Volume

Two

ST MARY'S SCIENCE DEPARTMENT:

PHYSICS

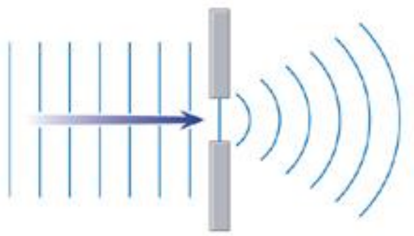
A LEVEL PHYSICS **YEAR 1**

STUDENT INDEPENDENT WORK BOOK

WAVES

3.3.2: REFRACTION, DIFFRACTION AND INTERFERENCE

NAME	
PHYSICS CLASS	
MODULE TEACHER	
ALPS GRADE	



A-LEVEL PHYSICS

TOPIC 3

INDEPENDENT WORK BOOK 2

THIS MUST BE BROUGHT TO ALL PHYSICS LESSONS.

Contents

3.3.2.1 Interference
3.3.2.2 Diffraction
3.3.2.3 Refraction at a Plane Surface

Overview

GCSE studies of wave phenomena are extended through a development of knowledge of the characteristics, properties, and applications of travelling waves and stationary waves.

Topics treated include refraction, diffraction, superposition and interference.

IMPORTANT NOTE
This book contains all of the activities you can carry out independently in your study periods to enhance your understanding in A-Level Physics.

You may work through the activities in this book and mark this work yourself. You work will then be reviewed by your teacher in KS5 file checks. This work is in addition to the class work and homework you carry out.

This book may also be used as a revision resource for intervention, internal assessments and external assessments.
Please keep this in your student file.

As part of this course you are expected to **read through this preparatory reading book** and **complete the independent study tasks**.

This work will not be assessed but will be monitored by your class teacher.

This must be completed by the deadline set by your class teacher.

Definition List

Definitions you must learn for this module.

Key Word	Symbol	Definition
Coherent		When two sources of waves having a constant phase difference and the same frequency.
Critical Angle	θ_c	The angle of incidence of a light ray that must be exceeded for total internal reflection to occur. It is also the angle of incidence where the angle of refraction is zero.
Diffraction		The spreading of waves on passing through a gap or near an edge.
Diffraction Grating		A plate with many closely ruled parallel slits on it.
Fringe Spacing	w	The perpendicular distance between the centre of two fringes of the same type e.g. bright fringe and bright fringe (adjacent maxima or minima).
Interference		The formation of points of cancellation and reinforcement where two coherent waves pass through each other.
Intensity	I	The power per unit area of a wave.
Laser		a device which produces a parallel coherent beam of monochromatic light.
Maxima		Points produced when waves with a $n\lambda$ path difference (or $n2\Pi$ phase difference) constructively interfere.
Minima		Points produced when waves with a $n/2\lambda$ path difference (or $n\Pi$ phase difference) destructively interfere.
Modal Dispersion		The lengthening of a light pulse as it travels along an optical fibre, due to rays that repeatedly undergo total internal reflection having to travel a longer distance than the rays that undergo less total internal reflection.
Monochromatic Light		Light of single wavelength (and frequency) – the same colour.
Optical Fibre		A thin, flexible transparent fibre used to carry light pulses from one end to the other.
Path Difference		The difference in distances from two coherent sources to an interference fringe.
Phase Difference		The fraction of a cycle between the vibrations of two vibrating particles, measured either in degrees or radians.

Superposition		The effect of two waves adding together when they meet. This can be either displacement or any vector property of a wave
Refraction		The change in direction of a wave when it crosses a boundary where its speed changes. In refraction, frequency must remain constant.
Refractive Index	**n**	The speed of light in free space compared to the speed of light in the substance.
Total Internal Reflection		Occurs when a light ray travelling in a substance is reflected at the boundary with a substance of lower refractive index, if the angle of incidence is greater than a certain value known as the critical angle.
Young's Fringes		The parallel bright and dark fringes observed when light from a narrow-slit passes through two closely spaced slit.

IMPORTANT NOTE
These definitions must be memorised by students.

You will be tested on your knowledge of these definitions.

Equations
The equations below are used in this module.

Quantity/Concept	Equation(s)
Intensity	$I = P / A$ This is not given in your examination.
Fringe Spacing	$w = \frac{\lambda D}{s}$
Distance Between Slits on a Diffraction Grating	$d = n\lambda / \sin \theta$
Maximum Number of Diffraction Orders	$n = d / \lambda$ This is not given in your examination.
Refractive Index	$n = c/c_s$
Relative Refractive Index	${}_1n_2 = c_1 / c_2$ ${}_1n_2 = n_1 / n_2$ These two equations can be equated to each other.
Snell's Law	$n_1 \sin\theta_1 = n_2 \sin\theta_2$
Critical Angle	$\sin \theta_c = n_2 / n_1 = {}_1n_2$

IMPORTANT NOTE
These equations must be memorised by students.

You will be tested on these equations.

The Language of Measurement

The following subject specific vocabulary provides definitions of key terms used in the A-level Science specifications.

Accuracy
A measurement result is considered accurate if it is judged to be close to the true value.

Calibration
Marking a scale on a measuring instrument.
This involves establishing the relationship between indications of a measuring instrument and standard or reference quantity values, which must be applied.
For example, placing a thermometer in melting ice to see whether it reads 0 °C, to check if it has been calibrated correctly.

Data
Information, either qualitative or quantitative, that has been collected.

Errors
See also uncertainties.

Measurement error
The difference between a measured value and the true value.
anomalies
These are values in a set of results which are judged not to be part of the variation caused by random uncertainty.

Random error
These cause readings to be spread about the true value, due to results varying in an unpredictable way from one measurement to the next.
Random errors are present when any measurement is made, and cannot be corrected. The effect of random errors can be reduced by making more measurements and calculating a new mean.

Systematic error
These cause readings to differ from the true value by a consistent amount each time a measurement is made.
Sources of systematic error can include the environment, methods of observation or instruments used.
Systematic errors cannot be dealt with by simple repeats. If a systematic error is suspected, the data collection should be repeated using a different technique or a different set of equipment, and the results compared.

Zero error
Any indication that a measuring system gives a false reading when the true value of a measured quantity is zero, e.g. the needle on an ammeter failing to return to zero when no current flows.
A zero error may result in a systematic uncertainty.

Evidence
Data which has been shown to be valid.

Fair test
A fair test is one in which only the independent variable has been allowed to affect the dependent variable.

Hypothesis
A proposal intended to explain certain facts or observations.

Interval
The quantity between readings, e.g. a set of 11 readings equally spaced over a distance of 1 metre would give an interval of 10 centimetres.

Precision
Precise measurements are ones in which there is very little spread about the mean value. Precision depends only on the extent of random errors – it gives no indication of how close results are to the true value.

Prediction
A prediction is a statement suggesting what will happen in the future, based on observation, experience or a hypothesis.

Range
The maximum and minimum values of the independent or dependent variables; important in ensuring that any pattern is detected.
For example, a range of distances may be quoted as either:
'From 10 cm to 50 cm'
or
'From 50 cm to 10 cm'

Repeatable
A measurement is repeatable if the original experimenter repeats the investigation using same method and equipment and obtains the same results.

Reproducible
A measurement is reproducible if the investigation is repeated by another person, or by using different equipment or techniques, and the same results are obtained.

Resolution
This is the smallest change in the quantity being measured (input) of a measuring instrument that gives a perceptible change in the reading.

Sketch graph
A line graph, not necessarily on a grid, that shows the general shape of the relationship between two variables. It will not have any points plotted and although the axes should be labelled they may not be scaled.

True value
This is the value that would be obtained in an ideal measurement.

Uncertainty
The interval within which the true value can be expected to lie, with a given level of confidence or probability, e.g. "the temperature is 20 °C ± 2 °C, at a level of confidence of 95%.

Validity
Suitability of the investigative procedure to answer the question being asked. For example, an investigation to find out if the rate of a chemical reaction depended upon the concentration of one of the reactants would not be a valid procedure if the temperature of the reactants was not controlled.

Valid conclusion
A conclusion supported by valid data, obtained from an appropriate experimental design and based on sound reasoning.

Variables
These are physical, chemical or biological quantities or characteristics.

Categoric variables
Categoric variables have values that are labels. E.g. names of plants or types of material.

Continuous variables
Continuous variables can have values (called a quantity) that can be given a magnitude either by counting (as in the case of the number of shrimp) or by measurement (e.g. light intensity, flow rate etc.).

Control variables
A control variable is one which may, in addition to the independent variable, affect the outcome of the investigation and therefore must be kept constant or at least monitored.

Dependent variables
The dependent variable is the variable of which the value is measured for each change in the independent variable.

Independent variables
The independent variable is the variable for which values are changed or selected by the investigator.

IMPORTANT NOTE
These definitions must be memorised by students.

You will be tested on your knowledge of these definitions.

SECTION 1

INDEPENDENT STUDY TASK

Instructions

Read through the information from the student preparatory book and then produce revision posters on the key points highlighted on the following pages.

These notes should be used as a revision resource for assessments.

INDEPENDENT STUDY TASK 1

Produce an **information sheet** on interference patterns.

This is an independent study task to carried out outside of lesson.

INDEPENDENT STUDY TASK 2

Produce an **information sheet** on the diffraction required practicals.

This is an independent study task to carried out outside of lesson.

INDEPENDENT STUDY TASK 3

Produce an **information sheet** on refraction.

This is an independent study task to carried out outside of lesson.

INDEPENDENT STUDY TASK 4

Produce an **information sheet** on total internal reflection.

This is an independent study task to carried out outside of lesson.

SECTION 2

KNOWLEDGE CHECKER

Instructions

Read through the information from the student preparatory book and then answer the following questions from the different parts of the topics.

These questions are designed to introduce the different parts of this module.

Use the mark schemes to review your knowledge and understanding.

QUESTIONS

Use the preparatory reading notes to answer these questions.

A1. What is diffraction?

[1 Mark]

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A2. Do all waves diffract?

[1 Mark]

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A3. What does Young's experiment show about the nature of light?

[1 Mark]

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A4. Write down Young's double slit formula.

[1 Mark]

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A5. How is the diffraction grating pattern for white light different from the pattern for laser light?

[1 Mark]

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A6. What equation is used to find the angle between the nth order maximum and the incident beam for a diffraction grating?

[1 Mark]

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A7. Why does light go fastest in a vacuum and slowdown in other media?

[1 Mark]

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A8. What is the formula for the critical angle for a ray of light at a water/air boundary?

[1 Mark]

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A9. What happens to the number of photons in a light beam if the intensity increases?

[1 Mark]

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A10. It is found that a beam of light into the air disappears when the spotlight is pointed at any angle of less than 41.25° to the floor. Calculate the refractive index of water.

[1 Mark]

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A11. Light travels in diamond at 1.24×10^8 m/s. Calculate the refractive index of diamond.

