Wallace Hall Academy

CfE Higher Physics

Unit 2 - Waves
Notes

Name ____________________

Waves Revision

You will remember the following equations related to Waves from National 5.

d = vt **f = n/t** **v = fλ** **T=1/f**

They form an integral part of the Higher Waves topic and although they are not covered specifically in the course they do come up regularly in questions.

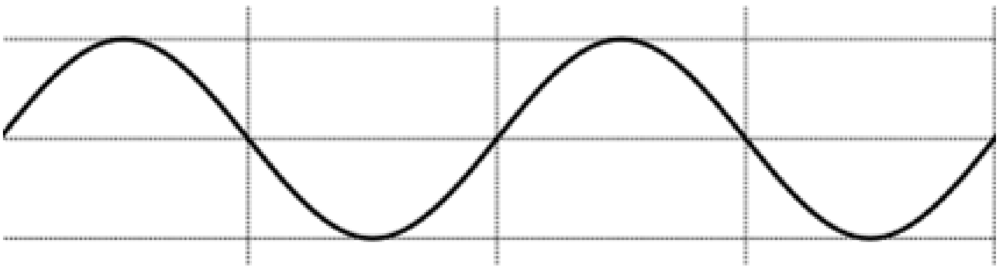
<u>Example 1</u>
A wave travels a distance of 20 m in 4 s at a frequency of 8 Hz. Calculate the wavelength of the wave.

<u>Solution</u>

<u>Example 2</u>
A wave has two crests which pass 3 s apart moving at a speed of 40 cms^{-1}. Calculate the wavelength of the wave.

<u>Solution</u>

It is also important that you are able to determine the wavelength and amplitude of a wave from a diagram.

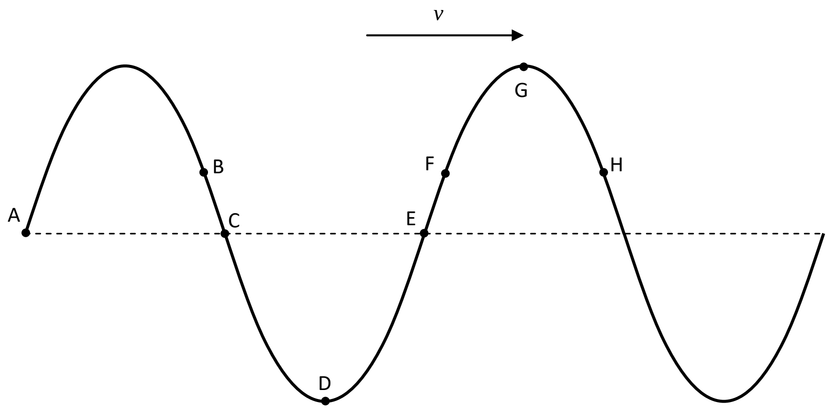


Phase, coherence and interference

Phase

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. e.g. a crest and a trough



Points ___ & ___ or ___ & ___ are in phase.

Points ___ & ___ or ___ & ___ or ___ & ___ are exactly out of phase.

Coherence

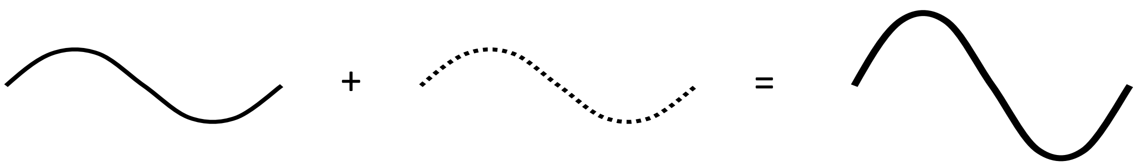
Two sources that are oscillating with a constant phase relationship are said to be coherent. This means the two sources also have the same frequency. Interesting interference effects can be observed when waves with a similar amplitude which come from coherent sources meet

Interference

Interference is the test for a wave. Many things can reflect, refract, diffract or disperse but only a wave can interfere. There are two types of interference that you need to know about, constructive and destructive.

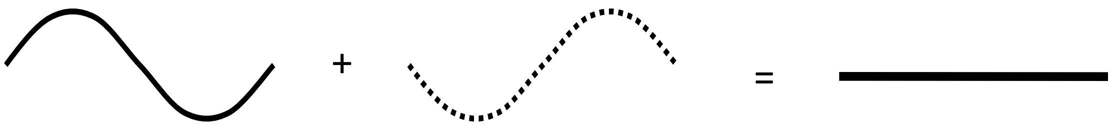
Constructive interference

When two waves meet in phase constructive interference occurs and a maxima is produced.



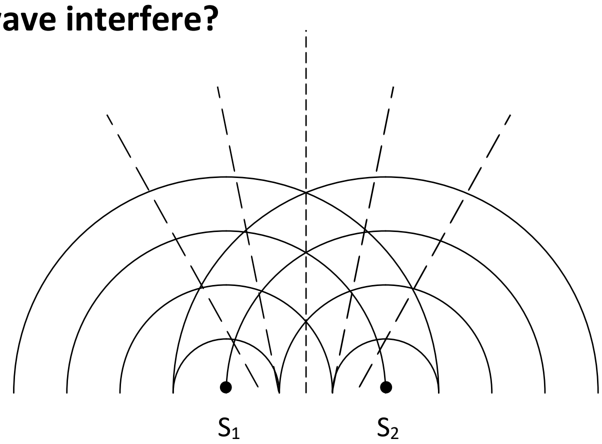
Destructive interference

When two waves meet exactly out of phase destructive interference occurs and a minima is produced.



