Wave particle duality

Q1.

Figure 1 shows a modern version of the apparatus used by Hertz to investigate the properties of electromagnetic waves. Electromagnetic waves are continuously emitted from a dipole transmitter. The electromagnetic waves are detected by a dipole receiver.

An oscilloscope is used to display the amplitude of the detected signal at the dipole receiver.

Figure 1

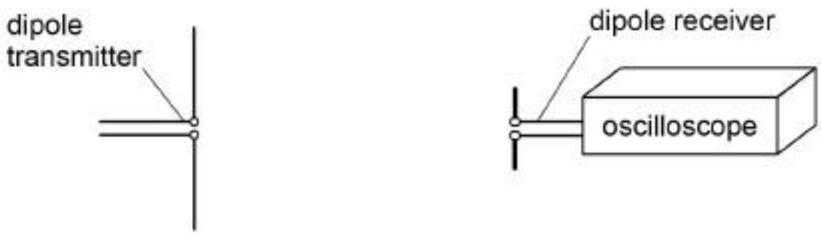
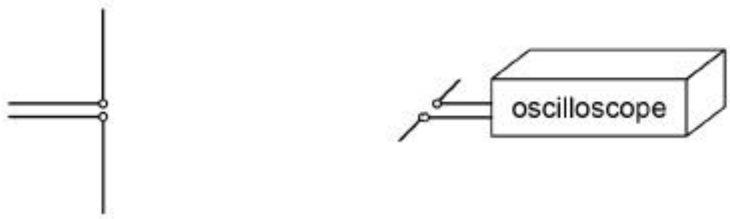


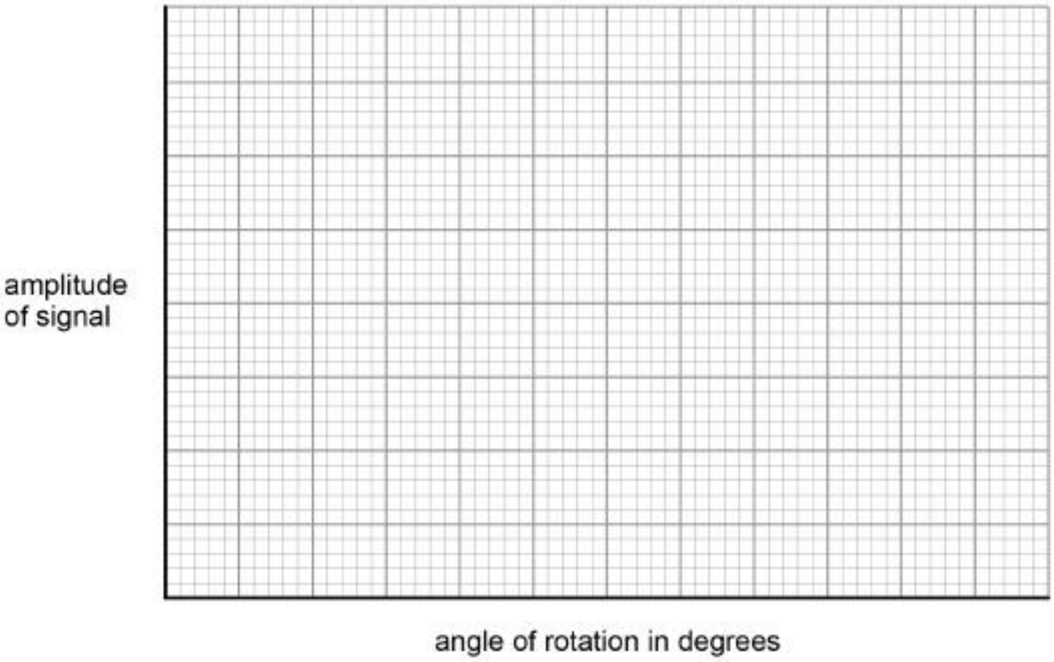
Figure 2 shows the same apparatus when the dipole receiver has been rotated through an angle of 90°

Figure 2



(a) Sketch a graph on **Figure 3** to show how the amplitude detected by the dipole receiver varies with angle of rotation as the receiver is turned through 360°
Start your graph from the position shown in **Figure 1**.

Figure 3



(3)

(b) Maxwell derived the equation $c = \dfrac{1}{\sqrt{\mu_0 \varepsilon_0}}$ for the speed c of electromagnetic waves, where μ_0 is the permeability of free space and ε_0 is the permittivity of free space.

Explain, using a suitable calculation, why this equation led to the conclusion that light is an electromagnetic wave.

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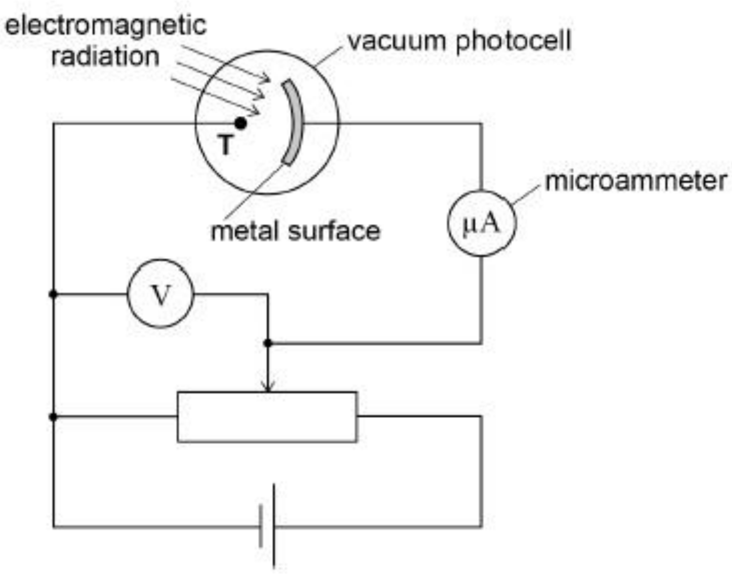
(2)

(Total 5 marks)

Q2.

