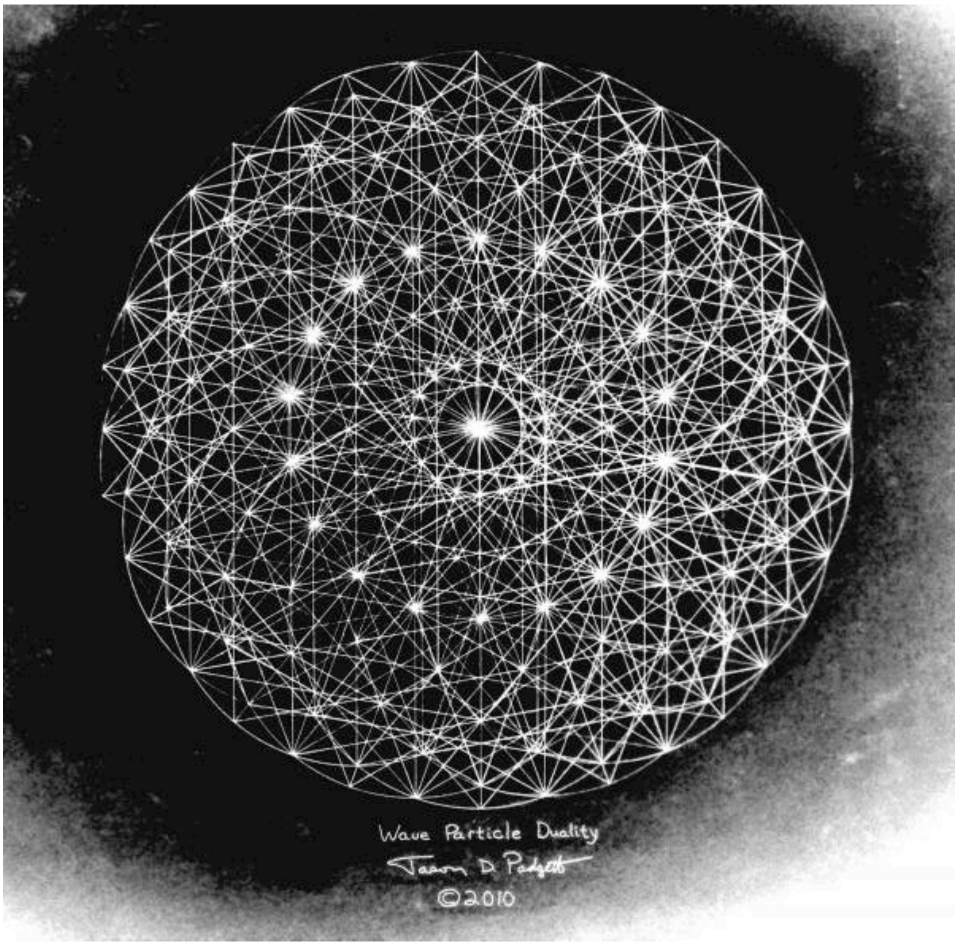
HIGHER PHYSICS

Particles and waves



http://images.fineartamerica.com/images-medium/wave-particle-duality-ii-jason-padgett.jpg

Part 2 - Waves

HIGHER PHYSICS

4 WAVE PARTICLE DUALITY

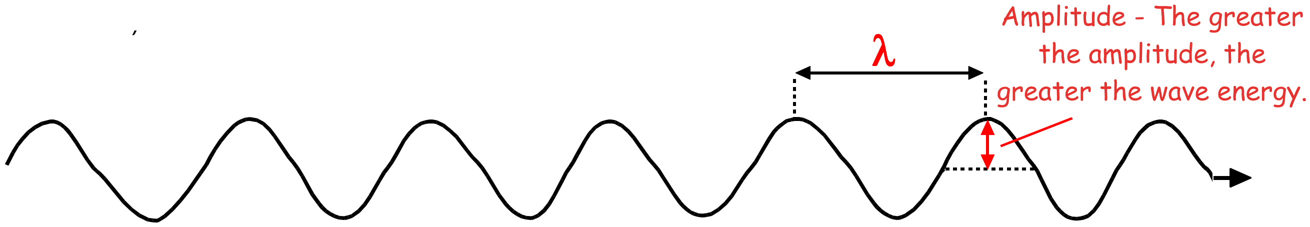
Can you talk about:

a) 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.

CLASSICAL WAVE THEORY

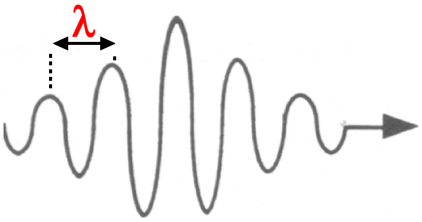
Electromagnetic energy (such as light) behaves as a **continuous wave** - It can be **reflected**, **refracted** and **diffracted**. More importantly, it can produce **interference** (which is the test for wave motion).



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

Such a continuous electromagnetic wave has a **velocity** (**v**) of 3 x 10^8 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.



A photon of electromagnetic 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**:

http://www.toonpool.com/user/1080/files/einstein_with_tongue_out_463225.jpg
http://images.wikia.com/ed/images/0/0d/Plank.png

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 x 10^8 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**):

$$E \propto f \qquad \text{or} \qquad E = \text{constant} \times f$$

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

$$\mathbf{E = h\,f}$$

energy of photon (unit: J)

frequency of photon (unit: Hz)

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

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 $f = \frac{v}{\lambda} = \frac{3\times10^{8}}{589\times10^{-9}} = \underline{5.09\times10^{14}\ \text{Hz}}$.

(b) $E = hf = (6.63\times10^{-34}) \times (5.09\times10^{14})$
$= \underline{3.37\times10^{-19}\ \text{J}}$.

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 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**.

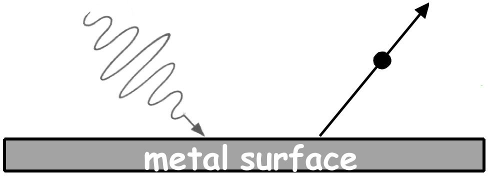
THRESHOLD FREQUENCY (f_0)

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

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 = energy of photon - work function of metal



work function = hf_0

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

$$h\,f = hf_0 + 1/2\ m\,v^2$$

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

f: frequency of photon

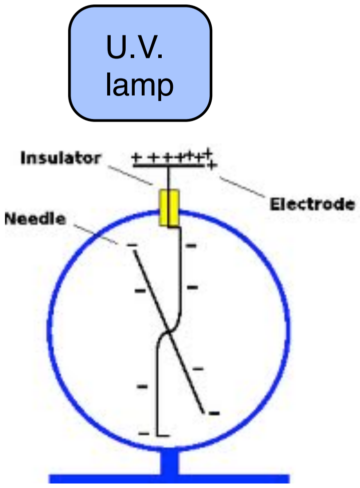
h: Planck's constant = 6.63×10^{-34} Js

f_0: threshold frequency (minimum frequency photon must have to eject electron)

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

v: maximum velocity of 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.

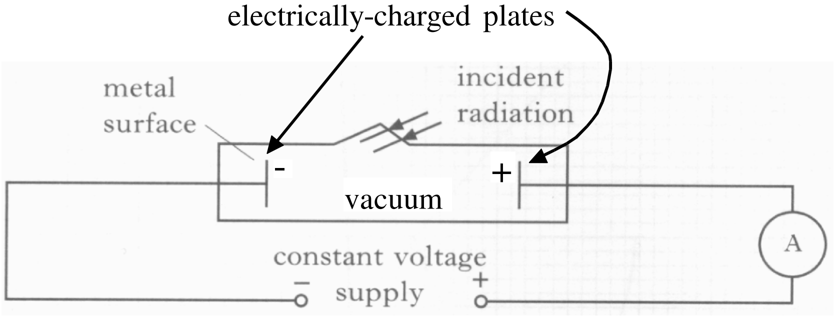
If **white light** (which contains photons of all 7 colours of the visible spectrum- red, orange, yellow, green, blue, indigo and violet) is shone onto the zinc plate, the needle does not fall. Photons of these colours of light do not have high enough energy to eject electrons from the zinc surface -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

Below a certain frequency [the threshold frequency (fo)], 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 (fo), 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 directly proportional to the irradiance of the radiation.

HIGHER PHYSICS

5) INTERFERENCE and DIFFRACTION

Can you talk about:

a) 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.

b) 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.

c) 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**.

WAVES - An Introduction

Waves carry energy from one place to another.
Waves can be classified as mechanical or electromagnetic.