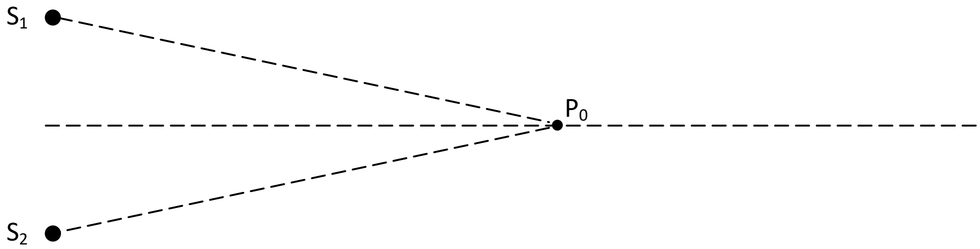
What types of wave interfere?

Interference is generally demonstrated by placing two coherent sources near each other. This can be done with two separate sources but is more commonly done by having one source and splitting it in two with a pair of slits as shown in the diagram. The solid lines indicate the crests of the waves coming from S_1 and S_2. The dotted lines indicate where constructive interference is occurring where the crests of the waves from the two sources meet.

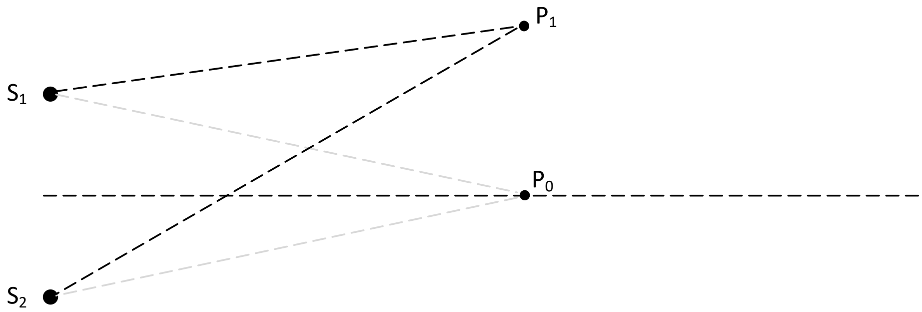


Microwave interference and path difference

Two sources S_1 and S_2 in phase and 3 cm apart, wavelength 1 cm



- P_0 is a point on the centre line of the interference pattern.
- P_0 is the same distance from S_1 as it is from S_2.
- The path difference between S_1P_0 and S_2P_0 = 0
- Waves arrive at P_0 in phase and therefore constructive interference occurs

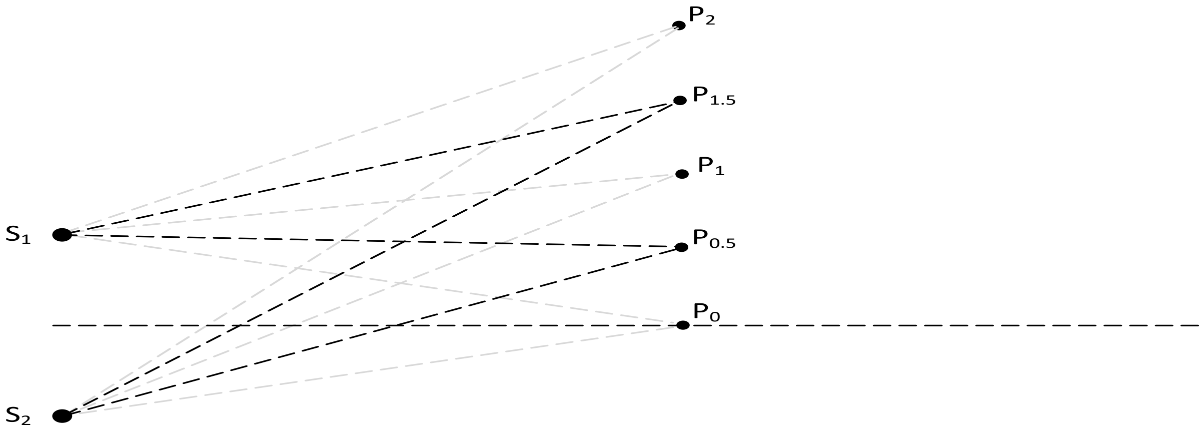


- P_1 is a point on the first line of constructive interference out from the centre line of the interference pattern.
- P_1 is one wavelength further from S_2 than it is from S_1.
- The path difference between S_1P_1 and $S_2P_1 = 1 \times \lambda$
- Waves arrive at P_1 in phase and therefore constructive interference occurs.

Constructive interference occurs when:

path difference = $m\lambda$

where m is an integer and λ is the wavelength of the wave (m).



