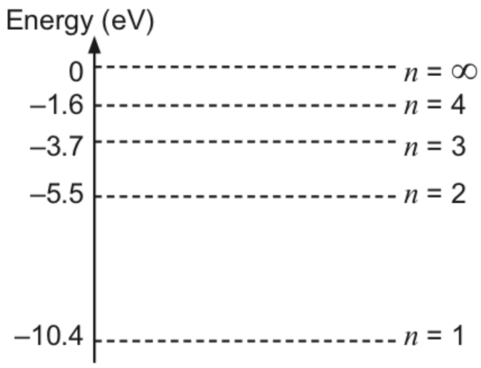
$^1/_\lambda$ ($\times 10^6$ m^{-1})

W-20

YEAR 12 PHYSICS
ASSIGNMENT 6 - LIGHT & ATOMIC PHYSICS

Name: Solutions **Mark:** $\overline{}$ 113

1. Some of the electron energy levels for atomic mercury are shown in the following diagram.



Indicate which one of the following transitions is the most energetic by circling it.
(1 mark)

$n = 4$ to $n = 3$ $\qquad$ $n = 2$ to $n = 1$ $\qquad$ $n = 4$ to $n = 1$ (1)

Determine the frequency and wavelength of the light emitted when the atom makes the most energetic of the above transitions. (3 marks)

$$E_4 - E_1 = hf$$

$$\Rightarrow [-1.60 - (-10.4)](1.60 \times 10^{-19}) = (6.63 \times 10^{-34}) f \quad (1)$$

$$\Rightarrow f = 2.12 \times 10^{15} \text{ Hz} \quad (1)$$

$$c = f\lambda$$

$$\Rightarrow \lambda = \frac{3.00 \times 10^8}{2.12 \times 10^{15}}$$

$$= 1.41 \times 10^{-7} \text{ m} \quad (1)$$

Frequency is 2.12×10^{15} Hz $\qquad$ Wavelength is 1.41×10^{-7} m

2. A light beam is directed toward a metal surface and electrons are ejected from it. The wavelength of the incident beam is varied between 238 nm (ultraviolet) and 464 nm (green). The maximum kinetic energy of the ejected photoelectrons is measured and recorded in the table below.

(a) Complete the following table by calculating the missing energy of the incident photons for each wavelength. Show your working in the space below. (2 marks)

Wavelength of incident light (nm)	Energy of incident light (eV)	Maximum kinetic energy of photoelectrons (eV)
238	5.22	3.12
250	4.97	2.87
284	4.38	2.28
351	3.54	1.44
416	2.99	0.89
464	2.68	0.58

$$E = hf = \frac{hc}{\lambda}$$
$$= \frac{(6.63\times10^{-34})(3.00\times10^{8})}{(238\times10^{-9})}$$
$$= 8.36\times10^{-19}\ J$$
$$= \underline{5.22\ eV} \quad (1)$$

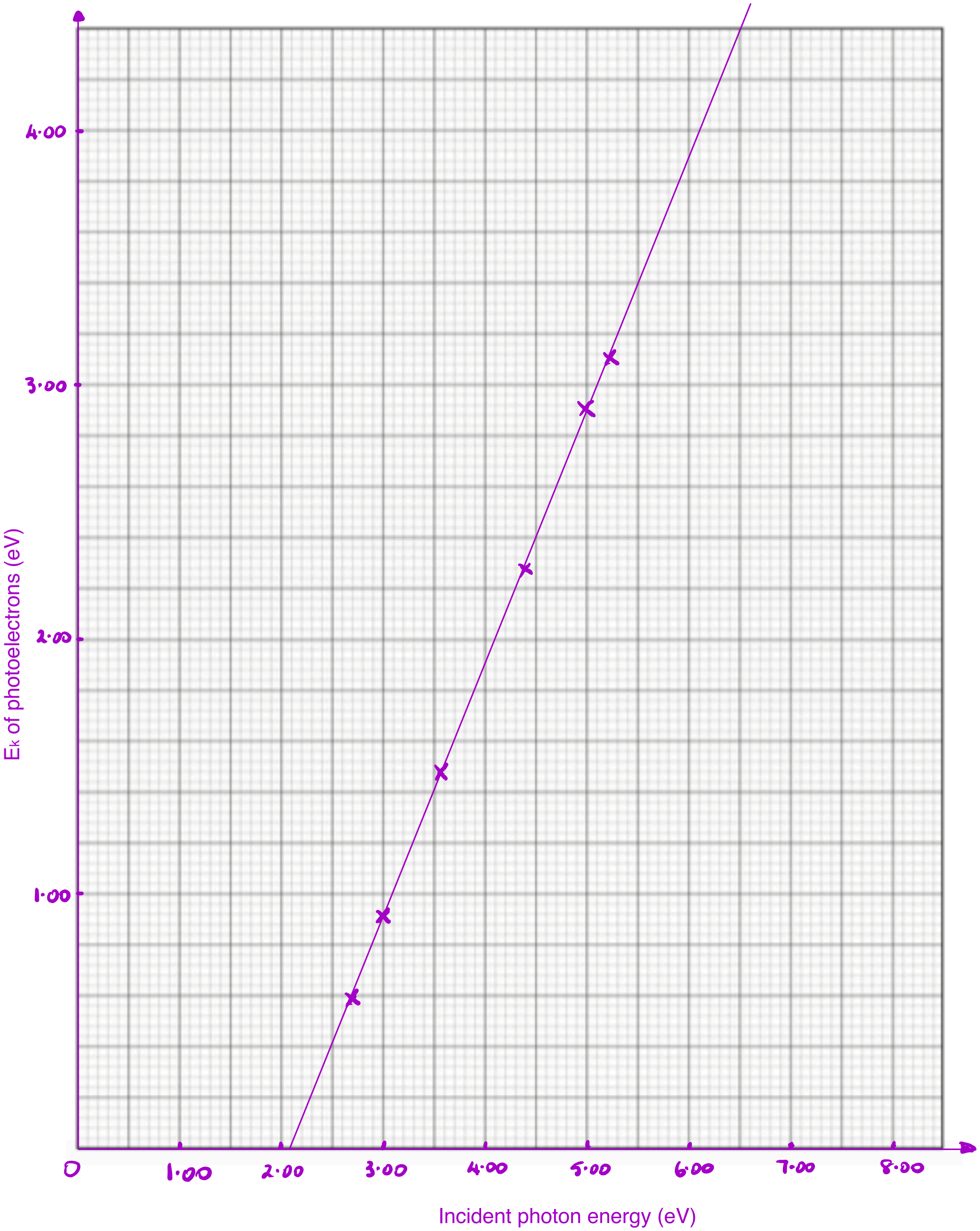
$$E = hf = \frac{hc}{\lambda}$$
$$= \frac{(6.63\times10^{-34})(3.00\times10^{8})}{(351\times10^{-9})}$$
$$= 5.67\times10^{-19}\ J$$
$$= \underline{3.54\ eV} \quad (1)$$

