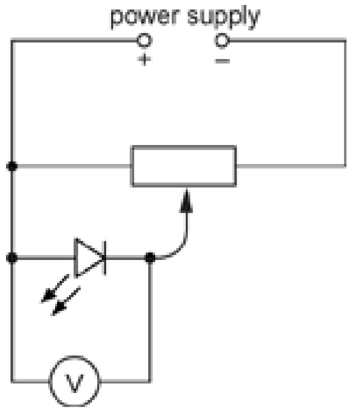
1(a). A student carries out an investigation to determine the value of the Planck constant, *h*.

They use the circuit shown below



Initially the LED emits no light.

The student slowly increases the p.d. across the LED.

They record the p.d. *V* on the voltmeter when the LED just starts to emit light.

The measurement is repeated for LEDs that emit light with different frequencies *f*.

The student views the LED through a cardboard tube when making each measurement.

Explain how this can help to improve the accuracy of each measurement.

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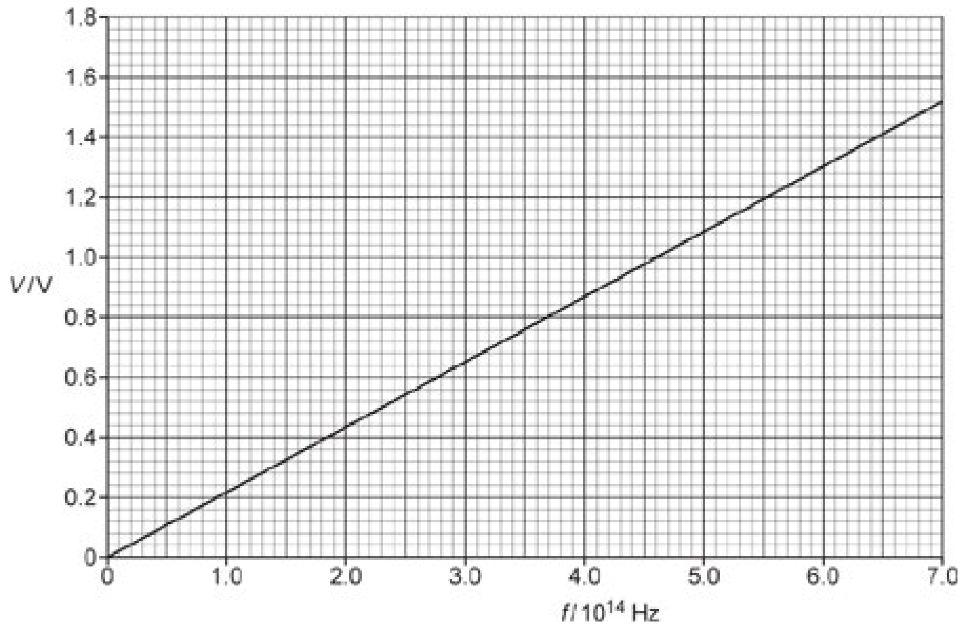
____ **[2]**

(b). The student plots a graph of *V* against *f*, as shown below.



Calculate a value for the Planck constant using the graph.

Planck constant = ... J s **[3]**

(c). An accepted value for the Planck constant is 6.63×10^{-34} J s.

Calculate the percentage uncertainty in the student's results.

percentage uncertainty = ... % **[2]**

(d). One of the LEDs emits red light. Another of the LEDs emits blue light.

The red LED emits 3.3×10^{15} photons per second.

The blue LED emits light with frequency 6.38×10^{14} Hz.

The manufacturer lists the power rating of each of the LEDs as 1 mW.

The student states that there are more photons emitted per second from the blue LED than from the red LED.

Deduce, by calculation, whether the student is correct.

Use $h = 6.63 \times 10^{-34}$ J s.

[3]

2(a). Einstein's photoelectric equation can be used to explain the photoelectric effect.

$hf = \Phi + KE_{max}$

State what is meant by the quantity KE_{max}.

[1]

(b). The photoelectric effect can be demonstrated using a gold leaf electroscope.