- $P_{0.5}$ and $P_{1.5}$ are points of destructive interference out from the centre line of the interference pattern.
- $P_{0.5}$ is half a wavelength further from S_2 than it is from S_1.
- $P_{1.5}$ is one and a half a wavelengths further from S_2 than it is from S_1.
- The path difference between $S_1P_{0.5}$ and $S_2P_{0.5}$ = $0.5 \times \lambda$
- The path difference between $S_1P_{1.5}$ and $S_2P_{1.5}$ = $1.5 \times \lambda$
- Waves arrive at $P_{0.5}$ and $P_{1.5}$ exactly out of phase and therefore desstructive interference occurs.

Destructive interference occurs when:

$$\textbf{path difference} = (m + \tfrac{1}{2})\lambda$$

where m is an integer and λ is the wavelength of the wave (m).

<u>Example</u>
A microwave source produces an interference pattern where the path difference is 12 cm at the fourth order maxima.

a. Calculate the wavelength of the microwaves.
b. Calculate the frequency of the microwaves.

<u>Solution</u>

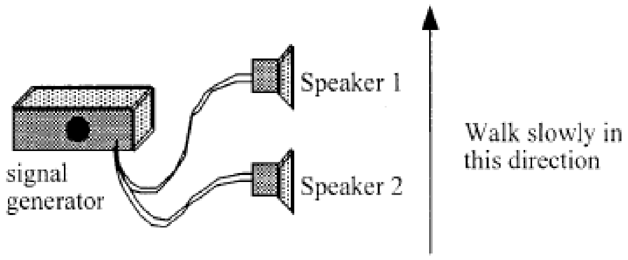
<u>Example</u>
A microwave source with a wavelength of 3.4 cm produces an interference pattern.

a. Calculate the path difference to the second order minima.

<u>Solution</u>

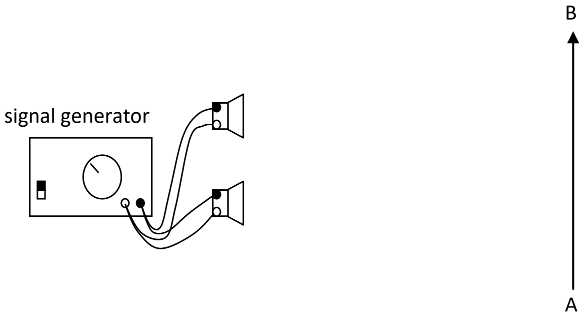
Interference of sound waves

If we set up the apparatus as shown and walk slowly across the 'pattern' we should be able to listen to the effect on the **loudness** of the sound heard. The effect heard happens as there will be points where the sound is louder [constructive interference] and points where the sound is quieter [destructive interference]. The waves that meet at your ear will have travelled different distances from each loudspeaker. In reality because of reflections from the floor, walls and ceiling this experiment never really works very well.



Example:

A student sets up two loudspeaker a distance of 1·0 m apart in a large room. The loudspeakers are connected in parallel to the same signal generator so that they vibrate at the same frequency and in phase.



The student walks from A and B in front of the loudspeakers and hears a series of loud and quiet sounds.

a) Explain why the student hears the series of loud and quiet sounds.

b) The signal generator is set at a frequency of 500 Hz. The speed of sound in the room is 340 m s^{-1}. Calculate the wavelength of the sound waves from the loudspeakers.

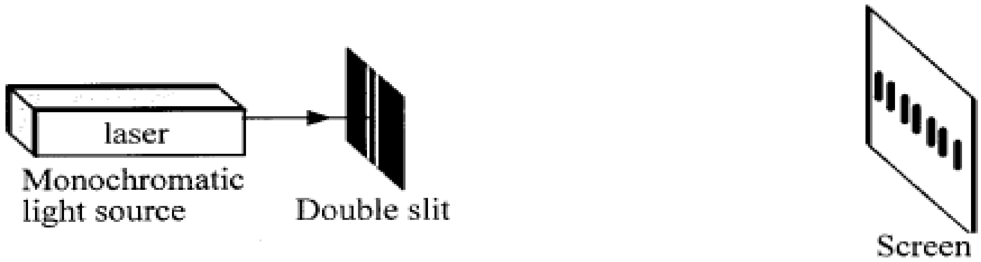
c) The student stands at a point 4·76 m from loudspeaker and 5·78 m from the other loudspeaker. State the loudness of the sound heard by the student at that point. Justify your answer.

d) Explain what will happen to the sound level at positions of destructive interference if one of the loudspeakers is turned off.

Solution:

Interference of light

Two sources of coherent light are needed to produce an interference pattern. Two separate light sources such as lamps cannot be used to do this, as there is no guarantee that they will be coherent (same phase difference). The two sources are created by producing two sets of waves from one monochromatic (single frequency) source. A laser is a good source of this type of light.



When we set up an experiment like the one shown we see an alternate series of bright and dark fringes.

When light from the two slits meets exactly in phase constructive interference occurs and a maxima (bright fringe) is seen.
When light from the two slits meets exactly out of phase destructive interference occurs and a minima (dark fringe) is seen.

The above experiment was first devised in 1801 by Thomas Young and is known as Young's double slit experiment. He obviously didn't have a laser to complete the experiment but using technology available at the time was able to formulate the following equation for the location of bright fringes and constructive interference.