(b) Plot the data from the table above on the grid provided, demonstrating the relationship between the energy of the incident photons on the horizontal axis and the maximum kinetic energy of photoelectrons on the vertical axis. Draw the line of best fit. (4 marks)

(c) Using your graph, determine the work function of the metal. Express your answer in appropriate significant figures and include units. (4 marks)

$$\phi = x\text{-axis intercept}$$
$$= \underline{2.10\ eV}$$

Line of best fit used (1)
X-incercept used (1)
2.10 +/- 0.10 (1)
eV (units) (1)



Axes in correct places (1)
Axes labelled (1)
Data points plotted (1)
Line of best fit drawn correctly (1)

(d) Explain how the failure of red light to cause the emission of electrons demonstrates the particle nature of light. (3 marks)

- Red light does not have enough energy to cause the emission of electrons. (1)
- Classical Physics allows for the energy supplied by the light to build up over time, which doesn't happen. (1)
- Photons of light (acting as particles) cause the emission of electrons instantly if their energy is above the work function. (1)

(e) In this photoelectric effect investigation, light is best described as a particle. There are other characteristics that demonstrate light to be a wave. State ***one*** such characteristic and describe how this demonstrates wave behaviour. (3 marks)

- State a phenomenon such as interference, diffraction or polarisation. (1)
- Describe wave-like phenomena using examples such as double slit, interferometer, diffraction grating, thin film, etc. (1)
- Should describe the interference pattern produced. (1)

3. Silicon is a semi-conducting material commonly used to make photovoltaic cells. Manufacturers of a solar-powered watch wanted to determine the work function of the silicon under low levels of artificial light. To test the solar-powered watch, the manufacturer used a light source which emitted photons with wavelengths of 510.6 nm and 578.2 nm. The photoelectrons emitted were found to have a maximum kinetic energy of 5.36×10^{-20} J.

(a) State why **all** photoelectrons emitted from the silicon do not have the same kinetic energy for a given incident wavelength. (1 mark)

- Electrons from two to three atoms down in the lattice require more energy to leave the surface.
- The work function is the minimum energy required to remove an electron from the surface.

Either OK (1)

(b) Determine the maximum energy in joules of the highest energy incident photons. (2 marks)

$$E = hf = \frac{hc}{\lambda} \quad (1)$$

$$= \frac{(6.63 \times 10^{-34})(3.00 \times 10^{8})}{(510.6 \times 10^{-9})}$$

$$= \underline{3.89 \times 10^{-19}\ \text{J}} \quad (1)$$

(c) Calculate the work function of the silicon in joules. (3 marks)

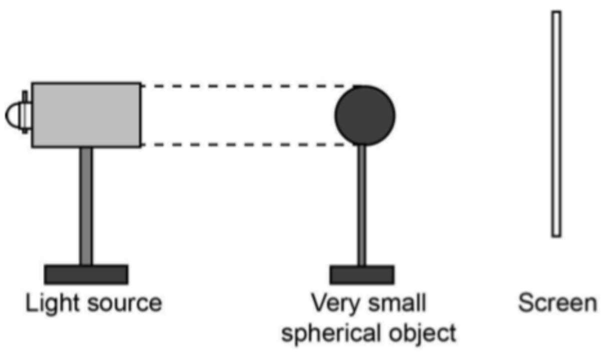
$$E = hf = \phi + E_k(max)$$

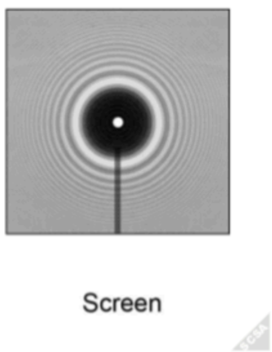
$$\Rightarrow \quad \phi = hf - E_k(max) \quad (1)$$

$$= 3.89 \times 10^{-19} - 5.36 \times 10^{-20} \quad (1)$$

$$= \underline{3.35 \times 10^{-19}\ \text{J}} \quad (1)$$

4. An experiment was conducted to investigate the nature of light. A parallel beam of monochromatic light was directed at a very small spherical object and a white screen was positioned behind the object (Diagram 1). The pattern observed on the white screen is shown in Diagram 2. (Note: diagrams not to scale.)