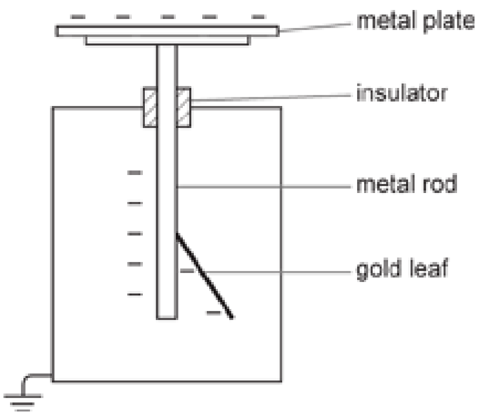
The electroscope consists of a metal plate attached to a metal rod.

A thin gold leaf is attached to the metal rod.

When the electroscope is charged the leaf rises.

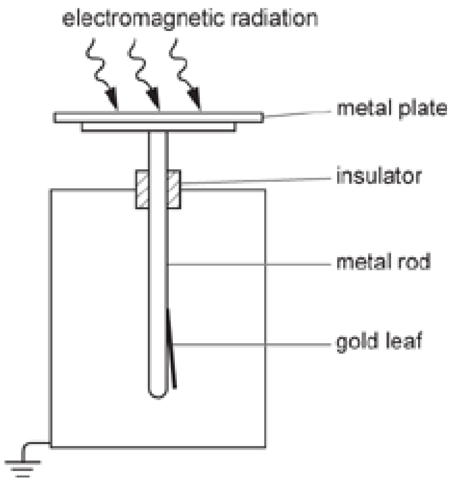
Initially the electroscope has an excess of electrons.

The electroscope is negatively charged and the leaf rises to the position shown below.



Electromagnetic radiation is then directed at the metal plate.

The leaf falls to the position shown below.



Explain this observation.

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____ **[3]**

(c). The investigation is repeated using electromagnetic radiation with a frequency lower than the threshold frequency for the metal.

The leaf does **not** fall.

Explain why.

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____ **[2]**

3. In a demonstration of the photoelectric effect the clean surface of a metal is radiated with photons of electromagnetic radiation.

Electrons are released from the surface of the metal.

The intensity of the radiation is then increased.

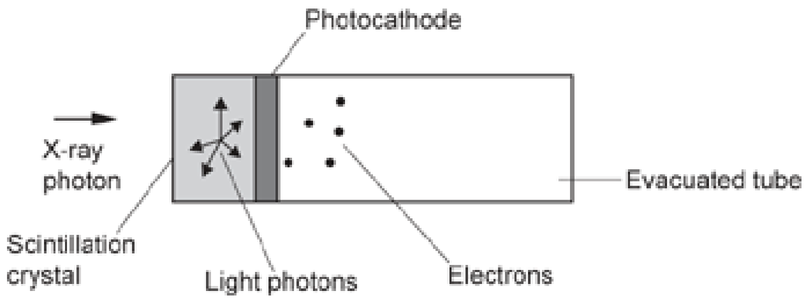
Which statement is correct?

A The energy of the photons increases.
B The rate of emission of electrons increases.
C The maximum kinetic energy of the emitted electrons increases.
D There is no change to the emitted electrons.

Your answer ☐ **[1]**

4(a). The diagram shows part of an X-ray telescope which uses a crystal scintillation device to detect low energy X-rays from the stars.

X-rays hit the crystal and cause it to emit visible light photons. These travel to the photocathode in an evacuated tube. The photocathode uses the light photons to produce electrons.



Each X-ray photon detected by the telescope has an energy of 32 keV.

The light photons have a wavelength of 510 nm.

The efficiency of the crystal is 15%.

Show that each X-ray photon produces about 2000 light photons.

[3]

(b). The photocathode has a work function of 2.3 eV.

i. Explain what is meant by the *work function*.

[1]

ii. Calculate the maximum kinetic energy of the electrons leaving the photocathode.

maximum kinetic energy = ... J **[2]**

iii. 12 X-ray photons are detected every minute.

Use your answer to **(a)** to calculate the current *I* leaving the photocathode. Assume that all the photons of light produce photoelectrons.

I = ... A **[2]**

iv. State one other assumption you have made to enable you to calculate the current *I* in **(b)(iii)**.

