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3.4 Diffraction

PHYSICS

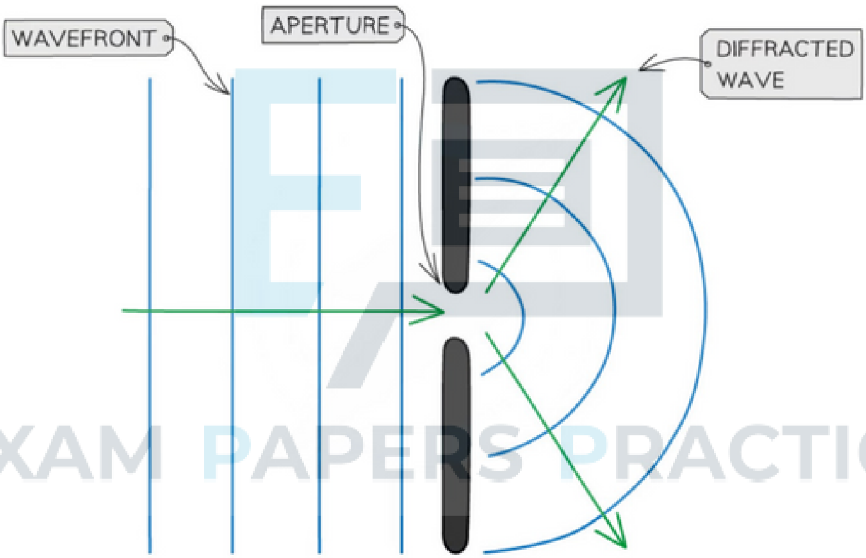
AQA A Level Revision Notes

3.4 Diffraction

CONTENTS

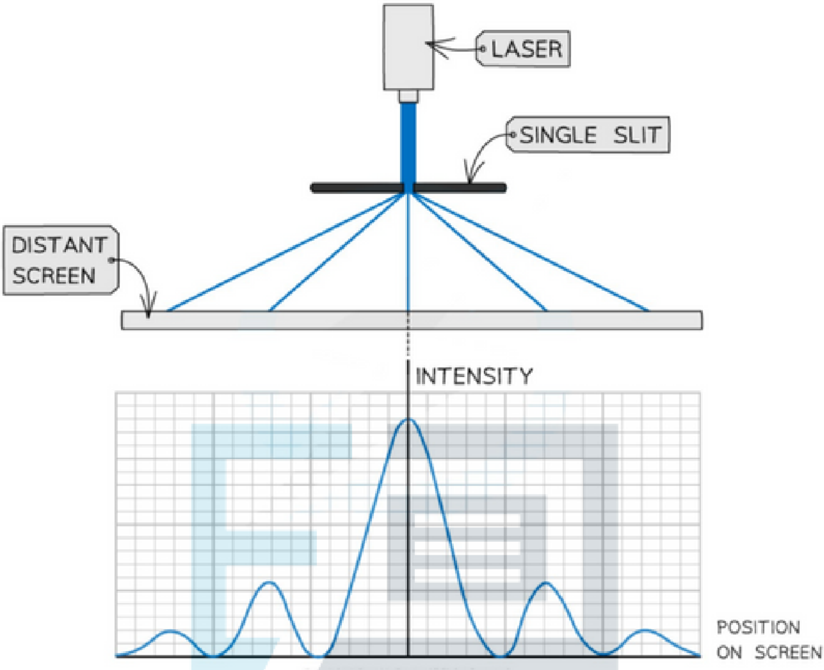
Diffraction

- Diffraction is the **spreading out** of waves when they pass an obstruction
  - This obstruction is typically a narrow slit known as an aperture
- The extent of diffraction depends on the width of the gap compared with the wavelength of the waves
  - Diffraction is the most prominent when the width of the slit is approximately **equal** to the wavelength