(a) Discuss how the pattern in Diagram 2 was produced. (5 marks)

- As the light waves pass the edges, diffraction occurs. (1)
- The waves interfere beyond the object. (1)
- Constructive interference gives rise to the light areas. (1)
- Destructive interference gives rise to the dark areas. (1)
- The bright spot is caused by constructive interference (path difference is zero). (1)

(b) From this experiment, what conclusion can be made regarding the nature of light? (1 mark)

- Light behaves as a wave. (1)

5. An experiment was conducted to observe changes in colour and intensity as a bar of dull grey tungsten metal was heated from room temperature. When heated to 200 °C, the tungsten is observed as remaining grey and dull. When heated to 700 °C, the tungsten is observed as red and dull, and at 2700 °C, the tungsten is observed as white and bright.

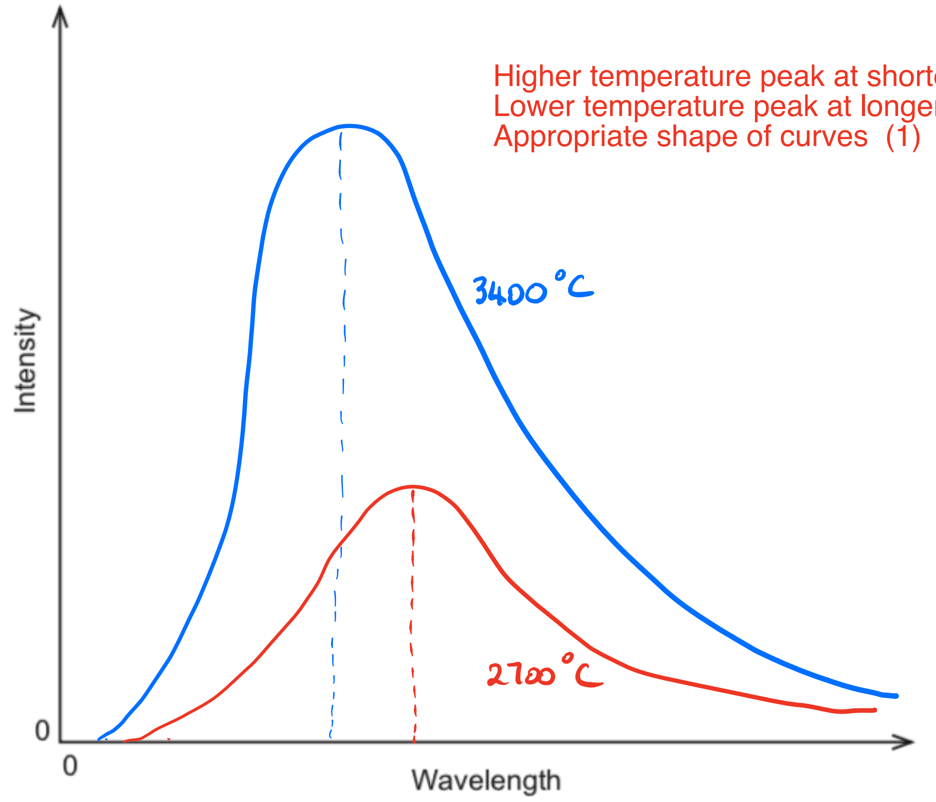
(a) Describe why the colour and intensity of the tungsten changes as it is heated. (2 marks)

- As the atoms are heated, they vibrate faster and produce a higher frequency and change in colour. (1)
- As the temperature increases, more atoms are vibrating at faster speeds so the intensity increases. (1)

Could describe black body radiation where the dominant wavelength decreases with temperature increase. (1)
As temperature increases, the power increases and intensity increases. (1)

(b) The tungsten is heated further until it starts melting at approximately 3400 °C. Use the axes below to sketch labelled graphs of intensity against wavelength for the two observed spectra at 2700 °C and 3400 °C. (3 marks)

Higher temperature peak at shorter wavelength (1)
Lower temperature peak at longer wavelength (1)
Appropriate shape of curves (1)



6. It is imagined that solar sails made from highly reflective thin sheets of metal might propel spacecraft on solar winds without the need for a propulsion system.

A space agency conducted an experiment to determine the possibility of propelling a spacecraft using a solar sail. To simulate the contribution of photons in solar wind, they used a highly collimated (focused) beam of light. This beam of light contained 2.50×10^{18} photons, with each photon having a wavelength of 487 nm. A highly-reflective mirror of mass 3.00 μg was used to simulate the solar sail. The collimated beam is fired at 90.0° to the surface of the highly-reflective mirror in a vacuum.

(a) Calculate the magnitude of the momentum of each photon. (2 marks)

$$\lambda = \frac{h}{p}$$

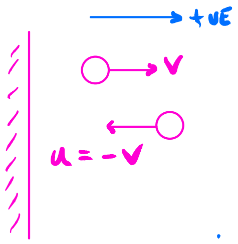
$$\Rightarrow p = \frac{h}{\lambda} \quad (1)$$

$$= \frac{6.63 \times 10^{-34}}{487 \times 10^{-9}}$$

$$= \underline{1.36 \times 10^{-27} \text{ kgms}^{-1}} \quad (1)$$

When the photon beam collides with the mirror, momentum (equal to the product of mass and velocity) is conserved and the mirror moves.