[1 Mark]

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A12. Explain the ways in which the cladding is designed to keep transmitted light inside an optical fibre.

[1 Mark]

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Use the preparatory reading notes to answer these questions.

ADVANCED SECTION

Questions **A13-A14** refer to the following statement.

Yellow laser light of wavelength 6.0 x 10^{-7}m is transmitted through a diffraction grating of 4.0 x 10^{5} lines per metre.

A13. Calculate the angle to the normal at which the first and second order bright lines are seen.

[1 Mark]

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A14. State whether there is a fifth order line. Explain your answer.

[1 Mark]

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Use the preparatory reading notes to answer these questions.

MARK SCHEME

A1. What is diffraction?

[1 Mark]

Diffraction is when a wave spreads out when they come through a narrow gap or go around obstacles.

A2. Do all waves diffract?

[1 Mark]

All waves diffract.

A3. What does Young's experiment show about the nature of light?

[1 Mark]

This shows light has a wave nature.

A4. Write down Young's double slit formula.

[1 Mark]

$w = \lambda D / s$

A5. How is the diffraction grating for white light different from the pattern for laser light?

[1 Mark]

Laser light produces a single diffraction pattern, white light produces a diffraction grating with all colours of the spectrum.

A6. What equation is used to find the angle between the nth order maximum and the incident beam for a diffraction grating.

[1 Mark]

$n\lambda = d\sin\Theta$

A7. Why does light go fastest in a vacuum and slowdown in other media?

[1 Mark]

Light slows down because it interacts with the particles in them – the more optically dense a material is, the more light slows down.
A vacuum has no particles for the light to interact with.

A8. What is the formula for the critical angle for a ray of light at a water/air boundary?

[1 Mark]

$\sin \Theta_c = n_{air} / n_{water}$

A9. What happens to the number of photons in a light beam if the intensity increases?

[1 Mark]

The number of photons in the beam increases if the intensity increases.

A10. It is found that a beam of light into the air disappears when the spotlight is pointed at any angle of less than 41.25° to the floor. Calculate the refractive index of water.

[1 Mark]

Critical Angle = 90 – 41.25 = 48.75°
$\sin \Theta_c = n_{air} / n_{water} = 1/ n_{water}$
$n_{water} = 1 / \sin\Theta_c = 1 / \sin 48.75^o$
$n_{water} = 1.330 = 1.330$

A11. Light travels in diamond at 1.24×10^8 m/s. Calculate the refractive index of diamond.

[1 Mark]

$n_{diamond} = c / c_{diamond} = (3.00 \times 10^8) / (1.24 \times 10^8) = 2.419 = 2.42$

A12. Explain the ways in which the cladding is designed to keep transmitted light inside an optical fibre.

[1 Mark]

The cladding has a lower refractive index than the fibre, to allow total internal reflection.
It also protects the cable from scratches and damage which may let light escape.

ADVANCED SECTION

Questions **A13-A14** refer to the following statement.
Yellow laser light of wavelength 6.0×10^{-7}m is transmitted through a diffraction grating of 4.0×10^5 lines per metre.

A213. Calculate the angle to the normal at which the first and second order bright lines are seen.

[1 Mark]

$d\sin\Theta = n\lambda$
$n = 1$
$\sin\Theta = \lambda /d = 6.0 \times 10^{-7} \times 4.0 \times 10^5 = 0.24$
$\Theta = 13.886 = 14^o$

$d\sin\Theta = n\lambda$
$n = 2$
$\sin\Theta = 2\lambda /d = 6.0 \times 10^{-7} \times 4.0 \times 10^5 = 0.48$
$\Theta = 28.685 = 29^o$

A14. State whether there is a fifth order line. Explain your answer.

[1 Mark]

No.
Putting n = 5 into the equation gives a Θ above 90°, this is impossible.

SECTION 3

QUESTIONS

Instructions

Read through the information from the student preparatory book and then answer the following questions from the different parts of the topics.

Use the mark schemes to review your knowledge and understanding.

TOPIC: 3.3.2.1 Interference
SPEC CHECK

Specification	Completed?
Path difference. Coherence.	
Interference and diffraction using a laser as a source of monochromatic light.	
Young's double-slit experiment: the use of two coherent sources or the use of a single source with double slits to produce an interference pattern.	
Fringe spacing, $w = \frac{\lambda D}{s}$	
Production of interference pattern using white light.	
Show awareness of safety issues associated with using lasers.	
Describe and explain interference produced with sound and electromagnetic waves.	
Appreciation of how knowledge and understanding of nature of electromagnetic radiation has changed over time.	
Investigate two-source interference with sound, light and microwave radiation.	

EXPERIMENTAL TECHNIQUE

Microwaves form interference patters just like any other electromagnetic wave. Simple interference patterns can be achieved by using a single source of microwaves and allowing the waves to pass through two slits, in the same way as visible light was passed through two very narrow slits in the Young double slit experiment. The wavelength of microwaves is considerably larger (~3 cm) than that of visible light (~400 nm), and so the slits need to be much larger and further apart.

Experiment

You are provided with the following equipment: three metal sheets on stands, a microwave receiver connected to a data logger, a 3 cm microwave transmitter, and a metre rule.

1. Draw a diagram to show how this equipment could be set up to produce and record an interference pattern from two sources.

[3 Marks]

2. Explain how you could record the intensity of the interference pattern using the receiver and the data logger. Include a suggested sample rate for the data logger.

[3 Marks]

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3. Suggest suitable values for the gap between the metal sheets, and the distance between the metal sheets and the receiver (*D*). Explain your reasoning.

[4 Marks]

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Sample data

1. Use the sample readings in **Table 1** to plot a graph of millivolts against distance, from the centre point between the two gaps.

Draw a smooth line of best fit (a curve) through the points.

[5 Marks]

2. Use your graph to measure the fringe spacing *w*, and hence calculate the wavelength of the microwaves using the equation $\lambda = \frac{ws}{D}$, where *s* is the gap separation equal to 8 cm, and *D* is the distance from the metal sheets to the receiver, equal to 35 cm at the centre.

[3 Marks]

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Table 1 Intensity of microwave diffraction fringes

Distance from centre to left / cm	30	28	26	24	22	20	18	16	14	12	10	8	6	4	2
Receiver reading / mV	10	1	2	2	1	2	5	23	41	23	9	7	2	9	33

Distance from centre to right / cm	30	28	26	24	22	20	18	16	14	12	10	8	6	4	2	0
Receiver reading / mV	14	28	20	11	9	3	2	13	14	22	40	28	10	9	28	40

Analysis of uncertainty

1. Estimate the uncertainty in the fringe spacing *w*, the distance *D*, and the measurement of the slip separation *s*.

[3 Marks]

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2. State which uncertainty will be the most significant factor in the uncertainty of the wavelength?

[1 Mark]

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3. Find an estimate for the uncertainty in the calculated value of the wavelength.

[1 Mark]

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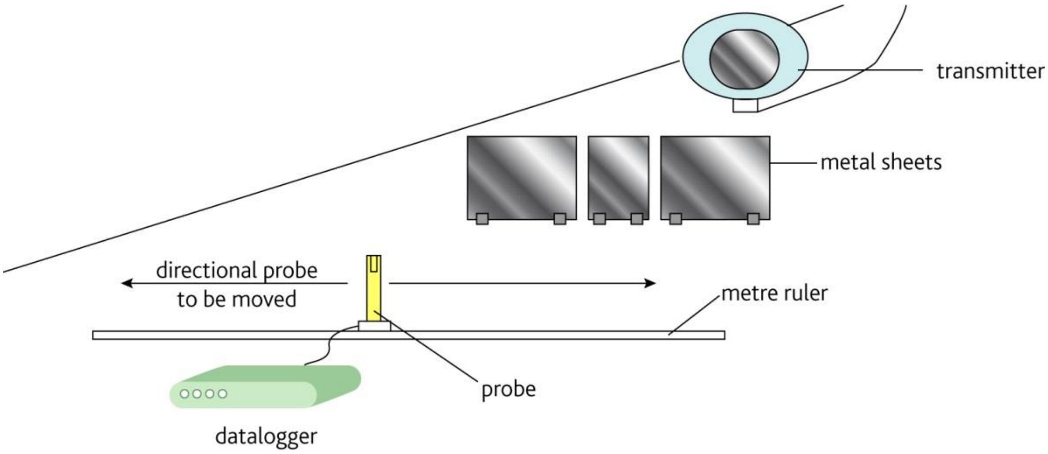
ANSWERS

1. Award *1 mark* for a basic diagram showing how two slits could be formed,

1 mark for noting that the probe should be moved along a line parallel to the metal sheets,

And *1 mark* for a suitable measurement system for the position of the pattern (the ruler).



2. The probe should be moved along the length of the ruler from left to right, producing a series of maxima and minima on the data logger (*1 mark*).

The data logger should be programmed to take readings about every 2 cm (*1 mark*).

If the probe is moved across 50 cm in a time of about 10 s this equates to a sample rate of 2 or 3 readings per second (*1 mark*).

3. The gap between the metal sheets should be in the range of 1–4 cm (*1 mark*) since this is comparable to the wavelength of microwaves (*1 mark*).

The distance between the metal sheets and the probe (*D*) should be in the range 30–60 cm (*1 mark*) to give adequate separation of the peaks (*1 mark*).

Since the equation assumes that sin θ = tan θ, which only works for small angles, the relationship will only work for a range of about 28 cm (based on a value of D = 35 cm).

Sample data: answers

1. Labelled axes with even scales (*1 mark*)

Award 2 marks for accurate plotting of all data points, *1 mark* for over half accurately plotted.

Data points cover over half of the area of the graph (*1 mark*)

Smooth curve of best fit (*1 mark*)

2. The distance between the first maximum on each side of the centre line should be measured (*1 mark*), and divided by two to find the average separation (*1 mark*). The value of wavelength comes to approximately 2.7 cm (*1 mark*).

Analysis of uncertainty: answers

1. The uncertainty in the measurement between the maxima on the graph has a value of about 1 cm in 10 cm, i.e. 10%. (*1 mark*)

The error in *D* is about 0.5 cm in 35 cm, which is about 1.5%. (*1 mark*)

The uncertainty in *s*, the gap separation, is about 0.5 cm in 8 cm, which is about 6%. (*1 mark*)

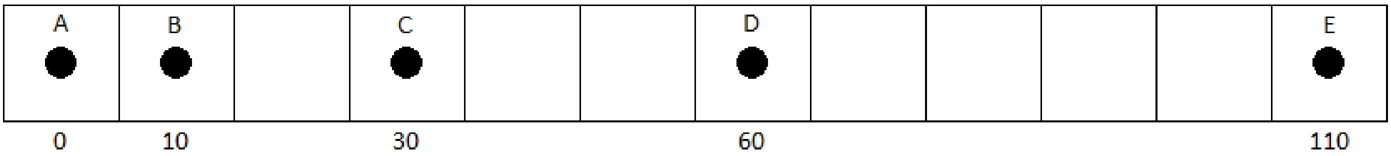
2. The uncertainty in the measurement between the maxima on the graph is the most significant uncertainty in this experiment. (*1 mark*)

3. The total percentage uncertainty is therefore about 18%. (*1 mark*)

PRACTICAL SKILLS

Complete the following practical skills-based task to improve your experimental understanding of this part of the course in preparation for **Physics Paper 3.**

Five speakers are set into a box in the formation as shown in the diagram below. By measuring the separation of the loud interference fringes at different distance from the speaker box it is possible to deduce which speakers are emitting a sound of wavelength (λ) 0.17 m.



