

Unit 2: Particles and Waves



Summary Notes Part 1

Refraction

Have you ever wondered why a straight stick appears bent when partially immersed in water; the sun appears oval rather than round when it is about to set or the pavement shimmers on a hot summer's day? Could you explain why diamonds sparkle or how a rainbow is formed? These are some of the effects caused by the refraction of light as it passes at an angle from one medium to another. In this section we will study refraction and its applications.



Refraction

Refraction is the property of light which occurs when it passes from one medium to another. While in one medium the light travels in a straight line. Light, and other forms of electromagnetic radiation, do not require a medium through which to travel.

Light travels at its greatest speed in a vacuum. Light also travels at almost this speed in gases such as air. The speed of any electromagnetic radiation in space or a vacuum is 3.00×10^8 m s⁻¹.

Whenever light passes from a vacuum to any other medium its speed decreases. Unless the light is travelling perpendicular (90°) to the boundary between the media this then results in a change in direction.

It is the change in the speed of the light that causes refraction. The greater the change in speed, the greater the amount of refraction.

Media such as glass, perspex, water and diamond are optically more dense than a vacuum. Air is only marginally more dense than a vacuum when considering its optical properties.



Refractive Index

If we carry out the experiment below;



We find that the graph gives a straight line. This shows that sin $\theta 1 / \sin \theta 2 = k$

This constant is known as the *refractive index* and is given the symbol n

<u>sin θ1 / sin θ2 = n</u>

The absolute refractive index of a material, n, is the refractive index of that material compared to the refractive index of a vacuum. The absolute refractive index of a vacuum (and therefore also air) is 1.0.

Snell's Law:

 $n_1 \sin \theta_1 = n_2 \sin \theta_2$

Where medium 1 is a vacuum or air, and therefore $n_1 = 1.0$, this simplifies to:

 $\sin \theta_1 = n_2 \sin \theta_2$ or $n = \frac{Sin\theta_1}{Sin\theta_2}$ (remember only when θ_1 is in air)

If the refraction occurs between any 2 mediums though we can still use;

 $n_1 \sin \theta_1 = n_2 \sin \theta_2$ which when rearranged gives;

$$\frac{\sin\theta_1}{\sin\theta_2} = \frac{n_1}{n_2}$$

Measuring the Refractive Index of Glass

The refractive index of glass can be measured by directing a ray of light through optical blocks and measuring the appropriate angles in the glass and the surrounding air.



Refractive Index and Frequency

The frequency of a wave is determined by the source that makes it. It must remain unchanged as it moves through different materials, i.e. the same number of peaks and troughs, otherwise it would no longer be the same wave.

However, we know that the speed of the wave changes so, given the relationship $v = f\lambda$, the wavelength of the wave must be changing. If we consider a wave moving from air to glass then frequency of wave in air = frequency of wave in glass.

Since $f = v/\lambda$ this can be written as

 $v_1/\lambda_1 = v_2/\lambda_2$

Rearranging gives

 $v_1/v_2 = \lambda_1/\lambda_2$

This can be equated to the relationship we found in the last lesson. So,

$$\frac{n_2}{n_1} = \frac{\sin\theta_1}{\sin\theta_2} = \frac{\lambda_1}{\lambda_2} = \frac{\nu_1}{\nu_2}$$

Example

Calculate the speed of light in glass of refractive index 1.50.

Solution

$$v_1/v_2 = n_2/n_1$$

3 x 10⁸/ $v_2 = 1.5/1$
 $v_2 = 3 x 10^8 / 1.5$
 $= 2 x 10^8 ms^{-1}$

Dependence of Refraction on Frequency

The refractive index of a medium depends upon the frequency (colour) of the incident light.

We saw in the last topic that when light enters a glass prism, it separates into its component colours and produces a spectrum. This happens because each frequency (colour) is refracted by a different amount.

Since violet is refracted more than red it follows that the refractive index for violet light must be greater than the refractive index for red light.



Critical Angle and Total Internal reflection

When light travels from a medium of high refractive index to one of lower refractive index (e.g. glass into air), it bends away from the normal. If the angle within the medium θ_i is increased, a point is reached where the refracted angle, θ_r , becomes 90_o.



How to measure the Critical Angle.

Apparatus: Ray box and single slit, 12 V power supply, semicircular perspex block, sheet of white paper, protractor



Instructions

1. Place the block on the white paper and trace around its outline. Draw in the normal at the midpoint B.

2.Draw a line representing the angle θ_i = 10°, the line AB in the diagram above.

