AREA 4 – Ideas about light and matter

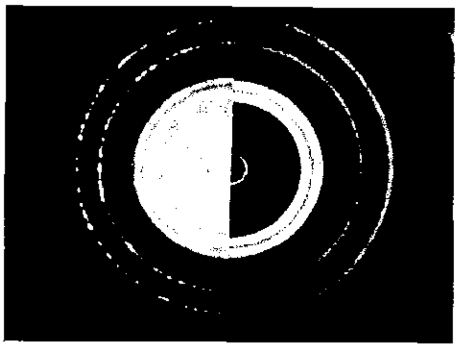


Figure 1

Figure 1 shows a picture of diffraction of X-rays and electrons through aluminium foil. The picture has been made by combining an X-ray diffraction pattern (on the right) with an electron diffraction pattern (on the left). The pictures are to the same scale and the X-rays have a photon energy of 70 keV.

Question 1

Calculate the wavelength of the 70 keV X-rays.

($h = 4.14 \times 10^{-15}$ eV s, $c = 3.0 \times 10^{8}$ m s^{-1})

$$E = \frac{hc}{\lambda} \quad \lambda = \frac{hc}{E} \quad \lambda = \frac{4.14 \times 10^{-15} \times 3 \times 10^{8}}{70 \times 10^{3}}$$

1.77×10^{-11} m

2 marks

Question 2

What is the de Broglie wavelength of the electrons?

Same spacing → same wavelength

1.77×10^{-11} m

2 marks

AREA 4 – continued

Questions 1 and 2 together 24%
average 1.76

Question 3 12 % average 0.64

Calculate the kinetic energy of the electrons in keV.

($h = 6.6 \times 10^{-34}$ J s, $m_e = 9.1 \times 10^{-31}$ kg, $e = 1.6 \times 10^{-19}$ C)

$p = \frac{h}{\lambda}$ $E = \frac{p^2}{2m}$ $\frac{7.7\times10^{-16}}{1.6\times10^{-19}} = 4.8\times10^{3}$

3.7×10^{-23} 7.7×10^{-16} J

$p = \frac{6.6\times10^{-34}}{1.77\times10^{-11}}$ $E = \frac{(3.7\times10^{-23})^2}{2\times9.1\times10^{-31}}$

4.8 keV

4 marks

Question 4 59 %

Which of the statements (A–D) best explains why it is possible to compare X-ray and electron diffraction patterns?

A. X-rays can exhibit particle-like properties.

B. Electrons can exhibit wave-like properties.

C. Electrons are a form of high energy X-rays.

D. Both electrons and X-rays ionise matter.

B

2 marks

Young's double slit experiment is set up by students in a laboratory as shown in Figure 2. Monochromatic light is shone onto the slits which are placed at a large distance from the screen. The intensity pattern produced on the screen is a pattern of light and dark bands.

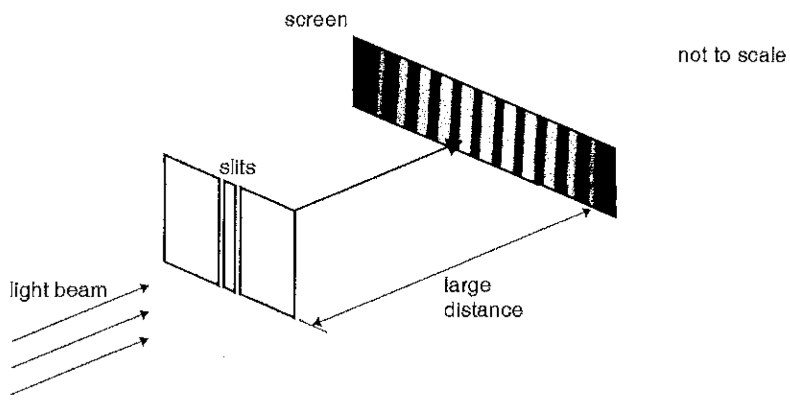


Figure 2

The students then wonder what will happen if the light used is white light rather than monochromatic light. All the students agree that there will be bands of colour on the screen, but have different opinions about the centre band. Pat expects a white band in the centre while Robyn believes a coloured band will be produced.

Question 5 9% average 0.89

Select which of the students is correct and justify your answer in the space below.

Pat / Robyn

Pat correct

Bright bands – constructive interference

Central band corresponds to a path difference = 0 and independent of the wavelength so it will be maximum for all wavelengths and so will be white

3 marks

Blue light of frequency 6.25×10^{14} Hz is shone onto the sodium photocathode of a photocell. The graph of the photoelectric current versus potential difference is shown in Figure 3.

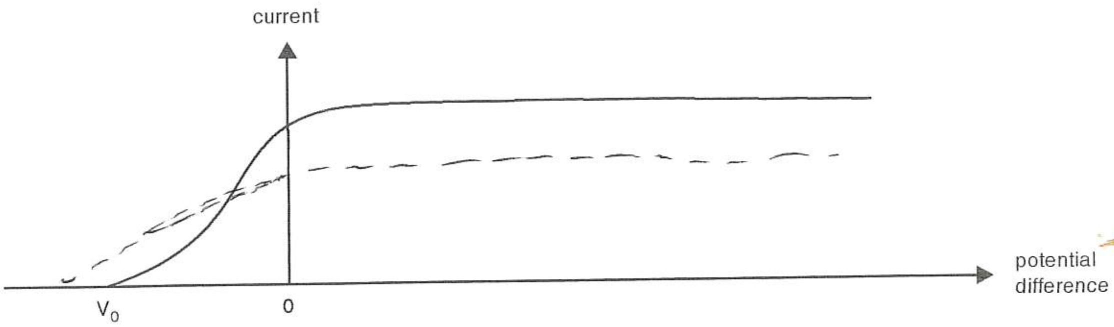


Figure 3

The threshold frequency for sodium is 5.50×10^{14} Hz.

Question 6 19 % average 0.77

What is the cut-off potential, V_0, when blue light of frequency 6.25×10^{14} Hz is shone onto the sodium photocathode of this photocell.

($h = 4.14 \times 10^{-15}$ eV s)

$E_{K\,max} = hf - W \quad W = hf_0$

$V = h(f - f_0)$

$V = 4.14 \times 10^{-15} (6.25 - 5.5) \times 10^{14}$

0.31 V

3 marks

Question 7 24 %

On **Figure 3** sketch the curve expected if the light is changed to **ultraviolet** with a **lower intensity** than the original.

2 marks

END OF QUESTION AND ANSWER BOOK

Katie and Jane are discussing wave-particle duality. Jane wonders whether wave-particle duality might explain why she missed hitting the softball in a recent match – maybe the wave nature of the softball allowed it to diffract around the bat! Katie said that this was not a reasonable explanation and that we cannot see the wave nature of a softball.

A softball has a mass of 0.20 kg and the pitcher throws it at about 30 m s^{-1}.

Question 4 29% average 1.36

Explain to Jane, using an appropriate calculation, why she would be unable to see the wave nature of a moving softball.

($h = 6.63 \times 10^{-34}$ J s)

$$\lambda = \frac{h}{p} = \frac{6.63 \times 10^{-34}}{0.2 \times 30}$$

$\lambda = 1.1 \times 10^{-34}$ m

$\lambda \ll$ size of the bat, diffraction will not happen.

3 marks

In an experiment to demonstrate the photoelectric effect, physics students allow light of various frequencies to fall on a metal surface in a photocell. The photoelectrons are decelerated across a retarding voltage, and the stopping potential, V_s, is measured for each frequency. The data they obtained is graphed in Figure 2.

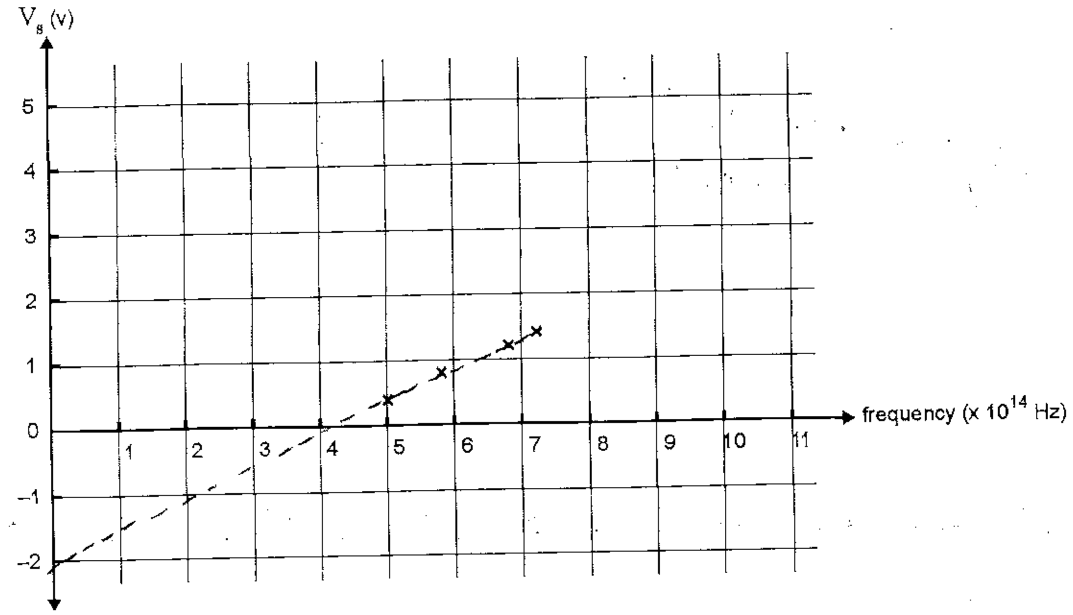


Figure 2

The students use the data points on the graph to determine a value for the work function of the metal.

Question 5 35%

Determine the magnitude and unit of the work function for this metal surface.

Read from the graph

Magnitude 1,6 -2,2	Unit eV

2 marks

 2004

AREA 4 – Ideas about light and matter

Cesium metal is illuminated by green light with a wavelength of 550 nm.

Question 1 53%

Calculate the energy of a photon of green light.

