Physics Factsheet
www.curriculum-press.co.uk Number 264

Investigation of Interference Effects in Light – Young´s Slits and Diffraction Grating

All A Level specifications place emphasis on experimental skills and techniques. While you will not be required to do a practical exam, you will be expected to have carried out experiments and investigations and acquired skills. There will be questions on these skills on the A Level papers.

This Factsheet looks at the investigation of interference effects in light with Young´s Slits and a Diffraction Grating. The experiments themselves address "Apparatus and Technique Reference Areas" a, c, e, and j (using analogue instruments to take measurements, being aware of ways of increasing accuracy, using calipers and/or micrometers, and using laser and/or other light sources, slits and diffraction gratings). It will also cover other aspects of the practical procedures requirements for all specifications.

> ***Exam Hint:*** *There will be questions about experimental techniques on the A Level papers.*

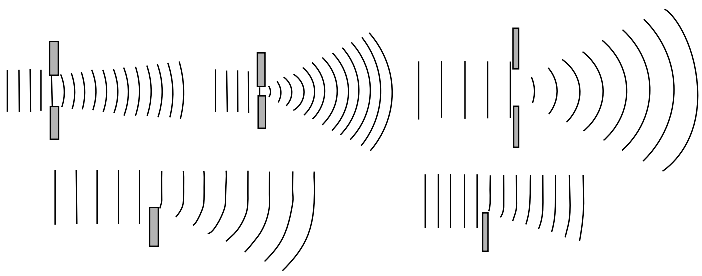
The types of question will fall into 1 of 4 categories:
1. Questions set in a practical context, but centring on the science, not the practical considerations.
2. Questions requiring aspects of the practical procedure to be understood, in order to answer the question about the underlying science.
3. Questions directly on the required practical procedures.
4. Questions involving applying skills from the "Required Practical Procedure Apparatus and Techniques" list.

Nature of Light
Light exhibits effects which are characteristic of waves, and was for a time considered to be absolutely a wave. More recent experiments demonstrated results which are characteristic of a stream of particles and light is now considered to be a sort of hybrid of waves and particles; a concept known as the "Wave-Particle Duality".

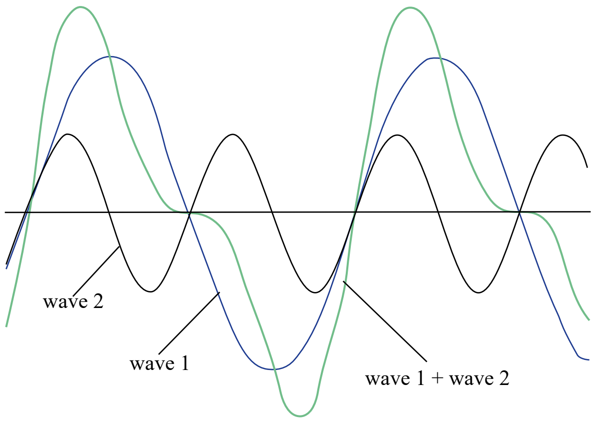
This Factsheet concentrates on the wave characteristics of light.

> *Test your understanding:*
> *1. From your GCSE knowledge, state 2 effects which are characteristic of waves.*

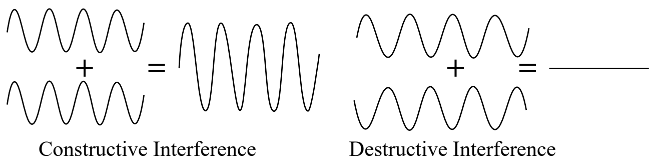
Basic Ideas
1. Light is an ***Electromagnetic wave*** – a travelling series of changing electric and magnetic fields.
2. **Diffraction** is the spreading out of a wave through a gap or around an edge.



3. **Superposition**
The Principle of Superposition states that if two waves occupy the same space the total displacement at any point is the sum of the contributions from the two individual waves.



