Higher Physics
Particles and Waves 2
Notes

Teachers Booklet

Learning Outcomes – Interference and diffraction

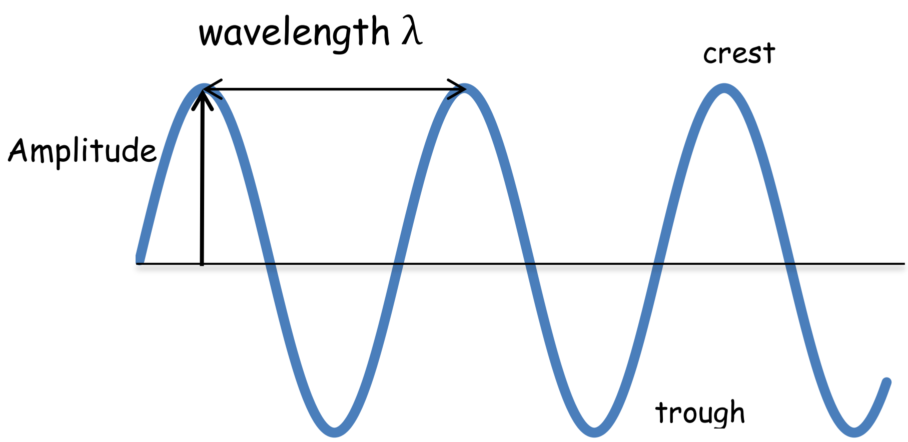
This builds on information from

N5 Waves and Radiation
H Particles and Waves book 1

At the end of this section you should be able to

- State that coherent waves have
  - a constant phase relationship
  - the same frequency
  - the same wavelength
  - the same velocity
- Describe constructive and destructive interference in terms of phase between two waves.
- Calculate the path difference between two waves
- State that maxima are produced when the path difference between waves is a whole number of wavelengths
- State that minima are produced when the path difference between waves is an odd number of half wavelengths.
- Use path diff = $m\lambda$ OR path diff = $(m + \frac{1}{2})\lambda$ where m = 0,1,2... to solve problems involving the path difference between waves, wavelength and order number.
- Use the equation $m\lambda = d \sin\theta$ to solve problems involving grating spacing, wavelength, order number and angle to the maximum

Waves - Background



All waves carry energy.

Mechanical waves are produced by moving particles – these include water waves, sound waves ad waves on a spring.

Electromagnetic waves are caused by varying electric and magnetic fields.

The energy of a wave depends on its amplitude.

When waves are created the frequency of the wave is the same as the frequency of the source and does not change once the wave is created.

Equations

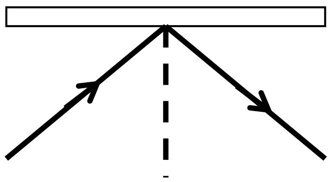
$$f = \frac{N}{t} \qquad v = f\lambda \qquad T = \frac{1}{f}$$

Where f = frequency (Hz)
N = number of waves
t = time (s)
v = wavespeed (ms^{-1})
λ = wavelength (m)
T = period of wave (s)

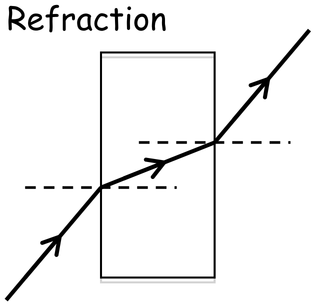
Wave Properties - Interference

All waves undergo the following four properties

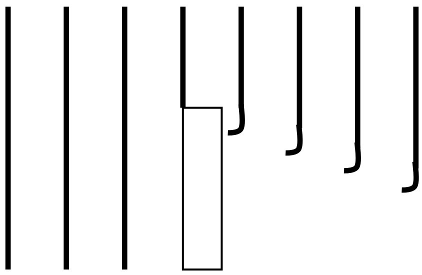
Reflection



Refraction



Diffraction



Interference

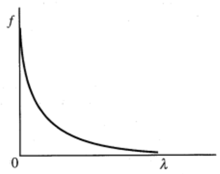
Waves which have the same amplitude, frequency and have a fixed phase difference are described as COHERENT.

To produce coherent waves, use a single source

Example 1

Which graph shows the relationship between frequency f and wavelength λ of photons of electromagnetic radiation?

A



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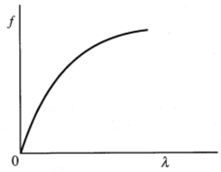
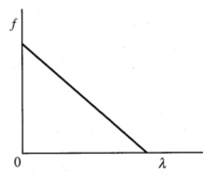
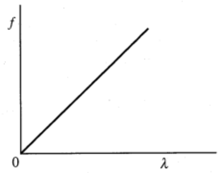


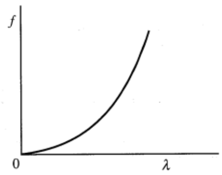
E



B



D

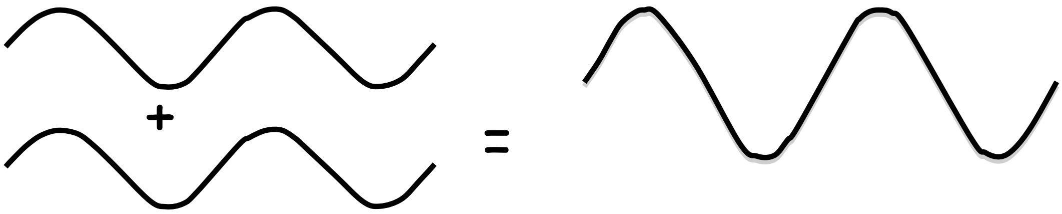


A

SQA 2005 Q15

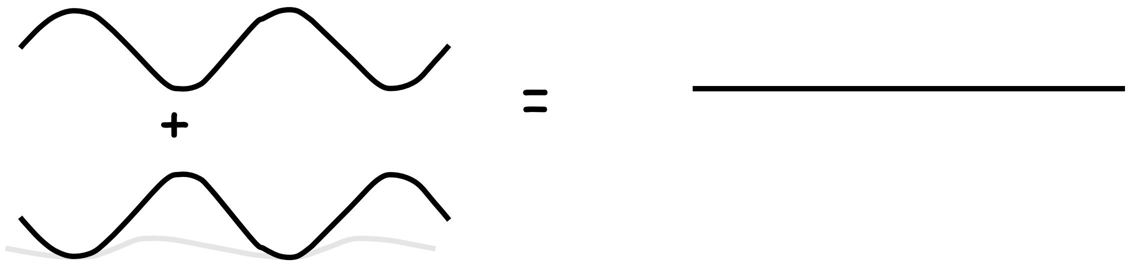
Wave Properties – Interference

- Two waves which have the same frequency, wavelength and velocity are described as being in phase if a crest coincides with a crest and a trough coincides with a trough.



This is called CONSTRUCTIVE INTERFERENCE.

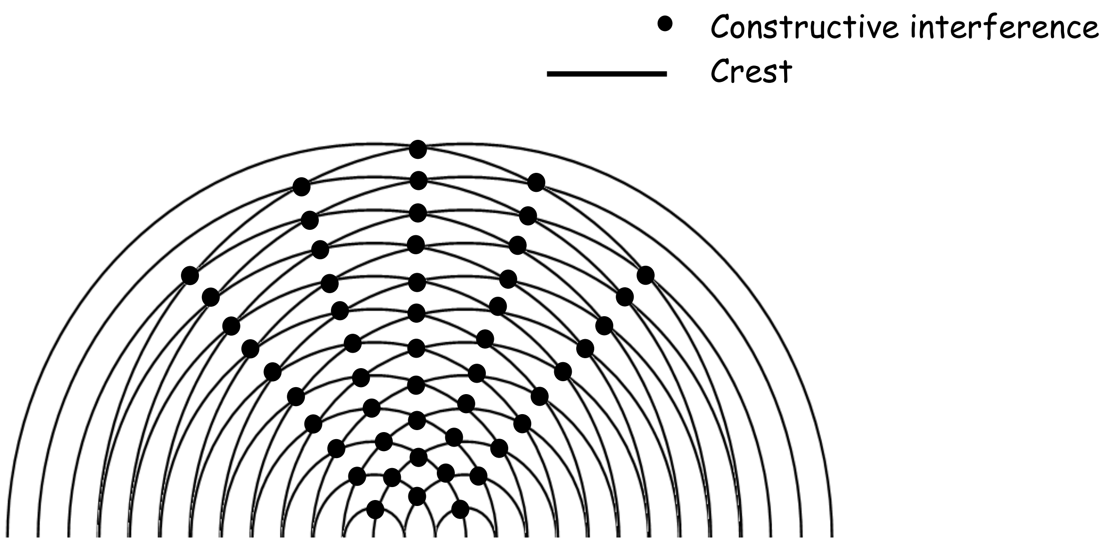
Two waves which have the same frequency, wavelength and velocity are described as being out of phase if a crest coincides with a trough and a trough coincides with a crest.



This is called DESTRUCTIVE INTERFERENCE.
Destructive interference is the test for a wave.

Interference of Water waves

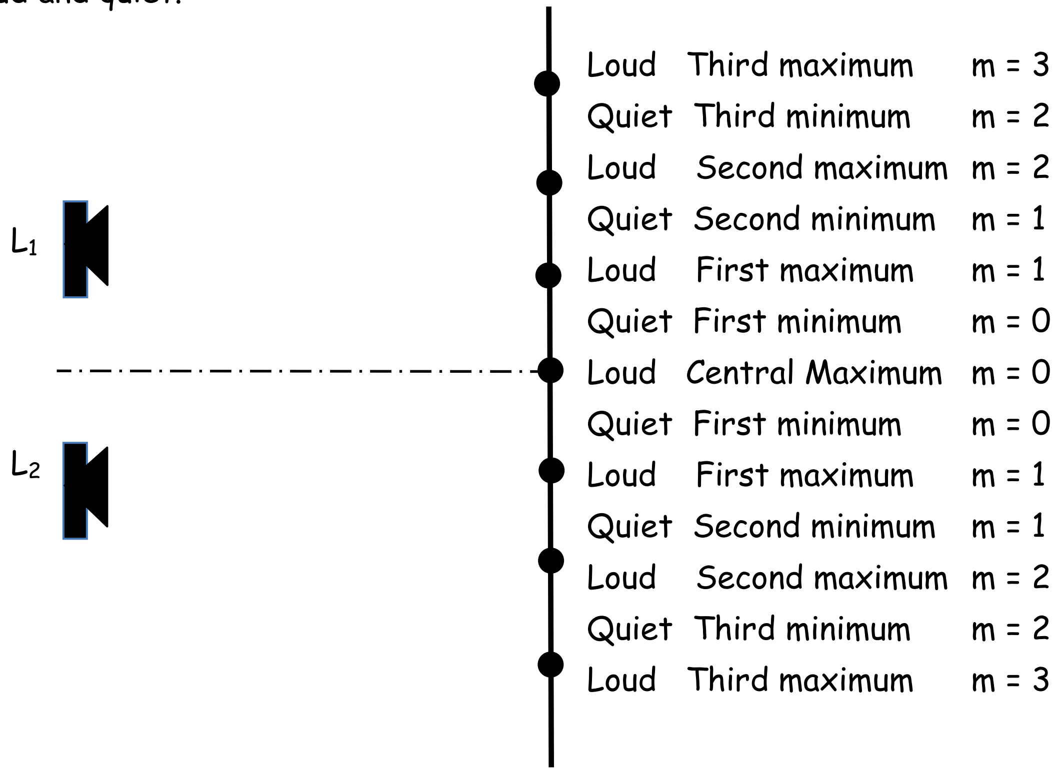
An interference pattern is produced when two sets of circular water waves overlap and combine.



