $v = f \lambda$ applies to the wave.

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

QUANTUM THEORY

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

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



As with **classical wave theory**, each **photon** has a **velocity** (v) of $3 \times 10^8 \text{ ms}^{-1}$ 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):

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

$$\begin{array}{ccc} \text{energy of photon} & \text{--- } \boxed{E = h f} & \text{--- frequency of photon} \\ \text{(unit: J)} & & \text{(unit: Hz)} \end{array}$$

Planck's constant = $6.63 \times 10^{-34} \text{ Js}$

Example

In air, a photon of **yellow** light has a wavelength of 589 nm (i.e., $589 \times 10^{-9} \text{ m}$).
Calculate: (a) the **frequency** of the photon; (b) the **energy** of the photon.

(a)

$$v = f \lambda$$

$$f = \frac{v}{\lambda} = \frac{3 \times 10^8}{589 \times 10^{-9}} = 5.09 \times 10^{14} \text{ Hz}$$

(b)

$$E = hf$$

$$= (6.63 \times 10^{-34}) \times (5.09 \times 10^{14})$$

$$= 3.37 \times 10^{-19} \text{ J}$$

THE PHOTOELECTRIC EFFECT

Work Function

The electrons in a metal are held on a surface by attractive forces.

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

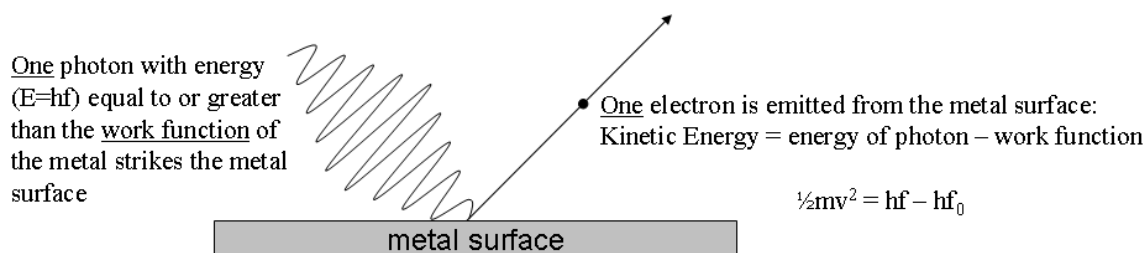
*The **work function** of a metal is the minimum energy which must be supplied to enable an electron to escape from the metal surface.*

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 is 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_0)

A photon must have a minimum energy equal to the **work function** of a metal and hence a **minimum frequency** (f_0) to release an electron from the metal surface. This **minimum frequency (f_0)** is called the **threshold frequency** of the metal. Each metal has its own unique value of threshold frequency (f_0).

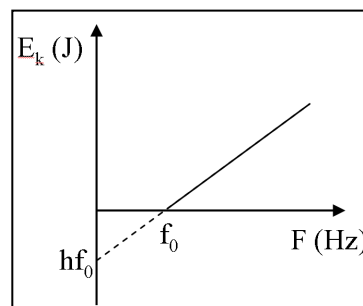


Photoelectric emission is described by Einstein's Photoelectric equation:

energy of the photon	work function of the metal	kinetic energy given to the emitted electron
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$$hf = hf_0 + \frac{1}{2}mv^2$$

h = Planck's Constant ($6.63 \times 10^{-34} \text{Js}$)
 f = frequency of photon
 f_0 = threshold frequency of the metal surface
 m = mass of the electron ($9.11 \times 10^{-31} \text{kg}$)
 v = maximum velocity of the electron



Laboratory Demonstration of the Photoelectric Effect

An **electroscope** (with a **zinc plate** on top) is **negatively-charged** - The zinc plate, stem and needle are covered with negatively-charged electrons, so the needle is **repelled** by the stem.

When photons of **ultra-violet** radiation are shone onto the zinc plate, they 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 needle - The needle is no longer repelled by the stem, so it falls. If the irradiance of the ultra-violet radiation is **increased**, the needle falls faster because more ultra-violet photons strike the zinc plate, so electrons are emitted from the zinc faster.

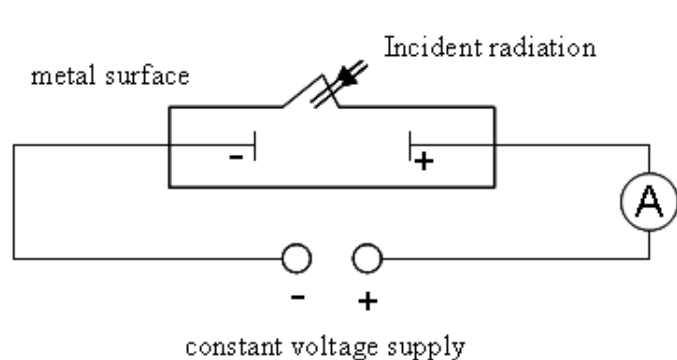
If **white light** (which contains photons of all colours of the visible spectrum- red, orange, yellow, green, blue, indigo and violet) is shone onto the zinc plate, the needle does not fall. Photons of these colours of light do not have high enough energy to eject electrons from the zinc surface - The 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 needle 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 electroscope is **positively-charged**, the needle does not fall when the metal plate is illuminated by electromagnetic radiation of any energy/frequency because the stem and needle **lack electrons**, so cannot replace the electrons emitted from the metal plate.

Investigating The Photoelectric Effect

The apparatus below or a simulation can be 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.

Below a certain frequency [the threshold frequency (f_0)], 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_0), more electrons are emitted - the photoelectric current increases.