WAVES

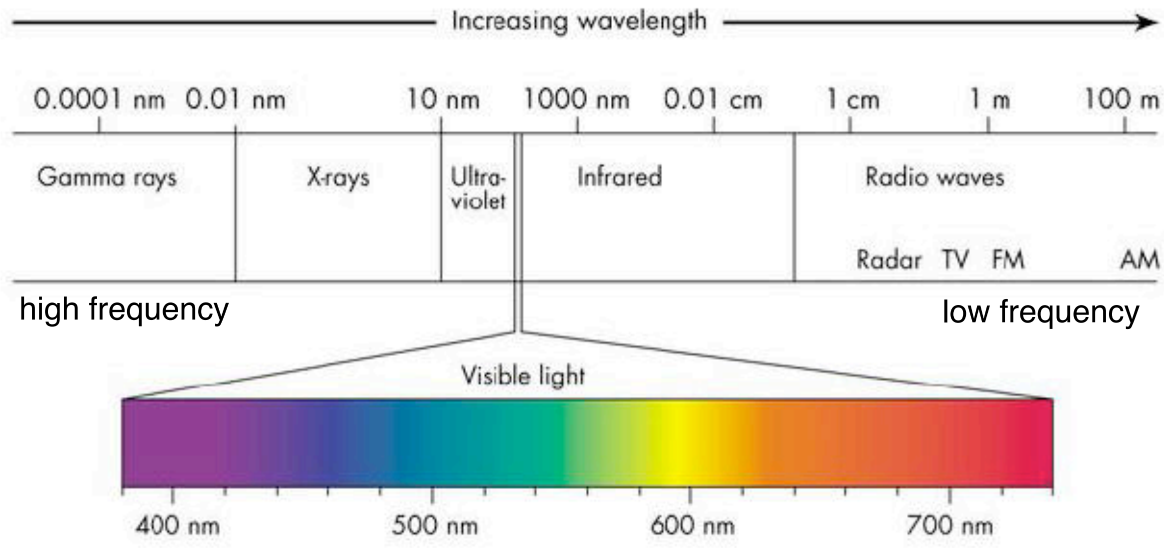
Mechanical Waves

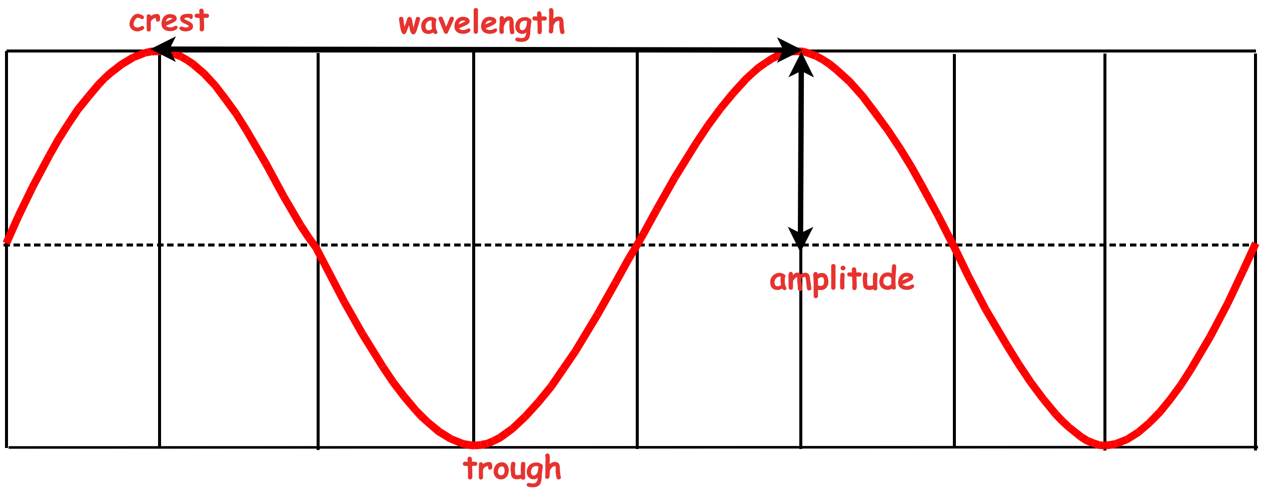
These are produced by a disturbance (such as a **vibrating object**) in a material and are transmitted by the particles of the material vibrating to and fro about a fixed point.
These waves can often be seen or felt - For example, **water waves**, **waves on a spring** and **sound waves** in various 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 **3×10^8 ms^{-1}**.

The electromagnetic spectrum





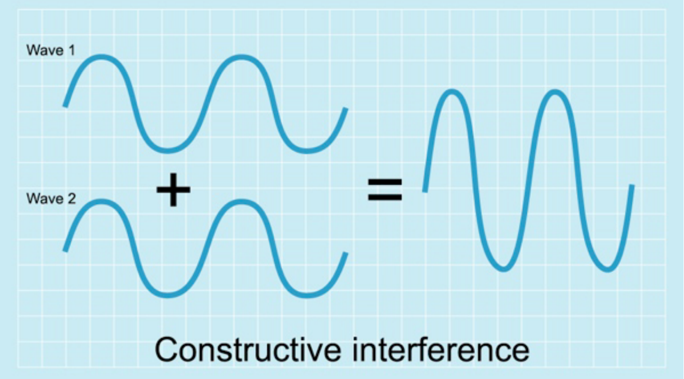
THE FREQUENCY OF A WAVE NEVER CHANGES AFTER THE WAVE LEAVES THE SOURCE

Interference of Waves

When 2 waves meet, they overlap/combine - This is known as **interference**.
There are 2 types of **interference**:

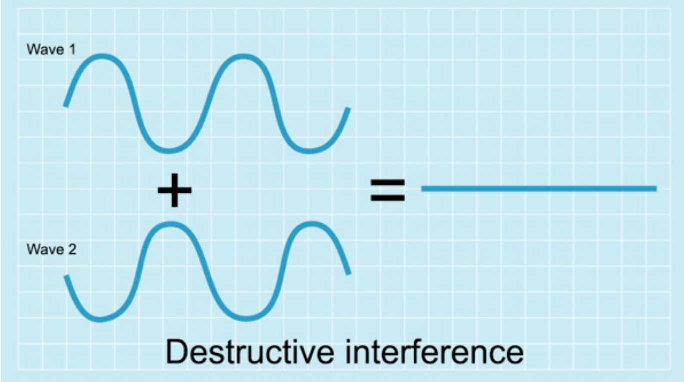
Constructive Interference

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



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.



http://astro-canada.ca/_en/_illustrations/a4313_interference_en_g.jpg

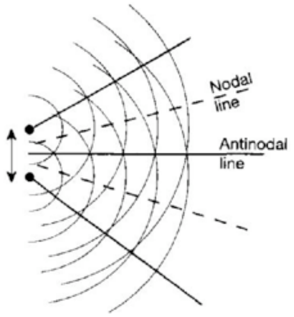
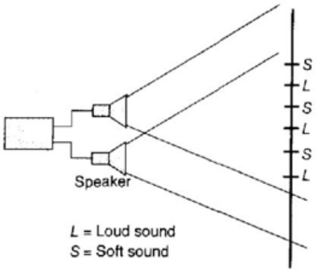
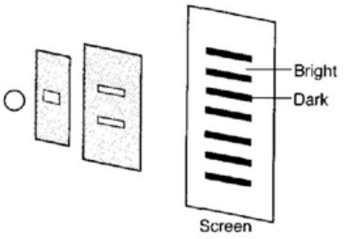
Destructive Interference -The test for wave motion

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 **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.

		
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, 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 = $m\lambda$

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

		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

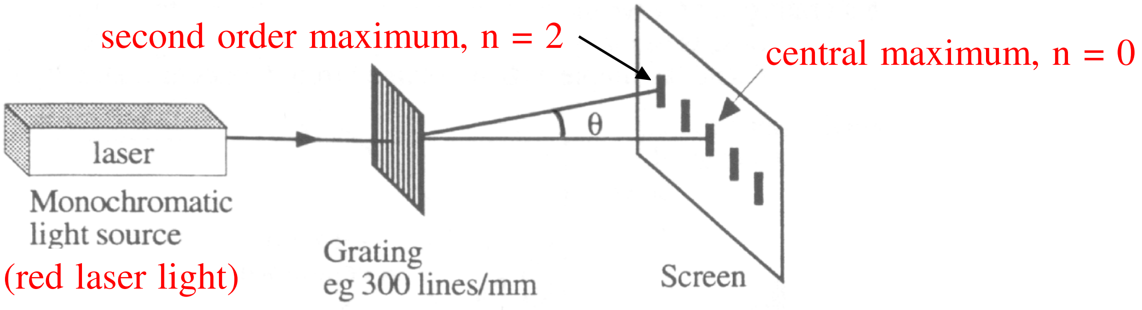
Diffraction Grating for the Interference of Light

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:

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

m = 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)

$M\lambda = D\ SIN\ \theta$

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°.