4. **Constructive and *Destructive* Interference**
For the particular case in which the two waves are of the ***same frequency*** and either ***in-phase*** or completely ***out-of-phase*** then ***constructive*** or ***destructive*** interference results.



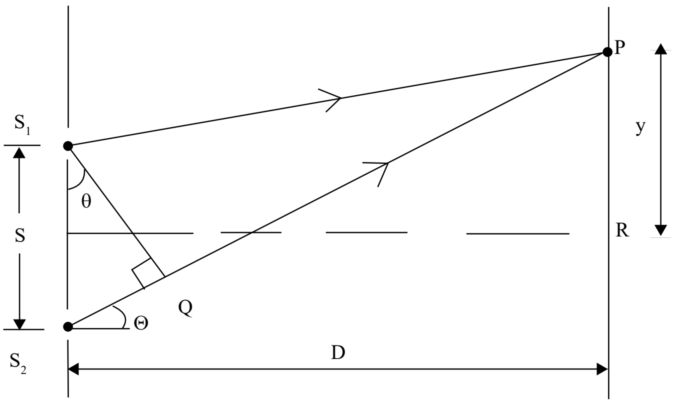
Constructive interference results in a wave with the sum of the amplitudes of the original waves (i.e. double if they were of the same amplitude), and destructive interference in a zero wave if they were of the same amplitude.

5. **Interference Patterns**
An interference pattern will result if waves from 2 slits reach a distant screen, having travelled different length paths to the same place on the screen, giving constructive interference in some places and destructive interference in others. However, in practice, for the pattern to be visible and remain stable, the following conditions must be met:
(i) The 2 sources must be **coherent**. That is, they must have the same wavelength and have a constant phase relation between them. With white light, the 2 slits must receive light from a **single source** because there are random phase shifts in light every few seconds that would destroy the pattern. This is achieved by having light from a single source, passing through a single slit and then through the double slit. Alternatively, light from a laser can be used since this does not suffer the random shifts.
(ii) The distance between the slits should be of the same order of magnitude as the wavelength of light.

(iii)The distance between the slits must be small compared to the distance to the screen. This is because approximations are used in the theory which do not hold unless this condition is met.

The Theory

Consider the set-up below:



Waves from S_1 and S_2 travel to the point P. The wave from S_2 has travelled an extra distance, S_2Q, compared to the wave from S_1. Provided the waves are coherent, if S_2Q is a whole number of wavelengths then the waves arriving at P from S_1 will always interfere constructively with those from S_2 and the point P will be a bright spot. If the distance S_2Q is an odd number of half-wavelengths then the waves at P will always interfere destructively and P will be a dark spot. The resulting interference pattern will be a series of equally spaced light and dark fringes.

Young´s fringes in red light.

For a stable pattern, the sources must be coherent. The slit width, s must be same order of magnitude as λ, D must be large compared to s.

Test your understanding:
2. What is meant by "coherence" of two light sources?
3. What conditions must be met to achieve a stable interference pattern?

The Formula

For the point P to be a first bright fringe:

$S_2Q = \lambda$ where λ is the wavelength of the light.

From the diagram $\sin\Theta = S_2Q / s$ where s is the slit width.

But ***provided D is much larger than s,*** then, to a good approximation, $\sin\Theta = y/D$ where y is the fringe separation.

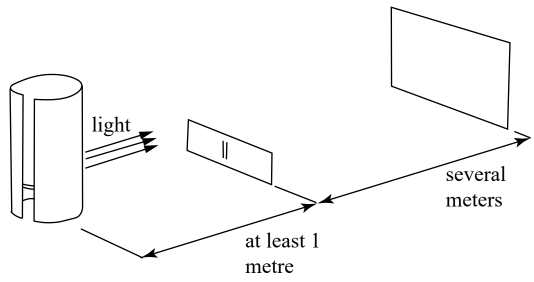
So $\lambda = s\sin\Theta = sy/D$

For a Young´s Double Slit pattern

$\lambda = sy/D$

Wavelength of light — Slit separation — Fringe separation — Distance to screen

All units m. (Remember to change any given units as required).