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 then directly proportional to the irradiance of the radiation.

An Introduction to Waves

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.

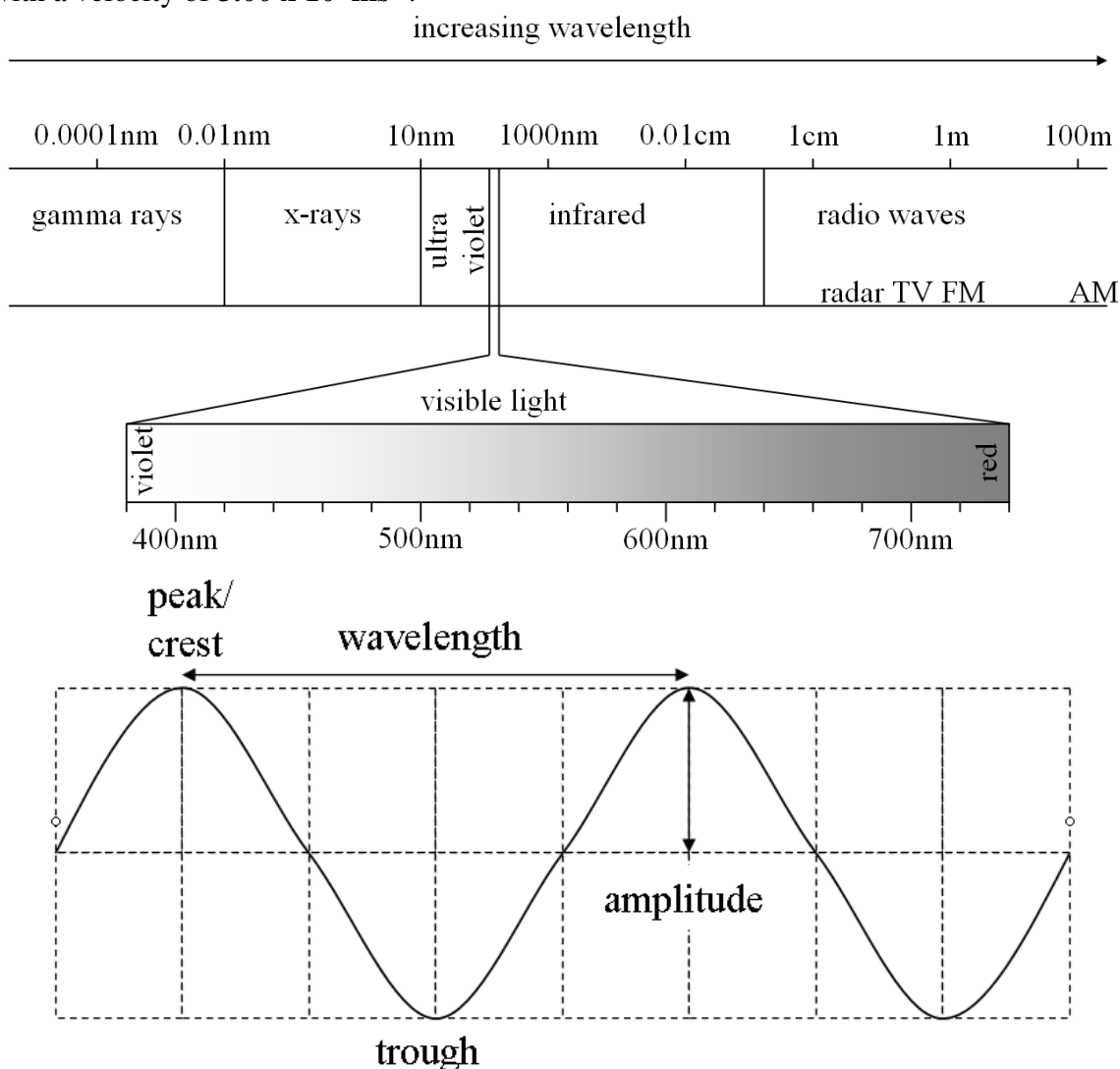
These waves can often be seen or felt - For example, **water waves**, **waves on a spring** and **sound waves** in various materials.

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 $3.00 \times 10^8 \text{ ms}^{-1}$.



The frequency of a wave is determined by its source. The frequency of the wave never changes after the wave leaves the source

Interference of Waves

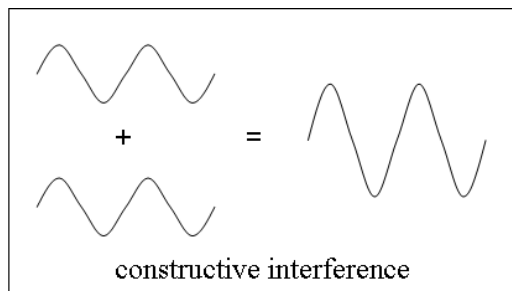
When 2 waves meet, they overlap/combine - This is known as **interference**.

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.

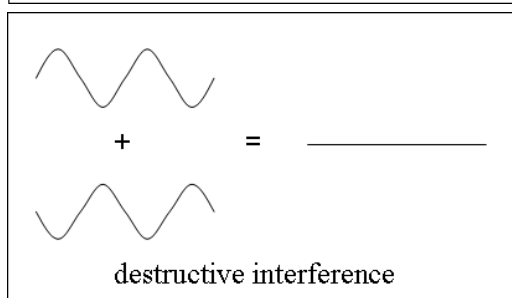
The superposition of these two waves results in a stronger signal.



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.

The superposition of these two waves causes the signals to be cancel each other out.