$m = 2.$

$\lambda = ?$

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

$\sin \theta = \sin 25° = 0.423$

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

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

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

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

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

To determine value for d in metres:

Grating has 300 slits (lines) per mm
= 300 x 1 000 = 300 000 slits per m

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

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

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 - towards the red end of the visible spectrum;**
2) **Decrease 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

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

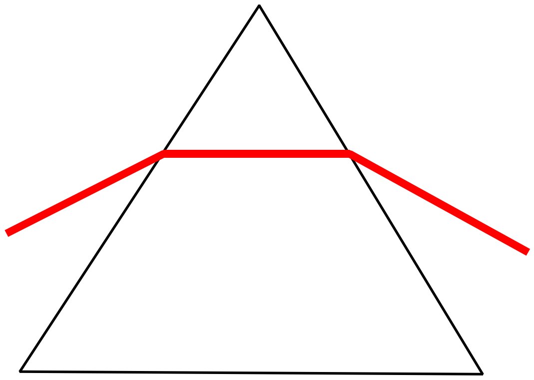
Wavelength of blue light = $4.9 \text{ x } 10^{-7}\text{m} = 490 \text{ nm}$
Wavelength of green light = $5.4 \text{ x } 10^{-7} \text{ m} = 540 \text{ nm}$
Wavelength of red light = $7.0 \text{ x } 10^{-7} \text{ m} = 700 \text{ nm}$

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

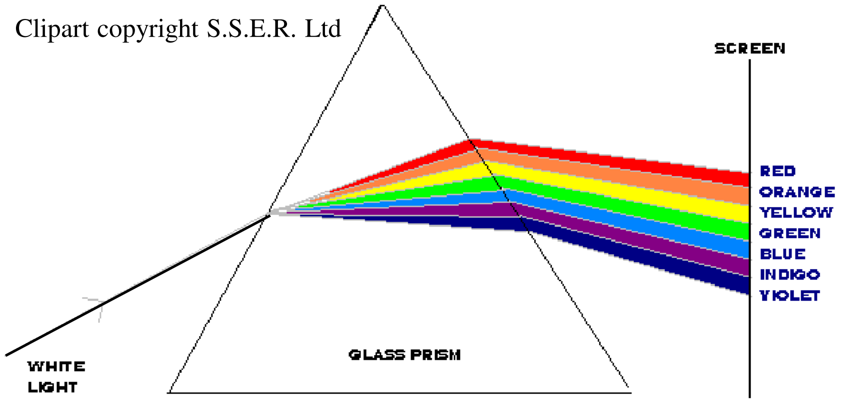
If you can't remember these values, similar values will be quoted in the data sheet you receive with your final exam paper - The data on this sheet refers to the wavelength of the red, green and blue spectral lines of the element cadmium.

Comparing White Light Spectra from Prisms and Gratings

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: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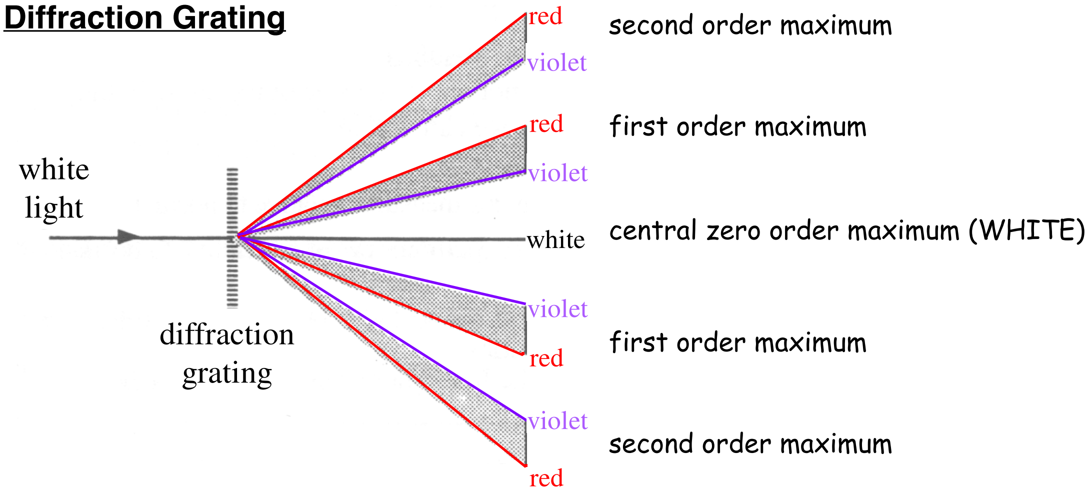
DISPERSION OF WHITE LIGHT BY A PRISM

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.

HIGHER PHYSICS

6) REFRACTION of LIGHT

Can you talk about:

a) Refraction

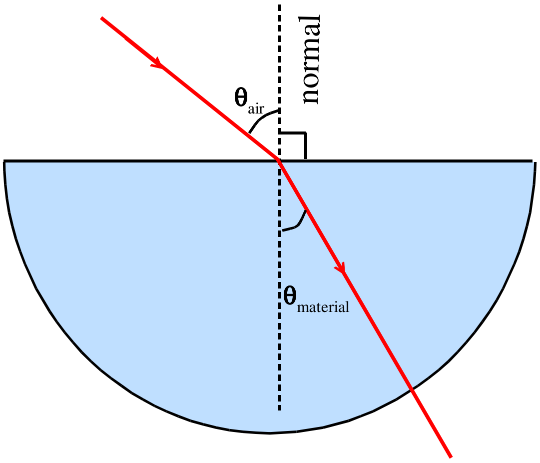
- **Refractive index** of a material as the **ratio** of the sine of **angle of incidence** in a vacuum (air) to the sine of **angle of refraction** in the material.
- Refractive index of **air** is treated as the same as that of a **vacuum**.
- Situations where light travels from a **more dense** to **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**.

b) Critical angle and total internal reflection

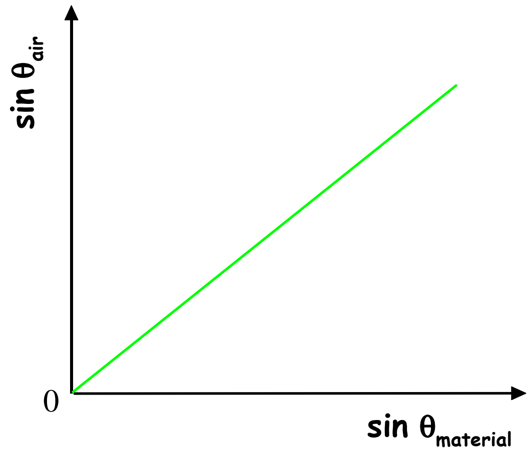
- Investigating **total internal reflection**, including **critical angle** and its relationship with **refractive index**.

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:

$$\sin\theta_{air} \;\alpha\; \sin\theta_{material}$$

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 :

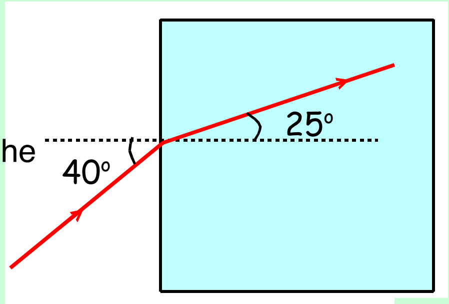
$$\text{refractive index (n)} = \frac{\sin\theta_{air}}{\sin\theta_{material}}$$

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 for each different wavelength of light (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

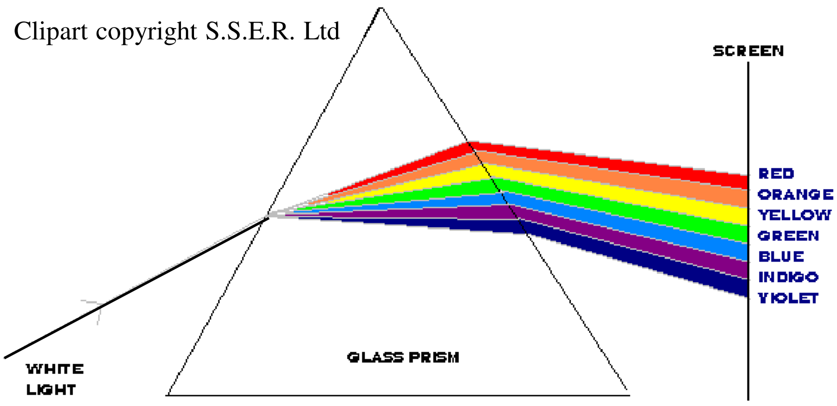
Calculate the refractive index of the glass block shown:



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

$$n = 1.52$$

Refractive Index and Frequency of Light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DISPERSION OF WHITE LIGHT BY A PRISM

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:

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

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

$$n = \frac{v_{\text{air}}}{v_{\text{material}}} \qquad 1.5 = \frac{3 \times 10^8}{v}$$

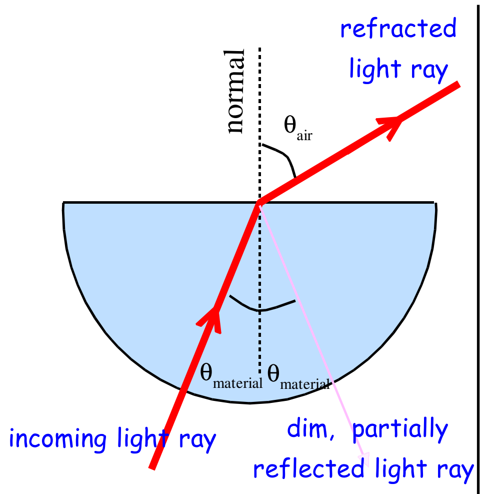
$$v = 2 \times 10^8 \text{ ms}^{-1}$$

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.

