IB · IB DIPLOMA PROGRAMME PHYSICS · FIRST ASSESSMENT 2025

IB Diploma Physics

One practice paper for each of the five themes of the current IB Diploma Programme Physics course, carrying all three of the formats the real papers use: Paper 1A multiple choice, a Paper 1B data-based question, and Paper 2 short-answer and extended response — with the SL and HL split drawn where the course draws it.

PAPERS	QUESTIONS	TOTAL MARKS	FIGURES
5	**50**	**272**	**26**

EVERY PAPER IN THIS FILE

ASSESSMENT

Paper 1 has two parts: 1A is multiple choice, and 1B is data-based questions drawn from the experimental work of the course, with no recall in it at all. Paper 2 is short-answer and extended-response across the whole syllabus. HL papers are longer and reach the HL-only sub-topics. The data booklet is provided in every paper, so no question tests whether you can remember an equation.

DEMAND

The command term sets the demand, and the papers are written that way. "State" earns one mark for one line; "explain" is not creditworthy without a mechanism; "discuss" and "evaluate" need both sides weighed before a conclusion is reached. The extended-response part that closes each Paper 2 question is where HL candidates separate from one another, and those parts are pitched there rather than at the level of the calculation before them.

Theme A · Space, time and motion

Kinematics, forces and momentum, work energy and power, and — at HL — rigid body mechanics and Galilean and special relativity.

SUGGESTED TIME	TOTAL MARKS	QUESTIONS	MULTIPLE CHOICE
60 minutes	**55**	**10**	**6**

SECTION	**A · Space, time and motion**
IN THE FORMAT OF	Paper 1A (multiple choice), Paper 1B (data-based), and Paper 2 (short answer and extended response)
ROUTES	SL only — 7 questions, 39 marks. SL and HL — the whole paper, 10 questions, 55 marks. Every question is tagged in the left margin.
DEMAND	**Routine 3 · Demanding 6 · Discriminating 1**
	The command term sets the demand, and the papers are written that way. "State" earns one mark for one line; "explain" is not creditworthy without a mechanism; "discuss" and "evaluate" need both sides weighed before a conclusion is reached. The extended-response part that closes each Paper 2 question is where HL candidates separate from one another, and those parts are pitched there rather than at the level of the calculation before them.
SYLLABUS POINTS	A.1 · A.2 · A.3 · A.4 · A.5

INSTRUCTIONS

- Answer all questions in the spaces provided.
- Show your working. Method marks are awarded even where the final answer is wrong.
- Give your answers to a sensible number of significant figures, with a unit.
- The mark scheme for this paper follows the last question.

THE PAPER

Theme A · Space, time and motion

Answer all questions. 55 marks in 60 minutes.

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1 SL

MULTIPLE CHOICE · ROUTINE · A.1 **[1]**

A ball is launched from level ground at 20 m s^{-1} at an angle of 30° above the horizontal. Air resistance is negligible. How long does the ball take to reach its maximum height?

A 0.51 s

B 1.0 s

C 1.8 s

D 2.0 s

Answer

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2 SL

MULTIPLE CHOICE · DEMANDING · A.2 **[1]**

A book rests on a table. Which pair of forces is a Newton's third law pair?

A the weight of the book and the normal force of the table on the book

B the weight of the book and the force of the book on the table

C the normal force of the table on the book and the force of the book on the table

D the weight of the book and the weight of the table

Answer

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3 SL

MULTIPLE CHOICE · ROUTINE · A.2

[1]

A resultant force acts on a stationary object of mass 0.50 kg. The force–time graph is a triangle rising from zero at t = 0 to a peak of 40 N at t = 0.10 s and falling back to zero at t = 0.20 s. What is the speed of the object at t = 0.20 s?

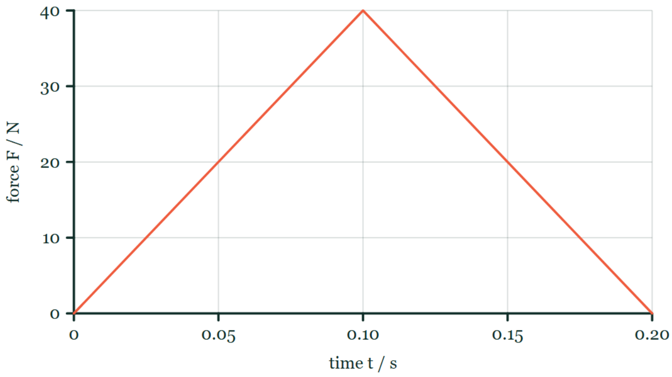

Figure 1 *A graph of force F / N against time t / s on gridded axes, the force axis marked 0 to 40 N and the time axis 0 to 0.20 s. The plotted line rises straight from the origin to 40 N at t = 0.10 s and falls straight back to zero at t = 0.20 s, so the trace is a triangle standing on the time axis.*

A 4.0 m s^{-1}

B 8.0 m s^{-1}

C 16 m s^{-1}

D 20 m s^{-1}

Answer

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4 SL

MULTIPLE CHOICE · ROUTINE · A.3

[1]

A crane lifts a load of mass 250 kg through a vertical height of 12 m in 8.0 s at constant speed. What is the useful output power of the crane?

A 375 W

B 2.5 kW

C 3.7 kW

D 29 kW

Answer

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5 HL

MULTIPLE CHOICE · DEMANDING · A.4

[1]

A disc of moment of inertia I rotates freely about a vertical axis at angular speed ω. A second, stationary disc of moment of inertia 2I is dropped onto it and the two rotate together. What is the new angular speed?

A ω/3

B ω/2

C 2ω/3

D 3ω

Answer

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6 HL

MULTIPLE CHOICE · DEMANDING · A.5

[1]

A spacecraft travels past Earth at 0.60c. A clock on board measures a time interval of 2.0 s between two events that occur at the same place on the spacecraft. What is the interval between those events as measured from Earth?

A 1.2 s

B 1.6 s

C 2.5 s

D 3.3 s

Answer

A student determines the acceleration of free fall using a simple pendulum. She measures the period T for several lengths L and processes the data as shown. Theory predicts $T = 2\pi\sqrt{L/g}$.

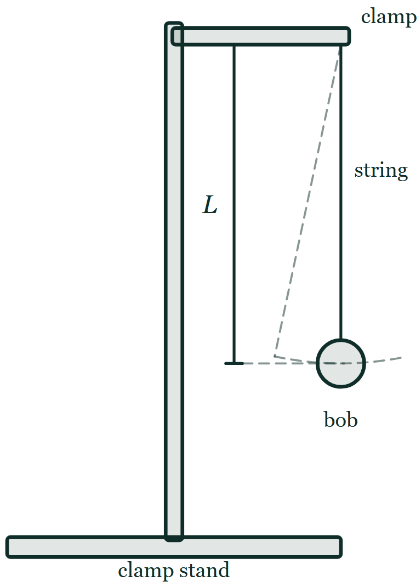

Figure 2 *Side view of the apparatus. A vertical rod in a heavy base carries a horizontal clamp arm, and a string hangs from the clamp jaws with a small spherical bob tied to its lower end. A dimension line beside the string marks the length L, running from the point of suspension down to the centre of the bob. A dashed line shows the string displaced to one side and a dashed arc through the bob shows the path it follows as it swings.*

The student's processed data

L / m	0.400	0.600	0.800	1.000	1.200
T / s	1.269	1.554	1.794	2.006	2.198
T^2 / s^2	1.610	2.415	3.219	4.024	4.829

(a) SHOW (THAT) **[3]**

Show that a graph of T^2 against L should be a straight line through the origin, and state an expression for its gradient.

(b) DETERMINE **[3]**

Determine the gradient of the line, and hence determine a value for g.

(c) OUTLINE **[3]**

The uncertainty in each value of L is ±0.005 m and the uncertainty in each value of T is ±0.002 s. Outline why the uncertainty in T^2 is not ±0.002 s^2, and determine the uncertainty in T^2 for the shortest pendulum.

(d) EVALUATE **[3]**

The student's line of best fit has a small positive intercept on the T^2 axis rather than passing through the origin. Evaluate two possible reasons for this.

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8 SL

STRUCTURED · DEMANDING · A.1 · A.2 **[11]**

A ball of mass 0.150 kg is thrown horizontally at 12 m s^{-1} from the top of a building 25 m high. Air resistance is negligible until part (d).

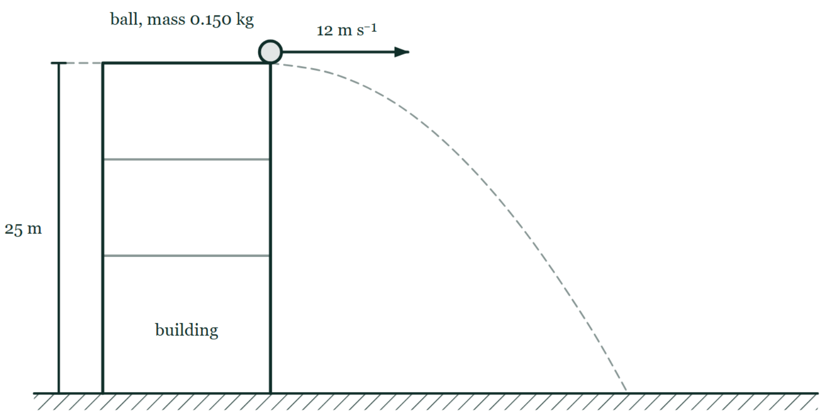

Figure 3 *Side view. A building stands on level hatched ground, its height marked by a dimension line labelled 25 m running from roof level down to the ground. A small ball, labelled as having mass 0.150 kg, sits at the right-hand edge of the roof, and a horizontal arrow from the ball labelled 12 m s⁻¹ points away from the building. A faint dashed curve traces the path the ball follows from the roof edge down to the ground.*

(a) CALCULATE **[2]**

Calculate the time taken for the ball to reach the ground.

(b) DETERMINE **[3]**

Determine the speed of the ball as it reaches the ground.

(c) DETERMINE **[2]**

Determine the magnitude of the impulse delivered to the ball by gravity during its flight.

(d) EXPLAIN **[4]**

In reality air resistance is not negligible. Explain how the horizontal distance travelled and the time of flight each differ from the values calculated above.

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9 SL

STRUCTURED · DEMANDING · A.3 **[12]**

A cyclist and her bicycle have a combined mass of 78 kg. She rides up a straight road inclined at 4.0° to the horizontal at a constant speed of 5.5 m s^{-1}. The total resistive force opposing her motion is 25 N.

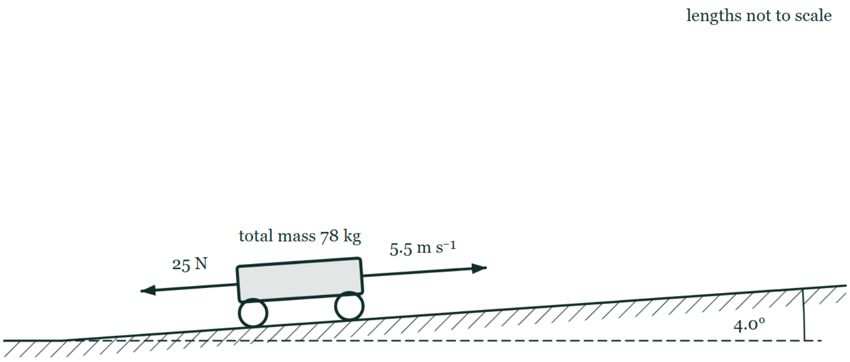

Figure 4 *Side view, drawn not to scale. A road climbs to the right from level ground, and the angle between the road and a dashed horizontal line drawn from the foot of the slope is marked 4.0°. The cyclist and bicycle are drawn as one wheeled body on the road, labelled total mass 78 kg. An arrow from the front of the body points up the slope and is labelled 5.5 m s^{-1}; a second arrow from the rear points down the slope and is labelled 25 N.*

(a) DEFINE **[1]**

Define power.

(b) DETERMINE **[2]**

Determine the component of the total weight acting down the slope.

(c) CALCULATE **[3]**

Calculate the useful power output of the cyclist.

(d) DETERMINE **[2]**

The cyclist's body converts chemical energy to mechanical work with an efficiency of 22%. Determine the rate at which she uses chemical energy.

(e) DISCUSS **[4]**

At the top of the hill the cyclist stops pedalling and freewheels down the other side, which has the same gradient. Discuss whether she reaches a constant speed, and what determines its value.

10 STRUCTURED · DISCRIMINATING · A.4 · A.5 **[14]**

HL

Part 1. A uniform solid cylinder of mass 2.0 kg and radius 0.15 m rolls without slipping down a slope, starting from rest at a height of 1.2 m above the bottom. The moment of inertia of a uniform solid cylinder about its axis is $\frac{1}{2}MR^2$. Part 2. A spacecraft passes Earth at a constant speed of 0.80c. The spacecraft has a proper length of 90 m.

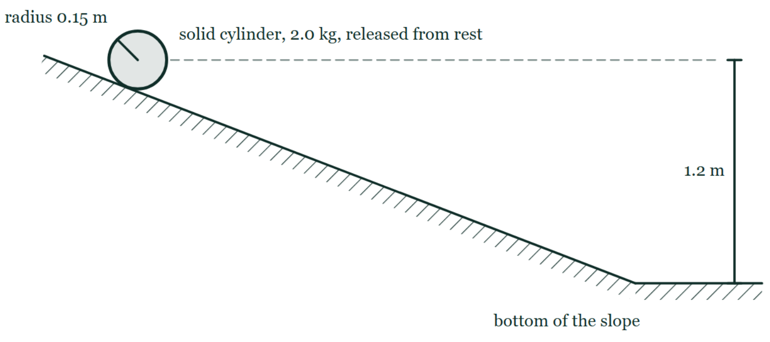

Figure 5 *Side view. A straight hatched slope runs down from the upper left to a horizontal surface at the lower right. A cylinder is drawn end-on resting on the slope near the top, labelled solid cylinder, 2.0 kg, released from rest, with a line from its centre to the rim labelled radius 0.15 m. A dashed horizontal line runs to the right from the level of the cylinder's centre, and a dimension line marks 1.2 m between that level and the horizontal surface at the bottom of the slope.*

(a) SHOW (THAT) **[4]**

Show that the translational speed of the cylinder at the bottom of the slope is about 4.0 m s^{-1}.

(b) DETERMINE **[3]**

Determine the fraction of the cylinder's total kinetic energy at the bottom that is rotational.

(c) CALCULATE **[3]**

Calculate the length of the spacecraft as measured by an observer on Earth.

(d) EXPLAIN **[4]**

An observer on the spacecraft claims that it is the Earth that is 0.80c and that Earth's distances are contracted, not the spacecraft's. Explain why both observers are correct, and outline what would have to change for one of them to be wrong.

MARK SCHEME

Theme A · Space, time and motion — mark scheme

One line per mark, as an examiner would award them. A note under a part is the error that part is set to catch.

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1 SL — MULTIPLE CHOICE · ROUTINE · A.1 — **[1]**

A ball is launched from level ground at 20 m s^{-1} at an angle of 30° above the horizontal. Air resistance is negligible. How long does the ball take to reach its maximum height?

KEY **B** **1.0 s**

C uses the horizontal component, 20 cos 30°, instead of the vertical one. D is the total time of flight rather than the time to the top.

AO2

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2 SL — MULTIPLE CHOICE · DEMANDING · A.2 — **[1]**

A book rests on a table. Which pair of forces is a Newton's third law pair?

KEY **C** **the normal force of the table on the book and the force of the book on the table**

A is chosen by most candidates because the two forces are equal and opposite — but they act on the same body and are of different types, so they are a balanced pair, not a third law pair. A third law pair acts on two different bodies and is always the same kind of force.