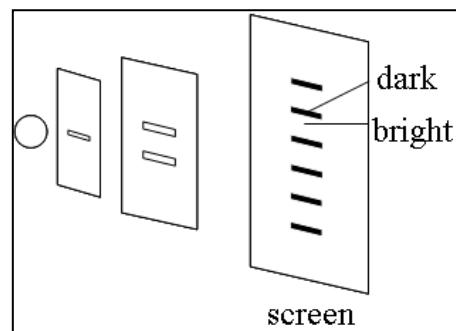
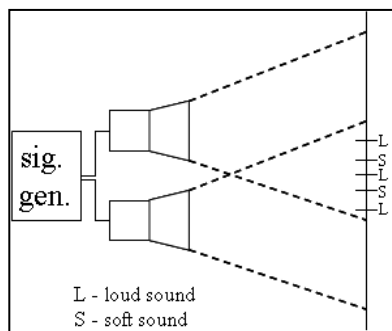
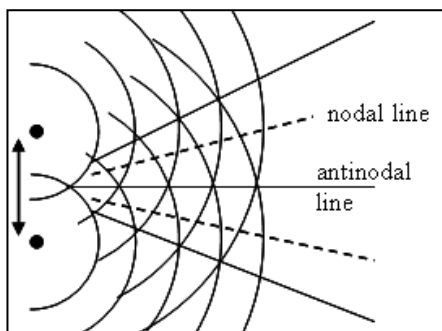
Destructive Interference - The test for wave motion

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.

Coherent Waves

If 2 waves are **coherent**, they have the same **frequency**, similar **amplitude** and **have a constant phase relationship**. In order to achieve this, a **single source** must be used to produce the 2 waves.



Water Waves

At points of constructive interference the water wave has a maximum amplitude.

At points of destructive interference the water appears calm.

Sound Waves

At points of constructive interference a loud sound can be detected.

At points of destructive interference a soft sound can be detected

Light Waves

At points of constructive interference, bright fringes are observed.

At points of destructive interference dark fringes are observed.

Path difference, Wavelength and Interference

The maxima in an interference pattern are numbered as shown.

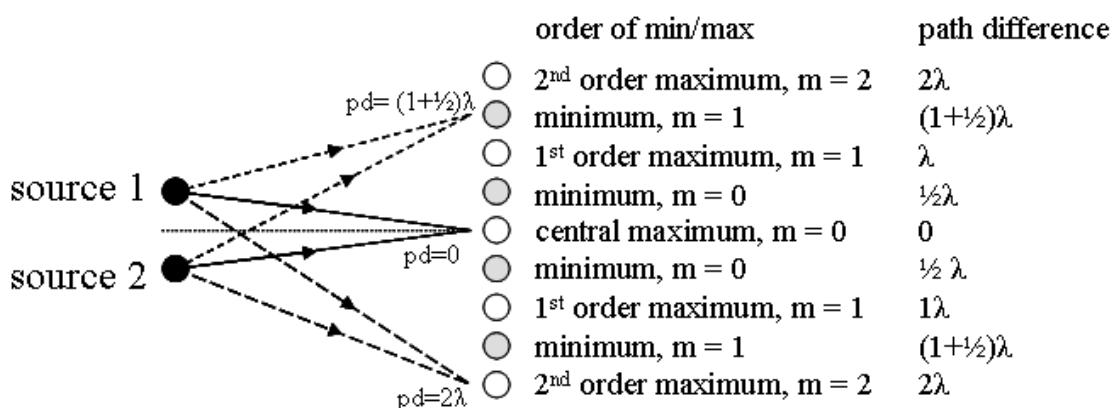
To reach the central maximum, $m = 0$ (which is always the strongest), waves from both sources have to travel the same distance.

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 = $m \lambda$

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

where $m = 0, 1, 2, 3...$



Diffraction Grating for the Interference of Light

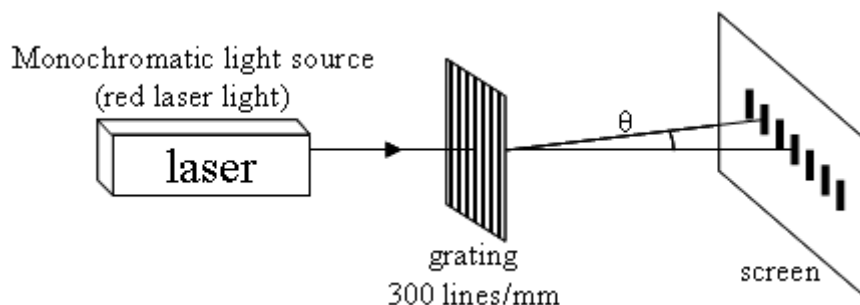
To produce a **bright** and **sharp** interference pattern for light, a **diffraction grating** is used in preference to a Young's double slit.

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.



The **grating equation** can be applied here:

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

m = order of maximum

λ = wavelength of light (m)

d = distance between slits on diffraction grating (m)

θ = angle between central maximum and maximum of order m (°)

Example - Experimental determination of the wavelength of red light

Matthew used the apparatus on the previous page 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° .

To determine value for d in m:

Grating has 300 slits (lines) per mm
 $= 300 \times 1\,000 = 300\,000$ slits per m

$$\text{distance between slits, } d = \frac{1}{300,000}$$

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

$$m = 2$$

$$\lambda = ?$$

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

$$\theta = 25^\circ$$

$$2\lambda = (3.33 \times 10^{-6}) \times \sin 25^\circ$$

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

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

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

Changing the distance between maxima

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

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, increase λ - towards the red end of the visible spectrum;
- 2) Decrease d, the slit separation - have more lines per mm.
- 3) Move the screen further away from the diffraction grating.