The diagram shows a vacuum photocell in which a metal surface is illuminated by electromagnetic radiation of a single wavelength. Electrons emitted from the metal surface are collected by terminal **T** in the photocell. This results in a photocurrent, I, which is measured by the microammeter.



The potential divider is adjusted until the photocurrent is zero.

The potential difference shown on the voltmeter is 0.50 V

The work function of the metal surface is 6.2 eV

(a) Calculate the wavelength, in nm, of the electromagnetic radiation incident on the metal surface.

wavelength = ____________________ nm

(3)

(b) The intensity of the electromagnetic radiation is increased. No adjustment is made to the potential divider.

The classical wave model and the photon model make different predictions about the effect on the photocurrent.

Explain the effect on the photocurrent that each model predicts and how experimental observations confirm the photon model.

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(3)

(c) The potential divider in the diagram is returned to its original position so that a photocurrent is detected by the microammeter.
The potential divider is then adjusted to increase the potential difference shown on the voltmeter.

Explain why the photocurrent decreases when this adjustment to the potential divider is made.

(2)

(d) The apparatus shown in the diagram above is used to investigate three different metal surfaces **A**, **B** and **C**.
The table shows, for each of the three surfaces, a voltmeter reading V and the corresponding photocurrent I. The same source of electromagnetic radiation is used throughout the investigation.

	V/V	I/μA
Metal surface **A**	1.5	56
Metal surface **B**	2.5	56
Metal surface **C**	2.5	78

Which conclusion about the relationship between the work functions of **A**, **B** and **C** is correct?

Tick (✓) the correct box.

A > B > C. ☐

A < B < C. ☐

B > A > C. ☐

B < A < C. ☐

(1)
(Total 9 marks)

Q3.

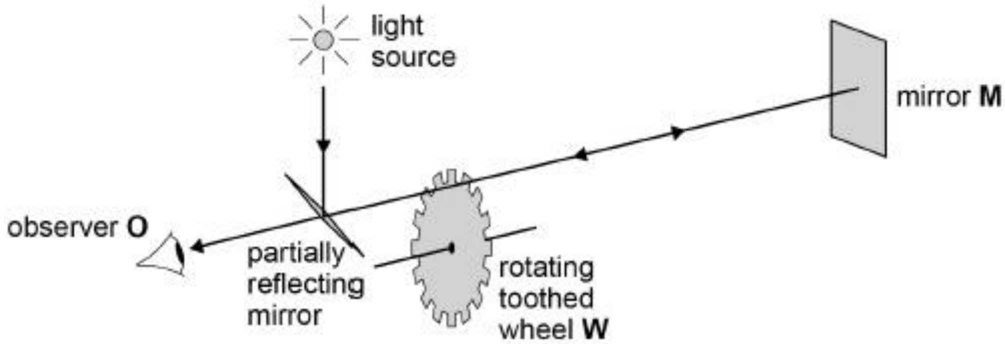
Which statement suggests that electrons have wave properties?
Tick (✓) the correct answer.

Electrons are emitted in photoelectric effect experiments.	☐
Electrons are released when atoms are ionised.	☐
Electrons produce dark rings in diffraction experiments.	☐
Electron transitions in atoms produce line spectra.	☐

(Total 1 mark)

Q4.

The diagram shows the apparatus Fizeau used to determine the speed of light.



The following observations are made.

A When the speed of rotation is low the observer sees the light returning after reflection by the mirror **M**.

B When the speed of the wheel is slowly increased the observer continues to see the light until the wheel reaches a certain speed. At this speed the observer cannot see the light.

(a) Explain these observations.

Observation A

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____

Observation B

(2)

(b) The table shows data from Fizeau's experiment at the instant when observation B is made.

d, distance from **M** to **W**	8.6 km
f, number of wheel revolutions per second	12
n, number of teeth in the wheel	720

It can be shown that the speed of light c is given by the equation

$$c = 4dnf$$

Discuss whether the data in the table are consistent with the present accepted value for the speed of light.

(2)

(c) The speed of the wheel is further increased.

Deduce the value of f when the observer would next be unable to see light returning from the mirror.

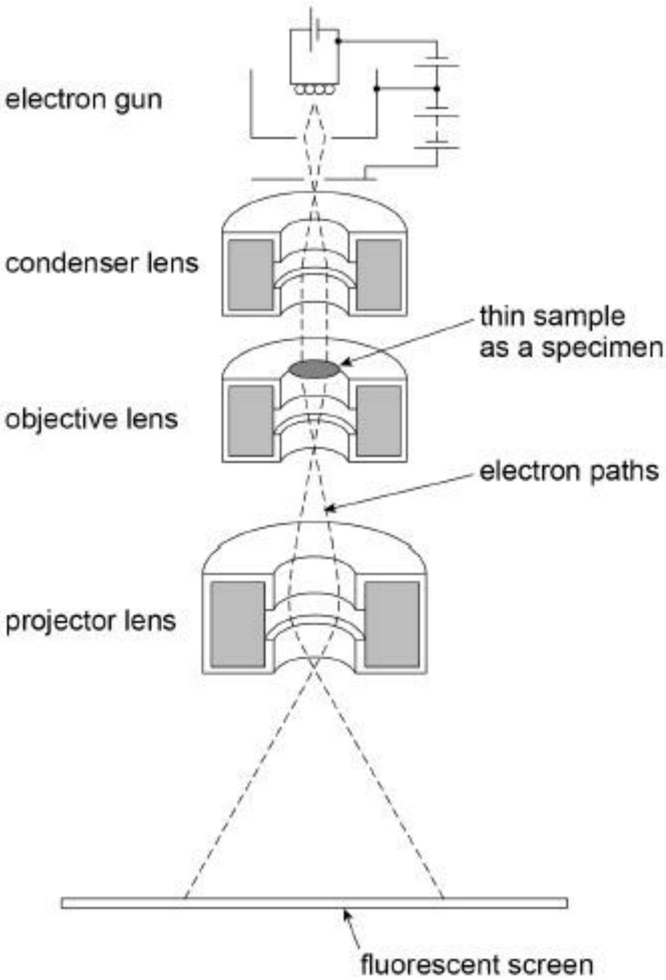
(2)

(d) Explain how the nature of light is implied by Maxwell's theory of electromagnetic waves and Fizeau's result.