AO2

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3 SL — MULTIPLE CHOICE · ROUTINE · A.2 — **[1]**

A resultant force acts on a stationary object of mass 0.50 kg. The force–time graph is a triangle rising from zero at t = 0 to a peak of 40 N at t = 0.10 s and falling back to zero at t = 0.20 s. What is the speed of the object at t = 0.20 s?

KEY **B** **8.0 m s^{-1}**

The impulse is the area under the graph, ½ × 0.20 × 40 = 4.0 N s, and dividing by the mass gives 8.0 m s^{-1}. C treats the graph as a rectangle of height 40 N; A stops at the impulse and forgets to divide by the mass.

AO2

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4 SL — MULTIPLE CHOICE · ROUTINE · A.3 — **[1]**

A crane lifts a load of mass 250 kg through a vertical height of 12 m in 8.0 s at constant speed. What is the useful output power of the crane?

KEY **C** **3.7 kW**

D is the work done rather than the power, with the division by time omitted. B omits g.

AO2

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5 HL — MULTIPLE CHOICE · DEMANDING · A.4 — **[1]**

A disc of moment of inertia I rotates freely about a vertical axis at angular speed ω. A second, stationary disc of moment of inertia 2I is dropped onto it and the two rotate together. What is the new angular speed?

KEY **A** **ω/3**

No external torque acts about the axis, so $I\omega = (I + 2I)\omega'$ and $\omega' = \omega/3$. B is the answer of a candidate who assumes the second disc is identical to the first.

AO2

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6 HL

MULTIPLE CHOICE · DEMANDING · A.5 **[1]**

A spacecraft travels past Earth at 0.60c. A clock on board measures a time interval of 2.0 s between two events that occur at the same place on the spacecraft. What is the interval between those events as measured from Earth?

KEY **C** **2.5 s**

A and B are shorter than the proper time, which no observer can measure — the proper time is always the shortest interval between two events, so the Earth reading must be larger. With $\gamma = 1.25$, the answer is 2.5 s.

A02

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7 SL

DATA ANALYSIS · DEMANDING · A.1 **[12]**

A student determines the acceleration of free fall using a simple pendulum. She measures the period T for several lengths L and processes the data as shown. Theory predicts $T = 2\pi\sqrt{(L/g)}$.

(a) SHOW (THAT) · A02 **[3]**

Show that a graph of T^2 against L should be a straight line through the origin, and state an expression for its gradient.

1. squares the relationship: $T^2 = 4\pi^2L/g$
2. this is of the form $y = mx$ with no constant term, so the line passes through the origin
3. gradient = $4\pi^2/g$

(b) DETERMINE · A02 **[3]**

Determine the gradient of the line, and hence determine a value for g.

1. gradient = (4.829 − 1.610) / (1.200 − 0.400) = 3.219 / 0.800
2. gradient = 4.02 $s^2\ m^{-1}$
3. $g = 4\pi^2/4.02 = 9.8\ m\ s^{-2}$

(c) OUTLINE · A04 **[3]**

The uncertainty in each value of L is ±0.005 m and the uncertainty in each value of T is ±0.002 s. Outline why the uncertainty in T^2 is not ±0.002 s^2, and determine the uncertainty in T^2 for the shortest pendulum.

1. squaring a quantity doubles its fractional (percentage) uncertainty, so the absolute uncertainty is not carried through unchanged
2. fractional uncertainty in T = 0.002/1.269 = 0.16%, so fractional uncertainty in T^2 = 0.32%
3. uncertainty in T^2 = 0.0032 × 1.610 = ±0.005 s^2

(d) EVALUATE · A03 **[3]**

The student's line of best fit has a small positive intercept on the T^2 axis rather than passing through the origin. Evaluate two possible reasons for this.

1. a systematic error in the measurement of L — for example measuring to the top of the bob rather than to its centre, so every length is recorded too short
2. a systematic error in timing — for example consistently starting the stopwatch late, though this would need to affect longer pendulums proportionately less to produce an intercept rather than a change of gradient
3. evaluates which is more likely, noting that a constant offset in L produces exactly a constant intercept and is therefore the better explanation

The third mark is for choosing between the two rather than listing both. "Evaluate" asks for a judgement, and answers that stop at a list earn two marks out of three.

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8 SL

STRUCTURED · DEMANDING · A.1 · A.2 **[11]**

A ball of mass 0.150 kg is thrown horizontally at 12 m s^{-1} from the top of a building 25 m high. Air resistance is negligible until part (d).

(a) CALCULATE · AO2 **[2]**

Calculate the time taken for the ball to reach the ground.

1. $25 = \frac{1}{2} \times 9.81 \times t^2$
2. $t = 2.26$ s

(b) DETERMINE · AO2 **[3]**

Determine the speed of the ball as it reaches the ground.

1. vertical component $v_y = 9.81 \times 2.26 = 22.2$ m s^{-1}
2. horizontal component is unchanged at 12 m s^{-1}
3. speed $= \sqrt{(12^2 + 22.2^2)} = 25$ m s^{-1}

(c) DETERMINE · AO2 **[2]**

Determine the magnitude of the impulse delivered to the ball by gravity during its flight.

1. impulse = change in momentum = m × change in vertical velocity = 0.150 × 22.2
2. impulse = 3.3 N s, directed vertically downwards

(d) EXPLAIN · AO3 **[4]**

In reality air resistance is not negligible. Explain how the horizontal distance travelled and the time of flight each differ from the values calculated above.

1. air resistance acts opposite to the velocity, so it has both a horizontal and a vertical component throughout the flight
2. the horizontal component decelerates the ball, so the horizontal velocity is no longer constant and the horizontal distance is smaller
3. the vertical component acts upward as the ball falls, reducing the downward acceleration below g
4. so the ball takes longer to fall the same 25 m, and the time of flight increases

   The commonest wrong answer says the time of flight is unchanged because "horizontal and vertical motions are independent". That independence is a consequence of the only force being vertical, and it fails as soon as a velocity-dependent force acts.

9 SL

STRUCTURED · DEMANDING · A.3 **[12]**

A cyclist and her bicycle have a combined mass of 78 kg. She rides up a straight road inclined at 4.0° to the horizontal at a constant speed of 5.5 m s^{-1}. The total resistive force opposing her motion is 25 N.

(a) DEFINE · AO1 **[1]**

Define power.

1 the rate at which work is done, or the rate at which energy is transferred

(b) DETERMINE · AO2 **[2]**

Determine the component of the total weight acting down the slope.

1 component = $mg \sin \theta = 78 \times 9.81 \times \sin 4.0°$

2 = 53 N

(c) CALCULATE · AO2 **[3]**

Calculate the useful power output of the cyclist.

1 at constant speed the driving force balances the weight component and the resistive force: $F = 53 + 25 = 78$ N

2 $P = Fv = 78 \times 5.5$

3 $P = 4.3 \times 10^2$ W

(d) DETERMINE · AO2 **[2]**

The cyclist's body converts chemical energy to mechanical work with an efficiency of 22%. Determine the rate at which she uses chemical energy.

1 input power = 429 / 0.22

2 = 1.9×10^3 W

(e) DISCUSS · AO3 **[4]**

At the top of the hill the cyclist stops pedalling and freewheels down the other side, which has the same gradient. Discuss whether she reaches a constant speed, and what determines its value.

1 on the way down, the component of weight along the slope now acts in the direction of motion and accelerates her

2 the resistive force increases with speed, mainly because air resistance rises steeply with speed

3 she reaches a constant speed when the resistive force has grown to equal the 53 N component of weight down the slope

4 the value of that speed is set by how quickly the resistive force grows with speed — by her frontal area, her posture and the air density, not by her mass alone

10 HL

STRUCTURED · DISCRIMINATING · A.4 · A.5 **[14]**

Part 1. A uniform solid cylinder of mass 2.0 kg and radius 0.15 m rolls without slipping down a slope, starting from rest at a height of 1.2 m above the bottom. The moment of inertia of a uniform solid cylinder about its axis is $\frac{1}{2}MR^2$. Part 2. A spacecraft passes Earth at a constant speed of 0.80c. The spacecraft has a proper length of 90 m.

(a) SHOW (THAT) · AO2 **[4]**

Show that the translational speed of the cylinder at the bottom of the slope is about 4.0 m s^{-1}.

1. $Mgh = \frac{1}{2}Mv^2 + \frac{1}{2}I\omega^2$, with $I = \frac{1}{2}MR^2$
2. applies the rolling condition $\omega = v/R$, so $\frac{1}{2}I\omega^2 = \frac{1}{4}Mv^2$
3. $Mgh = \frac{3}{4}Mv^2$, so $v = \sqrt{(4gh/3)}$
4. $v = \sqrt{(4 \times 9.81 \times 1.2 / 3)} = 3.96 \approx 4.0$ m s^{-1}

(b) DETERMINE · AO2 **[3]**

Determine the fraction of the cylinder's total kinetic energy at the bottom that is rotational.

1. rotational KE = $\frac{1}{4}Mv^2$, translational KE = $\frac{1}{2}Mv^2$
2. total = $\frac{3}{4}Mv^2$
3. fraction rotational = $(\frac{1}{4})/(\frac{3}{4}) = 1/3$

The fraction is the same for every uniform solid cylinder, whatever its mass, radius or the height of the slope — a point worth making, because it is what the cancellation in part (a) was telling you.

(c) CALCULATE · AO2 **[3]**

Calculate the length of the spacecraft as measured by an observer on Earth.

1. $\gamma = 1/\sqrt{(1 - 0.80^2)} = 1/0.60 = 1.67$
2. $L = L_0/\gamma = 90/1.67$
3. L = 54 m

(d) EXPLAIN · AO3 **[4]**

An observer on the spacecraft claims that it is the Earth that is 0.80c and that Earth's distances are contracted, not the spacecraft's. Explain why both observers are correct, and outline what would have to change for one of them to be wrong.

1. both frames are inertial, and the principle of relativity states that the laws of physics are the same in all inertial frames
2. there is no experiment either observer can do to establish that they are the one "really" moving, so neither frame is privileged
3. each measures the other's length as contracted because they disagree about which events are simultaneous, and a length measurement requires locating both ends at the same time
4. the symmetry would be broken only if one observer accelerated — an accelerating frame is not inertial, and that observer would feel the acceleration and know it

The best-discriminating part on the paper. Relativity of simultaneity is the mark that separates a candidate who has understood the argument from one who has memorised the formulae.

Theme B · The particulate nature of matter

Thermal energy transfers, the greenhouse effect, gas laws, current and circuits, and — at HL — thermodynamics.

SUGGESTED TIME	TOTAL MARKS	QUESTIONS	MULTIPLE CHOICE
60 minutes	**53**	**10**	**6**

SECTION — **B · The particulate nature of matter**

IN THE FORMAT OF — Paper 1A (multiple choice), Paper 1B (data-based), and Paper 2 (short answer and extended response)

ROUTES — SL only — 8 questions, 39 marks.   SL and HL — the whole paper, 10 questions, 53 marks. Every question is tagged in the left margin.

DEMAND — **Recall 1 · Routine 3 · Demanding 4 · Discriminating 2**

The command term sets the demand, and the papers are written that way. "State" earns one mark for one line; "explain" is not creditworthy without a mechanism; "discuss" and "evaluate" need both sides weighed before a conclusion is reached. The extended-response part that closes each Paper 2 question is where HL candidates separate from one another, and those parts are pitched there rather than at the level of the calculation before them.

SYLLABUS POINTS — B.1 · B.2 · B.3 · B.4 · B.5

INSTRUCTIONS

- Answer all questions in the spaces provided.
- Show your working. Method marks are awarded even where the final answer is wrong.
- Give your answers to a sensible number of significant figures, with a unit.
- The mark scheme for this paper follows the last question.

THE PAPER

Theme B · The particulate nature of matter

Answer all questions. 53 marks in 60 minutes.

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1 SL

MULTIPLE CHOICE · ROUTINE · B.1 **[1]**

A 2.0 kW heater supplies energy to 0.30 kg of ice at 0 °C until it has all melted. The specific latent heat of fusion of ice is 3.3×10^5 J kg^{-1}. How long does this take, assuming no losses?

A 5.0 s

B 50 s

C 165 s

D 500 s

Answer

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2 SL

MULTIPLE CHOICE · DEMANDING · B.2 **[1]**

The solar constant is 1360 W m^{-2} and the Earth's average albedo is 0.30. What is the average intensity of solar radiation absorbed per square metre of the Earth's surface?

A 238 W m^{-2}

B 340 W m^{-2}

C 952 W m^{-2}

D 1360 W m^{-2}

Answer

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3 SL

MULTIPLE CHOICE · ROUTINE · B.3 **[1]**

A fixed mass of ideal gas is at 27 °C. It is heated at constant volume until its pressure has doubled. What is the new temperature?

A 54 °C

B 327 °C

C 600 °C

D 873 °C

Answer

4
SL

MULTIPLE CHOICE · ROUTINE · B.5

[1]

A wire of resistivity ρ, length L and cross-sectional area A has resistance R. A second wire of the same material has twice the length and twice the diameter. What is its resistance?

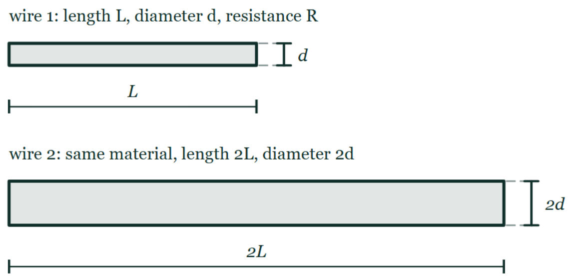

Figure 1 *Two wires of the same material are drawn one above the other, each as a long bar seen from the side. The upper one is labelled wire 1: length L, diameter d, resistance R, with a dimension line under it marking L and a small dimension at its end marking the diameter d. The lower one is drawn twice as long and twice as thick and labelled wire 2: same material, with dimension lines marking 2L along it and 2d across its end.*

A R/2

B R

C 2R

D 4R

Answer

5
HL

MULTIPLE CHOICE · DEMANDING · B.4

[1]

An ideal gas is compressed adiabatically. Which statement is correct?

A No thermal energy enters or leaves the gas, and its temperature falls.

B No thermal energy enters or leaves the gas, and its temperature rises.

C Thermal energy leaves the gas, and its temperature stays constant.

D Thermal energy enters the gas, and its temperature rises.

Answer

6
SL

MULTIPLE CHOICE · RECALL · B.1

[1]

Which method of thermal energy transfer can occur through a vacuum?

A conduction only

B convection only

C radiation only

D all three

Answer

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7 DATA ANALYSIS · DEMANDING · B.1 **[11]**

SL

A student determines the specific heat capacity of a liquid. She places 0.500 kg of the liquid in a well-insulated container with an electric heater of constant power 50.0 W and records the temperature at intervals.

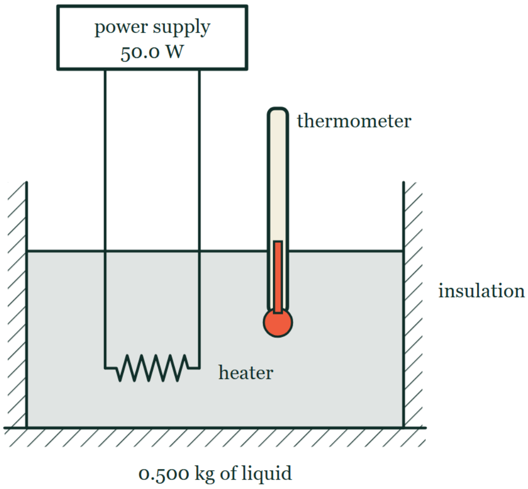

Figure 2 *Section through the apparatus. A container holding the liquid, labelled 0.500 kg of liquid, is surrounded on its sides and base by hatched insulation. A coiled heating element is immersed near the bottom of the liquid, and its two leads run up out of the open top of the container to a box labelled power supply, 50.0 W. A thermometer stands in the liquid with its bulb well below the surface and its stem projecting above the container.*

The student's readings

t / s	**0**	**120**	**240**	**360**	**480**
θ / °C	20.0	22.9	25.7	28.6	31.4

(a) DETERMINE **[3]**

Determine the gradient of a graph of temperature against time, and explain why the gradient rather than a single pair of readings should be used.