($h = 4.14 \times 10^{-15}$ eV s, $c = 3.00 \times 10^{8}$ m s^{-1})

$$E_{ph} = \frac{hc}{\lambda} = \frac{4.14 \times 10^{-15} \times 3 \times 10^{8}}{550 \times 10^{-9}}$$

[illegible] eV

2.26

2 marks

The work function of cesium is 2.10 eV.

Question 2

Calculate the maximum kinetic energy of the electrons ejected from the metal surface when green light illuminates cesium metal.

$$E_{K_{max}} = hf - W$$
$$= E_{ph} - W$$
$$= 2.26 - 2.1$$

0.16 eV

2 marks

Questions 1 and 2 together 53%

Violet light now illuminates the cesium metal and the maximum kinetic energy of the photoelectrons is 2.80 eV.

Question 3 41 % average 1.5

Show that the maximum speed of the electrons ejected from the metal surface is 9.9×10^5 m s^{-1}.

($e = 1.6 \times 10^{-19}$ C, $m_e = 9.1 \times 10^{-31}$ kg)

$E_{k\,max}(eV) = hf - W$

$E_k(J) = E_k(eV) \times 1.6 \times 10^{-19}$

$E_k = \frac{mv^2}{2}$ $v = \sqrt{\frac{2E_k(J)}{m}}$

$v = 9.9 \times 10^5$ m s^{-1}

3 marks

An electron is accelerated from rest between two parallel charged plates in a vacuum with a potential difference of 100 V as shown in Figure 1 below. The plates are separated by a distance of 0.02 m.

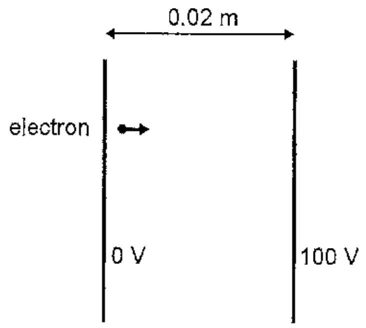


Figure 1

Question 4 82 %

Calculate the electric field strength between the parallel plates.

$$E = \frac{V}{d} = \frac{100}{0.02}$$

5000	V m^{-1}

2 marks

Question 5 34% average 1.7

Calculate the de Broglie wavelength of the electron just before it hits the positive plate.

($e = 1.6 \times 10^{-19}$ C, $m_e = 9.1 \times 10^{-31}$ kg, $h = 6.63 \times 10^{-34}$ J s)

$$E_K = eV$$

$$p = \sqrt{2mE_K}$$

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

$$\lambda = \frac{6.63 \times 10^{-34}}{\sqrt{2 \times 9.1 \times 10^{-31} \times 1.6 \times 10^{-19} \times 100}}$$

1.2×10^{-10}	m

4 marks

Figure 2 shows the energy levels of an atom.

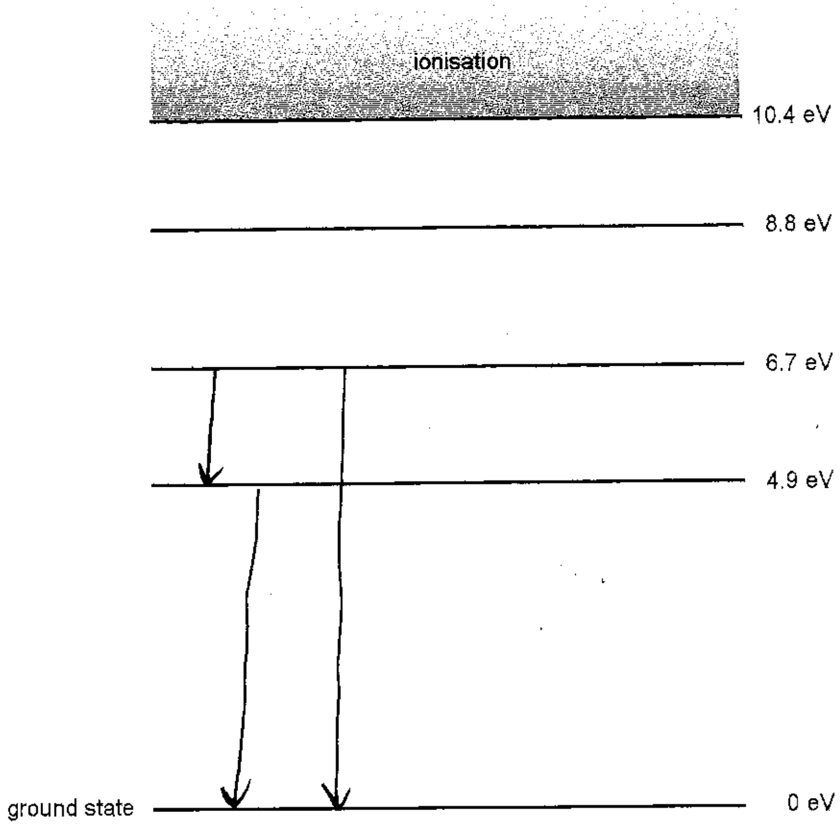


Figure 2

Question 6 41%

For atoms in the 2nd excited state (6.7 eV), calculate **all** the possible energies of the photons emitted from transitions back to the ground state.

1.8 4.9 6.7 eV

3 marks

END OF QUESTION AND ANSWER BOOK

Question 3

The students use a light source that emits a large range of frequencies. They use filters which allow only certain frequencies from the source to shine onto the plate. Most of the students' filters produce frequencies below the cut-off frequency. Alice says that if they increase the intensity of light, these frequencies below the cut-off frequency will be able to produce emitted photoelectrons.

They experiment and find Alice is incorrect. Comment whether this experimental evidence supports the wave-like or the particle-like theory of light.

It support the particle theory.
According to wave theory electrons will be emitted at any frequency if the intensity is sufficient.
According to the particle theory energy of photon is related to frequency, not intensity so if frequency is below threshold no electrons will be emitted

3 marks

Use the following information to answer Questions 4 and 5.

Neutrons are subatomic particles and, like electrons, can exhibit both particle-like and wave-like behaviour.

A nuclear reactor can be used to produce a beam of neutrons, which can then be used in experiments.

The neutron has a mass of 1.67×10^{-27} kg.

The neutrons have a de Broglie wavelength of 2.0×10^{-10} m.

Question 4

Calculate the speed of the neutrons.

$$\lambda = \frac{h}{p} = \frac{h}{mv} \qquad v = \frac{h}{m\lambda}$$

$$v = \frac{6.63 \times 10^{-34}}{1.67 \times 10^{-27} \times 2 \times 10^{-10}}$$

2.0×10^{3} m s^{-1}

2 marks

Question 5

The neutron beam is projected onto a metal crystal with interatomic spacing of 3.0×10^{-10} m.

Would you expect to observe a diffraction pattern? Explain your answer.

There will be a diffraction pattern as wavelength is similar to the spacing.

2 marks

4 and 5 24% av 2.4

Use the following information to answer Questions 3–5.

A group of students is studying Young's double slit experiment using microwaves (λ = 3.0 cm) instead of light.

A microwave detector is moved along the line PQ, and the maxima and minima in microwave intensity are recorded.

The experimental apparatus is shown in Figure 1.

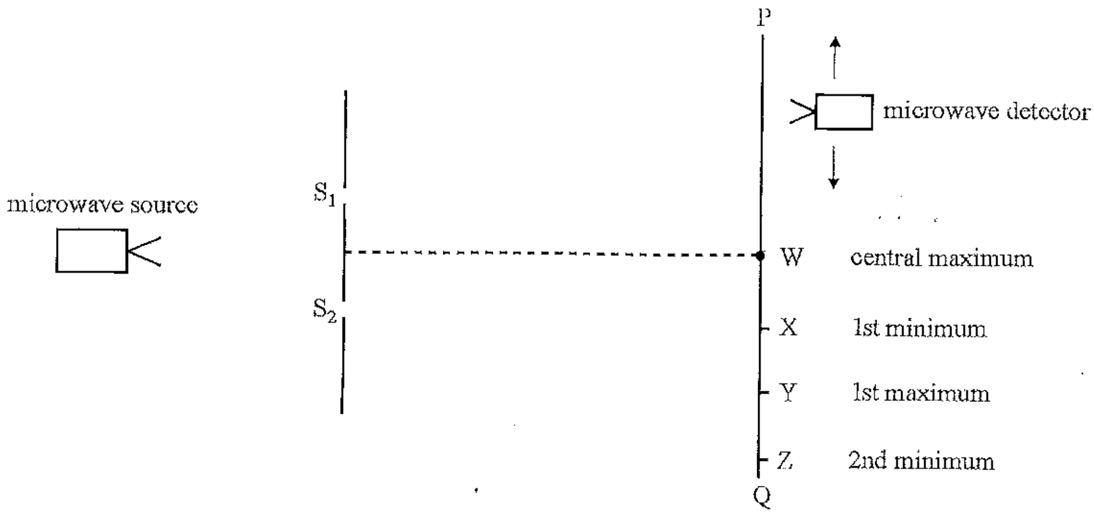


Figure 1

Question 3 48%

What is the path difference $S_1Z - S_2Z$ in cm?

4.5 cm

PD = 3/2 λ

2 marks

Question 4 20%

Explain why there is a maximum in microwave intensity detected at point Y.

PD = λ → constr. interf.