Approximate Wavelength of blue, green and red light

It is useful to know approximate values for the wavelengths of blue, green and red light.

$$\text{Wavelength of blue light - } 4.5 \times 10^{-7} \text{ m} = 450 \text{ nm}$$

$$\text{Wavelength of green light - } 5.5 \times 10^{-7} \text{ m} = 550 \text{ nm}$$

$$\text{Wavelength of red light - } 6.5 \times 10^{-7} \text{ m} = 650 \text{ nm}$$

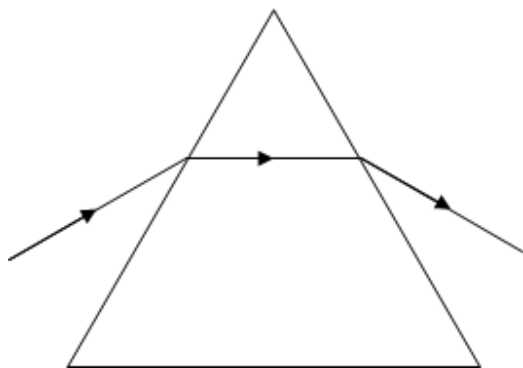
$$* 1 \text{ nanometre (nm)} = 1 \times 10^{-9} \text{ m}$$

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.

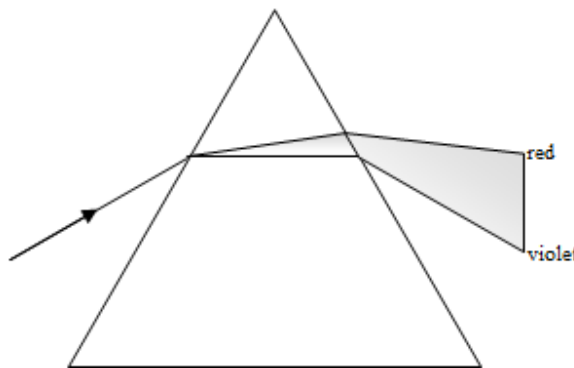
Comparing White Light Spectra from Prisms and Gratings

Prism

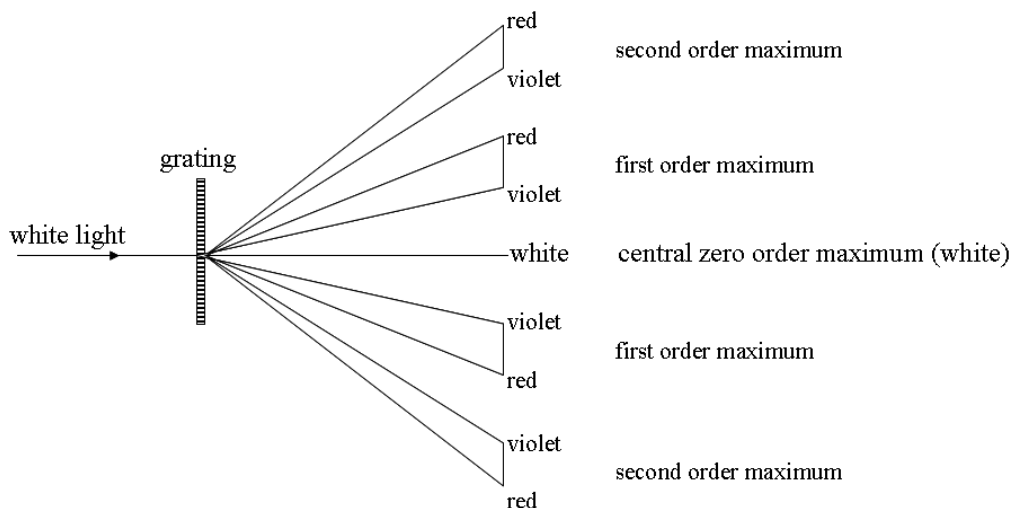
When a ray of **monochromatic** (e.g., **red**) light is passed through a glass prism, the ray is **refracted**:



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



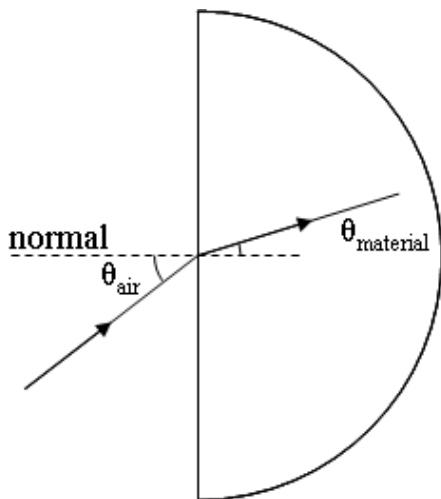
Diffraction Grating



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 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: $\sin\theta = \frac{m\lambda}{d}$
Spectrum is brighter.	Spectra are less bright. The energy is divided between several spectra.

Refractive index of a material, n

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 0° from the normal, the ray changes **direction** on entering the material (due to a change in **speed**) - The ray is **refracted**:

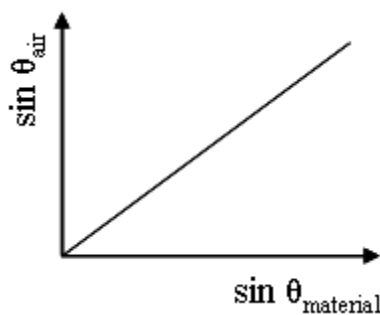


On entering the material, the light ray changes direction **towards the normal**.