1. The shaded lamp has a single slit.
2. The double slit is at least a metre from the lamp.
3. The screen is several metres from the double slit.
4. The experiment would need to be performed in a darkened room.
5. Using laser light would give monochrome fringes and could be done in a semi-darkened room.

BUT take care using a laser. Ensure that no-one is in the path of the laser or looks along the beam.

Test your understanding:
4. A student is intrigued with the Young´s Slit experiment and decides to try it at home using car headlights as the two light sources. Give reasons why he will not achieve a visible pattern.

Worked example

You have been given a worksheet by your teacher to carry out an investigation to find the wavelength of the light from a laser, but it only gives the outline of the set-up as above; you have to make decisions as to what to measure and how to measure it.

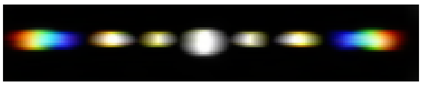
1. *What will you measure?*
2. *Explain how you will carry out each measurement.*
3. *Choose one of your measurements and explain how the method you have chosen is more accurate than an alternative method of doing it.*
4. *Explain any necessary safety precautions.*
5. *Explain how you will calculate the value of the wavelength from your measurements.*

Answers:

1. *(a) The slit width, s*
   (b) The distance D from double slit to the screen
   (c) The fringe separation, y
2. *(a) The slit width is probably marked on the double slit by the manufacturers.*
   (b) I would measure D with an athletics tape or similar long tape measure.
   (c) I would determine the fringe separation using a travelling microscope. I would measure 20 fringes and divide the reading by 20.
3. *The fringe separation is too small a quantity to be measured accurately with a ruler, and a travelling microscope is more convenient than callipers or a micrometre, which are usually used to measure the size of solid objects or gaps, rather than distances on a flat screen. Measuring 20 fringes and dividing by 20 reduces the uncertainty in the value.*
4. *A laser must be used carefully. No-one should be allowed to look along the beam and the beam should not be trained onto anyone.*
5. *The wavelength is given by the formula λ = sy/D*

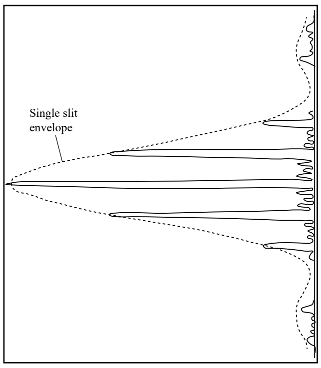
The Diffraction Grating

A diffraction grating is a device with a series of parallel lines ruled on it. Light going through the grating produces a pattern as shown below:



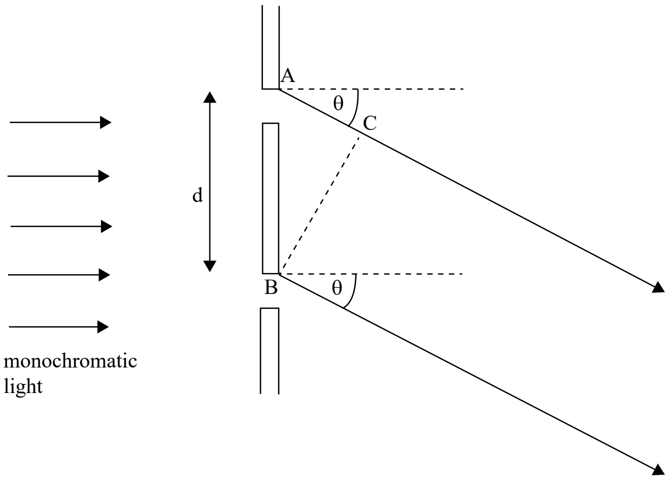
Source: http://media4.picsearch.com/is?U061GVoA9QzWkScUDNNgsNeTYBuIvwJsf4DJGkOg2dQ&height=13

The relative intensity graph for a diffraction grating shows how the intensity of the light after diffraction through a diffraction grating compares with the pattern produced by diffraction through a single slit (shown by the Single slit envelope).