Diffraction: when waves pass through a narrow gap, they spread out

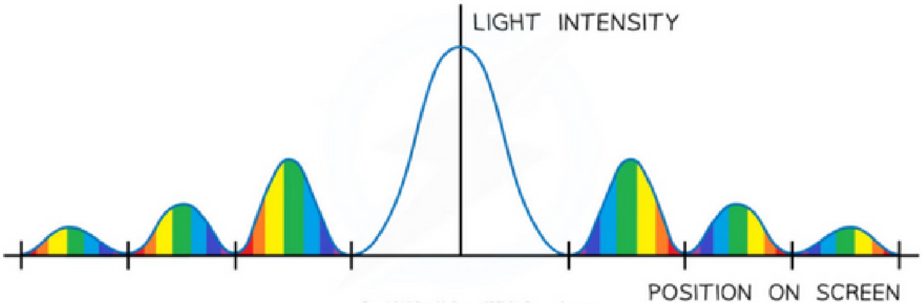
- Diffraction is usually represented by a wavefront as shown by the vertical lines in the diagram above
- The only property of a wave that changes when it diffracts is its **amplitude**
  - This is because some energy is dissipated when a wave is diffracted through a gap
- The **diffraction pattern** of light can be represented as a series of light and dark fringes which show the areas of maximum and minimum intensity
- If a laser emitting blue light is directed at a single slit, where the slit width is larger than the wavelength of the light, it will spread out as follows:



The intensity pattern of blue laser light diffracted through a single slit

- The features of the single slit diffraction pattern are:
  - A central maximum with a high intensity
  - Subsidiary maxima equally spaced, successively smaller in intensity and half the width of the central maximum

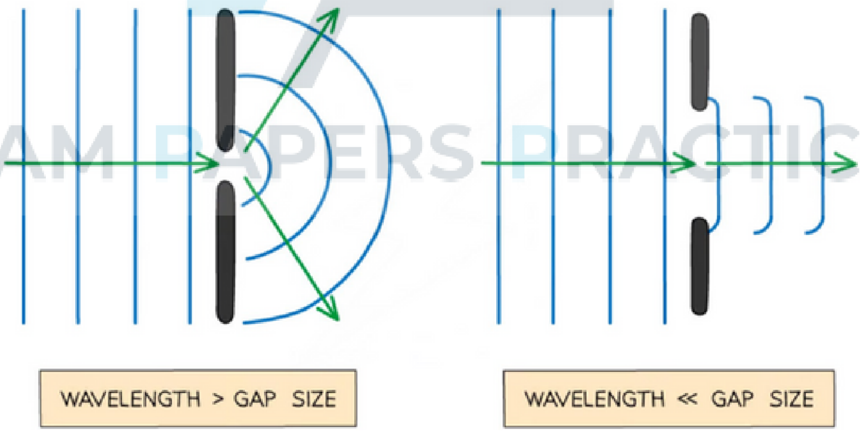
- If the laser were to be replaced by a non-laser source emitting white light:
  - The central maximum would be **white**
  - All maxima would be composed of a **spectrum**
  - The shortest wavelength (violet / blue) would appear **nearest** to the central maximum
  - The longest wavelength (red) would appear **furthest** from the central maximum
  - The fringe spacing would be smaller and the maxima would be wider



Qualitative treatment of the variation of the width of the central diffraction maximum with wavelength and slit width

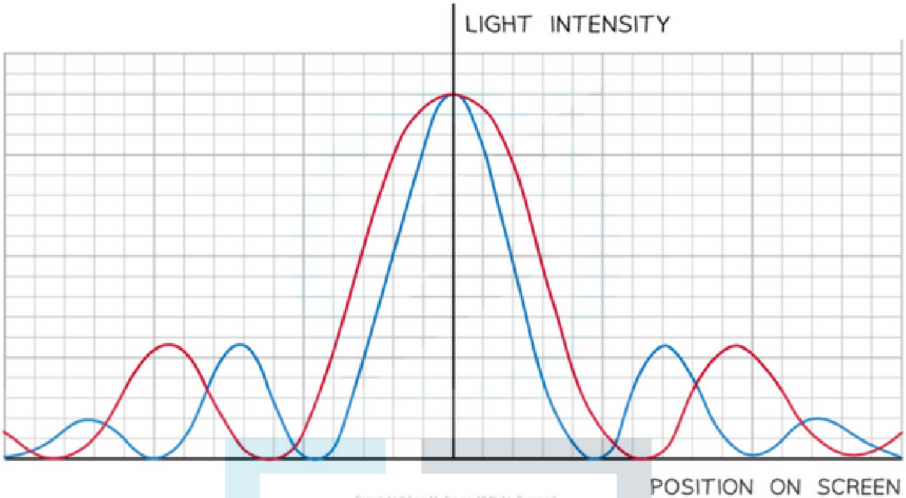
Single Slit Diffraction

- As discussed above, the effects of diffraction are most prominent when the gap size is approximately the same or smaller than the wavelength of the wave
- As the gap size increases, the effect gradually gets less pronounced until, in the case that the gap is much larger than the wavelength, the waves are no longer spread out



The size of the gap (compared to the wavelength) affects how much the waves spread out when diffracted

- If the blue laser were to be replaced with a red laser:
  - The wavelength of red light is longer so the light would diffract **more**
  - The intensity fringes would therefore be **wider**



The intensity pattern of red laser light shows longer wavelengths diffract more than shorter wavelengths

- If the slit was made narrower:
  - The intensity would **decrease**
  - The fringe spacing would be **wider**

Worked Example

When a wave is travelling through air, which scenario best demonstrates diffraction?