[1]

5. Which sequence shows the energies below in **increasing** order of magnitude?

1 The change in kinetic energy of an electron accelerated through a potential difference of 1 V.
2 The kinetic energy of a proton with a velocity of 1000 ms^{-1}.
3 The energy of an X-ray photon with a frequency of 3×10^{17} Hz.

A 1 2 3
B 3 1 2
C 2 1 3
D 1 3 2

Your answer ☐ **[1]**

6. In 1929, the Nobel prize was awarded to Louis de Broglie for his discovery of the wave nature of electrons.

Describe, with the aid of a suitable diagram:

- how an experiment can be safely conducted to demonstrate the wave nature of electrons
- how the observations indicate the wave nature of electrons
- how an estimate of the de Broglie wavelength of the electrons compares with an estimate of the de Broglie wavelength for a car travelling at a speed of 110 Km / h on a motorway.

Diagram

[6]

7(a). Electromagnetic radiation is incident on a metal plate. Photoelectrons are emitted.

The maximum kinetic energy of the emitted photoelectrons is 1.9 eV.

i. Show that the maximum kinetic energy of the emitted photoelectrons, is about 3.0×10^{-19} J.

[1]

ii. Determine the wavelength λ of the incident electromagnetic radiation.

λ = ... m **[3]**

(b). The intensity of the incident radiation is doubled.

State the change, if any, on

i. the maximum kinetic energy of the photoelectrons emitted from the surface of the metal plate

[1]

ii. the rate of emission of the photoelectrons.

[1]

(c).

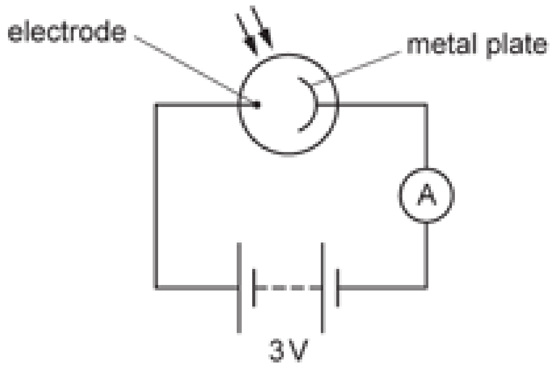
i. State why electrons are emitted.

[1]

ii. The metal plate has a threshold frequency of 990 THz.
State what is meant by the term **threshold frequency**.

[1]

8(a). A light meter is used to measure the intensity of electromagnetic radiation. The meter consists of a metal plate and an electrode within an evacuated glass tube. It is connected to a circuit with an ammeter, a battery of e.m.f. 3.0 V and negligible internal resistance.



Electromagnetic radiation is incident on the metal plate. Electrons are released due to the photoelectric effect and are attracted to the electrode.

Explain why the frequency of the electromagnetic radiation must be above a minimum value for electrons to be released.

[3]

(b).

i. The reading on the ammeter is proportional to the intensity of the radiation. Use your knowledge of the photoelectric effect to explain why.

[3]

ii. When the light meter is irradiated with monochromatic radiation of frequency 8.2×10^{15} Hz, the number of electrons emitted every second is 3.1×10^{18} s^{-1}.

The surface area of the metal plate normal to the incident radiation is 4.9×10^{-3} m^2.

Determine the intensity of the radiation.

intensity = ... W m^{-2} **[4]**

9. An LED is designed to emit red light. In an experiment, the potential difference across the LED is gradually increased. It begins to emit light when the potential difference reaches a value V_0.

The experiment is repeated for an LED designed to emit green light. A different value of V_0 is observed.

Which row of the table describes the values in the second experiment?

	change to V_0	change to wavelength of emitted light
A	decrease	increase
B	decrease	decrease
C	increase	increase
D	increase	decrease

Your answer ☐ **[1]**

10. Electromagnetic radiation is incident on a clean metal plate. Electrons are released from the surface of the plate.

Which statement is correct?

A The energy of a photon is directly proportional to its frequency.
B The kinetic energy of the released electrons depends on the rate of incidence of photons.
C The photoelectric effect demonstrates the wave-like nature of electromagnetic radiation.
D The rate at which electrons are released depends on the frequency of the radiation.

Your answer ☐ **[1]**

11. An electron beam is passed through a thin slice of graphite and a diffraction pattern is produced.

The approximate spacing between the carbon atoms in the graphite is *d*.
The approximate de Brogie wavelength of an electron in the beam is *λ*.

