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AQA A LEVEL PHYSICS (7408): QUESTIONS BY TOPIC

Turning points in physics (3.12)

A Level Physics (7408) · Section 3.12

37 questions · 315 marks · Mark schemes included

AQA A Level Physics (7408), June 2017 – June 2025

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 Piccadilly Business Centre, Unit C, Aldow Enterprise Park
Blackett Street, Manchester, M12 6AE

HOW TO USE THIS BOOKLET

Questions are grouped by specification sub-topic and run from the lowest mark tariff to the highest within each one.

Click any row below to jump straight to that sub-topic or question.

On every question page, click ANSWER in the top-right corner to jump to its mark scheme.

Diagrams, graphs, tables and data are printed exactly as they appeared in the original papers.

QUESTION	SOURCE	MARKS	PAGE
3.12.1 THE DISCOVERY OF THE ELECTRON		10 Qs · 95 marks	4
1. Q2	7408/3 Section B: Turning points in physics June 2023	6	5
2. Q1	7408/3 Section B: Turning points in physics June 2024	6	7
3. Q1	7408/3 Section B: Turning points in physics June 2017	7	9
4. Q1	7408/3 Section B: Turning points in physics June 2019	8	11
5. Q1	7408/3 Section B: Turning points in physics November 2020	8	14
6. Q1	7408/3 Section B: Turning points in physics June 2018	9	17
7. Q1	7408/3 Section B: Turning points in physics June 2023	11	20
8. Q2	7408/3 Section B: Turning points in physics June 2022	12	23
9. Q2	7408/3 Section B: Turning points in physics June 2024	12	26
10. Q1	7408/3 Section B: Turning points in physics June 2025	16	28
3.12.2 WAVE-PARTICLE DUALITY		16 Qs · 134 marks	32
11. Q2	7408/3 Section B: Turning points in physics June 2025	4	33
12. Q2	7408/3 Section B: Turning points in physics June 2018	5	34
13. Q3	7408/3 Section B: Turning points in physics June 2024	5	36
14. Q3	7408/3 Section B: Turning points in physics June 2022	6	37
15. Q3	7408/3 Section B: Turning points in physics June 2025	6	39
16. Q3	7408/3 Section B: Turning points in physics June 2019	8	40
17. Q3	7408/3 Section B: Turning points in physics November 2020	8	42
18. Q3	7408/3 Section B: Turning points in physics June 2023	8	44
19. Q2	7408/3 Section B: Turning points in physics June 2017	9	46
20. Q3	7408/3 Section B: Turning points in physics June 2018	9	49
21. Q3	7408/3 Section B: Turning points in physics June 2017	10	52
22. Q2	7408/3 Section B: Turning points in physics June 2019	10	54
23. Q2	7408/3 Section B: Turning points in physics November 2021	10	56
24. Q1	7408/3 Section B: Turning points in physics June 2022	11	59
25. Q2	7408/3 Section B: Turning points in physics November 2020	12	62
26. Q1	7408/3 Section B: Turning points in physics November 2021	13	64
3.12.3 SPECIAL RELATIVITY		11 Qs · 86 marks	67
27. Q5	7408/3 Section B: Turning points in physics June 2017	3	68
28. Q4	7408/3 Section B: Turning points in physics June 2017	6	69
29. Q3	7408/3 Section B: Turning points in physics November 2021	6	70
30. Q4	7408/3 Section B: Turning points in physics November 2021	6	71



QUESTION	SOURCE	MARKS	PAGE
31. Q4	7408/3 Section B: Turning points in physics June 2022	6	72
32. Q4	7408/3 Section B: Turning points in physics November 2020	7	74
33. Q4	7408/3 Section B: Turning points in physics June 2019	9	76
34. Q4	7408/3 Section B: Turning points in physics June 2025	9	78
35. Q4	7408/3 Section B: Turning points in physics June 2023	10	80
36. Q4	7408/3 Section B: Turning points in physics June 2018	12	82
37. Q4	7408/3 Section B: Turning points in physics June 2024	12	86



QUESTIONS

37 questions · 315 marks · 3 sub-topics



SUB-TOPIC 3.12.1

THE DISCOVERY OF THE ELECTRON

Sub-topic 3.12.1 · 10 questions · 95 marks · lowest tariff first



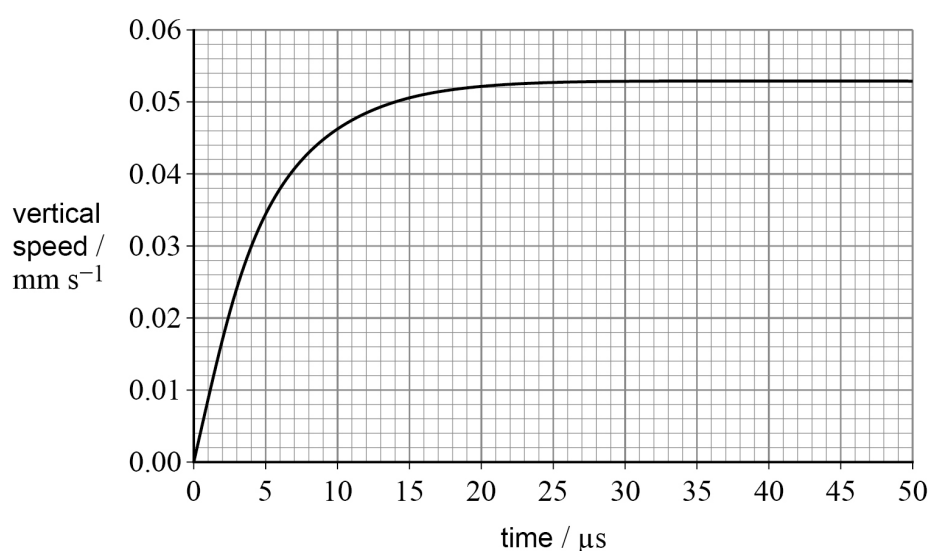
0 2

In an experiment to determine the electronic charge, a charged oil drop falls from rest between two uncharged plates.

The oil drop has a weight of 1.2×10^{-14} N and a radius of 6.8×10^{-7} m. Ignore the buoyancy force of the air on the oil drop.

Figure 2 shows the variation of the vertical speed of the oil drop with time.

Figure 2

**0 2 . 1**

Calculate the viscosity of the air between the plates.

[3 marks]

viscosity = _____ N s m^{-2}



0	2	.	2
---	---	---	---

During the experiment, an electric field is produced between the plates and is adjusted until the oil drop is stationary.
The electric field strength is 18.8 kV m^{-1} .

Discuss whether the outcome of the experiment is consistent with the accepted value for electronic charge.

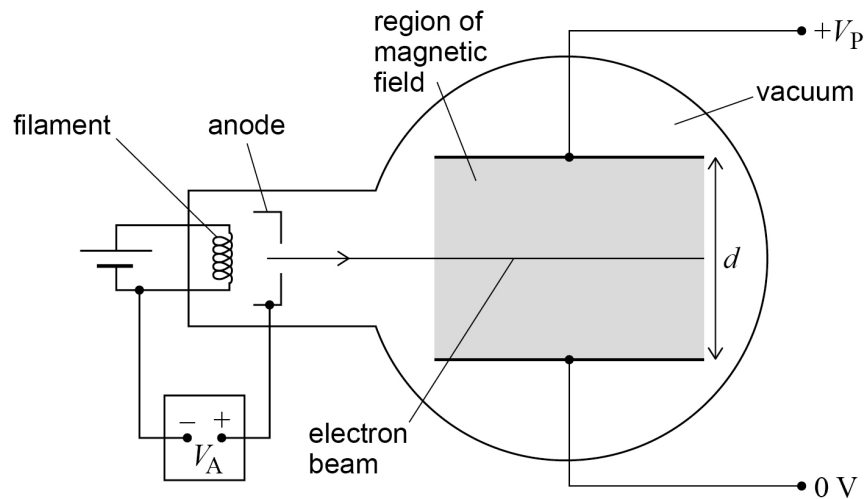
[3 marks]



0	1	.	1
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Figure 1 shows apparatus used in an experiment to measure the specific charge of the electron.

Figure 1



Electrons are accelerated by the potential difference V_A .

The electrons then enter the region between two parallel metal plates, shown shaded in **Figure 1**. The parallel metal plates are separated by a distance d with a potential difference V_p across them. In the same region there is a uniform magnetic field of flux density B into the plane of the diagram.

Explain why the electron beam is undeflected in the shaded region shown in **Figure 1**.
[2 marks]

0 1 . 2 Determine, using the following data, a value for the specific charge of the electron.

$$B = 1.59 \text{ mT}$$

$$V_{\text{p}} = 1.51 \text{ kV}$$

$$d = 5.0 \text{ cm}$$

$$V_{\text{A}} = 1.00 \text{ kV}$$

[4 marks]

specific charge = _____ C kg^{-1}

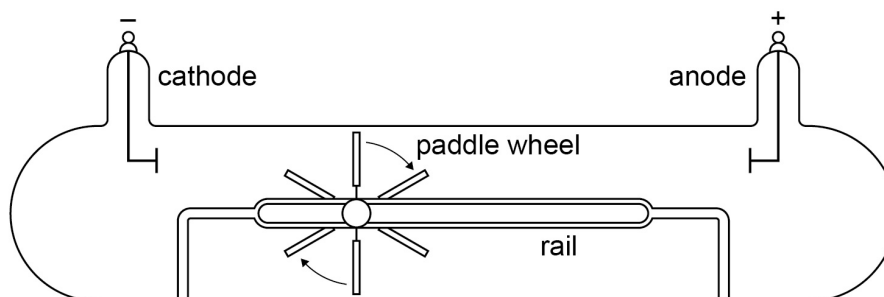


0	1
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Figure 1 shows a gas discharge tube devised by William Crookes in one of his investigations.

When a large potential difference is applied between the cathode and anode the paddle wheel is seen to rotate and travel along the rail towards the anode.

Figure 1



0	1	.	1
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Explain how this experiment led Crookes to conclude that cathode rays are particles and that these particles caused the movement of the paddle.

[2 marks]

0	1	.	2
---	---	---	---

Later experiments showed that cathode rays are electrons in motion.

Explain how cathode rays are produced in a gas discharge tube.

[3 marks]

0	1	.	3
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In a particular gas discharge tube, air molecules inside the tube are absorbed by the walls of the tube.

Suggest the effect that this absorption may have on the motion of the paddle wheel.

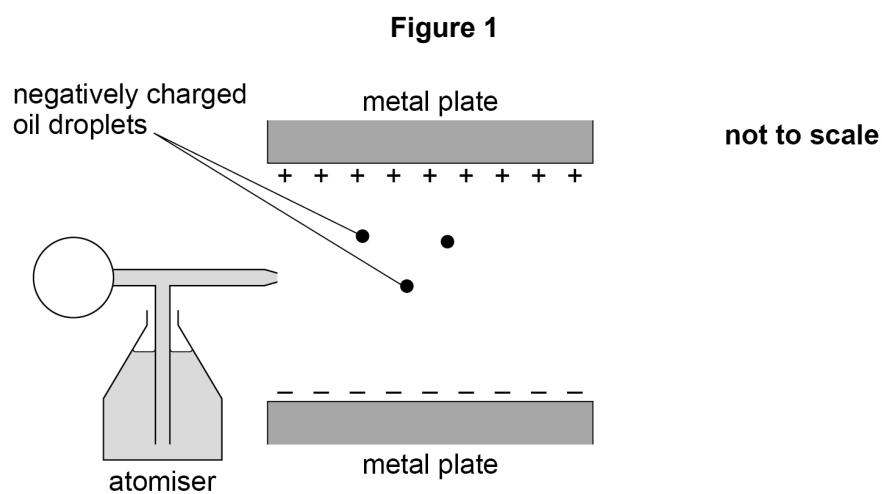
Give a reason for your answer.

[2 marks]



0	1
---	---

Figure 1 shows an experiment to measure the charge of the electron.



Negatively charged oil droplets are sprayed from the atomiser into the gap between the two horizontal metal plates. A potential difference is applied between the metal plates.

One of the droplets remains stationary.

0	1	.	1
---	---	---	---

Identify the forces acting on the stationary droplet.
In your answer you should state the relationship between the forces.

The upthrust on the droplet due to the air it displaces is negligible.

[2 marks]

0 1 . 2

The potential difference between the plates is changed to zero and the droplet falls at a terminal velocity of $1.0 \times 10^{-4} \text{ m s}^{-1}$.

The density of the oil is 880 kg m^{-3}

The viscosity of air is $1.8 \times 10^{-5} \text{ N s m}^{-2}$

Show that the radius of the droplet is about $1 \times 10^{-6} \text{ m}$.

Assume that the droplet is spherical.

[3 marks]

Question 1 continues on the next page



0	1	.	3
---	---	---	---

The potential difference between the plates is restored to its initial value and the droplet becomes stationary.

The charge on the droplet is $-4.8 \times 10^{-19} \text{ C}$.

A student suggests that, if the droplet splits into two spheres of equal size, both spheres would remain stationary.

Deduce whether this suggestion is correct.

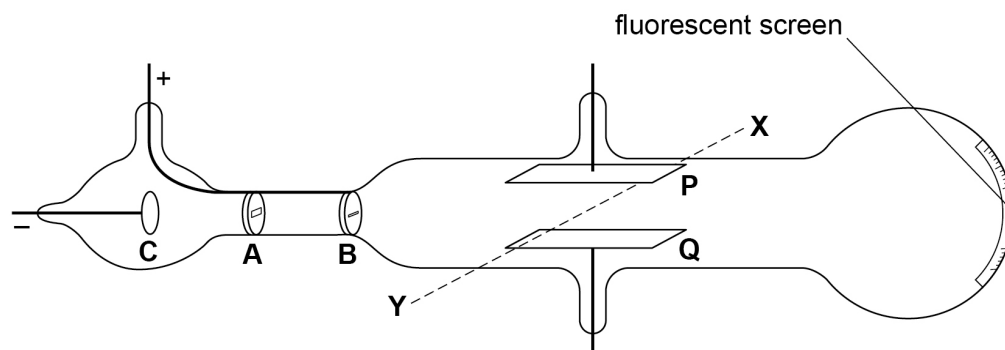
[3 marks]



0	1
---	---

Figure 1 shows a diagram of a discharge tube used by JJ Thomson to investigate cathode rays.

Figure 1



The direction **XY** is horizontal and at right angles to the axis of the tube.

0	1	.	1
---	---	---	---

When correct connections are made to a high-voltage power supply, a cathode ray is produced. The cathode ray hits the centre of the fluorescent screen.

Describe how a cathode ray is produced in the discharge tube in **Figure 1**.

[2 marks]

0 1 . 2

P and **Q** are metal plates that can be attached to a second power supply.

In an experiment, a potential difference (pd) is applied across **P** and **Q** so that **P** is positively charged and **Q** is negatively charged. This deflects the cathode ray.

Then a magnetic field is applied between the plates so that the cathode ray follows its original path to the centre of the screen.

What is the direction of the magnetic field?

Tick (✓) **one** box.

[1 mark]

from **P** to **Q**

☐

from **Q** to **P**

☐

from **X** to **Y**

☐

from **Y** to **X**

☐

Question 1 continues on the next page



0 1 . 3

Changes are made to the apparatus so that the particles in the cathode ray travel with a greater speed as they pass between plates **P** and **Q**.

Explain how the cathode ray is restored to its original path by adjusting:

- only the electric field strength between **P** and **Q**
- only the magnetic flux density.

[3 marks]

electric field strength only _____

magnetic flux density only _____

0 1 . 4

Using the apparatus in **Figure 1**, Thomson determined the specific charge of the particles in the cathode rays. Thomson compared this result with the specific charge of the hydrogen ion.

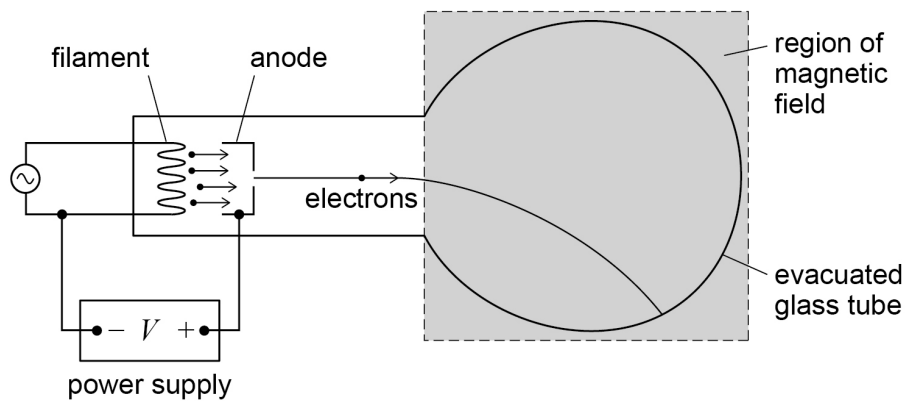
Discuss the significance of Thomson's results for the particles in cathode rays, when compared with the specific charge of the hydrogen ion.