A. UV radiation through a gate post

B. Sound waves passing a steel rod

C. Radio waves passing between human hair

D. X-rays passing through atoms in a crystalline solid

ANSWER: D

- Diffraction is most prominent when the wavelength is close to the aperture size
- UV waves have a wavelength between $4 \times 10^{-7} - 1 \times 10^{-8}$ m so won't be diffracted by a gate post
- Sound waves have a wavelength of $1.72 \times 10^{-2} - 17$ m so would not be diffracted by the diffraction grating
- Radio waves have a wavelength of $0.1 - 10^{6}$ m so would not be diffracted by human hair
- X-rays have a wavelength of $1 \times 10^{-8} - 4 \times 10^{-13}$ m which is roughly the gap between atoms in a crystalline solid
  - Therefore, the correct answer is **D**

Exam Tip

When drawing diffracted waves, take care to keep the wavelength (the distance between each wavefront) constant. It is only the amplitude of the wave that changes when diffracted.

3.4.2 The Diffraction Grating

The Diffraction Grating

- A diffraction grating is a plate on which there is a **very large** number of parallel, identical, close-spaced slits
- When monochromatic light is incident on a grating, a pattern of narrow bright fringes is

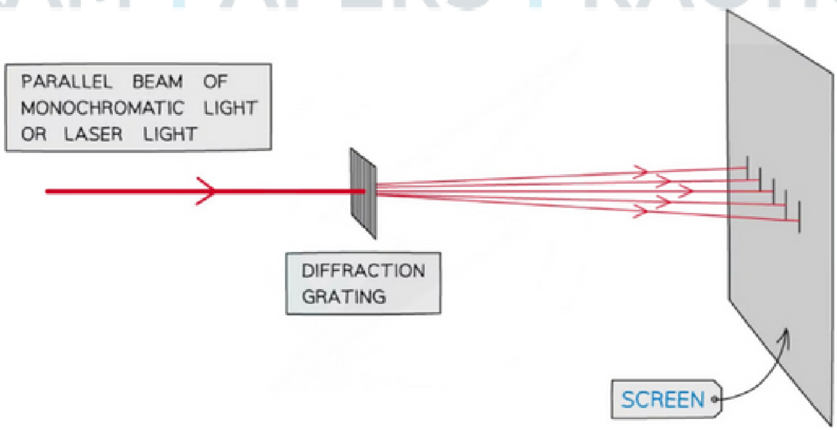
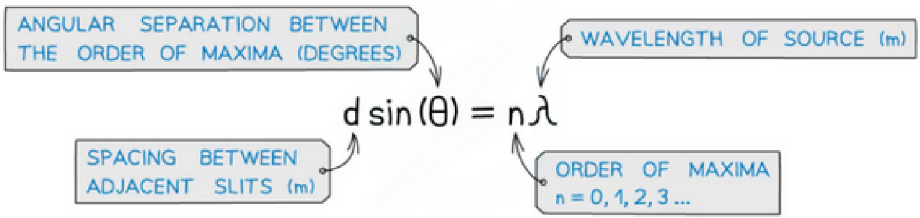


Diagram of diffraction grating used to obtain a fringe pattern

- The angles at which the maxima of intensity (constructive interference) are produced can be deduced by the diffraction grating equation:

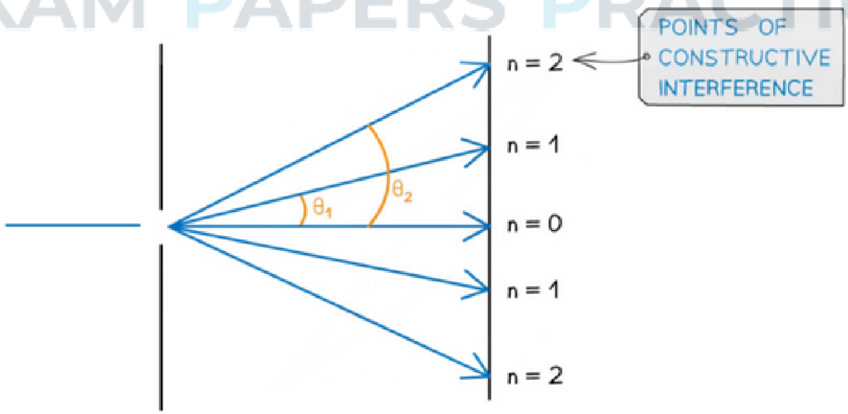


- Exam questions sometime state the **lines per m** (or per mm, per nm etc.) on the grating which is represented by the symbol *N*
- *d* can be calculated from *N* using the equation

$$d = \frac{1}{N}$$

Angular Separation

- The angular separation of each maxima is calculated by rearranging the grating equation to make θ the subject
- The angle θ is taken from the centre meaning the higher orders are at greater angles



Angular separation

- The angular separation between two angles is found by subtracting the smaller angle from the larger one
- The angular separation between the first and second maxima n_1 and n_2 is $\theta_2 - \theta_1$

Orders of Maxima

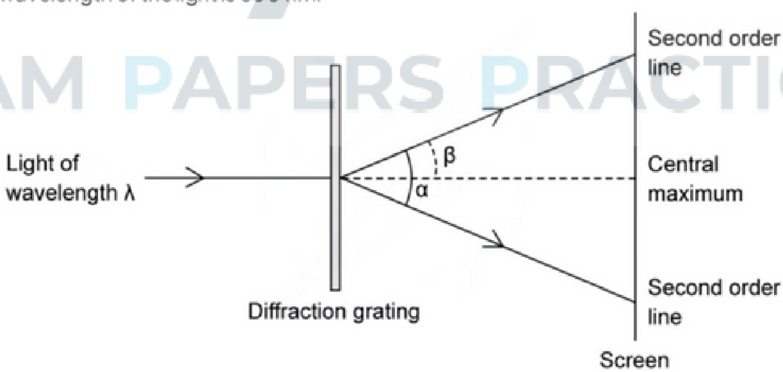
- The maximum angle to see orders of maxima is when the beam is at right angles to the diffraction grating
  - This means $\theta = 90^o$ and $\sin\theta = 1$
- The highest order of maxima visible is therefore calculated by the equation:

$$n = \frac{d}{\lambda}$$

- Note that since n must be an integer, if the value is a decimal it must be rounded **down**
  - E.g If n is calculated as 2.7 then $n = 2$ is the highest order visible

Worked Example

An experiment was set up to investigate light passing through a diffraction grating with a slit spacing of 1.7 μm. The fringe pattern was observed on a screen. The wavelength of the light is 550 nm.



Calculate the angle α between the two second-order lines.

STEP 1

DIFFRACTION GRATING EQUATION

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

$n = 2$ FOR THE SECOND ORDER LINE

$D = 1.7\ \mu m$

$\lambda = 550\ nm$

STEP 2

REARRANGE FOR $\sin(\theta)$

$$\sin(\theta) = \frac{n\lambda}{d}$$

STEP 3

SUBSTITUTE IN VALUES

$$\sin(\theta) = \frac{2 \times 550 \times 10^{-9}}{1.7 \times 10^{-6}} = 0.64705... = 0.65 \ (2\ s.f.)$$

STEP 4

FIND θ THROUGH THE INVERSE SINE

$$\sin^{-1}(0.65) = 40.54^{\circ}$$

STEP 5

θ IS ANGLE FROM THE CENTRE TO THE SECOND ORDER LINE (β ON THE DIAGRAM)