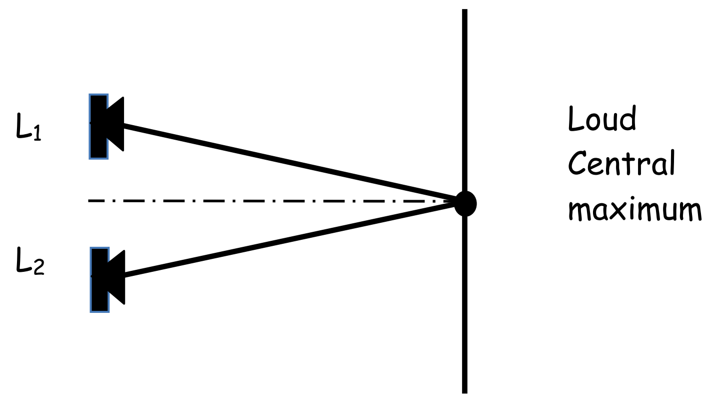
Wave Properties – Interference of Sound

If we have two loudspeakers connected to the same source the sound produced is coherent because it has the same frequency, the same wavelength and is produced with a constant phase difference.

The sound waves produce an interference pattern like that produced by water waves, but instead of patterns of light and dark we get patterns of loud and quiet.



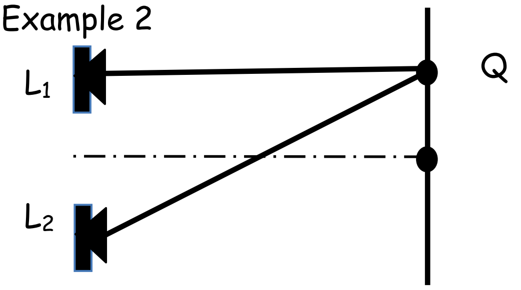
A maximum occurs when the path difference is a whole number of wavelengths. Path difference = $m\lambda$ (where m = 0,1,2,3...)
A minimum occurs when the path difference is multiple of half a wavelength. Path difference = $(m + \frac{1}{2})\lambda$ (where m = 0,1,2,3...)



Both waves travel the same distance to arrive at the central maximum.

Path difference – Sound waves

Example 2



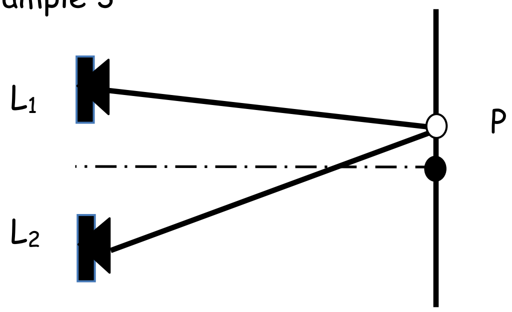
Loud
First order
maximum

The distance L_1Q is 47cm and L_2Q is 49 cm. Calculate the wavelength of the wave if Q is the first order maximum.

Path difference = 49 – 47 = 2 cm

First order maximum = λ = 2cm = 0.02m

Example 3



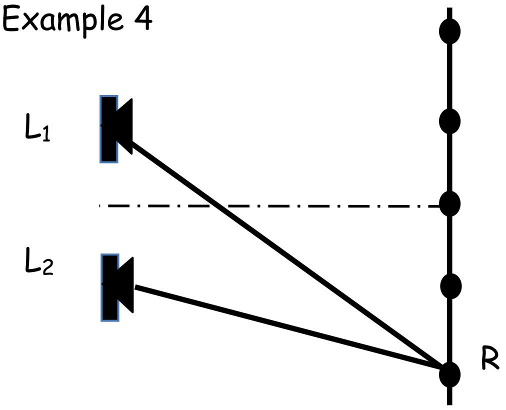
Quiet
First
minimum

The distance L_1P is 47cm and the distance L_2P is 45.5cm. Calculate the wavelength of the wave if P is the first minimum.

Path difference = 47 – 45.5 = 1.5cm

First minimum = $\lambda/2$ ➔ $\lambda = 2 \times 1.5$ = 3cm = 0.03m

Example 4



The distance L_1R is 47cm and the distance L_2R is 41cm. Calculate the wavelength of the wave if P is the second order maximum.

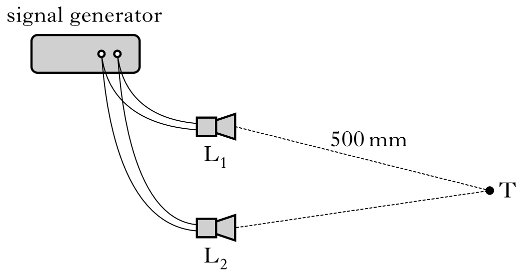
Path difference = 47 – 41 = 6cm

Second order maximum = 2λ ➔ $\lambda = 6/2$ = 3cm = 0.03m

Path difference – Sound waves

Example 5

Two identical loudspeakers, L_1 and L_2, are connected to a signal generator as shown.



An interference pattern is produced and a minimum is detected at point T. The wavelength of the sound is 40 mm. The distance from L_1 to T is 500 mm. The distance from L_2 to T is

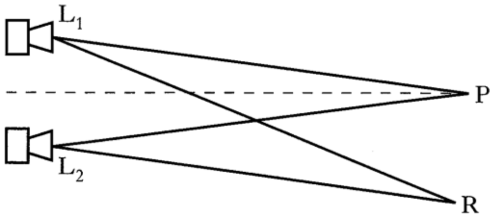
A 450 mm
B 460 mm
C 470 mm
D 480 mm
E 490 mm

A minimum is produced when the path difference is half a wavelength.
If λ = 40mm then $\lambda/2$ =20mm.
The distance from L_2 to T must be either 20mm or 60mm less than 500mm.
The only option is D – 480mm

SQA 2011 Q 15

Example 6

Two identical loudspeakers, L_1 and L_2, are operated at the same frequency and in phase with each other. An interference pattern is produced.



At position P, which is the same distance from both loudspeakers, there is a maximum intensity.
The next maximum intensity is at position R, where L_1R = 5.6 m and L_2R = 5.3 m. The speed of sound = 340 ms^{-1}.
The frequency of the sound emitted by the loudspeakers is given by

A $\frac{5.6-5.3}{340}$ Hz

B $\frac{340}{5.6+5.3}$ Hz

C $\frac{340}{5.6-5.3}$ Hz

D 340 x (5.6 – 5.3) Hz

E 340 x (5.6 + 5.3) Hz

$f = v/\lambda$ 340/ path difference

C

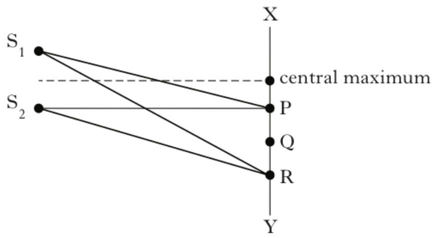
SQA 2004 Q 14

Path difference – electromagnetic waves

Path difference calculations can also be carried out with other types of wave.

Example 7

S_1 and S_2 are sources of coherent waves. An interference pattern is obtained between X and Y.



The first order maximum occurs at P, where S_1P = 200mm and S_2P = 180mm. Calculate the path difference at R, the third order maximum.

(S_1P – S_2P) = 200 – 180 = 20mm. This is the first order maximum so the path difference = λ = 20mm.

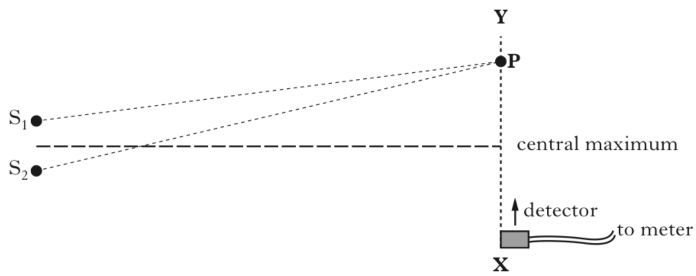
At the third order maximum the path difference = 3 λ

so (S_1R – S_2R) = 3 x 20 = 60mm

SQA 2012 Revised Q 9

Example 8

A student is using different types of electromagnetic radiation to investigate interference. In the first experiment, two identical sources of microwaves, S_1 and S_2, are positioned a short distance apart as shown.



(i) The student moves a microwave detector from X towards Y. The reading on the meter increases and decreases regularly. Explain. in terms of waves, what causes the minimum readings to occur.

Waves meet out of phase OR crests meet troughs OR appropriate diagram

(ii) The **fourth** maximum from the central maximum is located at P. The distance from S_1 to P is 620 mm and the wavelength of the waves is 28mm. Calculate the distance from S_2 to P.

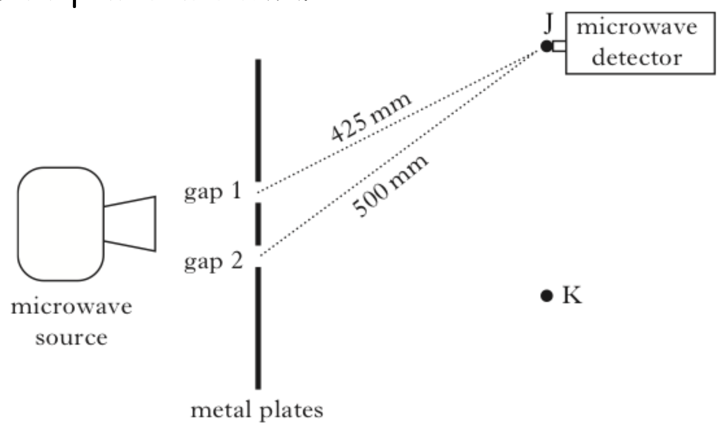
Path diff = $m\lambda$. So path diff = 4 x 28mm = 112mm

S_2P = 620 + 112 = 732 mm

SQA 2012 revised Q28 (a)

Example 9

In this experiment, microwaves of wavelength 30mm pass through the gaps between metal plates as shown.



(a) The distances from each of the gaps to point J are shown in the diagram. Use this information to determine whether point J is a point of constructive or destructive interference.
You must justify your answer by calculation.