(b) Calculate the recoil velocity of the mirror when the beam of light reflects from it. (4 marks)



$$\Delta v\,(\text{photon}) = v - u$$

$$= v - (-v) \quad (1)$$

$$= 2v$$

$$\Rightarrow \Delta p\,(\text{photon}) = 2 \times p\,(\text{photon})$$

$$\therefore \Delta p\,(\text{photons}) = 2 \times N \times p\,(\text{photon}) \quad (1)$$

$$\Delta p\,(\text{sail}) = \Delta p\,(\text{photons})$$

$$\Rightarrow m\,\Delta v = \frac{2hN}{\lambda}$$

$$\Rightarrow \Delta v = \frac{2(1.36 \times 10^{-27})(2.50 \times 10^{18})}{3.00 \times 10^{-9}} \quad (1)$$

$$= 2.27 \text{ ms}^{-1}$$

$$\therefore \underline{\text{Recoil velocity} = 2.27 \text{ ms}^{-1} \text{ backwards}} \quad (1)$$

(c) Outline **two** possible limitations of using solar sail technology to propel a spacecraft. (2 marks)

One:

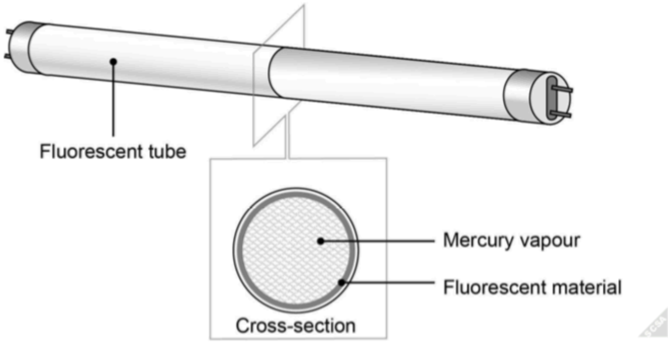
Any two of the following:

• photon density decreases rapidly with distance from the sun
• need a large sail to provide enough force to accelerate even a moderate mass
• light from other stars will affect it when far away from a sun
• force from the sail must be larger than the force of gravity from the sun or other celestial bodies
• large and fragile sails affected by space debris
• can't sail towards the sun
• difficult to steer

Two:

[1 mark each]

7. A fluorescent light contains mercury vapour which is excited by an electric discharge from end to end inside the tube. This excitation causes some of the mercury atoms to ionise or produce high energy photons. These high energy photons then interact with the fluorescent material coating the inside of the tube to produce visible light.



Some of the energy levels below the ionisation level for a mercury atom are shown in the energy level diagram below.

	Ionisation level	$16{\cdot}7 \times 10^{-19}$
n = 4	-4.38×10^{-19} J	$12{\cdot}32 \times 10^{-19}$
n = 3	-6.02×10^{-19} J	$10{\cdot}68 \times 10^{-19}$
n = 2	-9.25×10^{-19} J	$7{\cdot}45 \times 10^{-19}$
n = 1	-16.7×10^{-19} J	0 J

A photon with energy of 17.9×10^{-19} J collides with an electron in the ground state of a vaporised mercury atom.

(a) Calculate the velocity of any electron emitted from the ground state mercury atom. (3 marks)

$$E_K(\text{electron}) = E_{\text{photon}} - E_{\text{ionisation}}$$
$$= 17{\cdot}9 \times 10^{-19} - 16{\cdot}7 \times 10^{-19}$$
$$= 1{\cdot}2 \times 10^{-19}\ \text{J} \quad (1)$$

$$E_K = \tfrac{1}{2} m v^2$$
$$\Rightarrow v = \sqrt{\frac{2E_K}{m}} \quad (1)$$
$$= \sqrt{\frac{2(1{\cdot}2 \times 10^{-19})}{9{\cdot}11 \times 10^{-31}}}$$
$$= \underline{5{\cdot}13 \times 10^{5}\ \text{ms}^{-1}} \quad (1)$$

(b) Describe why some of the mercury atoms in the tube need to be ionised. (2 marks)

- to create free electrons (1)

- to hit other mercury atoms to excite electrons and produce more photons

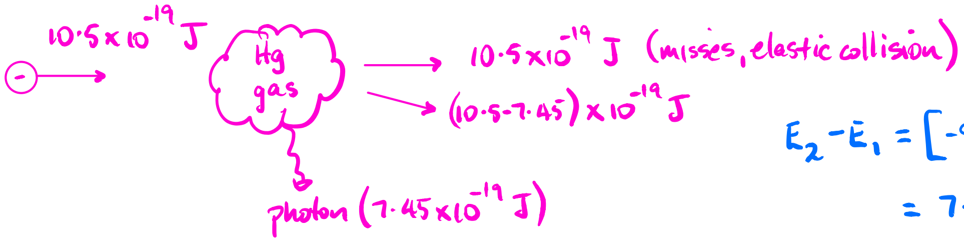
or
- to create charges for pathway for electrical current

or
- to produce high energy photons for fluorescence to occur

[Any one - 1 mark]

An electron with energy of 10.5 × 10^{-19} J collides with a ground state electron in a mercury atom.

(c) Calculate the possible energies the incident electron can have after this collision. (3 marks)



$$E_2 - E_1 = [-9.25 - (-16.7)] \times 10^{-19}$$
$$= 7.45 \times 10^{-19} \text{ J} \quad (1)$$

$$\therefore \text{Scattered energy} = (10.5 - 7.45) \times 10^{-19}$$
$$= \underline{3.05 \times 10^{-19} \text{ J}} \quad (1)$$

Also, $\underline{E = 10.5 \times 10^{-19} \text{ J}}$ (elastic collision) (1)

(d) Determine the part of the spectrum to which the lowest energy emitted photons belong when subject to an incident electron with energy 10.5 × 10^{-19} J. (2 marks)

$$E = hf = \frac{hc}{\lambda}$$
$$\Rightarrow \lambda = \frac{hc}{E}$$
$$= \frac{(6.63 \times 10^{-34})(3.00 \times 10^{8})}{(7.45 \times 10^{-19})}$$
$$= 2.67 \times 10^{-7} \text{ m} \quad (1)$$

$\therefore$ Transitions are in UV part of the spectrum (1)

The photons emitted from the electron transition of the mercury atom then interact with the fluorescent material coating the inside of the tube.