(b) DETERMINE **[3]**

Determine the specific heat capacity of the liquid.

(c) OUTLINE **[2]**

Outline why the container being well insulated matters more at the end of the experiment than at the beginning.

(d) SUGGEST **[3]**

The heater and the container itself also absorb energy. Suggest how this affects the value obtained for c, and suggest one way of accounting for it.

8 STRUCTURED · DEMANDING · B.1 · B.3 **[11]**

SL

A sealed rigid container of volume $5.0 \times 10^{-3}\ m^3$ holds nitrogen gas at a pressure of 2.4×10^5 Pa and a temperature of 290 K. Nitrogen may be treated as an ideal gas.

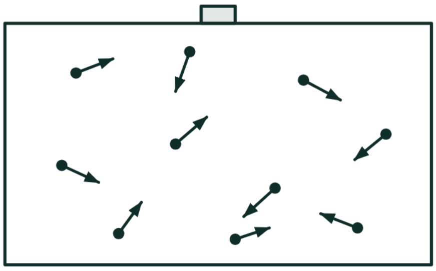

Figure 3 *A rectangular container with thick walls and a stopper in its top is labelled sealed rigid container. Inside, ten molecules are drawn as dots, each carrying a short arrow of its own direction and length so that the molecules are moving randomly, several of them towards the walls. To the right of the container stand the labels nitrogen gas, $V = 5.0 \times 10^{-3}\ m^3$, $p = 2.4 \times 10^5$ Pa and $T = 290$ K.*

(a) CALCULATE **[2]**

Calculate the amount of gas in the container, in moles.

(b) DETERMINE **[2]**

Determine the average kinetic energy of a nitrogen molecule in the container.

(c) EXPLAIN **[3]**

The container is warmed to 350 K. Explain, in terms of the behaviour of the molecules, why the pressure increases.

(d) EXPLAIN **[4]**

Outline two assumptions of the ideal gas model, and explain why real nitrogen behaves less like an ideal gas at very high pressure.

9 SL

STRUCTURED · DISCRIMINATING · B.2 **[12]**

The Earth may be modelled as a black body of average surface temperature 288 K. The Stefan–Boltzmann constant is 5.67×10^{-8} W m^{-2} K^{-4}.

(a) CALCULATE **[2]**

Calculate the power radiated per square metre by the Earth's surface at this temperature.

(b) DETERMINE **[3]**

The average intensity of solar radiation absorbed by the Earth is 238 W m^{-2}. Determine the temperature the Earth's surface would have if it radiated only this absorbed power directly to space.

(c) EXPLAIN **[4]**

Explain, using your answers to (a) and (b), how the greenhouse effect accounts for the difference between 255 K and the observed 288 K.

(d) DISCUSS **[3]**

A student says that because the Earth's surface radiates 390 W m^{-2} but absorbs only 238 W m^{-2} from the Sun, energy is being created. Discuss this claim.

10 HL

STRUCTURED · DISCRIMINATING · B.4 · B.5 **[13]**

Part 1. A cell of e.m.f. 6.0 V and internal resistance 0.75 Ω is connected to an external resistor of resistance 3.0 Ω. Part 2. A fixed mass of ideal monatomic gas is taken from state X to state Y by two different routes: an isothermal expansion, and an adiabatic expansion to the same final volume.

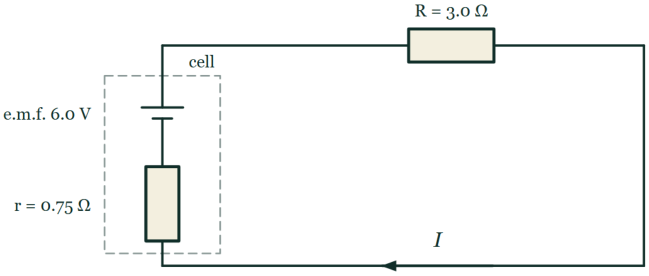

Figure 4 *Circuit diagram of a single series loop. On the left a dashed boundary encloses the cell itself: a cell symbol with its long positive plate uppermost, labelled e.m.f. 6.0 V, in series with a resistor labelled r = 0.75 Ω. The two terminals cross the dashed boundary and the loop continues round to a resistor in the upper wire labelled R = 3.0 Ω. An arrow on the lower wire, labelled I, marks the direction of the conventional current.*

(a) CALCULATE **[3]**

Calculate the current in the circuit and the terminal potential difference of the cell.

(b) DETERMINE **[3]**

Determine the percentage of the power produced by the cell that is dissipated inside the cell itself.

(c) COMPARE **[4]**

Compare the final temperature and the work done by the gas for the isothermal and the adiabatic expansions to the same final volume.

(d) EXPLAIN **[3]**

Explain why the entropy of the gas increases during the isothermal expansion but is unchanged during a reversible adiabatic expansion.

MARK SCHEME

Theme B · The particulate nature of matter — mark scheme

One line per mark, as an examiner would award them. A note under a part is the error that part is set to catch.

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1 SL — MULTIPLE CHOICE · ROUTINE · B.1 — **[1]**

A 2.0 kW heater supplies energy to 0.30 kg of ice at 0 °C until it has all melted. The specific latent heat of fusion of ice is 3.3×10^5 J kg^{-1}. How long does this take, assuming no losses?

KEY **B** **50 s**

The energy required is $mL = 9.9 \times 10^4$ J, and dividing by 2000 W gives 50 s. C divides by the mass instead of multiplying by it.

AO2

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2 SL — MULTIPLE CHOICE · DEMANDING · B.2 — **[1]**

The solar constant is 1360 W m^{-2} and the Earth's average albedo is 0.30. What is the average intensity of solar radiation absorbed per square metre of the Earth's surface?

KEY **A** **238 W m^{-2}**

Two steps are needed and each is often missed. B applies the factor of 4 — the ratio of the Earth's surface area to the disc that intercepts the beam — but forgets the albedo. C applies the albedo but forgets the factor of 4.

AO2

---

3 SL — MULTIPLE CHOICE · ROUTINE · B.3 — **[1]**

A fixed mass of ideal gas is at 27 °C. It is heated at constant volume until its pressure has doubled. What is the new temperature?

KEY **B** **327 °C**

A doubles the Celsius temperature, which is the error the question is set to catch. The gas laws work in kelvin: 300 K doubles to 600 K, which is 327 °C.

AO2

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4 SL — MULTIPLE CHOICE · ROUTINE · B.5 — **[1]**

A wire of resistivity ρ, length L and cross-sectional area A has resistance R. A second wire of the same material has twice the length and twice the diameter. What is its resistance?

KEY **A** **R/2**

C doubles for the length and forgets that the area depends on the square of the diameter. Doubling the diameter quadruples the area, so the two changes give 2/4 = ½.

AO2

---

5 HL — MULTIPLE CHOICE · DEMANDING · B.4 — **[1]**

An ideal gas is compressed adiabatically. Which statement is correct?

KEY **B** **No thermal energy enters or leaves the gas, and its temperature rises.**

A gets the definition right and the consequence wrong. In an adiabatic process $Q = 0$, so $\Delta U = W$: work done on the gas raises its internal energy with nowhere for the energy to escape, and the temperature rises. C describes an isothermal compression.

AO2

---

6 SL

MULTIPLE CHOICE · RECALL · B.1 **[1]**

Which method of thermal energy transfer can occur through a vacuum?

KEY **C radiation only**

Conduction and convection both need particles to carry or move the energy. Radiation is an electromagnetic wave and needs no medium at all.

AO1

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7 SL

DATA ANALYSIS · DEMANDING · B.1 **[11]**

A student determines the specific heat capacity of a liquid. She places 0.500 kg of the liquid in a well-insulated container with an electric heater of constant power 50.0 W and records the temperature at intervals.

(a) DETERMINE · AO4 **[3]**

Determine the gradient of a graph of temperature against time, and explain why the gradient rather than a single pair of readings should be used.

1 gradient = (31.4 − 20.0)/480 = 0.0238 °C s^{-1}

2 the gradient uses all five readings, so random errors in individual temperature measurements partly cancel

3 and a straight line confirms that the rate of heating is constant, which the calculation assumes

(b) DETERMINE · AO2 **[3]**

Determine the specific heat capacity of the liquid.

1 $P = mc(d\theta/dt)$

2 c = P / (m × gradient) = 50.0 / (0.500 × 0.0238)

3 $c = 4.2 \times 10^3\ \mathrm{J\ kg^{-1}\ K^{-1}}$

(c) OUTLINE · AO3 **[2]**

Outline why the container being well insulated matters more at the end of the experiment than at the beginning.

1 the rate of energy transfer to the surroundings depends on the temperature difference between the liquid and the room

2 at the start the liquid is near room temperature and loses almost nothing; by the end it is 11 °C above the room and the losses are largest

This is why the graph would curve slightly downward at long times in a real experiment, and why a candidate should not simply extend the run to get a bigger temperature rise.

(d) SUGGEST · AO3 **[3]**

The heater and the container itself also absorb energy. Suggest how this affects the value obtained for c, and suggest one way of accounting for it.

1 some of the 50.0 W raises the temperature of the heater and container rather than the liquid

2 the liquid therefore warms more slowly than the model assumes, the gradient is smaller, and the calculated value of c is too large

3 account for it by repeating the experiment with a different mass of liquid and using the difference, or by determining the thermal capacity of the container separately and subtracting it

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8 SL

STRUCTURED · DEMANDING · B.1 · B.3 **[11]**

A sealed rigid container of volume 5.0×10^{-3} m³ holds nitrogen gas at a pressure of 2.4×10^5 Pa and a temperature of 290 K. Nitrogen may be treated as an ideal gas.

(a) CALCULATE · AO2 **[2]**

Calculate the amount of gas in the container, in moles.

1. $n = pV/RT = (2.4 \times 10^5 \times 5.0 \times 10^{-3})/(8.31 \times 290)$
2. $n = 0.50$ mol

(b) DETERMINE · AO2 **[2]**

Determine the average kinetic energy of a nitrogen molecule in the container.

1. $E_k = (3/2)k_BT = 1.5 \times 1.38 \times 10^{-23} \times 290$
2. $E_k = 6.0 \times 10^{-21}$ J

(c) EXPLAIN · AO2 **[3]**

The container is warmed to 350 K. Explain, in terms of the behaviour of the molecules, why the pressure increases.

1. the average kinetic energy of the molecules increases, so their mean speed increases
2. each molecule therefore strikes the walls more frequently
3. and each collision produces a larger change of momentum, so the average force per unit area on the walls rises

(d) EXPLAIN · AO3 **[4]**

Outline two assumptions of the ideal gas model, and explain why real nitrogen behaves less like an ideal gas at very high pressure.

1. the molecules have negligible volume compared with the volume of the container
2. there are no intermolecular forces except during collisions, and all collisions are elastic
3. at very high pressure the molecules are pushed close together, so their own volume is no longer negligible compared with the space available
4. and at those separations the intermolecular attractions are significant, so the molecules exert less force on the walls than the model predicts

9 SL

STRUCTURED · DISCRIMINATING · B.2 **[12]**

The Earth may be modelled as a black body of average surface temperature 288 K. The Stefan–Boltzmann constant is 5.67×10^{-8} W m^{-2} K^{-4}.

(a) CALCULATE · AO2 **[2]**

Calculate the power radiated per square metre by the Earth's surface at this temperature.

1 $I = \sigma T^4 = 5.67 \times 10^{-8} \times 288^4$

2 $I = 390$ W m^{-2}

(b) DETERMINE · AO2 **[3]**

The average intensity of solar radiation absorbed by the Earth is 238 W m^{-2}. Determine the temperature the Earth's surface would have if it radiated only this absorbed power directly to space.

1 sets $\sigma T^4 = 238$

2 $T^4 = 238/5.67 \times 10^{-8} = 4.20 \times 10^9$

3 $T = 255$ K

(c) EXPLAIN · AO3 **[4]**

Explain, using your answers to (a) and (b), how the greenhouse effect accounts for the difference between 255 K and the observed 288 K.

1 the Earth's surface radiates in the infrared, at wavelengths determined by its temperature

2 greenhouse gases in the atmosphere absorb strongly in the infrared while remaining largely transparent to the incoming shorter-wavelength solar radiation

3 the absorbed energy is re-emitted in all directions, so a substantial part returns to the surface

4 the surface therefore receives energy from the Sun and from the atmosphere, and must warm to 288 K before it radiates 390 W m^{-2} and reaches equilibrium

The mark most often missed is the second: the effect depends on the atmosphere treating incoming and outgoing radiation differently, and an answer that says only "the gases trap heat" has not said why the trapping is one-way.

(d) DISCUSS · AO3 **[3]**

A student says that because the Earth's surface radiates 390 W m^{-2} but absorbs only 238 W m^{-2} from the Sun, energy is being created. Discuss this claim.

1 the claim is wrong: it counts only one of the two sources of energy arriving at the surface

2 the surface also receives roughly 150 W m^{-2} of infrared radiation emitted downward by the atmosphere, so the total input balances the 390 W m^{-2} output

3 the atmosphere in turn radiates to space, and it is the top of the atmosphere — not the surface — where the 238 W m^{-2} balance with space must hold

A genuinely discriminating part. The energy balance holds at every level, but at different levels between different pairs of quantities, and candidates who have learned only the surface figures cannot resolve the apparent paradox.

10 HL

STRUCTURED · DISCRIMINATING · B.4 · B.5 **[13]**

Part 1. A cell of e.m.f. 6.0 V and internal resistance 0.75 Ω is connected to an external resistor of resistance 3.0 Ω. Part 2. A fixed mass of ideal monatomic gas is taken from state X to state Y by two different routes: an isothermal expansion, and an adiabatic expansion to the same final volume.

(a) CALCULATE · AO2 **[3]**

Calculate the current in the circuit and the terminal potential difference of the cell.

1. $I = \varepsilon/(R + r) = 6.0/3.75 = 1.6$ A
2. $V = IR = 1.6 \times 3.0$
3. $V = 4.8$ V

(b) DETERMINE · AO2 **[3]**

Determine the percentage of the power produced by the cell that is dissipated inside the cell itself.

1. power in r = $I^2 r = 1.6^2 \times 0.75 = 1.92$ W
2. total power = $\varepsilon I = 6.0 \times 1.6 = 9.6$ W
3. percentage = 1.92/9.6 = 20%

(c) COMPARE · AO3 **[4]**

Compare the final temperature and the work done by the gas for the isothermal and the adiabatic expansions to the same final volume.

1. isothermal: the temperature is unchanged by definition, so $\Delta U = 0$ and the work done by the gas equals the thermal energy absorbed
2. adiabatic: no thermal energy enters, so the work done by the gas comes entirely from its internal energy
3. the adiabatic expansion therefore ends at a lower temperature than the isothermal one
4. and because its pressure falls faster with volume, the area under its curve is smaller — less work is done by the gas

(d) EXPLAIN · AO3 **[3]**

Explain why the entropy of the gas increases during the isothermal expansion but is unchanged during a reversible adiabatic expansion.