Which statement is correct?

A $\lambda \approx d$

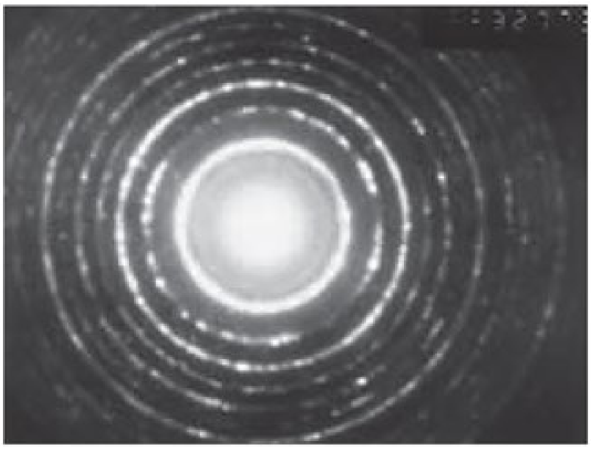
B $\lambda \approx \frac{1}{d}$

C $\lambda \gg d$

D $\lambda \ll d$

Your answer ☐ **[1]**

12(a). The picture shows an electron diffraction pattern produced by graphite in a cathode-ray tube.



A potential difference (p.d.) 5 kV is used to accelerate the electrons.

i. Calculate the work done *W* on the electrons.

W = ... J **[1]**

ii. Calculate the de Broglie wavelength *λ* of the accelerated electrons.

λ = ... m **[2]**

iii. Suggest a value for the spacing between the graphite atoms.
Justify your answer.

____

____

____ **[1]**

(b). Describe the experiment that produces this pattern. Draw a labelled diagram of the apparatus to help you.

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____ **[4]**

(c). Explain why light and dark circles as shown in the picture are produced, stating what this evidence provides about electron behaviour.

____

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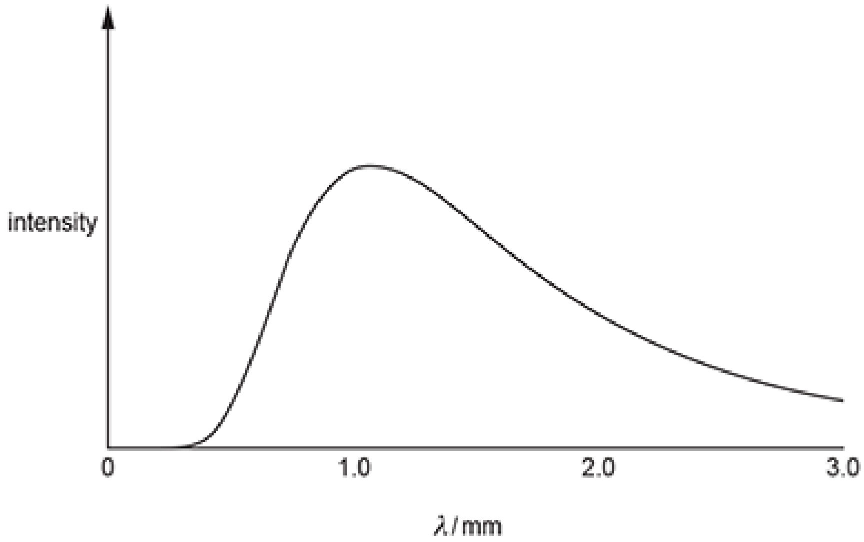
____ **[3]**

13. Astronomers can detect microwave background radiation coming from space in every direction.

The temperature of this microwave radiation is 2.7 K and its **total** intensity is about 3×10^{-6} W m^{-2}.

The figure below shows how the intensity of the microwave background radiation varies with its wavelength λ.

The **peak** intensity is at a wavelength of 1.1 mm.



This spectrum of microwave background radiation changes with temperature according to Wien's displacement law.

i. Suggest and explain how the spectrum might have looked in the distant past. You may draw on the figure to support your answer.

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[2]

ii. Calculate the energy of a photon which has a wavelength of 1.1 mm.

energy = ... J **[2]**

iii. Estimate the number of photons of microwave background radiation incident per second on the back of your hand.