(e) Explain how the emitted photons produced by the mercury atoms produce visible light in the fluorescent material. (3 marks)

- The high energy photons (UV) are absorbed causing the electrons of the fluorescent material to jump to a higher state. (1)
- These electrons then fall back to the ground state in a series of steps. (1)
- Emitting light some of which is in the visible spectrum. (1)

8. An experiment was conducted to determine a value for Planck's constant. The experiment involved setting up five individual, single-frequency light emitting diodes (LEDs). Each LED only emits one frequency of light when a turn-on voltage (voltage above a certain threshold value) is applied across its terminals.

The relationship between the frequency of the emitted light and the voltage is given by the equation below.

$E = hf = q_e(V_0 + k)$ where h is Planck's constant
f is the frequency of light emitted by the diode
q_e is the charge on an electron V_0 is the turn on voltage
k is the threshold voltage (constant dependent on the material)

The experiment produced the following results.

LED colour	Maximum wavelength (λ) (nm)	Turn on voltage (V_0)	(1) $(\times 10^6)$ 1/λ (m⁻¹)
Blue	450	2.53	2.2
Green	550	2.04	1.8
Yellow	570	1.88	1.8
Red	690	1.37	1.4
Infra-red	890	0.88	1.1

Values (1)

(a) Complete the table above for values of 1/λ. (2 marks)

(b) Plot a graph of voltage against 1/λ, with voltage on the y-axis, and draw a line of best fit. Error bars are not required. (5 marks)

(c) Use the graph to calculate the gradient of the line of best fit. Show construction lines. (3 marks)

$$\text{gradient} = \frac{4.32 - 0.00}{(3.4 - 0.5)\times 10^6} \quad (1)$$

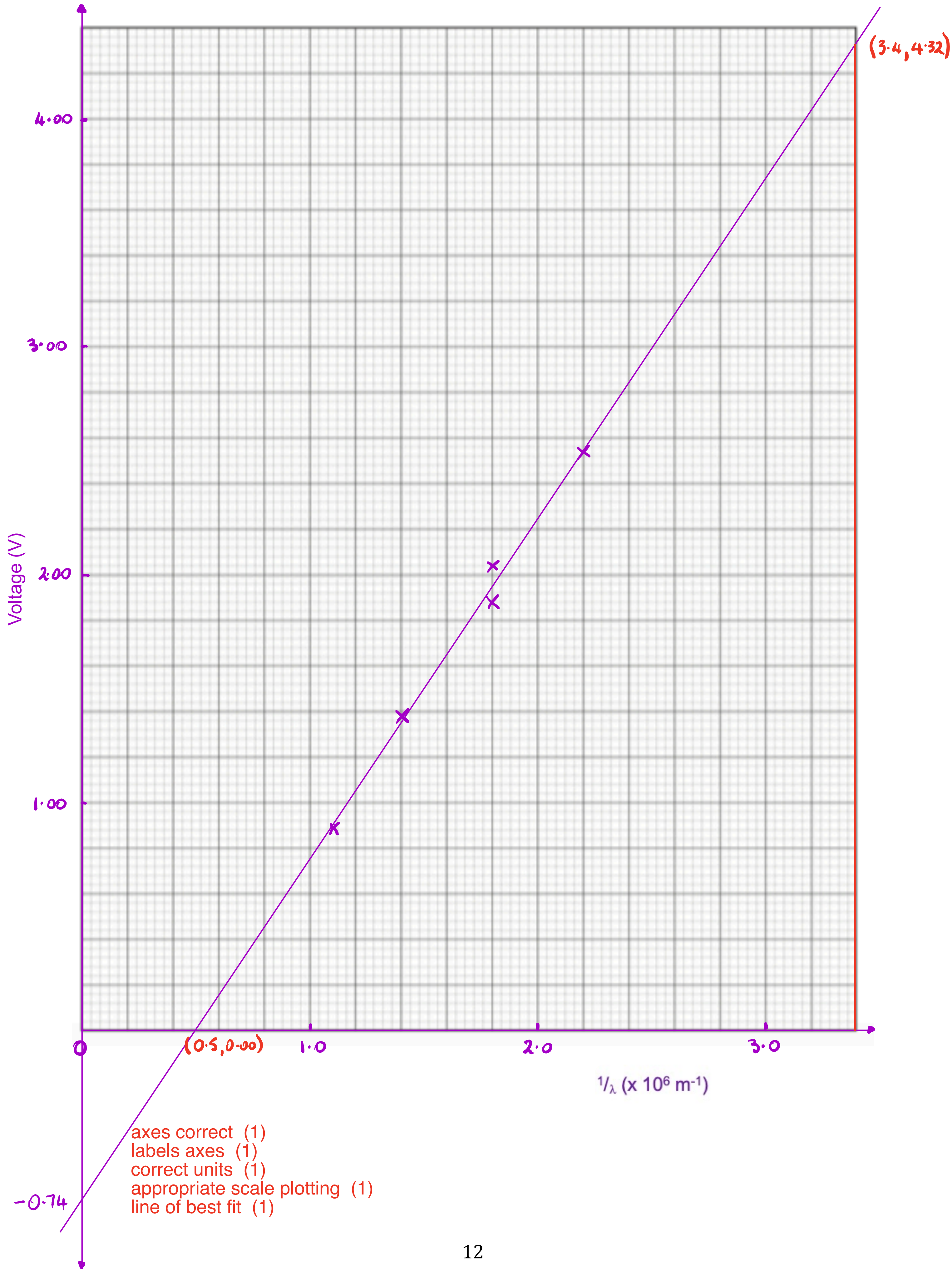
Construction line (1)

