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)

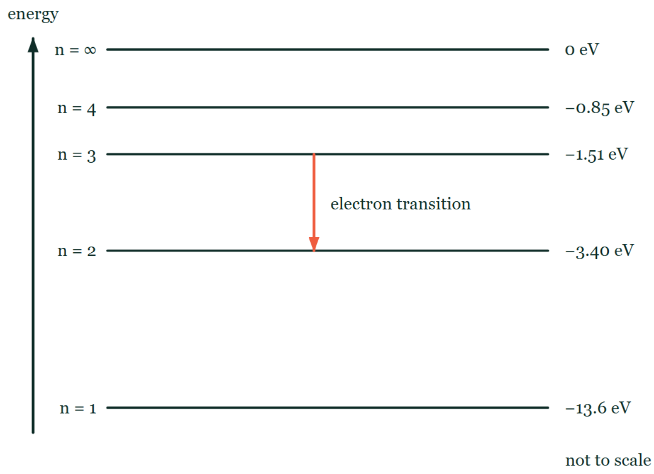

Fig. 1.1 *An energy level diagram for a hydrogen atom, drawn not to scale, with energy increasing up the page. Five horizontal levels are shown: the ground state n = 1 at −13.6 eV, then n = 2 at −3.40 eV, n = 3 at −1.51 eV, n = 4 at −0.85 eV, and n = ∞ at 0 eV. A vertical arrow drawn between the −1.51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

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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

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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

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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

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

HL

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?

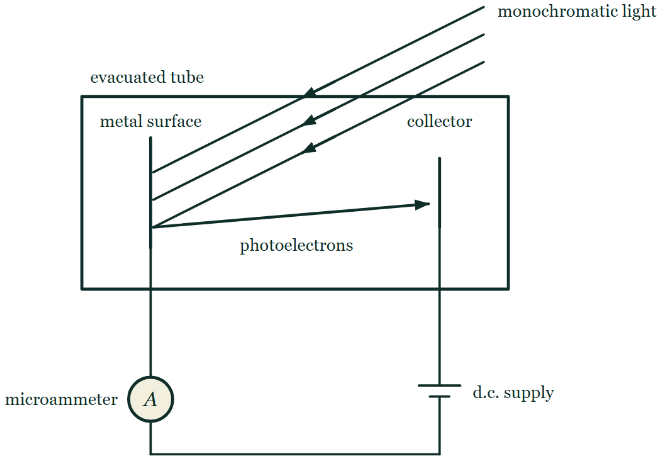

Fig. 6.1 *A photoelectric cell drawn as an evacuated tube. Inside it a flat metal plate stands on the left and a smaller collecting electrode on the right. A beam of monochromatic light enters through the top of the tube and falls on the face of the plate that faces the collector, and an arrow across 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 $A = A_0 e^{-\lambda t}$.

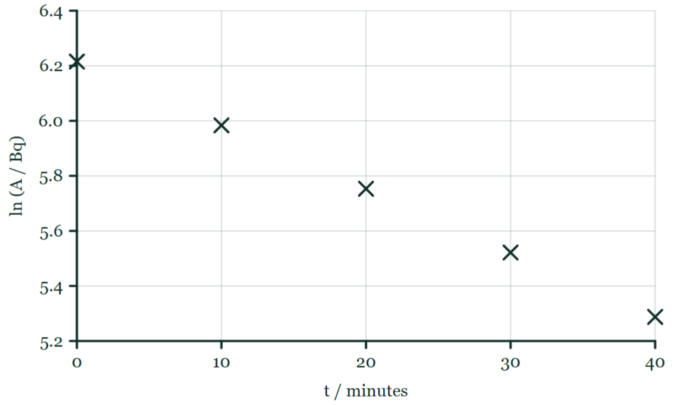

Fig. 7.1 *A gridded graph with ln (A / Bq) on the vertical axis, scaled from 5.2 to 6.4 in steps of 0.2, plotted against t / minutes on the horizontal axis, scaled from 0 to 40 in steps of 10. The five processed readings given in the table are plotted as small crosses, one at each ten-minute interval, 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 STRUCTURED · DEMANDING · E.1 · E.3 **[12]**

SL

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

SL

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.

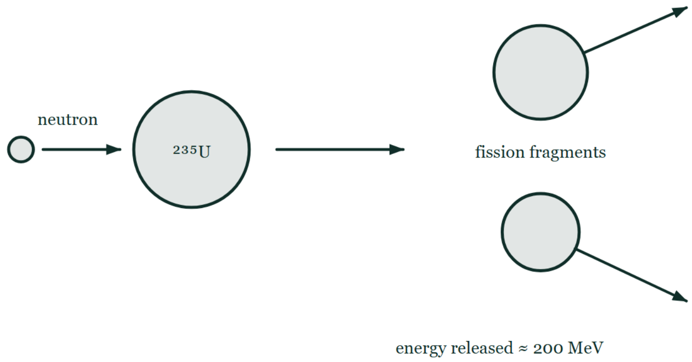

Fig. 9.1 *A schematic of a single induced fission event, read from left to right. A small neutron on the left travels to the right towards a large circle labelled ^{235}U. An arrow from that nucleus leads to the products: two unequal fission fragments drawn as circles one above the other, each with its 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.

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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.

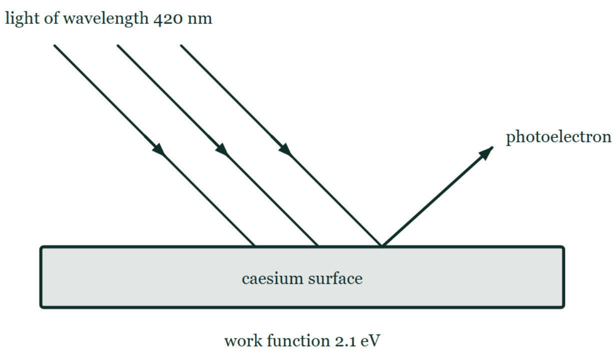

Fig. 10.1 *Three parallel rays of light of wavelength 420 nm slant down to the right and meet the flat upper face of a block labelled as a caesium surface with a work function of 2.1 eV. From a point on that same face, further to the right of where the light lands, a single arrow slants up and to the 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 = $(5.288 - 6.215)/(40 - 0) = -0.0232\ \text{min}^{-1}$
2. $\lambda = 0.0232\ \text{min}^{-1}$
3. $t_{1/2} = \ln 2 / \lambda = 0.693/0.0232$
4. $t_{1/2}$ = 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 STRUCTURED · DISCRIMINATING · E.2 **[13]**
HL

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 4 MARKS · 7%	**Demonstrate knowledge** Recall facts, concepts and terminology, and state methodologies and techniques used in the course.
AO2 33 MARKS · 58%	**Understand and apply knowledge** Apply concepts, terminology and techniques to familiar and unfamiliar situations, including numerical work.
AO3 17 MARKS · 30%	**Analyse, evaluate and construct** Analyse and evaluate data, methods, claims and explanations, and construct a reasoned argument or conclusion.
AO4 3 MARKS · 5%	**Demonstrate the application of skills** Design and evaluate investigations, handle raw and processed data, treat uncertainties, and communicate results.