Values in cm

Experimental Data

Here are the separations of the fringes at different distances from the speaker box.

Distance to Speaker, D (m)	Fringe Separation, w (m)			Mean w (m)		Speaker Separation, s (m)
1.00	0.20	0.21	0.21			
1.50	0.33	0.33	0.29			
2.00	0.41	0.47	0.42			
2.50	0.52	0.56	0.51			
3.00	0.63	0.66	6.63			
3.50	0.77	0.72	0.73			
4.00	0.89	0.84	0.82			
4.50	0.91	0.98	0.99			

Analysis

A1. In this experiment what were the independent and dependent variables?

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A2. What was the precision in the wavelength value and distances from the speaker?

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A3. Calculate the mean values of the fringe separation for each distance to the speaker.

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A4. What is the uncertainty in the fringe separation for a distance of 2.00m?

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A5. Calculate this as a percentage of the mean.

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A6. What is the uncertainty in the fringe separation for a distance of 3.50m?

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A7. Calculate this as a percentage of the largest value at this distance.

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A8. What is the uncertainty in the fringe separation for a distance of 4.50m?

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A9. Calculate this as a percentage of the smallest value at this distance.

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A10. What is the name given to the error responsible for the spread in the fringe separations?

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A11. Use the equation $w = \frac{\lambda D}{s}$ to calculate the speaker separation for each distance to the speaker.

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A12. What is a percentage uncertainty in the value of s for when D = 2.50m?

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A13. Calculate the mean value of the speaker separation.

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A14. Either: plot a graph of D on the y axis against w on the x axis and use your gradient to calculate s. Or plot a graph of D against $\frac{w}{\lambda}$ and your gradient will equal s. A column has been left for the values of $\frac{w}{\lambda}$.

A15. Does your graph support the value of s obtained from the table?

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A16. Which speakers does this suggest are emitting the sound?

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CHALLENGE QUESTION

To assess your understanding, answer the following higher-level question on this topic.

1.1 In an experiment to investigate microwaves, a microwave detector D is placed between a microwave transmitter T and a flat metal sheet.

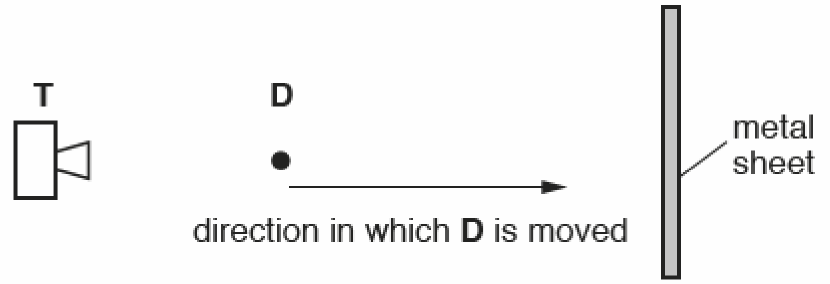

Fig. 7.1

The detected signal at D shows regions of maximum and minimum intensity as D is moved towards the metal sheet as shown in **Fig. 7.1**. The distance between adjacent regions of maximum and minimum intensities is 72 mm.
Explain the presence of the regions of maximum and minimum intensity and determine the frequency of the microwaves.
The speed of microwaves in air is 3.0×10^8 m s^{-1}.

[6 Marks]

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1.2 In another experiment using microwaves, a metal grille G consisting of a series of long metal rods is placed between the transmitter T and the detector D as shown in **Fig. 7.2.**

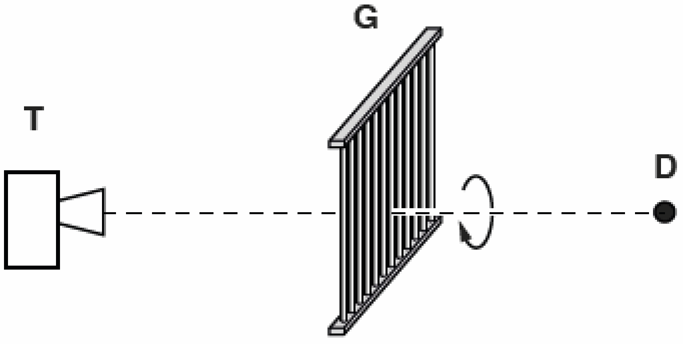

Fig. 7.2

The grille is slowly rotated through 180° about the line joining T and D. The detected signal at D varies from zero to maximum and back to zero again.
Explain why the detected signal behaves in this way.

[2 Marks]

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MARK SCHEME

Question	Answer	Marks	Guidance
1.1	**Level 3 (5–6 marks)** Clear explanation of observations **and** correct determination of frequency. *There is a well-developed line of reasoning which is clear and logically structured. The information presented is relevant and substantiated.* **Level 2 (3–4 marks)** Clear explanation of observations **or** correct method to determine the frequency **or** some explanation of observations and some method for the determination of the frequency *There is a line of reasoning presented with some structure. The information presented is in the most-part relevant and supported by some evidence.* **Level 1 (1–2 marks)** Has limited explanation of observations **or** limited evidence of method to determine the frequency *There is an attempt at a logical structure with a line of reasoning. The information is in the most part relevant.* **0 marks** No response or no response worthy of credit.	**B1 x6**	**Indicative scientific points may include:** Explanation of observations • Metal sheet reflects microwaves • Idea/description of superposition • Constructive/destructive interference • Standing wave pattern between T and plate • Maxima are antinodes and and minima are nodes. • Phase difference at nodes and antinodes • Distance between successive maxima/minima is $\lambda/2$ • Distance between adjacent regions of maximum and minimum intensities is $\lambda/4$ Determination of frequency • $f = \frac{v}{\lambda}$ • $\lambda = 4 \times 72$ mm = 288 mm • $f = \frac{3\times10^8}{288\times10^{-3}} = 1.04 \times 10^9\text{Hz}$
1.2	Microwaves from **T** are transverse/polarised wtte At 0° or 180° the grille blocks (all) the (polarised) waves <u>and</u> at 90°the grille allows all the microwaves to pass.	**B1** **B1**	**Allow** E field perpendicular to direction of motion **Allow** explanation in terms of $I = I_0\cos^2\theta$
	Total	**8**	

TOPIC: 3.3.2.2 Diffraction
SPEC CHECK

Specification	Completed?
Appearance of the diffraction pattern from a single slit using monochromatic and white light.	
Qualitative treatment of the variation of the width of the central diffraction maximum with wavelength and slit width.	
Plane transmission diffraction grating at normal incidence.	
Derivation of $d\sin\theta = n\lambda$	
Applications of diffraction gratings.	

EXTENDED WRITING

To enhance your skills in answering examination questions for the A-Level examinations, complete the following task.

It is possible to find the wavelength of a laser by using either a double slit or a diffraction grating. Describe the necessary procedure in order to obtain an accurate and reliable value using both methods.

Your answer should include:

- The experimental set up needed with a description of what would be observed
- Details of any measurements that you would take or need
- An explanation of how the wavelength will be found
- Details of how to improve the accuracy of your measurements.

ANSWERING SPACE

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MARK SCHEME

P	**Praise. What were the positive aspects of the work? What did they do well? What skills did they demonstrate?**

I	**Improvements. What were the literacy issues in the piece of work?**		*Write in ink.*		*Draw in Pencil.*		*Use a ruler.*	
	Always use capital letters at the beginning of a sentence.		Learn the spellings identified in your work.					
	Always use capital letters for proper nouns.		Ensure sentences make sense.					
	Make sure you write on the line and not above or below it.		Use correct punctuation.					
	Use scientific vocabulary appropriate to the task.		Vary your sentences to demonstrate your understanding.					

D answer		B answer		A* answer	
The setup is described as a laser being pointed at the diffraction grating and spots being seen…		…on a screen, one is directly behind the grating with a (mirrored) pattern of equal bright spot…		…the laser must be perpendicular to the diffraction grating.	
You would measure the order (or number) of spot (n) and the corresponding angle (θ)…		…from n=0 (or straight through). You would need to be given the distance between two adjacent slits (d) (or calculate it from the lines per mm)…		…accuracy is improved by using trigonometry to calculate the angle and/or using a large distance to the screen.	
Wavelength (λ) is calculated using the equation: $d\sin\theta = n\lambda$ or $\lambda = \frac{d}{n}\sin\theta$…		…accuracy can be improved by calculating a mean value of the angle (θ) for each value of n…		…and further by plotting a graph of n (x) against sinθ (y), plotting a line of best fit where the gradient is equal to λ/d.	
The setup is described as a laser being pointed at the double slit with light and dark fringes…		…on a screen, there is a bright fringe directly behind the slit and all are the same width…		…the laser must be perpendicular to the double slit.	
You would measure the distance to the screen (D) and the fringe width (w)…		…which is the distance from one bright fringe to the next bright fringe. You would need to be given the slit separation (s)…		…accuracy is improved by using a large distance to the screen and/or by measuring the width of several fringes and calculating a mean.	
Wavelength (λ) is calculated using the equation: $w = \frac{\lambda D}{s}$ or $\lambda = \frac{ws}{D}$…		…accuracy can be improved by finding the value of w at different distances to the screen (D) and calculating a mean value of λ…		…and further by plotting a graph of D (x) against w (y), plotting a line of best fit where the gradient is equal to λ/s.	

N	**Next Steps. How can they move their work onto the next grade? What didn't they include?**	**Grade**	**Effort**

CHALLENGE QUESTION

To assess your understanding, answer the following higher-level question on this topic.

1. Fig. 26.1 shows an arrangement used to demonstrate a particular wave phenomenon.

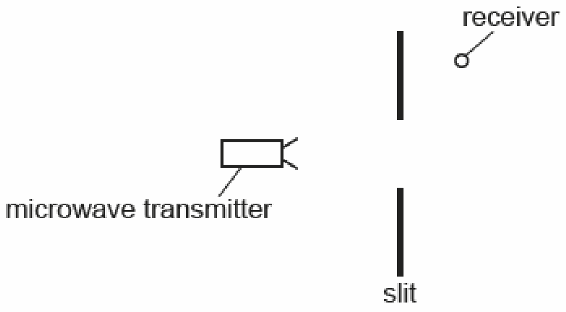

Fig. 26.1

A metal sheet with a wide slit is placed between a microwave transmitter and a receiver. The microwaves have a frequency of 11 GHz.