1. entropy change for a reversible process is $\Delta S = Q/T$
2. in the isothermal expansion the gas absorbs thermal energy at constant temperature, so Q is positive and ΔS is positive — and in molecular terms the same molecules now occupy a larger volume, so there are more available microstates
3. in a reversible adiabatic expansion $Q = 0$, so $\Delta S = 0$: the increase in volume is exactly offset by the narrowing of the molecular speed distribution as the gas cools

The last clause is what makes the answer complete. Candidates who argue only from volume conclude that entropy must rise in both cases, which is the misconception this part exists to catch.

Theme C · Wave behaviour

Simple harmonic motion, the wave model, wave phenomena including interference and diffraction, standing waves and resonance, and the Doppler effect.

SUGGESTED TIME	TOTAL MARKS	QUESTIONS	MULTIPLE CHOICE
60 minutes	**55**	**10**	**6**

SECTION — **C · Wave behaviour**

IN THE FORMAT OF — Paper 1A (multiple choice), Paper 1B (data-based), and Paper 2 (short answer and extended response)

ROUTES — SL only — 7 questions, 39 marks. SL and HL — the whole paper, 10 questions, 55 marks. Every question is tagged in the left margin.

DEMAND — **Routine 2 · Demanding 6 · Discriminating 2**

The command term sets the demand, and the papers are written that way. "State" earns one mark for one line; "explain" is not creditworthy without a mechanism; "discuss" and "evaluate" need both sides weighed before a conclusion is reached. The extended-response part that closes each Paper 2 question is where HL candidates separate from one another, and those parts are pitched there rather than at the level of the calculation before them.

SYLLABUS POINTS — C.1 · C.2 · C.3 · C.4 · C.5

INSTRUCTIONS

- Answer all questions in the spaces provided.
- Show your working. Method marks are awarded even where the final answer is wrong.
- Give your answers to a sensible number of significant figures, with a unit.
- The mark scheme for this paper follows the last question.

Theme C · Wave behaviour

Answer all questions. 55 marks in 60 minutes.

---

1 SL

MULTIPLE CHOICE · DEMANDING · C.1 **[1]**

The amplitude of a mass–spring oscillator is doubled while its mass and spring constant are unchanged. What happens to its period and to its total energy?

A period unchanged, energy doubled

B period unchanged, energy quadrupled

C period doubled, energy doubled

D period doubled, energy quadrupled

Answer

---

2 SL

MULTIPLE CHOICE · ROUTINE · C.2 **[1]**

A sound wave of frequency 256 Hz travels through air at 340 m s^{-1} and then passes into water, where its speed is 1500 m s^{-1}. What are its frequency and wavelength in the water?

A 256 Hz and 1.33 m

B 256 Hz and 5.86 m

C 1130 Hz and 1.33 m

D 58 Hz and 5.86 m

Answer

---

3 SL

MULTIPLE CHOICE · DEMANDING · C.4

[1]

A pipe of length 0.85 m is closed at one end and open at the other. The speed of sound in air is 340 m s^{-1}. What is the frequency of the fundamental note?

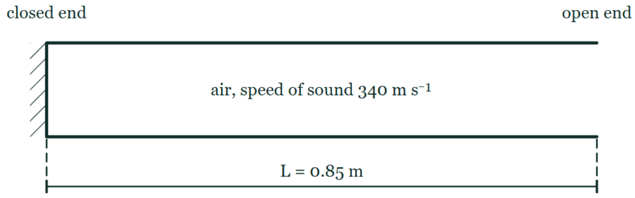

Figure 1 *Side view of a horizontal pipe drawn as a long rectangle lying on its side. Its left-hand end is sealed by a wall drawn with hatching behind it and labelled 'closed end'; its right-hand end has no wall drawn across it and is labelled 'open end'. The air column inside carries the note 'air, speed of sound 340 m s^{-1}', and a dimension line beneath the pipe, with a tick at each end, marks its length as L = 0.85 m from the closed end to the open end.*

A 100 Hz

B 200 Hz

C 400 Hz

D 800 Hz

Answer

4 MULTIPLE CHOICE · ROUTINE · C.5 **[1]**

SL

An ambulance siren emits a note of frequency 512 Hz. The ambulance travels at 25 m s^{-1} towards a stationary observer. The speed of sound in air is 340 m s^{-1}. What frequency does the observer hear?

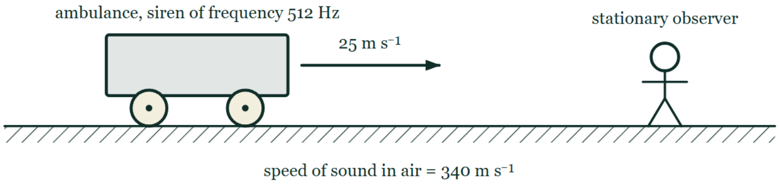

Figure 2 *Side view along a straight road, drawn as a hatched ground line. On the left an ambulance stands on the road, labelled 'ambulance, siren of frequency 512 Hz'. A horizontal arrow leaves the front of the ambulance and points to the right, labelled 25 m s^{-1}. Well ahead of it, on the same road, a person stands still, labelled 'stationary observer'. A note below the road reads 'speed of sound in air = 340 m s^{-1}'.*

A 477 Hz

B 512 Hz

C 553 Hz

D 590 Hz

Answer

5 HL

MULTIPLE CHOICE · DEMANDING · C.3 **[1]**

Monochromatic light passes through a single slit and forms a diffraction pattern on a distant screen. The slit is then made narrower. What happens to the width of the central maximum and to its intensity?

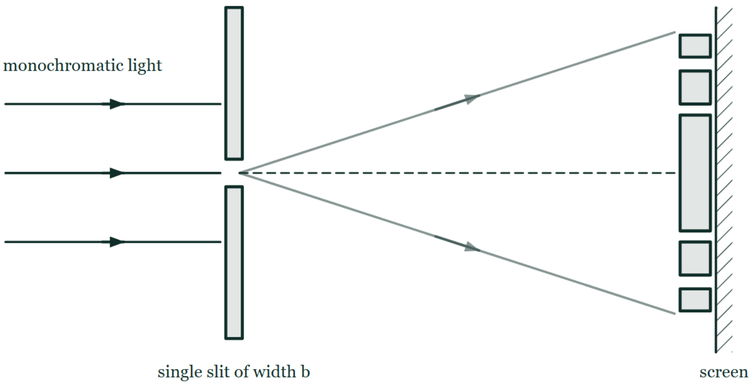

Figure 3 *Plan view of the arrangement. Three parallel rays of monochromatic light travel from the left towards an opaque barrier drawn as two vertical bars; only the middle ray meets the narrow gap between them, which is labelled 'single slit of width b'. Beyond the slit, two faint rays spread out above and below a dashed straight line that continues from the slit to a screen at the far right. On the screen a row of bright bands is drawn, centred on the dashed line, with the band on the line noticeably taller than the pairs of bands above and below it.*

A width increases, intensity decreases

B width increases, intensity increases

C width decreases, intensity decreases

D width decreases, intensity increases

Answer

---

6 HL

MULTIPLE CHOICE · DEMANDING · C.1 **[1]**

A particle undergoes simple harmonic motion described by $x = x_0 \sin(\omega t)$. At what displacement is the kinetic energy equal to the potential energy?

A $x_0/4$

B $x_0/2$

C $x_0/\sqrt{2}$

D x_0

Answer

A student investigates the oscillations of a mass hanging from a vertical spring, expecting the period to satisfy $T = 2\pi\sqrt{(m/k)}$, where k is the spring constant.

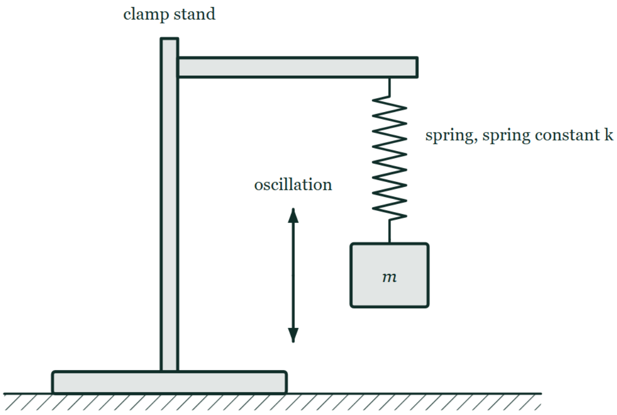

Figure 4 *Side view of the apparatus on a bench. A vertical rod rises from the heavy base of a clamp stand, and a horizontal clamp arm projects from the top of the rod. A helical spring hangs from the end of the arm and is labelled 'spring, spring constant k'. A rectangular block labelled m hangs from the lower end of the spring. Beside the mass a vertical double-headed arrow labelled 'oscillation' shows that it moves up and down about its hanging position.*

The student's processed data

m / kg	0.100	0.200	0.300	0.400	0.500
T / s	0.444	0.628	0.770	0.889	0.993
T^2 / s^2	0.197	0.395	0.592	0.790	0.987

(a) DETERMINE **[4]**

Determine the gradient of a graph of T^2 against m, and hence determine the spring constant k.

(b) EXPLAIN **[2]**

Explain why the student plotted T^2 against m rather than T against m.

(c) SUGGEST **[2]**

In practice the line of best fit for a real spring has a small positive intercept on the T^2 axis. Suggest a physical reason for this.

(d) OUTLINE **[3]**

Outline how the student should time the oscillations to keep the uncertainty in T small, and state one reason why timing a single oscillation would be unsatisfactory.

---

8 SL

STRUCTURED · DEMANDING · C.2 · C.4 **[12]**

A string of length 0.60 m is stretched between two fixed points. When plucked, it vibrates in its fundamental mode at a frequency of 250 Hz.

(a) DETERMINE **[3]**

Determine the speed of the transverse waves on the string.

(b) DESCRIBE **[4]**

Describe how a standing wave is formed on the string, and state what distinguishes a standing wave from a progressive wave.

(c) CALCULATE **[2]**

Calculate the frequency of the third harmonic of this string, and state how many nodes it has, including the two at the ends.

(d) EXPLAIN **[3]**

The tension in the string is increased. Explain what happens to the fundamental frequency, and explain why the length of the string does not change the speed of the waves on it.

---

9 STRUCTURED · DISCRIMINATING · C.3 **[12]**

SL

Coherent light of wavelength 633 nm from a laser is incident normally on a pair of narrow parallel slits separated by 0.25 mm. An interference pattern is observed on a screen 2.40 m from the slits.

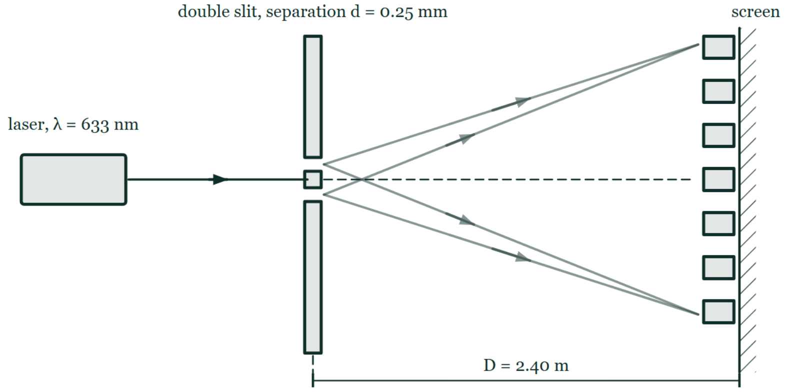

Figure 5 *Plan view. A laser at the left, labelled 'laser, λ = 633 nm', sends a beam horizontally to an opaque barrier, which has two narrow slits, one just above and one just below the beam line, separated by a short bar; the barrier is labelled 'double slit, separation d = 0.25 mm'. Beyond it, faint lines from the two slits spread out towards a screen at the right, where a column of equally spaced bright fringes is drawn, one of them on the dashed line that continues straight on from the slits. A dimension line beneath marks the slit-to-screen distance as D = 2.40 m.*

(a) DETERMINE **[3]**

Determine the separation of adjacent bright fringes on the screen.

(b) EXPLAIN **[3]**

Explain, in terms of path difference, why a bright fringe appears at the centre of the pattern and why dark fringes appear either side of it.

(c) SUGGEST **[3]**

One of the two slits is now covered with a filter that halves the amplitude of the light passing through it. Suggest how the appearance of the pattern changes.

(d) COMPARE **[3]**

The double slit is replaced by a diffraction grating of 500 lines per millimetre, illuminated by the same laser. Compare the pattern produced with the double-slit pattern.

---

10 HL

STRUCTURED · DISCRIMINATING · C.1 · C.5 **[14]**

A particle of mass 0.25 kg undergoes simple harmonic motion with amplitude 8.0 cm and period 1.6 s. Separately, a star in a distant galaxy emits a spectral line of laboratory wavelength 486.1 nm, which is observed on Earth at 487.5 nm.

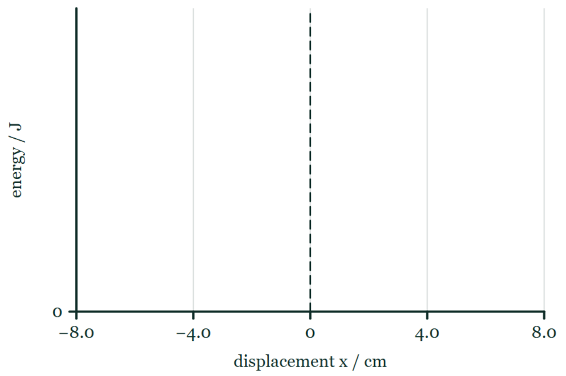

Figure 6 *A pair of empty axes provided for the sketch. The horizontal axis is labelled 'displacement x / cm' and is scaled from −8.0 through 0 to +8.0, with faint gridlines at −8.0, −4.0, 0, +4.0 and +8.0 and a dashed vertical line drawn at x = 0. The vertical axis is labelled 'energy / J' and carries only a zero at its foot, so no numerical scale is imposed. No curve of any kind is drawn on the axes.*

(a) DETERMINE **[4]**

Determine the total energy of the oscillating particle.

(b) SKETCH **[3]**

Sketch, on the same axes, graphs of the kinetic energy and of the potential energy of the particle against displacement, from $-x_0$ to $+x_0$.

(c) DETERMINE **[4]**

Determine the speed at which the star is moving relative to the Earth, and state whether it is approaching or receding.

(d) EXPLAIN **[3]**

Explain why the Doppler shift for light is treated differently from the Doppler shift for sound when the source and the observer are both moving.

MARK SCHEME

Theme C · Wave behaviour — mark scheme

One line per mark, as an examiner would award them. A note under a part is the error that part is set to catch.

1 SL — MULTIPLE CHOICE · DEMANDING · C.1 — **[1]**

The amplitude of a mass–spring oscillator is doubled while its mass and spring constant are unchanged. What happens to its period and to its total energy?

KEY **B** **period unchanged, energy quadrupled**

The independence of period from amplitude is the defining feature of simple harmonic motion, which rules out C and D. Total energy is ½kx_0^2, so it goes as the square of the amplitude — A halves that dependence.

AO2

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2 SL — MULTIPLE CHOICE · ROUTINE · C.2 — **[1]**

A sound wave of frequency 256 Hz travels through air at 340 m s^{-1} and then passes into water, where its speed is 1500 m s^{-1}. What are its frequency and wavelength in the water?

KEY **B** **256 Hz and 5.86 m**

The frequency is fixed by the source and does not change at a boundary, which eliminates C and D at once. The wavelength changes with the speed: 1500/256 = 5.86 m.