(3)
(Total 9 marks)

Q5.

The diagram shows the main parts of a transmission electron microscope (TEM).



(a) What is the process by which electrons are produced in an electron gun?
Tick (✓) the correct box.

Beta particle emission	☐
Electron diffraction	☐
Photoelectric effect	☐
Thermionic emission	☐

(1)

(b) The electrons in a particular TEM have a kinetic energy of 4.1×10^{-16} J.
Relativistic effects are negligible for this electron energy.

Suggest, with a calculation, whether the images of individual atoms can, in principle, be resolved in this TEM.

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(3)

(c) A typical TEM can accelerate electrons to very high speeds and form high resolution images.

Explain:

- the process of image formation, and
- the factors that affect the quality of, and the level of detail in, the image.

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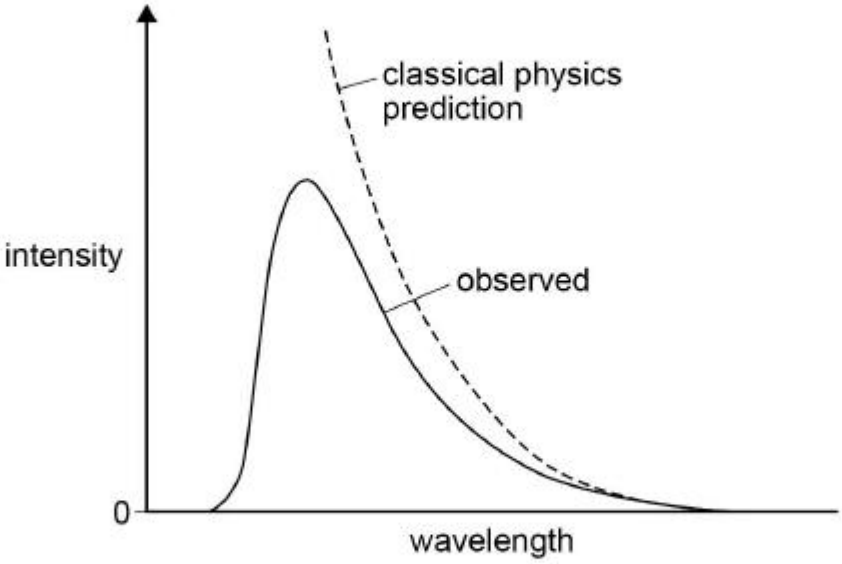
(6)

(Total 10 marks)

Q6.

The solid line on the graph below shows how the intensity of radiation from a black body varies with wavelength at a particular temperature. The dotted line shows the variation as predicted by classical physics.



(a) Explain why the difference between the predicted and experimental curves is called the ultraviolet catastrophe.

(2)

(b) Describe the difference between the classical physics view and the quantum theory proposal made by Max Planck that enabled the distribution of the shape of the intensity−wavelength graph to be correctly predicted.

(2)

(c) Discuss the evidence that the photoelectric effect provides in support of the quantum theory.

(3)
(Total 7 marks)

Q7.

In a transmission electron microscope (TEM) electrons are accelerated by a potential difference V between a cathode and anode. The de Broglie wavelength λ of the accelerated electrons depends on V.

(a) Identify which of the following represents the relationship between λ and V. Ignore relativistic effects.

Tick (✓) the correct answer in the right−hand column

	✓ if correct
$\lambda \propto \sqrt{V}$	
$\lambda \propto V$	
$\lambda \propto \frac{1}{V}$	
$\lambda \propto \frac{1}{\sqrt{V}}$	

(1)

(b) TEMs operate using wavelengths of about 0.1 nm.

Explain why operation at such wavelengths makes the instrument such an important research tool.

(2)

(c) State and explain **two** factors that limit the detail in the image produce by a TEM.

1 ______

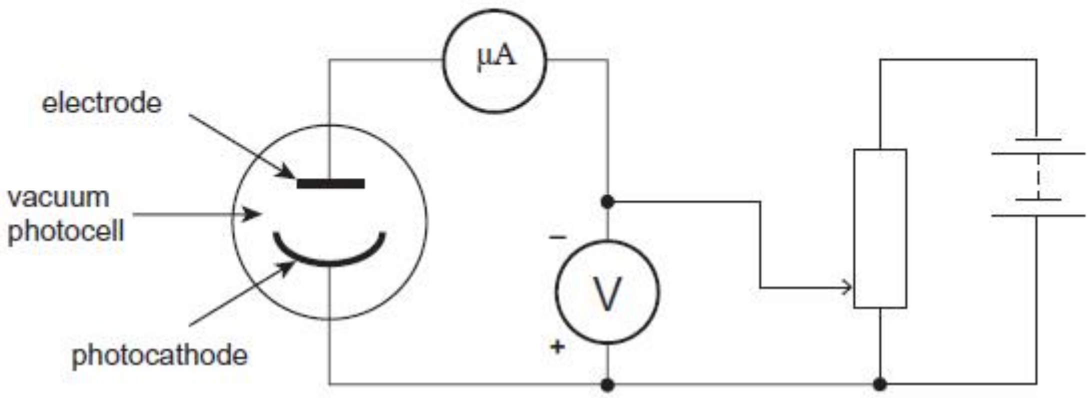
2. ______

(4)

(Total 7 marks)

Q10.

(a) The arrangement shown in the diagram is used by a student in a photoelectric effect experiment.



Monochromatic light falls on the photocathode. A current is recorded when the potential difference (pd) between the photocathode and the electrode is zero. The student gradually increases the magnitude of the pd between the photocathode and electrode and makes observations of the effect this has on the current.

Describe and explain the observations that you would expect the student to make. In your answer you should refer to:

- the stopping potential
- the kinetic energy of the photoelectrons

- how Einstein's photoelectric equation applies to this experiment.

The quality of your written communication will be assessed in your answer.

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(6)

(b) Using the circuit in the diagram, the stopping potential recorded is 0.24 V when light of wavelength 490 nm is incident on the surface of the photocathode.