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

where m is the order number (1, 2, 3, 4…), λ is the wavelength of the light (m), d is the spacing between the two slits (m) and θ is the angle of deviation of the bright fringe from the centre line (^{0}).

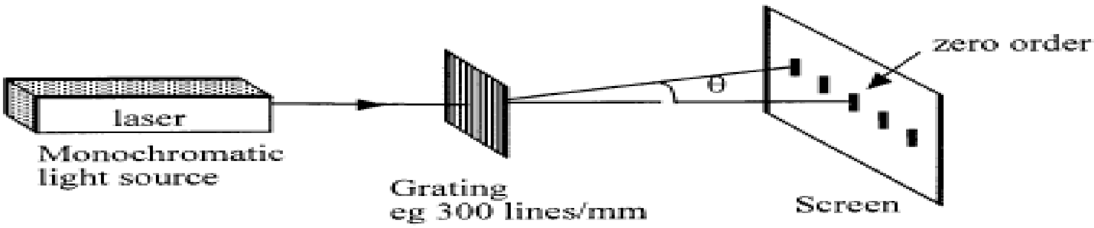
Example:
A laser of wavelength 580 nm is shone onto a pair of slits which are 0.2 mm apart and an interference pattern is observed on a far away screen.

a. Calculate the angle where the third order maxima will be found.
b. If the slits are moved closer together describe what will happen to the pattern on the screen.
c. If one slit is now covered over what explain what will happen to the pattern on the screen.

Solution:

Interference of light using a grating

When conducting light interference experiments it is more common to use a grating rather than a double slit. 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 so much more light is transmitted through and a clearer interference pattern is seen.



Gratings are listed in lines/cm or lines/mm and we must perform a calculation in order to determine 'd' which is the spacing between adjacent slits on a grating. To do this we must first convert the value into lines/m then divide 1 by the lines/m to find d.

For example, if a grating is	200 lines/cm
we multiply this by 100 to get	20000 lines/m
then divide 1 by the lines/m to get d	1/20000 = 5×10^{-5} m

<u>Example:</u>
A grating is described as having 500 lines/mm. Calculate the grating spacing for this grating.

<u>Solution:</u>

Measuring the wavelength of light – experiment

As a class you will now complete the above experiment to determine the wavelength of red light.

Grating used =

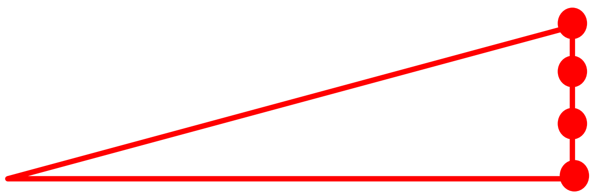
Distance between grating and screen =

d =

Distance to third order maxima =

m =

θ =



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.

Diagram of white light interference

The central fringe is white because at that position, the path difference for all wavelengths present is zero, therefore all wavelengths will meet in phase.

The visible spectra can be explained using the formula $m\lambda = d \sin(\theta)$. If d and m are fixed, the angle θ depends on the wavelength. The bigger the wavelength, the bigger the angle for constructive interference to occur, hence why red light is deviated the most and blue the least.

Determining the wavelength of red, green and blue light experiment

Aim: To determine the wavelength of red, green and blue light

Diagram: Shown above

Method:

Results:

Red light Green light Blue light

Calculations:

Red light | Green light | Blue light

Conclusion:

Evaluation:

Comparing Spectra from Prisms and Gratings

There are two ways of creating visible spectra that we now know about. One method used diffraction and interference (diffraction grating) and the other method uses refraction and dispersion (triangular prism).

Diagram of spectra created by a diffraction grating

Many spectra created

Red deviated the most

Diagram of spectra created using a triangular prism

Only 1 spectra created

Blue deviated the most

As you can see there are two clear differences between the spectra which are produced.

Refraction

Refraction occurs when light changes speed when passing from one medium to another. Usually this change in speed is also accompanied by a change in direction. How much the speed of light changes and how much its direction changes depends on the refractive index of the material involved. The bigger the refractive index, the bigger the changes in speed and direction. Air (a vacuum) has a refractive index of 1. All other materials have a refractive index of greater than 1, usually in the 1.2 to 1.8 range, although it can be higher.

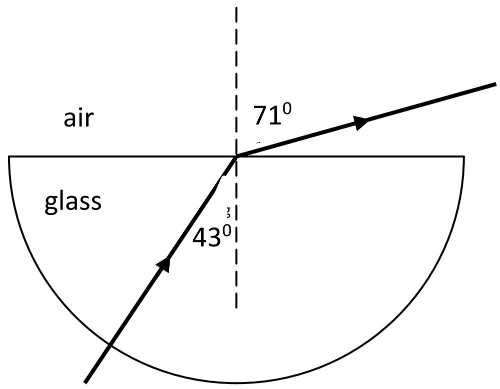
The equation which links the refractive index of a material to the incident and refracted angles is shown below.

$$\mathbf{n = \frac{\sin(\theta_1)}{\sin(\theta_2)}}$$

Where n is the refractive index (no units), θ_1 is the angle in air $(^0)$ and θ_2 is the angle in the medium $(^0)$. Note that θ_1 is always bigger than θ_2.