3.Draw a line representing the angle $\theta_i = 60^\circ$, the line DB in the diagram above.

4. Direct the raybox ray along AB and gradually rotate the paper so that the ray moves from 10° to 60°.

5. Stop moving the paper when the refracted ray emerges at 90° to the normal. Mark the incident ray at which this happens.

6.Continue to move the paper and note what happens to the ray beyond this point.

If the angle in the medium is greater than the critical angle, then no light is refracted and **Total Internal Reflection** takes place within the medium.



Most of incident lightLight refirefracted into air.PartiallyWeak, partially reflected ray.stronger.



Partially reflected ray stronger.

No light refracted into air. All light reflected back into medium. Total internal reflection occurs.

Deriving the critical angle At the critical angle, $\theta m = \theta c$ and $\theta a = 90^{\circ}$ $\frac{\sin \theta_a}{\sin \theta_m} = \frac{\sin 90^{\circ}}{\sin \theta_c} = \frac{1}{\sin \theta_c}$ $n = -\frac{1}{\sin \theta_c}$ $\vdots \theta_a = 90^{\circ}$ $\boxed{\theta_m}$ The mean of the product of the pr

For angles of incidence less than the critical angle some reflection and some refraction occur. The energy of the light is split along two paths.

For angles of incidence greater than the critical angle only reflection occurs, i.e. total internal reflection, and all of the energy of the light is reflected inside the material.



Fibre Optics

An optical fibre uses the principle of total internal reflection. The rays of light always strike the internal surface of the glass at an angle greater than the critical angle. A commercial optical fibre has a fibre core of high refractive index surrounded by a thin, outer cladding of glass with lower refractive index than the core. This ensures that total internal reflection takes place.



Diamonds

The critical angle from glass to air is about 42° but it varies from one medium to another. The material with the smallest critical angle (24.4°) is diamond. That is why they sparkle so much!

As most rays of light will strike the diamond at an angle greater than it's critical angle, rays of light car easily be made to totally internally reflect inside by careful cutting of the stone. The refraction at the surfaces then splits the light into a spectrum of colours!

Waves Revision

Area to look over!!! Amplitude, wavelength, crests and troughs, Period of a wave, Frequency, Wave speed, Reflection, refraction and Diffraction.

Phase

Phase and Coherence

Two points on a wave that are vibrating in exactly the same way, at the same time, are said to be **in phase**, e.g. two crests, or two troughs.

Two points that are vibrating in exactly the opposite way, at the same time, are said to be **exactly out of phase**, or **180° out of phase**, e.g. a crest and a trough



Coherent Sources

Two sources that are oscillating with a constant phase relationship are said to be **coherent**. This means the two sources also have the same frequency. Interesting interference effects can be observed when waves with a similar amplitude and come from coherent sources meet



Interference of water waves

If two point sources produce two sets of circular waves, they will overlap and combine to produce an interference pattern. The semicircular lines represent crests; the troughs are between the crests.



The points of constructive interference form waves with larger amplitude and the points of destructive interference produce calm water. The positions of constructive interference and destructive interference form alternate lines which spread out from between the sources. As you move across a line parallel to the sources, you will therefore encounter alternate large waves and calm water.







Constructive interference occurs when:

path difference = $m\lambda$ where m is an integer



- c) The student stands at a point 4.76 m from loudspeaker and 5.78 m from the other loudspeaker. State the loudness of the sound heard by the student at that point. Justify your answer.
- d) Explain why it is better to conduct this experiment in a large room rather than a small room

Solution

a) The student hears a series of loud and quiet sounds due to interference of the two sets of sound waves from the loudspeakers. When the two waves are in phase there is constructive interference and when the two waves are exactly out of phase there is destructive interference

b)
$$v = f\lambda$$

 $340 = 500 \times \lambda$

λ = <u>0·68 m</u>

c) Path difference = 5.78 - 4.76 = 1.02 m

Number of wavelengths = $1.02/0.68 = 1.5\lambda$

A path difference of 1.5λ means the waves are exactly out of phase. The student hears a quiet sound.
d) In a small room, sound waves will reflect off the walls and therefore other sound waves will also interfere with the waves coming directly from the loudspeakers.