1.1 Calculate the wavelength λ of the microwaves.

[1 Mark]

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λ = ... m

1.2 The receiver detects no microwaves in the position shown in **Fig. 26.1.**
The metal sheet is replaced by another sheet with a narrow slit of width of a few centimetres, as shown in **Fig. 26.2**. The positions of the transmitter, receiver and the metal sheet are unchanged.

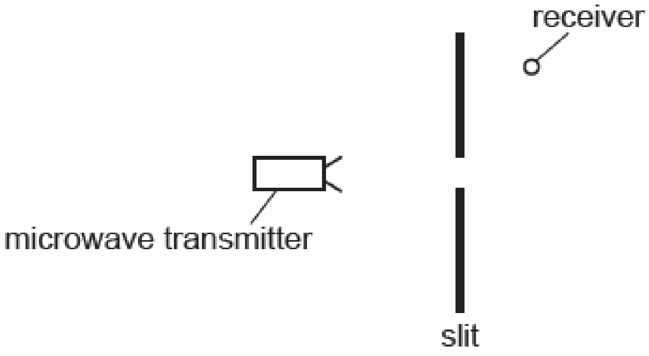

Fig. 26.2

Explain why the receiver now detects microwaves.

1.3 Light travels from air to water. The refractive index of water is greater than the refractive index of air.
Compare the speed, frequency and wavelength of light in air and in water.

[3 Marks]

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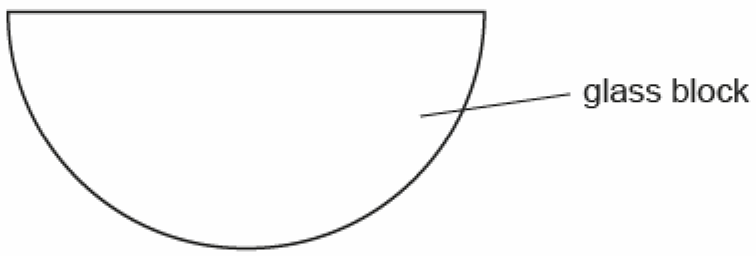
1.4 A student is given a semi-circular glass block.
Describe with the aid of a ray diagram how an experiment can be conducted to accurately determine the critical angle for light within the glass block and hence the refractive index of the glass.

[3 Marks]



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TOPIC: 3.3.2.3 Refraction at a Plane Surface

SPEC CHECK

Specification	Completed?
Refractive index of a substance, $n = \frac{c}{c_s}$	
Students should recall that the refractive index of air is approximately 1.	
Snell's law of refraction for a boundary $n_1 \sin \phi_1 = n_2 \sin \phi_2$	
Total internal reflection $\sin \phi_c = \frac{n_2}{n_1}$	
Simple treatment of fibre optics including the function of the cladding.	
Material and modal dispersion.	
Understand the principles and consequences of pulse broadening and absorption.	

SUPPORT QUESTIONS

Refraction is the change in direction of light when it passes, at an angle, across a boundary between two transparent substances, such as air and glass.

Refraction does not occur if the light passes across the boundary at 90° to the surface.

Refraction occurs because light travels at different speeds in different materials. Light travels more slowly in an optically dense material (i.e. a material with a higher **refractive index**).

The refractive index, *n*, is a measure of the optical density of a material relative to air. It is given by the equation $n_1 = \frac{c}{c_1}$, where c is the speed of light in air and c_1 is the speed of light in the material of interest. The refractive index has no units.

The greater the difference in refractive index between two substances, the more the light is refracted at the boundary.

The **normal** is an imaginary line, used on ray diagrams, and is drawn at 90° to the surface.

The **angle of incidence** is the angle between the light ray *arriving* at the boundary and the normal.

The **angle of refraction** is the angle between the light ray *leaving* the boundary and the normal.

A light ray bends *towards* the normal when the ray passes from a material with a lower refractive index to a material with a higher refractive index ($n_1 < n_2$). The angle of refraction is less than the angle of incidence.

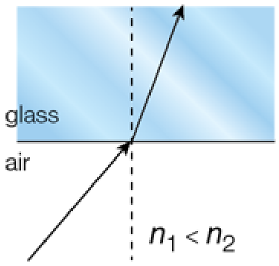

Figure 1

A light ray bends *away from* the normal when the ray passes from a material with a higher refractive index to a material with a lower refractive index ($n_1 > n_2$). The angle of refraction is greater than the angle of incidence.

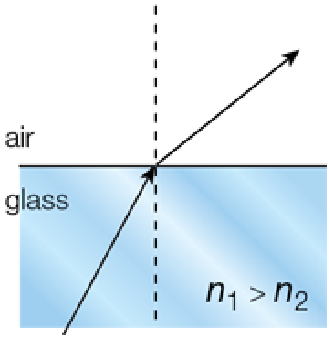

Figure 2

Some common refractive index values are provided in Table 1.

$n_{water} > n_{air}$ $n_{glass} > n_{air}$ $n_{glass} > n_{water}$

Material	Refractive index
air	1.00
water	1.33
glass	1.50

Make sure you remember these values.

Table 1 *Some common refractive index values*

Snell's law relates the angle of incidence, the angle of refraction, and the refractive index of each material:

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

Worked Example

Question

A ray of light, passing from glass into water, strikes the boundary at an angle of 35° to the normal. The refractive index of glass is 1.5 and the refractive index of water is 1.33. Calculate the angle of refraction.

Answer

Step 1

Draw a diagram.

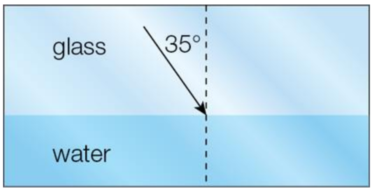

Figure 3

Make sure you read the question carefully and are clear where the light is coming from and where it is going to.

Step 2

Write down Snell's law and identify the values.

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

The light passes from glass (n_1) into water (n_2). The angle of incidence, θ_1, is given in the question. You have been asked to calculate the angle of refraction, θ_2.

$n_1 = 1.5$

$n_2 = 1.33$

$\theta_1 = 35°$

θ_2 =? (*This is the angle you need to find.*)

Step 3

Substitute the values into the equation n and rearrange to find θ_2.

$1.5 \sin 35 = 1.33 \sin \theta_2$

$1.5 \times 0.5736 = 1.33 \sin \theta_2$

During the calculation, write down values to a higher number of significant figures.

$\sin\theta_2 = \dfrac{1.5 \times 0.5736}{1.33}$

$= 0.6469$

$\theta_2 = \sin^{-1}(0.6469)$ *On your calculator: [shift][sin] 0.6469*

$= 40.3°$

$= 40°$

Give the answer to two significant figures, since this is the smallest number of significant figures quoted for values given in the question.

Q1. A ray of light, travelling in air, passes into a glass block at an angle of 65° to the normal in air. The refractive index of glass is 1.5.

Calculate the angle of refraction. **[2 marks]**

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Q2. A ray of light, travelling in glass, passes through the glass–air boundary at an angle of 25° to the normal in the glass. The refractive index of glass is 1.5.

Calculate the angle of refraction. **[2 marks]**

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Q3. A ray of light, travelling in air, passes into water. The angle of refraction is 23°. The refractive index of water is 1.33.

Calculate the angle of incidence. **[2 Marks]**

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Q4. The refractive index of acrylic glass is 1.49. The speed of light in air is approximately 3×10^8 ms^{-1}.

Calculate the speed of light in acrylic glass. **[2 Marks]**

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Q5. A ray of light, travelling in liquid water, passes into an ice cube at an angle of 25.5° to the normal in water. The ray of light is refracted to an angle of 25.9° to the normal in the ice. The refractive index of liquid water is 1.33.

Calculate the refractive index of ice. **[3 Marks]**

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ANSWERS

Q1. 37° to two significant figures (37.2°) (*2 marks*)

Q2. 39° to two significant figures (39.3°) (*2 marks*)

Q3. 31° to two significant figures (31.3°) (*2 marks*)

Q4. 2×10^8 ms^{-1} (*2 marks*)

Q5. 25.9° to three significant figures (*3 marks*)

Refraction is the change in direction of light when it passes, at an angle, across a boundary between two transparent substances, such as air and glass.

If a ray of light passes from a more optically dense material into a less optically dense material with an angle of incidence greater than the **critical angle** (θ_c), the ray is **totally internally reflected.** This means that the ray is reflected into the first material instead of passing into the second material, as shown in Figure 1.

The usual laws of reflection are obeyed – the **angle of reflection** is equal to the **angle of incidence**.

- A more optically dense material has a higher refractive index, n_1.
- A less optically dense material has a lower refractive index, n_2.

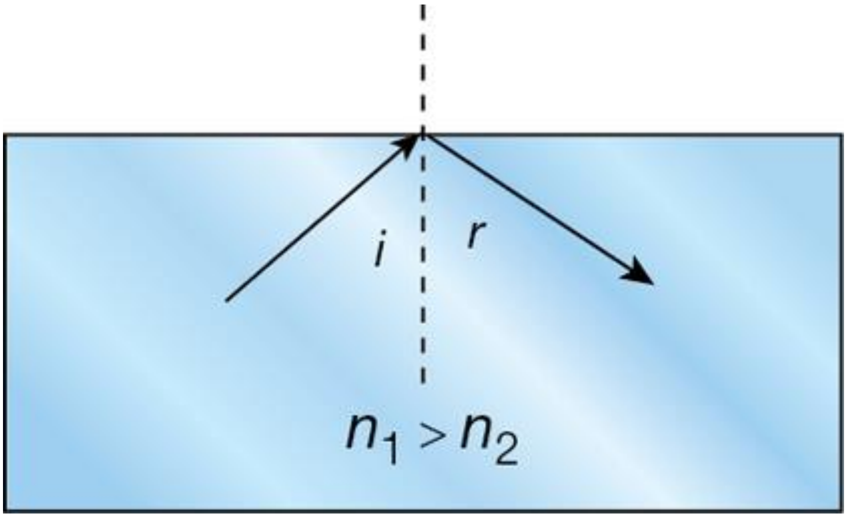

Figure 1 *Total internal reflection*

If the angle of incidence is equal to the critical angle ($\theta_i = \theta_c$) then the **angle of refraction** is 90° and the ray travels along the boundary between the two materials, as shown in Figure 2.