AO2

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3 SL — MULTIPLE CHOICE · DEMANDING · C.4 — **[1]**

A pipe of length 0.85 m is closed at one end and open at the other. The speed of sound in air is 340 m s^{-1}. What is the frequency of the fundamental note?

KEY **A** **100 Hz**

B is the answer for a pipe open at both ends. A closed pipe has a node at the closed end and an antinode at the open end, so the fundamental fits only a quarter of a wavelength into its length: $\lambda = 4L = 3.4$ m.

AO2

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4 SL — MULTIPLE CHOICE · ROUTINE · C.5 — **[1]**

An ambulance siren emits a note of frequency 512 Hz. The ambulance travels at 25 m s^{-1} towards a stationary observer. The speed of sound in air is 340 m s^{-1}. What frequency does the observer hear?

KEY **C** **553 Hz**

A is the frequency heard after the ambulance has passed, obtained by using the wrong sign. Any answer below 512 Hz can be discarded for an approaching source before the arithmetic begins.

AO2

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5 HL — MULTIPLE CHOICE · DEMANDING · C.3 — **[1]**

Monochromatic light passes through a single slit and forms a diffraction pattern on a distant screen. The slit is then made narrower. What happens to the width of the central maximum and to its intensity?

KEY **A** **width increases, intensity decreases**

C is the intuitive answer — a narrower slit ought to give a narrower patch — and it is exactly backwards. The angular width of the central maximum is $2\lambda/b$, so narrowing b spreads the pattern out, while less light passes through and the pattern is dimmer.

AO2

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6 HL

MULTIPLE CHOICE · DEMANDING · C.1 **[1]**

A particle undergoes simple harmonic motion described by $x = x_0 \sin(\omega t)$. At what displacement is the kinetic energy equal to the potential energy?

KEY **C** $x_0/\sqrt{2}$

B is the answer of a candidate who splits the displacement in half rather than the energy. The potential energy goes as x^2, so it is half the total when $x^2 = x_0^2/2$.

AO2

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7 SL

DATA ANALYSIS · DEMANDING · C.1 **[11]**

A student investigates the oscillations of a mass hanging from a vertical spring, expecting the period to satisfy $T = 2\pi\sqrt{(m/k)}$, where k is the spring constant.

(a) DETERMINE · AO2 **[4]**

Determine the gradient of a graph of T^2 against m, and hence determine the spring constant k.

1. $T^2 = (4\pi^2/k)m$, so the gradient is $4\pi^2/k$
2. gradient = (0.987 − 0.197)/(0.500 − 0.100) = 0.790/0.400
3. gradient = 1.98 $s^2\ kg^{-1}$
4. $k = 4\pi^2/1.98 = 20\ N\ m^{-1}$

(b) EXPLAIN · AO4 **[2]**

Explain why the student plotted T^2 against m rather than T against m.

1. T against m would be a curve, from which no constant can be read directly
2. squaring produces a linear relationship, so a straight line both tests the model and gives k from a single gradient

(c) SUGGEST · AO3 **[2]**

In practice the line of best fit for a real spring has a small positive intercept on the T^2 axis. Suggest a physical reason for this.

1. the spring itself has mass, and part of it oscillates along with the hanging mass
2. so the effective oscillating mass exceeds the mass added, giving a non-zero period as the added mass tends to zero — the intercept corresponds to roughly one third of the spring's own mass

   The one-third figure is not required for the marks, but a candidate who names the spring's own mass as the cause has given the answer the mark scheme is looking for.

(d) OUTLINE · AO4 **[3]**

Outline how the student should time the oscillations to keep the uncertainty in T small, and state one reason why timing a single oscillation would be unsatisfactory.

1. time at least 10 or 20 complete oscillations and divide by the number
2. start and stop the timing as the mass passes through the equilibrium position, where it moves fastest, using a fixed reference marker
3. the reaction-time uncertainty of about 0.2 s is a large fraction of a single period of about 0.5 s, but only a small fraction of a 10-oscillation total

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8 SL

STRUCTURED · DEMANDING · C.2 · C.4 **[12]**

A string of length 0.60 m is stretched between two fixed points. When plucked, it vibrates in its fundamental mode at a frequency of 250 Hz.

(a) DETERMINE · AO2 **[3]**

Determine the speed of the transverse waves on the string.

1. in the fundamental mode the string carries half a wavelength, so $\lambda = 2L = 1.2$ m
2. $v = f\lambda = 250 \times 1.2$
3. $v = 300\ \text{m s}^{-1}$

(b) DESCRIBE · AO1 **[4]**

Describe how a standing wave is formed on the string, and state what distinguishes a standing wave from a progressive wave.

1. a wave travels along the string and reflects at the fixed end, and the reflected wave travels back along the string
2. the two waves have the same frequency, speed and amplitude and travel in opposite directions, so they superpose
3. the superposition produces fixed nodes where the two always cancel and antinodes where they always reinforce
4. a standing wave transfers no energy along the string, and every point between adjacent nodes oscillates in phase — unlike a progressive wave, in which phase changes steadily along the direction of travel

(c) CALCULATE · AO2 **[2]**

Calculate the frequency of the third harmonic of this string, and state how many nodes it has, including the two at the ends.

1. $f_3 = 3 \times 250 = 750$ Hz
2. 4 nodes

(d) EXPLAIN · AO3 **[3]**

The tension in the string is increased. Explain what happens to the fundamental frequency, and explain why the length of the string does not change the speed of the waves on it.

1. the wave speed on a string increases with tension, so v rises
2. the wavelength of the fundamental is fixed at 2L by the geometry, so $f = v/\lambda$ increases
3. the speed depends only on the tension and the mass per unit length of the string — properties of the medium — and not on how much of that medium is between the supports

9 STRUCTURED · DISCRIMINATING · C.3 **[12]**

SL

Coherent light of wavelength 633 nm from a laser is incident normally on a pair of narrow parallel slits separated by 0.25 mm. An interference pattern is observed on a screen 2.40 m from the slits.

(a) DETERMINE · AO2 **[3]**

Determine the separation of adjacent bright fringes on the screen.

1. $s = \lambda D/d$
2. $s = (633 \times 10^{-9} \times 2.40)/(0.25 \times 10^{-3})$
3. $s = 6.1 \times 10^{-3}$ m (6.1 mm)

(b) EXPLAIN · AO2 **[3]**

Explain, in terms of path difference, why a bright fringe appears at the centre of the pattern and why dark fringes appear either side of it.

1. at the centre the two paths are equal, so the path difference is zero and the waves arrive in phase and interfere constructively
2. moving away from the centre, the path difference grows
3. where it reaches half a wavelength the waves arrive antiphase and cancel, giving a dark fringe; where it reaches a whole wavelength they reinforce again

(c) SUGGEST · AO3 **[3]**

One of the two slits is now covered with a filter that halves the amplitude of the light passing through it. Suggest how the appearance of the pattern changes.

1. the fringe separation is unchanged, because it depends only on λ, D and d
2. the dark fringes are no longer completely dark, because the two amplitudes no longer cancel exactly
3. so the contrast between bright and dark fringes is reduced, and the bright fringes are dimmer

The best-discriminating part of the paper. Almost every candidate can find the fringe spacing; far fewer see that the visibility of a two-source pattern depends on the amplitudes being matched.

(d) COMPARE · AO3 **[3]**

The double slit is replaced by a diffraction grating of 500 lines per millimetre, illuminated by the same laser. Compare the pattern produced with the double-slit pattern.

1. the grating produces maxima that are much sharper and narrower, separated by wide dark regions, rather than broad fringes of gradually varying brightness
2. the maxima are much further apart, because the slit separation of 2.0×10^{-6} m is far smaller than 0.25 mm
3. each maximum is brighter, because light from many thousands of slits contributes to it rather than from only two

10 STRUCTURED · DISCRIMINATING · C.1 · C.5 **[14]**

HL

A particle of mass 0.25 kg undergoes simple harmonic motion with amplitude 8.0 cm and period 1.6 s. Separately, a star in a distant galaxy emits a spectral line of laboratory wavelength 486.1 nm, which is observed on Earth at 487.5 nm.

(a) DETERMINE · AO2 **[4]**

Determine the total energy of the oscillating particle.

1. $\omega = 2\pi/T = 2\pi/1.6 = 3.93$ rad s^{-1}
2. $E\_total = ½m\omega^2x_0^2$
3. $E = ½ \times 0.25 \times 3.93^2 \times 0.080^2$
4. $E = 1.2 \times 10^{-2}$ J

(b) SKETCH · AO2 **[3]**

Sketch, on the same axes, graphs of the kinetic energy and of the potential energy of the particle against displacement, from $-x_0$ to $+x_0$.

1. potential energy is a parabola with a minimum of zero at $x = 0$, rising to the total energy at $x = \pm x_0$
2. kinetic energy is an inverted parabola, maximum at $x = 0$ and zero at $x = \pm x_0$
3. the two curves sum to a constant at every displacement, and cross at $x = \pm x_0/\sqrt{2}$

(c) DETERMINE · AO2 **[4]**

Determine the speed at which the star is moving relative to the Earth, and state whether it is approaching or receding.

1. $\Delta\lambda = 487.5 - 486.1 = 1.4$ nm
2. $\Delta\lambda/\lambda_0 = v/c$, so $v = c(1.4/486.1)$
3. $v = 8.6 \times 10^5$ m s^{-1}
4. the observed wavelength is longer, so the light is redshifted and the star is receding

(d) EXPLAIN · AO3 **[3]**

Explain why the Doppler shift for light is treated differently from the Doppler shift for sound when the source and the observer are both moving.

1. sound travels through a medium, so the equations distinguish a moving source from a moving observer — the two give different shifts for the same relative speed
2. light needs no medium, and its speed is the same in every inertial frame
3. so only the relative velocity of source and observer can matter, and a single expression covers every case

   This is a Nature of Science point as much as a physics one, and it is the sort of connection the extended-response part of a Paper 2 question is set to reward.

Theme D · Fields

Gravitational fields, electric and magnetic fields, motion of charges in electromagnetic fields, and — at HL — electromagnetic induction.

SUGGESTED TIME	TOTAL MARKS	QUESTIONS	MULTIPLE CHOICE
60 minutes	**52**	**10**	**6**

SECTION **D · Fields**

IN THE FORMAT OF Paper 1A (multiple choice), Paper 1B (data-based), and Paper 2 (short answer and extended response)

ROUTES SL only — 6 questions, 37 marks. SL and HL — the whole paper, 10 questions, 52 marks. Every question is tagged in the left margin.

DEMAND **Routine 2 · Demanding 7 · Discriminating 1**

The command term sets the demand, and the papers are written that way. "State" earns one mark for one line; "explain" is not creditworthy without a mechanism; "discuss" and "evaluate" need both sides weighed before a conclusion is reached. The extended-response part that closes each Paper 2 question is where HL candidates separate from one another, and those parts are pitched there rather than at the level of the calculation before them.

SYLLABUS POINTS D.1 · D.2 · D.3 · D.4

INSTRUCTIONS

- Answer all questions in the spaces provided.
- Show your working. Method marks are awarded even where the final answer is wrong.
- Give your answers to a sensible number of significant figures, with a unit.
- The mark scheme for this paper follows the last question.

THE PAPER

Theme D · Fields

Answer all questions. 52 marks in 60 minutes.

1 SL

MULTIPLE CHOICE · ROUTINE · D.1 **[1]**

A planet has twice the mass and twice the radius of the Earth. The gravitational field strength at the Earth's surface is g. What is the field strength at the surface of the planet?

A g/4

B g/2

C g

D 2g

Answer

2 SL

MULTIPLE CHOICE · DEMANDING · D.2 **[1]**

Two identical conducting spheres carry charges of +6.0 nC and −2.0 nC. They are touched together and then separated to their original distance apart. How does the magnitude of the force between them change?

A It becomes zero.

B It is reduced to one third of its original value.

C It is reduced to one twelfth of its original value.

D It increases to twelve times its original value.

Answer

3 SL

MULTIPLE CHOICE · ROUTINE · D.3

[1]

A proton moves in a circular path of radius r in a uniform magnetic field of magnitude B, perpendicular to its velocity. If the speed of the proton is doubled, what is the new radius?

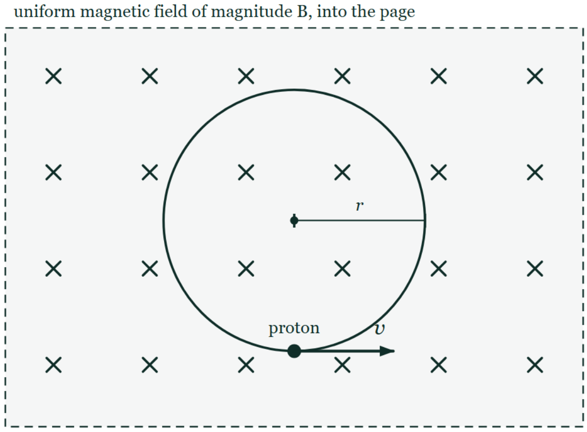

Figure 1 *A rectangular region bounded by a dashed line is filled with an evenly spaced grid of crosses and labelled 'uniform magnetic field of magnitude B, into the page'. Inside the region a complete circle is drawn: the path followed by the proton. A line from the centre of the circle out to the circle is marked with a tick at each end and labelled r. A solid dot on the circle at its lowest point is labelled 'proton', and from that dot an arrow labelled v points horizontally to the right, along the tangent to the circle.*

A r/2

B r

C 2r

D 4r

Answer

4

HL

MULTIPLE CHOICE · DEMANDING · D.1

[1]

A satellite of mass m is in a circular orbit of radius r around a planet of mass M. What is its total energy?

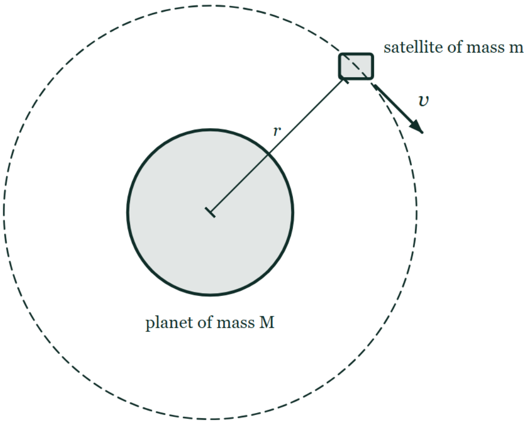

Figure 2 *A planet is drawn as a large shaded circle labelled 'planet of mass M'. A dashed circle, concentric with the planet and well outside it, is labelled 'circular orbit'. A small rectangle sitting on the dashed circle, above and to the right of the planet, is labelled 'satellite of mass m'. A short arrow from the satellite, drawn along the tangent to the orbit and labelled v, shows the direction in which it travels. A line runs from the centre of the planet out to the satellite and is labelled r.*

A $-GMm/(2r)$

B $-GMm/r$

C $+GMm/(2r)$

D zero

Answer

5 HL

MULTIPLE CHOICE · DEMANDING · D.4 **[1]**

A bar magnet is dropped, north pole downward, through a horizontal copper ring. Which describes the force on the magnet as it approaches the ring and after it has passed through?