(i) Calculate the work function of the surface material.

work function = ____________________ J

(3)

(ii) The polarity of the battery in the diagram is now reversed and light of 490 nm is incident on the photocathode. The energy of the light falling on the surface of the photocathode each second is 6.1 μJ.

Calculate the maximum current that the microammeter could record.

maximum current = ____________________ μA

(2)

(Total 11 marks)

Q11.

(a) Maxwell predicted the existence of electromagnetic waves that travelled in free space.

Identify the **two** quantities that vary in an electromagnetic wave and state the phase relationship between them.

Quantity 1 ____________________

Quantity 2 ____________________

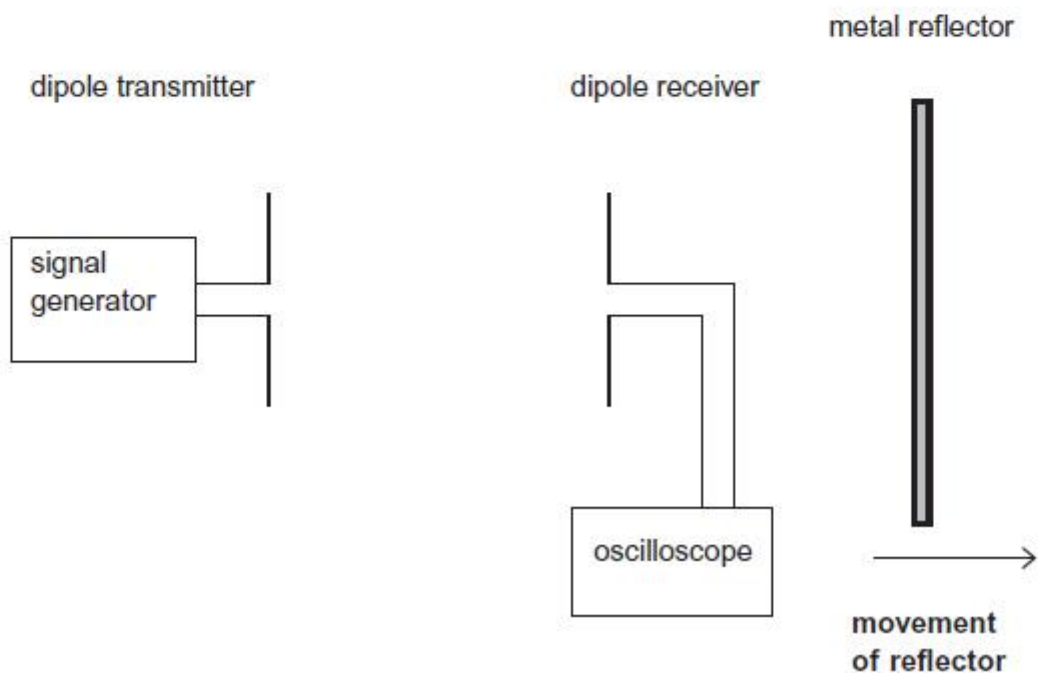
____

Phase relationship ____________________

____

(2)

(b) Hertz determined the speed of electromagnetic waves and found that they travelled at 3.0×10^8 m s^{-1}. The diagram shows an arrangement using radio waves that is similar to that used by Hertz in his determination.



The dipole transmitter radiates an electromagnetic wave of frequency 2.2 GHz.
A signal is detected by the dipole receiver.
When the metal reflector is moved in the direction shown in the diagram, the detected signal strength alternates between maximum and minimum intensities.

(i) Explain why the detected signal strength changes from a maximum to a minimum as the metal reflector is moved.

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(3)

(ii) Determine the least distance the reflector has to move for the detected signal strength to change from a maximum to a minimum to confirm Hertz's value for the speed of electromagnetic radiation.

least distance = ____________________ m

(2)

(iii) Which **one** of the following observations originally led to the conclusion that light is an electromagnetic wave?

Place a tick (✓) in the right-hand column to show the correct answer.

	✓ if correct
Light is diffracted when it falls on a narrow slit.	
Light travels at 3×10^8 m s^{-1} in free space.	
Light changes speed when it enters a medium of different optical density.	
Light can be polarised when it passes through Polaroid.	

(1)

(Total 8 marks)

Q12.

(a) (i) Describe how Newton used the corpuscular theory to explain the refraction of light as it passes from one substance into a substance of higher optical density.

____

____

(3)

(ii) Huygens used a wave theory to explain refraction.

Explain why the corpuscular theory was rejected in favour of a wave theory to explain refraction.

(2)

(iii) Describe and explain the difference in the appearance of the fringes in Young's double-slit experiment that are predicted by the corpuscular theory and by the wave theory for light.

(2)

(b) Electromagnetic waves and matter are now known to exhibit both particle and wave behaviour. The photons for a particular X-ray wavelength have energy 5.0 keV.

Calculate the potential difference through which an electron has to be accelerated so that its de Broglie wavelength is the same as that of this X-ray.

(4)
(Total 11 marks)

Q1.

(a) Pattern shows:

Maximum at start and shows minimum of zero (never negative) ✓

Correct periodicity zeros/maxima 180° apart ✓

(ie angles in right places)

Curvature rather than spikes ie 

(The graph should fall to zero – (NB First and last parts should ideally be curved not as illustrated here)

If negative then can get second mark only

Assume that bottom of graph grid is zero unless otherwise stated

Must be numbers on x-axis

Ignore if graph shows what happens beyond 360

If only one minimum shown then loses this mark

Allow if shown starting at zero

Freehand sketch so allow if clear attempt to show curvature in most of sketch or arches

3

(b) Correct substitution leading to a calculation of the speed of electromagnetic wave

$\frac{1}{\sqrt{(4\pi \times 10^{-7})(8.85 \times 10^{-12})}}$ = 3.0 (2.9986) × 10^{8} m s^{-1}

1

Comment that this speed agrees with the measured speed of light

Or speed determined from experiments

Or similar to Fizeau's result

1

[5]

Q2.