Thomas Young

In 1801, Young devised and performed an experiment to measure the wavelength of light. It was important that the two sources of light that form the pattern be coherent. The difficulty confronting Young was that the usual light sources of the day (candles, lanterns, etc.) could not serve as coherent light sources. Young's method involved using sunlight that entered the room through a pinhole in a window shutter. A mirror was used to direct the pinhole beam horizontally across the room. To obtain two sources of light, Young used a small paper card to break the single pinhole beam into two beams, with part of the beam passing by the left side of the card and part of the beam passing by the right side of the card. Since these two beams emerged from the same source - the sun - they could be considered coming from two coherent sources. Light waves from these two sources (the left side and the right side of the card) would interfere. The interference pattern was then projected onto a screen where measurements could be made to determine the wavelength of light.

Today's classroom version of the same experiment is typically performed using a laser beam as the source. Rather than using a note card to split the single beam into two coherent beams, a carbon-coated glass slide with two closely spaced etched slits is used. The slide with its slits is most commonly purchased from a manufacturer who provides a measured value for the slit separation distance - the **d** value in Young's equation. Light from the laser beam diffracts through the slits and emerges as two separate coherent waves. The interference pattern is then projected onto a screen where reliable measurements can be made for a given bright spot with order value **m**. Knowing these values allows a student to determine the value of the wavelength of the original light source.



Thomas Young's Double Slit Experiment



Young's Double Slit Experiment

In 1801 Thomas Young showed that an interference pattern could be produced using light. At the time this settled the long running debate about the nature of light in favour of light being a wave.



Passing light from the lamp through the single slit ensures the light passing through the double slit is coherent. An interference pattern is observed on the screen.



The path difference between S_1P and S_2P is one wavelength.

As the wavelength of light λ is very small the slits separation d must be very small and much smaller than the slits to screen distance D. Angle θ between the central axis and the direction to the first order maximum is therefore very small. For small angles $\sin \theta$ is approximately equal to $\tan \theta$, and the angle θ itself if measured in radians.

Hence from the two similar triangles:

From triangle BAN:
$$\theta = \frac{\lambda}{d}$$
 also from triangle PMO: $\theta = \frac{\Delta x}{D}$
Thus $\frac{\Delta x}{D} = \frac{\lambda}{d}$ or $\Delta x = \frac{\lambda D}{d}$

Giving the fringe separation between adjacent fringes Δx

$$\Delta x = \frac{\lambda D}{d}$$

To produce a widely spaced fringe pattern:

- (a) Very closely separated slits should be used since $\Delta x \propto 1/d$.
- (b) A long wavelength light should be used, i.e. red, since $\Delta x \propto \lambda$.

(Wavelength of red light is approximately 7.0×10^{-7} m, green light approximately 5.5×10^{-7} m and blue light approximately 4.5×10^{-7} m.)

(c) A large slit to screen distance should be used since $\Delta x \propto D$.

The Grating

A grating consists of many equally spaced slits positioned extremely close together. Light is diffracted through each slit and interference takes place in a similar fashion to the double slit we used when we investigated the interference of light. The advantage of the grating is that it has many more slits (up to 7500 per mm in our school set) so much more light is transmitted through and a clearer interference pattern is seen.



Gratings

A double slit gives a very dim interference pattern since very little light can pass through the two narrow slits. Using more slits allows more light through to produce brighter and sharper fringes.



As in Young's Double Slit Experiment the first order bright fringe is obtained when the path difference between adjacent slits is one wavelength λ .

Therefore:

$$\sin\theta_1 = \frac{\lambda}{d}$$
 and $\lambda = d\sin\theta_1$

The second order bright fringe is obtained when the path difference between adjacent slits is two wavelengths 2λ .

Therefore:

 $\sin\theta_2 = \frac{2\lambda}{d}$ and $2\lambda = d\sin\theta_2$

The general formula for the mth order spectrum is: $m\lambda = d \sin \theta$

Where;

m = order of the maximum

- λ = wavelength of light
- d = separation of slits
- θ = angle from zero order to mth maximum.