2 marks

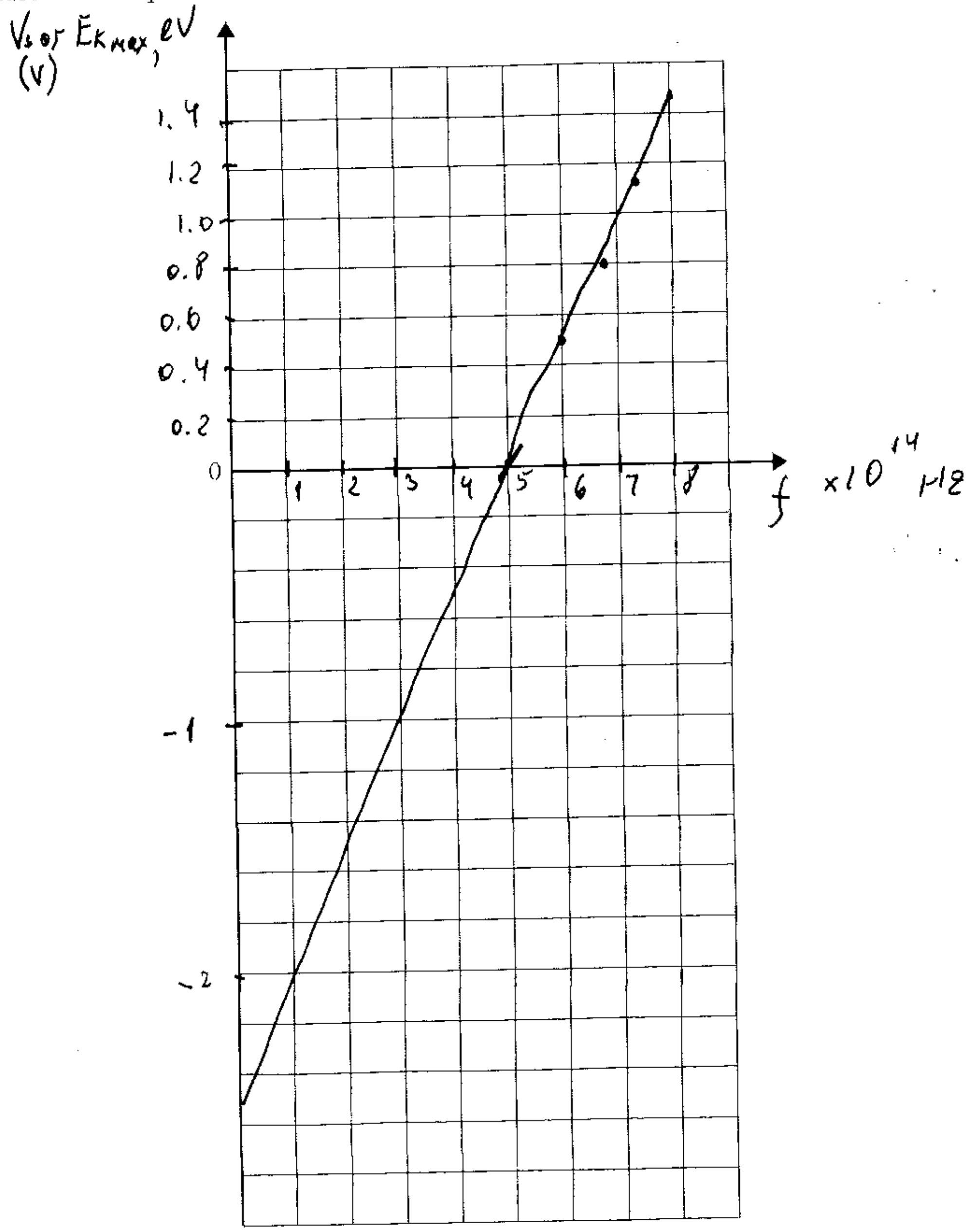
The data that the students gathered is shown in the table below.

Frequency (Hz)	Stopping voltage (Vs)
6.0×10^{14}	0.50
6.6×10^{14}	0.80
7.2×10^{14}	1.10
8.0×10^{14}	1.50

Question 6 36 %

Draw a suitable graph from the data above.

Label axes and provide units.



3 marks

Use the data from your graph in Question 6 to answer Questions 7 and 8.

Question 7 28%

What value did the students determine from the graph for Planck's constant? Include a unit.

4.3–5.7

gradient

Magnitude	Unit
$4.3-5.7 \times 10^{-15}$	eV s

3 marks

Question 8 42%

The work function is the minimum energy (eV) required to remove a photoelectron from a metal.
What value did the students determine from the graph for the work function of the metal of the plate?

2.2 – 2.6 eV

from graph or $h \times f_0$ (5×10^{14})
(from q7 from graph)

2 marks

Use the following information to answer Questions 11 and 12.

Figure 4 shows the quantised energy levels in the hydrogen atom, relative to the ground state.

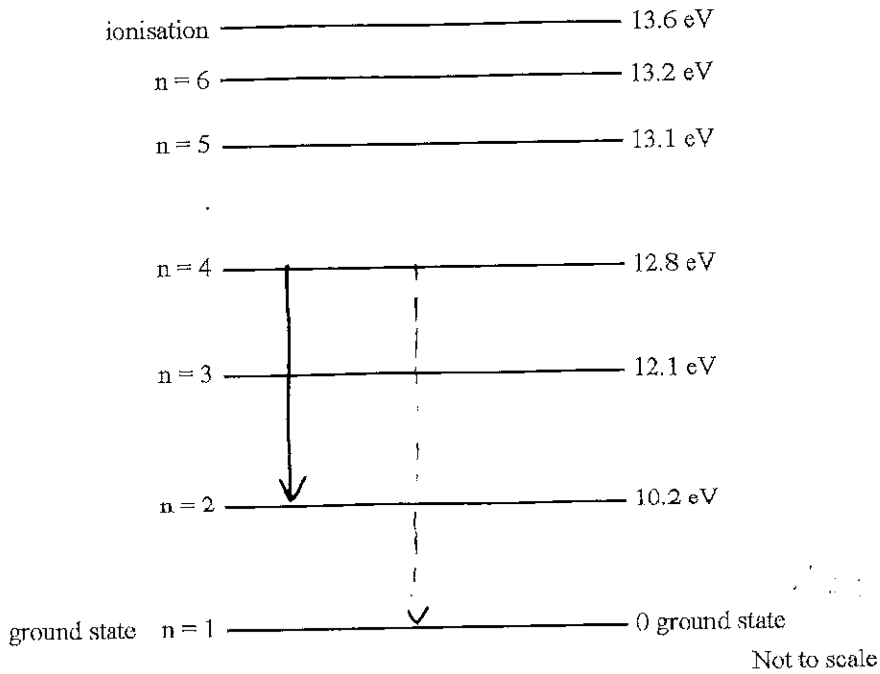


Figure 4

Question 11 63 %

A photon has an energy of 2.6 eV.

Indicate, by an arrow, on the energy level diagram in Figure 4, the transition corresponding to the emission of this photon.

2 marks

Question 12

What is the shortest wavelength photon that can be emitted when an atom decays from the n = 4 level?

$\Delta E = 12.8\ eV$ ✓

$\lambda = \frac{hc}{\Delta E}$

$\lambda = \frac{4.14 \times 10^{-15} \times 3 \times 10^{8}}{12.8} = 9.7 \times 10^{-8}\ m$

97 nm

2 marks

END OF SECTION A

Area of study 2 – Interactions of light and matter

Question 1 39%

At the time of Young's double-slit experiment there were two competing models of the nature of light.

Explain how Young's experiment supported one of these models compared with the other.

Young's experiment demonstrated interference effects. Interference effects support the wave model of light. The particle modol could not explain the interference

3 marks

Question 2 38%

Einstein's explanation of the photoelectric effect reopened the question about the nature of light.

Explain briefly how the results of the photoelectric effect experiment supported a competing model to the one supported by Young's experiment.

The photoelectric effect supports the particle model of light.
Particle model predicts threshold frequency and dependance of stoping voltage (maximum kinetic energy of electrons) on frequency and not on intencity.
The wave model predicts increase of energy of the electrons with increase in intencity, that any frequency will produce electrons and time delay.

3 marks

Question 4 28%

The pattern of bright and dark bands is shown in Figure 2 below.

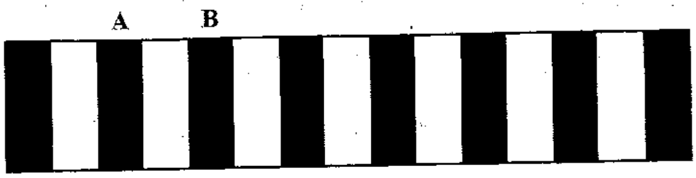


Figure 2

Precision measurement shows that the **path difference** to the middle of dark band **A** (that is, the distance $AS_2 - AS_1$) is greater than the path difference to the middle of dark band **B** by 496 nm. From this information, determine the wavelength of the laser. You may include a diagram.

Difference in PD = λ

496 nm

2 marks

The following information relates to Questions 5 7.

The photoelectric effect occurs when photons falling on a metal surface cause the emission of electrons. Einstein's equation for the photoelectric effect can be written as follows.

$$E_{K\,max} = hf - W$$

Kristy and Adrian have set up an experiment to study the energy of photoelectrons emitted from a potassium plate. Their apparatus consists of

- a light source
- a set of filters, each of which allows through only one wavelength
- an evacuated tube containing a potassium plate onto which the light falls, and a collector electrode.

A variable DC source allows a voltage (stopping voltage) to be applied between the potassium plate and the collector electrode. A voltmeter (V_s) measures this voltage, and a microammeter (A) reads the current.

Their apparatus is shown in Figure 3.

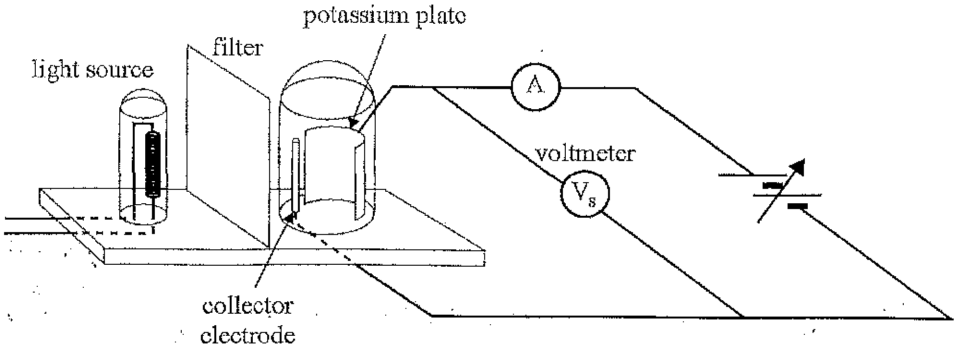


Figure 3

Question 5 21 % average 1.4

Explain **in words** the physical meaning of the terms $E_{K\,max}$, f, and W in the equation above. Your explanation must show how each term relates to the experiment in Figure 3.