[2 marks]

0	1
---	---

Figure 1 shows apparatus which can be used to determine the specific charge of an electron.

Figure 1



Electrons are emitted from the filament and accelerated by a potential difference between the filament and anode to produce a beam. The beam is deflected into a circular path by applying a magnetic field perpendicular to the plane of the diagram.

0	1
---	---

1

Describe the process that releases the electrons emitted at the filament.

[3 marks]

0 1 . 2

Table 1 shows the data collected when determining the specific charge of the electron by the method shown in **Figure 1**.

Table 1

potential difference V that accelerates the electrons	320 V
radius r of circular path of the electrons in the magnetic field	4.0 cm
flux density B of the applied magnetic field	1.5 mT

Show that the specific charge of the electron is given by the expression $\frac{2V}{B^2 r^2}$

[2 marks]

0 1 . 3

Using data from **Table 1**, calculate a value for the specific charge of the electron. Give your answer to an appropriate number of significant figures.

[2 marks]

specific charge of the electron = _____ C kg⁻¹

Question 1 continues on the next page



0	1	.	4
---	---	---	---

At the time when Thomson measured the specific charge of the particles in cathode rays, the largest specific charge known was that of the hydrogen ion.

State how Thomson's result for the specific charge of each particle within a cathode ray compared with that for the hydrogen ion and explain what he concluded about the nature of the particles.

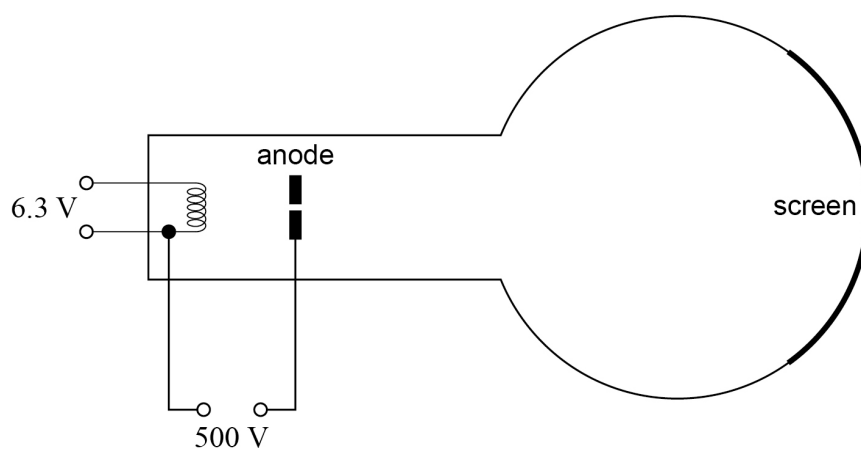
[2 marks]



0 1

In **Figure 1**, a beam of electrons travels through the aperture in the anode and hits the screen.

Figure 1



0 1 . 1

Explain how the electrons that form the beam are emitted.

[1 mark]

0 1 . 2

Show that the maximum speed of the electrons in the beam is about $1.3 \times 10^7 \text{ m s}^{-1}$.

[1 mark]

0 1 . 3

A student suggests that the apparatus can be used to demonstrate the wave properties of electrons in the beam, provided that the aperture in the anode has a suitable diameter.

Discuss whether the student is correct.
Support your answer with a calculation.

[3 marks]

Question 1 continues on the next page



0	1	.	4
---	---	---	---

In 1897, J J Thomson determined a value for the specific charge of an unknown particle.

The unknown particle is now known to be the electron.

Describe **one** method to determine the specific charge of the electron.

Your answer should include:

- a description of the apparatus used and the measurements made
- a description of how the specific charge can be determined using these measurements
- an explanation of the conclusion made by Thomson from the value that he determined.

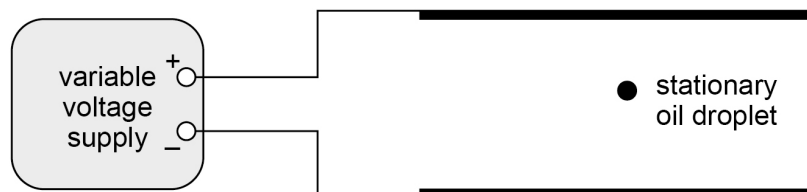
[6 marks]



0 2

Robert Millikan experimented with oil drops to determine a value for the electronic charge.

Figure 4 shows a stationary oil droplet between two horizontal metal plates. The plates are connected to a variable voltage supply so that the upper plate is positive. The oil droplet has mass m and charge Q .

Figure 4**0 2 . 1**

State and explain the sign of the charge on the oil droplet.

[1 mark]

The variable voltage supply is set to zero volts. The oil drop falls. The constant speed v_1 of the falling oil droplet is found to be $3.8 \times 10^{-5} \text{ m s}^{-1}$ and the following measurements are recorded:

$$\begin{aligned} \text{density of oil} &= 910 \text{ kg m}^{-3} \\ \text{viscosity of air} &= 1.8 \times 10^{-5} \text{ N s m}^{-2} \end{aligned}$$

0 2 . 2

Show that the mass m of the oil droplet is about $8 \times 10^{-16} \text{ kg}$.

[3 marks]

02.3

The variable voltage supply is adjusted so that the oil droplet rises at a constant speed v_2 . The potential difference (pd) across the plates is V and the distance between the plates is d .

In his experiment, Millikan measured the constant speed v_1 of a falling droplet when the pd was zero. He compared this with the speed v_2 of the same droplet when the droplet was made to rise.

Show that
$$\frac{v_2}{v_1} = \frac{VQ}{dmg} - 1$$

[2 marks]**02.4**

The following measurements are made for the droplet in Question **02.2** when it is rising at constant speed.

$$V = 715 \text{ V}$$

$$v_2 = 1.1 \times 10^{-4} \text{ m s}^{-1}$$

The separation of the plates $d = 11.6 \text{ mm}$.

Deduce, using the equation in Question **02.3**, whether the value of the charge for this droplet is consistent with the currently accepted value of the electronic charge.

[3 marks]

Question 2 continues on the next page



0	2	.	5
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After Millikan published his results, it was found that he had used a value for the viscosity of air that was smaller than the actual value.

Discuss the effect this error had on Millikan's value of the electronic charge.

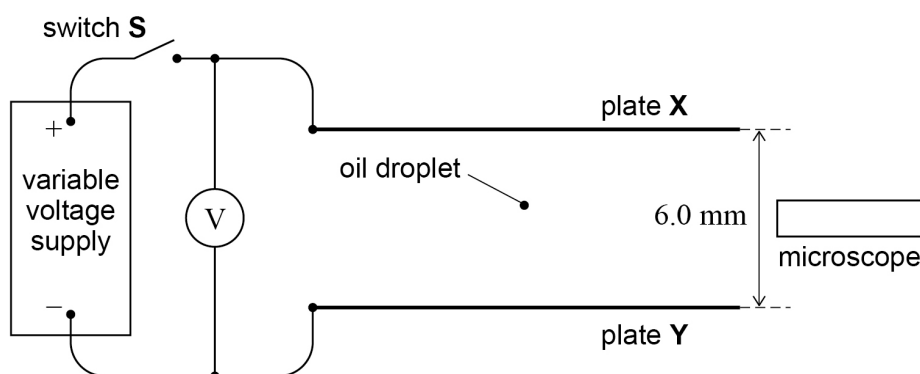
[3 marks]



0 2 . 1

Figure 2 shows a cross-sectional view of the arrangement that Millikan used to determine the charge on the electron.

Figure 2



Millikan's initial step was to determine the radius of the oil droplet.

Explain how Millikan used this apparatus to determine the radius of the oil droplet.

In your answer you should:

- describe the procedure used, the measurements taken and any additional data required
- describe how the radius was determined from the measurements
- state the physical principles and assumptions involved in the determination of the radius.

[6 marks]

Question 2 continues on the next page

0 2 . 2

On one occasion, the radius of a droplet was determined to be 1.20×10^{-6} m. When the droplet was stationary, the voltmeter reading was 467 V.

Show that the charge on the droplet was approximately 8×10^{-19} C.

density of oil = 880 kg m^{-3}

[3 marks]

0 2 . 3 Table 1 shows the percentage uncertainty in each quantity.

Table 1

Quantity	Percentage uncertainty
radius of oil droplet	4%
density of oil	1%
gravitational field strength	0.1%
potential difference	0.2%
distance between the plates	2%

Show that the absolute uncertainty in your answer to Question **02.2** is approximately $\pm 1 \times 10^{-19} \text{ C}$.

Go on to discuss whether this uncertainty allows your answer to Question **02.2** to be used to support the quantisation of electric charge.

[3 marks]



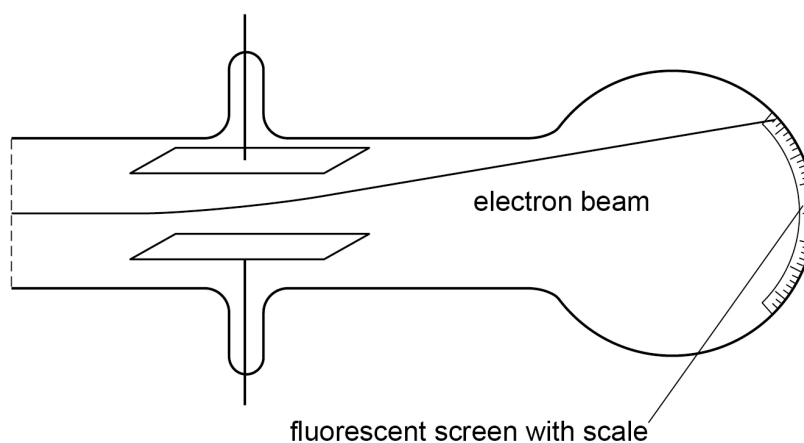
0 1

This question is about Thomson's determination of the electron's specific charge.

You should **not** use the values of the electron charge, mass or specific charge from the data and formulae booklet in this question.

Figure 1 shows part of the apparatus that Thomson used to measure the specific charge of the electron.

Figure 1

**0 1****. 1**

A modern version of Thomson's apparatus uses thermionic emission in the production of the electron beam.

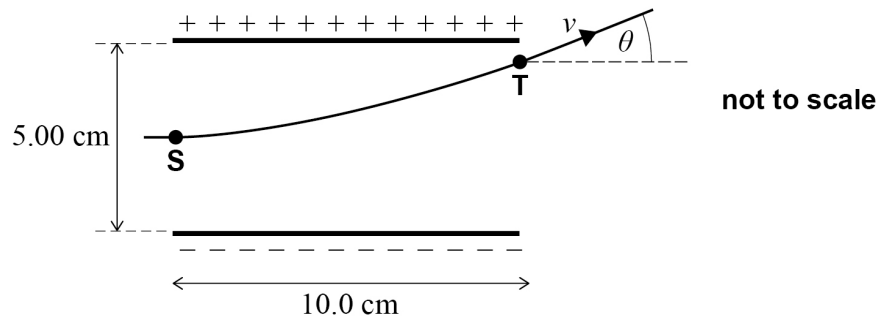
Suggest how the electron beam is produced in this modern version.
You should include a labelled diagram and suitable values for the power supplies used.

[3 marks]

Question 1 continues on the next page

A potential difference (pd) of 750 V is applied between the horizontal parallel plates. **Figure 2** shows the plates and the path of the electrons.

Figure 2



The electrons enter the electric field between the plates at **S** and leave it at **T** with speed v . Beyond **T** the electrons travel in a straight line at an angle θ . θ is read from a scale on a fluorescent screen.

The plates are of length 10.0 cm and are separated by a distance of 5.00 cm.

0 1 . 2

A uniform magnetic field of flux density 0.640 mT is now applied between the plates. This returns the electron beam to its undeflected position.

Show that the horizontal component of the velocity of the electrons is approximately $2.3 \times 10^7 \text{ m s}^{-1}$.

[2 marks]

The magnetic field is switched off and θ is measured to be 25° .

0 1 . 3

Show that the vertical component of the velocity of the electrons at **T** is approximately $1.1 \times 10^7 \text{ m s}^{-1}$.

[1 mark]

0 1 . 4

Show that the vertical acceleration of the electrons between the plates is approximately $2.5 \times 10^{15} \text{ m s}^{-2}$.

[2 marks]**0 1 . 5**

Determine a value for the specific charge of the electron.

[3 marks]

specific charge = _____ C kg^{-1}

0 1 . 6

Explain the significance of the result of Thomson's determination.

[2 marks]

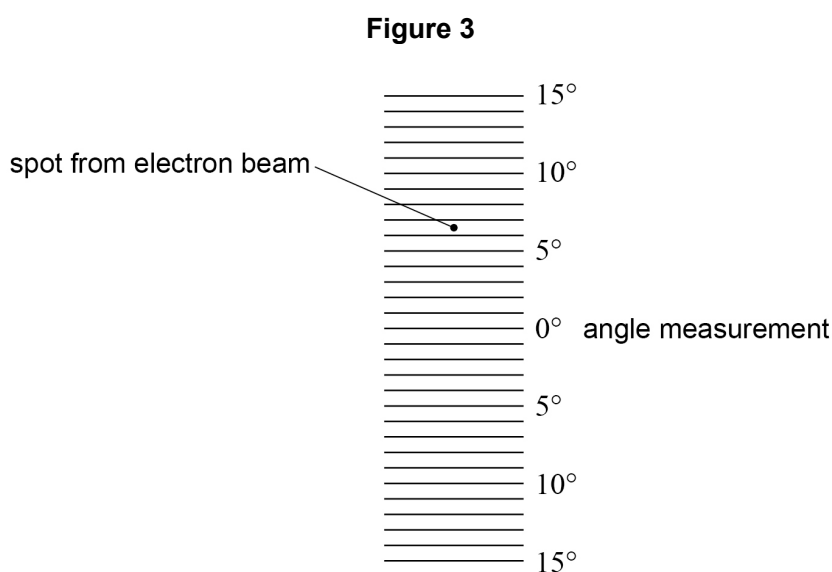
Question 1 continues on the next page



01.7

Some students are given a version of the apparatus to repeat Thomson's experiment.

Figure 3 shows a section of the measuring scale on the fluorescent screen and the spot from the electron beam.



The students consider two methods for minimising the percentage uncertainty in the measurement of the angle.

Method 1:

- choose a magnetic flux density B
- then set the magnetic flux density to B with no pd
- then adjust only the pd until the beam is horizontal
- then switch off the magnetic field and measure the angle θ .

Method 2:

- choose an angle θ
- then set the pd so that the spot from the electron beam is at θ with no magnetic field
- then adjust only the magnetic field until the beam is horizontal.

Discuss both of these methods with reference to the percentage uncertainty in θ that they will produce.

In your answer, suggest which method will minimise the percentage uncertainty. No calculations are required.

[3 marks]

SUB-TOPIC 3.12.2

WAVE-PARTICLE DUALITY

Sub-topic 3.12.2 · 16 questions · 134 marks · lowest tariff first



0 2

In the early 1900s a contradiction between experimental results and theoretical predictions was termed the ultraviolet catastrophe.

0 2 . 1

Compare these experimental results and theoretical predictions.
You may sketch and label a graph or graphs on **Figure 4** as part of your answer.

[3 marks]**Figure 4****0 2 . 2**

A proposal was made that allowed a resolution of the contradiction.

Outline this proposal.

[1 mark]

0	2
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Figure 2 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 2



Figure 3 shows the same apparatus when the dipole receiver has been rotated through an angle of 90°

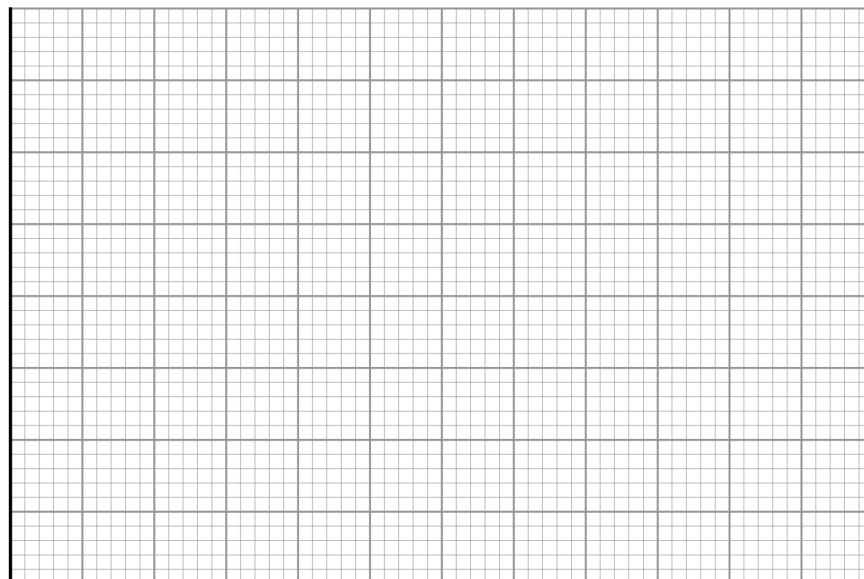
Figure 3

0 2 . 1

Sketch a graph on **Figure 4** 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 2**.