Path difference = 500 – 425 = 75mm
Number of wavelengths = 75/30 = 2.5
Destructive interference.
(SQA did not accept 'a minimum' or 'deconstructive'

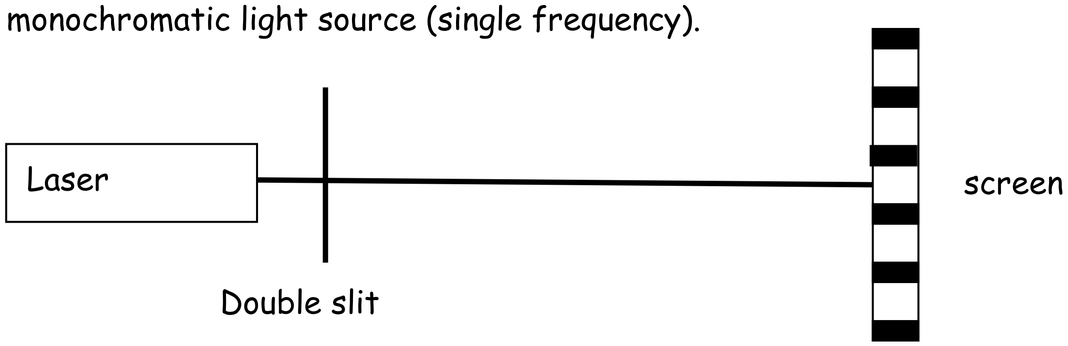
(b) The microwave detector is now moved to point K which is a point of destructive interference.
Gap 1 is then covered with a sheet of metal.
Does the strength of the signal detected at K increase, decrease or stay the same? You must justify your answer.

Increases
Destructive interference no longer occurs OR now only one sest of waves so they cannot cancel out
OR suitable diagram showing destructive interference before, then no interference.

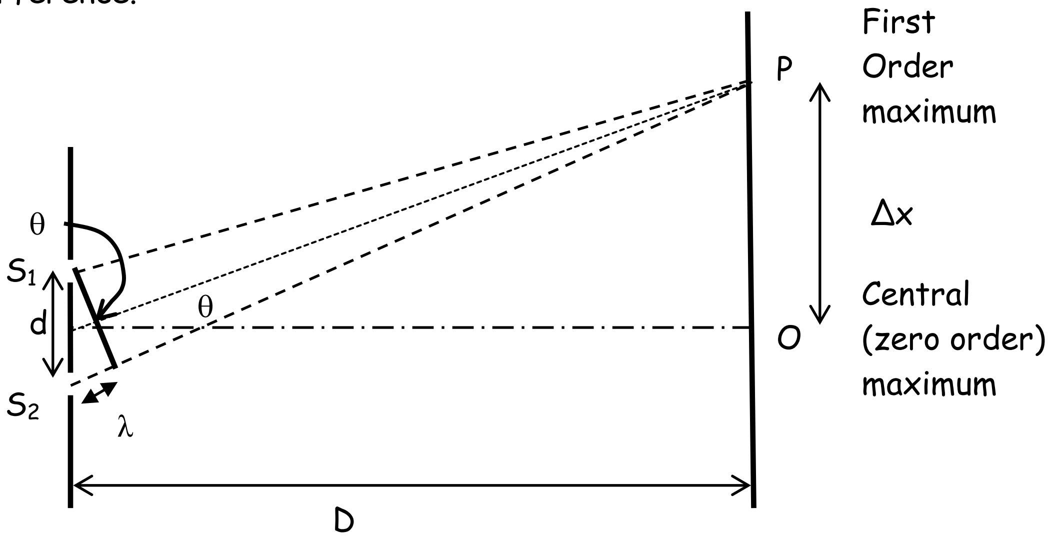
SQA 2014 Q28 (b)

Interference pattern - Light

To produce an interference pattern using light the light source is passed through a blackened slide which has two parallel slits cut into it to allow light through. A laser is used as the light source because it is a monochromatic light source (single frequency).



The screen shows a bright central point, with a pattern of light and dark patches on either side, showing constructive and destructive interference.



The path difference between S_1P and S_2P is one wavelength, λ.
The slit separation, d, is very small and is much smaller than the distance to the screen, D.
The triangle formed between the screen and the light sources and the triangle at the sources are similar triangles – they have the angle θ in common.

$\tan\theta = \frac{\Delta x}{D}$ For small angles sin θ is approximately equal to tan θ $\sin\theta = \frac{\lambda}{d}$

This is written as

$m\lambda = d\,sin\theta$ where m = 0,1,2,3…for maxima

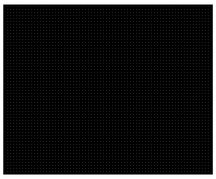
m = $\frac{1}{2}, \frac{3}{2}, \frac{5}{2}, \frac{7}{2}$ … for minima

NOTE – old exam papers may use n rather than m as in $n\lambda = d\,sin\theta$

Interference pattern - Light

Gratings

To make the pattern of light and dark areas (fringes) brighter and sharper we need more light. This is done using a grating which has multiple slits



The slit separation, d, is calculated from the number of lines per mm.

Example 10
If the number of lines on a diffraction grating is 200 lines per mm, calculate the slit separation, d.

3. find the number of lines per metre
   200 lines per mm = 200,000 lines per m
4. Calculate the separation
   d = $\frac{1}{200{,}000}$ = 5 x 10^{-6}m

Example 11
If the number of lines on a diffraction grating is 500 lines per mm, calculate the slit separation, d.

1. find the number of lines per metre
   500 lines per mm = 500,000 lines per m
2. Calculate the separation
   d = $\frac{1}{500{,}000}$ = 2 x 10^{-6}m

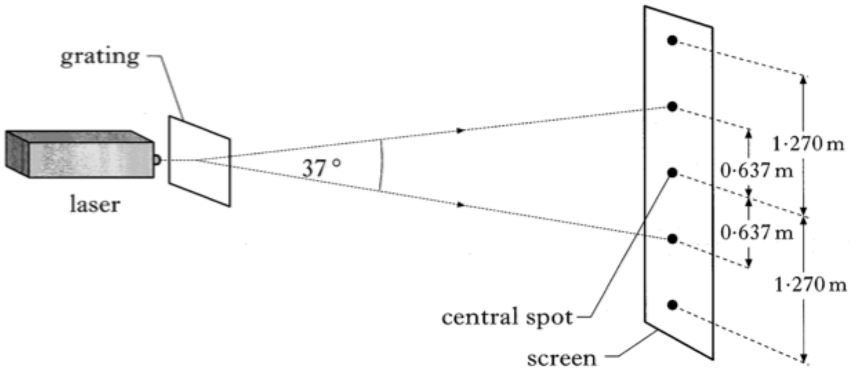
Since $m\lambda = d\sin\theta$

- If we increase the number of lines per mm, d gets smaller, so the angle between the central fringe and the fringe being measured will increase.

- If we increase the wavelength of the light the angle between the central fringe and the fringe being measured will increase.

Interference pattern - Light

Example 12
In an experiment, laser light of wavelength 633nm is incident on a grating.
A series of bright spots are seen on a screen placed some distance from the grating. The distance between these spots and the central spot is shown.



Calculate the number of lines per metre on the grating.

$m\lambda = d \sin\theta$

$1 \times 633 \times 10^{-9} = d \times \sin(37/2)$

$d = 1.99 \times 10^{-6}$ m

Number of lines per metre = $\frac{1}{2 \times 10^{-6}} = 5.0 \times 10^{5}$

SQA 2004 Q 28 (b)

Example 13
Light of wavelength 486×10^{-9}m is viewed using a grating with a slit spacing of 2.16×10^{-6}m.
Calculate the angle between the central maximum and the second order maximum.

$m\lambda = d \sin\theta$

$2 \times 486 \times 10^{-9} = 2.16 \times 10^{-6} \times \sin\theta$

$\sin\theta = 0.45$ $\theta = 26.7°$

SQA 2001 Q 27 (a)

Example.14
Monochromatic light is incident on a grating and the resulting interference pattern is viewed on a screen. The distance between neighbouring areas of constructive interference on the screen:
is *increased* when the screen is moved further away from the grating,
is *increased* when light of a greater wavelength is used,
is *decreased* when the distance between the slits is increased.

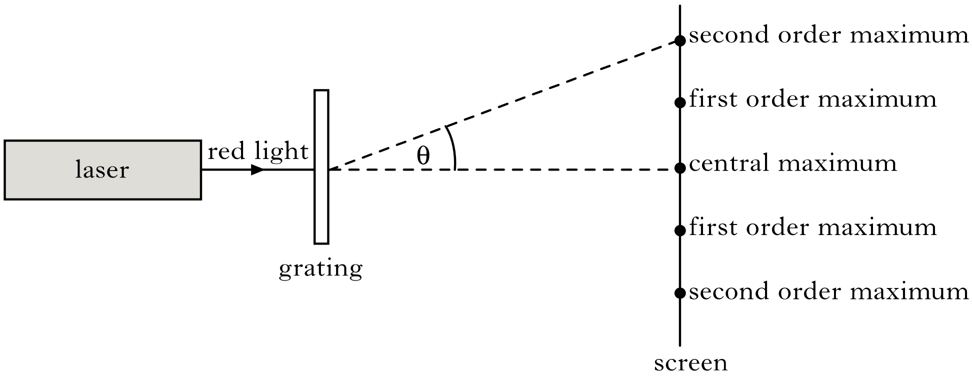
SQA 2003 Q 15 adapted

Interference pattern - Light

Example 15

A laser produces a narrow beam of monochromatic light.

(a) Red light from a laser passes through a grating as shown.



A series of maxima and minima is observed.
Explain in terms of waves how a **minimum** is produced.

Wave meet out of phase OR crest meets trough
OR path differences = $(m + \frac{1}{2})\lambda$

(b) The laser is now replaced by a second laser, which emits blue light.
Explain why the observed maxima are now closer together.

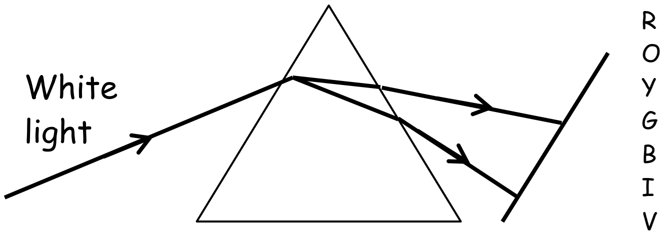
λ blue light is shorter than λ red light and $m\lambda = d \sin\theta$
Or $\sin\theta = m\lambda/d$

(c) The wavelength of the blue light from the second laser is 4.73×10^{-7} m. The spacing between the lines on the grating is 2.00×10^{-6} m
Calculate the angle between the central maximum and the second order maximum.