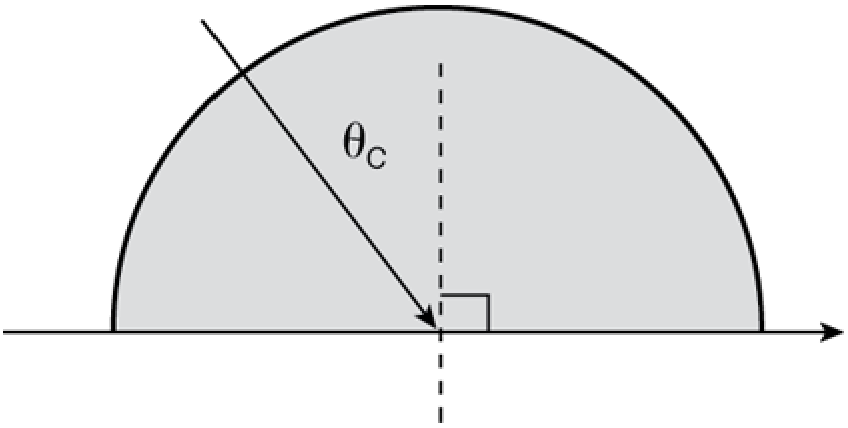

Figure 2 *Refraction along the boundary occurs when* $\theta_i = \theta_c$

The critical angle can be calculated using either Equation 1 or Equation 2.

Equation 1 $n_1 \sin \theta_c = n_2 \sin 90°$

Equation 2 $\sin \theta_c = \frac{n_2}{n_1}$ (since $\sin 90° = 1$)

It is often easier to use *Equation 1* since n_1 and n_2 are more easily identified.

Exam-style optics questions often:

- contain a diagram which you should use to help you answer the question
- require you 'to complete the path of the ray' on a ray diagram
- require the use of geometry
- require the use of the equation $n_1 \sin \theta_1 = n_2 \sin \theta_2$ in more than one way.

Worked example

Exam-style question

An equilateral triangular glass prism is made of glass of refractive index 1.48. A ray of red light is incident at P at an angle of 40° to the normal, as shown in Figure 3.

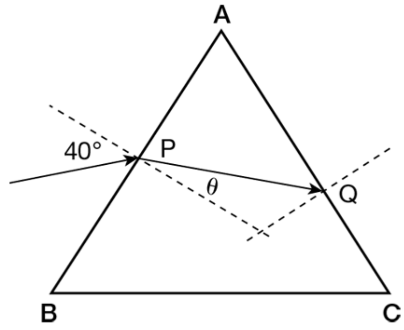

Figure 3

a Calculate the angle of refraction, θ.

b Calculate the critical angle between the glass and air.

c Draw the path of the ray after it reaches Q, marking any values of angles on Figure 3.

Answer

a Step 1

Write down Snell's law and identify the values.

Snell's law: $n_1 \sin \theta_1 = n_2 \sin \theta_2$

The light passes from air (n_1) into glass (n_2). The angle of incidence, θ_1, is 40° and the angle of refraction is θ_2.

$n_1 = 1$

$n_2 = 1.48$

$\theta_1 = 40°$

$\theta_2 = \theta = ?$ *This is the angle you need to find.*

Step 2

Substitute the values into the equation and rearrange to find θ.

$1.0 \sin 40 = 1.48 \sin \theta$

$\sin \theta = \frac{\sin 40}{1.48} = 0.4343$

$\theta = \sin^{-1}(0.4343)$ *On your calculator: [shift][sin] 0.4343*

$= 25.74 = 26°$ (to two significant figures)

b Step 1

Write down Snell's law and identify the values.

Snell's law: $n_1 \sin \theta_1 = n_2 \sin \theta_2$

Part **b** asks for the critical angle between the glass and air, so the light now passes from glass (n_1) into air (n_2). The angle of incidence, θ_1, is equal to the critical angle, which you need to find. The critical value is defined as the angle of incidence for which the angle of refraction, θ_2, is equal to 90°.

$n_1 = 1.48$

$n_2 = 1$

$\theta_1 = \theta_c = ?$ *This is the angle you need to find.*

$\theta_2 = 90°$

Step 2

Substitute the values into the equation and rearrange to find θ_c.

$1.48 \sin \theta_c = 1.0 \sin 90°$

$= 1$

$$\sin \theta_c = \frac{1}{1.48}$$

$= 0.6757$

$\theta_c = \sin^{-1}(0.6757)$ *On your calculator: [shift][sin] 0.6757*

$= 42.5°$

$= 43°$ to two significant figures

c Step 1

Before you can draw the ray, you need to find the angle of incidence at Q and see if it is bigger or smaller than the critical angle to find out what happens next. Use what you know about the geometry of triangles.

angle APQ $= 90 - \theta$ $= 90 - 26$ $= 64°$	*the normal is at 90° to the surface, by definition use the value of θ you calculated in part **a***
angle PAQ $= 60°$ angle AQP $= 180 - 64 - 60$ $= 56°$	*all angles in an equilateral triangle are 60°, the sum of the internal angles of a triangle is 180°*
angle of incidence at Q $= 90 - 56$ $= 34°$	*this is the angle between the ray and the normal at Q, it is helpful to mark all angles on the diagram as you work them out*

Step 2

Compare the angle of incidence with the critical angle.

angle of incidence at Q = 34°

θ_c = 43° *this is the value of θ_c you calculated in part **b***

The angle of incidence at Q is less than the critical angle, so the ray is not totally internally reflected. The ray passes from glass (refractive index of 1.48) into air (refractive index of 1) and so is refracted away from the normal.

Step 3

Draw the refracted ray on the diagram.

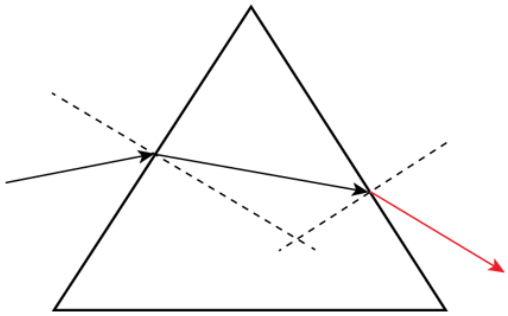

Figure 4

Q1. A ray of light is travelling in glass towards a glass-air boundary at an angle of incidence equal to 60.

Q1.1. Find the critical angle for the glass-air boundary.

The refractive index of glass is 1.5 and the refractive index of air is 1.0.

[2 Marks]

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Q1.2 Describe and explain what will happen to the ray of light when it reaches the glass–air boundary.

[2 Marks]

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Q2. In an optical fibre, a ray of light strikes the core at **A**.
It is then refracted, as shown in Figure 5, and hits the core–cladding boundary at B at the critical angle *c*.
Refractive index of cladding is 1.45.
Refractive index of core is 1.48.

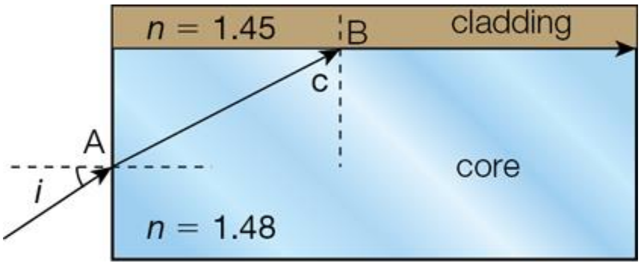

Figure 5

Q2.1 Calculate the critical angle at **B**.

[2 Marks]

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Q2.2 Calculate the angle of refraction at **A**.

[1 Mark]

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Q2.3 Calculate the angle of incidence in air at **A**.

[2 Marks]

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Q3. The triangular prism shown in the diagram has a right angle at **A** and 45° angles at **B** and **C**. A ray parallel to BC enters the prism at **P** and is refracted as shown in **Figure 6**.
Refractive index of glass = 1.5.

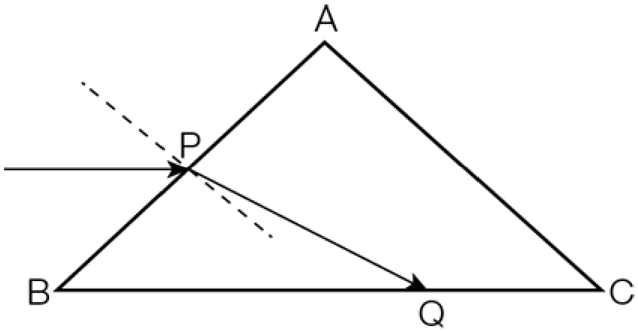

Figure 6

Q3.1 State the angle of incidence in air.

[1 Mark]

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Q3.2 Calculate the angle of refraction at P.

[2 Marks]

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Q3.3 Calculate the critical angle as the ray travels from glass into air.

[2 Marks]

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Q3.4 Mark on the diagram the path of the ray of light when it reaches **Q**.

[1 Mark]

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ANSWERS

Q1.1. 42° to two significant figures (41.8°) (*2 marks*)

Q1.2 angle of incidence > critical angle, so total internal reflection occurs
(the ray is reflected from the boundary with an angle of reflection of 60 °) (*2 marks*)

Q2.1 78° to two significant figures (78.4°) (*2 marks*)

Q2.2 90 − 78.4 = 11.6 ° = 12 ° to two significant figures (*1 mark*)

Q2.3 17° to two significant figures (17.3°) (*2 marks*)

Q3.1 45° (*1 mark*)

Q3.2 28° to two significant figures (28.1°) (*2 marks*)

Q3.3 42° to two significant figures (41.8°) (*2 marks*)

Q3.4 PQB = 17°
Angle of incidence = 73°
Angle of incidence > critical angle, so total internal reflection occurs (*1 mark*)

EXTENSION
Questions

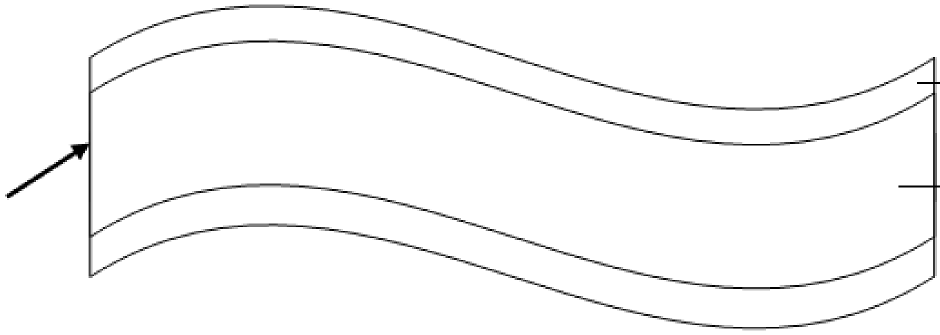

Figure 1 *Simplified diagram of an optical fibre*

Q1. Look at Figure 1.

Q1.1. Explain why the cladding is so important in communication applications, apart from providing protection for the fibre.

[2 Marks]

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Q1.2. Comment on the speed of the light as it enters and leaves the fibre.

[2 Marks]

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Q2. Carefully continue the path of the ray of light through the optical fibre to the far end, obeying the laws of reflection and refraction. Mark any normal lines clearly and label any known angles.