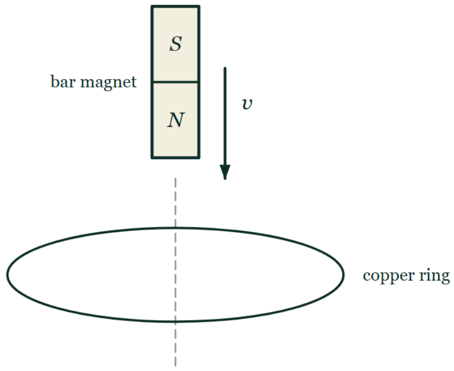

Figure 3 *Side view. A bar magnet is drawn vertically above a horizontal copper ring, with its two halves marked S at the top and N at the bottom, so that the north pole is the end facing the ring. An arrow beside the magnet, labelled v, points vertically downward. A faint dashed line continues from the bottom of the magnet straight down through the centre of the ring, which is drawn as a flattened ellipse to show it lying horizontally, and is labelled 'copper ring'.*

A upward as it approaches, upward after it has passed

B upward as it approaches, downward after it has passed

C downward as it approaches, upward after it has passed

D there is no force, because copper is not magnetic

Answer

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6 HL

MULTIPLE CHOICE · DEMANDING · D.2 **[1]**

Which statement about equipotential surfaces and field lines is correct for any static field?

A They are parallel to one another.

B They are perpendicular to one another.

C Work is done moving a charge along a field line but not along an equipotential.

D Both B and C are correct.

Answer

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7 DATA ANALYSIS · DEMANDING · D.2 **[10]**

SL

A student measures the magnetic flux density B at various perpendicular distances r from a long straight wire carrying a steady current I. Theory predicts $B = \mu_0 I/(2\pi r)$.

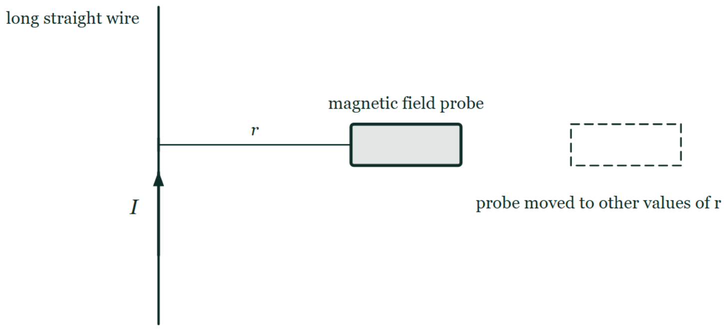

Figure 4 *A long straight wire is drawn vertically and labelled 'long straight wire'. An arrow drawn along the wire and labelled I gives the direction of the current in it. To the right of the wire, at the same height, a small rectangle labelled 'magnetic field probe' has its near face towards the wire, and a dimension line running perpendicular from the wire to that face is labelled r. A dashed outline of the probe, drawn further to the right at the same height, carries the note 'probe moved to other values of r'.*

The student's processed data

r / m	**0.020**	**0.025**	**0.040**	**0.050**	**0.100**
B / μT	50.0	40.0	25.0	20.0	10.0
1/r / m^{-1}	50.0	40.0	25.0	20.0	10.0

(a) EXPLAIN **[2]**

Explain why a graph of B against 1/r is plotted rather than a graph of B against r.

(b) DETERMINE **[4]**

Determine the gradient of the line, and hence determine the current in the wire.

(c) SUGGEST **[2]**

The student's measurements at the largest distances scatter more about the line than those close to the wire. Suggest why.

(d) OUTLINE **[2]**

Outline one systematic error that would make every value of B too large, and state how it would show up on the graph.

8 SL

STRUCTURED · DEMANDING · D.1 **[12]**

A planet has mass 6.4×10^{23} kg and radius 3.4×10^{6} m. The gravitational constant is 6.67×10^{-11} N m^{2} kg^{-2}.

(a) CALCULATE **[2]**

Calculate the gravitational field strength at the surface of the planet.

(b) DETERMINE **[3]**

Determine the escape speed from the surface of the planet.

(c) EXPLAIN **[3]**

Explain why gravitational potential is always negative, and state what a gravitational potential of -1.3×10^{7} J kg^{-1} at the planet's surface means.

(d) DISCUSS **[4]**

The planet has almost no atmosphere, while the Earth retains a substantial one. Discuss how the escape speed helps to explain this difference.

9 SL

STRUCTURED · DEMANDING · D.2 · D.3 **[12]**

An electron is accelerated from rest through a potential difference of 500 V and then enters a region of uniform magnetic field of magnitude 2.5 mT, travelling perpendicular to the field. The mass of an electron is 9.11×10^{-31} kg and its charge has magnitude 1.60×10^{-19} C.

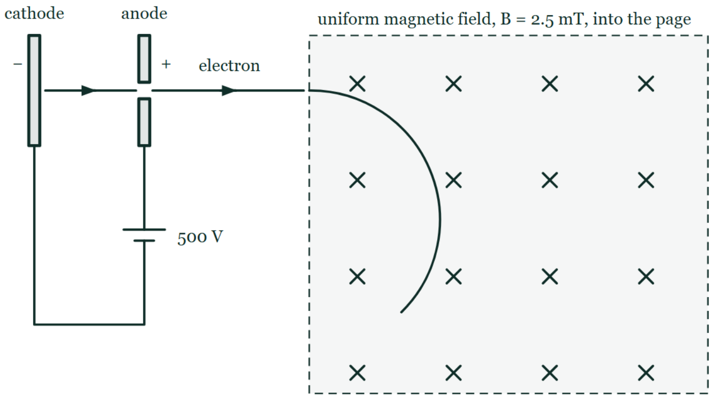

Figure 5 *Side view of the arrangement. At the left a cathode plate marked − faces an anode plate marked + which has a small hole in it at the level of the beam; below, the two plates are joined by wires through a cell labelled 500 V, whose positive terminal is connected to the anode. Arrows show an electron leaving the cathode, passing through the hole in the anode and travelling on to the right, where it crosses into a large rectangular region drawn with a dashed boundary and filled with crosses, labelled 'uniform magnetic field, B = 2.5 mT, into the page'. Inside that region the electron's path is drawn as an arc that curves steadily downwards away from its original straight line.*

(a) DETERMINE **[3]**

Determine the speed of the electron as it enters the magnetic field.

(b) DETERMINE **[3]**

Determine the radius of the circular path followed by the electron in the field.

(c) EXPLAIN **[3]**

Explain why the speed of the electron is unchanged while it moves within the magnetic field, even though its velocity is changing continuously.

(d) COMPARE **[3]**

A uniform electric field is now applied in the same region instead of the magnetic field, perpendicular to the electron's initial velocity. Compare the resulting path and the resulting speed with those in the magnetic field.

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10 HL STRUCTURED · DISCRIMINATING · D.4 **[12]**

A flat rectangular coil of 250 turns and area 3.2×10^{-3} m² is rotated at a constant rate in a uniform magnetic field of magnitude 85 mT. The axis of rotation is perpendicular to the field. The coil completes 50 revolutions per second.

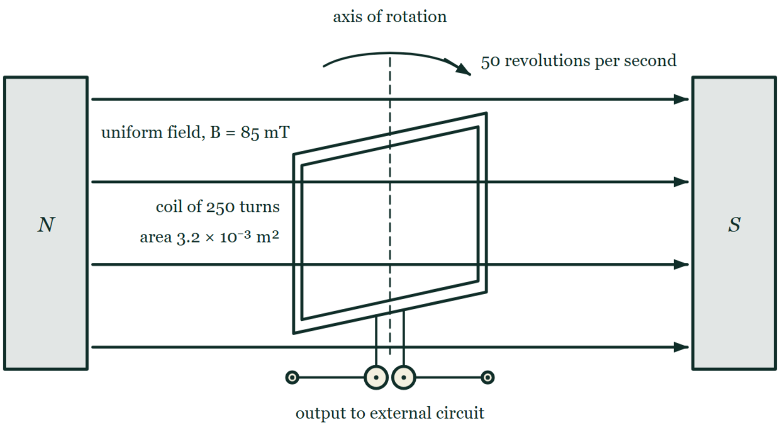

Figure 6 *A rectangular coil hangs between the flat faces of two poles, the north pole a block on the left and the south pole a block on the right. Four evenly spaced horizontal arrows run across the gap from the north pole to the south pole, and a note reads 'uniform field, B = 85 mT'. The coil is drawn obliquely, as a rectangle turned so that its plane lies at an angle to the field, and is labelled 'coil of 250 turns' and 'area 3.2 × 10⁻³ m²'. A vertical dashed line through the middle of the coil is labelled 'axis of rotation', with a curved arrow above it and the note '50 revolutions per second'. Two leads run down from the bottom of the coil to a pair of slip rings with brushes, whose terminals are labelled 'output to external circuit'.*

(a) STATE **[2]**

State Faraday's law of electromagnetic induction.

(b) DETERMINE **[3]**

Determine the maximum e.m.f. induced in the coil.

(c) EXPLAIN **[3]**

Explain why the induced e.m.f. is zero at the instant when the plane of the coil is perpendicular to the magnetic field, even though the flux through the coil is greatest at that moment.

(d) DISCUSS **[4]**

The output of the coil is connected to a resistor. Discuss the energy transfers taking place, and explain why more mechanical power must be supplied to keep the coil rotating at 50 revolutions per second once the resistor is connected.

Theme D · Fields — mark scheme

One line per mark, as an examiner would award them. A note under a part is the error that part is set to catch.

1 SL

MULTIPLE CHOICE · ROUTINE · D.1 **[1]**

A planet has twice the mass and twice the radius of the Earth. The gravitational field strength at the Earth's surface is g. What is the field strength at the surface of the planet?

KEY **B** **g/2**

C is chosen by candidates who assume the two doublings cancel. In $g = GM/R^2$, the radius enters squared, so doubling both mass and radius gives 2/4 = ½.

AO2

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2 SL

MULTIPLE CHOICE · DEMANDING · D.2 **[1]**

Two identical conducting spheres carry charges of +6.0 nC and −2.0 nC. They are touched together and then separated to their original distance apart. How does the magnitude of the force between them change?

KEY **B** **It is reduced to one third of its original value.**

Touching shares the total charge of +4.0 nC equally, giving +2.0 nC on each, so the product of the charges falls from 12 nC^2 to 4 nC^2 and the force to one third. A is chosen by candidates who think the charges neutralise — they only partly do. The force also changes from attraction to repulsion, but the question asks about its magnitude.

AO2

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3 SL

MULTIPLE CHOICE · ROUTINE · D.3 **[1]**

A proton moves in a circular path of radius r in a uniform magnetic field of magnitude B, perpendicular to its velocity. If the speed of the proton is doubled, what is the new radius?

KEY **C** **2r**

B is the answer of a candidate who remembers that the period of circular motion in a magnetic field is independent of speed, which is true but is not what was asked. From $r = mv/(qB)$, the radius is proportional to the speed.

AO2

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4 HL

MULTIPLE CHOICE · DEMANDING · D.1 **[1]**

A satellite of mass m is in a circular orbit of radius r around a planet of mass M. What is its total energy?

KEY **A** **$-GMm/(2r)$**

B is the potential energy alone, forgetting that the satellite also has kinetic energy of $+GMm/(2r)$. The total is negative, which is what makes the orbit bound.

AO2

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5 HL

MULTIPLE CHOICE · DEMANDING · D.4 **[1]**

A bar magnet is dropped, north pole downward, through a horizontal copper ring. Which describes the force on the magnet as it approaches the ring and after it has passed through?

KEY **A** **upward as it approaches, upward after it has passed**

B is the intuitive answer — the ring appears to repel then attract — but Lenz's law makes the induced effect oppose the motion in both stages. Approaching, the ring repels; receding, it attracts; and both act upward on a falling magnet. D confuses ferromagnetism with induction.

AO2

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6 HL

MULTIPLE CHOICE · DEMANDING · D.2 **[1]**

Which statement about equipotential surfaces and field lines is correct for any static field?

KEY **D** **Both B and C are correct.**

Both statements are true and follow from the same fact: if a field had a component along an equipotential, moving a charge along it would do work and the potential would change. Candidates who stop at the first true statement they meet choose B or C.

AO2

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7 SL

DATA ANALYSIS · DEMANDING · D.2 **[10]**

A student measures the magnetic flux density B at various perpendicular distances r from a long straight wire carrying a steady current I. Theory predicts $B = \mu_0 I/(2\pi r)$.

(a) EXPLAIN · AO4 **[2]**

Explain why a graph of B against 1/r is plotted rather than a graph of B against r.

1. B is inversely proportional to r, so a graph of B against r is a curve from which no constant can be read
2. plotting against 1/r linearises the relationship, so the gradient gives $\mu_0 I/(2\pi)$ directly and the straightness of the line tests the inverse proportionality

(b) DETERMINE · AO2 **[4]**

Determine the gradient of the line, and hence determine the current in the wire.

1. gradient $= (50.0 - 10.0) \times 10^{-6} / (50.0 - 10.0) = 1.0 \times 10^{-6}$ T m
2. gradient $= \mu_0 I/(2\pi)$
3. $I = 2\pi \times 1.0 \times 10^{-6} / (4\pi \times 10^{-7})$
4. $I = 5.0$ A

(c) SUGGEST · AO3 **[2]**

The student's measurements at the largest distances scatter more about the line than those close to the wire. Suggest why.

1. the field is weakest at large r, so the reading is a smaller fraction of the probe's full scale and the percentage uncertainty in each reading is larger
2. the Earth's magnetic field and any stray fields are a larger fraction of the measured value at those distances

(d) OUTLINE · AO3 **[2]**

Outline one systematic error that would make every value of B too large, and state how it would show up on the graph.

1. the probe not being zeroed before the measurements, or the Earth's field component along the probe not being subtracted, would add a constant to every reading
2. the line would still be straight but would not pass through the origin — it would have a positive intercept on the B axis

   The reasoning to reward is the link between the kind of error and its signature on the graph: a constant offset moves the intercept, a scale error changes the gradient.

---

8 SL

STRUCTURED · DEMANDING · D.1 **[12]**

A planet has mass 6.4×10^{23} kg and radius 3.4×10^{6} m. The gravitational constant is 6.67×10^{-11} N m^{2} kg^{-2}.

(a) CALCULATE · AO2 **[2]**

Calculate the gravitational field strength at the surface of the planet.

1 $g = GM/R^2 = 6.67 \times 10^{-11} \times 6.4 \times 10^{23} / (3.4 \times 10^{6})^2$

2 $g = 3.7$ N kg^{-1}

(b) DETERMINE · AO2 **[3]**

Determine the escape speed from the surface of the planet.

1 escape requires the total energy to be zero: $\frac{1}{2}mv^2 = GMm/R$

2 $v = \sqrt{(2GM/R)} = \sqrt{(2 \times 6.67 \times 10^{-11} \times 6.4 \times 10^{23} / 3.4 \times 10^{6})}$

3 $v = 5.0 \times 10^{3}$ m s^{-1}

(c) EXPLAIN · AO2 **[3]**

Explain why gravitational potential is always negative, and state what a gravitational potential of -1.3×10^{7} J kg^{-1} at the planet's surface means.

1 gravitational potential is defined as zero at infinity, and gravity is always attractive

2 so bringing a mass in from infinity releases energy, and its potential energy must be less than zero everywhere else

3 the value means that 1.3×10^{7} J of energy must be supplied to move each kilogram from the surface to infinity

(d) DISCUSS · AO3 **[4]**

The planet has almost no atmosphere, while the Earth retains a substantial one. Discuss how the escape speed helps to explain this difference.

1 the molecules of a gas have a distribution of speeds, with some far above the mean at any temperature

2 molecules whose speed exceeds the escape speed at the top of the atmosphere can leave the planet permanently

3 this planet's escape speed of 5.0 km s^{-1} is less than half the Earth's 11.2 km s^{-1}, so a much larger fraction of its molecules exceed it

4 over geological time that fraction is lost, and the lightest gases go first — which is why any remaining atmosphere is thin and dominated by the heavier molecules

9 SL

STRUCTURED · DEMANDING · D.2 · D.3 **[12]**

An electron is accelerated from rest through a potential difference of 500 V and then enters a region of uniform magnetic field of magnitude 2.5 mT, travelling perpendicular to the field. The mass of an electron is 9.11×10^{-31} kg and its charge has magnitude 1.60×10^{-19} C.