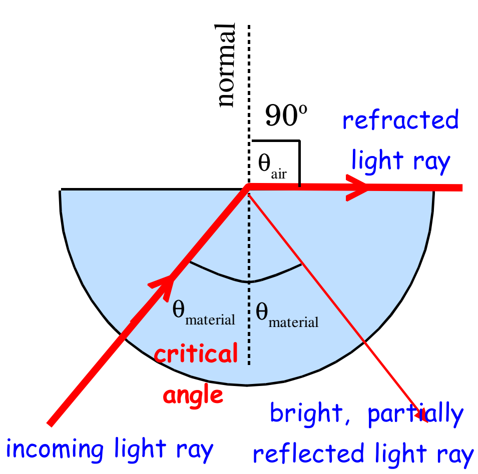
$$n = \frac{\lambda_{\text{air}}}{\lambda_{\text{material}}} \qquad 1.47 = \frac{700 \times 10^{-9}}{\lambda}$$

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

CRITICAL ANGLE and TOTAL INTERNAL REFLECTION

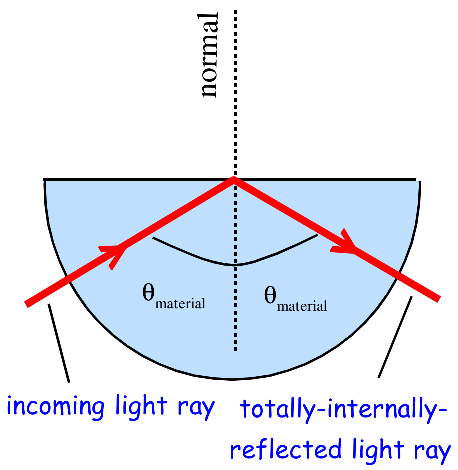


When a monochromatic light ray is passed from air into a semi-circular crown glass block at an angle of incidence close to the normal line, most of the light ray is **refracted** into the air at the flat surface. A small amount of the light is **reflected** back into the glass by the flat surface - the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



If the angle of incidence between the incoming light ray and the normal line is increased**,** 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.

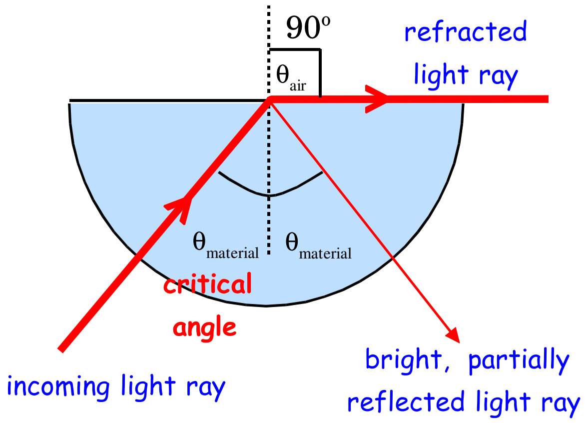


If the angle of incidence between the incoming light ray and the normal line is increased **above** the **critical angle**, **all** of the light ray is **reflected** back into the glass by the flat surface.

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), $\theta_{air} = 90°$.

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

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

7) SPECTRA

Can you talk about:

a) Irradiance and the inverse square law

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

b) 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.
- **Plank'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.

IRRADIANCE OF RADIATION

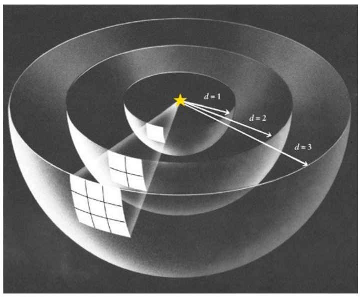
The **irradiance** of radiation striking a surface is the **power** of the radiation per **unit area** of the surface:

watts (W)

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

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

square metres (m^2)



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.

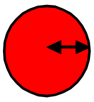
At any distance (**r**) from the source, the **irradiance** of light depends on the **surface area** of the light **sphere**.

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).

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



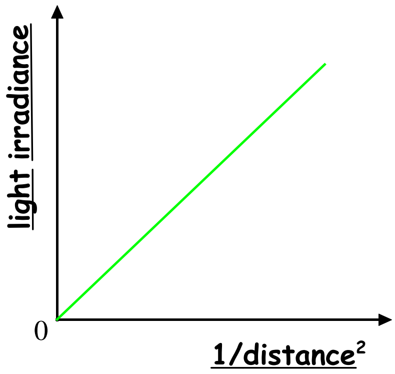
Cross-section of laser beam.
Radius = 0.0005 m.

$$= \frac{0.0001}{3.14 \text{ x } 0.0005^2} = 127 \text{ Wm}^{-2}$$

An irradiance of 127 Wm^{-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).

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

$$I_1d_1^2 = I_2d_2^2$$



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?

$I_1d_1^2 = I_2d_2^2$

$50 \text{ x } 0.52 = I_2 \text{ x} 0.72$

$12.5 = 0.49 \, I_2$

$I_2 = \frac{12.5}{0.49} = 25.5 \text{ Wm}^{-2}$

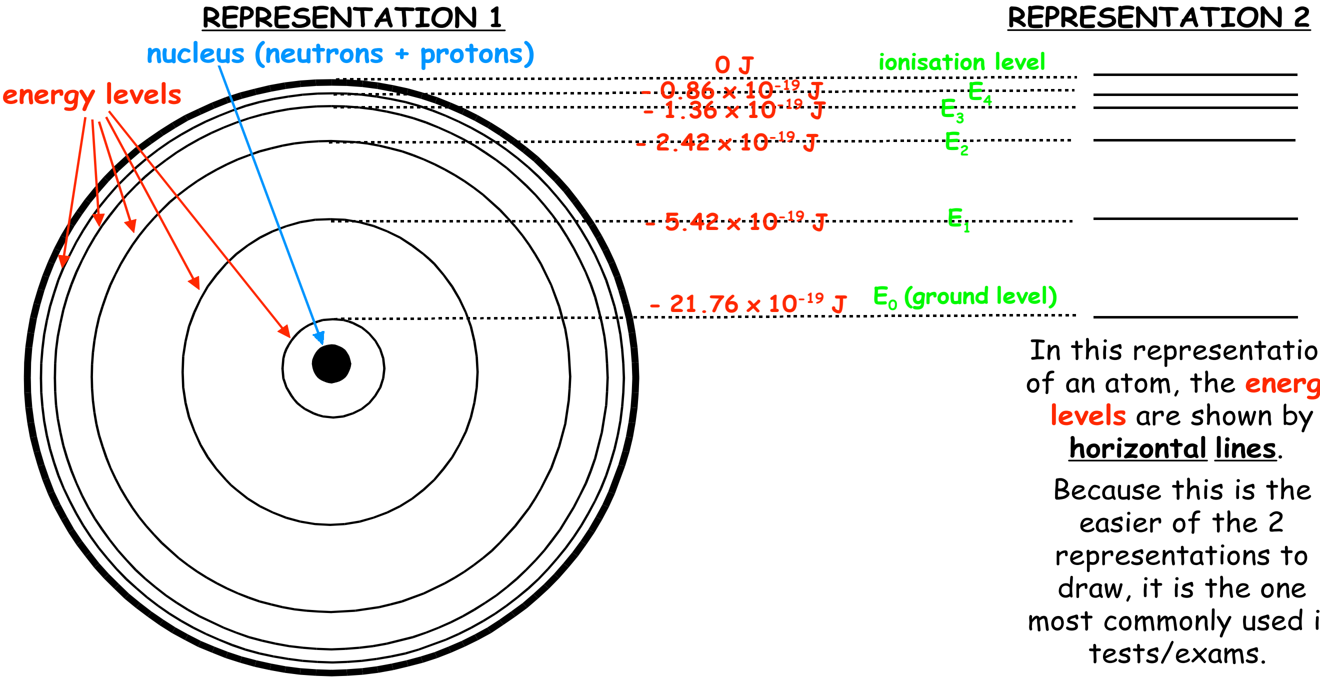
RUTHERFORD-BOHR MODEL OF THE ATOM

The **electrons** circle around 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**.

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**.

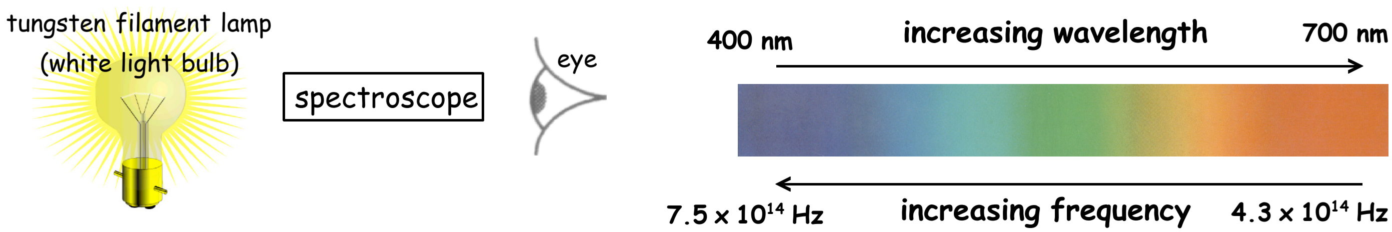
ATOMIC SPECTRA

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

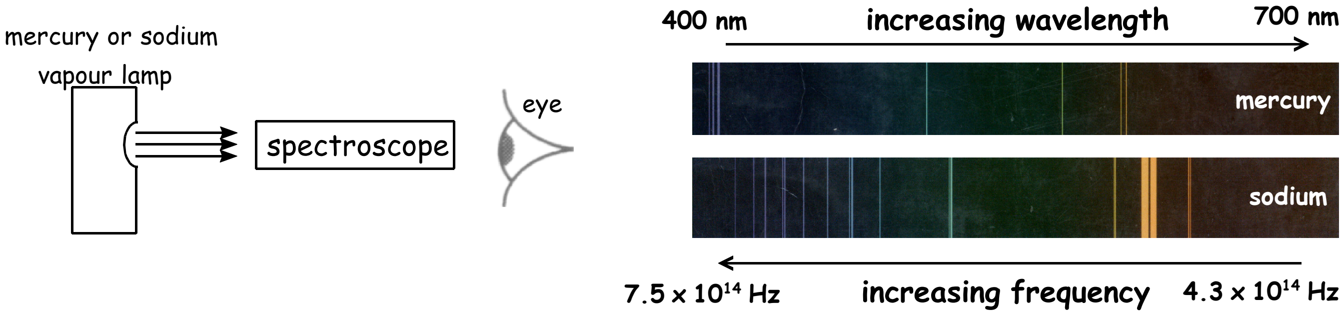
A tungsten filament lamp (a normal light bulb) emits **white light**. When the **white light** is passed through a spectroscope, a **continuous spectrum** is obtained. This contains all colours of the **visible spectrum:**