$E_{K\,max}$ – maximum kinetic energy of emitted electrons.

f – frequency of the light after passing through the filter or frequency of the light incident on potassium plate

W - work function, minimum energy required to emit an electron

Question 12 20 %

De Broglie suggested that the quantised energy states of the atom could be explained in terms of electrons forming standing waves.

Describe how the concept of standing waves can help explain the quantised energy states of an atom. You may include a diagram.

If circumference of the orbit = $n\lambda$ (n - positive integer), a standing wave is formed, so electrons of those specific wavelengths could exist in the atom. Different wavelengths correspond to specific energies, so only these energy states are possible in the atom

2 marks

END OF SECTION A

The photoelectric effect experiment supports the particle model of light rather than the wave model of light.

The following are observed in a photoelectric effect experiment.

Observation 1: The number of emitted electrons (the photocurrent) depends on the intensity of the incident light.

Observation 2: The energy of emitted electrons depends only on the frequency of the incident light and is independent of the intensity.

Observation 3: The energy of the emitted electrons depends on the metal surface involved.

The particle model can account for all the above three observations.

The wave model can explain two of these observations but not a third.

Question 2 10 %. average 1.1

Select the observation that the wave model **cannot** explain.

Explain how the particle model satisfactorily explains this observation.

Observation number 2

Energy of the incident photons depends on frequency. One photon interacts with one electron, so energy of emitted electrons will depend on frequency. Change in intencity of the light results in the change of the number of photons but not their energy.

3 marks

The following information relates to Questions 3 and 4.

Two students are studying interference of light.

They use a laser of wavelength 580 nm.

Question 3 73 %

What is the energy (in eV) of one photon of the light from the laser? Show your working.

$$E = \frac{hc}{\lambda} = \frac{4.14 \times 10^{-15} \times 3 \times 10^{8}}{580 \times 10^{-9}}$$

2.14 eV

2 marks

The students set up the laser, two slits, S_1 and S_2, and a screen on which an interference pattern is observed, as shown in Figure 1a.

The pattern they observe on the screen is also shown in Figure 1b.

C indicates the centre of the pattern.

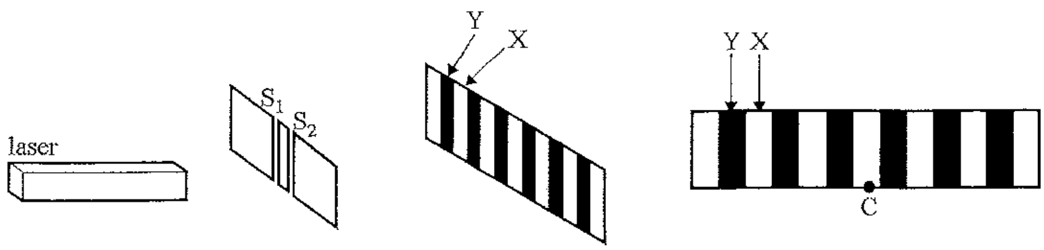


Figure 1a **Figure 1b**

X is at the centre of a bright band. Y is at the centre of the dark band next to X and further away from the centre of the pattern.

The path difference $S_2X–S_1X$ is 1160 nm.

Question 4 50 %

What is the path difference $S_2Y–S_1Y$? Show your working.

X: 1160 = 2λ

Y: PD = $\frac{5}{2}$λ

= $\frac{5}{2}$ × 580

1450 nm

2 marks

The following information relates to Questions 7–10.

Students study diffraction of electrons by a crystal lattice.

The apparatus is shown in Figure 4a.

In this apparatus electrons of mass 9.1×10^{-31} kg are accelerated to a speed of 1.5×10^{7} m s^{-1}.

The electrons pass through the crystal, and the diffraction pattern is observed on a fluorescent screen. The pattern the students observe is shown in Figure 4b.

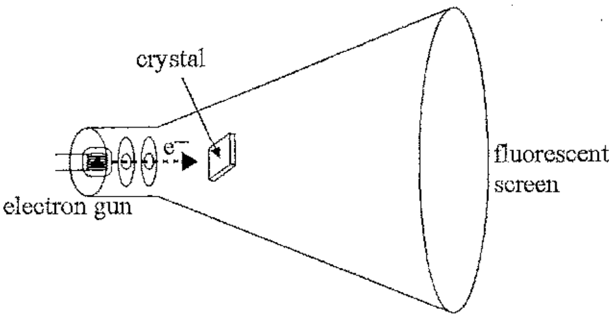


Figure 4a

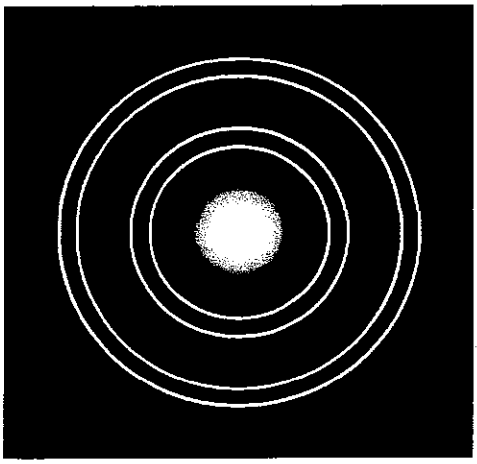


Figure 4b

Question 7 50 %

Calculate the de Broglie wavelength of the electrons. Show your working.

$$\lambda = \frac{h}{p} = \frac{h}{mv} = \frac{6.63 \times 10^{-34}}{9.1 \times 10^{-31} \times 1.5 \times 10^{7}}$$

0.0486 nm

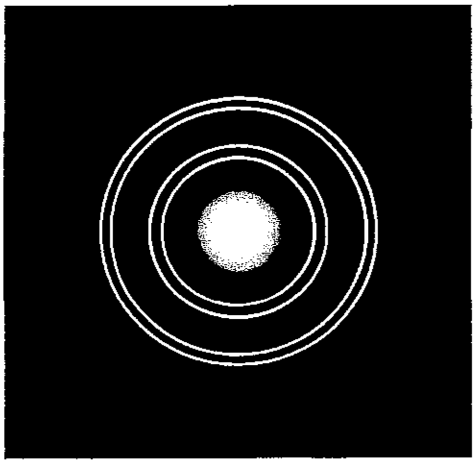
2 marks

Question 8 36%

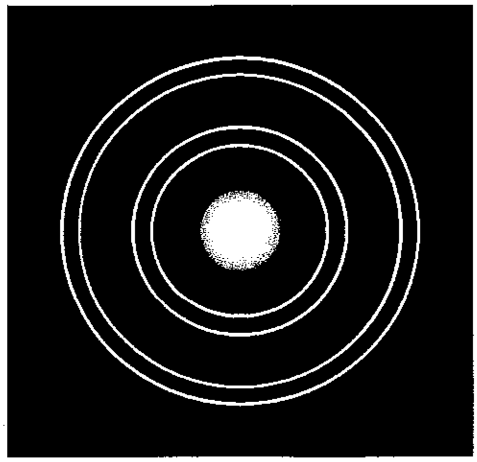
The students now increase the accelerating voltage and hence the speed of the electrons.

Which one of the options below now best shows the pattern they will observe on the screen?

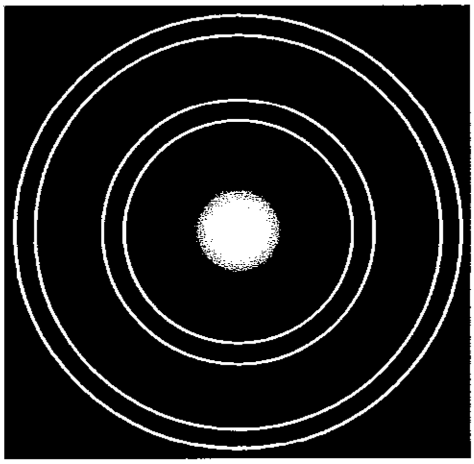
Explain your answer.



option A



option B (identical to original pattern)



option C

A

Voltage ↑ → speed ↑ → p ↑ → $\lambda = \frac{h}{p}$ ↓ → spacing ↓

2 marks

Figure 5a shows the diffraction with electrons of 600 eV. The students now replace the electron gun with an X-ray source. Then they observe the pattern shown in Figure 5b below.

Figures 5a and 5b are drawn to the same scale.

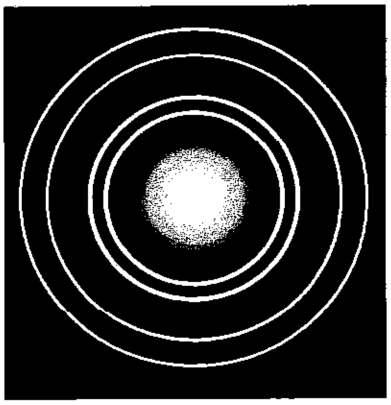


Figure 5a

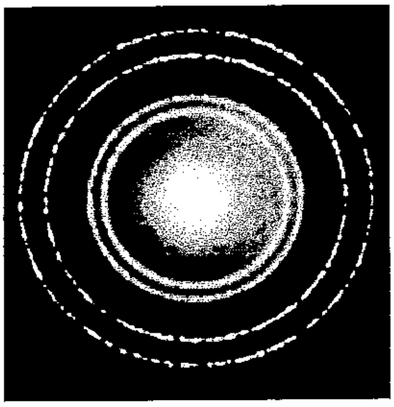


Figure 5b

Question 9 56%

Explain why the electrons and the X-rays produce a very similar pattern.

$\lambda_{el} = \lambda_X$

2 marks

Question 10 12 % average 0.6

Estimate the energy, in eV, of a photon of these X-rays. Show your working.

$E_{el} = 600 eV$
$= 600 \times 1.6 \times 10^{-19}$
$= 9.6 \times 10^{-17} J$

$P_{el} = \sqrt{2mE}$ in J

$E_{x-ray} = pc$

$p_{el} = p_x$

$P_{el} = \sqrt{2 \times 9.1 \times 10^{-31} \times 9.6 \times 10^{-17}}$
$= 1.32 \times 10^{-23}$ Ns

2.48×10^{4} eV

$E_{x\text{-}ray} = 1.32 \times 10^{-23} \times 3 \times 10^{8} = 3.96 \times 10^{-15} J$
$3.96 \times 10^{-15} \div 1.6 \times 10^{-19} = 2.48 \times 10^{4} eV$

3 marks

Use the following information to answer Questions 5–9.