$$= \underline{1.5 \times 10^{-6}\ \text{Vm}} \quad (1)$$

(d) Use the gradient from part (c) and the provided equation to calculate a value for Planck's constant. (3 marks)

$$E = hf = \frac{hc}{\lambda} = q_e(V_0 + k)$$
$$= V_0 q_e + kq_e$$
$$\Rightarrow \frac{hc}{\lambda} = V_0 q_e \quad (\text{since } kq_e = \text{constant})$$
$$\Rightarrow h = \frac{V_0 q_e \lambda}{c}$$
$$= \frac{q_e(\text{gradient})}{c} \quad (1)$$

$$h = \frac{(1.60\times10^{-19})(1.5\times10^{-6})}{(3.00\times10^{8})} \quad (1)$$
$$= \underline{8.0\times10^{-34}\ \text{Js}} \quad (1)$$



axes correct (1)
labels axes (1)
correct units (1)
appropriate scale plotting (1)
line of best fit (1)

(e) From your graph, determine the value for k in this experiment. (2 marks)

From the graph: y-intercept $= -0{\cdot}74$ V

Construction on graph (1)

$\Rightarrow \underline{k = 0{\cdot}74 \text{ V}}$ (1)

At the x-intercept, $V_o = 0$ and $\frac{1}{\lambda} = 0{\cdot}5 \times 10^{6} \text{ m}^{-1}$.

$\therefore E = \frac{hc}{\lambda} = q_e (V_o + k)$

$\Rightarrow (6{\cdot}63 \times 10^{-34})(3{\cdot}00 \times 10^{8})(0{\cdot}5 \times 10^{6}) = (1{\cdot}60 \times 10^{-19})(0 + k)$ (1)

$\Rightarrow \underline{k = 0{\cdot}62 \text{ V}}$ (1)

Either method OK.
Range: 0.60 - 0.95 acceptable

(f) Describe **two** possible sources of experimental error in the performance of this experiment and how they might be modified to produce a more accurate result. (4 marks)

One:

Sources of error
Any two of the following:
- accuracy of wavelength
- accuracy of voltage readings
- energy required to start LED lights (may not be same for each light)

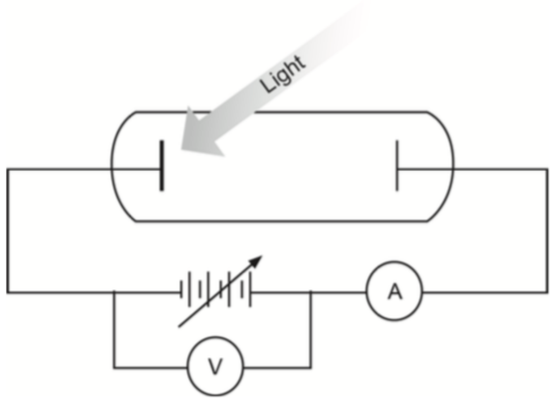
[1 mark each]

Two:

Produces a more accurate result
Any two of the following:
- repeat readings of voltage
- repeat reading of wavelength
- use more accurate voltage devices
- repeat the experiment several times and average the results
- use a wider/greater range of LED lights

[1 mark each]

9. When light is shone on a metal plate, electrons may be emitted from the plate. This is called the 'photoelectric effect'. The apparatus below shows incident light of wavelength 450 nm striking a metal plate. The number of photons striking the plate per second can also be controlled by varying the brightness of the incident light. The current produced by the light is initially measured by the ammeter (A). Initially, the ammeter (A) reads a current. The stopping potential (V) is then adjusted until the ammeter reads 0 A.



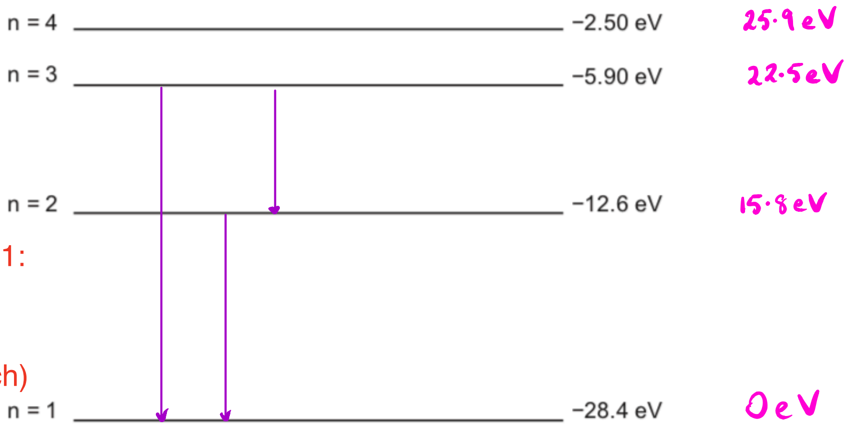
Assume the frequency of the light remains above the threshold frequency of the metal. In the table below, describe what would happen to the initial reading on A and the final reading on V, if the following changes were made. Use the terms 'increase', 'decrease' or 'unchanged'.