(a) Converts 6.2 eV, 0.5 eV or 6.7 eV to J
eg 6.2 × 1.6 × 10^{-19} J or 9.9(2) × 10^{-19} seen
for 0.5 eV 8.0 × 10^{-20} seen
for 6.7eV 1.07 × 10^{-18} seen ✓

$\lambda = \frac{hc}{E}$ or substitution $E = \frac{6.63 \times 10^{-34} \times 3 \times 10^{8}}{\lambda}$

With one of the above values included for energy✓

190 (185,186 or 187) nm ✓

NB use of λ=h/mv is a PE and scores 0

May use $f = \frac{E}{h}$ *and then* $\lambda = \frac{c}{f}$

Treat incorrect E in the same way

Guidance

Use of 0.5 eV gives 4.0 × 10^{-25}

6.2 eV 3.2 × 10^{-26}

6.7 eV 3.0 × 10^{-26}

These will score 1

8.0 × 10^{-20} gives 2500 nm

9.9(2) × 10^{-19} 200 nm

These will score 2

1 sf answers are not allowed so correct working with answer 186 nm rounded to 200 nm will also score 2

1
1
1

(b) **Classical Wave Model**

Wave model predicts an increase in the photocurrent
Plus one from

- As energy transferred into each electron increases (over time) /energy of the emitted electrons increases
- Electrons can gain sufficient KE to reach T
- Electrons can leave the surface with greater KE✓

Photon Model

The photon model predicts no change in the photocurrent
Or photocurrent remains at zero ✓

One from

- The energy of a photon depends on the frequency not the intensity
- Energy of each incident photon remains the same
- KE of electrons leaving the surface does not change
- Electrons released are still unable to reach T✓

NB The response has to discuss the effect of each theory on the maximum KE of the electrons when they leave the surface

Discussions that relate to threshold frequency or delay before emission are not relevant

3

(c) Fewer electrons will have sufficient energy to move away from the surface/or to reach T/anode
Or
Electrons need more energy to cross the gap
Or
Some of the electrons released were more tightly bound to the surface
Or

Electrons have a range of energies(when emitted from surface)
or
Some electrons use more of the photon energy to escape from the surface (this is related to the energy of the photoelectrons). ✓

Fewer electrons per second have sufficient kinetic energy to reach T scores 2

1

Fewer electrons per second/rate at which electrons reach T will reach terminal T/cross the gap
(the per second part captures what is going on in terms of the current)✓

Do not allow

Fewer photoelectrons per second flowing through the circuit

1

(d) A > B > C ✓

1

[9]

Q3.

3rd box

(Electrons produe dark rings in diffraction experiments) ✓

[1]

Q4.

(a) Observation A – When rotation speed is low the light returns through the original gap. ✓

Condone an answer where candidate has substituted tooth for gap throughout.

1

Observation B – The light is blocked when it hits an adjacent tooth on return from the mirror. ✓

1

(b) $c = 4 \times 8600 \times 720 \times 12 = 2.97 \times 10^8\ ms^{-1}$ ✓

1

Comparison to speed of light $3.0 \times 10^8\ ms^{-1}$ and judgement that they are similar. ✓

Speed of light must be given to 2 or 3 significant figures.

1

(c) Must go past a gap and to the next tooth ✓

Accept a clear diagram as an alternative

36 rotations per second / Hz ✓

2

(d) Maxwell's theory of electromagnetic waves predicted a value for the speed of electromagnetic waves ✓

Fizeau's result is close to the predicted speed (of electromagnetic waves) ✓

Implies that light is an electromagnetic wave. ✓

3

[9]

Q5.

(a)

	Tick (✓) if correct
Beta particle emission	
Electron diffraction	
Photoelectric effect	
Thermionic emission	✓

1

(b) Use of $\lambda = \frac{h}{\sqrt{(2mE)}}$ seen including correct substitution

1

$\lambda = 2.4 \times 10^{-11}$ (m)

1

Statement to the effect that this is similar to or less than 0.1 nm/atomic dimension/diameter of the atom (so individual atoms can be resolved).

1

Condone missing unit

Allow a correct conclusion that follows from an incorrect value of λ

3

(c) **The mark scheme gives some guidance as to what statements are expected to be seen in a 1 or 2 mark (L1), 3 or 4 mark (L2) and 5 or 6 mark (L3) answer.**

Guidance provided in section 3.10 of the 'Mark Scheme Instructions' document should be used to assist in marking this question.

Mark	Criteria	QoWC
6	At least six of the likely statements will be covered to a good standard including at least three from image formation and at least three from quality and detail.	The student presents relevant information coherently, employing structure, style and SP&G to render meaning clear. The text is legible.
5	At least five of the likely statements will be covered to a good standard including at	

	least two from image formation and at least one from quality and detail.	
4	At least three of the likely statements will be covered to a good standard. The response must include one of both image formation and factors affecting quality and detail.	The student presents relevant information and in a way which assists the communication of meaning. The text is legible. SP&G are sufficiently accurate not to obscure meaning.
3	At least two of the likely statements will be covered to a good standard. The response must include one of both image formation and factors affecting quality and detail.	
2	At least two of the likely statements from image formation or quality and level of detail will be covered to a good standard. The other area (if covered) will have errors and omissions.	The student presents some relevant information in a simple form. The text is usually legible. SP&G allow meaning to be derived although errors are sometimes obstructive.
1	One of the likely statements will be covered to a good standard.	
0	No relevant coverage of the likely statements.	The student's presentation, SP&G seriously obstruct understanding..

The following statements are likely to be present.

<u>Process of Image formation</u>

- Electrons through the middle of the lenses are undeviated
- Electrons on the edges are deflected by magnetic fields toward the axis of the TEM
- The condenser lens deflects the electrons into a wide parallel beam incident uniformly on the sample.
- The objective lens then forms an image of the sample.
- The projector lens then casts a second image onto the fluorescent screen.

Factors affecting the quality and level of detail

- Wavelength depends on speed of the electrons
- Lower the wavelength gives greater the detail.
- Emitted electrons come from a heated cathode and therefore have a speed distribution dependent on temperature.
- The speed of the electrons is not always the same which causes different pathways through the lens and so aberration.
- The sample thickness reduces the speed of the electrons increasing the wavelength and decreasing the detail.