The angle θ_{material} is always less than the angle θ_{air} .

If you change θ_{air} several times, measure θ_{air} and θ_{material} each time, then calculate values for $\sin \theta_{\text{air}}$ and $\sin \theta_{\text{material}}$, you can plot a graph of $\sin \theta_{\text{air}}$ against $\sin \theta_{\text{material}}$.

The graph you obtain is a straight line passing through the origin:



The graph shows that:

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

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

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

or

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

The constant is known as the **refractive index** of the material. It is given the symbol **n**. There are no units for refractive index.

Definition of refraction: Refraction is defined by how much light **changes speed** in a material. A change in direction may result, but only when the light is incident at an angle from the normal.

Also note:

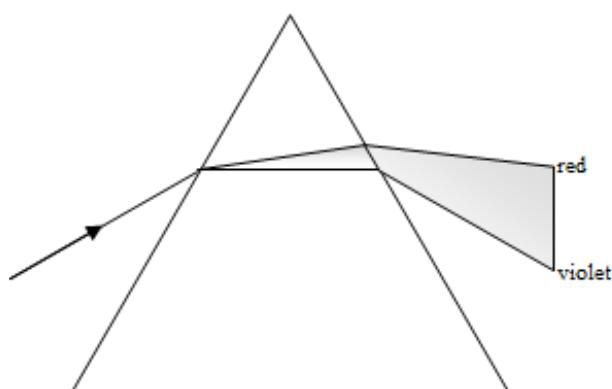
- This equation applies to any material that light can pass through, e.g. glass, plastic, water.
- Each material has its own distinct value of refractive index for each different frequency of light (n is always equal to or greater than 1).
- The greater the refractive index, the greater the change in 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 a glass block where the angle of incidence of light entering the block is 40° and the angle of refraction is 25° :

$$n = \frac{\sin \theta_{\text{air}}}{\sin \theta_{\text{material}}} = \frac{\sin 40^\circ}{\sin 25^\circ} = \frac{0.643}{0.423}$$

$$n = 1.52$$

Refractive index and Frequency of Light

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 it 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**.

Refractive Index, Angles, Velocity and Wavelength of Light

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

velocity decreases

wavelength decreases

frequency remains constant

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

$$\text{refractive index} = \frac{\sin \theta_1}{\sin \theta_2} = \frac{\text{velocity 1}}{\text{velocity 2}} = \frac{\text{wavelength 1}}{\text{wavelength 2}}$$

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

Example

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

$$n = \frac{v_{\text{air}}}{v_{\text{material}}}$$

$$1.5 = \frac{3 \times 10^8}{v_{\text{material}}}$$

$$v = 2 \times 10^8 \text{ ms}^{-1}$$

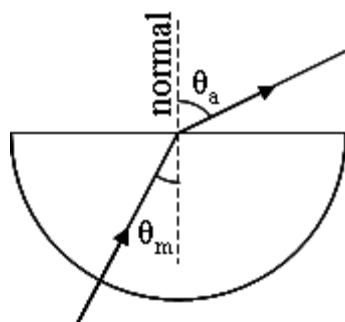
Red light (wavelength 700 nm in air) is passed into a plastic material of refractive index 1.47. Calculate the wavelength of the light in the plastic.

$$n = \frac{\lambda_{\text{air}}}{\lambda_{\text{material}}}$$

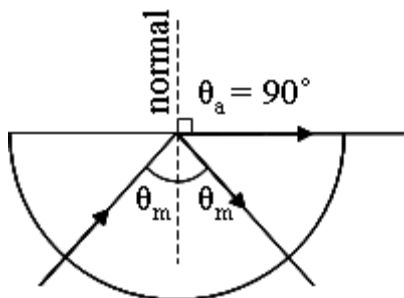
$$1.47 = \frac{700 \times 10^{-9}}{v_{\text{material}}}$$

$$\lambda = 4.76 \times 10^{-7} \text{ m} = 476 \times 10^{-9} \text{ m} = 476 \text{ nm}$$

Critical Angle and Total Internal Reflection

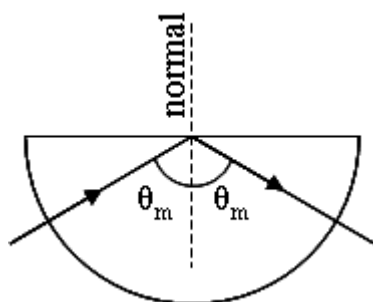


When a monochromatic light ray is passed from air into a semi-circular transparent block, as shown, resulting in the ray leaving the block at an angle of incidence close to the normal line, most of the light ray is **refracted** into the air at the flat surface. A small amount of the light may be **reflected** back into the glass by the flat surface.



If the angle of incidence between the incoming light ray and the normal line is increased, some of the light ray is **refracted** along the flat surface into the air (at 90° to the normal line). Some light is **reflected** back into the glass by the flat surface

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



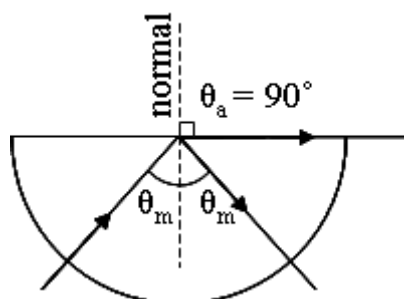
If the angle of incidence between the incoming light ray and the normal line is increased **above the critical angle**, **all** of the light ray is **reflected** back into the glass by the flat surface.