[3 marks]

Figure 4

amplitude
of signal

angle of rotation in degrees

0 2 . 2

Maxwell derived the equation $c = \frac{1}{\sqrt{\mu_0 \epsilon_0}}$ 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.

[2 marks]



0	3
---	---

Hertz did an experiment to determine the speed of radio waves.

Describe this experiment.

In your answer you should:

- include a labelled diagram
- state the measurements that were taken
- describe how the data were used to determine the speed of radio waves.

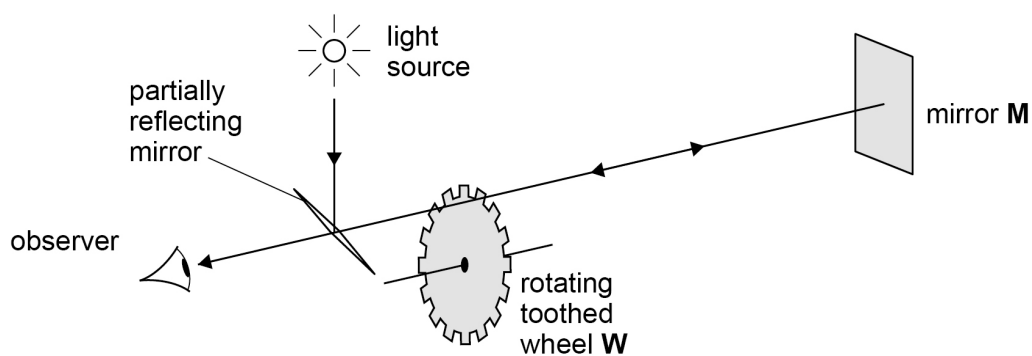
[5 marks]



0 3

Figure 5 shows the arrangement used by Fizeau to determine the speed of light.

Figure 5



The toothed wheel **W** is rotated and the reflected light from a distant mirror **M** is observed.

The speed of light is calculated from the equation

$$c = 4dnf_0$$

where d is the distance from **W** to **M** and
 n is the number of teeth on the rotating wheel **W**.

0 3 . 1

State what f_0 represents in the equation.

[2 marks]

0 3 . 2

The experiment is attempted using a rotating wheel with 720 teeth that can be rotated at up to 620 revolutions per minute.

The distance between **W** and **M** is 8.5 km.

Deduce whether the speed of light can be determined with this particular arrangement.

[2 marks]

0 3 . 3

The determination of the speed of light took on extra significance when Maxwell derived the wave-speed equation

$$c = \frac{1}{\sqrt{\epsilon_0 \mu_0}}$$

State how ϵ_0 and μ_0 are related to the types of field in the wave.

[2 marks]

ϵ_0 _____

μ_0 _____



0	3
---	---

The work of Fizeau, Foucault, Hertz and Maxwell contributed to our understanding of the nature of light.

Fizeau measured the speed of light in air.

Foucault confirmed that light travels faster in air than in water.

Hertz measured the speed of radio waves in air.

Maxwell developed a theory that was used to obtain the speed of light.

Discuss how the work of these four scientists contributed to our understanding of the nature of light.

In your answer you should refer to:

- the two pre-1800 models for the nature of light
- the predictions that these models made about the speed of light
- Maxwell's theory
- the significance of the measurements made by Fizeau, Foucault and Hertz.

Do **not** include any experimental details in your answer.

[6 marks]



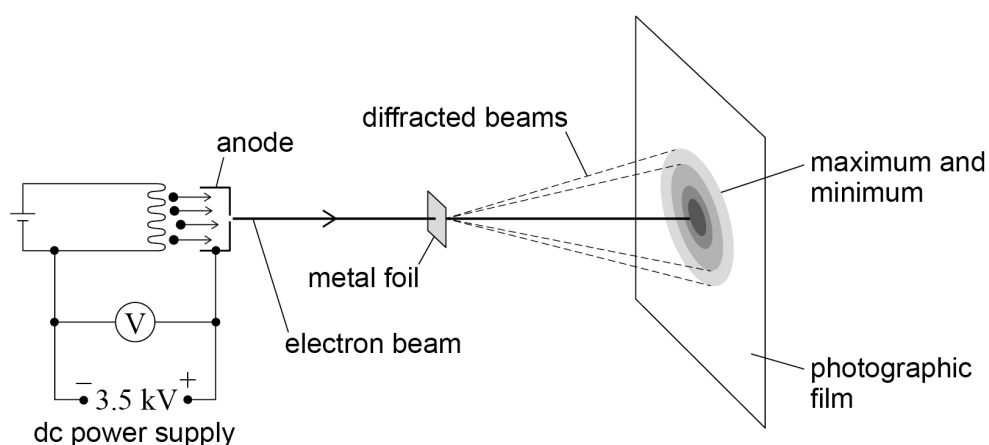
0 3

Figure 3 shows part of the apparatus used to investigate electron diffraction.

Electrons were accelerated through a potential difference to form a beam which was then incident on a thin metal foil.

Regions of maximum and minimum intensity formed on a photographic film behind the foil.

Figure 3

**0 3****1**

State de Broglie's hypothesis.

[2 marks]

0 3**2**

The voltmeter in **Figure 3** shows a reading of 3.5 kV.

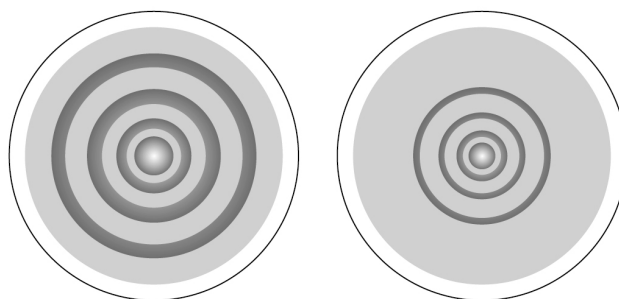
Determine whether this voltmeter reading is consistent with a de Broglie wavelength for the electrons in the beam of about 0.02 nm.

[2 marks]

0 3 . 3

The experiment is repeated using a similar arrangement to that shown in **Figure 3**. **Figure 4** shows the diffraction patterns from the two experiments.

Figure 4



first experiment

second experiment

State and explain **two** independent changes that could be made to the arrangement in **Figure 3** to produce the result shown for the second experiment in **Figure 4**.

[4 marks]

First change _____

Second change _____

03.1

The scanning tunnelling microscope (STM) uses a process called quantum tunnelling.

Explain what is meant by quantum tunnelling of an electron in an STM.
You may include a diagram as part of your answer.

[2 marks]

Question 3 continues on the next page

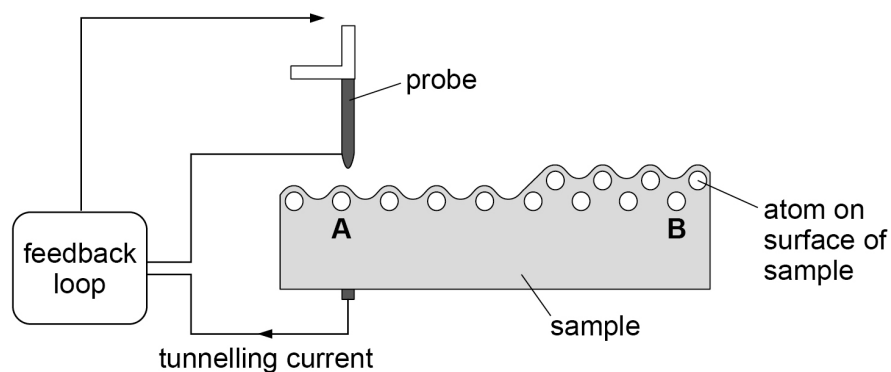


0 3 . 2

An STM is used to map the positions of the atoms between points **A** and **B** on the surface of a sample.

Figure 3 shows some of the features of the operation of an STM.

Figure 3



The STM in **Figure 3** is in constant-current mode.

Describe how the STM creates a map of the positions of one row of atoms on the surface of the sample from **A** to **B**.

[3 marks]

0 3 . 3

The smallest size of objects that the STM can resolve is similar to the de Broglie wavelength of the tunnelling electrons.

Deduce whether electrons with kinetic energies less than 1.5 eV are suitable to map the surface in **Figure 3**.

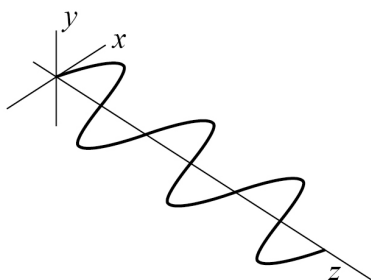
[3 marks]

0 3

An electromagnetic wave is propagating through space.

Figure 3 shows the variation of the magnetic flux density of the wave with distance. The magnetic field is in the xz plane. The y -axis is at right-angles to the xz plane.

Figure 3



0 3 . 1

Draw and label on **Figure 3**:

- the corresponding electric field
- the direction of propagation of the wave.

[1 mark]

0 3 . 2

Which scientist proposed the electromagnetic wave model of light?

Tick (✓) **one** box.

[1 mark]

Hertz

☐

Huygens

☐

Maxwell

☐

Young

☐

0 3 . 3

Another theory of the nature of light was proposed by Isaac Newton.

Describe how Newton's theory was used to explain the refraction of light as it moves from air into glass.

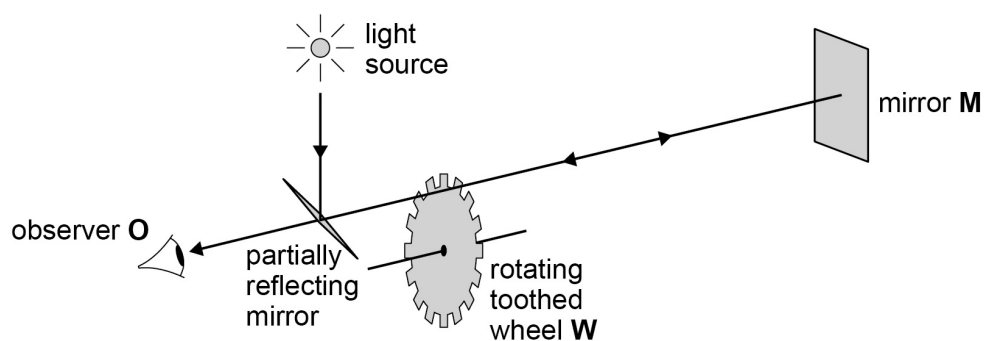
[3 marks]

Question 3 continues on the next page

0 3 . 4

Describe a demonstration using visible light that can be performed in a school laboratory to show that Newton's theory is not correct.

[3 marks]

0 2**Figure 2** shows the apparatus Fizeau used to determine the speed of light.**Figure 2**

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.

0 2**1**

Explain these observations.

[2 marks]

Observation A

Observation B

0 2 . 2

Table 1 shows data from Fizeau's experiment at the instant when observation B is made.

Table 1

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 **Table 1** are consistent with the present accepted value for the speed of light.

[2 marks]

0 2 . 3

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 marks]

Question 2 continues on the next page



0

2

. 4

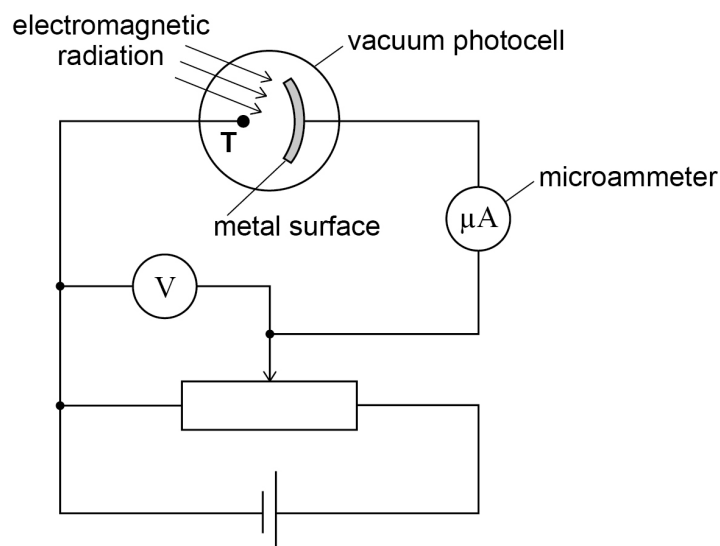
Explain how the nature of light is implied by Maxwell's theory of electromagnetic waves and Fizeau's result.

[3 marks]



0 3

Figure 5 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.

Figure 5

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

0 3 . 1

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

[3 marks]

wavelength = _____ nm

0 3 . 2

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.

[3 marks]

0 3 . 3

The potential divider in **Figure 5** 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 marks]

Question 3 continues on the next page



03.4

The apparatus shown in **Figure 5** is used to investigate three different metal surfaces **A**, **B** and **C**.

Table 2 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.

Table 2

	V/V	$I/\mu A$
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.

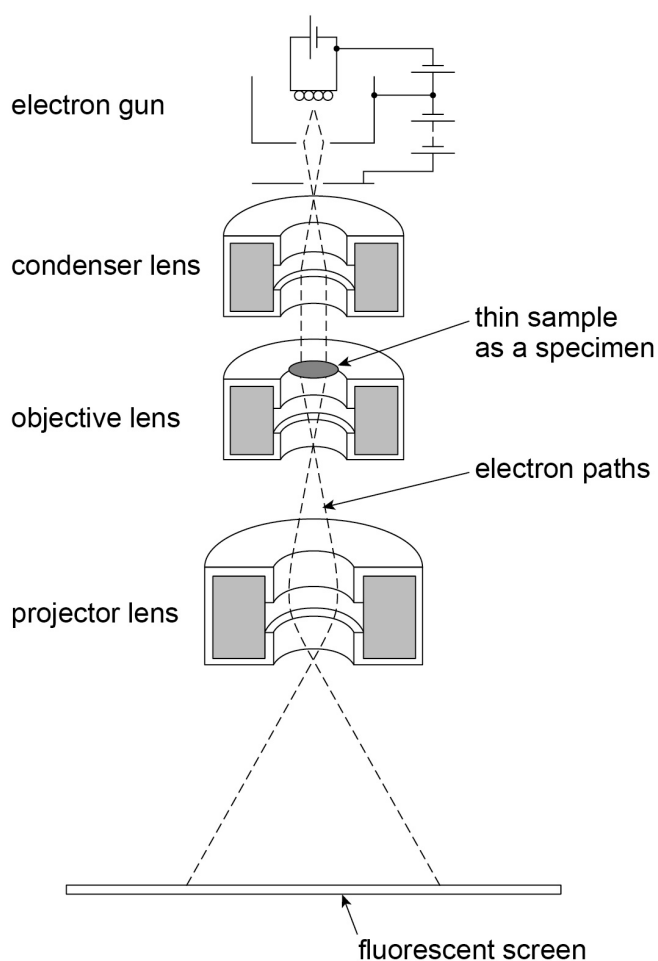
[1 mark]

A > B > C☐**A < B < C**☐**B > A > C**☐**B < A < C**☐

0 3

Figure 3 shows the main parts of a transmission electron microscope (TEM).

Figure 3



0 3 . 1

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

[1 mark]

Beta particle emission

☐

Electron diffraction

☐

Photoelectric effect

☐

Thermionic emission

☐

0	3	.	2
---	---	---	---

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.

[3 marks]

Question 3 continues on the next page

0	3	.	3
---	---	---	---

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.

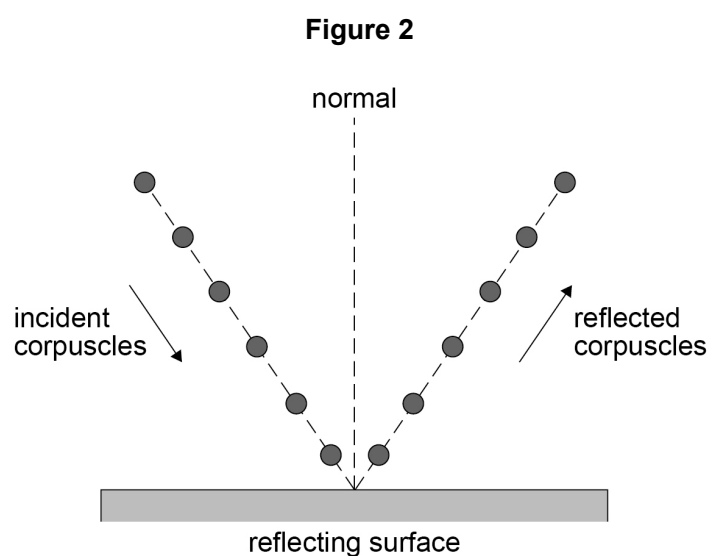
[6 marks]



0 2

Newton used a corpuscular theory of light to explain reflection.

Figure 2 shows how corpuscles would reflect from a horizontal surface.



0 2 . 1

What happens to the horizontal and vertical components of the velocity of the corpuscles, according to the theory, when they are reflected?

Tick (✓) **one** box.