(b) Line Spectra

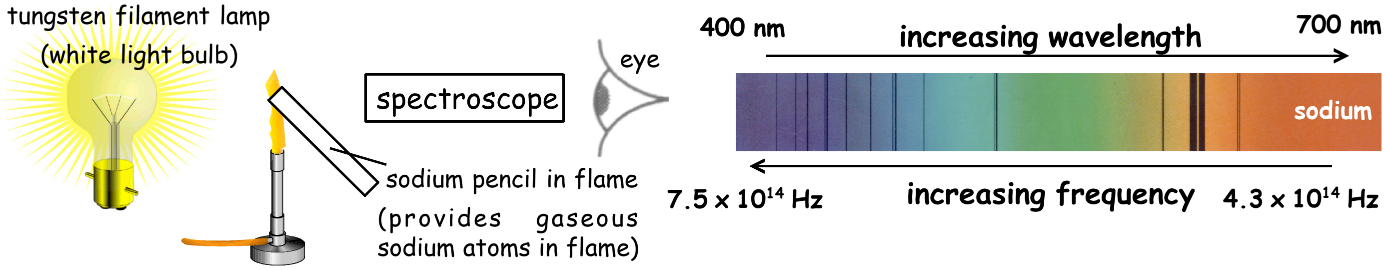
A **mercury vapour lamp** or **sodium vapour lamp** emits different photons of **specific frequency/wavelength** (and hence **colour). When the light is passed through a spectroscope, a series of different coloured lines on a black background is obtained. Each line occupies an exact position corresponding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



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.**

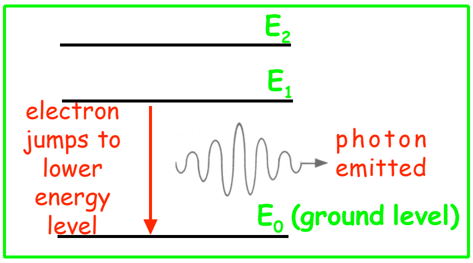
This equation applies:

$$\Delta E = h\ f$$

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

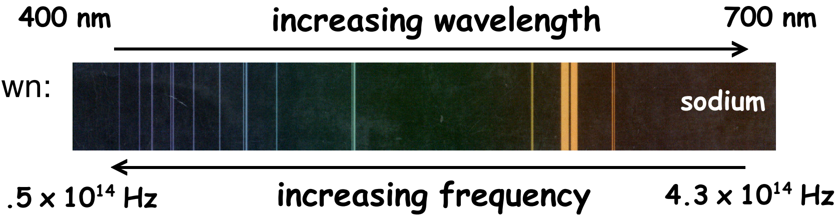
Planck's constant = 6.63×10^{-34} J s

frequency of photon emitted from atom



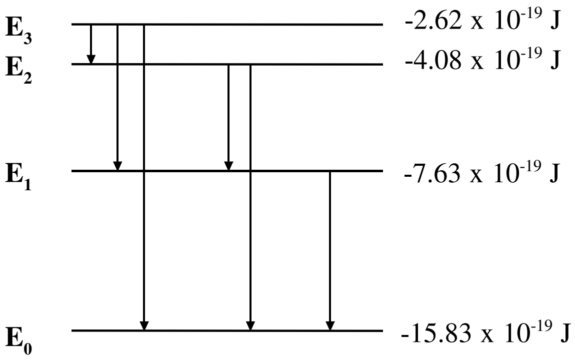
The emitted photon often has a frequency within the visible spectrum, so produces a coloured emission line in the atom's emission line spectrum. The photon may also have a frequency outwith the visible spectrum - in the infra-red or ultra-violet.

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. **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.

EXAMPLE

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.

$f = \Delta E/h$

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

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

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**.

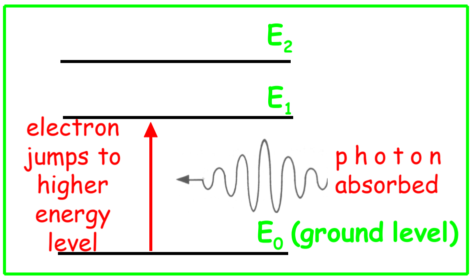
This equation applies:

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

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

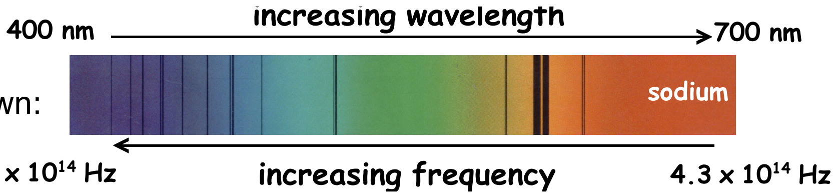
Planck's constant = 6.63×10^{-34} J s

frequency of photon absorbed by atom

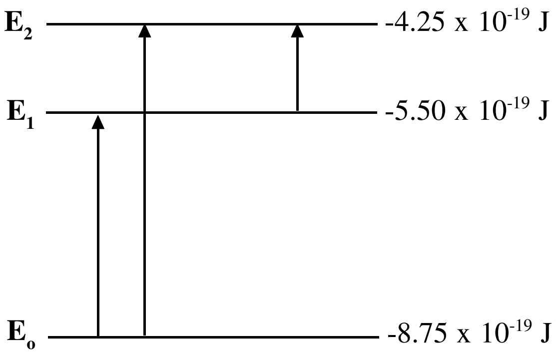


Various such electron transitions (jumps) of **different energy** are possible, provided **photons of suitable energy** are present to be **absorbed**.

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:



EXAMPLE

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

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

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

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

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

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.

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**.

Tutorial Questions

Section 4: Wave particle duality

Photoelectric effect

1. A 'long wave' radio station broadcasts on a frequency of 252 kHz.
   (a) Calculate the period of these waves.
   (b) What is the wavelength of these waves?

2. Green light has wavelength 546 nm.
   (a) Express this wavelength in metres (using scientific notation).
   (b) Calculate:
      (i) the frequency of these light waves
      (ii) the period of these light waves.

3. Ultraviolet radiation has a frequency $2{\cdot}0 \times 10^{15}$ Hz.
   (a) Calculate the wavelength of this radiation.
   (b) Calculate the period of this radiation.

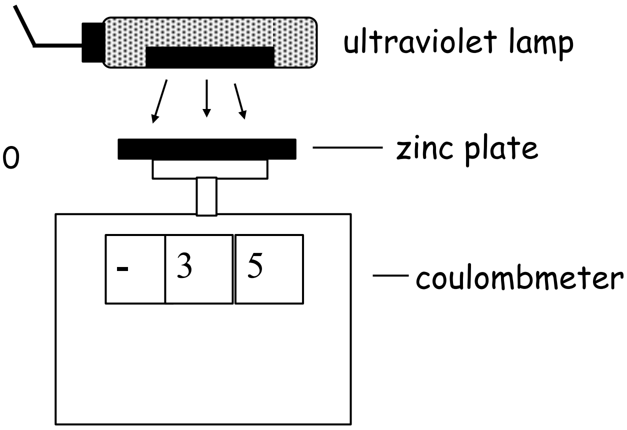
4. Blue light has a frequency of $6{\cdot}50 \times 10^{14}$ Hz. Calculate the energy of one photon of this radiation.

5. Red light has a wavelength of $6{\cdot}44 \times 10^{-7}$ m. Calculate the energy of one photon of this light.

6. A photon of radiation has an energy of $3{\cdot}90 \times 10^{-19}$ J. Calculate the wavelength of this radiation in nm.

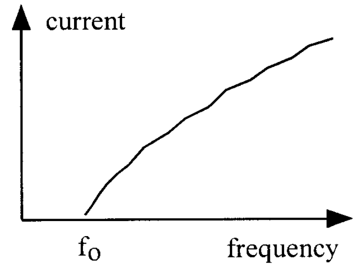
7. In an investigation into the photoelectric effect a clean zinc plate is attached to a coulombmeter, as shown.

   The threshold frequency of radiation for zinc is $6{\cdot}50 \times 10^{14}$ Hz.



   (a) The zinc plate is initially negatively charged.
   A lamp is used to shine ultraviolet radiation of frequency
   $6{\cdot}7 \times 10^{14}$ Hz onto the zinc plate.
   Describe and explain what happens to the reading on the coulombmeter.
   (b) The zinc plate is again negatively charged.
   Describe and explain the effect each of the following changes has on the reading on the coulombmeter:
      (i) moving the ultraviolet lamp further away from the zinc plate
      (ii) using a source of red light instead of the uv lamp. this has on the positive reading on the coulombmeter.
   (c) The zinc plate is now positively charged. The uv lamp is again used to irradiate the zinc plate. Describe and explain the effect

8. In a study of photoelectric currents, the graph shown was obtained.



(a) What name is given to the frequency f_o?
(b) Explain why no current is detected when the frequency of the incident radiation is less than f_o.