Example:
Calculate the refractive index for the block shown in the diagram.

Solution:



Experiment to determine the refractive index of a glass block

Aim: To determine the refractive index of a glass block

Diagram:

Method:

Results:

Angle in air (^{0})	Angle in glass block (^{0})	Sin (angle in air)	Sin (angle in glass block)

Plot sin (angle in glass block) on the x-axis and sin (angle in air) on the y-axis. The gradient of the line will be sin (angle in air) divided by sin (angle in glass block) which will give you the refractive index of the glass block.

Gradient calculation:

Conclusion:

Evaluation:

Refractive index, speed, wavelength and frequency

Speed

When light moves from air into another medium it slows down according to the equation shown.

$$\mathbf{n = \frac{\sin(\theta_1)}{\sin(\theta_2)} = \frac{v_1}{v_2}}$$

where n is the refractive index of the medium (no units), v_1 is the speed of light in air (3×10^8 ms^{-1}) and v_2 is the speed of light in the medium (ms^{-1}). Note that the speed of light in the medium is always less than the speed of light in air.

<u>Example:</u>
Calculate the speed at which light would travel through water with a refractive index of 1.35.

<u>Solution:</u>

Wavelength

When light moves from air into another medium it wavelength decreases according to the equation shown.

$$\mathbf{n = \frac{\sin(\theta_1)}{\sin(\theta_2)} = \frac{\lambda_1}{\lambda_2}}$$

where n is the refractive index of the medium (no units), λ_1 is the wavelength of light in air (m) and λ_2 is the wavelength of light in the medium (m). Note that the wavelength of light in the medium is always less than the wavelength of light in air.

<u>Example:</u>
Light has a wavelength of 633 nm in air and a wavelength of 412 nm in plastic. Calculate the refractive index of the plastic.

<u>Solution:</u>

Frequency

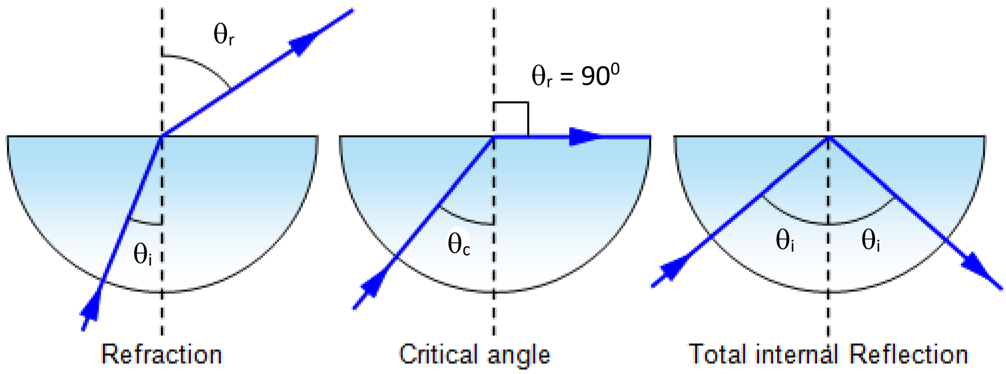
The frequency of light does not change when passing from air into other materials like glass or water. Because of the equation $v = f\lambda$ the v on the left hand side decreases and the λ on the right hand side decreases but the frequency remains constant. This comes up a lot in exams as pupils are easily tricked into thinking frequency changes.

Dependence of refraction on frequency

The refractive index of a medium depends upon the frequency (colour) of the incident light. Bigger frequencies (smaller wavelengths) experience a larger refractive index than smaller frequencies (larger wavelengths). This is shown in the diagram of the refraction of white light through a prism.

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 refracts 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. At this point the angle within the medium θ_i is known as the critical angle. At all incident angles below the critical angle light is refracted and at all angles above the critical angle light is totally internally reflected.