$m\lambda = d \sin\theta$
$2 \times 4.73 \times 10^{-7} = 2.00 \times 10^{-6} \sin\theta$
$\theta = 28.2°$

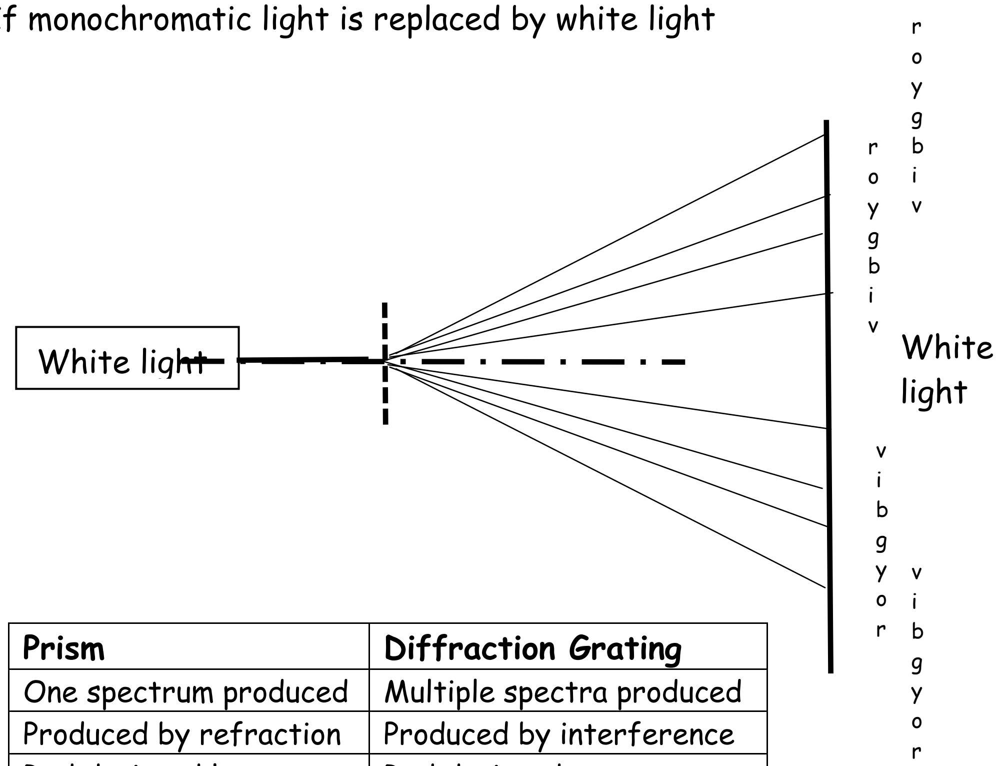
SQA 2009 Q 27

White Light



When white light passes through a prism the blue light is refracted most.

If monochromatic light is replaced by white light



Prism	Diffraction Grating
One spectrum produced	Multiple spectra produced
Produced by refraction	Produced by interference
Red deviated least	Red deviated most
Spectrum is bright	Spectra are less bright.
	Central image white

Spectra further out may overlap, making it difficult to decide what colours are seen.

Colour	Wavelength (nm)
Red	700
Green	550
Blue	490

$1\ \text{nm} = 1 \times 10^{-9}\text{m}$

These wavelengths can be found in the data table so do not need to be memorised, but it is useful to have an idea of the range.

White Light

Example 16

The spectrum of white light from a filament lamp may be viewed using a prism of a grating.

A student, asked to compare the spectra formed by the two methods made the following statements.

I. The prism produces a spectrum by refraction. The grating produces a spectrum by interference.

II. The spectrum formed by the prism shows all the wavelengths present in the white light. The spectrum formed by the grating shows only a few specific wavelengths.

III. The prism produces a single spectrum. The grating produces more than one spectrum

Which of the above statements is/are true?

I and III only

SQA 2001 Q 16 (adapted)

Example 17

One of the most important debates in scientific history asked the question

'Is light a wave or a particle?'

Use your knowledge of physics to comment on our understanding of this issue.

Light demonstrates reflection, refraction, diffraction and interference. This suggests it is a wave.

Light of an appropriate frequency (ultraviolet) causes electrons to be emitted from the surface of a metal (zinc) that has an appropriate work function (is reactive enough).This suggests that light acts like a particle. This is wave particle duality.

SQA 2013 revised Q28

Example 18 SQA 2011 Q 28 (a)

The first demonstration of the interference of light was performed by Thomas Young in 1801.

What does the demonstration of interference prove about light?

Light travels as waves/is a wave or Energy in light is carried as a wave

PW Problem Booklet 2
P4 Q 7 - 13

Learning Outcomes – Refraction of light

This builds on information from

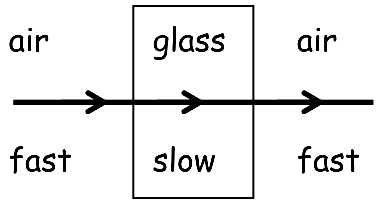
Waves and Radiation – Booklet 2 - Light

At the end of this section you should be able to

- State that the absolute refractive index of a material is the ratio of the speed of light in vacuum to the speed of light in the medium.
- Carry out calculations using the equation
  $n = \frac{sin\theta_{air}}{sin\theta_{material}}$
- Describe what happens when light travels from a more dense medium to a less dense medium.
- Carry out calculations using the equation
  $n = \frac{\lambda_{air}}{\lambda_{material}} = \frac{v_{air}}{v_{material}}$
- Variation of refractive index with frequency.
- State what is meant by the critical angle for a material.
- Calculate the critical angle for a material using
  $$sin\theta_c = \frac{1}{n}$$
- Use the critical angle to evaluate whether total internal reflection or refraction takes place when light is incident on a material at a certain angle.

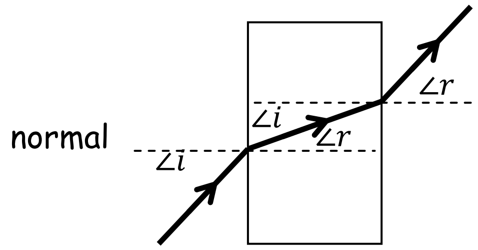
Refraction of light - Revision

When a wave enters a new medium the velocity may change.



If the wave enters at an angle this can also cause a change in direction.

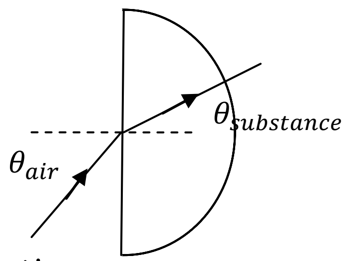
Angles are measured between the ray and the normal

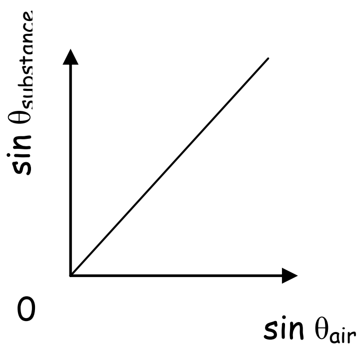


The amount of refraction that takes place depends on

- The wavelength of the light
- The type of material it passes through

Calculating Refractive Index





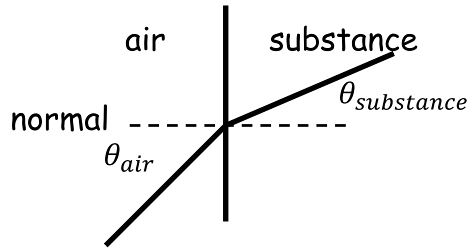
A laser is used to produce monochromatic light and is directed into a semicircular block as shown above. The angles θ_{air} and $\theta_{substance}$ are measured and the refractive index, n, is calculated using

$$n = \frac{\sin\theta_{air}}{sin\theta_{substance}}$$

For a more accurate result, and to get an average, many values of θ_{air} are used. The results can be plotted to give the graph shown above.

Refractive Index

$$n = \frac{\sin\theta_{air}}{sin\theta_{substance}}$$



- To get the refractive index **always** put air on the top, substance on the bottom.
- The value for refractive index is always equal to or greater than one.
- Refractive index has NO UNITS.
- Frequency **does not** alter.
- Velocity is less in the more optically dense material.

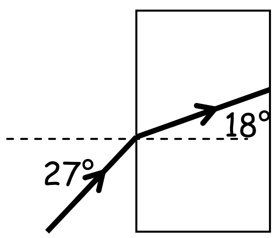
Since frequency is constant, λ and velocity change

$f_{air} = \frac{v_{air}}{\lambda_{air}}$ $\quad\quad$ $f_{substance} = \frac{v_{substance}}{\lambda_{substance}}$

Therefore

$$n = \frac{sin\theta_{air}}{sin\theta_{substance}} = \frac{\lambda_{air}}{\lambda_{substance}} = \frac{v_{air}}{v_{substance}}$$

Example 19

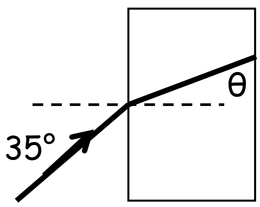


Calculate the refractive index of the material this block is made from

$n = \frac{\sin\theta_{air}}{sin\theta_{substance}} = \frac{\sin 27°}{\sin 18°} = 1.5$

AHS notes

Example 20



Calculate the value of the unknown angle θ if the refractive index is 1.4.

$n = \frac{\sin\theta_{air}}{sin\theta_{substance}} = \frac{\sin 35°}{\sin\theta°} = 1.4$

=> $\sin \theta_{substance} = \frac{\sin 35°}{1.4}$ => $\theta_s = 24°$

AHS notes

Refractive Index

Example 21
Calculate the velocity of light in a glass block which has a refractive index of 1.50.

$n = \frac{v_a}{v_s}$ => $1.5 = \frac{3 \times 10^8}{v_s}$ => $v_s = 2 \times 10^8\ ms^{-1}$

AHS notes

Example 22
Red light (λ = 700nm in air) is passed into a plastic material of refractive index 1.47. Calculate the wavelength of light in the plastic.

$n = \frac{\lambda_{air}}{\lambda_{substance}}$ => $1.47 = \frac{700}{\lambda_{substance}}$ => $\lambda_{substance} = \frac{700}{1.47}$

= 476nm

AHS notes

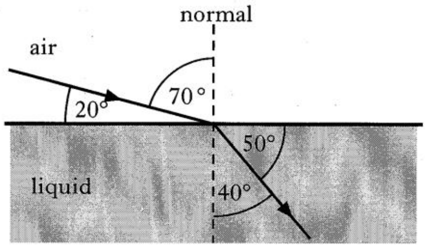
Example 23
Light travels from air into glass.
Which row in the table describes what happens to the speed, frequency and wavelength of the light?