Students set up the apparatus shown in Figure 2 to study the photoelectric effect.

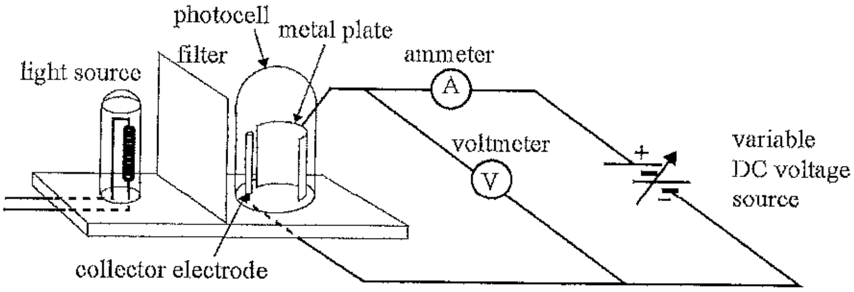


Figure 2

The apparatus consists of

- a source of white light
- a set of filters that only allow light of selected wavelengths to pass through
- a metal plate and a collector electrode enclosed in an evacuated (no air) glass case
- a voltmeter (V), ammeter (A) and variable DC voltage source in a circuit, as shown in Figure 2.

With a particular filter in place, the students gradually increase the voltage as measured by the voltmeter, V, from zero. They plot the current measured through the ammeter, A, as a function of the voltage measured by the voltmeter, V. This is shown in Figure 3.

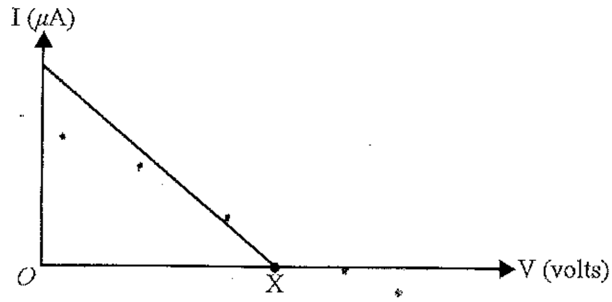


Figure 3

Question 5 5 % average 0.4

Explain why the current drops to zero at point X.

V_x - stop. voltage

$E_{k_{max}} = q V_x$

When voltage increases more and more electrons are stopped. When $V = V_x$ even most energetic electrons are stopped.

2 marks

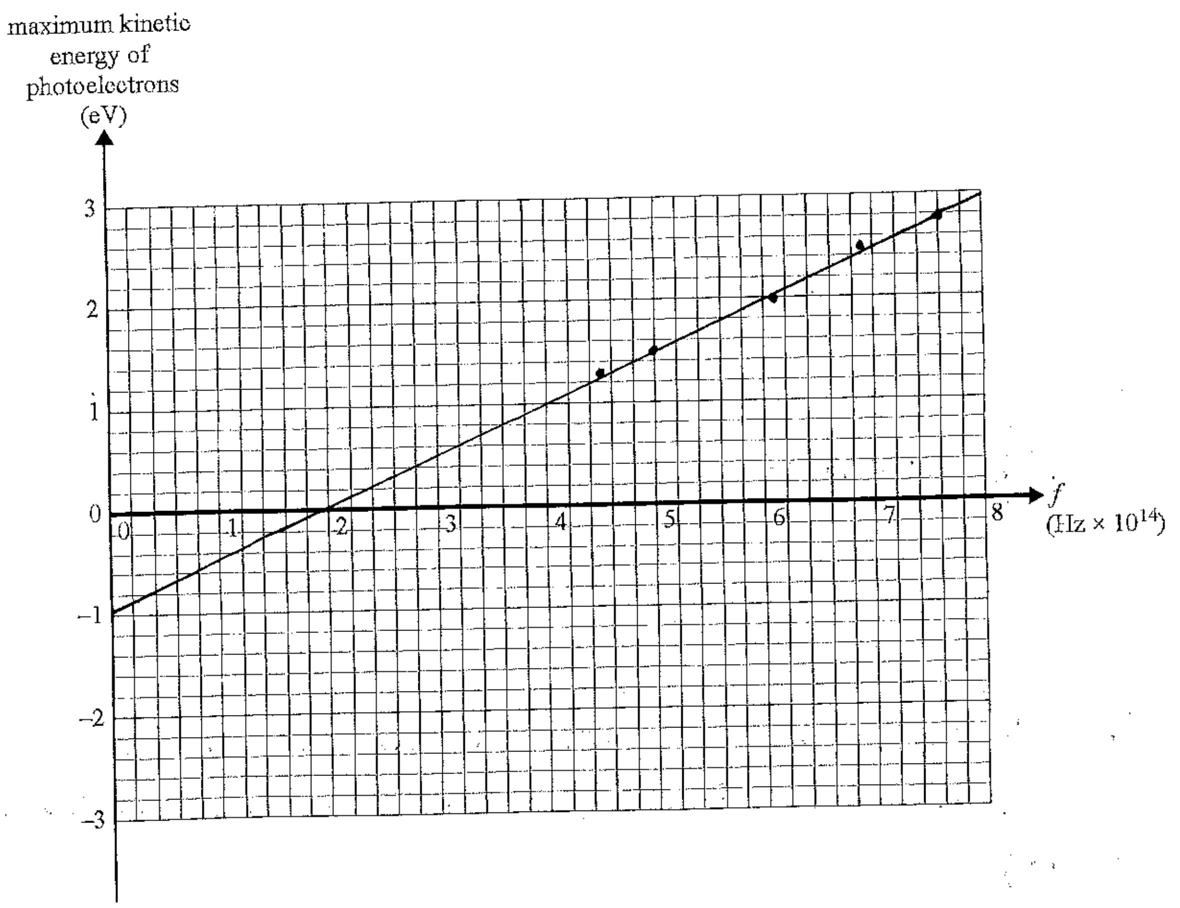
The students now use five different filters to give five frequencies of light falling on the plate, and measure the stopping voltage on the voltmeter for each frequency.

Their data is shown below.

Frequency (Hz)	Stopping voltage (V_S)
4.5×10^{14}	1.3
5.0×10^{14}	1.5
6.1×10^{14}	2.0
6.9×10^{14}	2.5
7.6×10^{14}	2.8

Question 6 67%

From this data, plot these points on the axes below and hence draw a line of best fit to show the maximum kinetic energy of the emitted electrons versus frequency falling on the metal plate.



3 marks

Question 7 49%

From your graph, what value of h, Planck's constant, would the students have obtained?
Show your working.

$$h = \frac{2.8-1.5}{(7.6-5.0)\times10^{14}}$$ gradient

Points used must be on a drawn line!

5×10^{-15} eV s

2 marks

Question 8 38%

From your graph, what is the **longest wavelength** which would cause a photoelectron to be emitted?

$$\lambda = \frac{c}{f_0}$$ (intercept from graph)

$$= \frac{3\times10^{8}}{2\times10^{14}}$$

1500 nm

2 marks

Question 9 23 %

Outline the conclusions about the nature of light that Einstein made from the observations of photoelectric experiments.

photons

$E_{ph} = hf$

1 aspekt of PhEl Ef.

Light behaves as a particles whose energy proportional to the frequency. 2 marks

Photoelectric effect showed existence of threshold frequency (minimum frequency and so minimum energy) necessary to emit electrons.

3 marks

Use the following information to answer Questions 10–12.

X-rays of wavelength 0.20 nm are directed at a crystal and a diffraction pattern is observed.

Question 10 68 %

Calculate the energy, in eV, of a photon of these X-rays.

$$E = \frac{hc}{\lambda} = \frac{4.14\times10^{-15} \times 3\times10^{8}}{0.2\times10^{-9}}$$

6210 eV

2 marks

Question 11 18 % average 0.5

The X-ray beam is replaced by a beam of electrons. A similar diffraction pattern is observed with the same spacing as in Question 10.

What must be the energy, in eV, of each electron to produce this pattern?

$$p_{x\text{-ray}} = \frac{h}{\lambda} \quad E_{el} = \frac{p^2}{2M}$$

$$p_{x\text{-ray}} = \frac{6.63\times10^{-34}}{0.2\times10^{-9}} = 3.315\times10^{-24}\ Ns \quad p_{x\text{-ray}} = p_{el}$$

$$E_{el} = \frac{(3.315\times10^{-24})^2}{2\times9.1\times10^{-31}} = 6.04\times10^{-18}\ J$$

$$\frac{6.04\times10^{-18}}{1.6\times10^{-19}} = 37.7\ eV$$

37.7 eV

2 marks

Question 12 61 %

Explain why these electrons also produce a diffraction pattern with the same spacing as the X-rays.

$\lambda_{el} = \lambda_{x}$

2 marks

Area of study 2 – Interactions of light and matter

Question 1

Vishvi is carrying out photoelectric effect experiments. Her apparatus is shown in Figure 1.

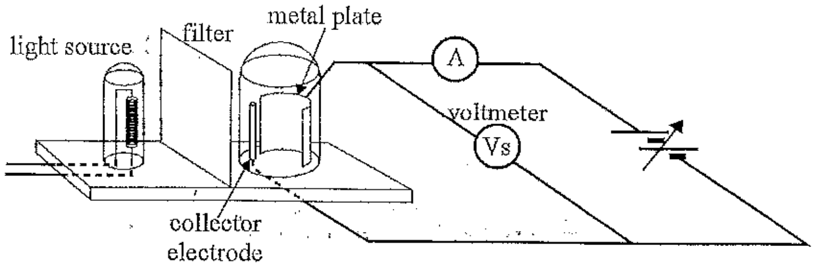


Figure 1

Vishvi uses two metal plates in the photoelectric cell. One plate is made of zinc and the other is made of aluminium. Vishvi uses light of a particular frequency to illuminate the zinc plate and then the aluminium plate, but finds that photoelectrons are emitted only by the zinc plate.

The threshold frequency of zinc for photoelectric emission is 7.40×10^{14} Hz and that of aluminium is 9.90×10^{14} Hz.

a. Calculate the maximum wavelength (in nm) of the light required to emit electrons from the zinc plate. 65 %

$\lambda = c/f$

405 nm

1 mark

b. In an effort to eject photoelectrons from the aluminium plate, Vishvi increases the intensity of the light beam, but still finds that no photoelectrons are emitted.