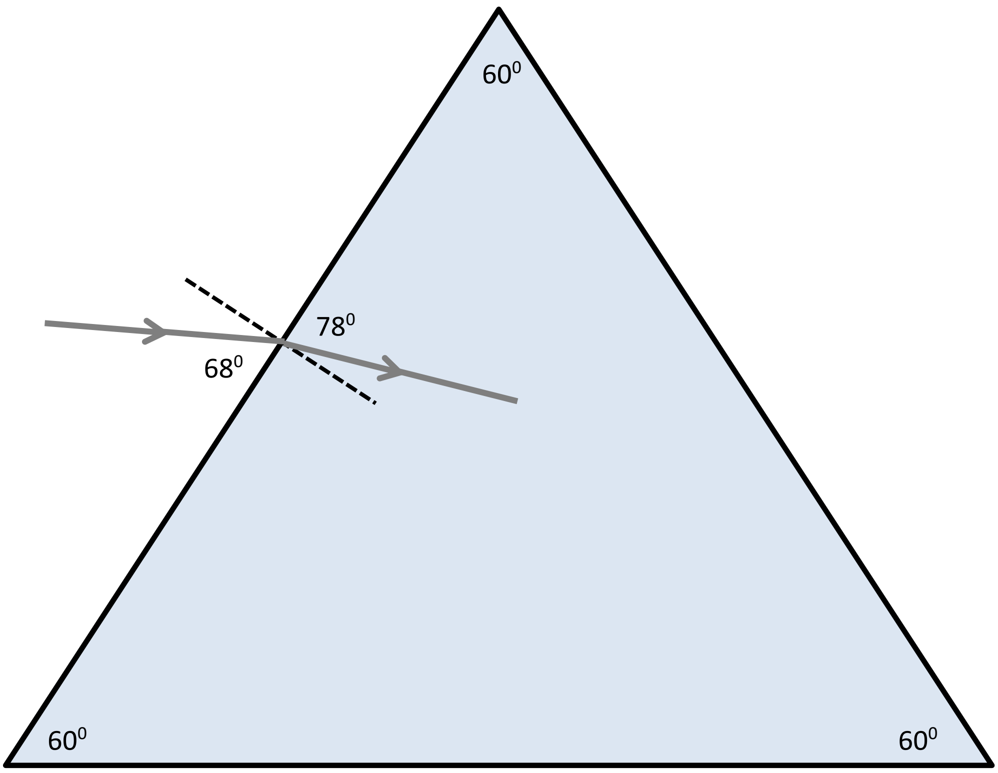
Calculating the critical angle

When light is incident at the critical angle then the angle of refraction is equal to 90^0.

Example:
Light is incident on a triangular prism as shown below.

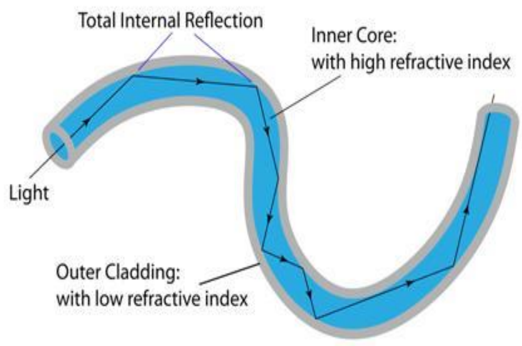
a. Calculate the refractive index of the glass block.
b. Calculate the critical angle for this combination of light and glass.
c. Complete the diagram to show the path of the ray of light through the glass block.

Solution:



Optical fibres

The most common use of total internal reflection is in optical fibres where light totally internally reflects many times down the length of the fibre. The cladding has a lower refractive index than the core as it is impossible to get total internal reflection when going from a low refractive index medium to a high refractive index medium.



Irradiance

Irradiance is the power per unit area.

$$\mathbf{I = \frac{P}{A}}$$

Where I is irradiance in (W m^{-2}), P is power (W) and A is area (m^2)

Example:
A light bulb of power 100 W illuminates an area of 12 m^2. Calculate the irradiance of light hitting the area.

Solution:

Example:
A laser of power 0.1 mW has a beam radius of 0.8 mm. Calculate the irradiance of the laser beam.

Solution:

You will notice that the irradiance of the laser beam is far greater than for the bulb, even though its power is far less. This is because light from a laser beam travels in one direction and does not diverge, unlike a bulb which projects light in all directions.

Irradiance and the inverse square law

Irradiance and distance experiment

Aim: To determine the relationship between irradiance and distance from a point source of light.

Diagram:

Method:

Results:

Distance from point source (cm)	Irradiance (Wm^{-2})	1/distance^2 (cm^{-2})
10		
14		
18		
22		
26		
30		

Plot 1/distance^2 (cm^{-2}) on the x-axis and irradiance (Wm^{-2}) on the y-axis.

Conclusion:

Evaluation:

From the graph you will notice that irradiance varies proportionally with the inverse square of the distance. Hence the name, inverse square law of radiation. This means we can use the following equation in calculations.

$$\mathbf{I_1 d_1^2 = I_2 d_2^2}$$

Where I_1 is the irradiance (Wm^{-2}) at distance d_1 (m) and I_2 is the irradiance (Wm^{-2}) at distance d_2 (m). **This equation is only true for point sources of light. A point source of light is a source of light which is small (a point source) in comparison to the distances measured in the experiment.**

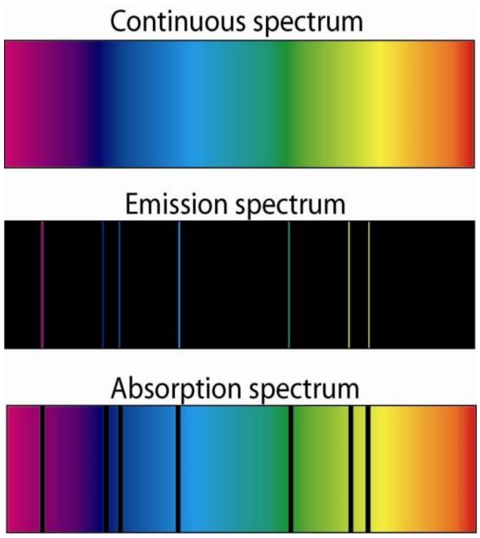
Example:
A point source of light has an irradiance of 12 Wm^{-2} at a distance of 20 cm from the source.

a. Calculate the irradiance at a distance of 10 cm from the source.
b. Calculate the irradiance at a distance of 30 cm from the source.