	Speed	Frequency	Wavelength
A	increases	stays constant	increases
B	increases	decreases	stays constant
C	stays constant	decreases	decreases
D	decreases	decreases	stays constant
E	decreases	stays constant	decreases

E

SQA 2006 Q16

Example 24
The diagram represents a ray of light passing from air into liquid. The refractive index of this liquid, relative to air is



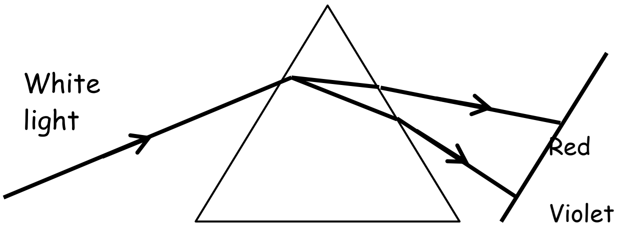
$$n = \frac{\sin\theta_{air}}{\sin\theta_{substance}} = \frac{\sin 70°}{\sin 40°}$$

= 1.46

SQA 2006 Q15 adapted

PW Problem Booklet 2
P5 Q 1 - 5

Refractive Index and Frequency



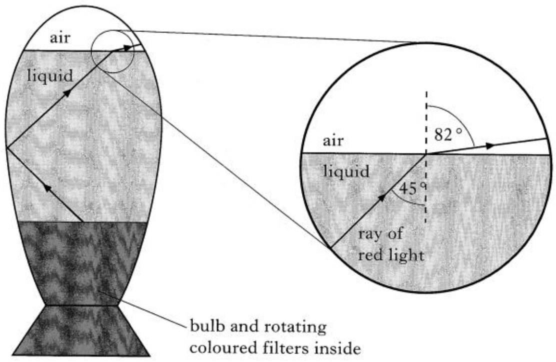
The refractive index of a medium depends on the frequency (colour) of the incident light.
This explains why white light splits up into the spectrum when it enters a prism. Each frequency within the white light is refracted by a different amount.

The diagram shows that

$$n_{violet} > n_{red} \quad \text{and} \quad v_{violet} < v_{red}$$

Example 25

A decorative lamp has a transparent liquid in the space above a bulb. Light from the bulb passes through rotating coloured filters giving red or blue light in the liquid.
A ray of red light is incident on the liquid surface as shown.



(a) Calculate the refractive index of the liquid for the red light.

(b) A ray of blue light is incident on the liquid surface at the same angle as the ray of red light.
The refractive index of the liquid for blue light is greater than that for red light. Is the angle of refraction greater thanm equal to or less than 82° for the blue light. Explain your answer.

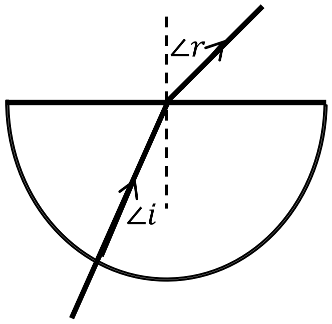
(a) $n = \frac{\sin\theta_{air}}{\sin\theta_{substance}} = \frac{\sin 82°}{\sin 45°} = 1.40$

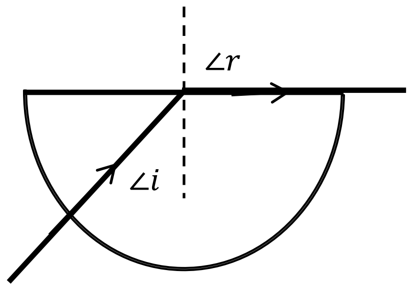
(b) $n \sin \theta_{liquid} = \sin \theta_{air}$
But $\sin \theta_{liquid}$ = constant and $n_{blue} > n_{red}$
$\sin \theta_{air}$ is now greater, hence θ_{air} is greater than 82°

SQA 2004 Q27 (a)

PW Problem Booklet 2
P6 Q 6,7

Critical Angle and Total Internal Reflection





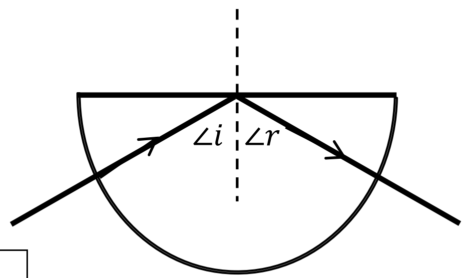
If the angle of incidence is small the light is refracted out of the block.

If the angle of incidence is increased the angle of refraction increases until it passes along the back wall of the block.

$$n = \frac{sin\theta_{air}}{sin\theta_{substance}} = \frac{\sin 90°}{\sin \theta_c} = \frac{1}{\sin \theta_c}$$

The angle at which this occurs is called the 'critical angle'.

If the angle of incidence is greater than the critical angle all of the light is reflected inside the material.
This is called **total internal reflection.**



$\angle i < \theta_c$	Refraction
$\angle \boldsymbol{i} = \boldsymbol{\theta_c}$	Light refracted at 90°
$\angle i > \theta_c$	Total internal reflection

AHS H notes

PW Problem Booklet 2
P7 Q 8 - 11

Irradiance and the Inverse Square Law

Example 26

Calculate the critical angle of water if it has a refractive index of 1.33.

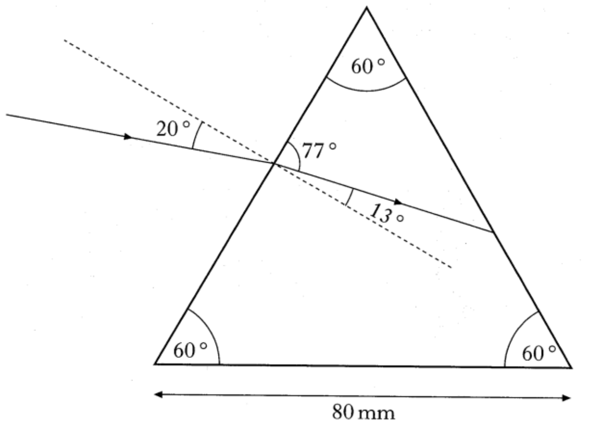
$$sin\theta_c = \frac{1}{n} = \frac{1}{1.33} => \theta_c = 48.8°$$

Example 27

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

$$sin\theta_c = \frac{1}{n} => n = \frac{1}{sin\theta_c} = \frac{1}{\sin 42.5°} = 1.48$$

Example 28
A ray of red light is directed at a glass prism of side 80mm as shown in the diagram below.



(a) Using information from this diagram, show that the refractive index of the glass for this red light is 1.52.

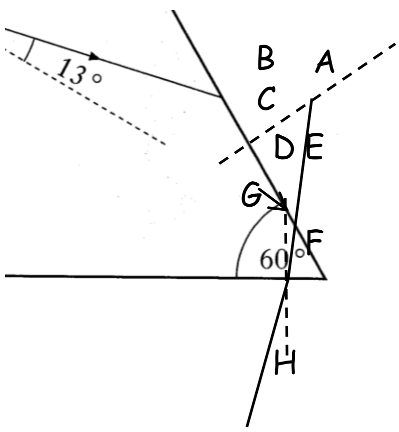
$$n = \frac{sin\theta_a}{sin\theta_s} = \frac{\sin 20°}{\sin 13°} = 1.52$$

(b) What is meant by the term *critical angle*?
This is the angle of incidence (inside medium) which causes light to emerge into a vacuum at 90° to the normal or along surface.
OR Incident angle at which total internal reflection takes place.

(c) Calculate the critical angle for the red light in the prism.

$$sin\theta_c = \frac{1}{n} = \frac{1}{1.52} => \ \theta_c = 41°$$

(d) Sketch a diagram showing the path of the ray of red light until after it leaves the prism. Mark on your diagram the values of all relevant angles.

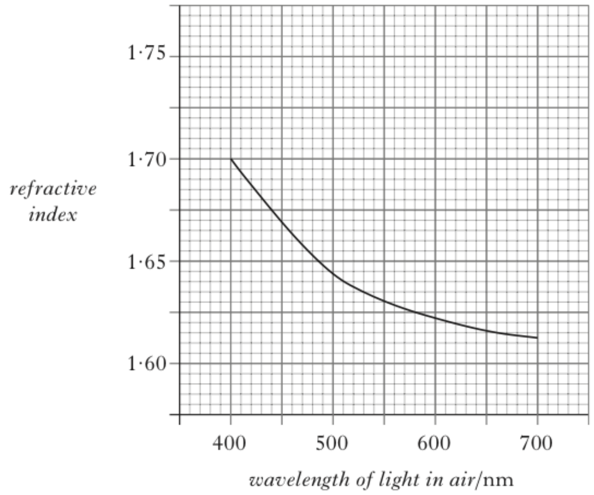


Angle A = 90°
Angle B = (180 – 60 – 77) = 43°
Angle C = 90 – 43 = 47°
Since 47° is greater than the critical angle total internal reflection occurs, so D is 47° and E is 43°.
Angle F = (180 – 60 – 43) = 77°
Angle G = 90 – 77 = 13°
Light refracts out at same angle as it came in at – Angle H = 20°

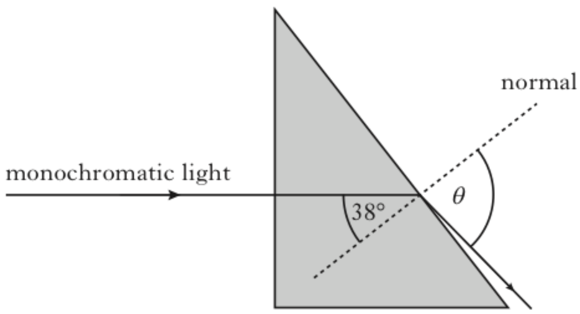
SQA 2002 Q 27

Example 29

Monochromatic light is shone into a triangular prism of flint glass.
The graph shows how the refractive index of flint glass varies with the wavelength of light in air.



(a) A ray of monochromatic light of wavelength 660nm in air passes through the prism as shown.



Calculate the angle of refraction θ.

(b) The ray of light is now replaced with one of shorter wavelength. Is the speed of this now ray in the prism less than, the same as or greater than the speed of the 660nm ray in the prism? Justify your answer.

(a) $n = \frac{sin\theta_a}{\sin\theta_s} => \sin\theta_a$ = 1.615 (from graph) x sin 38° => θa = 83.9°

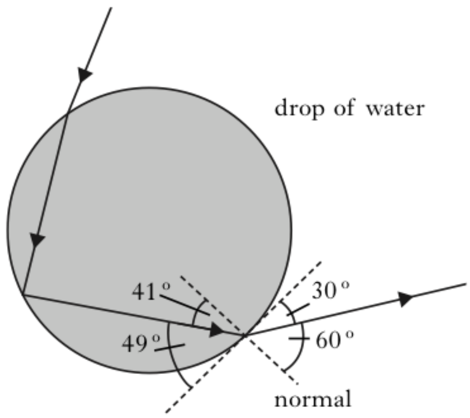
(b) Refractive index is larger (from graph - since wavelength is shorter)

$$n = \frac{v_a}{v_g} => \ v_g = \frac{v_a}{n} => velocity\ in\ glass\ is\ smaller$$

SQA 2014 Q 29

Example 30

A gardener observes a spectrum when sunlight illuminates the drops of water in a spray. This is because each drop of water is acting like a prism. The diagram below shows the path taken by light of wavelength 650 nm through a drop of water.



(a) What happens to the frequency of this light when it enters the drop of water?