Explain how this observation supports the particle model of light, but not the wave model of light. 10 %

average 1.0

The wave model predicted that by increasing the intensity of light it should provide enough energy to eject electrons. This did not happen.

Particle model predicted that increase in the intensity will increase number of photons, but not their energy. So photons will not have enough energy to eject electrons

3 marks

In another photoelectric experiment, Vishvi uses light with a frequency of 7.50×10^{14} Hz to eject photoelectrons from a sodium surface. The work function of sodium is 2.28 eV.

c. Calculate the maximum kinetic energy (in eV) of these photoelectrons. 77 %

$E_{K\,max} = hf - W$

$= 4.14\times10^{-15} \times 7.5 \times 10^{14} - 2.28$

0.825 eV

2 marks

d. Calculate the **stopping voltage** that would be required to just prevent the most energetic electrons from reaching the collector electrode. 41 %

0.825 V

1 mark

Question 2

Two students set up a two-slit interference experiment with a source of laser light, as shown in Figure 2.

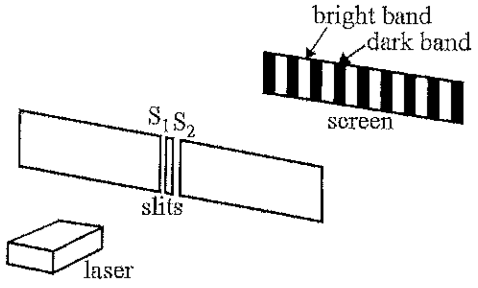


Figure 2
not to scale

The wavelength of the light from the laser is 612 nm. Figure 3 shows a sketch of the central section of the interference pattern that they obtain. The central band **C**, which is a bright band, is labelled.

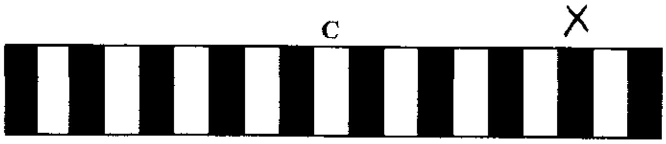


Figure 3

a. The light energy output of the laser is 5.0×10^{-3} J s^{-1}.
Calculate the number of photons leaving the laser every second. Write your answer in the box provided. 35%
average 0.8

$E = \frac{hc}{\lambda}$ $n = P/E = \frac{5\times10^{-3}}{3.25\times10^{-19}}$

$= \frac{6.63\times10^{-34}\times3\times10^{8}}{6.12\times10^{-7}} = 3.25\times10^{-19}$ J

1.54×10^{16}

2 marks

b. Explain why the central band of the pattern at point C is a bright band and not a dark band. 40%

PD = 0 constructive interference

2 marks

c. Another point on the pattern is further from slit S_1 than from slit S_2 by a distance of 2.142×10^{-6} m. Its position is to the **right** of point C in Figure 3, on page 16.

53 %

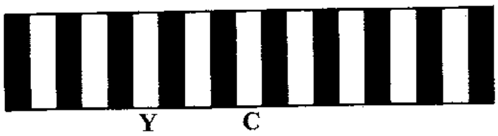
Indicate where this point is in Figure 3 by writing the letter X above the point. You must show your working.

$3.5\lambda = 7/2\lambda \rightarrow$ 4th dark

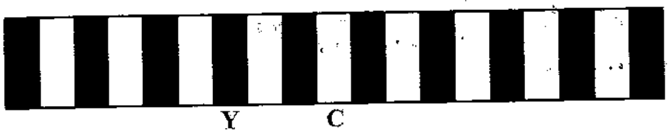
3 marks

Another laser that produces light of a different wavelength is now used. The pattern is now spaced more closely. Figure 4a shows the new pattern and Figure 4b shows the original pattern.

The second bright band to the left of C in the **new** pattern is at the position labelled **Y** in Figure 4a. In the original pattern (Figure 4b), this was the position of the second **dark** band to the left of C.



new pattern
Figure 4a



original pattern
Figure 4b

35 %

d. Calculate the wavelength of the light produced by this new laser.

$PD = 1.5\lambda_{old} = 2\lambda_{new}$

459 nm

2 marks

Question 3

A beam of electrons is travelling at a constant speed of 1.5×10^5 ms^{-1}. The beam shines on a crystal and produces a diffraction pattern. The pattern is shown in Figure 5. Take the mass of one electron to be 9.1×10^{-31} kg.

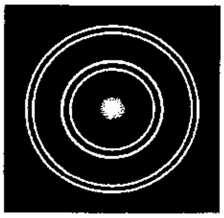


Figure 5

a. Calculate the kinetic energy (in eV) of one of the electrons. 47 %

$E_K = \frac{mv^2}{2} \times 1.6 \times 10^{-19}$

0.064 eV

2 marks

The beam of electrons is now removed and replaced by a beam of X-rays. The resulting pattern has the **same spacing** as that produced by the electron beam.

b. Calculate the energy (in eV) of one X-ray photon. 31 %

$p_{el} = p_x \therefore p_{el} = mv \quad \lambda_x = \frac{h}{p} \quad E = \frac{hc}{\lambda}$

$p_{el} = 9.1 \times 10^{-31} \times 1.5 \times 10^5 = 1.365 \times 10^{-25}$

or $E_x = pc$

256 eV

$E_x = 1.365 \times 10^{-25} \times 3 \times 10^8$

$= 4.1 \times 10^{-17}$

$\frac{4.1 \times 10^{-17}}{1.6 \times 10^{-19}} = 256$

3 marks

Question 4

Figure 6 shows the energy level diagram for the hydrogen atom.

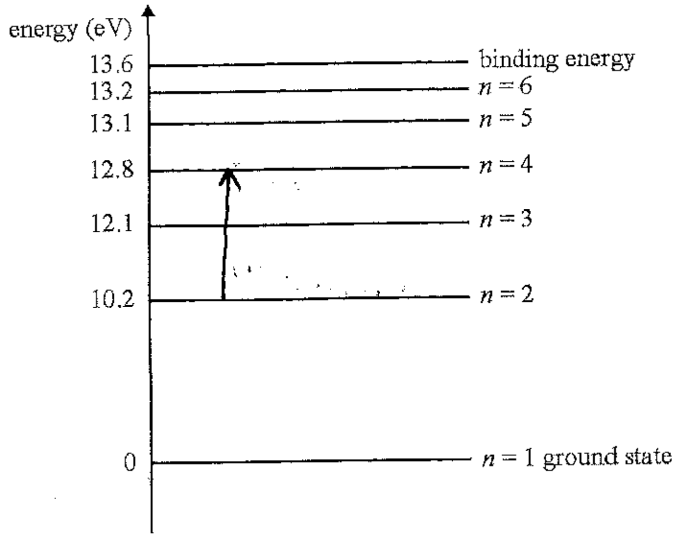


Figure 6

A particular hydrogen atom makes a transition from the $n = 2$ level to the $n = 4$ level by absorbing a photon.

a. Calculate the wavelength of the photon involved. 63 %

$E = \frac{hc}{\lambda}$ $E = 2.6 eV$ $\lambda = \frac{hc}{E} = \frac{4.14 \times 10^{-15} \times 3 \times 10^{8}}{2.6}$

478 nm

2 marks

The energy levels of the hydrogen atom are discrete (quantised) and there are no stable levels between them.

b. In terms of the properties of the electron, explain why only certain energy levels are stable. 27 % average 1.2

An electron has wave properties.
Only when the circumference of the orbit is a whole number of wavelengths will standing waves be formed.
Only electrons with energies related to those particular wavelengths will form stable levels.

3 marks

END OF SECTION A
TURN OVER

Question 20 (5 marks)

An energy-level diagram for a sodium atom is shown in Figure 25.

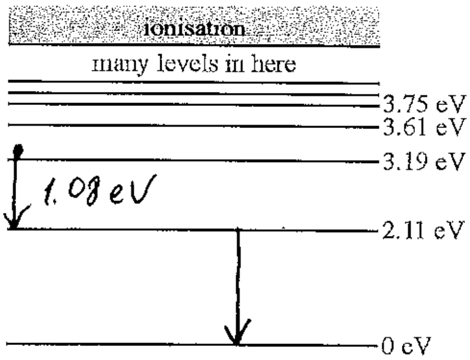


Figure 25

a. An atom is in the 3.19 eV state. It returns to the ground state, emitting one or more photons. Calculate the **longest** wavelength of light that could be emitted by the atom. 34% 2 marks

$\lambda = \frac{hc}{E} = \frac{4.14\times10^{-15}\times3\times10^{8}}{1.08}$

1.15×10^{-6} m

b. Explain, with a calculation, why the emission spectrum of sodium shows a spectral line at 588.63 nm. 3 marks

34%
average 1.3

$E = \frac{hc}{\lambda} = 2.11 eV$

∴ Transition from 2.11 eV to 0 eV.

Question 21 (7 marks)

Students are investigating the photoelectric effect by shining monochromatic light with a frequency of 1.00×10^{15} Hz onto a sodium plate. Their apparatus is shown in Figure 26.

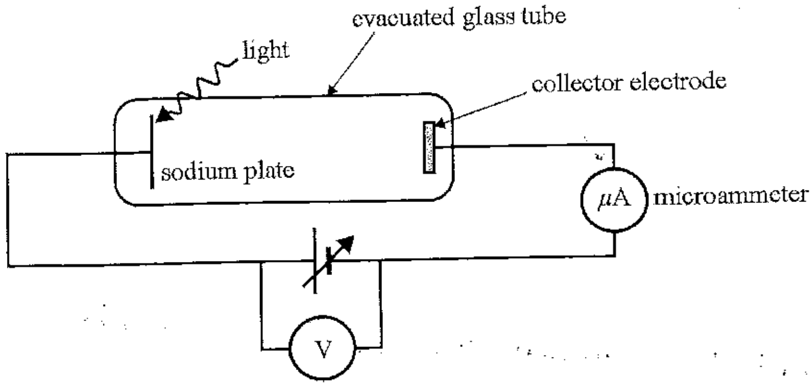


Figure 26

Figure 27 shows a graph of the relationship between the photocurrent and the reading on the voltmeter.