[6]

Q6.

(a) The observed and prediction using classical physics do not agree for short wavelengths.✓

This disagreement is in the ultraviolet part of the spectrum.✓

2

(b) In classical physics radiation is emitted as a continuous wave.✓

Planck proposed that energy is emitted in discrete amounts quanta.
or
Proposed that the energy of a quantum is *hf* where *f* is the frequency of the radiation.✓

2

(c) To remove electron from a surface requires a particular amount of energy / mention of work function.✓

In classical physics the energy arrives continuously so all frequencies should liberate electrons.✓

In practice, electrons are liberated only when frequency exceeds threshold (value) OWTTE.✓

3

[7]

Q7.

(a) $\lambda \propto \frac{1}{\sqrt{V}}$

1

(b) The resolution is improved for shorter wavelengths or shorter wavelengths enable more detailed images.✓

0.1 nm is the same order of magnitude as the diameter of an atom.✓

2

(c) Image not accurately focused / blurred✓

Due to electrons not all having the same speeds so focused to different points by the magnetic lenses.✓

Electrons slowed down passing through the sample.✓

Wavelength changes by different amounts as they pass through the sample so each wavelength diffracted differently.✓

4

[7]

Q10.

(a) **Marks awarded for this answer will be determined by the Quality of Written Communication (QWC) as well as the standard of the scientific response. Examiners should apply a 'best-fit' approach to the marking.**

Level 3 (5—6 marks)
Answer is full and detailed and is supported by an appropriate range of relevant points such as those given below:
- argument is well structured with minimum repetition or irrelevant points
- accurate and clear expression of ideas with only minor errors in the use of technical terms, spelling and punctuation and grammar

Level 2 (3—4 marks)
Answer has some omissions but is generally supported by some of the relevant points below:
- the argument shows some attempt at structure
- the ideas are expressed with reasonable clarity but with a few errors in the use of technical terms, spelling, punctuation and grammar

Level 1 (1—2 marks)
Answer is largely incomplete. It may contain valid points which are not clearly linked to an argument structure.
Unstructured answer
Errors in the use of technical terms, spelling, punctuation and grammar or lack of fluency

Level 0 Nothing of relevance

examples of possible points in the response

Observations
- Initially ammeter record current
- as pd increases the current decreases
- eventually current becomes 0

Emissions
- Photons / light cause emission of electrons
- Emitted electrons have KE (if photon energy > work function
- pd tends to stop emitted electrons reaching the electrode / anode (**not** stop electrons being emitted)
- Recognises that the electrode is negative w.r.t. the cathode or vice versa
- Recognises that there are a range of electron KEs
- Explains why there is a range of KEs
- Electrons with low energy stopped (first) so current decreases

Stopping potential

- The potential between the electrodes when the current = 0
- The potential that prevents electrons reaching the anode / electrode
- Stopping potential depends on maximum electron KE

Application of Einstein equation

- Use of $E_{k(max)} = hf - \varphi$
- Defines terms
- Explain / identifies that stopping potential × electron charge = atoms / molecules / electrons $V_s e = E_{k(max)}$

extra information

5-6 *will address 3 aspects well or all 4 with minor omissions in coherent response*

3-4 *will address three of the points with significant omissions or eg give good response to 2 parts*

1-2 *may give brief but relevant comments on*

• the emission

• what is meant by stopping potential

• Some attempt to apply Equation

0 *makes no relevant comment*

6

(b) (i) Kinetic energy of emitted electrons = $0.24 \times 1.6 \times 10^{-19}$ **or** 0.38×10^{-19}(J) seen ✓

energy of photon incident = $6.63 \times 10^{-34} \times 3 \times 10^{8} / 490 \times 10^{-9}$ or 4.06×10^{-19}(J) seen ✓

Work function = 3.68×10^{-19} (J) ✓

Or

energy of photon incident = $6.63 \times 10^{-34} \times 3 \times 10^{8} / 490 \times 10^{-9} = 4.06 \times 10^{-19}$(J) ✓

(energy of photon incident = 2.54 eV so) work function = 2.30 eV ✓

Work function = 3.7 (3.68) × 10^{-19} (J) ✓

Must see all values substituted to get the mark by substitution

3

(ii) No of electrons emitted = 6.1×10^{-6}/ their photon energy(1.5(1.48) × 10^{13} if correct) ✓

Current = Their electron number × 1.6×10^{-19} (2.4(2.37) μA if correct) ✓

Allow for first mark only

6.16×10^{-6}/work function

(1.65×10^{13})

Allow ecf for incorrect calculation of photon energy from (b))(i) or first step

2

Q11.

(a) electric field strength **and** magnetic flux density / magnetic field strength ✓

They are in phase with each other ✓
OR Phase difference = 0 (not 2π)

Allow E and B (not E field and B field)

Not electric field and magnetic field

Not allowed if quantities are mentioned are not related to electric and magnetic fields (e.g. frequency & wavelength) or no quantities given

2

(b) (i) Direct and reflected waves superpose
Waves arriving directly interfere with reflected waves.
Or Direct and reflected wave produce a stationary wave ✓

When a maximum constructive interference or explanation of condition and minimum destructive interference or explanation of condition Or maximum / constructive interference at antinode and minimum / destructive interference at a node ✓

Explains maximums / antinodes and minimums / nodes in terms of wavelengths, relative phase or path difference ✓
i.e.
there is constructive interference / antinode

- reflected wave travels whole number of wavelengths further
- path difference is whole number of wavelengths
- waves are in phase

destructive interference minimum/node when

- the direct and reflected waves interfere destructively
- the waves become antiphase / 180° out of phase
- path difference is $\lambda / 2$ or $(n+1/2)\lambda$

Do not allow superimpose

Do not allow out of phase

3

(ii) Wavelength = $\frac{3\times10^8}{2.2\times10^9}$ **or** 0.136 m (0.14) seen
or appreciates that the reflector has to move $\lambda/4$ ✓

0.034 or 0.035 (m) ✓

Penalise 1 sf answer

2

(c)

Light is diffracted when it falls on a slit	
Light travels as 3×10^8 m s^{-1} in free space	✓
Light changes speed when it enters a medium of	

different optical density	
Light can be polarised when it is passes through polaroid	

1

[11]

Q12.