(4 marks)

	Change 1: wavelength is changed to 490 nm. Photons/second remains unchanged.	Change 2: wavelength is changed to 400 nm. Photons/second is increased.
Initial A	unchanged	increases
Final V	decreases	increases

[1 mark each]

10. When gaseous mercury atoms are excited, they emit photons of varying wavelengths. Some of the energy levels in a mercury atom are shown in the diagram below.



3 to 1: 22.5 eV (possible) 4 to 1: 25.9 eV not possible (1)

diagram three lines with downward arrows (1 mark each)

A mercury lamp is used to produce light which is first fed through a filter that eliminates all wavelengths except those produced from the n = 2 to n = 1 transition. The resultant light is then shone onto a potassium metal plate whose work function is 2.00 eV.

(a) On the diagram above, show all the possible downward electron transitions that can occur in a mercury atom after a successful collision with an incoming electron with an energy of 23.0 eV. (4 marks)

(b) Calculate the wavelength of the photon from part (a) that strikes the potassium metal plate. (3 marks)

$$E_2 - E_1 = \frac{hc}{\lambda}$$

$$\Rightarrow \quad \lambda = \frac{hc}{E_2 - E_1}$$

$$= \frac{(6.63\times10^{-34})(3.00\times10^{8})}{[-12.6-(-28.4)](1.60\times10^{-19})} \quad (1)$$

Correct transition (1)

$$= \underline{7.87\times10^{-8}\ \text{m}} \quad (1)$$

(c) Calculate the maximum velocity of any electrons liberated from the potassium metal plate. Ignore relativistic effects. (5 marks)

$$E_2 - E_1 = hf = \phi + E_K(max)$$

$$\Rightarrow E_K = [-12.6 - (-28.4)] - 2.00 \quad (1)$$

$$= 13.8\,eV \quad (1)$$

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

$$\Rightarrow v = \sqrt{\frac{2E_k}{m}} \quad (1)$$

$$= \sqrt{\frac{2(13.8)(1.60\times10^{-19})}{(9.11\times10^{-31})}} \quad (1)$$

$$= \underline{2.20\times10^{6}\,ms^{-1}} \quad (1)$$

(d) State a formal definition of the term 'work function' and explain why part (c) refers to maximum velocity. (3 marks)

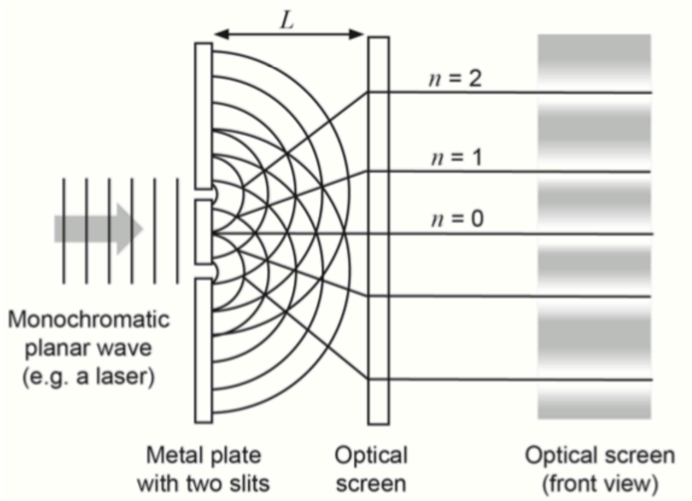
Work function is the minimum amount of work required to remove an electron from the (surface) of a metal. (1)

Maximum velocity is attained when liberated electrons have the maximum kinetic energy. (1)

Not all electrons have this as they are liberated from atoms below the surface and expend energy getting to the surface or other electrons collide with other electrons and lose energy. (1)

11. The first serious challenge to the particle theory of light was made by the English scientist Thomas Young in 1803. Young reasoned that if light were actually a wave phenomenon, as he suspected, then a similar interference effect observed with sound waves should occur for light. This line of reasoning led Young to perform an experiment which is nowadays referred to as 'Young's double-slit experiment'.

In Young's double-slit experiment, two very narrow parallel slits, separated by a distance *d*, are cut into a plate made of thin metal. Monochromatic light, from a distant light source, passes through the slits and eventually hits an optical screen a comparatively large distance *L* from the slits. The experimental setup is shown in the diagram below.