Unchanged

(b) Using information from the diagram, calculate the refractive index of the water for this wavelength of light.

$$n = \frac{sin\theta_a}{\sin\theta_s} = \frac{\sin 60}{\sin 41} = 1.32$$

(c) Calculate the critical angle for this wavelength of light in the water

$$\sin\theta_c = \frac{1}{n} = \frac{1}{1.32} => \theta_c = 49$$

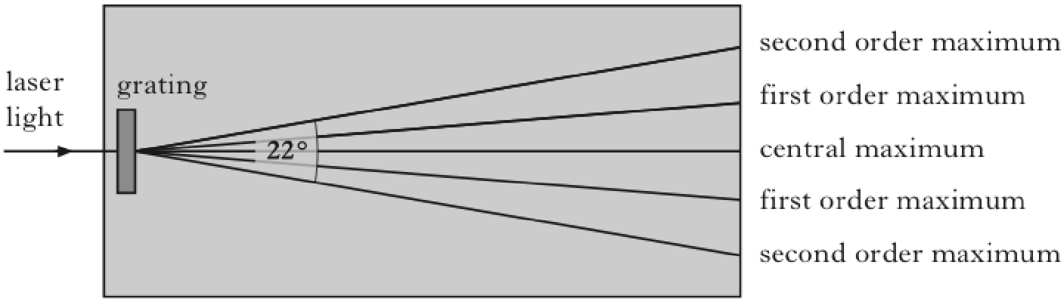
(d) Light of shorter wavelength also passes through the drop of water. Will the critical angle for this light be less than, equal to or greater than for light of wavelength 650nm

Justify your answer.

The critical angle will be less because the refractive index is larger.

SQA 2010 Q 28

Example 31
A grating is placed in a colourless liquid in a container. Laser light is incident on the grating along the normal. The spacing between the linds on the grating is 5 x 10^{-6}m. Interference occurs and the maxima produced are shown in the diagram.



(a) Calculate the wavelength of the laser light in the liquid

$$m\lambda = d \sin\theta \;\; => \;\; 2\lambda = 5\;x\;10^{-6}\;\;x \sin 11 \;\; => \;\; \lambda = 480\;nm$$

(b) The refractive index of the colourless liquid decreases as the temperature of the liquid increases.
The liquid is now heated.
What effect does this have on the spacing between the maxima? You must justify your answer.

The spacing of the maxima increases.
n decreases as liquid is heated.
Since $n = \frac{\lambda_a}{\lambda_s} => \lambda_s = \frac{\lambda_a}{n}$, so wavelength in liquid increases

$m\lambda = d \sin\theta$
sin θ = $\frac{m\lambda}{d}$
θ increases since λ increases

SQA 2011 Q28(b)

Learning Outcomes – Spectra

This builds on information from

Dynamics and Space – Space
Waves and Radiation - Wave characteristics and parameters
- Electromagnetic Spectrum and Light

At the end of this section you should be able to

- State that irradiance is power per unit area incident on a surface.
- Use $I = P/A$ to solve problems involving irradiance, the power of radiation incident on a surface area and the area of the surface.
- State that irradiance is inversely proportional to the square of the distance from a point source
- Use $I = k/d^2$ to solve problems involving irradiance and distance from a point light source.
- Explain what is meant by a point light source
- Explain the difference between what would be observed from a point light source in comparison to light from a laser.
- Describe the Bohr model of the atom.
- Illustrate what is meant by the terms
    - Ground state
    - Energy levels
    - Ionisation level
    - Zero potential energy for the Bohr model of the atom
- Describe what is observed in a line emission spectrum
- Describe what is observed in a continuous emission spectrum.
- Describe what is observed in an absorption spectrum
- Explain the mechanism of production of line emission spectra, continuous emission spectra and absorption spectra.
    - Describe electron energy level transitions for both absorption and emission of radiation
- Use $E_2 - E_1 = hf$ and $E = hf$ to solve problems involving energy levels and the frequency of the radiation emitted/absorbed.
- State that absorption lines in the spectrum of sunlight (Fraunhofer lines) provide evidence for the composition of the Sun's upper atmosphere

Irradiance

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

Where I = Irradiance (Wm^{-2})

P = Power (W)

A = Area (m^2)

Since Power = $\frac{\text{energy}}{\text{time}}$ Irradiance could also be expressed as the amount of light energy incident on each square metre of a surface per second.

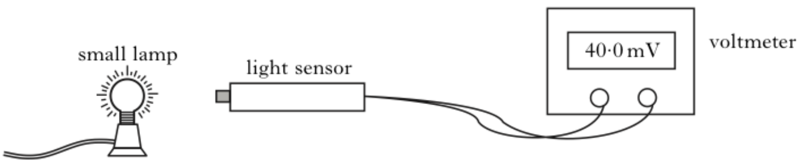
Example 32

A satellite is orbiting the Earth where the irradiance of the Sun's radiation is $1.4 kWm^{-2}$. Calculate the power received by the satellite's solar panels if they have an area of $15 m^2$

$I = \frac{P}{A}$ => $P = IA = 1.4 \times 10^3 \times 15 = 2.1 \times 10^4 W$ AHS H notes

Example 33

The diagram shows a light sensor connected to a voltmeter. A small lamp is placed in front of the sensor.



The reading on the voltmeter is 20 mV for each 1.0 mW of power incident on the sensor.

The reading on the voltmeter is 40.0 mV.

The area of the light sensor is $8.0 \times 10^{-5} m^2$.

Calculate the irradiance of light on the sensor.

40 mV is a power of 2 mW.

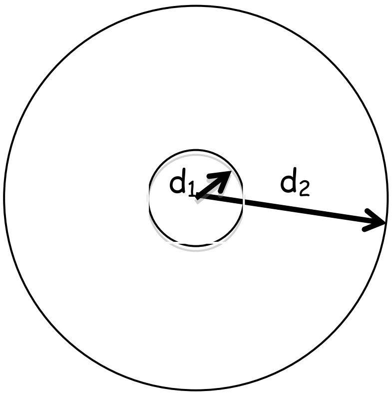
$$I = \frac{P}{A} = \frac{2 \times 10^{-3}}{8.0 \times 10^{-5}} = 25 Wm^{-2}$$

SQA 2008 Q28 (a)

A light is considered a point source if it emits light equally in all directions in three dimensions, creating a sphere around the light source. The source does not have to be small, but its size must be small in comparison to the distance from the observer to the source. This is why stars can be considered point sources.

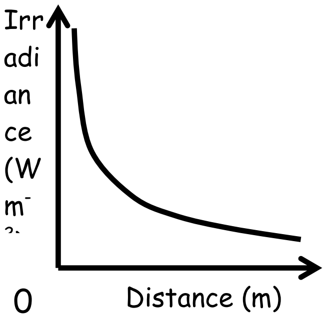
Irradiance and the Inverse Square Law

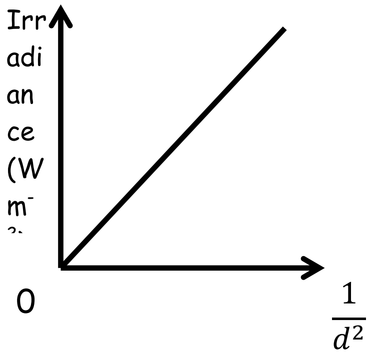
Light radiates out in all directions to make a sphere.



Irradiance is measured at different distances from the source.
The irradiance at distance d_1 is I_1.
The irradiance at distance d_2 is I_2.

A graph of I against d is plotted (graph 1).
A graph of I against $1/d^2$ is plotted (graph 2).





$I \propto \frac{1}{d^2}$ => $I = \frac{k}{d^2}$ => $Id^2 = k$ $\quad$ $I_1 d_1^2 = I_2 d_2^2$

Where I_1 = Irradiance at point 1 (Wm^{-2})
I_2 = Irradiance at point 2 (Wm^{-2})
d_1 = distance to point 1 (m)
d_2 = distance to point 2 (m)

Example 34
A student uses a lamp to investigate how irradiance varies with distance. The results are shown in the table below.

Distance (m)	0.5	0.7	0.9
Irradiance (Wm^{-2})	1.1	0.8	0.6

Can this new source be considered to be a point source of light? Use **all** the data to justify your answer.
For a point source $I_1 d_1^2 = I_2 d_2^2$

Distance (m)	0.5	0.7	0.9
Irradiance (Wm^{-2})	1.1	0.8	0.6
Id^2	0.28	0.39	0.49

Since the values are not equal the light is not a point source.

SQA 2008 Q28 (b)

Irradiance and the Inverse Square Law

Example 35

The irradiance on a wall from a light 0.4m away is 6 Wm^{-2}. What will the irradiance be if the distance is increased to 2m.

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

$$6 \times 0.4^2 = I \times 2^2$$

$$0.96 = 4I$$

$$I = 0.24\ Wm^{-2}$$

AHS H notes

Example 36

The irradiance of light from a point source is 20 Wm^{-2} at a distance of 5.0 m from the source.

What is the irradiance of the light at a distance of 25m from the source?

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

$$20 \times 5^2 = I \times 25^2$$

$$500 = 625I$$

$$I = 0.80\ Wm^{-2}$$

SQA 2011 Q 16 adapted

Example 37

Calculate the irradiance of a 100W light bulb at a distance of 2m.

The light spreads out in all directions .

Surface area of a sphere = $4\pi r^2$ = $4 \times \pi \times 2^2$ = 16π = 50.27 m^2

$$I = \frac{P}{A} = \frac{100}{50.27} = 1.99\ Wm^{-2}$$

AHS H notes

Example 38

The irradiance of light from a point source is 160 units at a distance of 0.50m from the source.

At a distance of 2.0m from this source, the irradiance is

A 160 units

B 80 units

C 40 units

D 10 units

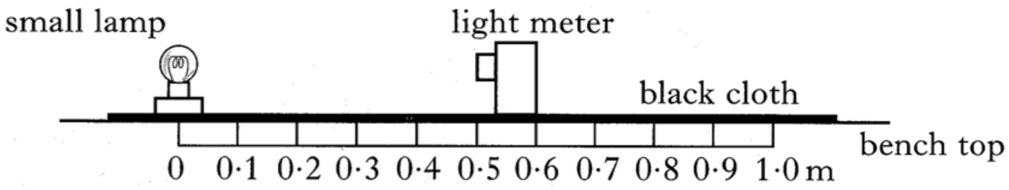
E 5 units

D

SQA 2014 Revised Q14

Example 39

A student carries out an experiment to investigate how irradiance on a surface varies with distance from a small lamp.
Irradiance is measured with a light meter.
The distance between the small lamp and the light level meter is measured with a metre stick.
The apparatus is set up as shown in a darkened laboratory.



The following results are obtained.

Distance from source (m)	0.20	0.30	0.40	0.50
Irradiance (units)	675	302	170	108

(a) What is meant by the term irradiance?

(b) Use **all** the data to find the relationship between irradiance I and distance d from the sourse.

(c) What is the purpose of the black cloth on top of the bench?

(d) A small lamp is replaced by a laser.
Light from the laser is shone onto the light meter.
A reading is taken from the light meter when the distance between it and the laser is 0.50 m
The distance is now increased to 1.00 m.
State how the new reading on the light meter compares with the one taken at 0.50m
Justify your answer.

(a) energy per second/power incident per square metre/on unit area

(b)

Distance from source (m)	0.20	0.30	0.40	0.50
Irradiance (units)	675	302	170	108
$I\ d^2$	27.0	27.2	27.2	27.0

Id^2 = constant $\qquad Id^2 = 27$

(c) Black cloth absorbs light/Black cloth prevents reflections from the bench top.OR Meter receives light only from the bulb

(d) (approximately) the same reading. Laser beam does not spread out/ diverge/ is parallel.