[4 Marks]

Q3.1 The refractive index of the material of the core is 1.52. Calculate the angle of refraction when the angle of incidence of the light is 40°.

[2 Marks]

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Q3.2 Calculate the speed of the light within the fibre.

[2 Marks]

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Q3.3 Estimate the refractive index of the cladding, giving a reason for your answer.

[2 Marks]

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Q4. Explain why optical fibres used in communications applications must be very narrow.

[4 Marks]

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Q5. Explain why monochromatic light must be used in optical fibre communications.

[4 Marks]

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Q6. When optical fibres are used for communication, information is transmitted in the form of a series of pulses of light. Show this using a diagram, and describe what can happen to the shape of the pulse as it travels down the fibre; include an explanation.

[3 Marks]

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Q7. Broadband networks have improved considerably in recent years as telecommunications companies have worked to increase the speed of internet access for their customers. You have just received a phone call from a broadband provider who is trying to tempt you to sign up with them – they say that their broadband is the best value and the fastest.

You know there are two means of fibre-optic broadband provision:

FTTC – the cable from the telephone exchange to the 'green cabinet' at the end of your road is fibre optic, but from the cabinet to your house is copper cable

FTTH – the cable from the telephone exchange all the way to the house is fibre optic

Explain to the salesperson why, before committing yourself to anything, you would like to know which of these two means of communication is on offer where you live, and why you will not commit if the answer is not the one you hope to receive.

[4 Marks]

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Q8. Different broadband packages are available from different providers, depending on how much information your household transmits and receives every month.

Using **Tables 1** and **2**, and considering your own personal usage of the Internet per month, decide which package would be best for you. Write a reasoned argument for your package choice, making sure your explanation would be suitable for someone with no understanding of the difference between kb, Mb, and Gb.

[4 Marks]

Table 1 Time of transmission for different downloads at various broadband speeds

	Download time *(s – seconds, m – minutes, h – hours)*					
Broadband speed (Mb/s)	**Email (75 kb)**	**Photo (4.25 Mb)**	**Video (6 Mb)**	**Album (100 Mb)**	**HD film (720 Mb)**	**TV series (32 Gb)**
2	0.038 s	2.1 s	3.0 s	50.0 s	6 m	4 h 26 m 40 s
20	0.0038 s	0.21 s	0.3 s	5.0 s	36.0 s	26 m 40 s
100	0.00075 s	0.043 s	0.06 s	1.0 s	7.2 s	5 m 20 s
300	0.00025 s	0.014 s	0.02 s	0.33 s	2.4 s	1 m 47 s

Table 2 Costs for various broadband packages

Broadband provider	**Download speed (Mb/s)**	**Download limit (Gb)**	**Cost per month**
T	17	unlimited	£3.50 = £16.70 line rental
V	38	20	£7.50 = £14.16 line rental
W	50	unlimited	£17.50 = £16.99 line rental
X	17	2	£21.50 = £16.40 line rental
Y	38	unlimited	£19.95 = £11.00 line rental
Z	17	10	£6.00 = £15.40 line rental

ANSWERS

Q1.1. Cladding prevents fibres being in direct contact, so prevents light crossing from one fibre to the other and data becoming insecure. Mention of 'cross-over'. (*2 marks*)

Q1.2. The light slows down as it enters the fibre and speeds up as it leaves. (*2 marks*)

Q2.

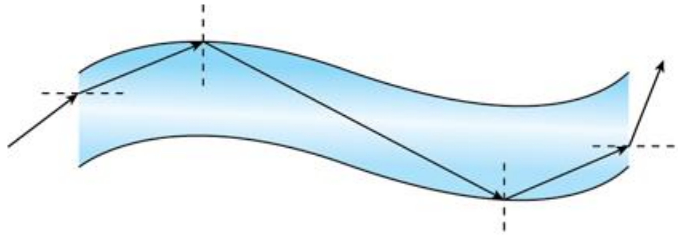

Figure 1 *Simplified diagram of an optical fibre showing path of light ray*

Ray bends towards the normal at the incident face.

Total internal reflection occurs twice (a good answer should mark the TIR angles as equal).

Ray bends away from the normal at the exit face. (*4 marks*)

Q3.1. $n_1 \sin i = n_2 \sin r$

$1 \sin 40 = 1.52 \sin r$ (students should recall that the refractive index of air is 1)

$\sin r = \frac{\sin 40}{1.52}$

$= 0.42$

$r = \sin^{-1} 0.42$

$= 25°$

Q3.2. $n_s = \frac{c}{c_s}$

$1.52 = \frac{3 \times 10^8}{c_s}$

$c_s = \frac{3 \times 10^8}{1.52}$

$= 1.97 \times 10^8 \text{ ms}^{-1}$

Q3.3. An acceptable answer would be 1.4 (any value less than 1.52). Total internal reflection can only occur if the incident substance (core) has a higher refractive index than the other substance (cladding). The lower the refractive index of the cladding, the lower the critical angle, so more light is totally internally reflected. (*2 marks*)

Q4. If the optical fibres are not narrow enough, modal (or multipath) dispersion will occur. The path of a totally internally reflected ray will be considerably longer than the path of an axial ray, per metre of fibre, and the pulse will lengthen. If the pulse becomes too long it will merge with the next pulse. (*4 marks*)

Q5. Monochromatic (single wavelength) light must be used to prevent material (or spectral dispersion) and pulse merging. If white light was used, for example, the pulse would lengthen because violet light travels through the fibre more slowly than red light. (*4 marks*)

Q6. Emergent pulses should be shown:

Attenuated compared to the original pulse due to loss of energy (e.g., due to absorption)

Longer compared to the original pulse due to material and modal dispersion. (*3 marks*)

Q7. Sensible arguments include:

With FTTC, the signal must be converted from light to electrical at the 'green box'.

More data can be sent via optical fibres more quickly, since attenuation and dispersion is lower than with copper cables; the bandwidth is higher.

Dispersion and attenuation depend on distance – if your house is further from the 'green box' then the limiting copper cable will have a bigger impact. (*4 marks*)

Q8. Students should provide data summarising their usage (estimate of number of emails, photos, etc., downloaded each month) and relate this to the cost of the packages. (*4 marks*)

CHALLENGE QUESTION

To assess your understanding, answer the following higher-level question on this topic.

1. A student investigates the path of a light ray through ethanol. **Fig. 8.1** shows ethanol in a rectangular glass container. Light of wavelength 5.2×10^{-7} m is incident on the container as shown.

Fig. 8.1 (not to scale)

The table below shows the refractive indices n and speeds of light v in various transparent media.

medium	*n*	v / m s^{-1}
air	1.00	3.00×10^8
ethanol		2.20×10^8
glass	1.52	
vacuum	1.00	3.00×10^8

1.1 Complete the table by calculating the missing values of n and v.

[2 Marks]

1.2 Determine the wavelength λ of the light in glass.

[1 Mark]

....

....

....

λ = ... m

Fig. 8.2 shows an enlarged version of a section of the left hand side of the glass container.

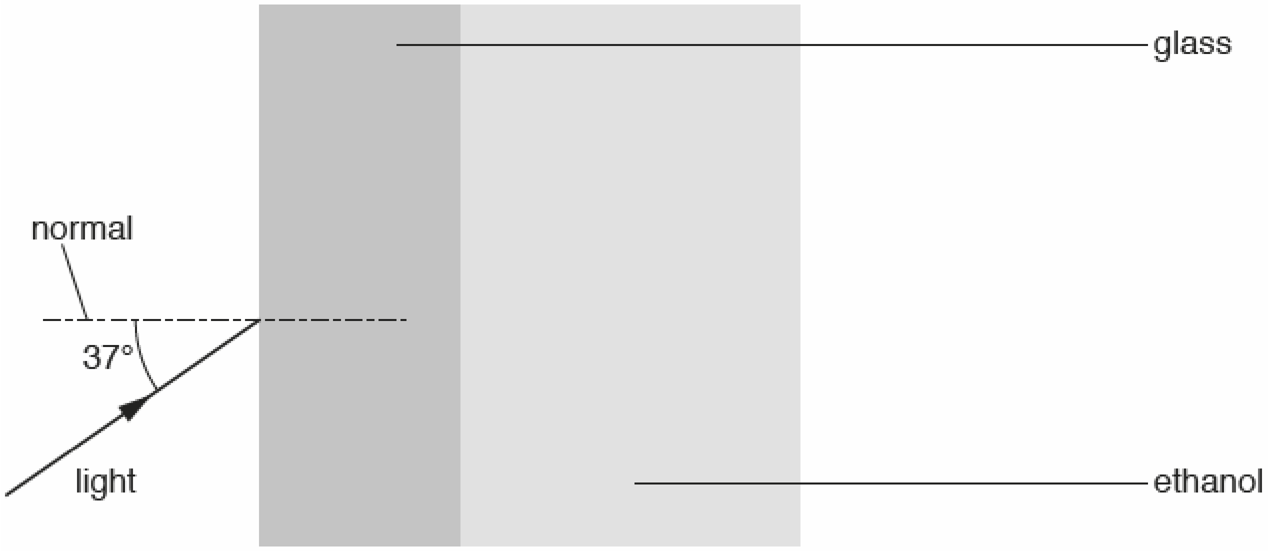

Fig. 8.2 (not to scale)

1.3 The light is incident on the glass at an angle of 37°.
Determine the angle of refraction θ in the glass.

[2 Marks]

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θ = ...°

1.4 Without any further calculation, sketch the ray of light as it passes through the glass into the ethanol.

[1 Mark]

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MARK SCHEME

Question	Answer	Marks	Guidance
1.1	1.36	B1	**Not** 1.3 or 1.4
	1.97×10^8	B1	**Not** 1.9 or 2.0
1.2	$\left(\frac{5.2\times10^{-7}}{1.52}=\right)$ $3.4(2) \times 10^{-7}$ (m)	B1	**Allow** 3.41×10^{-7} (m) **Not** ECF from (a)(i)
1.3	$\sin\theta = \frac{\sin 37}{1.52} (= 0.39593)$	C1	
	$\theta = 23(.3)°$	A1	
1.4	Ray in glass bends towards normal and ray in ethanol bends away from normal but at a smaller angle than 37° Rays are straight by eye	B1	**Note** Ray should not be parallel to incoming ray. **Not** angle of refraction is zero in glass
	Total	**6**	

EXTENDED WRITING

To enhance your skills in answering examination questions for the A-Level examinations, complete the following task.

Describe how you would use a power pack, ray box and other standard laboratory equipment to obtain accurate and reliable measurement of the refractive index and critical angle of a Perspex block. Your description should include:

- Details of the experimental set up (you may include a diagram) including a risk assessment
- Details of measurements you would take and how you would use your measurements to find the refractive index and critical angle
- An account of how you could check to see if a second block of Perspex has the same refractive index as the first block.
- Details of how to improve the accuracy and precision of your measurements.