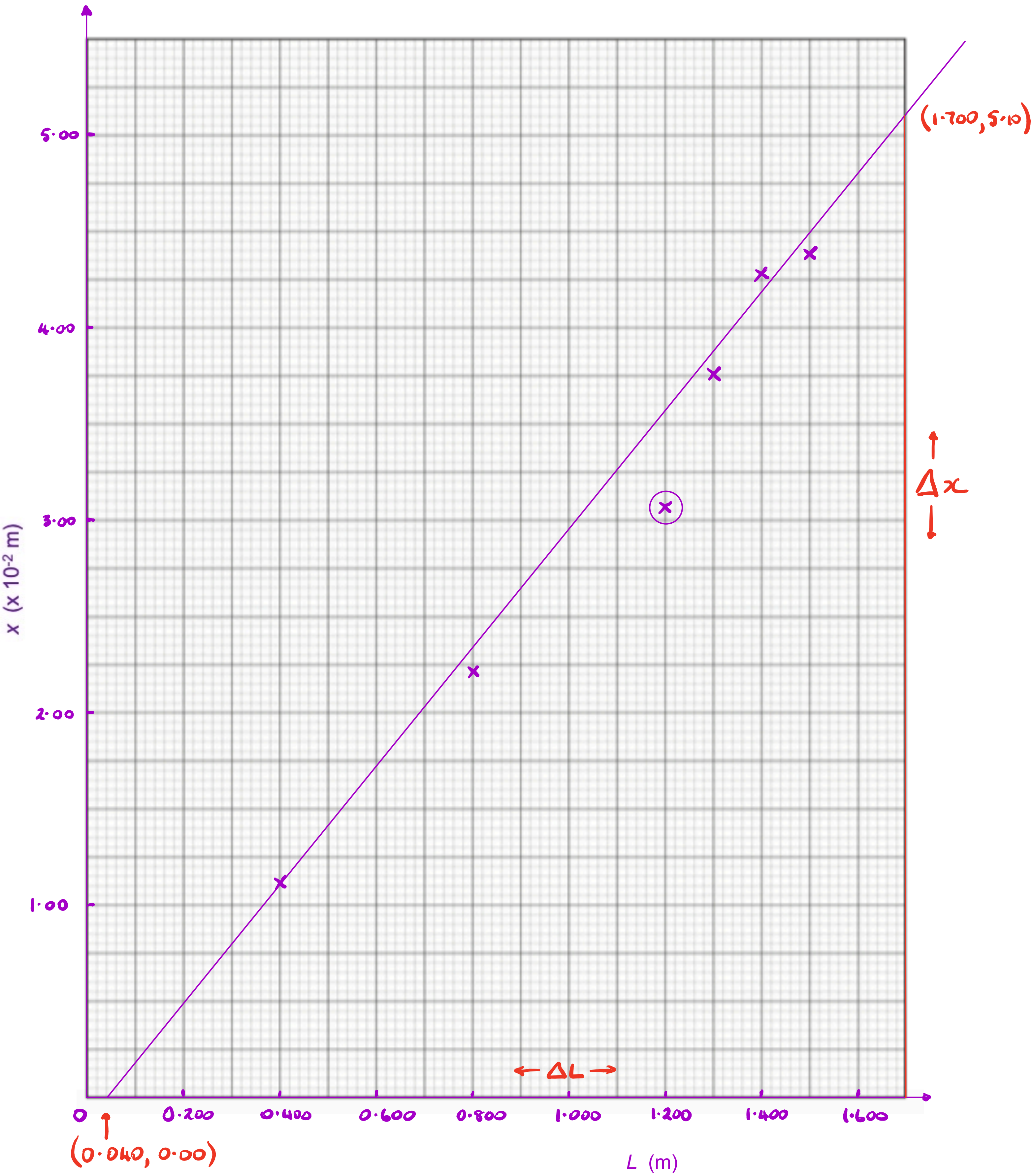
Young observed a series of alternating parallel light and dark bands on the screen, with the central band being bright. From his research, he established the following relationship between *L*, the distance between the slits and the screen; *d*, the distance between the two slits; *λ*, the wavelength of the monochromatic light and *x*, the distance between the centres of adjacent light bands in the interference patterns:

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

A group of students set up an experiment to measure the wavelength of light produced by a laser pointer. Using a commercially-produced metal plate where $d = 2.19 \times 10{-}5$ m, they varied the distance from the slits to the optical screen (*L*) and measured the distance between the centre light band and the one closest to it ($n = 1$). Their results are shown in the table below.

L (m) ± 0.002 m	0.400	0.800	1.200	1.300	1.400	1.500
x (m × 10^{-2}) ± 0.002 m	1.12	2.21	3.06	3.76	4.28	4.38

(a) Graph *x* vs *L* on the grid paper provided on page 23. Include the line of best fit. Do ***not*** include uncertainties. (5 marks)



correct orientation of axes (1)
correct labelling of axes including units (1)
accurate plotting (1)
line of best fit (not through origin) (1)
outlier clearly identified (1)

(b) From your graph, calculate the gradient of the line of best fit. Show construction lines on your graph. Use correct significant figures. (3 marks)

$$\text{gradient} = \frac{\Delta x}{\Delta L} = \frac{(5.10 - 0.00) \times 10^{-2}}{1.700 - 0.040}$$

$$= \underline{3.07 \times 10^{-2}} \quad (1)$$

Two points on line of best fit (1)

Correct significant figures (1)

(c) Using the gradient from part (b), calculate the wavelength of the monochromatic light used. Use correct significant figures. (4 marks)

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

$$\Rightarrow \quad \lambda = \frac{xd}{nL}$$

$$= \frac{d\,(\text{gradient})}{n} \quad (1)$$

$$= \frac{(2.19 \times 10^{-5})(3.07 \times 10^{-2})}{1} \quad (1)$$

$$= \underline{6.72 \times 10^{-7}\ \text{m}} \quad (1) \qquad \text{Significant figures (1)}$$

The students were disappointed when they found their answer was 10% different from the wavelength supplied by the manufacturers of the laser pointer. When the teacher helped them use the uncertainties associated with their experiment, they found the manufacture's value fell within the accepted range of uncertainty.

(d) Using the same values as in part (b), recalculate your gradient including uncertainties to show that a 10% difference falls within the accepted range. (5 marks)

Using $(0.040, 0.00)$ and $(1.700, 5.10 \times 10^{-2})$:

$$\Delta x = 5.10 \times 10^{-2} \pm 0.004\ \text{m} \quad (1)$$
$$= 5.10 \times 10^{-2} \pm 7.84\% \quad (1)$$

$$\Delta L = 1.66 \pm 0.004 \quad (1)$$
$$= 1.66 \pm 0.24\% \quad (1)$$

$\therefore$ Uncertainty $= 8.08\% < 10\%$, so it is **NOT** acceptable. (1)

The official solutions did not use as large a range of values to find the gradient. Hence this calculated value is less than expected.

Also, the line of best fit could be drawn steeper, giving an increase in the uncertainty beyond 10%.