SQA 2006 Q 28

Irradiance of Photons and Radiation

Since $E = hf$ then $E_{total} = Nhf$

Since $P = \frac{E}{t}$ then $P = \frac{Nhf}{t}$

Since t = 1s, P = Nhf

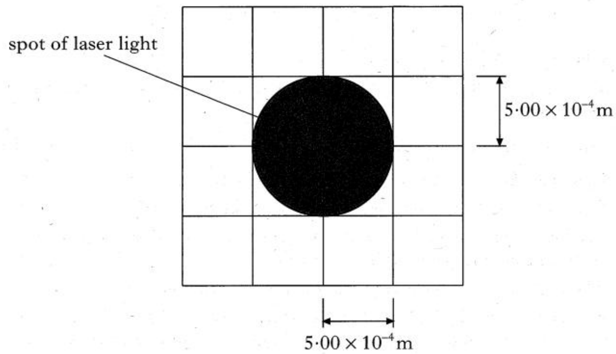
Since $I = \frac{P}{A}$ then $I = \frac{Nhf}{A}$

Since A = 1 m^2, I = Nhf

P = power (W)
E = Energy (J)
t = time (s)
h = Planck's constant
6.63×10^{-34} Js
f = frequency (Hz)
N = number of photons per second per m^2

Example 40

A laser beam is shone onto a screen which is marked with a grid. The beam produces a uniformly lit spot of radius 5.00×10^{-4}m as shown.



(a) The intensity of the spot of light on the screen is 1020 Wm^{-2}. Calculate the power of the laser beam.

(b) The distance between the screen and the laser beam is now doubled. State how the radius of the spot now compares with the one shown in the diagram.
You must justify your answer.

(a) Area = $\pi r^2 = 3.14 \times (5 \times 10^{-4})^2 = 7.85 \times 10^{-7}$ m^2
P = IA = $1020 \times 7.85 \times 10^{-7} = 8 \times 10^{-4}$ W

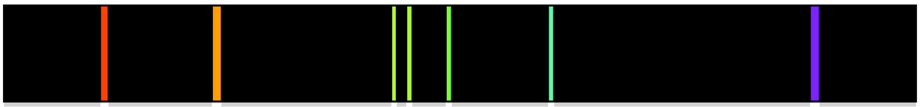
(b) The radius is approximately the same because the laser light is nearly parallel. (it is not a point source)
OR
The radius is slightly greater since the beam diverges a little.

SQA 2008 Q23

PW Problem Booklet 2
P9 Q 1 -5

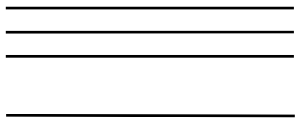
Line Spectra

Each element produces an individual line spectrum. This can be observed using a spectrometer and can be used to identify the element's presence.

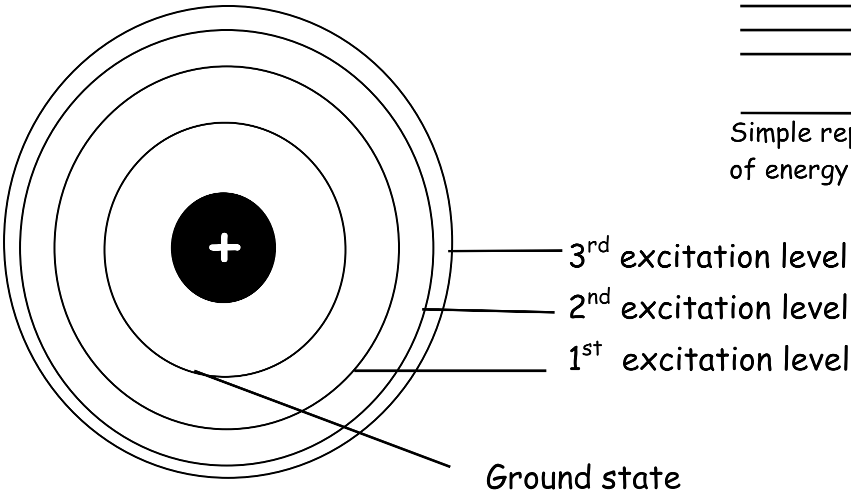


Emission Line spectrum for Helium

The Bohr model of the atom proposes that electrons occupy orbits at particular radii corresponding to particular energy states.



Simple representation of energy levels

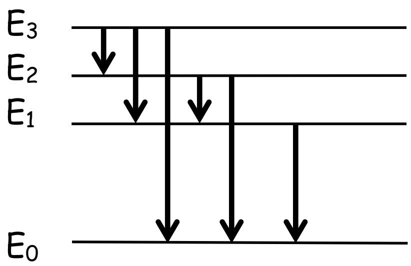


Ground state (E_0) is the orbit nearest the nucleus. This is where the electron has its lowest energy.

Excited states – electrons in higher energy levels

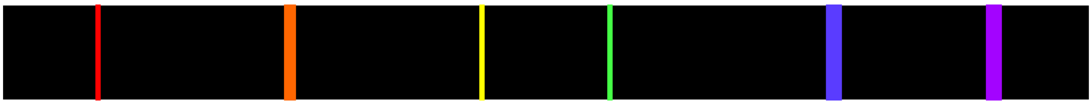
Ionisation level – this is where electrons gain enough energy to escape from the atom completely. By convention the electron is said to have zero energy when this happens meaning that the other levels have negative energy levels.

To move up an energy level – the electron needs energy.
To move down an energy level – the electron gives off energy as a photon.



When electrons drop down from a higher energy state to a lower energy state a photon of light is emitted.
There are six possible jumps corresponding to six lines in the line spectrum.

Line Spectra

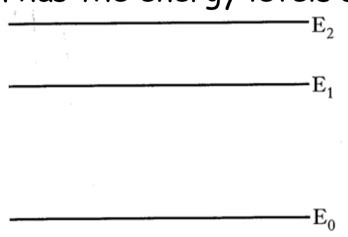


If many electrons make the same jump the spectral line corresponding to that frequency will be bright because many photons are being emitted. The more excitation levels, the more possible jumps.

NOTE – transitions occur from one level to another – partial values are not possible

Example 41

An atom has the energy levels shown.

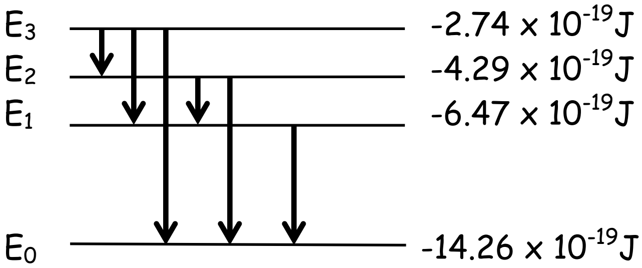


Electron transitions occur between all of these levels to produce emissions lines in the spectrum of this atom.

How many emission lines are produced by transitions between these energy levels?

3 emission lines. SQA 2004 Q16 (adapted)

Since the lines represent an energy state we can predict the energy needed to move up between levels or the energy released as a photon when an electron moves down between levels.



The move between E_2 and E_1 releases energy. We can predict the frequency of the light associated with this photon using $E = hf$

$$E_2 - E_1 = hf$$

$$(-4.29 \times 10^{-19}) - (-6.47 \times 10^{-19}) = 6.63 \times 10^{-34} \times f$$

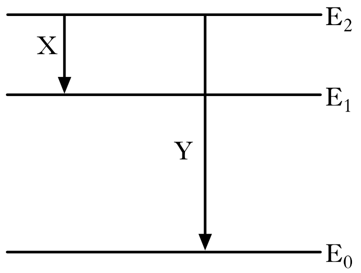
$$f = \frac{2.18 \times 10^{-19}}{6.63 \times 10^{-34}} = 3.29 \times 10^{14}\text{Hz}$$

Note – to calculate the energy this is the same as [6.47 – 4.29]

Line Spectra

Example 42

Part of the energy level diagram for an atom is shown.



X and Y represent two possible electron transitions.

Which of the following statements is/are correct?

I. Transition Y produces photons of higher frequency than transition X.

II. Transition X produces photons of longer wavelength than transition Y.

III. When an electron is in the energy level E_0, the atom is ionised.

A I only

B I and II only

C I and III only

D II and III only

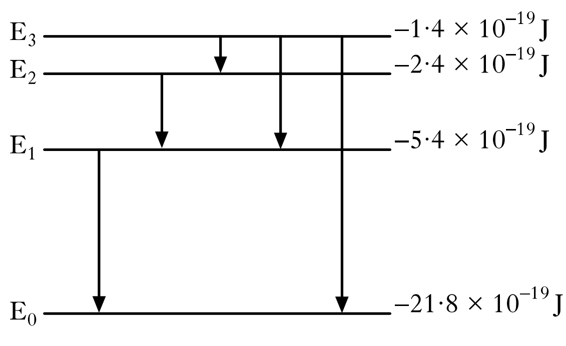
E I, II and III only

B

SQA 2008 Q 17

Example 43

The diagram represents some electron transitions between energy levels in an atom.



The radiation emitted with the shortest wavelength is produced by an electron making the transition

A E_1 to E_0

B E_2 to E_1

C E_3 to E_2

D E_3 to E_1

E E_3 to E_0

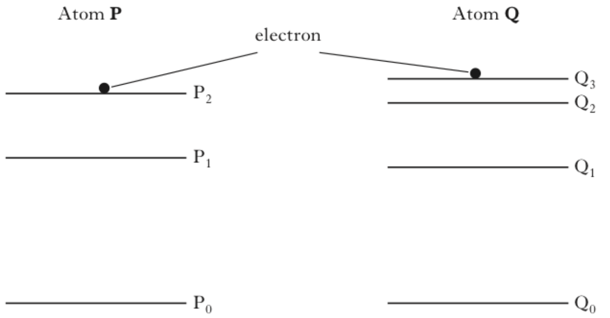
E

SQA 2007 Q 17

Line Spectra

Example 44

The following diagrams represent some of the energy levels for two difference atoms P and Q. The diagrams are drawn to the same scale.



Electrons are continuously excited to levels P_2 and Q_3. When electrons make transitions to lower energy levels, photons of light are emitted. This light is observed as various lines in the emission spectrum of each atom.

(a) For atom Q, determine the number of lines in the emission spectrum for the energy levels shown.

6

(b) Considering both atoms, identify the transition that produces radiation of the lowest frequency.

Q_3 to Q_2 (NOT between Q_3 and Q_2)

(c) The table shows information about the energy levels in atom P.

Energy Level	Energy (J)
P_2	-2.4×10^{-19}
P_1	-5.4×10^{-19}
P_0	-21.8×10^{-19}

Calculate the shortest wavelength of radiation emitted from atom P.

Shortest wavelength corresponds to highest frequency.