ANSWERING SPACE

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MARK SCHEME

P	**Praise. What were the positive aspects of the work? What did they do well? What skills did they demonstrate?**

I	**Improvements. What were the literacy issues in the piece of work?**		*Write in ink.*		*Draw in Pencil.*		*Use a ruler.*
	Always use capital letters at the beginning of a sentence.		Learn the spellings identified in your work.				
	Always use capital letters for proper nouns.		Ensure sentences make sense.				
	Make sure you write on the line and not above or below it.		Use correct punctuation.				
	Use scientific vocabulary appropriate to the task.		Vary your sentences to demonstrate your understanding.				

D answer		B answer		A* answer	
A (single/thin) ray of light is sent through (the block) at different angles (of incidence)...		...and the corresponding angle of refraction is measured...		...using a protractor.	
				...measured from the normal (owtte).	
The interval of incident angles is missing or described vaguely such as 'wide range of values'...		...the interval is present...		...between 0 ° and the critical angle.	
		The risk of burns from the bulb is stated...		...and an appropriate control measure is given.	
For each incident angle the refracted angle is measured (at least) three times...		...anomalous results are removed and a mean is calculated...		...accuracy is also improved by reducing the interval of $\theta_1$so $\theta_2$is measured at more values so a more detailed line (of best fit) can be drawn.	
The refractive index is calculated using $n = \frac{\sin\theta_1}{\sin\theta_2}$ and critical angle with $\sin\theta_C = \frac{1}{n}$...		...by plotting a graph of $\sin\theta_1$ (on the y axis) against $\sin\theta_2$ (on the x axis) and drawing a **#** line of best fit **~** ...		...the gradient is equal to the refractive index of the Perspex block.	
				#straight.	
				~that cuts the origin.	
You could repeat the experiment with the second block and compare the values of refractive index.		You could place the blocks next to each other and send a ray of light through both blocks...		...if they have the same value of n the ray should not bend as it travels from one to the other.	
The precision of the measurements could be improved by using protractor with smaller scale divisions (0.5 °)...		...the values of refractive index could be more precise by having smaller scale divisions on the graph...		...or using a computer program to draw the graph (previous statements needed for this to be awarded).	

N	**Next Steps. How can they move their work onto the next grade? What didn't they include?**	**Grade**	**Effort**

PRACTICAL SKILLS

Complete the following practical skills-based task to improve your experimental understanding of this part of the course in preparation for **Physics Paper 3.**

You are going to use experimental data on light being shone through a Perspex block to find its refractive index.
The incident angle is measured from the normal in the Perspex block and the refracted angle is measured from the normal out of the block in the air.

Experimental Data

The protractor used to measure the incident and refracted angle had a precision of 0.5°

Incident Angle, θ_1 (°)	**Refracted Angle, θ_2 (°)**			**Mean Refracted Angle, θ_2 (°)**	**Sin θ_1**	**Sin θ_2**
5.0	7.0	7.5	7.5			
10.0	14.5	15.5	15.0			
15.0	22.0	23.0	23.0			
20.0	31.0	30.0	31.0			
25.0	38.0	39.0	39.5			
30.0	47.5	47.5	47.5			
35.0	57.5	57.5	58.5			
40.0	71.5	71.5	73.0			

Analysis

A1. Calculate the mean values for the refracted angle for each incident angle.

A2. What type of error is responsible for the variation in readings for the refracted angle?

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A3. Calculate the uncertainty in the mean refracted angle for an incident angle of 15°.

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A4. What is this as a percentage of the mean refracted angle?

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A5. Calculate the uncertainty in the mean refracted angle for an incident angle of 30°.

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A6. What is this as a percentage of the mean refracted angle?

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A7. Which measurement is more precise?

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A8. Complete the columns labelled sin θ_1 and sin θ_2 and state your values to 3 decimal places.

A9. Plot a graph of sin θ_1 on the y axis and sin θ_2 on the x axis.

A10. Draw a line of best fit for the graph.

A11. The equation for the line is $\sin\theta_1 = \frac{1}{n}\sin\theta_2$, what does the gradient represent?

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....

A12. Calculate the gradient of your line.

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A13. What value for the refractive index, *n*, does your graph produce?

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The accepted refractive index of Perspex is 1.48.

A14. What is the difference between your value for the refractive index and the accepted value?

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A15. Work out this out as a percentage of the accepted value.

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A16. Use the equation $\sin\theta_C = \frac{1}{n}$ to calculate the critical angle of Perspex.

The accepted critical angle is 42.5°.

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A17. What is the difference between your value for the critical angle and the accepted value?

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A18. Calculate this as a percentage of the accepted value.

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A19. How could you prove that this was the critical angle? Describe how you would go about doing this.

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REVISION CHECKLIST

Specification reference	Checklist questions	
3.3.2.1	Can you define path difference and coherence?	☐
3.3.2.1	Can you explain interference and diffraction using a laser as a source of monochromatic light?	☐
3.3.2.1	Can you describe Young's double-slit experiment?	☐
3.3.2.1	Can you describe the use of two coherent sources or the use of a single source with double slits to produce an interference pattern?	☐
3.3.2.1	Can you explain fringe spacing using the equation $w = \frac{\lambda D}{s}$?	☐
3.3.2.1	Can you describe the production of an interference pattern using white light?	☐
3.3.2.1	Can you describe safety issues associated with using lasers?	☐
3.3.2.1	Can you describe and explain interference produced with sound and electromagnetic waves?	☐
3.3.2.1	Can you explain how our knowledge and understanding of the nature of electromagnetic radiation has changed over time?	☐
3.3.2.1	Have you carried out an investigation of interference effects using the Young double-slit experiment and the diffraction grating?	☐
3.3.2.2	Can you describe the appearance of the diffraction pattern from a single slit using monochromatic and white light?	☐
3.3.2.2	Can you describe how the width of the central diffraction maximum varies with wavelength and slit width?	☐
3.3.2.2	Can you describe the diffraction pattern when light is shone on a plane transmission diffraction grating at normal incidence?	☐

Specification reference	Checklist questions	
3.3.2.2	Can you derive $d\sin\theta = n\lambda$?	☐
3.3.2.2	Can you suggest some applications of diffraction gratings?	☐
3.2.2.3	Can you calculate the refractive index of a substance using $n = \frac{c}{c_s}$?	☐
3.2.2.3	Can you recall that the refractive index of air is approximately 1?	☐
3.2.2.3	Can you recall and use Snell's law of refraction ($n_1\sin\theta_1 = n_2\sin\theta_2$) for a boundary?	☐
3.2.2.3	Can you explain total internal reflection using $\sin\theta_c = \frac{n_2}{n_1}$?	☐
3.2.2.3	Can you explain fibre optics, including the function of the cladding?	☐
3.2.2.3	Can you explain material and modal dispersion?	☐
3.2.2.3	Can you explain the principles and consequences of pulse broadening and absorption?	☐

DATASHEET

DATA - FUNDAMENTAL CONSTANTS AND VALUES

Quantity	Symbol	Value	Units
speed of light in vacuo	c	3.00×10^8	$m\,s^{-1}$
permeability of free space	μ_0	$4\pi \times 10^{-7}$	$H\,m^{-1}$
permittivity of free space	ε_0	8.85×10^{-12}	$F\,m^{-1}$
magnitude of the charge of electron	e	1.60×10^{-19}	C
the Planck constant	h	6.63×10^{-34}	J s
gravitational constant	G	6.67×10^{-11}	$N\,m^2\,kg^{-2}$
the Avogadro constant	N_A	6.02×10^{23}	mol^{-1}
molar gas constant	R	8.31	$J\,K^{-1}\,mol^{-1}$
the Boltzmann constant	k	1.38×10^{-23}	$J\,K^{-1}$
the Stefan constant	σ	5.67×10^{-8}	$W\,m^{-2}\,K^{-4}$
the Wien constant	α	2.90×10^{-3}	m K
electron rest mass (equivalent to 5.5×10^{-4} u)	m_e	9.11×10^{-31}	kg
electron charge/mass ratio	$\frac{e}{m_e}$	1.76×10^{11}	$C\,kg^{-1}$
proton rest mass (equivalent to 1.00728 u)	m_p	$1.67(3) \times 10^{-27}$	kg
proton charge/mass ratio	$\frac{e}{m_p}$	9.58×10^7	$C\,kg^{-1}$
neutron rest mass (equivalent to 1.00867 u)	m_n	$1.67(5) \times 10^{-27}$	kg
gravitational field strength	g	9.81	$N\,kg^{-1}$
acceleration due to gravity	g	9.81	$m\,s^{-2}$
atomic mass unit (1u is equivalent to 931.5 MeV)	u	1.661×10^{-27}	kg

ALGEBRAIC EQUATION

quadratic equation $x = \dfrac{-b \pm \sqrt{b^2 - 4ac}}{2a}$

ASTRONOMICAL DATA

Body	Mass/kg	Mean radius/m
Sun	1.99×10^{30}	6.96×10^8
Earth	5.97×10^{24}	6.37×10^6

GEOMETRICAL EQUATIONS

arc length	$= r\theta$
circumference of circle	$= 2\pi r$
area of circle	$= \pi r^2$
curved surface area of cylinder	$= 2\pi rh$
area of sphere	$= 4\pi r^2$
volume of sphere	$= \frac{4}{3}\pi r^3$

Particle Physics

Class	Name	Symbol	Rest energy/MeV
photon	photon	γ	0
lepton	neutrino	ν_e	0
		ν_μ	0
	electron	$e^\pm$	0.510999
	muon	$\mu^\pm$	105.659
mesons	π meson	$\pi^\pm$	139.576
		π^0	134.972
	K meson	$K^\pm$	493.821
		K^0	497.762
baryons	proton	p	938.257
	neutron	n	939.551

Properties of quarks

antiquarks have opposite signs

Type	Charge	Baryon number	Strangeness
u	$+\frac{2}{3}e$	$+\frac{1}{3}$	0
d	$-\frac{1}{3}e$	$+\frac{1}{3}$	0
s	$-\frac{1}{3}e$	$+\frac{1}{3}$	-1

Properties of Leptons

		Lepton number
Particles:	$e^-, \nu_e; \mu^-, \nu_\mu$	$+1$
Antiparticles:	$e^+, \overline{\nu_e}, \mu^+, \overline{\nu_\mu}$	-1