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), $\theta_{\text{air}} = 90^\circ$



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

$$n = \frac{\sin 90^\circ}{\sin \theta_{\text{material}}}$$

$$n = \frac{1}{\sin \theta_{\text{material}}}$$

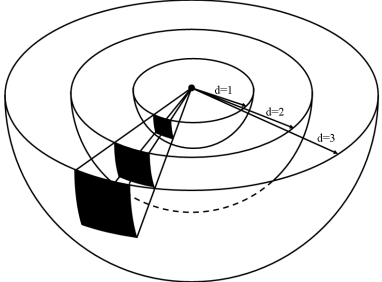
$$\boxed{\sin \theta_c = \frac{1}{n}}$$

Practical applications of Total Internal Reflection include: optic fibers, for use in telecommunications and endoscopy; prismatic binoculars and even some multi touch screens.

Irradiance of Radiation

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

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



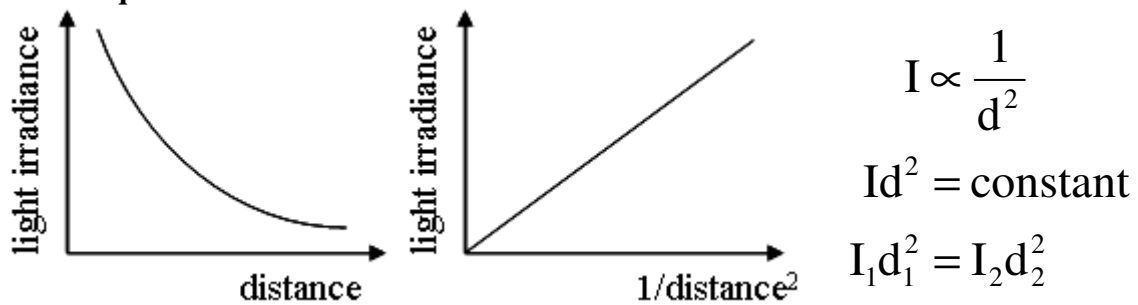
watts (W) square metres (m²)

watts per square metre (Wm⁻²)

A "perfect" source of light (known as a **point source**) emits light evenly in all directions. The light spreads out as a **sphere**, with the light source at its centre.

At any distance (**r**) from the source, the **irradiance** of light depends on the **surface area** of the light **sphere**.

There is also a relationship between **irradiance** and the **distance** from the source. It is an **inverse square law**.



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?

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

$$50 \times (0.5)^2 = I_2 \times (0.7)^2$$

$$12.5 = 0.49 \times I_2$$

$$I = \frac{12.5}{0.49} = 25.5 \text{ W m}^{-2}$$

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.

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).

$$\text{Irradiance} = \frac{\text{Power}}{\text{Area}} = \frac{\text{laser power rating}}{\pi \times \text{radius}^2}$$

$$= \frac{0.0001}{3.14 \times 0.0005^2} = 127 \text{ W m}^{-2}$$

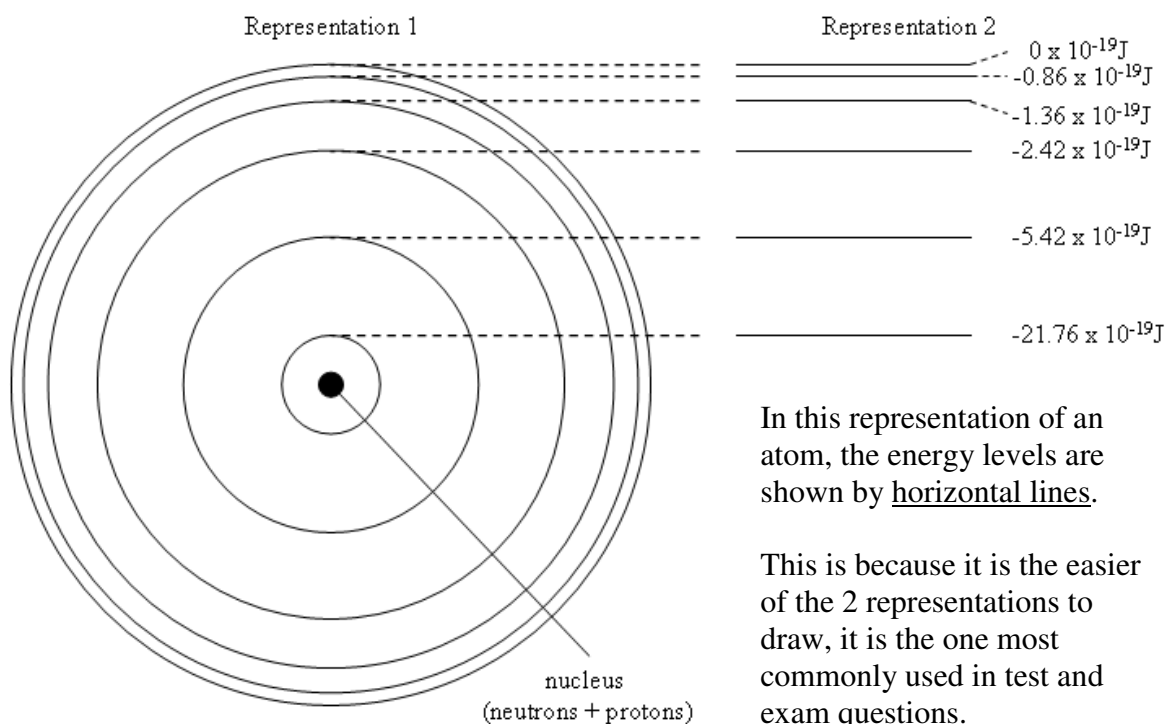
Rutherford-Bohr Model of the Atom

In this model the **electrons** orbit the **nucleus** of an atom 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**. This means the energy of the electrons is **quantised**.