P_2 to P_0

$\Delta E = (21.8 - 2.4) \times 10^{-19}$

$= 1.94 \times 10^{-18}$ J

E = hf and v = fλ

$E = h\frac{v}{\lambda}$ and $\lambda = \frac{hv}{E}$

$$\lambda = \frac{6.63 \ x\ 10^{-34} x\ 3\ x\ 10^{8}}{1.94\ x\ 10^{-18}}$$

$\lambda = 1.03\ x\ 10^{-7}$ m

SQA 2014 Q31

Example 44 (continued)

(d) (i) The emission line due to the transition from $P_2$to P_1 is the same colour as the emission line from Q_2toQ_1. Explain this observation

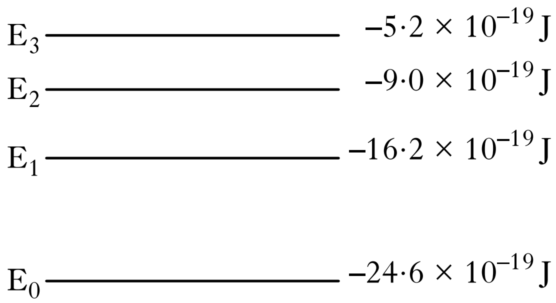
Energy gap **same** size (not similar)
Frequency of light emitted is same

(ii) The emission line due to the transition $P_2$to P_1 is brighter than the emission line from Q_2toQ_1. Explain this observation

($P_2$to P_1 is brighter because) **more** electrons make this transition **per second** and so more photons are emitted per second.
NOTE – a description of rate needs to be mentioned at least once

SQA 2014 Q31

Example 45
The following diagram shows some of the energy levels for a particular atom.



An electron is excited from energy levels E_2 to E_3 by absorbing light energy.
What frequency of light is used to excite this electron?

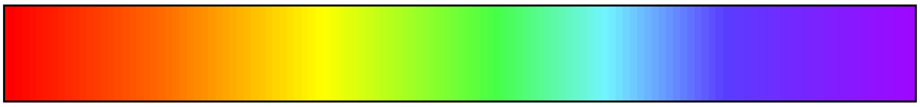
$\Delta E = hf$ or $W_2 - W_1 = hf$

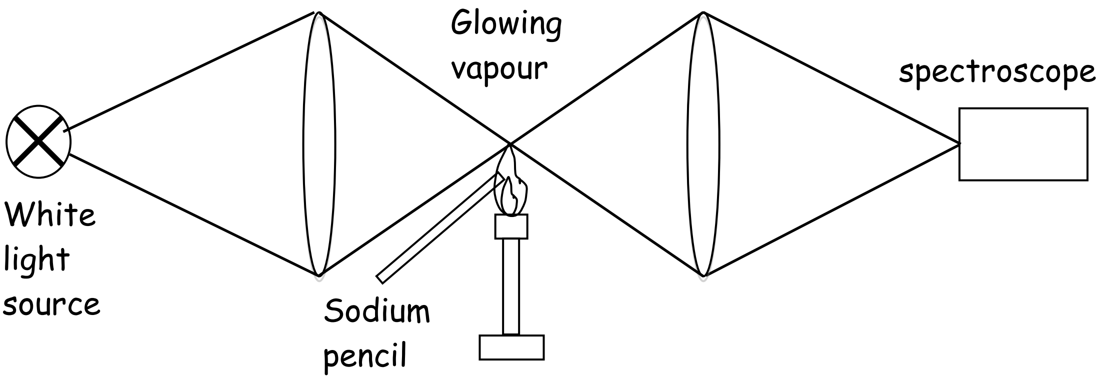
$-5.2 \times 10^{-19} - (-9.0 \times 10^{-19}) = 6.63 \times 10^{-34} \times f$
$f = 5.7 \times 10^{14}$Hz

SQA 2010 Q15 adapted

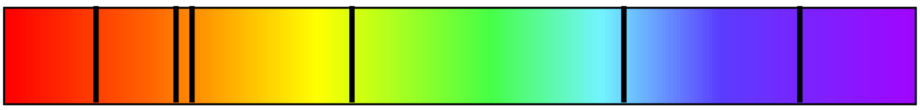
Absorption Spectra

White light causes a continuous spectrum when observed through a spectroscope or spectrometer.





When white light is passed through a coloured filter or a vapour the frequencies of light corresponding to the energy level transitions for that material are absorbed. This causes black lines on the continuous spectrum.



Fraunhofer Lines

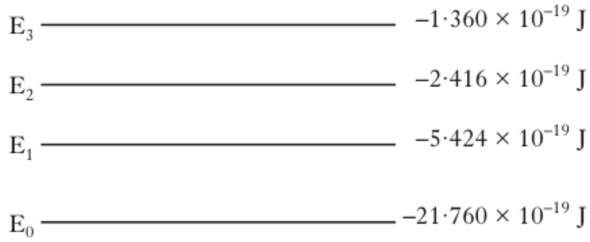
When the sun is observed through a spectroscope and absorption spectrum is produced. Gases present in the outer part of the sun absorb photons of particular frequency and this is what produces the absorption lines. They correspond to the emission lines of particular elements.
As a result the elements present in the atmosphere of the sun can be identified.
(Named after the German physicist who identified over 500 of these lines)

Absorption Spectra

Example 46

The Sun emits a continuous spectrum of visible light. When this light passes through hydrogen atoms in the Sun's outer atmosphere, certain wavelengths are absorbed.

The diagram shows some of the energy levels for the hydrogen atom.



(a) One of the wavelengths absorbed by the hydrogen atoms results in an electron transition from energy level E_1 to E_3. Calculate this wavelength.

Energy absorbed = $E_3 - E_1$

$= -1.360 \times 10^{-19} - (-5.424 \times 10^{-19})$

$= 4.064 \times 10^{-19}$ J

$E = hf$

$4.064 \times 10^{-19} = 6.63 \times 10^{-34} \times f$

$f = 6.13 \times 10^{14}$ Hz

$\lambda = \frac{c}{f} = \frac{3 \, x \, 10^{8}}{6.13 \, x \, 10^{14}}$ = 489 nm

(b) The absorption of this wavelength produces a faint dark line in the continuous spectrum from the Sun. In which colour of the spectrum is this dark line observed?

The light is blue or blue-green (NOT green).

OR consistent with (a) as long as in the visible spectrum.

(Data sheet 480 nm = blue, 486 nm blue-green, 509 nm green)

SQA 2011 Q30 (b)

Absorption Spectra

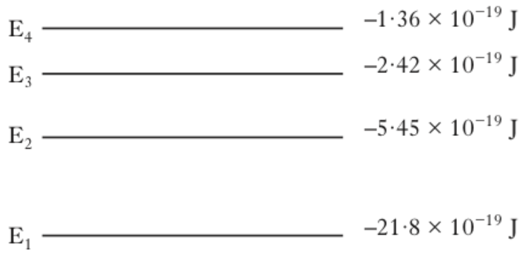
Example 47

A binary star is a star system consisting of two stars orbiting around each other.

One of the techniques astronomers use to detect binary stars is to examine the spectrum of light emitted by the stars. In particular they look for the changes in wavelength of a specific line called the hydrogen alpha line, over a period of time.

Accurate measurements of the wavelength of the hydrogen alpha line on Earth have determined it to be 656.28 nm.

The following diagram shows some of the energy levels for the hydrogen atom.



Radiation is emitted when electrons make transitions from higher to lower energy levels.

Which transition, between these energy levels, produces the hydrogen alpha line?

Justify your answer by calculation.

$$f = \frac{v}{\lambda} = \frac{3\ x\ 10^{8}}{656.28\ x\ 10^{-9}} = 4.57 \times 10^{14}\ \text{Hz}$$

$E = hf = 4.57 \times 10^{14} \times 6.63 \times 10^{-34} = 3.03 \times 10^{-19}$ J

This corresponds to the transition from E_3 to E_2 OR [$E_3 \rightarrow E_2$]

NOTE

[Mark not awarded if written E_2 to E_3 or as E_3 - E_2]

SQA 2014 Q25a

PW Problem Booklet 2
P10 Q 1 - 8

Laser

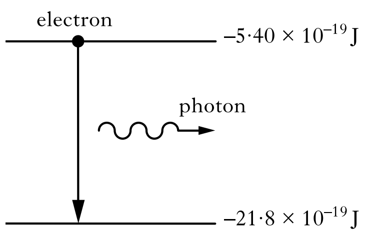
Electrons at a higher energy level are described as 'excited'. When they drop down to a lower energy level a photon is emitted. This can happen spontaneously, but can also be made to happen in a process called 'stimulated emission of radiation'.

Light Amplification (by the) Stimulated Emission (of) Radiation or LASER is an example of a device which uses this process.

Energy supplied to the material the laser is made from causes electrons to become excited. A photon of light stimulates these electrons at a higher energy level to drop down to a lower energy level, releasing more photons. These photons have the same frequency, same direction and are in phase with the photon causing their release, so can be described as coherent. More and more photons are emitted, creating the laser beam. Part of the beam is reflected back inside the laser.
Energy is supplied to the laser to cause electrons to go back to a higher energy level. The reflected photons are used to keep the process going.

The beam created by a laser is monochromatic, intense and does not spread out in the same way as a point source.

Example 48
In an atom, a photon of radiation is emitted when an electron makes a transition from a higher energy level to a lower energy level as shown



The wavelength of the radiation emitted due to an electron transition between the two energy levels is.

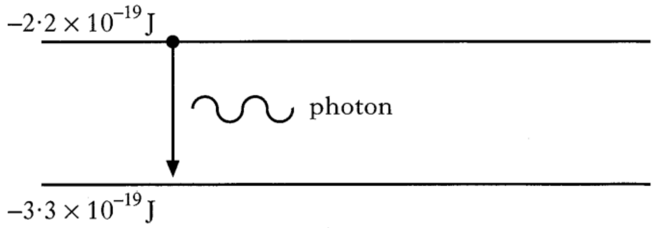
A 1.2×10^{-7} m
B 7.3×10^{-8} m
C 8.2×10^{6} m
D 1.4×10^{7} m
E 2.5×10^{15} m

SQA 2012 Q 12

Laser

Example 49

In a laser, a photon of radiation is emitted when an electron makes a transition from a higher energy level to a lower level, as shown below.



The energy in each pulse of radiation from the laser is 10J. How many photons are there in each pulse?

Energy difference = $-2.2 \times 10^{-19} - (-3.3 \times 10^{-19}) = 1.1 \times 10^{-19}$J

Number of photons = $\frac{10}{1.1 \, x \, 10^{-19}} = 9.1 \times 10^{19}$

SQA 2002 Q 17 (adapted)

Example 50

A laser produces a beam of light with a frequency of 4.74×10^{14}Hz.

(a) The laser has a power of 0.10mW. Explain why light from this laser can cause eye damage.

Very small area/diameter/radius
So
High irradiance because I = P/A

(b) Calculate the energy of each photon in the laser beam.

$E = hf$
$= 6.63 \times 10^{-34} \times 4.74 \times 10^{14}$
$= 3.14 \times 10^{-19}$J

SQA 2010 Q 29 (a), (b)