(a) (i) Appreciation that one component changes speed while the other component at right angles does not ✓

When entering a denser medium a corpuscle / light accelerates or its velocity / momentum increases <u>perpendicular to the interface</u> ✓

There is a (short range) attractive force between light <u>corpuscle</u> and the (denser) material ✓

Not allowed:

Attraction due to opposite charges

Force making them move faster is not enough

Accelerate in medium

Not gains energy

3

(ii) Light (was shown by experiment to) travel slower in (optically) denser medium OWTTE ✓

Condone 'waves..' instead of 'light'

OWTTE e.g. speed in vacuum higher than speed in other medium

Newton's theory required light to travel faster, wave theory suggested slower speed ✓
or
Newton's theory could not explain the slower speed
or
Huygens theory could explain the slower speed

Not allowed:

Reference to Young's two slit- question asks them about refraction

2

(iii) A corpuscular theory predicts only two (bright) lines / high intensity patches of light whereas a wave theory predicts many fringes ✓

Corpuscles can only travel in straight lines
or
waves can produce fringes because (diffract and) interfere / superpose / arrive in and out of phase / have different path differences ✓

Need to describe the patterns ie not just interference fringes are seen for the first mark

2

(b) Substitutes data in photon wavelength = *hc / E* ; Allow for substitution with no conversion to J ✓

2.48×10^{-10} m ✓

For electron: Substitution in $\lambda = \frac{h}{\sqrt{2mE}}$

2.48×10^{-10}(or their λ)

$= 6.6 \times 10^{-34} / (2 \times 9.11 \times 10^{-31} \times 1.6 \times 10^{-19}\ V)^{1/2}$ ✓

No conversion to J gives $\lambda \approx 4 \times 10^{-29}$ and $V \approx 9 \times 10^{38}$ V)

V = 24(.4) V ✓ $= 1.49 \times 10^{-18} / (\text{their } \lambda)^2$ ✓

Allow small rounding errors in dp

May calculate v using $v = h / m\lambda$ then substitution in
$V = \frac{1}{2} mv^2 / e$ ✓ (for third mark)

4

[11]

Examiner reports

Q1.

(a) There were two particular reasons why students failed to gain marks in this question. The first was that the amplitude cannot be negative, and the second was a failure to include any scale on the angle axis. Sketches were often quite poor, but these were treated generously providing the important features were shown. Some attempt to show curvature was expected to gain the final mark. Full marks were awarded to 42.5% of students.

(b) The straightforward substitution of data and computation gained the first mark. Substitution of the data was expected. The second mark was less frequently awarded (28.9% of students). The fact that Maxwell's result agreed with a measured or experimental value was essential. That Maxwell's equation for the speed gave a value that agreed with the 'accepted value' was insufficient.

Q2.

(a) All parts of question 3 exposed misunderstanding about the photoelectric effect. Part (a) tested application of the photoelectric equation. Firstly, to determine the wavelength, data in eV had to be converted to Joule somewhere in the response. The 0.50 V was the stopping voltage which relates to the maximum KE of an emitted electron in eV. This, added to the work function, gave the energy of the photon which produced this electron in eV. Then the equation $\lambda = hc/E_k$, with E_k in J, gave the answer. There was a good proportion (over 40%) of correct answers. The most common incorrect response used the work function alone to determine the wavelength with various other combinations of the energies in eV or J. Some made incorrect attempts to convert eV to J.

(b) A large number of students seemed not to have read this question carefully enough – there were relatively few convincing responses. Many responses explained why the photon model could explain why there is threshold frequency, which is not what was asked. In this question, there is no change to the incoming radiation other than intensity. Some students commented that as intensity increased there would be more photons arriving, so the number of photoelectrons produced would increase, so current would increase. However, what determines the current is not the number of electrons that are emitted but the number that can reach T. As the photon energy is fixed, students needed to appreciate that current could only increase if more electrons could reach T. As the maximum KE of the photons is the same, even though there are more of them, none can reach T so the current is unchanged. A high intensity wave could transfer, resulting in electrons with more KE, so these could reach T, producing a higher current. Over half of the students failed to score on this question.

(c) Just over a fifth of the students were able to make a comment that gave access to the first mark in the marking scheme, but very few of these referred to the current depending on the rate at which electrons reached T. In this part, the key knowledge of the photoelectric effect is that electrons are emitted with a range of kinetic energies. Students needed to appreciate that initially a current exists because, as there is no stopping voltage, all emitted electrons can reach T. As T becomes increasingly negative with respect to the metal surface, more and more electrons with KE less than the maximum KE cannot reach T. Nearly 70% of students made no headway at all with this question.

(d) 40% of the students identified the correct response.

Q3.

Students should be reminded to make it clear which answer they have chosen, and to avoid putting marks in more than one box. It was very accessible, with over 70% obtaining the mark.

Q4.

(a) Although many responses were detailed and showed understanding of Fizeau's experiment, few students explained with sufficient precision observations A and B. For observation A, a response explaining that light returned through the same gap was expected, while for observation B the correct response was that the light was blocked by the adjacent tooth.

(b) Few students had trouble with what proved to be a straightforward calculation. An explicit value for the accepted speed of light, to at least two significant figures, was expected, along with a statement of comparison to the calculated value. A large number of students failed to work with this level of care and attention to detail.

(c) An answer that was based on recall was not accepted as a deduction. Only a small fraction of students were able to construct a convincing deduction, although a good number were able to give the correct value for the frequency of rotation. The minimum expected as a deduction was that the light would be blocked at the next tooth.

(d) A good proportion of responses were well rehearsed to form a clear chain of logic between Maxwell's predicated speed for EM waves, congruence with Fizeau's result, and the implication that light is an EM wave. Some students went only as far as stating that Maxwell's theory predicted a value for the speed of light, meaning that the argument could not be completed. Another common mistake was to focus on various experimental results that show the wave nature of light or other electromagnetic waves.