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



A hydrogen atom has only 1 electron, but this electron can occupy any one of these energy levels. The electron may also 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 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**.

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

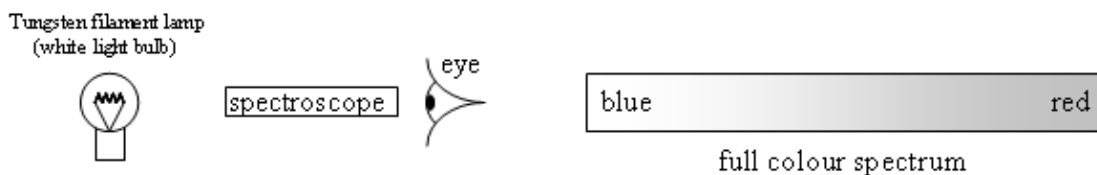
Different atoms produce different atomic spectra (e.g., mercury atoms produce a different spectrum from sodium atoms.)

As a result, an atom can be identified by observing its spectrum.

1) Emission Spectra

(a) Continuous Spectra

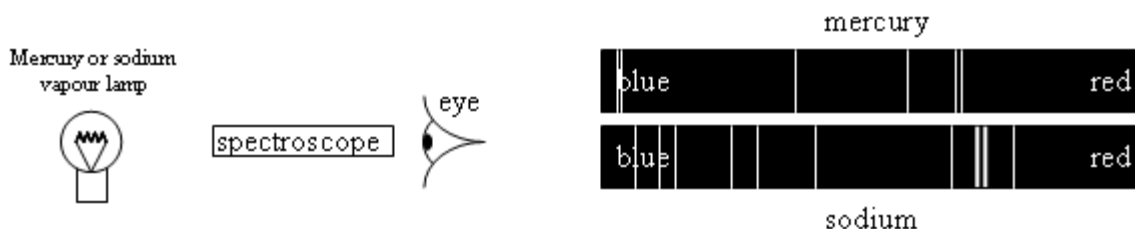
A tungsten filament lamp (a normal light bulb) emits **white light**. When the **white light** is passed through a spectroscope, a **continuous spectrum** is obtained. This contains all colours of the **visible spectrum**:



(b) Line Spectra

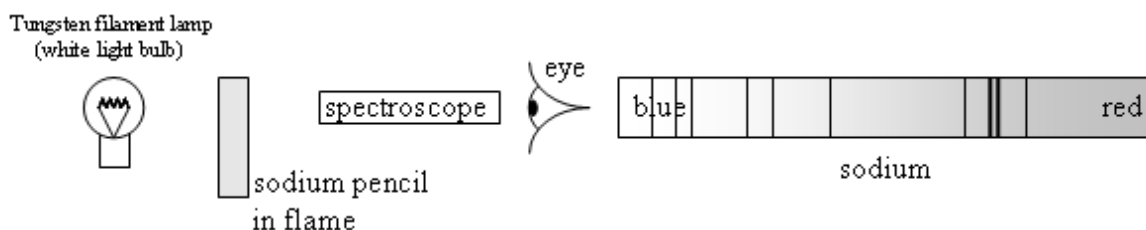
A mercury vapour lamp or sodium vapour lamp emits photons of **specific frequency** (and hence **colour**). When the light is passed through a spectroscope, a series of **different coloured lines on a black background** is obtained. Each line occupies an **exact position corresponding to its exact frequency/wavelength**.

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



2) Absorption Spectra

When **white light** (containing photons of all different frequencies 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.

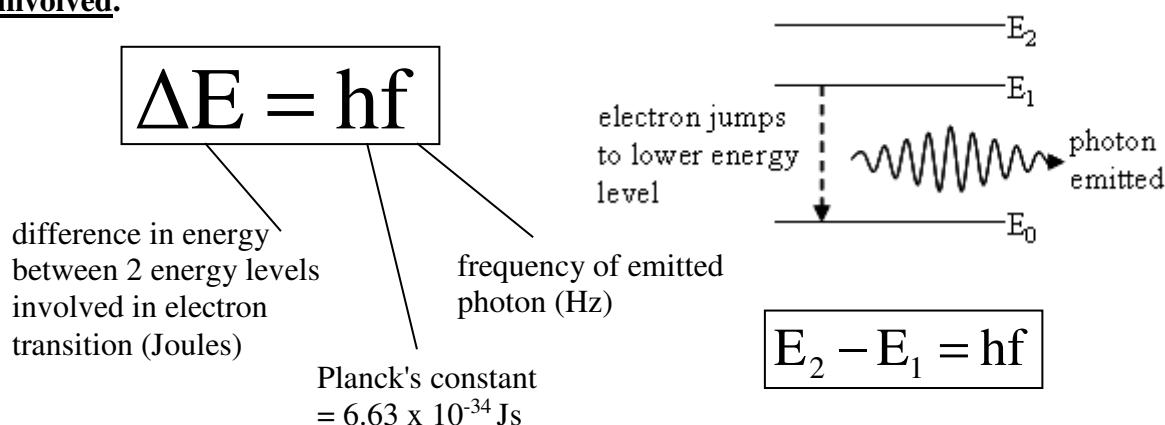


How Emission Line Spectra are Formed

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_0**).