9. For a certain metal, the energy required to eject an electron from the atom is $3{\cdot}30 \times 10^{-19}$ J.

(a) Calculate the minimum frequency of radiation required to emit a photoelectron from the metal.
(b) Explain whether or not photoemission would take place using radiation of:
    (i) frequency 4×10^{14} Hz
    (ii) wavelength 5×10^{-7} m.

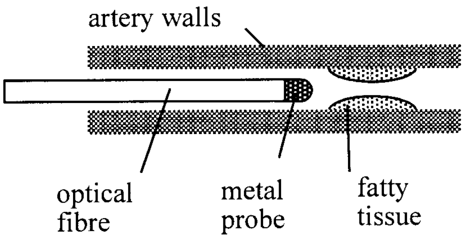
10. The minimum energy required to remove an electron from zinc is $6{\cdot}10 \times 10^{-19}$ J.

(a) What is the name is given to this minimum energy?
(b) Calculate the value of f_o for zinc.
(c) Photons with a frequency of $1{\cdot}2 \times 10^{15}$ Hz strike a zinc plate, causing an electron to be ejected from the surface of the zinc.
    (i) Calculate the amount of energy the electron has after it is released from the zinc.
    (ii) What kind of energy does the electron have after it is released?

11. Radiation of frequency $5{\cdot}0 \times 10^{14}$ Hz can eject electrons from a metal surface.

(a) Calculate the energy of each photon of this radiation.
(b) Photoelectrons are ejected from the metal surface with a kinetic energy of $7{\cdot}0 \times 10^{-20}$ J. Calculate the work function of this metal.

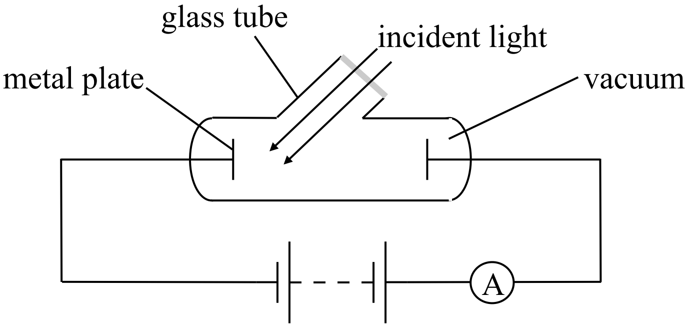
12. An argon laser is used in medicine to remove fatty deposits in arteries by passing the laser light along a length of optical fibre. The energy of this light is used to heat up a tiny metal probe to a sufficiently high temperature to vaporise the fatty deposit.



The laser has a power of 8·0 W. It emits radiation with a wavelength of 490 nm.

(a) How much energy is delivered from the laser in 5 s?
(b) Calculate the number of photons of this radiation required to provide the 5 s pulse of energy from the 8·0 W laser.

13. The apparatus shown is used to investigate photoelectric emission from a metal plate when electromagnetic radiation is shone on the plate. The irradiance and frequency of the incident radiation can be varied as required.



(a) Explain what is meant by 'photoelectric emission' from a metal.
(b) What is the name given to the minimum frequency of the radiation that produces a current in the circuit?
(c) A particular source of radiation produces a current in the circuit. Explain why the current in the circuit increases as the irradiance of the incident radiation increases.

14. State whether each of the following statements is true or false.

(a) Photoelectric emission from a metal occurs only when the frequency of the incident radiation is greater than the threshold frequency for the metal.

(b) The threshold frequency depends on the metal from which photoemission takes place.

(c) When the frequency of the incident radiation is greater than the threshold frequency for a metal, increasing the irradiance of the radiation will cause photoemission from the metal to increase.

(d) When the frequency of the incident radiation is greater than the threshold frequency for a metal, increasing the irradiance of the radiation will increase the maximum energy of the electrons emitted from the metal.

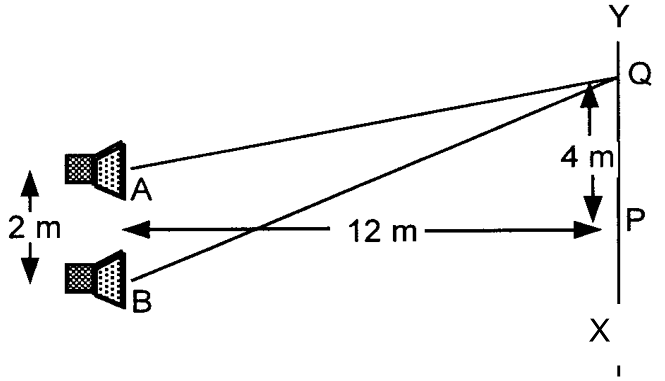
(e) When the frequency of the incident radiation is greater than the threshold frequency for a metal, increasing the irradiance of the incident radiation will increase the photoelectric current from the metal.

Section 5: Interference and diffraction

1. Explain how it is possible for interference to occur in the following situations:

   (a) a single loudspeaker emitting sound in a room with no other objects in the room
   (b) receiving radio reception in a car when passing large buildings.

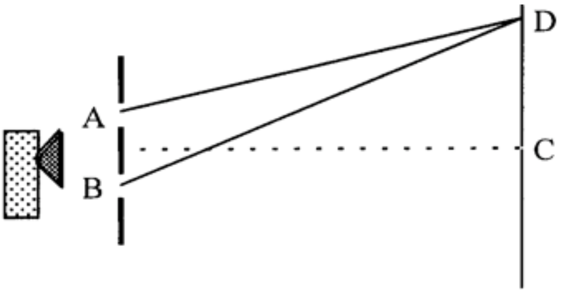
2. In an experiment on interference of sound, two loudspeakers A and B are connected in such a way that they emit coherent sound waves.



The loudspeakers are placed 2 m apart.
As a girl walks from X to Y she hears a point of maximum loudness at point P and the next maximum of loudness at point Q.

(a) Calculate the distances AQ and BQ.
(b) Calculate the wavelength of the sound.
(c) Calculate the frequency of the sound. (speed of sound in air is 330 ms^{-1})

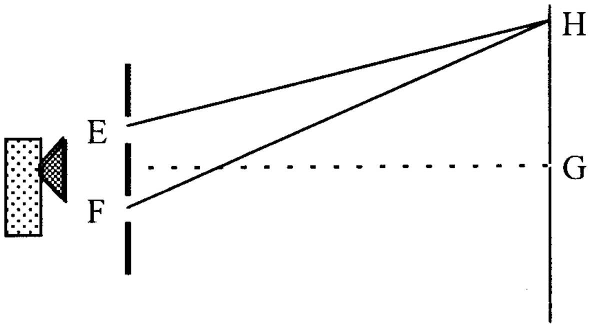
3. A microwave transmitter is placed in front of a metal plate that has two slits A and B as shown.



A microwave detector is moved along the line from C to D.
The zero- order maximum of radiation is detected at C and the first-order maximum is detected at D.
AD = 0·52 m and BD = 0·55 m.

(a) Calculate the path difference between paths AD and BD.
(b) What is the wavelength of the microwaves?
(c) Calculate the path difference from slits A and B to the second-order maximum.
(d) Calculate the path difference from slits A and B to the minimum of intensity between C and D.
(e) Calculate the path difference from slits A and B to the next minimum after D.
(f) What is the path difference from slits A and B to point C?

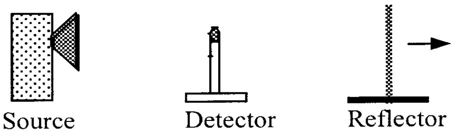
4. A microwave interference experiment is set up as shown.



E and F are two slits in a metal plate. A microwave detector is moved along the line GH. H is the second minimum from the straight through point at G. (This is sometimes called the first-order (m = 1) minimum, the first minimum being the zero order m = 0) Measurement of distances EH and FH gives: EH = 0·421 m and FH = 0·466 m.

Calculate the wavelength and frequency of the microwaves used.

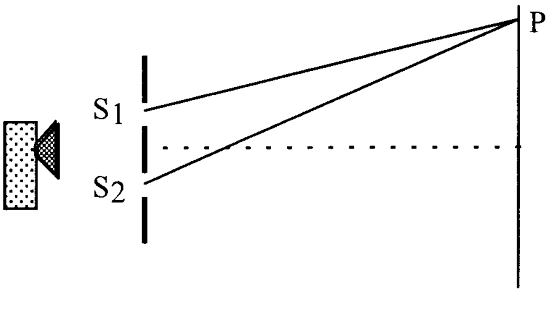
5. A microwave experiment is set up as shown.



The waves reflected from the metal reflector plate interfere with the incident waves from the source. As the reflector is moved away from the detector, a series of maxima and minima are recorded by the detector.
A maximum is found when the reflector is at a distance of 0·25 m from the detector. A further eight maxima are found as the reflector is moved to a distance of 0·378 m from the detector.

(a) Calculate the average distance between the maxima.
(b) Calculate the wavelength of the microwaves.
(c) Calculate the frequency of the microwaves.

6. A source of microwaves is placed in front of a metal sheet that has two slits S_1 and S_2 as shown.



A microwave detector shows a minimum at P. P is the position of the first-order minimum, ie it is the second minimum from the centre.
$S_1P = 0·421$ m $S_2P = 0·466$ m
Calculate the wavelength of the microwaves.