Source: http://hyperphysics.phy-astr.gsu.edu/hbase/phyopt/imgpho/muls5.gif

The Theory



Although the set-up seems similar to that of Young´s Slit, there are some differences:

1. The source is a long way from the grating, so the incoming light is considered to be parallel rays.
2. The screen is a long way from the grating, so, to a good approximation, the rays travelling to a particular point may also be considered to be parallel.
3. The fact that there are many gaps on the grating means that there is multiple interference between rays.
4. Theory uses angle Θ instead of s, y, and D.
5. For constructive interference between adjacent rulings, the path difference AC must be a whole number of wavelengths.

$$\sin\Theta = AC/d$$
$$\text{So, } AC = d\sin\Theta$$
$$\text{So for the bright images } d\sin\Theta = n\lambda$$

The series of images on either side of the central bright fringe has n=1; n=2; n=3 etc, known as first order, second order, third order images etc.

For a diffraction grating

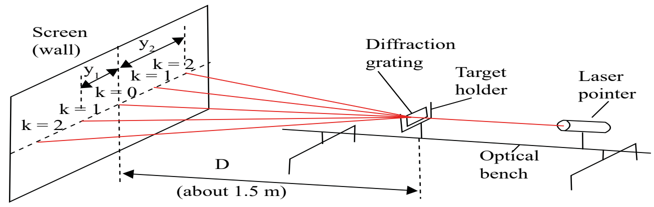
$$d \sin\Theta = n\lambda$$

Grating line separation/m — Angle of fringe — Image order (1,2,3….) — Wavelength/m

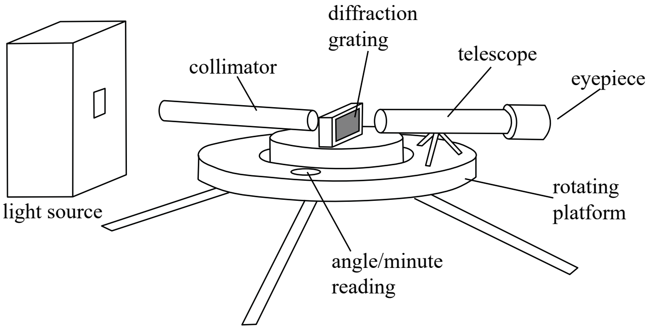
Test your understanding:

5. Explain why the fringes in a diffraction pattern are not all the same intensity.

Practical Set-up



The diagram shows a simple set-up to find the wavelength of laser light using a diffraction grating.
The set-up below shows a more sophisticated set-up.



Test your understanding:

6. Suggest reasons why the second set-up is an improvement of the first.

Errors and Uncertainties

No measurement can be 100% accurate or precise. Uncertainties are classified as "random" or "systematic". An example of a systematic error is the zero error on a meter – the fact that it does not read exactly zero when no measurement is being taken. A systematic error is always in the same direction – too high or too low. Random errors occur because nothing can be done precisely and are sometimes too high and sometimes too low. The uncertainty in a reading due to random errors can be reduced by repeating the reading and taking an average.

***Exam Hint:** There are likely to be questions about uncertainty on the A Level papers*

In these investigations the measurements are all of lengths or angles. It is important to choose an instrument with the appropriate degree of sensitivity. For the larger lengths, a metre ruler (or, for lengths longer than a metre, an athletics tape) would have uncertainty +/- ½ mm; so this is appropriate. The slit separations or grating separations are usually marked on the instrument with the manufacturer's tolerance quoted. In the Young´s Fringes investigation the uncertainty in the measurement of fringe separation can be reduced by measuring a number of fringes and dividing by that number.

In the diffraction grating investigation, the use of the spectrometer, with angle readings in seconds and minutes, greatly reduces the uncertainty in that measurement. Measuring the angle on one side, through to the other side, and dividing by 2, reduces the uncertainty to half.