Gratings and White Light It is possible to use a grating to observe the interference pattern obtained from a white light source. Since white light consists of many different frequencies (wavelengths), the fringe pattern produced is not as simple as that obtained from monochromatic light. Screen zero order central white fringe first order spectrum White second order spectrum light Grating (symmetrical on other source e.g. 300 lines/mm side of central maximum) Each fringe appears as a visible spectrum, apart from the central white fringe. Red is deviated the most, violet is deviated the least. The central fringe is white because at that position, the **path difference** for all wavelengths present is zero, therefore all wavelengths will arrive in phase. The central fringe is therefore the same colour as the

The first maximum occurs when the **path difference** is 1λ . Since blue light has a shorter wavelength than red light, the path difference will be smaller, so the blue maximum will appear closer to the centre. Each colour will produce a maximum in a slightly different position and so the colours spread out into a

source (in this case, white).

spectrum.

These effects can also be explained using the formula $m\lambda = d\sin\theta$. If d and m are fixed, the angle θ depends on the wavelength. So, for any given fringe number, the red light, with a longer wavelength, will be seen at a greater angle than the blue light. The higher order spectra overlap.



Irradiance and the Inverse Square Law

The irradiance of light / is defined as the amount of light energy incident on every square metre of a surface per

second. The equation for irradiance is therefore: $I=\frac{E}{At}$ This can be reduced to: $I=\frac{P}{A}$ Where: I = irradiance in W m⁻²
P = power in watts

A = area in m^2

Example;

A light bulb of power 100 W illuminates an area of 12 m². What is the irradiance of light hitting the area?

- Solution
- I = P/AI = 100 / 12I = 8.3 Wm⁻²

Why does irradiance matter?

An understanding of irradiance is relevant to a range of applications. For example, NASA monitors solar irradiance to understand the activity of the Sun and climate scientists study solar irradiance to research the impact of solar activity on the Earth's climate.

Interactions between solar radiation and the atmosphere of the Earth can impact on air quality, and understanding of irradiance can allow investigation of the composition of the Earth's atmosphere.

Excessive exposure to sunlight has been linked to the development of a range of skin cancers.

The performance of solar cells, an increasingly common use of solar radiation as an energy resource, requires an understanding of irradiance.

Irradiance and Laser Light

Light from a laser

- is monochromatic (one frequency)
- is coherent
- is irradiant
- forms a parallel beam.

Because the beam is intense and parallel, it is a potential hazard to the eye.

A laser of power 0.1 mW forming a beam of radius 0.5 mm produces a light intensity given by

$I = P/A = 0.1 \times 10^{-3} / \pi r^2 = 0.1 \times 10^{-3} / 7.85 \times 10^{-7} = 127 \text{ Wm}^{-2}$

An irradiance of this size is high enough to cause severe eye damage. It is far higher than the irradiance of light produced by a filament lamp.

Investigating irradiance

The relationship between irradiance of a point source and the distance from that source can be investigated using a simple experimental set up.

Activity

Aim: To investigate the variation of irradiance with distance from a point source of light.

Apparatus: 12 V power supply, 12 V lamp, light detector and meter, metre stick.



Instructions

- 1. Darken the room. Place the light detector a distance from the lamp.
- 2. Measure the distance from the light detector to the lamp and the intensity of the light at this distance.
- 3. Repeat these measurements for different distances between detector and lamp.
- 4. Plot a graph of light intensity against distance from the lamp.
- 5. Consider this graph and your readings and use an appropriate format to find the relationship between the light intensity and distance from the lamp.



This is described as an *inverse square law*.



Under certain situations an electrically charged object can be made to discharge by shining electromagnetic radiation at it. This can be best demonstrated by charging a device on which the charge stored can be measured, either a digital coulombmeter or a gold leaf electroscope. As charge is added to a gold leaf electroscope the thin piece of gold leaf rises up at an angle from the vertical rod to which it is attached.



It is found that the electroscope will only discharge if it is *negatively charged* and the incident light is of a sufficiently *high frequency*. What does this mean? *How do we explain our results*?

Well, the UV radiation is causing electrons to leave the metal, making it discharge. We call these electrons *photoelectrons*. We know that all electromagnetic waves deliver *energy* so if they deliver enough energy to a particular electron, surely that electron could use the energy to leave the metal surface.

So, why is that low frequency (long wavelength) radiation won't eject electrons but waves of higher frequency will. Wave theory says that *any* wave will deliver energy so surely if you shine *any* radiation onto the metal for long enough eventually enough energy will be delivered to allow electrons to leave. But this is not the case!

The effect can only be explained if we consider that electromagnetic radiation does not always behave like a wave - a smooth continuous stream of energy being delivered to a point. In this case you can only explain the effect if the radiation is behaving like packets of energy being delivered one by one. We call these packets of energy *quanta* or *photons*.