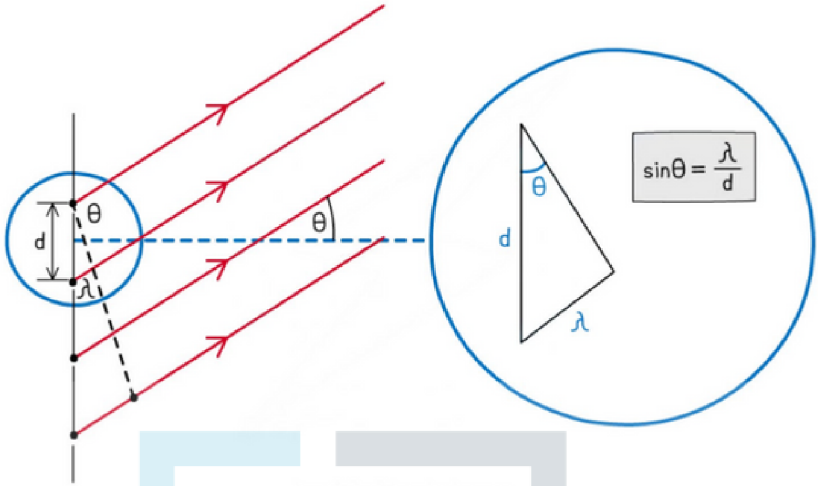
$$\alpha = \theta \times 2 = 81^{\circ} \ (2\ s.f.)$$

Exam Tip

Take care that the angle θ is the correct angle taken from the centre and **not** the angle taken between two orders of maxima.

Derivation of the Diffraction Grating Equation

- When light passes through the slits of the diffraction grating, the path difference at the zeroth order maximum is zero
- At the first order maxima, there is constructive interference, hence the path difference is λ
- Therefore, at the nth order maxima, the path difference is equal to $n\lambda$



Using this diagram and trigonometry, the diffraction grating equation can be derived

- Using trigonometry, an expression for the first order maxima can be written:

$$\sin\theta = \frac{\lambda}{d}$$

- Where:
  - θ = the angle between the normal and the maxima
  - λ = the wavelength of the light (m)
  - d = the slit separation (m)

- This means, for n = 1:

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

- Similarly, for n = 2, where the path difference is 2λ:

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

- Therefore, in general, where the path difference is $n\lambda$:

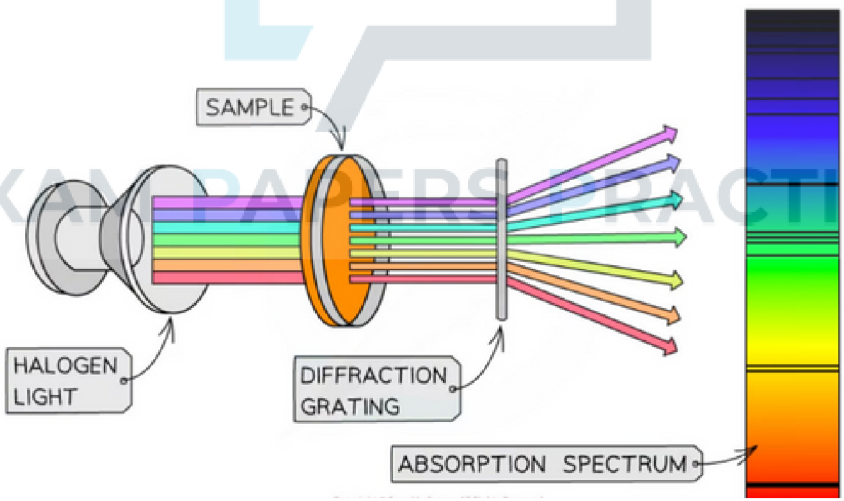
$$\sin\theta_n = \frac{n\lambda}{d}$$

- A small rearrangement leads to the equation for the diffraction grating:

$$d\sin\theta_n = n\lambda$$

Applications of Diffraction Gratings

- Diffraction gratings are useful for separating light of different wavelengths with high resolution
- They are used in spectrometers to:
  - Analyse light from stars
  - Analyse the composition of a star
  - Chemical analysis
  - Measure red shift / rotation of stars
  - Measure the wavelength / frequency of light from a star
  - Observe the spectra of materials
  - Analyse the absorption / emission spectra in stars
- Diffraction gratings also play a role in x-ray crystallography
  - X-rays are directed at a thin crystal sheet which acts as a diffraction grating to form a diffraction pattern
  - This is because the wavelength of x-rays is similar in size to the gaps between the atoms
  - This diffraction pattern can be used to measure the atomic spacing in certain materials



Diffraction gratings are most commonly used in spectrometers. These devices play a crucial role in areas of physics such as atomic physics and astrophysics

Exam Tip

Note that while you will be expected to know some applications of diffraction gratings, you will **not** be tested on specific apparatus or techniques such as spectrometry.When describing the use of spectrometers, avoiding using vague terms such as observe spectra', 'spectroscopy', 'view absorption / emission spectrum', 'compare spectra', 'look at light from stars'.