Uncertainty in the Final Calculation

Remember:

- If quantities are **added or subtracted**, the ***absolute*** uncertainties are added.
- If quantities are **multiplied or divided**, the ***% uncertainties*** are added.

Exam Hint: *When handling uncertainties, it is helpful to practise converting from absolute to % and vice-versa.*

Test your understanding:

7. In a Young's Slits investigation, the slit separation, s is given as 0.25mm +/- 2%. The distance D to the screen is measured with an athletics tape as 4m and the separation, for 4 fringes, with a ruler as 8.4cm.

(a) What is the absolute uncertainty in each of the measurements?

(b) What is the percentage uncertainty in each of the measurements?

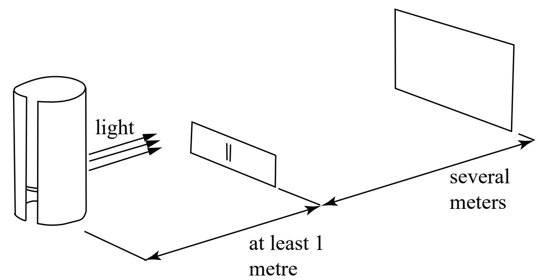
(c) What is the percentage uncertainty in the value of λ given by sy/D?

(d) Explain why the uncertainties in the measurements of the lengths might be greater than the standard accepted +/- 0.5mm.

(e) A pupil wished to reduce the uncertainty. Explain which measurement she should choose to change and why

Illustrations of Possible Exam Questions of Each Type

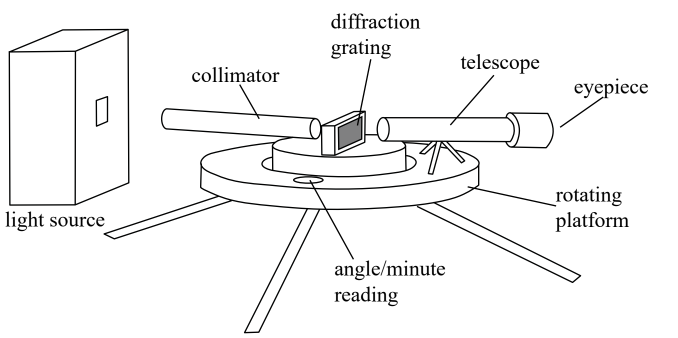
Type 1 (Set in practical context, but about the underlying science)
A student investigates the wavelength of light from a laser by using Young's Double Slit as shown below:



(a) What is the name of the effect which causes light to spread out around the slits?
(b) Describe the pattern seen on the screen.
(c) Explain why this effect occurs.

Type 2 (Aspects of the practical procedure need to be understood.)
A student tries to investigate the wavelength of light by using two different (non-laser) light sources to give an interference pattern.
(a) Explain why she will be unsuccessful.
(b) She tries with two laser sources. Explain why this will be successful.

Type 3 (Questions directly on the practical procedures.)
A student uses this apparatus to determine the wavelength of the light used.



(a) What is the purpose of the collimator?
(b) Describe the appearance of the pattern seen in the eyepiece.
(c) Explain why the student measured the angle from the first order image on one side to the first order image on the other side.
(d) Calculate the wavelength of the light used if the angle for the 1st order image is 19^o and the manufacturer quotes the grating spacing as 6000 lines/cm.
(e) How might the student reduce the uncertainty further?

Type 4 (Applying skills and techniques.)
The table shows results obtained from an investigation with a diffraction grating to determine the wavelength of the light used.

Order	Angle Θ / degrees min	Sin Θ	λ
1	7 30		
2	12 15		
3	16 45		
4	21 00		

The grating manufacturer quotes the line spacing as 3000 lines/cm.
(a) What is the spacing width, d?
(b) Complete the table by looking up sin θ and calculating each value for λ, given by these data.
(c) Find the average value of these values.
(d) Quote the absolute and % uncertainties for the final value.