[1 mark]

Horizontal component of velocity	Vertical component of velocity	Tick the correct box
Unchanged	Changed	☐
Changed	Unchanged	☐
Unchanged	Unchanged	☐
Changed	Changed	☐

Question 2 continues on the next page



0 2 . 2

Newton used the corpuscular theory to explain the refraction of light at an interface between air and water.

Huygens used the wave theory to explain the refraction of light at the interface.

Discuss the evidence that led to the rejection of Newton's corpuscular theory.

In your answer you should include

- how each theory explains refraction
- how experimental evidence led to the acceptance of the wave theory.

[6 marks]

Question 2 continues on the next page

0 2 . 3

Light is now known to behave as an electromagnetic wave.

Describe a plane-polarised electromagnetic wave travelling through a vacuum.
You may wish to draw a labelled diagram.

[3 marks]

0 2

In 1864, James Clerk Maxwell published a theory that included an equation for the speed of electromagnetic waves in a vacuum.

0 2 . 1

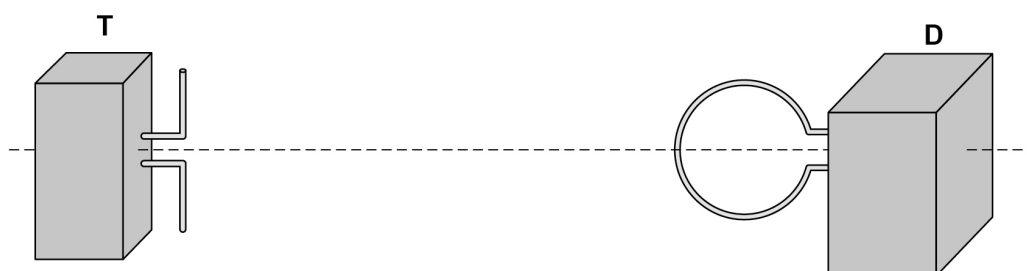
Show that Maxwell's theory agrees with the accepted value for the speed of light in a vacuum.

Use information from the Data and Formulae Booklet in your answer.

[2 marks]

Between 1886 and 1889, Heinrich Hertz completed a series of experiments in an attempt to verify Maxwell's theory. **Figure 3** shows a simplified arrangement similar to the one used by Hertz in one of his experiments.

Figure 3



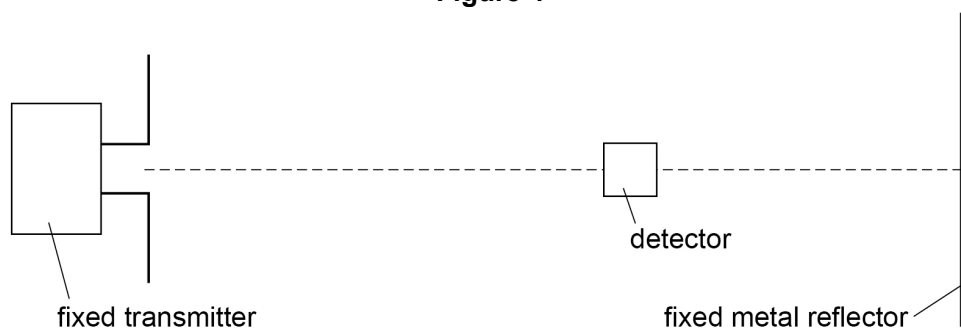
T is a radio wave transmitter with an aerial consisting of two vertical metal rods.
D is a detector that uses a conducting loop aerial.

0 2 . 3

In a different experiment Hertz used stationary waves to determine the speed of radio waves.

Figure 4 shows an experimental arrangement similar to the arrangement Hertz used.

Figure 4



Stationary waves are produced between the fixed transmitter and the fixed metal reflector.

In one experiment the distance between the transmitter and reflector is about 12 m and the transmitter frequency is 75 MHz.

Deduce whether this arrangement can be used to measure the speed of electromagnetic waves suggested by Maxwell's equation.

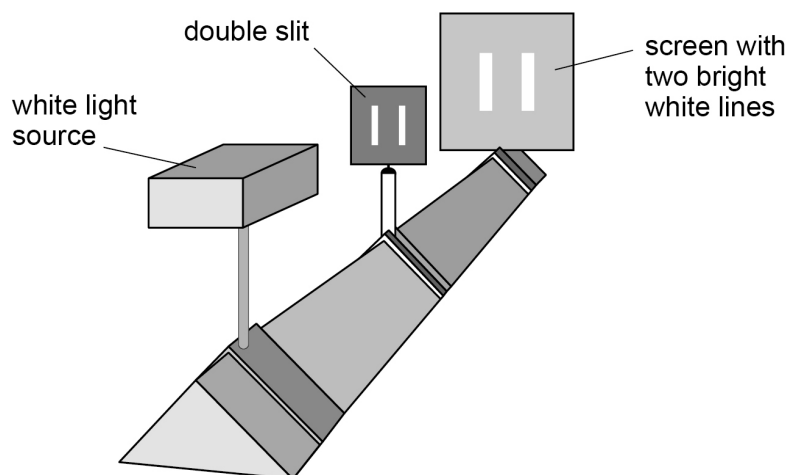
[4 marks]

0	1
---	---

In the 17th century, Isaac Newton proposed a theory to explain some of the properties of light. An alternative theory of light was proposed by Christiaan Huygens at about the same time.

A student uses the arrangement in **Figure 1** to investigate the two theories.

Figure 1



0	1	.	1
---	---	---	---

The student observes two bright white lines on the screen.

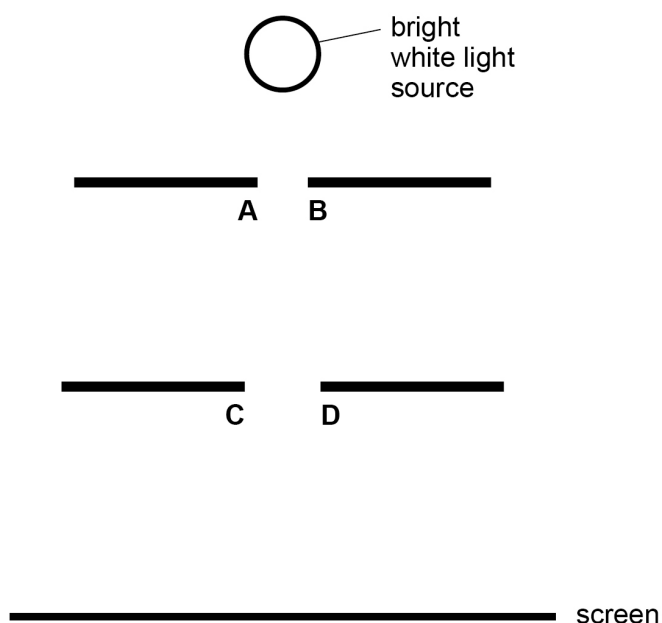
Explain how this observation supports Newton's theory of light.

[2 marks]

0 1 . 3

Shortly before the work of Newton and Huygens, Francesco Grimaldi carried out an experiment into the behaviour of light. **Figure 3** shows Grimaldi's arrangement.

Figure 3



A bright white light source is used to illuminate a small circular aperture, **AB**. The light from this aperture illuminates a second, slightly larger circular aperture, **CD**.

The light passing through both apertures arrives at a screen.

Newton's theory and Huygens' theory make different predictions about the appearance of the light on the screen.

Discuss these differences in appearance.

[3 marks]

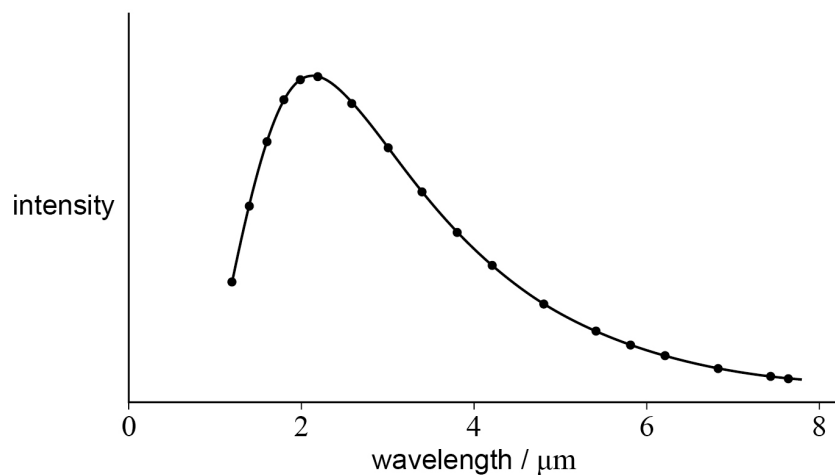
0 2

At the end of the 19th century new information was obtained about black-body radiation and the photoelectric effect. This information challenged classical physics theories.

In 1895, Wien and Lummer carried out experiments to measure black-body radiation accurately.

Figure 2 shows a typical black-body radiation curve of the type obtained by Wien and Lummer.

Figure 2

**0 2 . 1**

State what is meant by black-body radiation.

[2 marks]

0 2 . 2

Describe how the predictions of classical theory compare with Wien and Lummer's experimental results.

Annotate **Figure 2** as part of your answer.

[2 marks]

0 2 . 3

In 1900 Max Planck suggested a solution to the problems of the classical theory.

Outline the main aspects of his suggestion.

[2 marks]

Question 2 continues on the next page

0 2 . 4

Planck's suggestion was developed by Albert Einstein to explain the results of photoelectric effect experiments.

Discuss Einstein's explanation of photoelectricity and its significance in terms of the nature of electromagnetic radiation.

In your answer you should

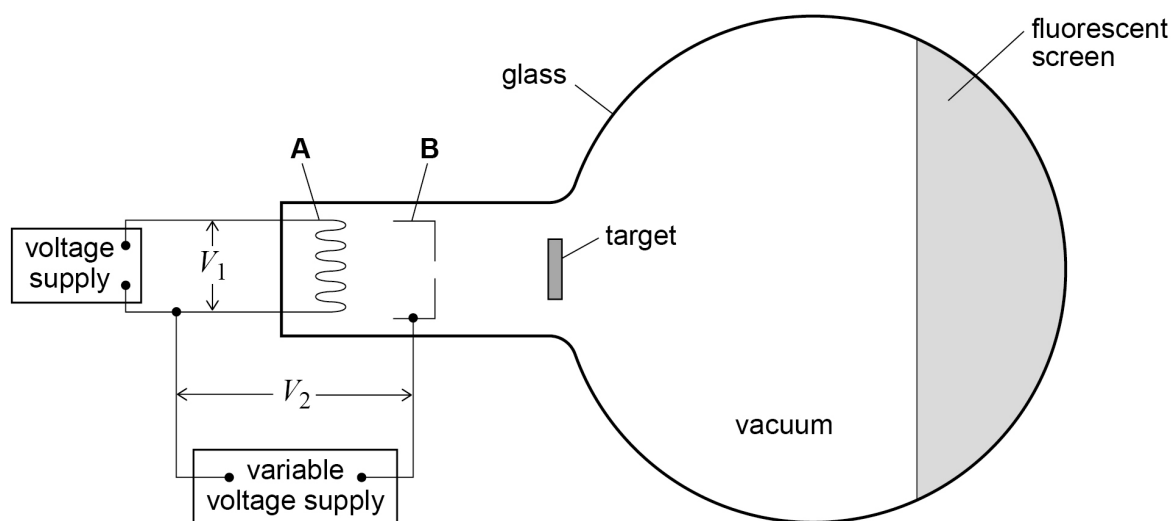
- describe **two** relevant observations made in photoelectric experiments
- explain the failure of classical physics to account for these observations
- include the main aspects of Einstein's theory and how he explained the observations.

[6 marks]

0 1

Figure 1 shows the apparatus used in an experiment to investigate electron diffraction and the de Broglie hypothesis.

Figure 1

**0 1 . 1**

Explain how high-speed electrons are produced in the apparatus in **Figure 1**.

In your answer you should:

- name parts **A** and **B**
- discuss the purposes of potential differences V_1 and V_2 .

[4 marks]

0	1	.	2
---	---	---	---

In the experiment, electrons are incident on a target made of a crystalline material. The electron wavelengths need to be about 50% the size of an atom to produce a diffraction pattern on the screen.

Suggest a suitable value for V_2 .
Support your answer with a calculation.

[4 marks]

$V_2 =$ _____ V

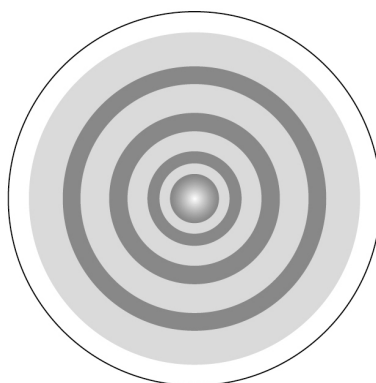
Question 1 continues on the next page



0 1 . 3

Figure 2 shows a typical diffraction pattern produced on the screen by the electrons.

Figure 2



Explain how measurements made with the apparatus in **Figure 1** can be used to support the de Broglie hypothesis.

[4 marks]

0 1 . 4

STM and TEM are abbreviations for two types of electron microscope.

Which row links the type of microscope to a relevant property of moving electrons?
Tick (✓) **one** box.

[1 mark]

STM	TEM
Moving electrons can cross a potential barrier.	Moving electrons can be deflected by a magnetic field.
Moving electrons can be deflected by a magnetic field.	Moving electrons can be deflected by a magnetic field.
Moving electrons can be deflected by a magnetic field.	Moving electrons can cross a potential barrier.
Moving electrons can cross a potential barrier.	Moving electrons can cross a potential barrier.

☐
☐
☐
☐

SUB-TOPIC 3.12.3

SPECIAL RELATIVITY

Sub-topic 3.12.3 · 11 questions · 86 marks · lowest tariff first



0	5
---	---

Cosmic rays detected on a spacecraft are protons with a total energy of 3.7×10^9 eV.

Calculate the velocity of the protons as a fraction of the speed of light.

[3 marks]

proton velocity = _____ c

END OF QUESTIONS



0	4	.	1
---	---	---	---

A student models a spacecraft journey that takes one year. The spacecraft travels directly away from an observer at a speed of $1.2 \times 10^7 \text{ m s}^{-1}$. The student predicts that a clock stationary relative to the observer will record a time several days **longer** than an identical clock on the spacecraft.

Comment on the student's prediction. Support your answer with a time dilation calculation.

[4 marks]

0	4	.	2
---	---	---	---

In practice, the gravitational field of the Sun affects the motion of the spacecraft and it does not travel directly away from the Earth throughout the journey.

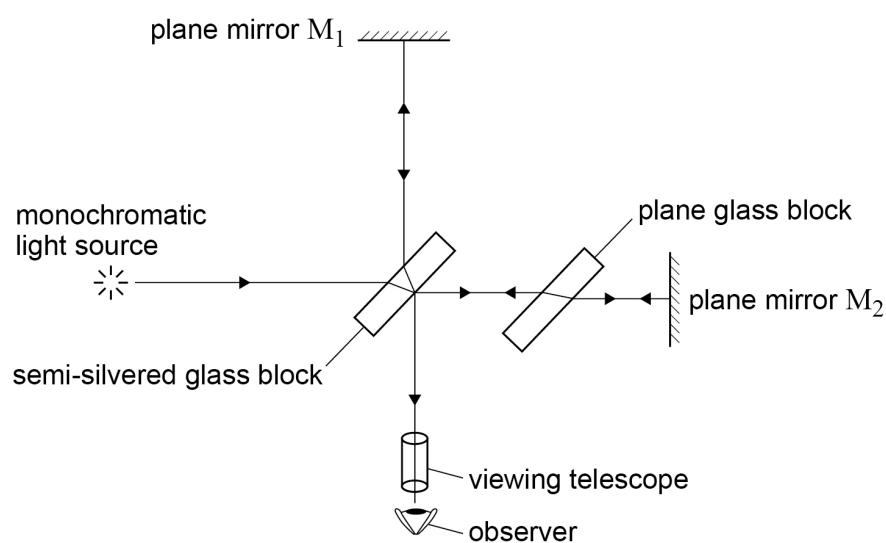
Explain why this means that the theory of special relativity cannot be applied to the journey.

[2 marks]

0	3
---	---

Figure 5 shows the features of a Michelson-Morley interferometer.

Figure 5



Explain how, using this arrangement, Michelson and Morley attempted to detect the absolute motion of the Earth.

In your answer you should:

- outline the experimental procedure
- explain the expected result of the experiment
- describe the actual result and explain the significance of this result.

[6 marks]

04.1

State what is meant by an inertial frame of reference.

[1 mark]

04.2

A pair of detectors is set up to measure the intensity of a parallel beam of unstable particles.

In the reference frame of the laboratory, the detectors are separated by a distance of 45 m. The speed of the particles in the beam is $0.97c$.

The intensity of the beam at the second detector is 12.5% of the intensity at the first detector.

Calculate the half-life of the particles in the reference frame in which they are at rest.