Solution:

Spectra

You will already know about spectra from National 5 Physics and from the Dynamics and Universe Unit at Higher. There are two types of spectra called continuous spectra and line spectra. A line spectra also has two types called line emission spectra and line absorption spectra. This section will explain how the different spectra are created.



Continuous spectra

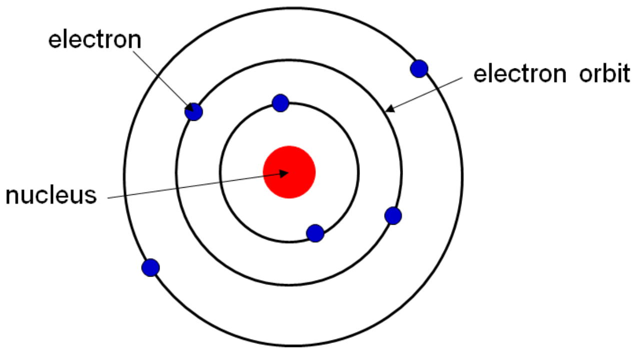
Continuous spectra can be created by separating white light from a hot source (bulb) using dispersion. The electrons are not bound to individual atoms so all visible colours from red through to blue are represented with no gaps.

Line Emission Spectra

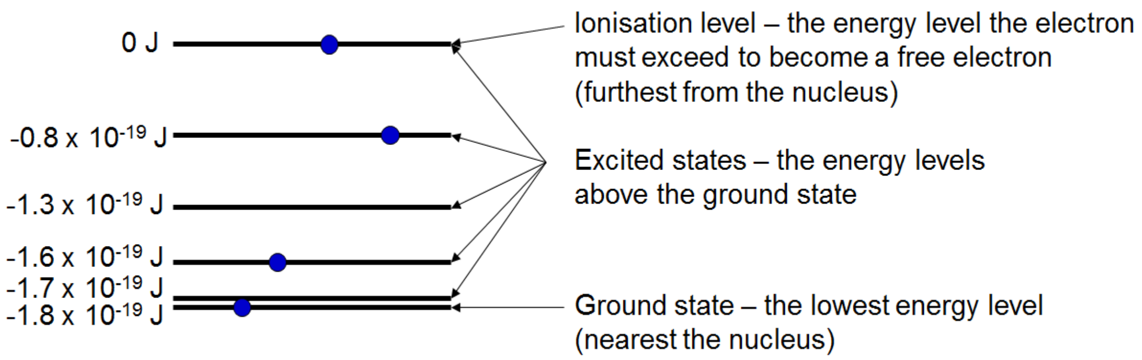
A line spectrum is emitted by excited atoms in a low pressure gas. Each element emits its own unique line spectrum that can be used to identify that element. As with the photoelectric effect, line emission spectra cannot be explained by the wave theory of light. In 1913, Neils Bohr, a Danish physicist, first explained the production of line emission spectra.

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 in different orbits have different energies.
- electrons can jump between allowed orbits.
    - If an electron absorbs a photon it moves up to a higher energy level.
    - If an electron moves to a lower energy level then a photon is emitted.



It is often easier to represent the Bohr model of the atom as shown below.

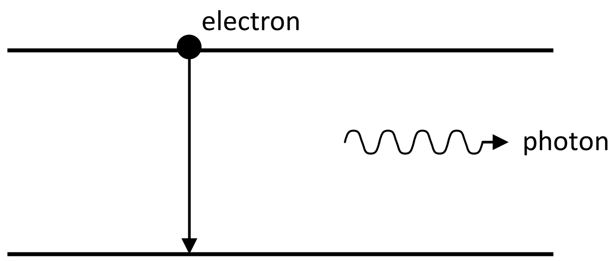


You will notice that all of the energy levels have been given negative energies. This is because an electron which becomes free from an atom by just exceeding the ionisation level will have zero kinetic energy. For example the electron in the -0.8×10^{-19} J level above will need to be given 0.8×10^{-19} J of energy to free it from the atom.

$$\mathbf{-0.8 \times 10^{-19} + 0.8 \times 10^{-19} = 0}$$

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. This can be represented by the following equation.



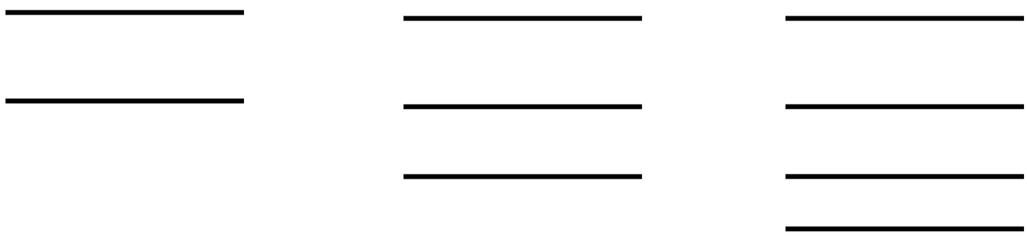
$$\mathbf{E_2 - E_1 = hf}$$

Where E_2 is the upper energy level (J), E_1 is the lower energy level (J), h is Planck's constant (6.63×10^{-34} Js) and f is the frequency of the emitted photon.