Q5.

(a) A very high proportion of students scored this simple recall mark.

(b) The calculation was done well by many students. Some students used an energy argument rather than the more straightforward direct substitution from the formula sheet. Where students did follow an energy argument, a common mistake was to confuse potential difference with velocity. Students in general were reasonably successful in arguing whether the electrons could resolve atoms. Few students were able to recall and use the approximate size of an atom and compare their value for the de Broglie wavelength with this; for those who did make some progress in this regard, a common mistake was to confuse the dimensions of the atom and nucleus.

(c) This question produced a wide range of levels of performance. Many students used the diagram provided to help structure their response to how the image was formed, and could support their answer with some detail about how the quality of the image was affected by the speed of the electrons. This meant that most responses fell into the middle band of performance, which was encouraging. The best responses named and described the function of three lenses well and went on to explain how resolution depended on the speed, and hence de Broglie wavelength, of the electrons. Some students were also able to detail how speed varied due to sample thickness and thermionic emission. Very few students explained sufficiently well how the electrons that travel through the centre of the TEM are unaffected by the lenses.

Q10.

(a) Responses that stated clearly the observations and gave convincing explanations were rare. Many did not answer the question and described the theory of the photoelectric effect without getting to the point of giving the effect on the current of the changing the potential difference in this experiment. Most who made a sensible attempt at the question stated that when the pd was established between the electrodes, the cathode would be increasingly positive. This was accepted although they should have mentioned that it was more positive with respect to the electrode and it would have been better to refer to the electrode becoming more negative. Students often referred to the stopping potential as the pd when the current was zero and then went on to try to explain the relationship between the stopping potential and the maximum kinetic energy. However, a significant proportion of the students incorrectly stated that V was equal to the maximum kinetic energy rather than eV.

The part of the explanation that was very poorly explained or not examined at all was why there would be a gradual decrease in the current up to the point when the stopping potential occurred. Relatively few discussed that electrons were emitted with a range of kinetic energies and the reason for this. Even those who did so often did not explain clearly why this leads to a gradual decrease in current as the pd increases. Some stated that all electrons were emitted with the same KE and the pd simply slowed them down so reducing the current.

Many argued that as the pd increases the maximum KE of the emitted electrons decreases to the point where no electrons are emitted at all and that some of the KE given to electrons by the photon is used up inside the metal to overcome the potential of the cathode. It is not clear in such explanations why an electrode that is at a constant potential (being connected to the positive terminal of the battery, and could even be earthed) can affect the energy needed remove an electron or, as many students put it, increase the work function. These students often did not refer to the stopping potential as the unique value that occurs for the maximum electron KE possible for a given photon energy but referred to every setting of the pd as the stopping potential. Their arguments often then confused the maximum KE of the electrons for any setting of the pd with the maximum KE that exists at the stopping potential as defined in the Einstein equation.

(b) (i) This was generally very well done. There were two steps in this calculation before the easy final step of subtracting the maximum KE of the emitted electrons from the photon energy. Firstly, the photon energy had to be calculated from hc/λ. This gives the photon energy in J. Some students thought the unit to be ev so multiplied by e to determine the photon energy. Secondly the maximum KE of the electron in J had to be found form eV_s(V_s being the stopping potential). Using this approach had less chance of error than that used by converting the photon energy to ev doing the subtraction in ev and then reconverting the answer to J. The use of incorrect powers of 10 were also a pitfall in this question.

(ii) This proved to be a demanding and low scoring question that provided a significant test of understanding. The current depends on the number of electrons n emitted per second and is equal to ne. The number of electrons emitted depends on number of photons per second arriving at the photocathode. The maximum current is when each of these photons causes the emission of an electron. The common misconception was to divide the energy arriving per second by the work function which could only be possible using a wave theory in which all electrons were emitted with zero KE.

Q11.

(a) This relatively straightforward question was not well done. Electric field and magnetic field were often quoted as the quantities. Many gave two properties of waves such as frequency and wavelength. Students were expected to recall that in an electromagnetic wave, electric field strength and magnetic flux density (or magnetic field strength) were the quantities that vary in phase with one another. The phase relationship mark could only be scored providing students gave some indication that electric and magnetic fields were relevant.

(b) (i) There were relatively few completely convincing responses. Firstly students needed to be clear as to what two waves were causing interference or stationary waves, the latter being a common basis for the explanation. A common statement was that the wave was ‘interfering with itself’. This does not convey the idea either of two waves travelling in opposite directions, as required for a stationary wave, or of the superposition of two waves, one coming directly form the transmitter and the other from the reflector. Students who used the incorrect scientific term ‘superimposing’ were penalised. Most students argued the basic idea of constructive Interference causing maximum amplitude and destructive a minimum but fewer went on to explain this in sufficient detail to score full marks. Some spoiled otherwise good responses by using the term ‘out of phase’ rather than antiphase, π or 180° when discussing minimum intensity.

(ii) Many students determined the wavelength successfully but fewer appreciated that the least distance moved by the reflector has to be $\lambda/4$ minimum distance so that the total path difference is $\lambda/2$.

(c) This question was answer correctly by almost half the students.

Q12.

(a) (i) Fewer than half the students were able to gain any credit in this question. Many only referred to the fact that light speeds up when it enters optically dense medium. Those who made progress often wrote vaguely about velocity change in one direction but not the other without reference to a surface or a reason of how this was explained in the theory. Some wrote ambiguously about light speeding up horizontally but not vertically without any reference to the orientation of the surface of the medium into which the light was entering.

(ii) Some students misread this question as why Newton’s reputation led to the theory being accepted rather than the wave theory. Discussion of the evidence from the measurement of the lower speed of light in dense material was required and an explanation that this contradicted the expectation from Newton’s corpuscular theory.

(iii) 80% of the students gained credit in this question and almost half of these gained both marks. Clear descriptions of the difference in the fringe patterns were often too vague but most gave an acceptable explanation of the difference in the expected patterns predicted by the two theories.

(b) This was well done by half the students who scored 3 or 4 of the available marks. Others who made progress usually arrived at the wavelength of the X-rays but did not know how to proceed.