[4 marks]

half-life = _____ s

04.3

In calculations involving time dilation, it is important to identify proper time.

Identify the proper time in the calculation in Question **04.2**.**[1 mark]**

END OF QUESTIONS

0 4 . 1

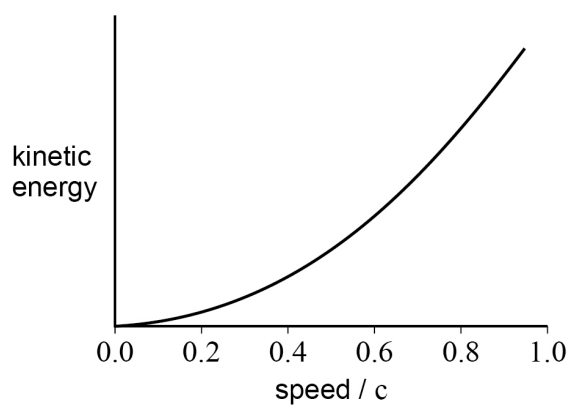
Bertozzi investigated how the kinetic energy of electrons varies with speed.

Which graph shows the variation of kinetic energy with speed?

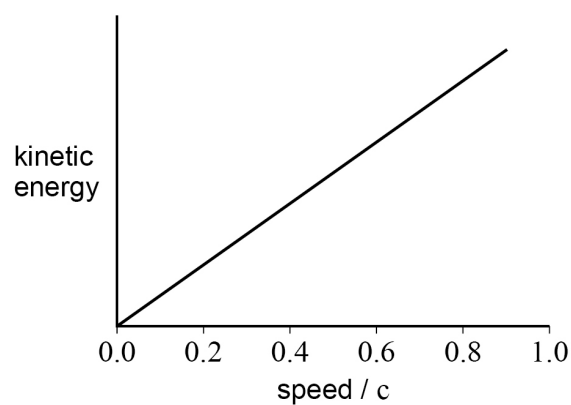
Tick (✓) **one** box.

[1 mark]

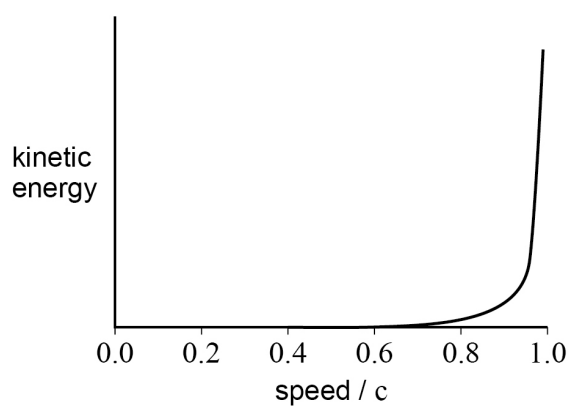
A



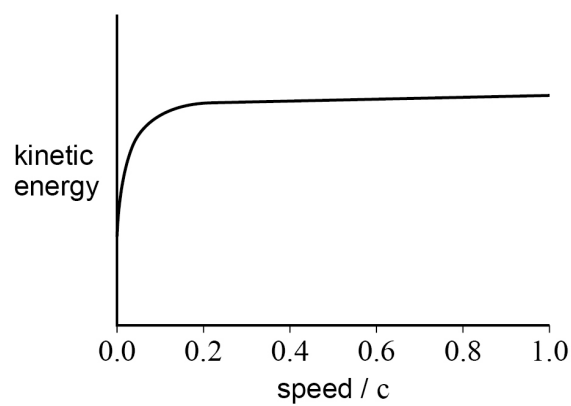
B



C



D



A

☐

B

☐

C

☐

D

☐

0 4 . 2

Calculate the speed of a particle when its kinetic energy is equal to its rest energy.

[3 marks]speed = _____ m s⁻¹**0 4 . 3**

Discuss the change in the observed mass of a spring when it is stretched.

[2 marks]

END OF QUESTIONS

0 4 . 1

A muon travels at a speed of $0.95c$ relative to an observer.

The muon travels a distance of 2.5×10^3 m between two points in the frame of reference of the observer.

Calculate the distance between these two points in the frame of reference of the muon.

[2 marks]

distance = _____ m

0 4 . 2

Measurements of muons created by cosmic rays can be used to demonstrate relativistic time dilation.

State the measurements made and the observation that provides evidence for relativistic time dilation.

[2 marks]

0	4	.	3
---	---	---	---

As the muons travel through the atmosphere, their speeds are reduced by interaction with the particles in the air.

Discuss, with reference to relativity, the effect that this reduction of speed has on the rate of detection of the muons on the surface of the Earth.

[3 marks]

END OF QUESTIONS



0 4

Table 1 shows data of speed v and kinetic energy E_k for electrons from a modern version of the Bertozzi experiment.

Table 1

$v / 10^8 \text{ m s}^{-1}$	E_k / MeV
2.60	0.5
2.73	0.7
2.88	1.3
2.96	2.6
2.99	5.8

0 4 . 1

Classical mechanics predicts that $E_k \propto v^2$.

Deduce whether the data in **Table 1** are consistent with this prediction.

[2 marks]

0 4 . 2Discuss how Einstein's theory of special relativity explains the data in **Table 1**.**[4 marks]**

0 4 . 3Calculate, in J, the kinetic energy of one electron travelling at a speed of $0.95c$.**[3 marks]**

kinetic energy = _____ J

END OF QUESTIONS

0 4

In a science-fiction novel, spaceship **A** transports cargo from planet **O** to planet **P**.

A travels at a constant speed of $0.50c$ in the reference frame of an observer on **P**.

0 4 . 1

The observer on **P** measures the distance from **O** to **P** as 1.4×10^{14} m.
Some of the cargo is food and must experience a journey time of no more than 10 days.

Determine whether **A** is able to deliver the cargo within this time.

[4 marks]

0 4 . 2

The observer on **P** measures the length of a cargo at rest on **P** to be 210 m.
There is a cargo hold along the full length of **A**.
The observer on **P** measures the length of **A** to be 200 m in the direction of travel while the spaceship is moving at $0.50c$.

Determine whether the cargo will fit into the cargo hold of **A**.

[4 marks]

0 4 . 3

Spaceships **A** and **B** are travelling towards each other along the same straight line. The speed of **B** is $0.30c$ with respect to **P**.

Figure 5 shows the situation.

Figure 5

B sends a radio signal to **A**.

What is the speed of the radio signal measured by **A**?

Tick (✓) **one** box.

[1 mark]

$0.20c$

☐

$0.40c$

☐

$0.80c$

☐

c

☐

$1.8c$

☐

END OF QUESTIONS



0 4

Einstein developed his theory of special relativity from two postulates. One postulate states that physical laws have the same form in all inertial frames.

0 4**1**

State the other postulate and explain how it is consistent with the equation:

$$c = \sqrt{\frac{1}{\mu_0 \epsilon_0}}$$

[2 marks]

A proton leaves a particle accelerator at point **X** and moves at a constant speed towards a target at point **Y**.

The speed of the proton is $2.5 \times 10^8 \text{ m s}^{-1}$ in the frame of reference of the target.

The distance **XY** in the frame of reference of the proton is 38 m.

0 4**2**

Calculate the distance **XY** in the frame of reference of the target.

[2 marks]

distance **XY** in the frame of reference of the target = _____ m



0 4 . 3 Show that the kinetic energy E_k of the proton is about 1.2×10^{-10} J.

[3 marks]

0 4 . 4 Sketch on **Figure 4** the variation of E_k with speed v for a proton.

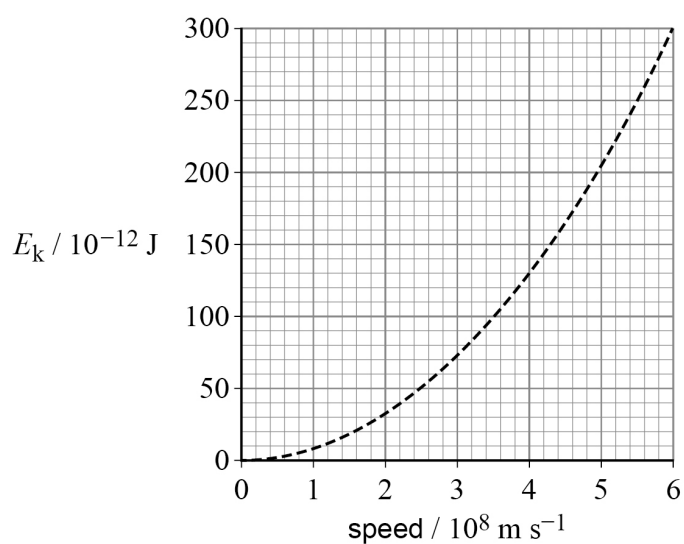
To help you, the dashed line represents

$$E_k = \frac{1}{2} m_0 v^2$$

where m_0 is equal to the mass of a proton at rest.

[3 marks]

Figure 4



END OF QUESTIONS

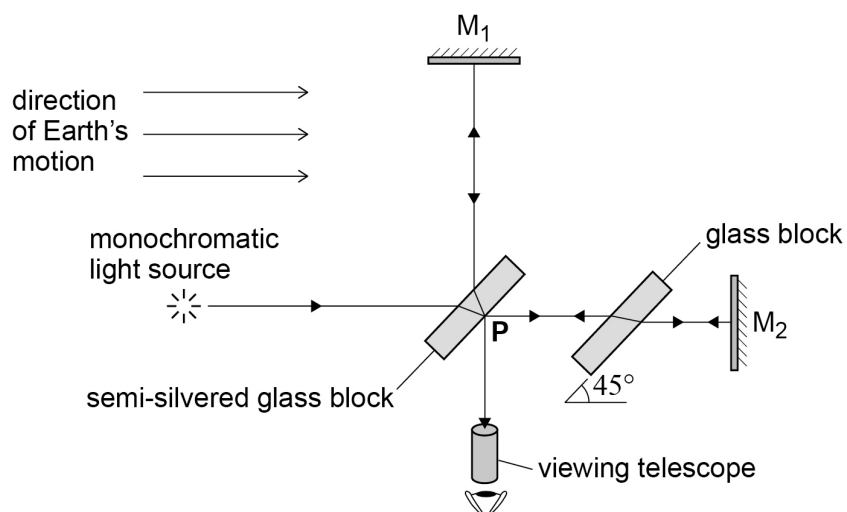


0 4

Figure 6 shows a diagram of the Michelson-Morley interferometer that was used to try to detect the absolute motion of the Earth through the ether (æther).

Light from the monochromatic source passes through the semi-silvered glass block and takes two different paths to the viewing telescope. The two paths, PM_1 and PM_2 , are the same length. Interference fringes are observed through the viewing telescope.

Figure 6



It was predicted that when the interferometer was rotated through 90° the fringe pattern would shift by 0.4 of the fringe spacing.

04.2

The Michelson-Morley experiment provides evidence for one of the postulates of Einstein's theory of special relativity.

State this postulate.

[1 mark]

04.3

State the other postulate of Einstein's theory of special relativity.

[1 mark]

Question 4 continues on the next page

04.4

One consequence of the special theory of relativity is length contraction.

Experimental evidence for length contraction is provided by the decay of muons produced in the atmosphere by cosmic rays.

Figure 7 shows how the percentage of the number of muons remaining in a sample changes with time as measured by an observer in a frame of reference that is stationary relative to the muons.

Figure 7



In a particular experiment, muons moving with a velocity $0.990c$ travel a distance of 1310 m through the atmosphere to a detector.

Determine the percentage of muons that reach the detector.

[4 marks]

percentage = _____ %

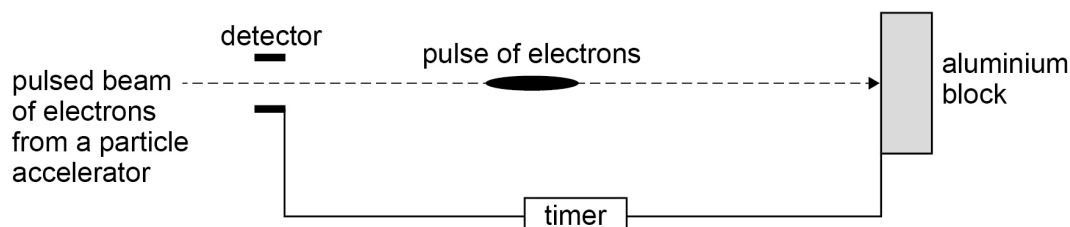
END OF QUESTIONS



0 4

Figure 3 shows a modern version of Bertozzi's experiment to measure the kinetic energy of high-speed electrons. A timer is used to measure the time taken for a pulse of electrons to travel from the detector to the aluminium block.

Figure 3



0 4 . 1

A potential difference (pd) of 1.30 MV is used to accelerate the electrons.

Show that each electron gains approximately 2×10^{-13} J of kinetic energy.

[1 mark]

0 4 . 2

These electrons cause the temperature of the aluminium block to increase by 68.0 K. The number of electrons that cause this increase in temperature is 4.50×10^{17} .

Deduce whether this increase in temperature is consistent with an accelerating pd of 1.30 MV.

specific heat capacity of aluminium = $903 \text{ J kg}^{-1} \text{ K}^{-1}$
 mass of aluminium block = 1.50 kg

[2 marks]

0 4 . 3 The speed of the electrons between the detector and the block is $2.88 \times 10^8 \text{ m s}^{-1}$.

Student **A** suggests that the non-relativistic equation for kinetic energy could be used.
Student **B** suggests that the relativistic equation for kinetic energy is required in this situation.

Evaluate the suggestions of student **A** and student **B**.
Support your answer with calculations.

[4 marks]

Question 4 continues on the next page



0 4 . 4 The timer in **Figure 3** records a time of 29.8 ns.

What is the proper time interval for an electron travelling from the detector to the aluminium block?

Tick (✓) **one** box.

[1 mark]

< 29.8 ns

☐

29.8 ns

☐

> 29.8 ns

☐

0 4 . 5 The electrons in **Figure 3** were accelerated from rest in 13 stages.

In each stage the electrons were accelerated by a pd of 100 kV.

As a result, an electron increases its speed and kinetic energy during each stage.

Compare, for an electron,

- its increase in speed for the first stage with that for the last stage
- its increase in kinetic energy for the first stage with that for the last stage.

Justify your answer.

No further calculations are required.

[4 marks]

END OF QUESTIONS



MARK SCHEMES

official mark schemes



$\frac{E^2}{2B^2V_A}$	$\frac{a}{v} = \frac{dB}{dx}$ Horizontal motion: $t = \frac{x}{v}$ Vertical motion: $(y = 0t + \frac{1}{2}at^2 = \frac{1}{2}at^2 \Rightarrow) a = 2y/t^2$ $(a = \frac{F}{m} = \frac{eV}{dm} \Rightarrow) \frac{e}{m} = \frac{da}{V}$ Or any of $\frac{e}{m} = \frac{2dy}{Vt^2} = \frac{2dyv^2}{Vx^2} = \frac{2yV}{dx^2B^2}$	$(\frac{eV}{d} = Bev \Rightarrow) v = \frac{V}{dB}$ (allow $\frac{E}{B}$ from measured E) Horizontal motion: $t = \frac{x}{v}$ $v_y = v \tan \theta$ Vertical motion ($v_y = 0 + at = at \Rightarrow) a = \frac{v_y}{t}$ $(a = \frac{F}{m} = \frac{eV}{dm} \Rightarrow) \frac{e}{m} = \frac{da}{V}$
Incorrect Methods		
Milikan's Oil drop / use of measured weight / Gas tube / Crooke's tube / Discharge tube Partial credit for one area ONLY can be awarded for a good treatment that includes all of the following - At least one experimental detail - Some measurements - Some calculation		Quantum Jumping or anything else These cannot address areas 1 and 2 Ignore use of undescribed velocity selector, mass spectrometer, ... No credit for measure Q and m and divide them.