7. A grating has 400 lines per millimetre.
Calculate the spacing between the lines on this grating.

8. A grating with 600 lines per millimetre is used with a monochromatic source of light. The first-order maximum is produced at an angle of 20·5° to the straight through position.
   (a) Calculate the wavelength of the light from the source.
   (b) A grating with 1200 lines per millimetre is now used.
   Calculate the angle between the zero maximum and the new first-order maximum.

9. Light of wavelength 600 nm is shone onto a grating having 400, 000 lines per metre.
Calculate the angle between the zero maximum and first-order maximum.

10. Light of wavelength $6{\cdot}50 \times 10^{-7}$ m is shone onto a grating. The angle between the zero- and third-order maxima is 31.5°.

   (a) Calculate the spacing between the slits on the grating.
   (b) Calculate the number of lines per mm on the grating.

11. Light of wavelength 500 nm is used with a grating having 500 lines per millimetre.
Calculate the angle between the first- and second-order maxima.

12. White light, with a range of wavelengths from 440 nm to 730 nm, is shone onto a grating having 500 lines per millimetre. A screen is placed behind the grating.

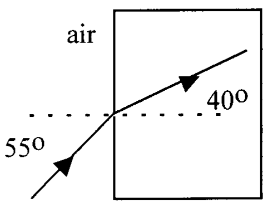
   (a) Describe the pattern seen on the screen.
   (b) Explain the type of pattern produced.
   (c) Calculate the angle between the extremes of the first-order maximum, ie the angle between violet and red.

13. A source of white light is set up in front of a grating. A green filter is placed between the source and the grating. The grating has 300 lines per millimetre.
A pattern of bright and dark bands is produced on a screen.

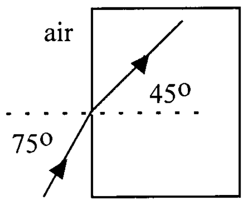
   (a) What is the colour of the bright bands produced on the screen?
   (b) Explain what happens to the spacing between the bright bands on the screen when each of the following changes is made:
      (i) using a blue filter instead of a green filter
      (ii) using a grating with 600 lines per millimetre
      (iii) using a source producing a greater irradiance of light
      (iv) moving the screen closer to the grating.

Section 6: Refraction of light

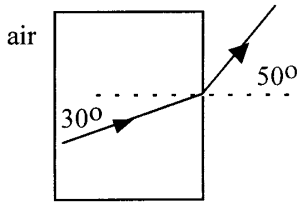
1. A ray of monochromatic light passes from air into rectangular blocks of different materials A, B and C as shown.



material A



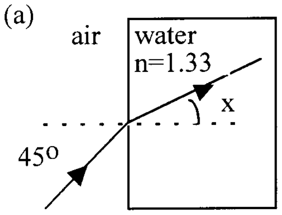
material B

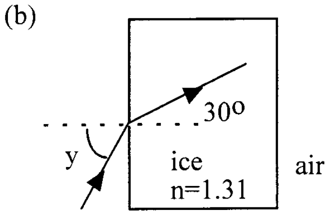


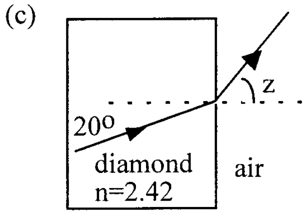
material C

Calculate the refractive index n of each of the materials for this light.

2. A ray of monochromatic light passes from air into a thin glass walled container of water, a rectangular block of ice and a rectangular block of diamond as shown in the diagrams.





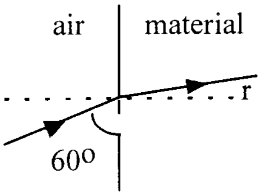


Calculate the values of the angles x, y and z in each of the diagrams.

3. A ray of monochromatic light passes from air into a certain material as shown.

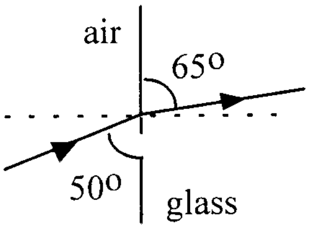
The refractive index of the material is 1·35.

(a) Calculate the value of angle r.
(b) Calculate the velocity of the light in the material.

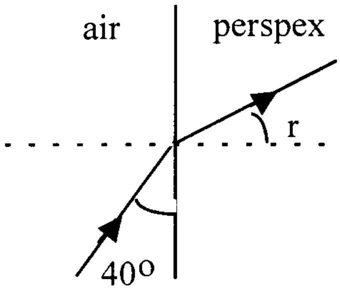


4. A ray of light of wavelength $6{\cdot}00 \times 10^{-7}$ m passes from air into glass as shown.

(a) Calculate the refractive index of the glass for this light.
(b) Calculate the speed of this light in the glass.
(c) Calculate the wavelength of this light in the glass.
(d) Calculate the frequency of this light in air.
(e) State the frequency of this light in the glass.



5. A ray of light of wavelength 500 nm passes from air into perspex.

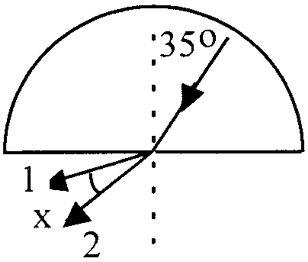


The refractive index of the perspex for this light is 1·50.

(a) Calculate the value of angle r.
(b) Calculate the speed of light in the perspex.
(c) Calculate the wavelength of this light in the perspex.

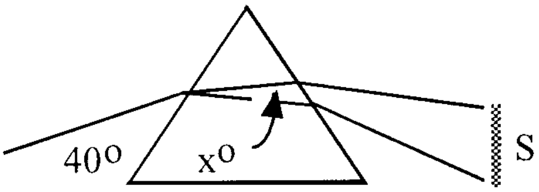
6. The refractive index for red light in crown glass is 1·513 and for violet light it is 1·532.

(a) Using this information, explain why white light can produce a spectrum when passed through crown glass.
(b) A ray of white light passes through a semi-circular block of crown glass as shown and produces a spectrum.



(i) Which exit ray is red and which exit ray is violet?
(ii) Calculate the angle of refraction in air for each of the exit rays.
(iii) Find angle x, the angle between the red and violet rays.

7. A ray of white light is dispersed, by a glass prism, producing a spectrum S.

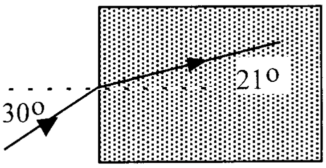


The angle x is found to be 0·7°.
The refractive index for red light in this glass is 1·51. Calculate the refractive index for blue light.

8. Calculate the critical angle for each material using the refractive n index given in the table below.

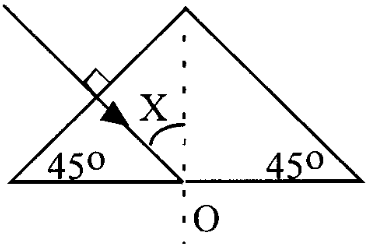
Material	**n**
Glass	1·54
Ice	1·31
Perspex	1·50

9. A beam of infrared radiation is refracted by a type of glass as shown.



(a) Calculate the refractive index of the glass for infrared.
(b) Calculate the critical angle of infrared radiation for this glass.

10. A ray of light enters a glass prism of absolute refractive index 1·52, as shown.



(a) Explain why the ray does not change direction on entering the glass prism.
(b) Calculate the value of angle X.
(c) Why does the ray undergo total internal reflection at O?
(d) Redraw the complete diagram showing the angles at O with their values.
(e) Explain what would happen when the experiment is repeated with a prism of material with refractive index 1·30.

11. The absolute refractive indices of water and diamond are 1·33 and 2·42, respectively.

(a) Calculate the critical angles for light in each of these materials when surrounded by air.
(b) Comment on the effect of the small critical angle of diamond on the beauty of a well-cut diamond.

Irradiance and inverse square law

1. A satellite is orbiting the Earth. The satellite has solar panels, with a total area of 15 m^2, directed at the Sun. The Sun produces an irradiance of 1·4 $kW\,m^{-2}$ on the solar panels. Calculate the power received by the solar panels.

2. A 100 W light source produces an irradiance of 0·2 $W\,m^{-2}$ at a distance of 2 m. The light source can be considered to be a point source. Calculate the irradiance produced at a distance of:

   (a) 1 m from the source
   (b) 4 m from the source.

3. An experiment is performed to measure the irradiance produced at different distances from a point source of light. The results obtained are shown in the table.

Distance from point source d /m	1·0	1·4	2·2	2·8	3·0
Irradiance I /$W\,m^{-2}$	85	43	17·6	10·8	9·4

   (a) Sketch the apparatus that could be used to obtain these results.
   (b) Use an appropriate format to show the relationship between the irradiance I and the distance d.
   (c) Calculate the irradiance at a distance of 5 m from the source.
   (d) At what distance from the source is the irradiance 150 $W\,m^{-2}$?

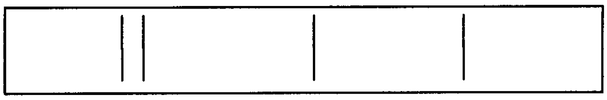
4. The radiation from the Sun produces an irradiance of 200 $W\,m^{-2}$ at a certain point on the surface of the Earth.

   (a) What area of solar cells would be required to produce a power output of 1 MW when the cells are considered to be 100% efficient?
   (b) The cells are only 15% efficient. What additional area of solar cells is required to produce a power output of 1 MW?