Assume that all emitted photons have the energy calculated in **(ii)**, and that the back of your hand has a surface area of 150 cm^2.

number of photons per second = ...s^{-1} **[2]**

iv. A scientist suggests that the microwave background radiation could be used as an energy source.

The scientist proposes using large tanks of water to absorb the microwave radiation.

Estimate the maximum rise in temperature that could be produced per second for a large cylindrical tank of depth 5.0 m. Assume that all microwave radiation incident on the top of the tank is absorbed.

density of water = 1000 kg m^{-3}
specific heat capacity of water = 4200 J kg^{-1} K^{-1}

maximum rise in temperature per second = ...°C s^{-1} **[3]**

14(a). The diagram below shows two parallel plates, **E** and **C**, in an evacuated glass tube.

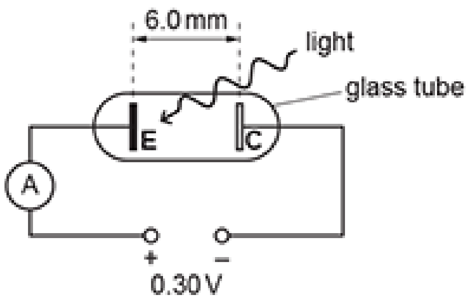


Plate **E** is made from potassium, which is sensitive to light. Plate **C** is not sensitive to light.

The separation between the plates is 6.0 mm and the potential difference between the plates is 0.30 V.

Light of frequency 6.3×10^{14} Hz is incident on plate **E**. The photoelectrons emitted from this plate have **maximum** kinetic energy 0.30 eV (4.8×10^{-20} J). The photoelectrons are repelled by the negative plate **C**. The ammeter reading is zero because these photoelectrons reach plate **C** with zero kinetic energy.

This question is about a photoelectron emitted perpendicular to plate **E** and with an initial kinetic energy of 4.8×10^{-20} J.

i. Show that the magnitude of deceleration of this photoelectron is 8.8×10^{12} ms^{-2}.

[3]

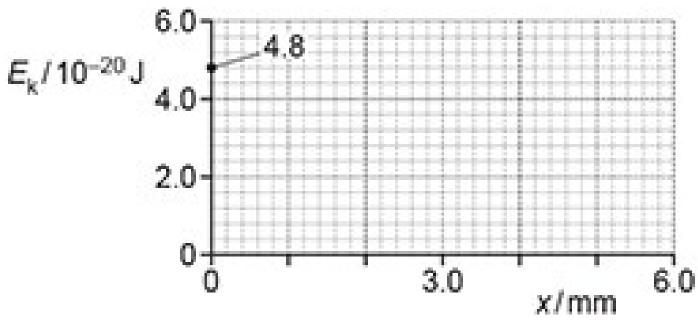
ii. Show that the initial speed of the photoelectron is about 3×10^{5} ms^{-1}.

[2]

iii. Calculate the time t taken by the photoelectron to travel from plate **E** to plate **C**.

t = ... s **[2]**

iv. Using the axes shown below, sketch a graph of kinetic energy E_k against distance x from plate **E**.



[2]

(b). Explain, in terms of photons, what happens to the ammeter reading when light of frequency greater than 6.3 × 10^{14} Hz is now incident on plate **E**.

____

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____ **[2]**

15(a). A light-emitting diode (LED) can be used to determine the Planck constant h. When the LED just starts to emit light, the equation below is valid

$$eV = \frac{hc}{\lambda}$$

where V is the potential difference (p.d.) across the LED, λ is the wavelength of the light emitted, c is the speed of light in vacuum and e is the elementary charge.

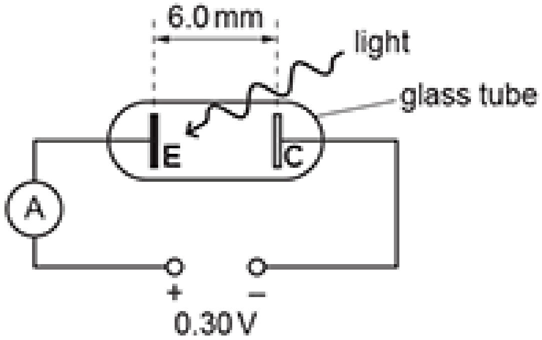
In the equation above, $\frac{hc}{\lambda}$ is the energy of a photon emitted from the LED. Determine the S.I. base units for h.

base units = ... **[2]**

(b). *Describe how an experiment can be carried out in the laboratory to determine *h* from a graph. Your description must include how *V* and λ are accurately determined. Assume that the values of *e* and *c* are known.