Question	Answers	Additional comments/Guidance	Mark	AO
02.1	(Reads off terminal speed from graph) to give $0.053 \pm 0.005 \text{ mm s}^{-1}$ ✓ Evidence of $mg = 6\pi\eta rv$ ✓ Substitutions seen to give $1.8 \times 10^{-5} \text{ (N s m}^{-2}\text{)} \checkmark$	Allow PoT error in MP1 If MP1 not given, allow ecf if read off misread Do not accept work from a gradient. W or mg or $1.2 \times 10^{-14} = 6\pi\eta rv$ is enough for MP2 Condone $\frac{4}{3}\pi r^3 \rho g = 6\pi\eta rv$ for MP2. Calculator value = $1.766425562 \times 10^{-5}$	3	2 × AO2 1 × AO3



Question	Answers	Additional comments/Guidance	Mark	AO
02.2	Evidence of $EQ = mg$ ✓ $Q = 6.4 \times 10^{-19}$ (C) ✓ Divides their Q by e to get number of electrons and makes sensible comment consistent with their value ✓	By substitution – allow PoT error for E in MP1 Allow $EQ = mg$ without substitution for MP1 Expect to see 4.0 or $3.99 \approx 4$ and therefore yes Condone for MP3 only (max 1) Use of $E = Q/4\pi\epsilon_0 r$ which gives $Q = 6.04 \approx 6$ so yes.	3	2 × AO2 1 × AO3
Total			6	

Question	Answers	Additional comments/Guidance	Mark	AO
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01.1	Electrostatic force and magnetic force are equal in magnitude OR opposite in direction / magnetic force down and electrostatic force up OR equal and opposite ✓ Electrostatic force and magnetic force are equal in magnitude AND opposite in direction / magnetic force down and electrostatic force up AND Balanced forces / resultant force = 0 (so travels in a straight line according to Newton 1 / no (vertical) acceleration according to Newton 2) ✓	Allow electric force / force from electric field / force due to potential difference / force due to plates for electrostatic force. Ignore references to gravity. Electric and magnetic forces being equal without reference to magnitude or opposite is not enough for MP1. Ignore references to a vacuum so no collisions between particles. Ignore references to the directions of fields. Do not allow answers which suggest that the magnitude of magnetic field is equal to the magnitude of the electric field. Condone cancel for balanced forces in mp2 Ignore counteract in mp2. Do not allow horizontal force for mp2.	2	2 AO2
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Question	Answers	Additional comments/Guidance	Mark	AO
01.2	$Bev = \frac{eV_{(P)}}{d}$ OR $v = \frac{V_{(P)}}{dB}$ ✓ $\frac{1}{2}mv^2 = eV_{(A)}$ OR $\frac{e}{m} = \frac{v^2}{2V_{(A)}}$ ✓ At least one correct from ✓ $v = \frac{1.51 \times 10^3}{5 \times 10^{-2} \times 1.59 \times 10^{-3}} (= 1.9 \times 10^7 \text{ m s}^{-1})$ $\frac{e}{m} = \frac{(\text{their } v)^2}{2 \times 1 \times 10^3}$ $\frac{e}{m} = \frac{(1.51 \times 10^3)^2}{2 \times 1 \times 10^3 \times (5 \times 10^{-2})^2 \times (1.59 \times 10^{-3})^2}$ $\frac{e}{m} = \frac{V_{(P)}^2}{2V_{(A)}d^2B^2}$ $1.8(0380523) \times 10^{11} \text{ C kg}^{-1}$ without using 1.60×10^{-19} or 9.11×10^{-31} ✓	Allow Q for e Condone mixed up V_A and V_P or no subscripts in first 2 marking points. $\frac{e}{m} = \frac{V_{(P)}^2}{2V_{(A)}d^2B^2}$ or any valid rearrangement gains mp1, mp2, mp3 Substituted data can gain MP1 and MP2 (in addition to MP3) Condone PoT errors in mp3 Do not credit values using 1.60×10^{-19} or 9.11×10^{-31} in mp3 or mp4 Do not allow 1.76×10^{11} for mp4 as this is from the data booklet not the data in the question. If no other marks are awarded, condone max 1 for $\frac{e}{m} = \frac{V}{2d^2B^2}$ with any or no V subscript	4	1 AO1 3 AO2
Total			6	

7

Question	Answers	Additional comments/Guidance	Mark	AO
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01.1	Cathode rays/electrons move from cathode toward anode	Accept move left to right.	1
	The paddle wheel has gained energy from cathode rays/electrons. ✓	Accept as alternatives for energy kinetic, energy/momentum/impulse ✓ Ignore references to force. Ignore references to applying a magnetic field.	1
01.2	Electrons are pulled out/escape from atoms OR gas atoms are ionised ✓	Condone molecules as alternative to atoms.	1
	(Positive ions generated near the cathode are attracted to the cathode causing free) electrons emitted from the cathode. ✓		1
	Electrons are accelerated toward the anode (by the potential difference) ✓	Do not accept attraction as an alternative to acceleration.	1
01.3	Reason: Idea of fewer electrons/cathode rays ✓ Effect: Paddle wheel rotates less ✓ OR Reason: Idea of electrons/cathode rays have higher energy/speed/momentum ✓ Effect: Paddle wheel rotates more ✓	Must score the reason mark to score the effect mark. Ignore references to air resistance. If no mark is awarded, one mark can be awarded for the effect of the paddle wheel rotating more where the reasoning is limited to less collisions of electrons with air molecules.	2
Total			7

6

Question	Answers	Additional Comments/Guidelines	Mark
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01.1	Equal (magnitudes) and opposite directions, AND one direction at least specified✓	between them. Must include idea of size and direction. e.g. weight down equals E force up/towards positive plate/away from negative plate. Do not allow 'balanced' or 'in equilibrium' for equals The forces can be in the form of formulae for MP1 and MP2 (e.g. Eq , EV/d , mg)	2	
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01.2	$m = 4\pi r^3 \rho / 3$ and $mg = 6\pi \eta r v$ seen ✓ $r^2 = 18 \eta v / 4 \rho g$ is seen in some form, in symbols or through substituted data, ✓ Correct use of equations to obtain $r = 9.7 \times 10^{-7} \text{ m}$ ✓	Do not allow backward calculation Can be seen by substitution. Can be seen in single equation: $4\pi r^3 \rho g / 3 = 6\pi \eta r v$ Do not award if v and V confused Do not condone 1sf answer. Must be clear answer refers to r, not r^2 for example. If no other mark given MP1 can be awarded if F used for mg, and/or volume AND density equations seen separately	3	AO2 1h
01.3	The number of excess electrons on the droplet is 3 ✓ In order for each half to remain stationary, the charge would have to split equally OR Due to the quantisation of charge, the charge cannot split equally ✓ It is not possible for both droplets to remain stationary / the student is wrong ✓	May be seen in terms of values of charge or e Award for idea that charge would have to be $1.5e$ Evidence for MP1 and MP2 may be seen together. E.g. charge on drops are e and $2e$, OR 1.6×10^{-19} and 3.2×10^{-19} Ignore reference to particles repelling each other	3	1 × AO3 2a 2 × AO3 2b

Total			8
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Question	Answers	Additional Comments/Guidance	Mark	ID details
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01.1	positive ions in tube are accelerated to C/cathode and strike surface/electrons in surface Electrons (in cathode) emitted and accelerated towards A (and B) (to form cathode ray).	Do not award MP3 if there is a suggestion of a p.d. between A and B		AO2.1e
1.2	Y to X ✓		1	AO2.1c
01.3	Reference to $v = E/B$ (when path straight) ✓ (Eg Electric force = magnetic force $Eq = Bqv$ $v = E/B$) (Therefore for greater v) Either increase E ✓ Or decrease B . ✓	For MP2 and MP3 there must be some correct supporting theory e.g. $F_M = Bqv$	3	AO3.1a



01.4	(Magnitude of) specific charge much greater (approximately x 2000) specific charge of hydrogen (ion), (largest then known). ✓ (If charges similar) Cathode rays particles <u>mass</u> much smaller than hydrogen ion and therefore smaller than atom. ✓	Do not condone “he deduced they were electrons” MP2 cannot be awarded if MP1 is incorrect. If no other creditable answer given, one mark can be awarded for stating that the sign of the specific charge of cathode ray is opposite to that of hydrogen ion.	2	AO1.1a
Total			8	

Question	Answers	Additional Comments/Guidance	Mark	ID details
	Electromagnetic/EM radiation✓ Spectrum with peak depending on temperature (of emitter	If no other mark awarded, allow 1 mark for (EM) radiation given off by perfect absorber	2	AO1.1a



01.1	energy to leave (the metal surface) or Work function (defines work function) ≤ energy supplied to an electron/electron energy ✓ Thermionic emission ✓	NOT allowed Reference to electrons leaving <u>atoms</u> or ionisation Allow Energy supplied sufficient to overcome the work function	3
01.2	Use one of $\frac{1}{2}mv^2 = eV$ and $r = \frac{mv}{Be}$ or $\frac{mv^2}{r} = Bev$ to arrive at $\frac{Ber}{m} = v$ or $v = \sqrt{\frac{2eV}{m}}$ or $v^2 = \frac{2eV}{m}$ or $\frac{e}{m} = \frac{v}{Br}$ or $\frac{e}{m} = \frac{v^2}{2V}$ ✓ substitution in the other equation and manipulates <u>correctly</u> and <u>clearly</u> to give $\frac{e}{m} = \frac{2V}{B^2r^2}$ ✓	Condone q for e Substitution in other equation and correct manipulation NB this is a show that so mark is not simply for stating the equation given I presented such that v (velocity) and V (voltage) are indistinguishable in manipulation then award only first mark	2

01.3	Correct substitution $\frac{e}{m} = \frac{2 \times 320}{(1.5 \times 10^{-3})^2 \times 0.040^2}$ and answer 1.8×10^{11} ✓ Answer to 2 sig figs ✓ Allow for incorrect answer following incorrect substitution in equation	As answer is on the data sheet must see correct substitution with all correct powers of ten	2
01.4	The specific charge of the cathode rays/the particles was(much) larger/greater than the hydrogen ion/proton ✓ This provided evidence that cathode rays were composed of electrons/particles which have a (very) small mass / have a high (negative) charge or Mass (much) smaller than the mass of a hydrogen (ion)/proton ✓	Not higher If mark 1 not given then 0 for the question Not lightest as substitute for mass	2
Total			9

Question	Answers	Additional Comments/Guidance	Mark
	Pattern shows: Maximum at start and shows minimum of zero (never negative)✓ Correct periodicity zeros/maxima 180° apart✓ (ie angles in right places)	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	



01.1	Idea that filament/metal is heated (by an electric current), giving (some) electrons in the metal (sufficient) energy to leave the surface ✓	Allow references to the work function (but not just ϕ) Thermionic emission is not enough by itself. Do not allow heating of electrons. Reject 'accelerated' (unless it is clearly after they leave the metal) / 'ionise' Ignore references to processes that take place after electron leaves the metal Ignore references to free electrons inside the metal	1	1 × AO1
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Question	Answers	Additional comments /Guidance	Mark	AO
01.2	Use of $\frac{1}{2}mv^2 = eV$ To give $v = 1.33 \times 10^7 \text{ (m s}^{-1}\text{)} \checkmark$	Must see 500V for the potential difference (not 506.3V or 493.7V) ≥ 3 SF required. 1.325×10^7 (do not allow 1.32×10^7)	1	1 × AO2

Question	Answers	Additional comments/Guidance	Mark	AO
01.3	Suggestion that, for diffraction to be demonstrated, hole diameter should be of same order of size as wavelength ✓ Evidence of $\lambda = \frac{h}{p}$ OR $\lambda = \frac{h}{\sqrt{2meV}}$ to give 5.5×10^{-11} (m) OR 5.6×10^{-11} (m) ✓ Idea that this diameter is smaller than an atom / too small for hole to be made and therefore this apparatus cannot be used (for this speed/wavelength) / the student is incorrect ✓	Do not allow $\lambda < \text{gap}$ or $\text{gap} < \lambda$ for MP1 (Must refer to gap not just anode) Discussions in terms of crystalline diffraction can score MP1 and MP2. Must calculate λ for MP2. Condone use of 506.3V or 492.7V as penalised in 1.2 Allow 1 SF or order of magnitude calculation. Do not ignore PoT for calculation. Ignore incorrect conversion to nm if m value given. Condone the idea that the student is correct in principle but this particular setup will not work. Do not allow ecf to MP3 unless their calculated hole diameter is of the order of 10^{-10} m or smaller in MP2.	3	3 × AO3



Question	Answers	Additional comments/Guidance	Mark	AO																
01.4	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.	For each area (bullet point), consider whether the response is fully addressed, partially addressed or not addressed. Typically, any missing points mean that the area is partially addressed.	6	4 × AO1 1 × AO2 1 × AO3																
	<table><tr><td>Mark</td><td>Criteria</td></tr><tr><td>6</td><td>All three areas covered with at least two aspects covered in some detail. 6 marks can be awarded even if there is an error and/or parts of one aspect missing.</td></tr><tr><td>5</td><td>A fair attempt to analyse all three areas. If there are several errors or missing parts then 5 marks should be awarded.</td></tr><tr><td>4</td><td>Two areas successfully discussed, or one discussed and two others covered partially. Whilst there will be gaps, there should only be an occasional error.</td></tr><tr><td>3</td><td>One area discussed and one discussed partially, or all three covered partially. There are likely to be several errors and omissions in the discussion.</td></tr><tr><td>2</td><td>Only one area discussed, or makes a partial attempt at two areas.</td></tr><tr><td>1</td><td>None of the three areas covered without significant error.</td></tr><tr><td>0</td><td>No relevant analysis.</td></tr></table>	Mark			Criteria	6	All three areas covered with at least two aspects covered in some detail. 6 marks can be awarded even if there is an error and/or parts of one aspect missing.	5	A fair attempt to analyse all three areas. If there are several errors or missing parts then 5 marks should be awarded.	4	Two areas successfully discussed, or one discussed and two others covered partially. Whilst there will be gaps, there should only be an occasional error.	3	One area discussed and one discussed partially, or all three covered partially. There are likely to be several errors and omissions in the discussion.	2	Only one area discussed, or makes a partial attempt at two areas.	1	None of the three areas covered without significant error.	0	No relevant analysis.	Significance Very large e/m (compared to value for hydrogen ion). (Hydrogen ion had largest known specific charge at the time.) Therefore particles have very small mass / very large charge (condone light for small mass)
	Mark	Criteria																		
	6	All three areas covered with at least two aspects covered in some detail. 6 marks can be awarded even if there is an error and/or parts of one aspect missing.																		
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	2	Only one area discussed, or makes a partial attempt at two areas.																		
	1	None of the three areas covered without significant error.																		
	0	No relevant analysis.																		
	Experimental procedures and measurements For a full answer everything should be directly measurable (not Electric Field, Kinetic Energy, velocity) Except no details are required for measurement of B																			
	Determination of e/m Answers should end in e/m = Expected to be in steps but can carry the algebra through Allow use of measured Electric Field here. A full answer should not include e or m as part of the calculation (likely to be found in working out v)																			
	If methods are mixed up this can be treated as full credit for one of procedures or determination or as a partial for both.																			
	The minimum response required to address an area fully is given below																			
	Fine Beam Tube																			
	Experimental procedure and measurements fine beam tube described / diagram including low pressure gas, (Perpendicular) magnetic field to cause electrons to move in a circle																			
	Radius of curved path <i>r</i> , Accelerating voltage <i>V</i> , Magnetic flux density <i>B</i>																			
	Determination of e/m $\left(\frac{1}{2}mv^2 = eV \text{ and } r = \frac{mv}{Be}\right)$ $\frac{e}{m} = \frac{2V}{r^2B^2}$																			
Total			11																	



Correct Alternative Methods		
Crossed Fields Experimental procedure and measurements Parallel plates with voltage applied. Magnetic field applied to produce balanced forces Accelerating voltage V_A When beam is <u>horizontal</u> : plate voltage V_p , plate separation d , magnetic flux density B Determination of e/m $\left(\frac{eV_p}{d} = Bev \Rightarrow\right) v = \frac{V_p}{dB}$ (allow $\frac{E}{B}$ from measured E) $\left(\frac{1}{2}mv^2 = eV_A \Rightarrow\right) \frac{e}{m} = \frac{v^2}{2V_A}$ or $\frac{e}{m} = \frac{V_p^2}{2d^2B^2V_A}$ or $\frac{e}{m} =$	Measure deflected distance Experimental procedure and measurements Initial balanced magnetic and electrical forces to produce <u>horizontal</u> beam Measure magnetic flux density B , plate p.d. V , distance between plates d and length of plates x With no magnetic field, measure vertical deflection y Determination of e/m $\left(\frac{eV}{d} = Bev \Rightarrow\right) v = \frac{V}{dB}$ (allow $\frac{E}{B}$ from measured E)	Measure deflected angle Experimental procedure and measurements Initial balanced magnetic and electrical forces to produce <u>horizontal</u> beam Measure magnetic flux density B , plate p.d. V , distance between plates d and length of plates x With no magnetic field, measure angle θ beam is deflected through Determination of e/m $\left(\frac{eV}{d} = Bev \Rightarrow\right) v = \frac{V}{dB}$ (allow $\frac{E}{B}$ from measured E)



02.1	(Drop stationary so) Electric force is opposite (in direction) to the weight AND electric field downwards/top plate positive/(electric) force towards positive plate so Q negative ✓	Give credit to answers shown on the diagram Allow forces expressed in symbols Do not allow suggestion that viscous force is involved Accept idea that the drop is attracted towards the positive plate. Accept bottom plate negative as an alternative to top plate positive.	1	AO1
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Question	Answers	Additional comments/Guidance	Mark	AO
02.2	(In free fall at terminal speed) $mg = 6\pi\eta rv$ ✓ Use of $m = \text{volume} \times \text{density}$ AND $V = \frac{4}{3}\pi r^3$ ✓ (to give $r = 5.9 \times 10^{-7} \text{ m}$) (use of volume of sphere and density) to give answer that rounds to $m = 7.7 \times 10^{-16} \text{ (kg)}$ ✓	At least 2 sf.	3	3 x AO2

Question	Answers	Additional comments/Guidance	Mark	AO
02.3	$\frac{vQ}{d} - mg = 6\pi\eta rv_2$ ✓ Convincing algebra combining with $mg = 6\pi\eta rv_1$ to give $v_2/v_1 = \text{answer}$ ✓	MP2 is contingent on MP1	2	2 x AO2

Question	Answers	Additional comments/Guidance	Mark	AO
02.4	Use of equation from 02.3 ✓ to show $Q = 4.9 \times 10^{-19} \text{ C}$ ✓ Evidence of dividing their Q by 1.6×10^{-19} to give a consistent conclusion ✓	Use of means by substitution or manipulation Accept answer that rounds to between 4.8 and $5.0 \times 10^{-19} \text{ C}$ Using the 'show that' value for the mass gives $Q = 4.96 \times 10^{-19} \text{ C}$ Only condone ecf in MP3 for an arithmetic error in the determination of Q .	3	2 x AO2 1 x AO3

Question	Answers	Additional comments/Guidance	Mark	AO
02.5	(Value of viscosity) affects calculation of mass/radius of droplet ✓ Smaller value of viscosity gives smaller force on droplet so smaller calculated weight/mass ✓ Ref to appropriate equation AND as mass is smaller then Q smaller (therefore e smaller). ✓	'affects' can be either increase or decrease in MP1 In MP2 allow use of relationship between the radius of the drop and the viscosity. Evidence of MP1 is likely to be seen in MP2. Do not condone use of $mg = 6\pi\eta rv$ on its own Appropriate means either the equation from 02.3 or relationship between weight and electric field force (e.g weight = $mg = EQ$)	3	3 x AO3
Total			12	

11

Question	Answers	Additional comments/Guidance	Mark	AO
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2.1

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
6	All three areas covered in some detail. 6 marks can be awarded even if there is an error and/or parts of one aspect missing.
5	All three areas covered, at least two in detail. Whilst there will be gaps, there should only be an occasional error.
4	Two areas successfully discussed, or one discussed and two others covered partially. Whilst there will be gaps, there should only be an occasional error.
3	One area discussed and one discussed partially, or all three covered partially. There are likely to be several errors and omissions in the discussion.
2	Only one area discussed, or makes a partial attempt at two areas.
1	None of the three areas covered without significant error.
0	No relevant analysis.