(a) DETERMINE · AO2 **[3]**

Determine the speed of the electron as it enters the magnetic field.

1. $eV = \frac{1}{2}mv^2$
2. $v = \sqrt{(2 \times 1.60 \times 10^{-19} \times 500 / 9.11 \times 10^{-31})}$
3. $v = 1.33 \times 10^7$ m s^{-1}

(b) DETERMINE · AO2 **[3]**

Determine the radius of the circular path followed by the electron in the field.

1. the magnetic force provides the centripetal force: $evB = mv^2/r$
2. $r = mv/(eB) = 9.11 \times 10^{-31} \times 1.33 \times 10^7 / (1.60 \times 10^{-19} \times 2.5 \times 10^{-3})$
3. $r = 3.0 \times 10^{-2}$ m

(c) EXPLAIN · AO2 **[3]**

Explain why the speed of the electron is unchanged while it moves within the magnetic field, even though its velocity is changing continuously.

1. the magnetic force is always perpendicular to the velocity
2. so it has no component along the direction of motion and does no work on the electron
3. the kinetic energy is therefore constant, and only the direction of the velocity changes

(d) COMPARE · AO3 **[3]**

A uniform electric field is now applied in the same region instead of the magnetic field, perpendicular to the electron's initial velocity. Compare the resulting path and the resulting speed with those in the magnetic field.

1. in the electric field the force is constant in magnitude and direction, so the path is parabolic rather than circular
2. the force has a component along the velocity once the electron has been deflected, so it does work and the speed increases
3. in the magnetic field the force turns with the velocity, keeping the path circular and the speed constant

10 STRUCTURED · DISCRIMINATING · D.4 **[12]**

HL

A flat rectangular coil of 250 turns and area 3.2×10^{-3} m² is rotated at a constant rate in a uniform magnetic field of magnitude 85 mT. The axis of rotation is perpendicular to the field. The coil completes 50 revolutions per second.

(a) STATE · AO1 **[2]**

State Faraday's law of electromagnetic induction.

1 the magnitude of the induced e.m.f. is equal to the rate of change of magnetic flux linkage

2 expressed as $\varepsilon = -N\, d\Phi/dt$, the minus sign expressing Lenz's law

(b) DETERMINE · AO2 **[3]**

Determine the maximum e.m.f. induced in the coil.

1 $\omega = 2\pi f = 2\pi \times 50 = 314$ rad s^{-1}

2 $\varepsilon_0 = NBA\omega = 250 \times 0.085 \times 3.2 \times 10^{-3} \times 314$

3 $\varepsilon_0 = 21$ V

(c) EXPLAIN · AO3 **[3]**

Explain why the induced e.m.f. is zero at the instant when the plane of the coil is perpendicular to the magnetic field, even though the flux through the coil is greatest at that moment.

1 the induced e.m.f. depends on the rate of change of flux, not on the flux itself

2 when the plane of the coil is perpendicular to the field the flux is at a maximum, and at a maximum its rate of change is momentarily zero

3 so the e.m.f. is zero there and greatest a quarter of a cycle later, when the flux is passing through zero and changing fastest

The relationship between a quantity and its rate of change, tested on a case where intuition points the wrong way. This is one of the most reliably discriminating parts in the whole theme.

(d) DISCUSS · AO3 **[4]**

The output of the coil is connected to a resistor. Discuss the energy transfers taking place, and explain why more mechanical power must be supplied to keep the coil rotating at 50 revolutions per second once the resistor is connected.

1 with the circuit closed, the induced e.m.f. drives a current through the coil and the resistor, and electrical energy is dissipated in the resistor as thermal energy

2 the current-carrying coil sits in the magnetic field, so it experiences a torque

3 by Lenz's law that torque opposes the rotation of the coil

4 so an external agent must do work against it, and the mechanical power supplied equals the electrical power dissipated — energy is conserved, with the coil acting as the converter rather than the source

Theme E · Nuclear and quantum physics

Structure of the atom, radioactive decay, fission, fusion and stars, and — at HL — quantum physics.

SUGGESTED TIME	TOTAL MARKS	QUESTIONS	MULTIPLE CHOICE
60 minutes	**57**	**10**	**6**

SECTION — **E · Nuclear and quantum physics**

IN THE FORMAT OF — Paper 1A (multiple choice), Paper 1B (data-based), and Paper 2 (short answer and extended response)

ROUTES — SL only — 8 questions, 43 marks. SL and HL — the whole paper, 10 questions, 57 marks. Every question is tagged in the left margin.

DEMAND — **Routine 2 · Demanding 6 · Discriminating 2**

The command term sets the demand, and the papers are written that way. "State" earns one mark for one line; "explain" is not creditworthy without a mechanism; "discuss" and "evaluate" need both sides weighed before a conclusion is reached. The extended-response part that closes each Paper 2 question is where HL candidates separate from one another, and those parts are pitched there rather than at the level of the calculation before them.

SYLLABUS POINTS — E.1 · E.2 · E.3 · E.4 · E.5

INSTRUCTIONS

— Answer all questions in the spaces provided.

— Show your working. Method marks are awarded even where the final answer is wrong.

— Give your answers to a sensible number of significant figures, with a unit.

— The mark scheme for this paper follows the last question.

Theme E · Nuclear and quantum physics

Answer all questions. 57 marks in 60 minutes.

1 SL

MULTIPLE CHOICE · DEMANDING · E.1 **[1]**

An electron in a hydrogen atom moves from an energy level of −1.51 eV to a level of −3.40 eV. What is the wavelength of the emitted photon? (hc = 1240 eV nm)

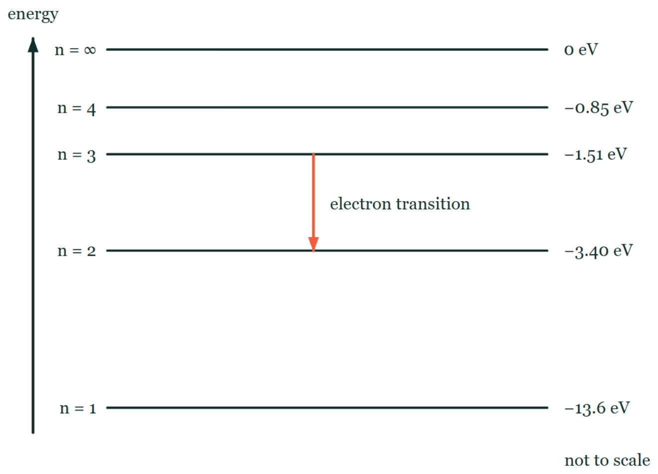

Fig. 1.1 *An energy level diagram for a hydrogen atom, drawn not to scale, with energy increasing up the page. Five horizontal levels are shown: the ground state n = 1 at −13.6 eV, then n = 2 at −3.40 eV, n = 3 at −1.51 eV, n = 4 at −0.85 eV, and n = ∞ at 0 eV. A vertical arrow drawn between the −1.51 eV level and the −3.40 eV level points downwards, marking the electron transition the question describes.*

A 254 nm

B 365 nm

C 656 nm

D 821 nm

Answer

2 SL

MULTIPLE CHOICE · ROUTINE · E.3 **[1]**

A nuclide undergoes beta-minus decay followed by alpha decay. Compared with the original nuclide, the final nuclide has:

A 4 fewer nucleons and 1 fewer proton

B 4 fewer nucleons and 2 fewer protons

C 4 fewer nucleons and 3 fewer protons

D 2 fewer nucleons and 1 fewer proton

Answer

3 SL

MULTIPLE CHOICE · DEMANDING · E.3 **[1]**

A sample contains 8.0×10^{20} nuclei of a radioactive isotope with a half-life of 12 days. How many nuclei remain undecayed after 36 days?

A 1.0×10^{20}

B 2.0×10^{20}

C 2.7×10^{20}

D 4.0×10^{20}

Answer

---

4 SL

MULTIPLE CHOICE · DEMANDING · E.4 **[1]**

Which statement about the binding energy per nucleon curve is correct?

A It rises steadily with nucleon number across the whole range.

B It peaks near iron, so both fusing lighter nuclei and splitting heavier nuclei release energy.

C It peaks near uranium, which is why uranium is used as a nuclear fuel.

D It is the energy released when a nucleus is formed from its nucleons, divided by the nucleon number, and is greatest for hydrogen.

Answer

---

5 SL

MULTIPLE CHOICE · ROUTINE · E.5 **[1]**

Two stars have the same surface temperature, but star P has four times the radius of star Q. What is the ratio of their luminosities, L_P : L_Q?

A 4 : 1

B 8 : 1

C 16 : 1

D 256 : 1

Answer

---

6 HL

MULTIPLE CHOICE · DEMANDING · E.2

[1]

In a photoelectric experiment, the intensity of the incident light is increased while its frequency is held constant. What happens to the maximum kinetic energy of the emitted photoelectrons and to the photocurrent?

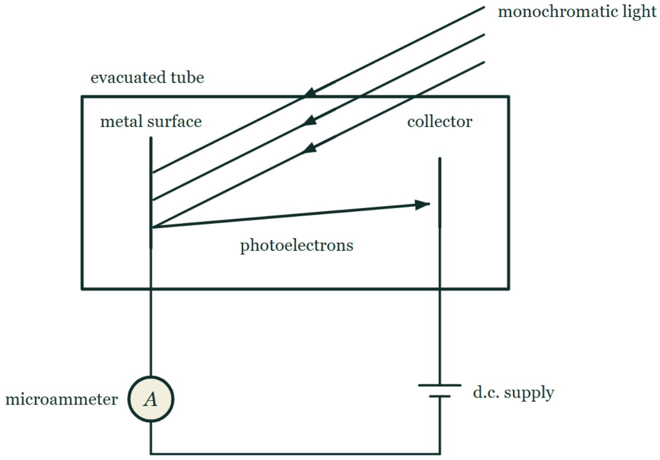

Fig. 6.1 *A photoelectric cell drawn as an evacuated tube. Inside it a flat metal plate stands on the left and a smaller collecting electrode on the right. A beam of monochromatic light enters through the top of the tube and falls on the face of the plate that faces the collector, and an arrow across the vacuum shows photoelectrons travelling from the plate to the collector. Outside the tube the plate is connected through a microammeter and along a wire to a d.c. supply, the positive terminal of which is the one joined back to the collector.*

A both increase

B maximum kinetic energy unchanged, photocurrent increases

C maximum kinetic energy increases, photocurrent unchanged

D both unchanged

Answer

7 SL

DATA ANALYSIS · DEMANDING · E.3

[12]

A student measures the activity A of a radioactive source at intervals, correcting each reading for background. She expects $A = A_0e^{(-\lambda t)}$.

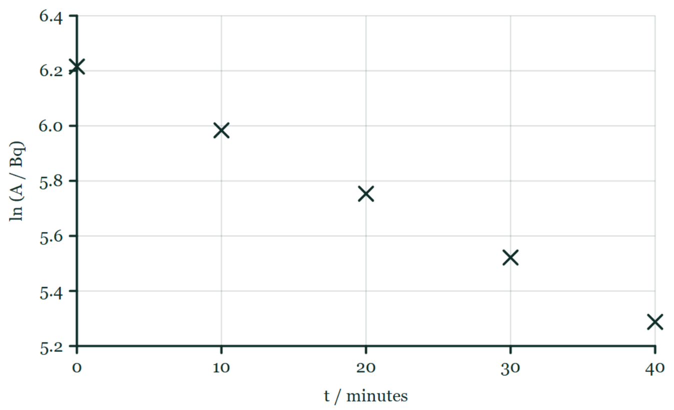

Fig. 7.1 *A gridded graph with ln (A / Bq) on the vertical axis, scaled from 5.2 to 6.4 in steps of 0.2, plotted against t / minutes on the horizontal axis, scaled from 0 to 40 in steps of 10. The five processed readings given in the table are plotted as small crosses, one at each ten-minute interval, and they fall steadily from left to right. No line has been drawn through the points.*

The student's processed data

t / minutes	0	10	20	30	40
A / Bq	500	397	315	250	198
ln (A / Bq)	6.215	5.984	5.753	5.521	5.288

(a) EXPLAIN **[3]**

Explain why a graph of ln A against t is plotted, and state what its gradient represents.

(b) DETERMINE **[4]**

Determine the decay constant and hence the half-life of the source.

(c) OUTLINE **[2]**

Outline why the readings had to be corrected for background before being processed.

(d) EXPLAIN **[3]**

The student's individual readings scatter about the line even after correction. Explain why this scatter cannot be removed by taking more care with the apparatus.

8 SL

STRUCTURED · DEMANDING · E.1 · E.3 **[12]**

The nuclide $^{226}_{88}Ra$ decays by alpha emission with a half-life of 1600 years. A sealed sample initially contains 3.0×10^{21} radium-226 nuclei.

(a) STATE **[2]**

State the nucleon number and the proton number of the nuclide produced by this decay.

(b) DETERMINE **[4]**

Determine the initial activity of the sample, in becquerel.

(c) EXPLAIN **[2]**

Explain what is meant by saying that radioactive decay is both random and spontaneous.

(d) EXPLAIN **[4]**

Explain why the emission spectrum of a gas consists of discrete lines rather than a continuous range of wavelengths, and outline what this shows about the atom.

9 SL

STRUCTURED · DISCRIMINATING · E.4 · E.5 **[14]**

In one fission event, a nucleus of ^{235}U absorbs a neutron and splits, releasing about 200 MeV of energy. In the core of the Sun, four hydrogen nuclei are effectively converted into one helium-4 nucleus, releasing about 26 MeV.

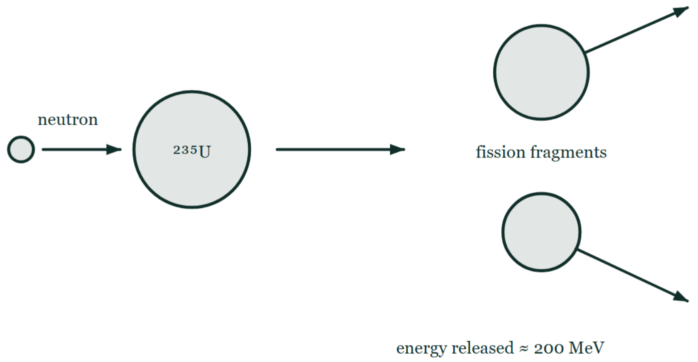

Fig. 9.1 *A schematic of a single induced fission event, read from left to right. A small neutron on the left travels to the right towards a large circle labelled ^{235}U. An arrow from that nucleus leads to the products: two unequal fission fragments drawn as circles one above the other, each with its own arrow showing it moving away from the other. Printed below the fragments is the energy released in the event, about 200 MeV.*

(a) DETERMINE **[4]**

Determine the energy released, in joules, per kilogram of uranium-235 undergoing fission. The mass of a ^{235}U atom may be taken as 3.9×10^{-25} kg.

(b) EXPLAIN **[3]**

Explain, in terms of binding energy per nucleon, why both fission of uranium and fusion of hydrogen release energy.

(c) EXPLAIN **[3]**

Explain why extremely high temperatures are required for fusion but not for fission.

(d) DISCUSS **[4]**

The Sun's luminosity is 3.8×10^{26} W. Discuss whether the fusion of hydrogen can account for the Sun's output over its estimated remaining lifetime of about 5×10^{9} years.