[6]

16. The diagram below shows two parallel plates, **E** and **C**, in an evacuated glass tube.



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The separation between the plates is 6.0 mm and the potential difference between the plates is 0.30 V.

Light of frequency 6.3×10^{14} Hz is incident on plate **E**. The photoelectrons emitted from this plate have **maximum** kinetic energy 0.30 eV (4.8×10^{-20} J). The photoelectrons are repelled by the negative plate **C**. The ammeter reading is zero because these photoelectrons reach plate **C** with zero kinetic energy.

Calculate the work function of potassium in eV.

work function = ... eV **[3]**

17. A proton of mass 1.67×10^{-27} kg is travelling at a speed of 2.0×10^{5} ms^{-1}.

The table below shows the mass and speed of four particles **A**, **B**, **C** and **D**.

Particle	Mass / kg	Speed / 10^{5} ms^{-1}
A	9.11×10^{-30}	5.0
B	8.80×10^{-28}	3.0
C	2.49×10^{-28}	2.0
D	3.34×10^{-27}	1.0

Which particle has the same de Broglie wavelength as the proton?

Your answer ☐ **[1]**

18. A gamma-ray photon of frequency 6.76×10^{22} Hz creates a particle-antiparticle pair. The particle-antiparticle pair have zero kinetic energy.

What is the mass of the particle?

A 2.49×10^{-28} kg
B 4.98×10^{-28} kg
C 7.47×10^{-20} kg
D 4.48×10^{-11} kg

Your answer ☐ **[1]**

19.

The table below shows the work function φ of four metals.

Metal	A	B	C	D
φ / eV	3.2	4.1	3.3	6.4

Electromagnetic radiation of wavelength 380 nm is incident on all the metals.

Photoelectrons are **just** emitted from metal **A**.

i. Explain, in terms of the energy of photons, why metal **C** will **not** emit photoelectrons.

____ **[1]**

ii. Calculate the maximum wavelength of the electromagnetic radiation in nm that will **just** eject photoelectrons from metal **D**.

maximum wavelength = ... nm **[1]**

iii. The metal **B** is now exposed to electromagnetic radiation of a different wavelength. The energy of each incident photon is 5.3 eV.

Calculate the minimum de Broglie wavelength λ of the emitted photoelectrons.

λ = ... m **[3]**

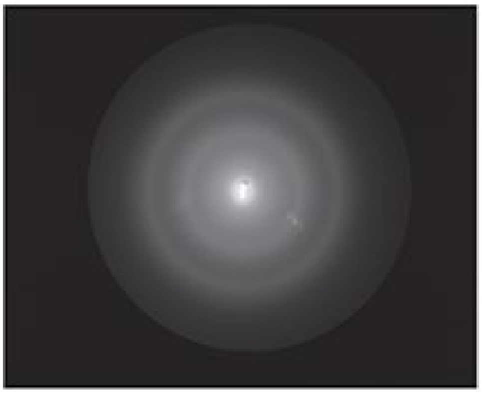
20. The photoelectric effect can be demonstrated using a gold-leaf electroscope. The zinc plate of the electroscope is negatively charged.
Ultraviolet radiation incident on the zinc collapses the gold leaf.
What is removed from the zinc plate by the incident radiation?

A electrons
B ions
C photons
D protons

Your answer ☐ **[1]**

21(a). A student is investigating electron diffraction. A beam of electrons is directed towards a thin slice of graphite in an evacuated tube.

The electrons are accelerated by a potential difference of 1800 V. The diagram below shows the pattern formed on the fluorescent screen of the evacuated tube.



Explain why this pattern is formed.

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____ **[3]**

(b). The relationship between the de Broglie wavelength λ and the accelerating potential difference *V* is

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

where *m* is the mass of the electron and *e* is the elementary charge.

Calculate the momentum *p* of an electron.

p = ... kg m s^{-1} **[2]**

END OF QUESTION PAPER