Method

Field is off or with the switch open
Measure time and distance (for falling drop)
(Measure distance using lines on microscope)
calculate velocity using $v = \frac{s}{t}$

Calculation (Just quoting formulae from the formulae and data booklet is not enough to partially address this area.)

$$m = \frac{4}{3}\pi\rho r^3$$

$$mg = 6\pi\eta r v$$

$$\text{leading to } r = \sqrt{\frac{9\eta v}{2\rho g}}$$

$$\text{or } r = \sqrt{\frac{9\eta v}{2\rho g}} \text{ quoted}$$

ρ is identified as the density of the **oil**
 η is identified as the viscosity of the **air**

Principles/Assumptions (This area is normally fully addressed by 2 statements.)

Falls at terminal velocity since weight = viscous drag force / Stokes' law

Air acts like a viscous fluid so Stokes' law applies.

Balanced forces according to Newton 1 or 2

Oil droplet is spherical (hence $V = \frac{4}{3}\pi r^3$)

Upthrust is negligible / can be ignored.

Any mention that air resistance is negligible or not present when field is off would not allow this area to be fully addressed.

Ignore reference to free fall.

6

6 AO1

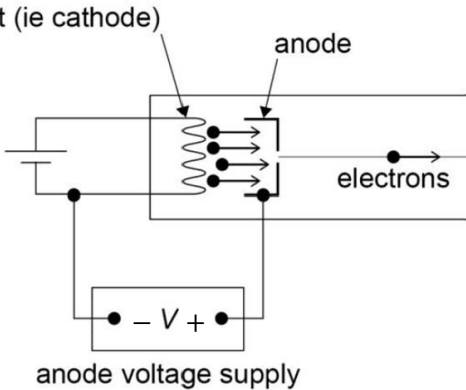
		Ignore details of Millikan's experiment that are not about determining r .		
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Question	Answers	Additional comments/Guidance	Mark	AO
02.2	Max ✓✓ - Substitution into $V = \frac{4}{3}\pi r^3 = \frac{4}{3}\pi \times (1.2 \times 10^{-6})^3$ - Substitution of $m = \rho V = 880 \times \text{their volume}$ - Substitution of $Q = \frac{dmg}{V} = \frac{6.0 \times 10^{-3} \times \text{their mass} \times 9.81}{467}$ $Q = 8.0(3) \times 10^{-19} \text{ (C)} \checkmark$	Max 2 if no equations are seen but only substitution (one for a correct substitution and one for correct answer) MP1 and MP2 require substitutions. Need ≥ 2 sf (no ecf in mp3)	3	3 AO2

Question	Answers	Additional comments/Guidance	Mark	AO
02.3	% uncertainty in $Q = 3 \times 4 + 1 + 0.1 + 0.2 + 2 = ((\pm)15(.3)\%) \checkmark_{1a}$ uncertainty in $Q = \frac{15}{100} \times 8.02 \times 10^{-19} = (\pm)1.2 \times 10^{-19} \text{ (C)} \checkmark_{2a}$ Alternative method for $\checkmark_1$ and $\checkmark_2$ max value of $Q =$ $\frac{4\pi \times (1.2 \times 10^{-6} \times 1.04)^3 \times 880 \times 1.01 \times 6 \times 10^{-3} \times 1.02 \times 9.81 \times 1.001}{3 \times 467 \times 0.998}$ $(= 9.3(3) \times 10^{-19} \text{ C})$ OR min value of $Q =$ $\frac{4\pi \times (1.2 \times 10^{-6} \times 0.96)^3 \times 880 \times 0.99 \times 6 \times 10^{-3} \times 0.98 \times 9.81 \times 0.999}{3 \times 467 \times 1.002}$ $(= 6.8(7) \times 10^{-19} \text{ C}) \checkmark_{1b}$ Correct use of max or min value with $8(.02) \times 10^{-19}$ or half the range using max and min if their max and/or min comes from a correct method with up to one error in each $\checkmark_{2b}$ $1.2 \times 10^{-19} > \frac{1.60 \times 10^{-19}}{2}$ therefore it is not possible to confirm charge quantisation (as any value is possible) $\checkmark_3$	Allow fractional uncertainties in $\checkmark_{1a}$ Allow ecf for Q and % uncertainty $\checkmark_3$ is independent if 1×10^{-19} is used or an answer that rounds to 1×10^{-19}. Alternatives for $\checkmark_3$ the possible range overlaps 4, 5, 6 electrons (allow 4, 5 or 5, 6 or 4, 6) Allow a calculated max and/or min value of Q $(8 \pm 1) \times 10^{-19}$ (expect 7 or 9) is not an (integer) multiple of 1.6×10^{-19} Condone because the uncertainty (not % uncertainty) is too close to 1.6×10^{-19}. Range or uncertainty or % uncertainty is too large is not enough without explicit comparison of absolute uncertainty with 1.60×10^{-19} in some form.	3	2 AO2 1 AO3
Total			12	

Question	Answers	Additional comments/Guidance	Mark	AO
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01.1	Max 2 from: ✓✓ • Vacuum / low pressure gas (in a glass tube) • Heater/filament/(thin) wire (correctly) connected to (ac or dc) power supply / has a current passing through it. • An accelerating potential difference (must not be ac) connected to an electrode with a hole referred to as anode or connected to the positive terminal of power supply. heater power supply $\leq 20\text{ V}$ and accelerating pd $> 200\text{ V}$ (less than 1000 kV) ✓	Answers may come from the written answer or a labelled diagram. Allow battery or cell symbol for dc power supply. A voltmeter is not sufficient for bullet 2 or bullet 3 but may be used to award MP3 if values are given. Condone resistor drawn for filament. BP3 do not allow horizontal plates (as shown in Figure 1). filament (ie cathode)  anode electrons anode voltage supply	3	AO1
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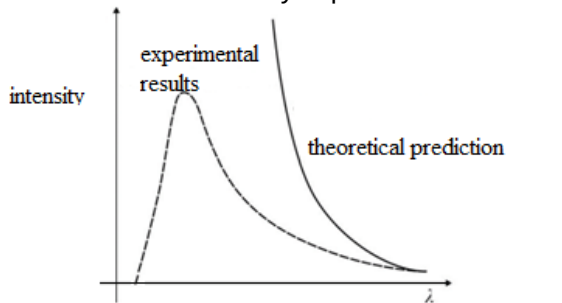
Question	Answers	Additional comments/Guidance	Mark	AO
01.2	$\frac{eV}{d} = Bev$ AND (therefore) $v = \frac{V}{dB}$ or $\frac{V}{d} = Bv$ ✓ $v = \frac{V}{dB} = \frac{750}{0.05 \times 0.64 \times 10^{-3}} = 2.34 \times 10^7$ ✓ (m s ⁻¹)	Do not allow use of 1.6×10^{-19} (unless cancelled) or 9.11×10^{-31} ≥ 3 SF required. Allow use of E for $\frac{V}{d}$ and Q for e .	2	AO2
01.3	$v_v = \text{their ans to 01.2} \times \tan 25^\circ = 1.09 \times 10^7$ (m s ⁻¹) OR $v = \frac{(\text{their ans to 01.2})}{\cos 25^\circ}$ and $v_v = v \sin 25^\circ$ (= 1.09×10^7 m s ⁻¹) ✓	Do not allow use of 1.6×10^{-19} or 9.11×10^{-31} ≥ 3 sf required. 2.3×10^7 m s ⁻¹ gives 1.07×10^7 m s ⁻¹ Allow ecf from their 01.2	1	AO2
01.4	$t = \frac{0.10}{(\text{their ans to 01.2})}$ ✓ ₁ (= 4.27×10^{-9} s) $a = \frac{(\text{their ans to 01.3} (-0))}{(\text{their } t)}$ (= 2.56×10^{15} m s ⁻²) ✓ ₂	Condone for 1 mark only $a = \frac{(\text{their ans to 01.3})^2}{2 \times 0.025}$ ✓ ₁₂ Do not allow use of 1.6×10^{-19} or 9.11×10^{-31} but ✓ ₁ can be awarded if this is only used in ✓ ₂ ≥ 3 sf required Allow ecf from their 01.3 and 01.2	2	AO2
01.5	$ma = \frac{qV}{d}$ or or $ma = QE$ ✓ ₁ $\left(\frac{e}{m} = \frac{ad}{V} = \right) \frac{(\text{their ans to 01.4} \times 0.050)}{750}$ ✓ ₂ $\frac{e}{m} = 1.7 \times 10^{11}$ ✓ ₃ (C kg ⁻¹) (cao)	Do not allow use of 1.6×10^{-19} or 9.11×10^{-31} in ✓ ₂ and ✓ ₃ but ✓ ₁ can be awarded. Do not allow answer with no working. Answer must follow from correct working. Allow $\frac{e}{m} = \frac{V \tan 25^\circ}{0.10 dB^2}$ OR $\frac{v_v}{0.10 B}$ OR $\frac{v_h \tan 25^\circ}{0.10 B}$ OR $\frac{a}{Bv_h}$ ✓ ₁ substitution ✓ ₂ Other approaches based on $\frac{1}{2}mv^2 = eV$ or B are likely to be incorrect.	3	AO2

Question	Answers	Additional comments/Guidance	Mark	AO
01.6	Specific charge was much larger / approx. 2000 times than the largest so far discovered / hydrogen ion / hydrogen nucleus / proton ✓₁ Electron has a much smaller mass than the hydrogen ion (proton) ✓₂	Do not allow references to hydrogen atom or just hydrogen in ✓₁ but condone in ✓₂. Ignore references to size. Ignore “or greater charge” larger in mp1 and smaller in mp2 is not sufficient without much/very/ Allow << and/or >> but not < or > A comparison is required in ✓₁ and ✓₂	2	AO1

Question	Answers	Additional comments/Guidance	Mark	AO
01.7	(Method 2 is preferred) Any three from: ✓✓✓ - Idea that in method 1 the spot is unlikely to be on a scale line when the magnetic field is off - Idea that (percentage) uncertainty/resolution is (likely to be) smaller for magnetic field reading than for angle. - Idea that using method 2 the pd can be adjusted to place (the centre of) the spot on a scale line - Using method 2 allows you to select the angle and therefore use a large value to minimise the % uncertainty in θ	Ignore any suggestion that there is a different number of measurements in the two methods. Ignore references to parallax error. Max 2 if method 2 is not preferred. Allow current reading for magnetic field reading Condone the idea that the angle can be set to an easily read value for bullet 3. Allow increase the accuracy instead of reduce the uncertainty in bullet 4. If no other marks awarded condone for max 1: method 2 because of the idea that θ does not have to be measured / is chosen / is set.	3	AO3
Total			16	

Question	Answers	Additional comments/Guidance	Mark	AO
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02.1	Any three from: ✓✓✓ - Experiment agreed with theory at high wavelengths / theory was correct at high wavelengths - The existence of a peak was shown by experiment but was not predicted by theory / can be shown by labelled curves. - The existence of a cut-off at low λ was shown by experiment but was not predicted by theory / can be shown by labelled curves if experimental line touches λ axis at low but non-zero λ with a correct theoretical line - Theory predicted intensity tends to infinity when wavelength tends to 0 which is not matched by experiment / the experimental graph not tending to infinity can be shown from the graph (but the theoretical intensity tending to infinity requires a written comment).	Any reference to non-EM radiation MAX 2. Condone a positive y-intercept except for bullet 4. Do not allow any bullet which is contradicted by the graph but reward comments that refer to behaviour beyond the range shown on the graph. To gain marks for labelled curves it must be clear which line is theoretical and which is experimental. Bullet 4: Condone intensity tends to infinity at UV (even with non-zero asymptote drawn) which is not matched by experiment. 	3	AO1
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Question	Answers	Additional comments/Guidance	Mark	AO
02.2	Light (waves) / (EM) radiation (is emitted) in quanta and idea that energy is proportional to frequency ✓	Do NOT accept photons / particles. Allow small packets of energy/waves for quanta. Condone energy for EM radiation.	1	AO1
Total			4	



Question	Answers	Additional comments/Guidance	Mark	AO
		Models before 1800		



02.1	(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)	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
02.2	<u>Correct substitution</u> leading to a calculation of the speed of electromagnetic wave. $\frac{1}{\sqrt{(4\pi \times 10^{-7})(8.85 \times 10^{-12})}} = 3.0 (2.9986) \times 10^8 \text{ m s}^{-1}$ Comment that this speed agrees with the <u>measured</u> speed of light Or speed determined from <u>experiments</u> <u>Or similar to Fizeau's result</u>		1 1
Total			5

8

Question	Answers	Additional Comments/Guidance	Mark
	Converts 6.2 eV, 0.5 eV or 6.7 eV to J eg $6.2 \times 1.6 \times 10^{-19} \text{ J}$ or $9.9(2) \times 10^{-19} \text{ J}$ seen for 0.5 eV $8.0 \times 10^{-20} \text{ J}$ seen for 6.7 eV $1.07 \times 10^{-18} \text{ J}$ 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 $\lambda = h/mv$ 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	1



03	Max 2 ✓✓ - Identified transmitter and detector as used by Hertz e.g. spark gap or dipole transmitter and dipole or loop receiver. - Correct placement of a (metal) reflector - Creation of a stationary (radio) wave with a reflector - Use a movable detector $\lambda = 2 \times \text{max to adjacent max}$ OR $2 \times \text{min to adjacent min}$ OR $4 \times \text{max to adjacent min}$ (divided by any multiples used in MP4) ✓ Use of a reflector (condone mirror) AND measure distance from (multiples of) max to max or min to min or max to min ✓ Use of a reflector (condone mirror) AND an attempt at a realistic measurement of λ AND $c = f\lambda$ ✓	Award 0 marks for answers which do not use radio waves. Ignore references to other experiments e.g. Fizeau. Ignore reference to use of computers or oscilloscopes. Evidence for MP1 and MP2 may come from a labelled diagram Condone MP1 and MP2 from other experiments with radio waves. Do not allow mirror for metal reflector in MP1 or MP2 but only penalise once. In MP3 and MP4 allow node for min and anti-node for max. A labelled diagram with λ clearly marked with an arrow (or equivalent) can gain MP3 Do not allow MP4 if first harmonic is used. MP4 may come from the diagram but a reference to what is measurement not just λ is required. Do not allow any reference to $v = \frac{s}{t}$ for MP5	5	5 AO1
Total			5	

Question	Answers	Additional comments/Guidance	Mark	AO
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03.1	frequency (of rotation) of W when no reflected light seen ✓ and idea that this is the lowest frequency ✓	MP2 is contingent on MP1 Do not accept 'first frequency' for MP2	2	2 x AO1
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Question	Answers	Additional comments/Guidance	Mark	AO
03.2	Either Calculate using equation (max measurable speed) $= 2.5 \times 10^8 \text{ m s}^{-1}$ OR Calculate value of f_0 (needed) $= 12(.25) \text{ Hz}/735 \text{ rev min}^{-1}$ ✓ Conclusion: No as the largest possible speed is less than the speed of light OR the frequency required to find the speed of light is greater than the maximum frequency. ✓	Condone alternative methods e.g. comparison of times etc. Unit needed for MP1 Condone ecf in MP2 only for an arithmetic error in MP1 e.g. incorrect conversion to Hz.	2	1 x AO1 1 x AO3

Question	Answers	Additional comments/Guidance	Mark	AO
03.3	ϵ_0 related to electric field strength (due to charged object) in free space ✓ μ_0 related to magnetic flux density/magnetic field strength (due to current carrying wire) in free space ✓	Accept vacuum for free space If no other mark given, award MAX 1 for ϵ_0 related to electric field (in free space) AND μ_0 related to magnetic field (in free space)	2	2 x AO1
Total			6	

Question	Answers	Additional comments/Guidance	Mark	AO
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03

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
6	All three areas covered in some detail. 6 marks can be awarded even if there is an error and/or parts of one aspect missing.
5	All three areas covered, at least two in detail. Whilst there will be gaps, there should only be an occasional error.
4	Two areas successfully discussed, or one discussed and two others covered partially. Whilst there will be several gaps, there should only be an occasional error.
3	One area discussed and one discussed partially, or all three covered partially. There are likely to be several errors and omissions in the discussion.
2	Only one area discussed, or makes a partial attempt at two areas.
1	None of the three areas covered without significant error.