Photons and energy levels

photon energy $E = hf = hc/\lambda$

photoelectricity $hf = \phi + E_{k\,(max)}$

energy levels $hf = E_1 - E_2$

de Broglie wavelength $\lambda = \frac{h}{p} = \frac{h}{mv}$

Waves

wave speed $c = f\lambda$ *period* $f = \frac{1}{T}$

first harmonic $f = \frac{1}{2l}\sqrt{\frac{T}{\mu}}$

fringe spacing $w = \frac{\lambda D}{s}$ *diffraction grating* $d \sin\theta = n\lambda$

refractive index of a substance s, $n = \frac{c}{c_s}$

for two different substances of refractive indices n_1 *and* n_2,

law of refraction $n_1 \sin\theta_1 = n_2 \sin\theta_2$

critical angle $\sin\theta_c = \frac{n_2}{n_1}$ for $n_1 > n_2$

Mechanics

moments moment $= Fd$

velocity and acceleration $v = \frac{\Delta s}{\Delta t}$ $a = \frac{\Delta v}{\Delta t}$

equations of motion $v = u + at$ $s = \left(\frac{u+v}{2}\right)t$

$v^2 = u^2 + 2as$ $s = ut + \frac{at^2}{2}$

force $F = ma$

force $F = \frac{\Delta(mv)}{\Delta t}$

impulse $F\,\Delta t = \Delta(mv)$

work, energy and power $W = F s \cos\theta$

$E_k = \frac{1}{2} m v^2$ $\Delta E_p = mg\Delta h$

$P = \frac{\Delta W}{\Delta t}$, $P = Fv$

$efficiency = \frac{useful\ output\ power}{input\ power}$

Materials

density $\rho = \frac{m}{V}$ *Hooke's law* $F = k\,\Delta L$

Young modulus $= \frac{tensile\ stress}{tensile\ strain}$ *tensile stress* $= \frac{F}{A}$ *tensile strain* $= \frac{\Delta L}{L}$

energy stored $E = \frac{1}{2}F\Delta L$

Electricity

current and pd $I = \frac{\Delta Q}{\Delta t}$ $V = \frac{W}{Q}$ $R = \frac{V}{I}$

resistivity $\rho = \frac{RA}{L}$

resistors in series $R_T = R_1 + R_2 + R_3 + \ldots$

resistors in parallel $\frac{1}{R_T} = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3} + \cdots$

power $P = VI = I^2R = \frac{V^2}{R}$

emf $\varepsilon = \frac{E}{Q}$ $\varepsilon = I(R + r)$

Circular motion

magnitude of angular speed $\omega = \frac{v}{r}$

$\omega = 2\pi f$

centripetal acceleration $a = \frac{v^2}{r} = \omega^2 r$

centripetal force $F = \frac{mv^2}{r} = m\omega^2 r$

Simple harmonic motion

acceleration $a = -\omega^2 x$

displacement $x = A \cos(\omega t)$

speed $v = \pm \omega \sqrt{(A^2 - x^2)}$

maximum speed $v_{max} = \omega A$

maximum acceleration $a_{max} = \omega^2 A$

for a mass-spring system $T = 2\pi \sqrt{\frac{m}{k}}$

for a simple pendulum $T = 2\pi \sqrt{\frac{l}{g}}$

Thermal physics

energy to change temperature $Q = mc\Delta\theta$

energy to change state $Q = m\,l$

gas law $pV = nRT$

$pV = NkT$

kinetic theory model $pV = \frac{1}{3} N m (c_{rms})^2$

kinetic energy of gas molecule $\frac{1}{2} m (c_{rms})^2 = \frac{3}{2} kT = \frac{3RT}{2N_A}$

Gravitational fields

force between two masses $F = \frac{Gm_1m_2}{r^2}$

gravitational field strength $g = \frac{F}{m}$

magnitude of gravitational field strength in a radial field $g = \frac{GM}{r^2}$

work done $\Delta W = m\Delta V$

gravitational potential $V = -\frac{GM}{r}$

$g = -\frac{\Delta V}{\Delta r}$

Electric fields and capacitors

force between two point charges $F = \frac{1}{4\pi\varepsilon_0} \frac{Q_1Q_2}{r^2}$

force on a charge $F = EQ$

field strength for a uniform field $E = \frac{V}{d}$

work done $\Delta W = Q\Delta V$

field strength for a radial field $E = \frac{1}{4\pi\varepsilon_0} \frac{Q}{r^2}$

electric potential $V = \frac{1}{4\pi\varepsilon_0} \frac{Q}{r}$

$E = \frac{\Delta V}{\Delta r}$

capacitance $C = \frac{Q}{V}$

$C = \frac{A\varepsilon_0\varepsilon_r}{d}$

capacitor energy stored $E = \frac{1}{2}QV = \frac{1}{2}CV^2 = \frac{1}{2}\frac{Q^2}{C}$

capacitor charging $Q = Q_0(1 - e^{-t/RC})$

decay of charge $Q = Q_0 e^{-t/RC}$

time constant RC

Magnetic fields

force on a current $F = BIl$

force on a moving charge $F = BQv$

magnetic flux $\Phi = BA$

magnetic flux linkage $N\Phi = BAN\cos\theta$

magnitude of induced emf $\varepsilon = N\dfrac{\Delta\Phi}{\Delta t}$

$N\Phi = BAN\cos\theta$

emf induced in a rotating coil $\varepsilon = BAN\omega\sin\omega t$

alternating current $I_{rms} = \dfrac{I_0}{\sqrt{2}}$ $V_{rms} = \dfrac{V_0}{\sqrt{2}}$

transformer equations $\dfrac{N_s}{N_p} = \dfrac{V_s}{V_p}$

$efficiency = \dfrac{I_s V_s}{I_p V_p}$

Nuclear physics

the inverse square law for γ radiation $I = \dfrac{k}{x^2}$

radioactive decay $\dfrac{\Delta N}{\Delta t} = -\lambda N,\ N = N_0 e^{-\lambda t}$

activity $A = \lambda N$

half-life $T_{½} = \dfrac{\ln 2}{\lambda}$

nuclear radius $R = R_0 A^{1/3}$

energy-mass equation $E = mc^2$

OPTIONS

Astrophysics

1 astronomical unit = 1.50×10^{11} m

1 light year = 9.46×10^{15} m

1 parsec = 206265 AU = 3.08×10^{16} m = 3.26 light year

Hubble constant, H = 65 km s^{-1} Mpc^{-1}

$M = \dfrac{\text{angle subtended by image at eye}}{\text{angle subtended by object at unaided eye}}$

in normal adjustment $M = \dfrac{f_o}{f_e}$

Rayleigh criterion $\theta \approx \dfrac{\lambda}{D}$

magnitude equation $m - M = 5\log\dfrac{d}{10}$

Wien's law $\lambda_{max} T = 2.9 \times 10^{-3}$ m K

Stefan's law $P = \sigma A T^4$

Schwarzschild radius $R_s \approx \dfrac{2GM}{c^2}$

Doppler shift for v << c $\dfrac{\Delta f}{f} = -\dfrac{\Delta\lambda}{\lambda} = \dfrac{v}{c}$

red shift $z = -\dfrac{v}{c}$

Hubble's law $v = Hd$

Medical physics

lens equations $P = \dfrac{1}{f}$

$m = \dfrac{v}{u}$

$\dfrac{1}{f} = \dfrac{1}{u} + \dfrac{1}{v}$

threshold of hearing $I_0 = 1.0 \times 10^{-12}$ W m^{-2}

intensity level $intensity\ level = 10\log\dfrac{I}{I_0}$

absorption $I = I_0 e^{-\mu x}$

$\mu_m = \dfrac{\mu}{\rho}$

ultrasound imaging $Z = \rho c$

$\dfrac{I_r}{I_i} = \left(\dfrac{Z_2 - Z_1}{Z_2 + Z_1}\right)^2$

half-lives $\dfrac{1}{T_E} = \dfrac{1}{T_B} + \dfrac{1}{T_P}$

Engineering physics

moment of inertia $I = \Sigma mr^2$

angular kinetic energy $E_k = \frac{1}{2}I\omega^2$

equations of angular motion

$\omega_2 = \omega_1 + \alpha t$

$\omega_2{}^2 = \omega_1{}^2 + 2\alpha\theta$

$\theta = \omega_1 t + \frac{\alpha t^2}{2}$

$\theta = \frac{(\omega_1 + \omega_2)\,t}{2}$

torque $T = I\,\alpha$

$T = F\,r$

angular momentum $angular\ momentum = I\omega$

angular impulse $T\Delta t = \Delta(I\omega)$

work done $W = T\theta$

power $P = T\omega$

thermodynamics $Q = \Delta U + W$

$W = p\Delta V$

adiabatic change $pV^\gamma = \text{constant}$

isothermal change $pV = \text{constant}$

heat engines

efficiency $= \frac{W}{Q_H} = \frac{Q_H - Q_C}{Q_H}$

maximum theoretical efficiency $= \frac{T_H - T_C}{T_H}$

work done per cycle = area of loop

input power = calorific value × fuel flow rate

indicated power = (area of $p - V$ loop) × (number of cycles per second) × (number of cylinders)

output or brake power $P = T\omega$

friction power = indicated power – brake power

heat pumps and refrigerators

refrigerator: $COP_{ref} = \frac{Q_C}{W} = \frac{Q_C}{Q_H - Q_C}$

heat pump: $COP_{hp} = \frac{Q_H}{W} = \frac{Q_H}{Q_H - Q_C}$

Turning points in physics

electrons in fields $F = \frac{eV}{d}$

$F = Bev$

$r = \frac{mv}{Be}$

$\frac{1}{2}mv^2 = eV$

Millikan's experiment $\frac{QV}{d} = mg$

$F = 6\pi\eta rv$

Maxwell's formula $c = \frac{1}{\sqrt{\mu_0\varepsilon_0}}$

$\lambda = \frac{h}{p} = \frac{h}{\sqrt{2meV}}$

special relativity $t = \frac{t_0}{\sqrt{1 - \frac{v^2}{c^2}}}$

$l = l_0\sqrt{1 - \frac{v^2}{c^2}}$

$E = mc^2 = \frac{m_0 c^2}{\sqrt{1 - \frac{v^2}{c^2}}}$

Electronics

resonant frequency $f_0 = \frac{1}{2\pi\sqrt{LC}}$

Q-factor $Q = \frac{f_0}{f_B}$

operational amplifiers: open loop $V_{out} = A_{OL}(V_+ - V_-)$

inverting amplifier $\frac{V_{out}}{V_{in}} = -\frac{R_f}{R_{in}}$

non-inverting amplifier $\frac{V_{out}}{V_{in}} = 1 + \frac{R_f}{R_1}$

summing amplifier $V_{out} = -R_f\left(\frac{V_1}{R_1} + \frac{V_2}{R_2} + \frac{V_3}{R_3} + \cdots\right)$

difference amplifier $V_{out} = (V_+ - V_-)\frac{R_f}{R_1}$

Bandwidth requirement:

for AM $bandwidth = 2f_M$

for FM $bandwidth = 2(\Delta f + f_M)$

Acknowledgements

This document has been produced by Mr J Turnbull.

All relevant information has been credited in the document.

This has been document has been produced for educational purposes only.

This document has been produced for the AQA A Level Physics Specification.

Student Voice

If you when using this document, you believe there is an improvement to made, please state this in the space below….

Only constructive and reasoned feedback will be considered.