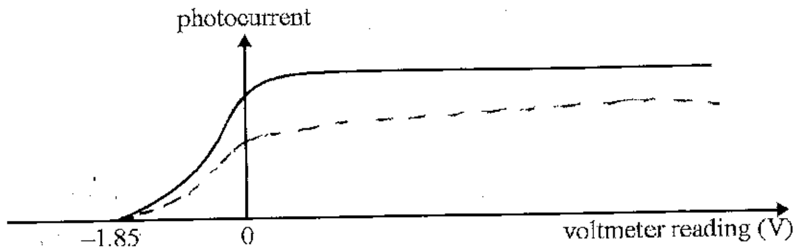


Figure 27

a. Use the information in the graph to calculate the maximum kinetic energy (in joules) of the photoelectrons. 42 % 1 mark

$E_{k\,max} = 1.85\,eV$

2.96×10^{-19} J

b. Calculate the work function (in eV) of sodium. 31 % 2 marks

$E_{k\,max} = hf - W$

$W = hf - E_{k\,max}$

$= 4.14 \times 10^{-15} \times 1 \times 10^{15} - 1.85$

2.29 eV

c. The intensity of the light is now reduced and the experiment is repeated. The students obtain a new graph of photocurrent against voltage. 53 %

Sketch the new graph on Figure 27. 2 marks

d. The students change the light source to one with a different frequency. They observe that the photocurrent is zero and remains at zero regardless of the size or sign of the voltage. 10 %

Explain this observation. average 0.5 2 marks

$hf < W \quad f < f_0$

Question 22 (9 marks)

The apparatus for a Young's double-slit experiment is shown in Figure 28.

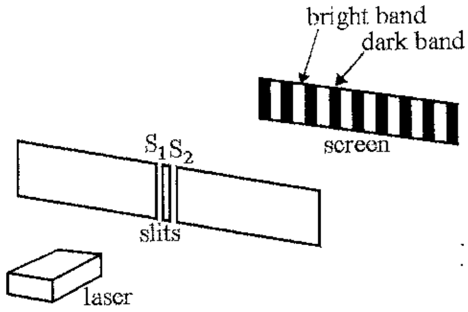


Figure 28
not to scale

a. A beam of green light ($\lambda = 550$ nm) is incident on the slits. 28 %

Describe the intensity at the exact centre of the interference pattern on the screen and give a reason for your answer. 2 marks

Bright as PD = 0

b. The beam is now replaced with light of a lower frequency. 61 %

The second dark band from the centre of the interference pattern would

A. become narrower.

B. remain in the same position.

C. move closer to the centre of the pattern.

D. move further away from the centre of the pattern. 1 mark

D

c. The path difference from the slits to the second bright band from the centre of the interference pattern is 1.4×10^3 nm.

25% average 1.0

Calculate the path difference (in metres) from the slits to the first dark band from the centre of the pattern.

3 marks

$2\lambda = 1.4 \times 10^3$ $\lambda = 700$ nm

$\lambda/2 = 3.5 \times 10^{-7}$

3.5×10^{-7} m

d. A student reads on a website that 'Young's experiment supports the particle model of light'. Explain, with reasons, whether the statement is correct or incorrect. 41%

3 marks

Incorrect.

Young's experiment demonstrates interference, which is a wave phenomenon.

Bright bands represent constructive interference, dar - destructive.

Or Particle model predicts just 2 bands on the screen.

Question 23 (5 marks)

Students aim X-rays with a photon energy of 80 keV at a thin metal foil. The resulting diffraction pattern is shown in Figure 29.

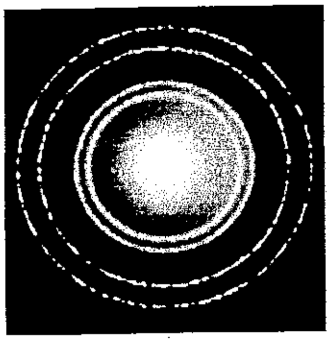


Figure 29

a. Calculate the magnitude of the momentum of a single X-ray photon. 31 % average 0.7 2 marks

$p = E/c \qquad p = \frac{80\times10^{3}\times1.6\times10^{-19}}{3\times10^{8}}$

4.3×10^{-23} kg m s^{-1}

b. The students are aware that electrons can also be used to form diffraction patterns. They wish to use a beam of electrons to form a diffraction pattern with fringe spacings identical to those in Figure 29. Student A says that the fringe spacing will be identical if the electrons have the same momentum as the X-rays. Student B says that the fringe spacing will be identical if the electrons have the same energy as the X-rays.

Which student is correct? Explain your answer. 26 % average 1.2 3 marks

A correct.

spacing determined by λ, so by p, not E.

END OF SECTION A

Area of study – Interactions of light and matter

Question 19 (3 marks)

A group of students carries out a two-slit interference experiment using light with a wavelength of 420 nm. The arrangement of the students' apparatus and the resulting interference pattern are shown in Figure 29.

The point M on the screen is at the centre of the interference pattern. There is a bright band at point P on the screen. It is the second bright band to the right of M, as shown.

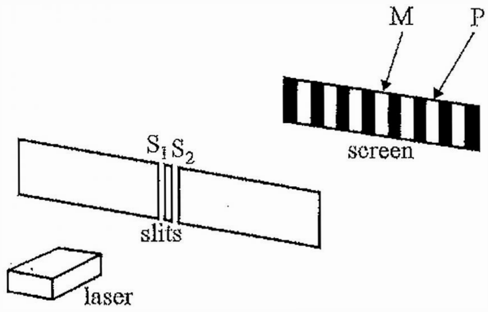


Figure 29

a. Calculate the path difference $S_1P - S_2P$. 60 % — 1 mark

2λ

840 nm

b. The students repeat the experiment using light of a different wavelength. They find that, at the point P on the screen, there is now a **dark** band. It is the second dark band to the right of M.

Calculate the wavelength of this light. Show your working. 46 % — 2 marks

$840 = 1.5\lambda$

560 nm

Question 20 (5 marks)

A group of students carry out an experiment where light of various frequencies is shone onto a metal plate. The maximum kinetic energy of the emitted electrons for each frequency is recorded and the results are plotted to produce the graph shown in Figure 30. Take Planck's constant as 6.63×10^{-34} J s.

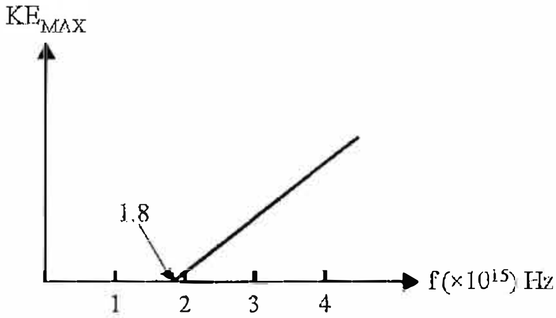


Figure 30

a. Calculate the work function of the metal in joules. 72 % — 2 marks

$W = h f_0 = 6.63 \times 10^{-34} \times 1.8 \times 10^{15}$

1.19×10^{-18} J

b. The intensity of the light is increased and the experiment is repeated with the same frequencies. The students find that the graph of frequency against maximum kinetic energy for this second experiment is exactly the same as for the first experiment. 7 % average 0.8

Explain why this result provides evidence for the particle-like nature of light. — 3 marks

According to the particle model increasing the intensity at the same frequency increase number of photons.
Energy of photons will be the same.
So kinetic energy of the ejected electrons would not change

Question 21 (8 marks)

Thuy is doing some experiments on the diffraction of photons. She is using a beam of photons with an energy of 4.1 eV.

a. Calculate the wavelength of a photon in this light beam. 65% 2 marks

$\lambda = hc/E$

$\frac{4.14\times10^{-15}\times3\times10^{8}}{4.1}$

3.0×10^{-7} m

The beam is incident on a small circular aperture and the resulting diffraction pattern is produced on a photon-sensitive screen behind the aperture. This pattern is shown in Figure 31.

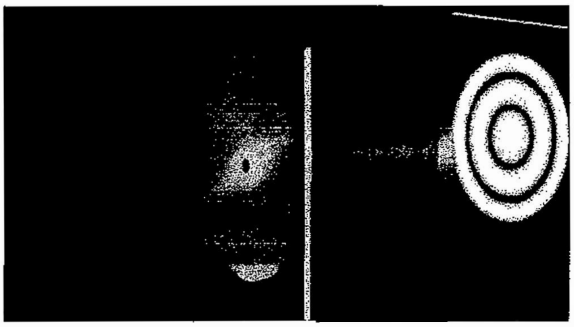


Figure 31

b. A second experiment is then performed with the same light beam incident on a circular aperture with a larger diameter. 55%

Complete the following sentence by circling the correct words that are shown in **bold** font. 1 mark

Corresponding rings in the second diffraction pattern would have diameters that are **larger than / the same size as / smaller than** the rings in the original pattern.

c. Give your reasoning for your answer to **part b.** 29% average 0.7 2 marks

$x = \frac{\lambda L}{d}$ d – diameter

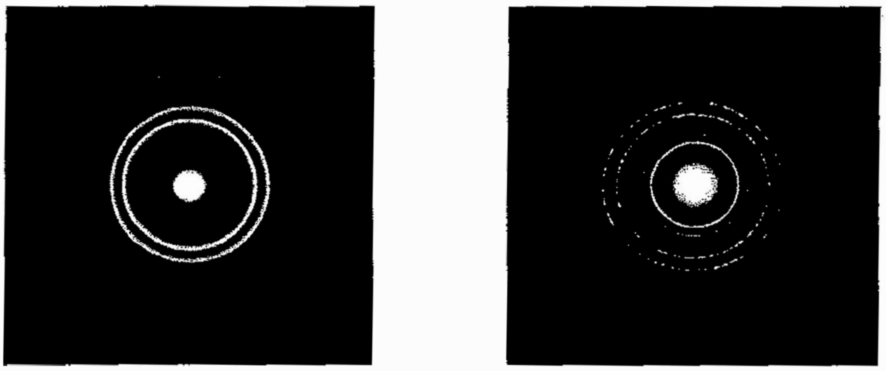
x - spacing between circles

or Amount of diffraction is inversely proportional to the size of the aperture. Size increased → Spread decrease

d. Thuy now carries out another experiment, comparing the diffraction of X-ray photons and electrons.