Number and brightness of lines on an emission spectra

The number of different energy of photons which can be emitted will depend on the number of energy levels each atom has. This is shown below in simple terms for 2, 3 and 4 energy levels.

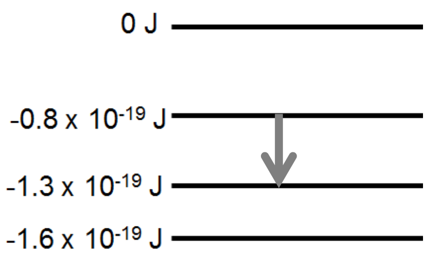
2 energy levels 3 energy levels 4 energy levels



The brightness of lines on an emission spectra will depend on how many electrons make a specific transition between levels. The more electrons making a specific transition, the more photons of that energy emitted , meaning the brighter the line.

Example:
The energy level diagram of an atom is shown with an electron moving between energy levels.

a. Calculate the energy of the photon emitted.
b. Calculate the frequency of the photon emitted.
c. Explain which transition would produce a photon with the highest wavelength.



Solution:

Line absorption spectra

Absorption spectra occur when light from a continuous spectra passes through a cold gas. The gas absorbs photons whose energies exactly match the differences in energy levels of its atoms. This means a line absorption spectra and a line emission spectra relating to the same element will be reciprocals of each other. All of the calculations which were true for line emission spectra also hold for line absorption spectra.

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. The same is true of other stars.

Waves

Describe why bright fringes can be observed on a far away screen if laser light is shone through a double slit.

Waves **meet exactly in phase** and constructively interfere to produce maxima

Describe why dark fringes can be observed on a far away screen if laser light is shone through a double slit.

Waves **meet exactly out of phase** and destructively interfere to produce minima

The distance between slits (grating spacing) is increased, describe what affect this will have on the position of maxima.

$m\lambda = d\sin(\theta)$ so if d increases, θ decreases and the maxima will be closer together

The wavelength of light incident on a grating is increased, describe what affect this will have on the position of maxima.

$m\lambda = d\sin(\theta)$ so if λ increases, θ increases and the maxima will be further apart

The frequency of light incident on a grating is increased, describe what affect this will have on the position of maxima.

$m\lambda = d\sin(\theta)$ so if f increases, λ decreases so θ decreases and the maxima will be closer together

When white light is incident on a diffraction grating fringes are produced. Explain why the central fringe is white.

All colours constructively interfere at this point and mix to create white light.

When white light is incident on a diffraction grating fringes are produced. Describe the arrangement of the red, green and blue sections of the spectrum on a far away screen.

$m\lambda = d\sin(\theta)$ so larger λ are diffracted to larger angles so red is diffracted more than green, which in turn is diffracted more than blue.

Describe 2 differences between the spectra created by a prism and the spectra created by a grating.

A prism creates 1 spectra, a grating creates several spectra. A prism causes blue light to be refracted the most and a grating causes blue light to be diffracted the least.

State what is meant by the refractive index of a material.

The ratio of speed of light in a vacuum divided by the speed of light in a material or the ratio of wavelength in a vacuum divided by the wavelength of light in a material.

Describe what happens to the speed, wavelength and frequency of light as it travels from a vacuum into a medium of high refractive index.

Frequency remains unchanged but wavelength and speed both decrease

Describe what effect wavelength has on the amount of refraction experienced.

Smaller wavelengths refract more than larger wavelengths

State what is meant by the term 'critical angle'.

At angles below the critical angle all light is refracted. At the critical angle light is refracted at 90^0. At angles above the critical angle all light is totally internally reflected.

Explain why total internal reflection can only occur when passing from a medium of high refractive index to a medium of lower refractive index.

When passing from a high refractive index medium to a low refractive index medium light refracts away from the normal. If the incident angle is increased the refracted angle will eventually exceed 90^0 and the light will totally internally reflect. When going from a low refractive index medium to a high refractive index medium light refracts towards the normal and so will never exceed the 90^0 needed for total internal reflection.

State the definition of irradiance.

Power per unit area

Describe what happens to the irradiance of a light source as the distance from it is increased.

Irradiance decreases

Describe what is meant by coherent light.

Light where there is no phase difference

State how many different wavelengths of light can be emitted from a 2 level energy level diagram.

1

State how many different wavelengths of light can be emitted from a 3 level energy level diagram.

3

State how many different wavelengths of light can be emitted from a 4 level energy level diagram.

6

On an energy level diagram state which level is known as the ground state.

The level at the bottom denoted by the largest negative value of energy

On an energy level diagram state which level is known as the ionisation level.

The level at the top denoted by zero energy

Describe which transition on an energy level diagram will give light of the largest frequency or energy.

A transition between the two levels with the largest energy gap between them

Describe which transition on an energy level diagram will give light of the smallest frequency or energy.

A transition between the two levels with the smallest energy gap between them

Describe which transition on an energy level diagram will give light of the largest wavelength.

A transition between the two levels with the smallest energy gap between them

Describe which transition on an energy level diagram will give light of the smallest wavelength.

A transition between the two levels with the largest energy gap between them