The idea that light could be delivered as packets of energy was initially put forward by Max Planck. Albert Einstein applied this theory to the photoelectric effect. It is for this work that he obtained the Nobel prize in 1921. Modern physics now takes the view that light can act both like a wave and like a particle without contradiction. This is known as *wave-particle duality*.

We can see that electrons are emitted if the following conditions are met:

- the radiation must have a high enough frequency (or short enough wavelength)
- the surface must be suitable the energy in UV radiation will not eject electrons from iron, copper, lead etc., but will from sodium and potassium, although these are a bit tricky to use!



Each photon has a frequency and wavelength associated with it just as a wave in the wave theory had. However, each photon has a particular energy that depends on its frequency, given by the equation below.

Where;

- E = energy of the photon (J)
- f = frequency of the photon (Hz)
- $h = Planck's constant = 6.63 \times 10{-}_{34} J s.$

From this equation it can be seen that the energy of each photon is directly proportional to its frequency. The higher the frequency the greater the energy.

Different frequencies of electromagnetic radiation can be directed at different types of charged metals. The metals can be charged either positively or negatively.

In most circumstances nothing happens when the electromagnetic radiation strikes the charged metal, for example the first two below. However, in a few cases, such as the third, a negatively charged metal can be made to discharge by certain high frequencies of electromagnetic radiation.



We can explain this **photoelectric effect** in terms of electrons within the metal being given sufficient energy to come to the surface and be released from the surface of the metal. The negative charge on the plate ensures that the electrons are then repelled away from the electroscope.

This cannot be explained by thinking of the light as a continuous wave. The light is behaving as if it were arriving in **discrete packets of energy** the value of which depends on the wavelength or **frequency** of the light. Einstein called these packets of energy **photons**.

The experimental evidence shows that photoelectrons are emitted from a metal surface when the metal surface is exposed to optical radiation of sufficient frequency. In the third case any photoelectrons which are emitted from the metal surface are immediately attracted back to the metal because of the attracting positive charge on the electroscope. The electroscope does not therefore discharge.

It is important to realise that if the **frequency** of the incident radiation is **not high enough** then no matter how great the **irradiance** of the radiation **no** photoelectrons are emitted. This critical or **threshold frequency**, f_o , is different for each metal. For copper the value of f_o is even greater than that of the ultraviolet part of the spectrum as no photoelectrons are emitted for ultraviolet radiation. Some metals, such as selenium and cadmium, exhibit the photoelectric effect in the visible light region of the spectrum.

One reason why different metals have different values of f_o is that energy is required to bring an electron to the metal surface and due to the different arrangements of atoms in different metals. Some metals will hold on to their electrons a little stronger than others. The name given to the small amount of energy required to bring an electron to the surface of a metal and free it from that metal is the **work function**.

Threshold frequency and work function

In general there is a minimum frequency of electromagnetic radiation required in order to eject electrons from a particular metal. This is called the *threshold frequency*, f_0 , and is dependent on the surface being irradiated.



Such an electron would escape but would have no kinetic energy. If the energy of the incoming electron, E = hf, is greater than the work function, then the extra energy will appear as kinetic energy of the electron.

$$E_k = E - E_o$$

 $E_k = hf - hf_o$

If a photon of incident radiation carries more energy than the work function value then the electron not only is freed at the surface but has "spare" kinetic energy and it can go places. An experiment can be carried out to demonstrate and quantify the photoelectric effect



Notice that the supply is opposing the electron flow

Initially with the supply p.d. set at 0 V, light of various wavelengths or frequencies is allowed to fall on the photocathode. In each case a small current is observed on the microammeter. The value of this current can be altered by altering the irradiance of the light as this will alter the number of photons falling on the cathode and thus the number of photoelectrons emitted from the cathode. In fact the photocurrent is directly proportional to the irradiance of the incident light - evidence that irradiance is related to the number of photons arriving on the surface

If when red light only is used the p.d. of the supply is slowly turned up in such a direction to oppose the electron flow, there comes a point when the p.d. is just sufficient to stop all the photoelectrons from reaching the anode. This is called the stopping potential for red. The photoelectrons are just not reaching the anode as they have not sufficient kinetic energy to cross the gap to the anode against the electric field. In fact their kinetic energy has all been turned to potential energy and they have come to rest.