10 HL

STRUCTURED · DISCRIMINATING · E.2 **[13]**

In a photoelectric experiment, light of wavelength 420 nm is incident on a caesium surface of work function 2.1 eV. Planck's constant is 6.63×10^{-34} J s and hc may be taken as 1240 eV nm.

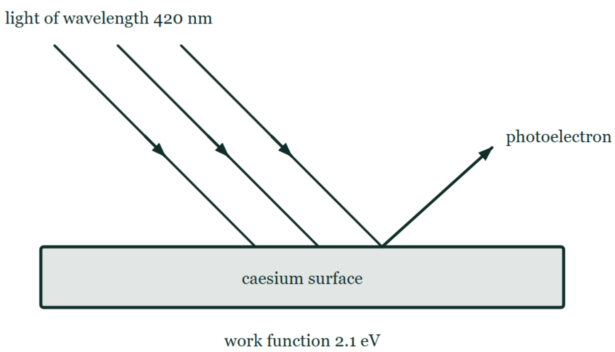

Fig. 10.1 *Three parallel rays of light of wavelength 420 nm slant down to the right and meet the flat upper face of a block labelled as a caesium surface with a work function of 2.1 eV. From a point on that same face, further to the right of where the light lands, a single arrow slants up and to the right, marking one photoelectron leaving the metal.*

(a) DETERMINE **[3]**

Determine the maximum kinetic energy of the emitted photoelectrons, in electronvolts.

(b) DETERMINE **[2]**

Determine the threshold wavelength for caesium.

(c) DETERMINE **[4]**

Determine the de Broglie wavelength of an electron emitted with the maximum kinetic energy found in (a).

(d) EXPLAIN **[4]**

Explain how the existence of a threshold frequency, and the absence of any measurable time delay before emission begins even in very dim light, together provide evidence against a purely wave model of light.

MARK SCHEME

Theme E · Nuclear and quantum physics — mark scheme

One line per mark, as an examiner would award them. A note under a part is the error that part is set to catch.

1 SL — MULTIPLE CHOICE · DEMANDING · E.1 **[1]**

An electron in a hydrogen atom moves from an energy level of −1.51 eV to a level of −3.40 eV. What is the wavelength of the emitted photon? (hc = 1240 eV nm)

KEY **C** **656 nm**

The photon energy is the difference between the levels, 1.89 eV, giving 1240/1.89 = 656 nm. B uses 3.40 eV and D uses 1.51 eV — both are the answers of a candidate who uses one level rather than the gap between them.

AO2

2 SL — MULTIPLE CHOICE · ROUTINE · E.3 **[1]**

A nuclide undergoes beta-minus decay followed by alpha decay. Compared with the original nuclide, the final nuclide has:

KEY **A** **4 fewer nucleons and 1 fewer proton**

Beta-minus raises the proton number by one and leaves the nucleon number unchanged; alpha lowers the proton number by two and the nucleon number by four. Net: −4 nucleons, −1 proton. B ignores the beta decay entirely.

AO2

3 SL — MULTIPLE CHOICE · DEMANDING · E.3 **[1]**

A sample contains 8.0×10^{20} nuclei of a radioactive isotope with a half-life of 12 days. How many nuclei remain undecayed after 36 days?

KEY **A** **1.0×10^{20}**

36 days is three half-lives, so the number is halved three times: 8.0 → 4.0 → 2.0 → 1.0. C divides by three, which is the answer of a candidate treating decay as linear.

AO2

4 SL — MULTIPLE CHOICE · DEMANDING · E.4 **[1]**

Which statement about the binding energy per nucleon curve is correct?

KEY **B** **It peaks near iron, so both fusing lighter nuclei and splitting heavier nuclei release energy.**

C reverses the position of the peak — uranium is used as a fuel precisely because it lies far to the right of the peak and can move towards it by splitting. D gets the definition right and the maximum wrong.

AO2

5 SL — MULTIPLE CHOICE · ROUTINE · E.5 **[1]**

Two stars have the same surface temperature, but star P has four times the radius of star Q. What is the ratio of their luminosities, $L_P : L_Q$?

KEY **C** **16 : 1**

D applies the fourth power to the radius instead of to the temperature. Luminosity is $4\pi R^2\sigma T^4$ — the radius enters squared, the temperature to the fourth.

AO2

6 HL

MULTIPLE CHOICE · DEMANDING · E.2 **[1]**

In a photoelectric experiment, the intensity of the incident light is increased while its frequency is held constant. What happens to the maximum kinetic energy of the emitted photoelectrons and to the photocurrent?

KEY **B** **maximum kinetic energy unchanged, photocurrent increases**

A is what the classical wave model predicts and is precisely the prediction the photoelectric effect refutes. Each photon carries hf regardless of intensity, so the maximum kinetic energy depends only on frequency; more intense light means more photons, hence more electrons per second.

AO2

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7 SL

DATA ANALYSIS · DEMANDING · E.3 **[12]**

A student measures the activity A of a radioactive source at intervals, correcting each reading for background. She expects $A = A_0e^{(-\lambda t)}$.

(a) EXPLAIN · AO4 **[3]**

Explain why a graph of ln A against t is plotted, and state what its gradient represents.

1. taking natural logarithms of $A = A_0e^{(-\lambda t)}$ gives $\ln A = \ln A_0 - \lambda t$
2. this is linear in t, so the points lie on a straight line if the decay is exponential — which the plot therefore also tests
3. the gradient is $-\lambda$, the negative of the decay constant

(b) DETERMINE · AO2 **[4]**

Determine the decay constant and hence the half-life of the source.

1. gradient = (5.288 − 6.215)/(40 − 0) = −0.0232 min^{-1}
2. $\lambda = 0.0232\ \text{min}^{-1}$
3. $t_{½} = \ln 2 / \lambda = 0.693/0.0232$
4. $t_{½}$ = 30 minutes

(c) OUTLINE · AO3 **[2]**

Outline why the readings had to be corrected for background before being processed.

1. the detector registers radiation from cosmic rays, rocks and other natural sources as well as from the sample
2. background adds a constant to every reading, which is a systematic error — it does not decay away, so an uncorrected plot of ln A against t would curve rather than being straight

(d) EXPLAIN · AO3 **[3]**

The student's individual readings scatter about the line even after correction. Explain why this scatter cannot be removed by taking more care with the apparatus.

1. radioactive decay is a random process — which nucleus decays, and when, cannot be predicted
2. so the number of decays counted in any fixed interval fluctuates about a mean value, and this fluctuation is a property of the process, not of the instrument
3. it can only be reduced by counting for longer or over more nuclei, since the fractional fluctuation falls as the total count rises — not by improving the apparatus

The distinction between an uncertainty inherent in the physics and one introduced by the measurement is a Nature of Science point the course returns to repeatedly, and radioactive decay is where it is cleanest.

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8 SL

STRUCTURED · DEMANDING · E.1 · E.3 **[12]**

The nuclide $^{226}_{88}Ra$ decays by alpha emission with a half-life of 1600 years. A sealed sample initially contains 3.0×10^{21} radium-226 nuclei.

(a) STATE · AO1 **[2]**

State the nucleon number and the proton number of the nuclide produced by this decay.

1. nucleon number 222
2. proton number 86

(b) DETERMINE · AO2 **[4]**

Determine the initial activity of the sample, in becquerel.

1. $t_{½} = 1600$ years $= 1600 \times 3.15 \times 10^7 = 5.04 \times 10^{10}$ s
2. $\lambda = \ln 2 / t_{½} = 0.693 / 5.04 \times 10^{10} = 1.37 \times 10^{-11}\ s^{-1}$
3. $A = \lambda N = 1.37 \times 10^{-11} \times 3.0 \times 10^{21}$
4. $A = 4.1 \times 10^{10}$ Bq

Converting the half-life to seconds before finding λ is worth a mark on its own, and is the step that leaves a candidate's activity out by a factor of 3×10^7 when it is missed.

(c) EXPLAIN · AO1 **[2]**

Explain what is meant by saying that radioactive decay is both random and spontaneous.

1. random: it cannot be predicted which nucleus will decay next, or when a particular nucleus will decay — only the probability per unit time is known
2. spontaneous: the decay is unaffected by external conditions such as temperature, pressure or chemical state

(d) EXPLAIN · AO3 **[4]**

Explain why the emission spectrum of a gas consists of discrete lines rather than a continuous range of wavelengths, and outline what this shows about the atom.

1. an atom emits a photon when an electron moves from a higher to a lower energy level
2. the photon energy equals the difference between the two levels, and its wavelength follows from $E = hc/\lambda$
3. only certain transitions are possible, so only certain photon energies — and hence only certain wavelengths — are emitted
4. this shows that the energy of an electron in an atom is quantised, taking only discrete values rather than any value in a range

9 SL

STRUCTURED · DISCRIMINATING · E.4 · E.5 **[14]**

In one fission event, a nucleus of ^{235}U absorbs a neutron and splits, releasing about 200 MeV of energy. In the core of the Sun, four hydrogen nuclei are effectively converted into one helium-4 nucleus, releasing about 26 MeV.

(a) DETERMINE · AO2 **[4]**

Determine the energy released, in joules, per kilogram of uranium-235 undergoing fission. The mass of a ^{235}U atom may be taken as 3.9×10^{-25} kg.

1. number of nuclei per kg = $1 / 3.9 \times 10^{-25} = 2.56 \times 10^{24}$
2. energy per fission = $200 \times 10^{6} \times 1.60 \times 10^{-19} = 3.2 \times 10^{-11}$ J
3. energy per kg = $2.56 \times 10^{24} \times 3.2 \times 10^{-11}$
4. = 8.2×10^{13} J kg^{-1}

(b) EXPLAIN · AO2 **[3]**

Explain, in terms of binding energy per nucleon, why both fission of uranium and fusion of hydrogen release energy.

1. energy is released whenever the products are more tightly bound — have a greater binding energy per nucleon — than the reactants
2. uranium lies to the right of the peak of the curve, so its fragments are closer to iron and more tightly bound
3. hydrogen lies far to the left, so helium formed from it is much more tightly bound

(c) EXPLAIN · AO2 **[3]**

Explain why extremely high temperatures are required for fusion but not for fission.

1. fusing nuclei are both positively charged and must be brought within range of the strong nuclear force
2. this requires them to overcome a large electrostatic repulsion, which needs very high kinetic energies and hence very high temperatures
3. a neutron has no charge, so it experiences no repulsion and can enter a uranium nucleus at ordinary — even low — energies

(d) DISCUSS · AO3 **[4]**

The Sun's luminosity is 3.8×10^{26} W. Discuss whether the fusion of hydrogen can account for the Sun's output over its estimated remaining lifetime of about 5×10^{9} years.

1. total energy required = $3.8 \times 10^{26} \times 5 \times 10^{9} \times 3.15 \times 10^{7} = 6.0 \times 10^{43}$ J
2. each helium nucleus formed releases 26 MeV = 4.2×10^{-12} J, using about 6.7×10^{-27} kg of hydrogen
3. so the mass of hydrogen required is about $6.0 \times 10^{43} \times 6.7 \times 10^{-27} / 4.2 \times 10^{-12} \approx 1 \times 10^{29}$ kg
4. this is around 5% of the Sun's mass of 2×10^{30} kg, and since fusion occurs only in the hot dense core rather than throughout the Sun, this is consistent with the estimated lifetime

An order-of-magnitude argument carried through to a judgement, which is what "discuss" asks for. A candidate whose numbers are within a factor of two and who reaches a supported conclusion earns full marks.

10 HL

STRUCTURED · DISCRIMINATING · E.2 **[13]**

In a photoelectric experiment, light of wavelength 420 nm is incident on a caesium surface of work function 2.1 eV. Planck's constant is 6.63×10^{-34} J s and hc may be taken as 1240 eV nm.

(a) DETERMINE · AO2 **[3]**

Determine the maximum kinetic energy of the emitted photoelectrons, in electronvolts.

1. photon energy = 1240/420 = 2.95 eV
2. $E_k(max) = hf - \varphi = 2.95 - 2.1$
3. $E_k(max) = 0.85$ eV

(b) DETERMINE · AO2 **[2]**

Determine the threshold wavelength for caesium.

1. at threshold $hf = \varphi$, so $\lambda_{max} = 1240/2.1$
2. $\lambda_{max} = 590$ nm

(c) DETERMINE · AO2 **[4]**

Determine the de Broglie wavelength of an electron emitted with the maximum kinetic energy found in (a).

1. $E_k = 0.85 \times 1.60 \times 10^{-19} = 1.36 \times 10^{-19}$ J
2. $p = \sqrt{2mE_k} = \sqrt{2 \times 9.11 \times 10^{-31} \times 1.36 \times 10^{-19}}$
3. $p = 4.98 \times 10^{-25}$ kg m s^{-1}
4. $\lambda = h/p = 6.63 \times 10^{-34} / 4.98 \times 10^{-25} = 1.3 \times 10^{-9}$ m

(d) EXPLAIN · AO3 **[4]**

Explain how the existence of a threshold frequency, and the absence of any measurable time delay before emission begins even in very dim light, together provide evidence against a purely wave model of light.

1. a wave model predicts that energy arrives continuously and spreads over the whole surface, so any frequency should eventually free an electron if the light shines long enough
2. instead, no electrons are emitted below the threshold frequency however intense or prolonged the illumination — so the energy must arrive in single indivisible amounts of size hf
3. a wave model also predicts a measurable delay in very dim light while an electron accumulates enough energy
4. no such delay is observed, because a single photon delivers all of its energy to a single electron in one interaction

Two separate observations, each with the wave prediction stated before the contradiction. Candidates who describe the results without saying what the wave model would have predicted earn half the marks at most, because the evidence is precisely the mismatch.

THE CHEAPEST MARKS ON ANY PAPER

What the command words are asking for

Every board publishes these and marks to them. A candidate who explains where the question said state has spent four minutes earning one mark; one who states where it said explain has earned none.

Define	Give the precise meaning of a word, phrase, concept or physical quantity.
State	Give a specific name, value or other brief answer without explanation or calculation.
Calculate	Obtain a numerical answer, showing the relevant stages in the working.
Describe	Give a detailed account.
Determine	Obtain the only possible answer, from the data or by reasoning.
Outline	Give a brief account or summary.
Compare	Give an account of the similarities between two or more items, referring to both throughout.
Discuss	Offer a considered and balanced review that includes a range of arguments, factors or hypotheses, supported by appropriate evidence.
Evaluate	Make an appraisal by weighing up the strengths and limitations.
Explain	Give a detailed account including reasons or causes.
Show (that)	Give the steps in a calculation or derivation.
Sketch	Represent by means of a graph showing a line and labelled but unscaled axes, with important features clearly identifiable.
Suggest	Propose a solution, hypothesis or other possible answer.

WHAT IS BEING TESTED

IB assessment objectives

Paper 1 has two parts: 1A is multiple choice, and 1B is data-based questions drawn from the experimental work of the course, with no recall in it at all. Paper 2 is short-answer and extended-response across the whole syllabus. HL papers are longer and reach the HL-only sub-topics. The data booklet is provided in every paper, so no question tests whether you can remember an equation.

AO1 12 MARKS · 4%	**Demonstrate knowledge** Recall facts, concepts and terminology, and state methodologies and techniques used in the course.
AO2 157 MARKS · 58%	**Understand and apply knowledge** Apply concepts, terminology and techniques to familiar and unfamiliar situations, including numerical work.
AO3 87 MARKS · 32%	**Analyse, evaluate and construct** Analyse and evaluate data, methods, claims and explanations, and construct a reasoned argument or conclusion.
AO4 16 MARKS · 6%	**Demonstrate the application of skills** Design and evaluate investigations, handle raw and processed data, treat uncertainties, and communicate results.