5. An experiment is set up in a darkened laboratory with a small lamp L1 with a power P. The irradiance at a distance of 0·50 m from the lamp is 12 $W\,m^{-2}$. The experiment is repeated with a different small lamp L2 that emits a power of 0·5 P. Calculate the irradiance at a distance of 0·25 m from this lamp.

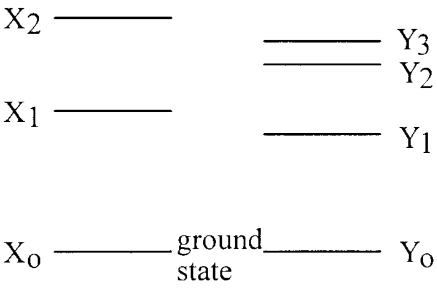
Line and continuous spectra

1. When the light emitted by a particular material is observed through a spectroscope, it appears as four distinct lines.



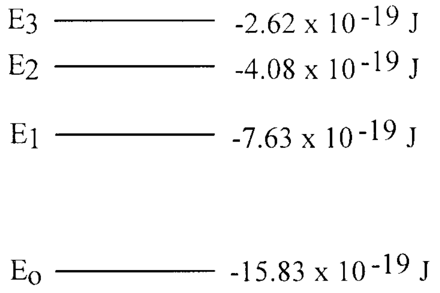
   (a) What name is given to this kind of emission spectrum?
   (b) Explain why a series of specific, coloured lines is observed.
   (c) The red line in the spectrum coincides with a wavelength of 680 nm. Calculate the energy of the photons of light that produced this line.
   (d) The spectroscope is now used to examine the light emitted from a torch bulb (filament lamp). What difference is observed in the spectrum when compared with the one in the diagram?

2. The diagram shows some of the energy levels for two atoms X and Y.



   (a) (i) How many downward transitions are possible between these energy levels of each atom?
       (ii) How many lines could appear in the emission spectrum of each element as a result of these energy levels?
       (iii) Copy the diagram of the energy levels for each atom and show the possible transitions.
   (b) Which transition in each of these diagrams gives rise to the emitted radiation of:
       (i) lowest frequency
       (ii) shortest wavelength?

3. The diagram shows some of the electron energy levels of a particular element.



(a) How many lines could appear in the emission spectrum of this element as a result of these levels?

(b) Calculate the frequencies of the photons arising from:

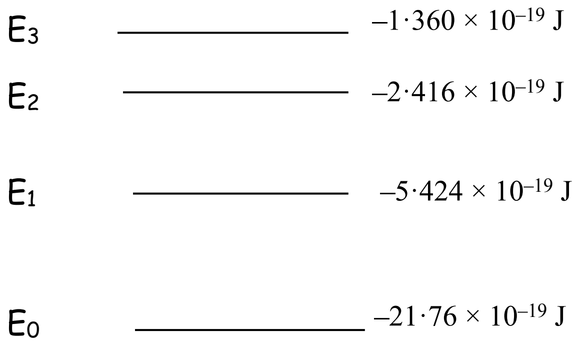
  (i) the largest energy transition

  (ii) the smallest energy transition.

  (iii) Show whether any of the emission lines in the spectrum correspond to frequencies within the visible spectrum.

  (iv) Explain which transition would produce the photons most likely to cause photoemission in a metal.

4. The diagram shows some of the electron energy levels in a hydrogen atom.



(a) How many emission lines are possible from electron transitions between these energy levels?

(b) Which of the following radiations could be absorbed by the electrons in a hydrogen atom?

  (i) frequency $2{\cdot}92 \times 10^{15}$ Hz

  (ii) frequency $1{\cdot}57 \times 10^{15}$ Hz

  (iii) wavelength $4{\cdot}89 \times 10^{-7}$ m.

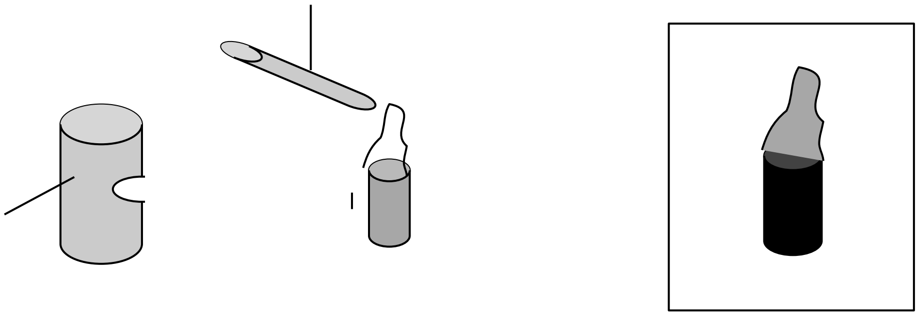
5. Explain why the absorption spectrum of an atom has dark lines corresponding to frequencies present in the emission spectrum of the atom.

6. (a) Explain the presence of the Fraunhofer lines, the dark lines that appear in the spectrum of sunlight.

(b) How are Fraunhofer lines used to determine the gases that are present in the solar atmosphere?

7. The light from a star can be analysed to show the presence of different elements in the star. How can the positions of the spectral lines for the elements be used to determine the speed of the star?

8. A bunsen flame is placed between a sodium vapour lamp and a screen as shown. A sodium 'pencil' is put into the flame to produce vaporised sodium in the flame.



(a) Explain why a dark shadow of the flame is seen on the screen.
(b) The sodium vapour lamp is now replaced with a cadmium vapour lamp. Explain why there is now no dark shadow of the flame on the screen.

Solutions

Section 4: Wave particle duality

Photoelectric effect

1. (a) $3{\cdot}97 \times 10^{-6}$ s (b) $1{\cdot}19 \times 10^{3}$ m

2. (a) $5{\cdot}46 \times 10^{-7}$ m (b) (i) $5{\cdot}49 \times 10^{14}$ Hz (ii) $1{\cdot}82 \times 10^{-15}$ s

3. (a) $1{\cdot}5 \times 10^{-7}$ m (b) $5{\cdot}0 \times 10^{-16}$ s

4. $4{\cdot}31 \times 10^{-19}$ J

5. $3{\cdot}09 \times 10^{-19}$ J

6. 510 nm

9. (a) $4{\cdot}98 \times 10^{14}$ Hz

10. (b) 9.20×10^{14} Hz (c) (i) 1.86×10^{-19} J ¶

11. (a) $3{\cdot}3 \times 10^{-19}$ J (b) $2{\cdot}6 \times 10^{-19}$ J

12. (a) 40 J (b) $9{\cdot}9 \times 10^{19}$

Section 5: Interference and diffraction

2. (a) AQ = 12·4 m, BQ = 13 m (b) 0·6 m (c) 550 Hz

3. (a) $3{\cdot}0 \times 10^{-2}$ m (b) $3{\cdot}0 \times 10^{-2}$ m (c) $6{\cdot}0 \times 10^{-2}$ m
(d) $1{\cdot}5 \times 10^{-2}$ m (e) $7{\cdot}5 \times 10^{-2}$ m (f) 0 m

4. Wavelength = $3{\cdot}0 \times 10^{-2}$ m Frequency = $1{\cdot}0 \times 10^{10}$ Hz

5. (a) 0·016 m (b) $3{\cdot}2 \times 10^{-2}$ m (c) $9{\cdot}4 \times 10^{9}$ Hz

6. 0·03 m

7. $2{\cdot}5 \times 10^{-6}$ m

8. (a) $5{\cdot}84 \times 10^{-7}$ m (b) 44·5°

9. 13·9°

10. (a) $3{\cdot}73 \times 10^{-6}$ m (b) 268

11. 15·5°

12. (c) 8·7°

Section 6: Refraction of light

1. material A n = 1·27 material B n = 1·37 material C n = 1·53

2. (a) x = 32·1° (b) y = 40·9 ° (c) z = 55·9 °

3. (a) 21·7 ° (b) $2{\cdot}2 \times 10^{8}$ ms^{-1}

4. (a) 1·52 (b) $1{\cdot}97 \times 10^{8}$ ms^{-1} (c) $3{\cdot}95 \times 10^{-7}$ m
(d) $5{\cdot}0 \times 10^{14}$ H (e) $5{\cdot}0 \times 10^{14}$ Hz

5. (a) 30·7° (b) 2.00×10^{8} ms^{-1} (c) 3.33×10^{-7} m

6. (b) (ii) ray 1 = 61·49°, ray 2 = 60·20° (iii) 1·29°

7. 1·54

8. glass = 40·5° ice = 49·8° perspex = 41·8° ¶

9. (a) 1·4 (b) 45·6° ¶

10. (b) 45°

11. (a) water = 48·8° diamond = 24·4°

Section 7: Spectra

Irradiance and inverse square law

1. 21 kW

2. (a) 0·8 Wm^{-2} (b) 0·05 Wm^{-2}

3. (c) 3·4 Wm^{-2} (d) 0·75 m

4. (a) 5000 m^2 (b) 28333 m^2

5. 24 Wm^{-2}

Line and continuous spectra

1. (c) $2{\cdot}93 \times 10^{-19}$ J

2. (a) (i) X 3; Y 6 (ii) X 3; Y 6
   (b) (i) X_2 to X_1: Y_3 to Y_2 (ii) X_2 to X_o; Y_3 to Y_o

3. (a) 6 lines
   (b) (i) $2{\cdot}0 \times 10^{15}$ Hz (ii) $2{\cdot}2 \times 10^{14}$ Hz

4. (a) 6 lines