If the red light is now replaced with violet light, and no other alterations are made, a current suddenly appears on the microammeter. This means that some electrons are now managing to get across from the cathode to the anode. Hence they must have started out their journey with more kinetic energy than those produced by red light. This means that photons of violet light must be carrying more energy with them than the photons of red light. No matter how strong the red light source is or how weak the violet light source the photons of violet light always "win".

If several experiments are done with photocells with different metal cathodes and in each case a range of different frequencies of light is used, graphs of maximum energy of photoelectrons against frequency of light can be plotted, as follows:



All metals are found to give straight line graphs which **do not** pass through the origin. However the gradient of each line is the same. This gradient is Planck's constant h.

The value of Planck's constant is 6.63×10^{-34} Js. The work function of the metal is the intercept on the energy axis.

From the straight line graph it can be seen that:

$$y = mx + c$$

$$E_k = mf + c$$

$$E_k = hf - W$$

Hence:

 $hf = W + E_k$

$$hf = hf_o + E_k$$

energy of absorbed photon = work function + kinetic energy of emitted electron.

or

Irradiance of photons

If N photons of frequency f are incident each second on each one square metre of a surface, then the energy per second (power) absorbed by the surface is:

$$P = \frac{E}{t} = \frac{\text{no of photons x energy of each photon}}{\text{time}} = \frac{N \times hf}{1} = Nhf$$

The irradiance, *I*, at the surface is given by the power per square metre.

$$I = \frac{P}{A} = \frac{N \times hf}{1} = Nhf$$
$$I = Nhf$$

Where;

- I = irradiance in W m^{-2}
- h = Planck's constant in J s
- f = frequency in Hz
- N = no of photons.

Note;

The energy transferred to the electrons depends *only* on the frequency of the photons. Higher irradiance radiation does not increase the velocity of the electrons; it produces *more* electrons of the same velocity.

Example;

A semiconductor chip is used to store information. The information can only be erased by exposing the chip to UV radiation for a period of time. The following data is provided. Frequency of UV used = 9.0×10^{14} Hz Minimum irradiance of UV radiation required at the chip = 25 Wm⁻²

Area of the chip exposed to radiation = $1.8 \times 10^{-9} \text{ m}^2$

Energy of radiation needed to erase the information = 40.5 mJ

a) Calculate the energy of a photon of the UV radiation used.

b) Calculate the number of photons of the UV radiation required to erase the information.

Solution

a)E = hf = 6.63 x 10^{-34} x 9.0 x 10^{14} = 5.967x 10^{-19} J

b) Energy of radiation needed to erase the information, $E_{total} = 40.5 \text{ mJ}$ $E_{total} = N(hf)$ $40.5 \times 10^{-6} = N \times 5.967 \times 10^{-19}$ $N = 40.5 \times 10^{-6} / 5.967 \times 10^{-19}$ $N = 6.79 \times 10^{13}$

Emission spectra

An emission spectrum is the range of colours given out (emitted) by a light source. There are two kinds of emission spectra: continuous spectra and line spectra. To view spectra produced by various sources, a spectroscope or spectrometer can be used.



Continuous spectra

In a continuous spectrum all frequencies of radiation (colours) are present in the spectrum. The continuous spectrum colours are red, orange, yellow, green, blue, indigo, violet.

CONTINUOUS SPECTRUM

Line spectra

Some sources of light do not produce continuous spectra when viewed through a spectroscope. They produce line spectra – coloured lines spaced out by different amounts. Only specific, well-defined frequencies of radiation (colours) are emitted.



Line Emission Spectra

A line spectrum is emitted by excited atoms in a low pressure gas. Each element emits its own unique line spectrum that can be used to identify that element. The spectrum of helium was first observed in light from the sun (Greek - helios), and only then was helium searched for and identified on Earth.

A line emission spectrum can be observed using either a spectroscope or a spectrometer using a grating or prism.



As with the photoelectric effect, line emission spectra cannot be explained by the wave theory of light. In 1913, Neils Bohr, a Danish physicist, first explained the production of line emission spectra. This explanation depends on the behaviour of both the electrons in atoms and of light to be quantised.

The electrons in a *free* atom are restricted to particular radii of orbits. A free atom does not experience forces due to other surrounding atoms. Each orbit has a discrete energy associated with it and as a result they are often referred to as energy levels.