Answers to "Test your understanding"

1. *Characteristics of waves which could be quoted include: reflection, refraction, interference, diffraction. The most significant ones here are interference and diffraction, since streams of particles can also show reflection and refraction.*
2. *Two light sources are coherent if they have the same frequency and a constant phase difference between them. With normal white light, this can be achieved only by splitting a single source to give two sources.*
3. *To achieve a stable interference pattern the slit separation must be of the same order of magnitude as the wavelength and D must be large compared to the slit separation.*
4. *The student would not achieve an observable pattern because the sources are not coherent and the separation is not of the same order of magnitude as the wavelength of the light.*
5. *The fringes are not all of the same brightness, because there is multiple interference from the fringes, so some destructive as well as some constructive at some points.*
6. *The second set-up is an improvement because:*
   (a) the incoming light is made into a parallel beam by the collimator.
   (b) The outgoing light is also made into a parallel beam by the telescope.
   (c) the angle can be easily and precisely read off the turntable.

7. (a) *Absolute uncertainties:*
   in s (2/100) × 0.25 = +/- 0.005mm
   D +/- 0.5mm (normal reading of a ruler)
   y 0.5mm on 4 fringes gives +/- 0.125mm on 1 fringe
   (b) *Percentage uncertainties:*
   in s 2% (quoted)
   D (0.5 / 4000) × 100 = 0.0013%
   y (0.125/2.1) × 100 = 6%
   (c) *Quantities are multiplied and divided, therefore add the %, uncertainties give 8%.*
   (d) *Although the uncertainty in the measurement from a scale is usually accepted to be half a scale division, in fact the larger uncertainty is in the observers positioning of the ruler.*
   (e) *Uncertainty in D is negligible compared to that of s and y; the uncertainty in s is fixed (unless she buys a more precise [i.e. more expensive] double slit with a lower uncertainty); so she should concentrate on finding a more precise way of measuring the fringe separation.*

Answers to Illustrations of Possible Questions

Type 1

(a) "Diffraction" is the effect which causes the spreading out of light around a gap or edge.
(b) The pattern on the screen is a series of parallel, equally spaced, bright and dark fringes.
(c) The slits are two coherent sources which give rise to overlapping waves reaching points on the screen. The waves interfere constructively if one has travelled a whole number of wavelengths more than the other to reach a particular point. This creates a double amplitude wave. They interfere destructively if one has travelled an odd number of half-wavelengths more than the other - giving a dark area.

Type 2

(a) The sources are not coherent, so the interference pattern is continually disrupted by random shifts in phase of the two sources.
(b) A laser source does not have the randon phase shifts, so the two lasers are coherent sources.

Type 3

a) The collimator produces parallel light.
b) (See the text) The pattern is a series of parallel fringes, either side of a central fringe, the images on either side are half width and becoming fainter away from the central image.
c) The student measures from the first order image on one side to first order image on the other side and idvides by 2 to reduce the uncertainty to half.
d) The line spacing is 6000 lines per cm.
   So the spacing is (1/6000)cm i.e. 1.67×10^{-6} m
   $\sin \Theta = 0.3256$ $\lambda = 1.67 \times 10^{-6} \times 0.3256 = 544$nm
(e) The student could reduce the uncertainty further by taking angle measurements for as many order image as are visible and averaging the value of wavelength given by each calculation.

Type 4

(a) $d = 1/3000$ cm $= 3.33 \times 10^{-6}$ m
   (Remember to convert to m)
(b)

Order	Angle Θ / /degrees min	Sin Θ	λ nm
1	7 30	0.1305	434
2	12 15	0.2122	353
3	16 45	0.2882	320
4	21 00	0.3584	295

(c) Average value of the 4 is (434 + 353 + 320 + 295)/4 = 350nm
(d) Absolute uncertainty is 434 -350 = 84nm
   % uncertainty = (84/350) × 100 = 24%

Acknowledgements:
This Physics Factsheet was researched and written by Janice Jones. The Curriculum Press,Deansgate, 62-70 Tettenhall Road, Wolverhampton,West Midlands WV1 4TZ . ISSN 1351-5136