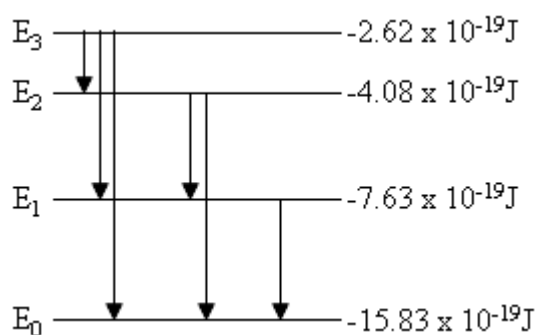
This process is **spontaneous** - We cannot predict when it will happen (just like we cannot predict when the radioactive decay of an atomic nucleus will take place.)

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



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.



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.

Some emission lines in an emission spectrum are brighter than others. These are caused by a larger number of electrons (from the same and other identical atoms) making the same energy transition, due to those transitions being more likely than others.

Example

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

$$\begin{aligned}\Delta E &= E_2 - E_1 \\ \Delta E &= -4.08 \times 10^{-19} - (-7.63 \times 10^{-19}) \\ \Delta E &= 3.35 \times 10^{-19} \text{ J} \\ \\ \Delta E &= hf \\ 3.35 \times 10^{-19} &= 6.63 \times 10^{-34} \times f \\ f &= \frac{3.35 \times 10^{-19}}{6.63 \times 10^{-34}} = 5.35 \times 10^{14} \text{ Hz}\end{aligned}$$

Advice:

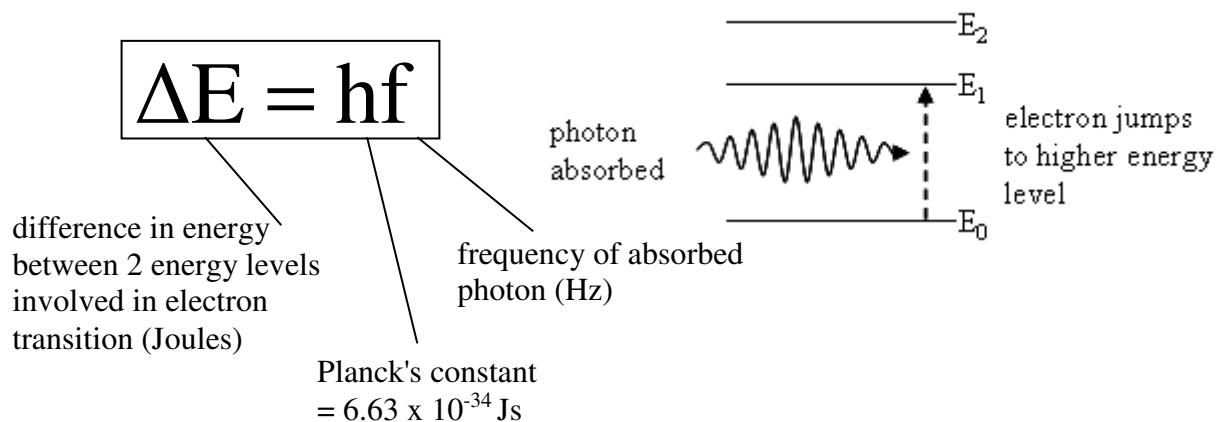
For these change in energy level calculations to find ΔE you may find it easier to find the difference between the two values if they were positive.

You will get the same answer and you are less likely to make any mistakes by subtracting a negative number from another negative number.

How Absorption Line Spectra are Formed

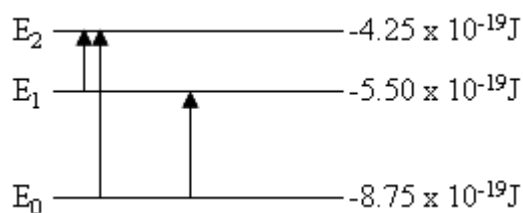
An **atom** can **absorb** a photon of **electromagnetic energy**. **The atom can only do so if the energy of the photon is exactly equal to the difference in energy (ΔE) between any 2 energy levels in the atom.**

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**.



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 later.



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.

Example

Calculate the energy and frequency of the photon absorbed when an electron jumps from energy level E_0 to energy level E_2 .

$$\Delta E = E_2 - E_0$$

$$\Delta E = -4.24 \times 10^{-19} - (-8.75 \times 10^{-19})$$

$$\Delta E = 4.50 \times 10^{-19} \text{ J}$$

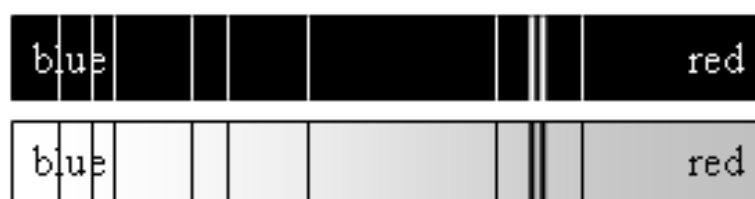
$$\Delta E = hf$$

$$4.50 \times 10^{-19} = 6.63 \times 10^{-34} \times f$$

$$f = \frac{4.50 \times 10^{-19}}{6.63 \times 10^{-34}} = 6.79 \times 10^{14} \text{ Hz}$$

Comparing Emission and Absorption Line of the same Element

If we consider that the energy transitions of the electrons are fixed to certain discrete changes in energy then only specific frequencies/colours are possible for emission and absorption. Therefore the colours seen in emission spectra **must** be the same as those seen to be missing from absorption spectra. These act like finger prints in identifying elements, particularly in astronomy.



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**, and re-emitted in random directions, thus reducing the **intensity of those frequencies** traveling outward from the sun.

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