The Bohr model is able to explain emission spectra as;

- electrons exist only in allowed orbits and they do not radiate energy if they stay in this orbit.
- electrons tend to occupy the lowest available energy level, i.e. the level closest to the nucleus.
- electrons in different orbits have different energies.
- electrons can only jump between allowed orbits. If an electron absorbs a photon of exactly the right energy, it moves up to a higher energy level.
- if an electron drops down from a high to a low energy state it emits a photon which carries away the energy, i.e light is emitted when electrons drop from high energy levels to low energy levels. The allowed orbits of electrons can be represented in an energy level diagram.

Energy level diagram



The electrons move between the energy levels by absorbing or emitting a photon of electromagnetic radiation with just the correct energy to match the gap between energy levels. As a result only a few frequencies of light are emitted as there are a limited number of possible energy jumps or transitions.

The lines on an emission spectrum are made by electrons making the transition from high energy levels (excited states) to lower energy levels (less excited states).



When the electron drops the energy is released in the form of a photon where its energy and frequency are related by the energy difference between the two levels. For example take an electron dropping from level two to one;

$$W_2 - W_1 = E = hf$$

From this calculation we can go on and work out the frequency of the emitted photon.



As we can see there are many different combination of gap between energy levels and as such there are numerous frequencies that can be emitted from one type of atom. From this we can say;

- The photons emitted may not all be in the visible wavelength.
- Only certain frequencies of light can be emitted from specific atoms.
- The larger the number of excited electrons that make a particular transition, the more photons are emitted and the brighter the line in the spectrum.



A hydrogen atom has only one electron. If the electron is given enough energy, it can escape completely from the atom. The atom is then said to be in an *ionisation state*.

The Continuous Spectrum

A continuous visible spectrum consists of all wavelengths of light from violet (~400 nm) to red (~700 nm). Such spectra are emitted by glowing solids (a tungsten filament in a lamp), glowing liquids or gases under high pressure (stars). In these materials the electrons are not *free*. The electrons are shared between atoms resulting in a large number of possible energy levels and transitions.

More about Spectra

Because each element has a different atomic structure, each element will produce a different line spectrum unique to that element. The line spectrum is a good way of identifying an element, a kind of 'atomic fingerprint'. Astronomers use this idea to identify elements in the spectrum of stars.

Most spectra contain bright lines and faint lines. This is because electrons sometimes favour particular energy levels. The transitions involving these energy levels will happen more often and hence lead to brighter lines in the emission spectrum, since more photons with that particular energy and frequency will be produced. How bright the line is depends on the number of photons emitted.

The energy to raise the electrons to the 'excited' higher levels can be provided in various ways:

- a high voltage, as in discharge tubes
- heat, as in filament lamps
- nuclear fusion, as in stars

Absorption Spectra

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



In practice it may be difficult to produce a line absorption spectrum. The apparatus below shows how to produce an absorption spectrum for a sodium flame.



White light from the compact light source is passed through a large lens and brought to a focus within a sodium flame. The light then passes through another lens and is brought to focus on the slit of a spectrometer. Viewing the spectrum produced through the spectrometer reveals a continuous spectrum with two black lines in the yellow region. This is the absorption spectrum of sodium. The black lines correspond to the position of the sodium D lines in the sodium emission spectrum. These lines correspond to the frequencies of the photons absorbed by the electrons within the sodium flame.



The energy absorbed by the electrons within the sodium flame will be emitted again as a photon of the same energy and frequency as the one absorbed, but it is highly unlikely that it will be emitted in the same direction as the original photon. Therefore the spectrum viewed through the spectrometer will show black absorption lines corresponding to the absorbed frequency of radiation.

Absorption Lines in Sunlight

The white light produced in the centre of the Sun passes through the relatively cooler gases in the outer layer of the Sun's atmosphere. After passing through these layers, certain frequencies of light are missing. This gives dark lines (Fraunhofer lines) that correspond to the frequencies that have been absorbed.



The lines correspond to the bright emission lines in the spectra of certain gases. This allows the elements that make up the Sun to be identified.

In summary

We have three types of spectrum;

- 1. Continuous, where there is a complete range of wavelength from Red to Violet created by sources such as tungsten lamps and stars
- 2. Emission, created by excited atoms in a low pressure gas. Each element emits its own unique line spectrum that can be used to identify that element.
- 3. Absorption, light passes through the a cooler gas and after passing through, certain frequencies of light are missing. This gives dark lines that correspond to the frequencies that have been absorbed.