A beam of X-ray photons is incident on a small circular aperture. The experiment is then performed with a beam of electrons incident on the same aperture.

The X-ray photons and electrons have the same energy. The diffraction patterns (shown in Figure 32) have the same general shape, but very different spacings.



X-ray photon diffraction — electron diffraction

Figure 32
not to scale

Explain why the electron diffraction pattern has a different spacing from the X-ray diffraction pattern, even though the electrons and the photons have the same energy. 10% average 1.0 — 3 marks

$\lambda_x \neq \lambda_e$

$p_x \neq p_e$

Diffraction spacing depends on the wavelength, so wavelength was different.
Wavelength related to the momentum, not to the energy

Question 22 (5 marks)

A simplified diagram of the energy levels for a mercury atom is shown in Figure 33.

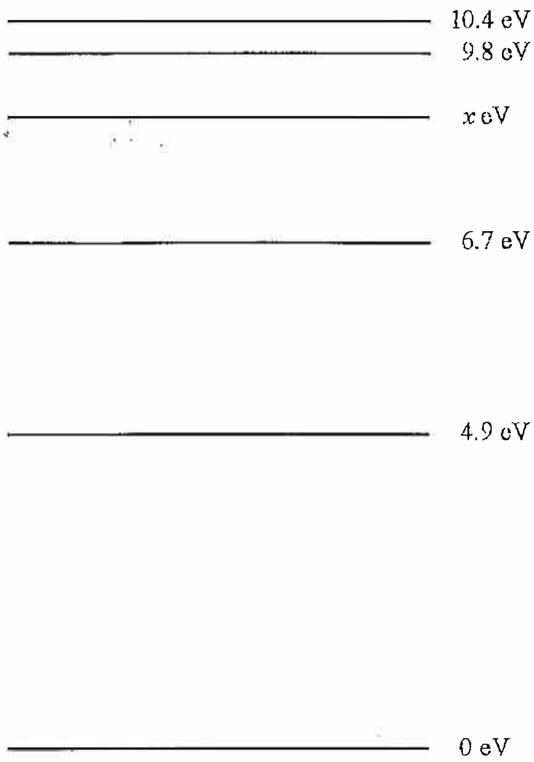


Figure 33

a. Explain why a mercury atom, while in the first excited state, is able to absorb a 1.8 eV photon, but cannot emit a photon of this energy. 32 % 2 marks

6.7 − 4.9 = 1.8

4.9 − 0 ≠ 1.8

b. In a sample of excited mercury atoms, all of the energy levels shown in Figure 33 are occupied. One of the energy levels in Figure 33 is labelled x eV. The emission spectrum of mercury shows lines at approximately 0.9 eV, 1.5 eV and 2.2 eV.

36 % average 1.2

Use this information and Figure 33 to calculate x. Give your reasoning. 3 marks

8.9 - 6.7 = 2.2

9.8 - 8.9 = 0.9

10.4 - 8.9 = 1.5

8.9 eV

Question 23 (5 marks)

According to one model of atoms, electrons in atoms move in stable circular orbits around the nucleus.
In an atom modelled in this way, an electron is moving at 2.0 × 10^6 m s^{-1}. Take the mass of an electron as 9.1 × 10^{-31} kg.

a. Calculate the de Broglie wavelength of this electron. Give your answer in nm. 45% 2 marks

$\lambda = h/p \quad \lambda = \frac{6.63 \times 10^{-34}}{9.1 \times 10^{-31} \times 2 \times 10^{6}} = 3.6 \times 10^{-10}$ m

0.36 nm

21% average 1.1

b. Describe how the wave nature of electrons can be used to explain the quantised energy levels in atoms. 3 marks

If $2\pi r = n\lambda$
standing wave is formed.
Only electrons with energies corresponding to these wavelengths exist.

END OF SECTION A

Question 20 (4 marks)

Physicists use the expression 'wave-particle duality' because light sometimes behaves like a particle and electrons sometimes behave like waves.

a. What evidence do we have that light can behave like a particle? Explain how this evidence supports a particle model of light. 50 %. 2 marks

Photoelectric effect.
Existence of the threshold frequency, dependence of stopping voltage on the frequency, no time delay.

b. What evidence do we have that electrons can behave like waves? Explain how this evidence supports a wave model of electrons. 23 %. average 0.6 2 marks

Electron diffraction.
Electrons diffracting on the crystal lattice make interference pattern on the screen. Interference and diffraction are wave phenomenons.

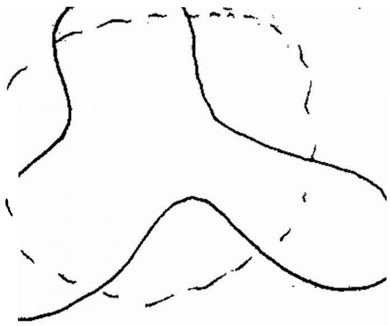
Question 21 (5 marks)

a. Use the model of quantised states of the atom to explain why only certain energy levels are allowed. 3 marks

23% average 1.1

Electrons have wave nature.
If $2\pi r = n\lambda$ the standing wave is formed.
Different allowed orbits correspond to different n.

b. Illustrate your answer with an appropriate diagram. 40% 2 marks



57%

Question 22 (2 marks)

Electrons (of mass 9.1×10^{-31} kg) have a de Broglie wavelength of 1.0×10^{11} m.

Calculate the speed of these electrons.

$\lambda = \frac{h}{mv}$ $v = \frac{h}{m\lambda}$

$$v = \frac{6.63 \times 10^{-}}{9.1 \times 10^{-31} \times 1 \times 10^{-11}}$$

$$= 7.3 \times 10^{7}\ ms^{-1}$$

END OF SECTION A
TURN OVER

Question 19 (10 marks)

Emily is conducting an experiment to investigate the photoelectric effect. The apparatus is shown in Figure 24. It consists of a light source, a filter and a photocell (a metal plate with a collecting electrode in a vacuum tube).

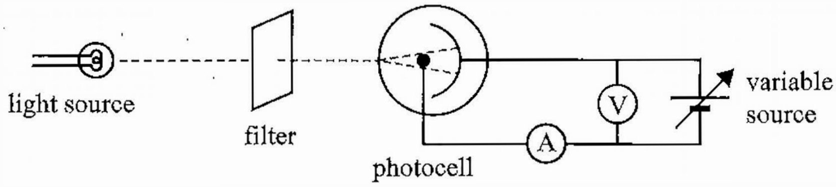


Figure 24

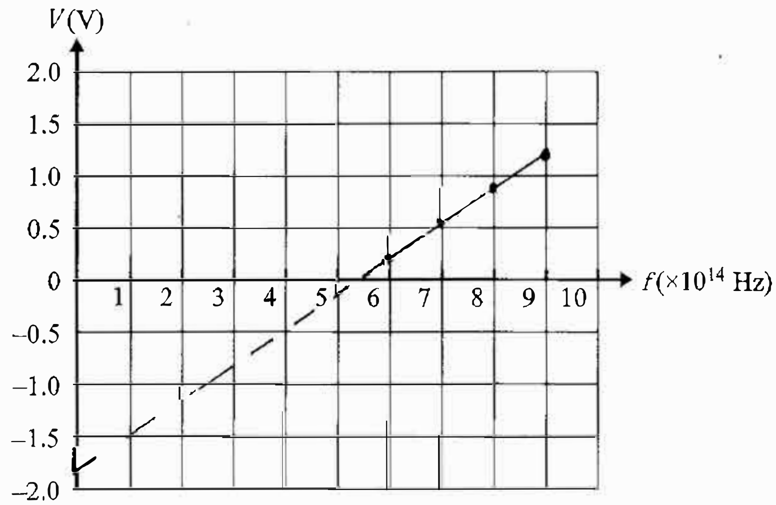
Emily uses various filters to shine a particular wavelength on the photocell.

She increases the voltage (V) until the current just goes to zero and records this voltage. Emily repeats this process for different frequencies.

Her results are shown in the table below.

Frequency (Hz)	Voltage (V)
6.0×10^{14}	0.16
7.0×10^{14}	0.52
8.0×10^{14}	0.88
9.0×10^{14}	1.20

a. On the axes below, plot Emily's data and draw the graph of voltage versus frequency. 81 % 2 marks



b. From the graph, determine the value Emily would have found for each of the following. 3 marks

34%

Planck's constant	$3.5 \pm 0.2 \times 10^{-15}$ eV s
Threshold frequency	5.5 ± 0.3 Hz
Work function of the metal	1.8 ± 0.2 eV

(± means allowed variation in student answers)

14% average 0.5

c. Explain how the recorded voltage measurements give information about the emitted photoelectrons. 2 marks

Voltage required to just stop fastest emitted electrons so represent the maximum Kinetic energy of electrons

d. For each frequency, Emily doubles the intensity of the incident light. 36% average 1.6

Describe the graph Emily will now obtain in comparison with the original graph. Do these two graphs support the wave model or particle model of light? Justify your answer. 3 marks

Graph same
Support particle theory of light
Energy of photons depends on f not intencity, intencity affect number of emitted electrons

Question 20 (7 marks)

A beam of electrons is produced in an electron gun.

The de Broglie wavelength of each electron is 0.36 nm.

a. Calculate the speed of the electrons. 51% 2 marks

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

$v = \frac{6.63 \times 10^{-34}}{9.1 \times 10^{-31} \times 3.6 \times 10^{-10}}$

2.0×10^{6} m s^{-1}

An experiment is undertaken to compare the diffraction of these electrons and X-rays. With a similar gap spacing, the diffraction patterns are found to be nearly identical.

b. Calculate the energy of the X-rays. Show each step of your working. 43% 3 marks

average 1.4

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

$E = \frac{4.14 \times 10^{-15} \times 3 \times 10^{8}}{3.6 \times 10^{-10}}$

3453 eV (3400–3500) was accepted

c. Explain why similar patterns are observed. 26% 2 marks

Diffraction depends on λ

Electrons have same λ.