Models before 1800

1 bullet partially covers this area, all 3 are required to fully cover this area.

- (Newton proposed) particle / corpuscular model and (Huygens proposed) wave model.
- Newton / particle / corpuscular model predicted that the speed of light in glass/water was faster than in air.
- Huygen / wave model predicted that the speed of light in glass/water was slower than in air.

[Allow a comparison based on (optical) density.]

Maxwell's theory

1 bullet partially covers this area, all 3 are required to fully cover this area.

- Idea that Maxwell predicted the existence of / the speed of **electromagnetic** waves.
- Maxwell's waves consisted of (oscillating) electric **fields** and magnetic **fields**.
- At least one extra detail: e.g. Maxwell wrote equations that related magnetic fields to electric fields / $c = \frac{1}{\sqrt{\mu_0 \epsilon_0}}$ where μ_0 is related to magnetic field strength and ϵ_0 is related to electric field strength / electric field and magnetic field oscillates perpendicular to each other and the direction of energy transfer / electric and magnetic field oscillate in phase

6

4 × AO1

2 × AO2

	<table><tr><td>0</td><td>No relevant comments</td></tr></table>	0	No relevant comments	<i>[Ignore the idea that Maxwell predicted the speed of light.]</i> Significance 1 bullet partially covers this area, 2 is enough to fully cover this area. • Foucault's experiment suggested wave/Huygen model was correct / particle/Newton/corpuscular model was incorrect. • Fizeau's measurement matched the prediction of the speed of electromagnetic waves suggesting that light was an electromagnetic wave. • Hertz's measurement equalling predicted speed of electromagnetic waves confirmed Maxwell's theory. <i>[Ignore idea that Hertz's measurement matching Maxwell's prediction showed radio waves were electromagnetic.]</i> <i>[Experiments given in question, so answer must link these experiments to their significance not just speeds matching.]</i>		
0	No relevant comments					
Total			6			

Question	Answers	Additional comments/Guidance	Mark	AO
	t or t or l or l identified and substituted into $t =$	$l = 1.4 \times 10^{14}$ $t = 10$ (days) or 864000 (s)		

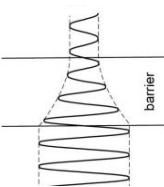


03.1	properties (and an associated) wavelength/$\lambda = \frac{h}{\text{momentum of the particle}}$ ✓	Condone mv for momentum Do not allow p unless defined (eg $p=mv$) Do not allow 'inversely proportional'	2	AO1 1a
03.2	Use of de Broglie equation $\lambda = h / \sqrt{2meV}$ to give 0.021 nm ✓ (Comparison of calculated value of λ to given value) and consistent conclusion ✓	Allow reverse calculation to give 3800V Allow 0.02 if substitution of 3500 V seen If no other mark given allow mp1 for substitution of 3500 into equation Allow ecf in MP2 only for POT error.	2	AO2 AO3
03.3	First Change One statement ✓ Relevant explanation ✓ Second Change One statement ✓ Relevant explanation ✓ Statement 1 Use target with greater spacing between atoms	Condone Statement: use particles of bigger mass (e.g. protons) smaller wavelength (at same speed) If no other marks are awarded, give 1 mark for stating that any one of the following could change but do not allow physics errors The target/spacing of atoms	Max 4	AO3 2b

	Explanation Larger separation gives rise to narrower fringes Statement 2 Increase the p.d. Explanation Reduces wavelength (which gives rise to narrower fringes) Statement 3 Decrease distance between foil and film Explanation for same angles, maxima closer together.	Potential difference Velocity of electrons Wavelength of electrons. Do not allow 'does not spread out as much'		
Total			8	

Question	Answers	Additional Comments/Guidance	Mark	ID details
	Calculation of constant of proportionality for at least two data sets ✓ Allow conversion to J	Alternative methods of calculation: Calculation of constant of proportionality and then using to calculate other E, v, v^2 and comparing with table. Checking ratio of $\frac{E_m}{E_n} \neq \frac{v_m^2}{v_n^2}$ 1 mark for any		102 1h



03.1		 electron 'wave' in sample		
03.2	Tip of probe maintained a certain distance (about 1nm) above surface. ✓ (Current from surface into probe due to tunnelling) When probe moves over higher layer of electrons, current increases ✓ (Through a feedback process) Tip is moved higher to reduce current to original value. (Distance moved by tip = distance new surface above/below original surface) ✓ (Hence surface mapped by position of tip.)	Allow reverse argument	3	AO1.1b X2 AO2.1e

03.3	Attempt to apply $\frac{1}{2}mv^2 = eV$ $\frac{1}{2} \times 9.11 \times 10^{-31} \times v^2 = 2.4 \times 10^{-19}$ ✓ If correct $v = 7.26 \times 10^5 \text{ (m s}^{-1}\text{)}$ Attempt to apply $\lambda = h/mv$ $= 6.63 \times 10^{-34} / (9.11 \times 10^{-31} \times 7.26 \times 10^5)$ ✓ $1.0 \times 10^{-9} \text{ m (cao)}$ with conclusion ✓ Alternative one step route: Attempt to put data in $\lambda = \frac{h}{\sqrt{2mE}}$ with no conversion to J ✓ Substitution of data with conversion to J ✓ Answer correct with conclusion ✓	Allow if no or incorrect conversion of eV to J Allow for use of their v in substitution Condone 1sf answer, but must have unit Example conclusion No - less energy (electron) would have longer wavelength and would be too long to map atom/wavelength should be smaller than 1nm	3	AO3.1a
Total			8	

Question	Answers	Additional Comments/Guidance	Mark	ID details
	$\lambda_0 = 2500 \text{ m}$			



03.1	Sinusoidal electric field in vertical plane, in phase with magnetic field AND Indication of direction perpendicular to both fields ✓	Expect to see arrow at either end of long axis line Condone only one of E or 'direction of propagation' not labelled. Accept 'direction' for 'direction of propagation'. Accept lower case e for E	1	1 × AO1
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Question	Answers	Additional comments/Guidance	Mark	AO
03.2	Maxwell ✓ CAO		1	1 × AO1

Question	Answers	Additional comments/Guidance	Mark	AO
03.3	Light is made of <u>corpuscles</u> ✓ When corpuscles meet boundary [any 2 from] ✓ • component of velocity/momentum parallel to surface unchanged • Component perpendicular to surface increases • (short range) force of attraction (to surface) • light travels faster in glass When corpuscles meet boundary [all 4] ✓ • component of velocity/momentum parallel to surface unchanged • Component perpendicular to surface increases • (short range) force of attraction (to surface) • bends towards the normal / angle of refraction < angle of incidence	Marks can be awarded for suitable labelled diagram Allow particles for corpuscles in MP2 and MP3 but not MP1. Condone references to horizontal/vertical components in MP2 but not MP3 unless clarified in diagram or text. Condone attracted / attraction for force of attraction Do not accept force of gravity but can still gain MP2 if 2 other points are made. Condone light bending wrong way for MP2 but not for MP3. Ignore short-range force of attraction to <u>normal</u> for MP2 but do not allow for MP3 If no other marks condone light is made of particles and one bullet from MP2 for 1 mark.	3	2 × AO1 1 × AO2

Question	Answers	Additional comments/Guidance	Mark	AO
03.4	Diffraction/interference experiment described ✓ describe / show in labelled diagram a feature that is only explained by waves e.g. series of maxima and minima, bright and dark, series of fringes, spectra (from diffraction grating not prism), bright spot in centre of double slit, intensity graph ... ✓ diffraction/interference/superposition is a wave phenomenon AND describe how the feature would look with particles e.g. two bright spots, no bright spot in the centre, etc ✓	MP1 is for the set up. MP2 is for what is seen. MP3 is for showing why Newton's theory is not correct. Marks can be awarded for suitable labelled diagram Expect description of Young's double slits experiment but allow any suitable diffraction experiment, eg single slit or grating. Stating 'Young's Double Slits' is insufficient. For MP1 experiment must be consistent with description given in MP2 and MP3. Ignore experiment to measure speed of light in glass or any reference to refraction including producing a spectra from a prism. Ignore references to polarisation. Interference pattern is not enough for MP2. If no other marks allow 1 mark for 2 from • Young's double slits • Interference/diffraction • Interference/diffraction is a wave phenomenon	3	2 × AO1 1 × AO3
Total			8	

Question	Answers	Additional comments/Guidance	Mark	AO
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02.1	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
02.2	$c = 4 \times 8600 \times 720 \times 12 = 2.97 \times 10^8 \text{ ms}^{-1}$ ✓	Speed of light must be given to 2 or 3 significant figures.	1
	Comparison to speed of light $3.0 \times 10^8 \text{ ms}^{-1}$ and judgement that they are similar. ✓		1
02.3	Must go past a gap and to the next tooth ✓	Accept a clear diagram as an alternative	2
	36 rotations per second / Hz ✓		
02.4	Maxwell's theory of electromagnetic waves predicted a value for the speed of electromagnetic waves ✓		3
	Fizeau's result is close to the predicted speed (of electromagnetic waves) ✓		
	Implies that light is an electromagnetic wave. ✓		
Total			9

7

Question	Answers	Additional Comments/Guidelines	Mark
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03.1		Use of 0.5 eV gives 4.0×10^{-25} 6.2 eV 3.2×10^{-26} 6.7 eV 3.0×10^{-26} <i>These will score 1</i> 8.0 $\times 10^{-20}$ gives 2500 nm 9.9(2) $\times 10^{-19}$ 200 nm <i>These will score 2</i> 1 sf answers are not allowed so correct working with answer 186 nm rounded to 200 nm will also score 2	1 1
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03.2	Classical Wave Model Wave model <u>predicts an increase</u> in the photocurrent <u>Plus one from</u> • as energy transferred into each electron increases (over time) /energy of the emitted electrons increases • electrons can gain sufficient KE <u>to reach T</u> • electrons can leave the surface with greater KE Photon Model The photon model <u>predicts no change</u> in the photocurrent Or photocurrent <u>remains at zero</u> <u>One from</u> • 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 <u>are still unable</u> 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
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Question	Answers	Additional Comments/Guidance	Mark
03.3	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 <u>per second/rate at which electrons reach T will reach terminal T/cross the gap</u> (the per second part captures what is going on in terms of the current)	Fewer electrons <u>per second</u> have <u>sufficient kinetic energy to reach T</u> scores 2 Do not allow fewer photoelectrons per second flowing through the circuit	1 1
03.4	$A > B > C$		1
Total			9

Question	Answers			Additional Comments/Guidance	Mark								
	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. <table><tr><th>Mark</th><th>Criteria</th><th>QoWC</th></tr><tr><td>6</td><td><u>A thorough and well communicated</u> discussion using most of the statements in bullets 1 2 and 3</td><td rowspan="2">The student presents relevant information coherently, employing structure, style and SP&G to render meaning</td></tr><tr><td>5</td><td><u>A explanation that includes</u> discussion using most of the statements in bullets 1 , 2 and 3 but may contain minor errors or omissions</td></tr></table>			Mark	Criteria	QoWC	6	<u>A thorough and well communicated</u> discussion using most of the statements in bullets 1 2 and 3	The student presents relevant information coherently, employing structure, style and SP&G to render meaning	5	<u>A explanation that includes</u> discussion using most of the statements in bullets 1 , 2 and 3 but may contain minor errors or omissions	The following statements are likely to be present: Bullet point 1 in question (Explanation of how shift expected) 1. PM_2 lies in the direction of the Earth's velocity. 2. Speed of light different in the two directions 3. The time taken for light to travel from P to M_2 and back to P would be greater than the time taken from P to M_1 and back to P 4. If the speed of light depends on the Earth's velocity through the ether. 5. Rotating the apparatus through 90° would cause the time difference to reverse/change.	
Mark	Criteria	QoWC											
6	<u>A thorough and well communicated</u> discussion using most of the statements in bullets 1 2 and 3	The student presents relevant information coherently, employing structure, style and SP&G to render meaning											
5	<u>A explanation that includes</u> discussion using most of the statements in bullets 1 , 2 and 3 but may contain minor errors or omissions												

03.1	<table><tr><td></td><td>Tick (✓) if correct</td></tr><tr><td>Beta particle emission</td><td></td></tr><tr><td>Electron diffraction</td><td></td></tr><tr><td>Photoelectric effect</td><td></td></tr><tr><td>Thermionic emission</td><td>✓</td></tr></table>		Tick (✓) if correct	Beta particle emission		Electron diffraction		Photoelectric effect		Thermionic emission	✓		1
	Tick (✓) if correct												
Beta particle emission													
Electron diffraction													
Photoelectric effect													
Thermionic emission	✓												
03.2	Use of $\lambda = \frac{h}{\sqrt{(2 m E)}}$ seen including correct substitution $\lambda = 2.4 \times 10^{-11}$ (m) 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).	Condone missing unit Allow a correct conclusion that follows from an incorrect value of λ	1 1 1										

Question	Answers	Additional Comments/Guidelines	Mark	
03.3	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.		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. <u>Factors affecting the quality and level of detail</u> - 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
	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	The student presents	

		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.	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.		
Total				10	

Question	Answers	Additional Comments/Guidelines	Mark
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02.1	Unchanged Changed			1	AO2 1a	
02.2	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.		The following statements are likely to be present. Area A Description of corpuscular explanation of refraction i)Light is made up of particles/corpuscles ii)Force acts attracting them to the water. iii)Attraction only affects motion at the interface/boundary. iv)Only one component of velocity / momentum (vertical) changes at the interface. v)The (vertical component of) velocity / momentum increases which causes the change in direction. Partial answers may be missing idea of Force (ii) or component AND boundary (iv)(iii)	6	AO1 1a	
	Guidance provided in section 3.10 of the ‘Mark Scheme Instructions’ document should be used to assist in marking this question.					
	Mark	Criteria				QWC
	6	All 3 areas A B and C covered Only allow minor omissions				The student presents relevant information coherently, employing structure, style and SP&G to render meaning clear. The text is legible.
	5	2 complete descriptions with one partial from A, B and C				
4	Full description of one area, with partial description of other two	The student presents relevant information and in a way which assists the communication of meaning.				

		OR Full descriptions of two areas with very little on third or nothing at all	The text is legible. SP&G are sufficiently accurate not to obscure meaning.	Area B Description of wave explanation of refraction i)Wave front is incident on interface ii)Huygens secondary <u>wavelets</u> at wave fronts. iii)Wavelets travel more slowly in the water. iv)The slowing down of the waves / wavelets causes the change in direction. A partial answer may have no reference to <u>wavelets</u> Area C Acceptance of wave theory Discussion of speed: (Newton's theory required light to travel faster in the water. And Huygens' theory required light to move more slowly in the water.) When the speed of light was measured in water, the value found supported Huygens' prediction. Discussion of wave properties Light was observed to show interference		
	3	A full description of one area and a partial description of one area OR A partial discussion of all three areas				
	2	A full discussion of one area OR A partial discussion of two areas	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	Only one area covered, and that partially.				
	0					

		effects that cannot be explained using corpuscular theory.) Interference effects in Young's double slit experiment can be explained by Huygens' wave theory but not by Newton's corpuscular theory. A partial answer will refer to only one piece of evidence.		
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02.3	(vibrations of) the <u>electric wave/field</u> and <u>magnetic wave/field</u> are: perpendicular to each other ✓ perpendicular to the labelled direction of motion ✓ in phase with each other ✓	Names of both waves needed for first mark But condone missing labels (E and B) on diagram if mentioned in text Condone single arrow unlabelled to represent direction of travel But Reward unlabelled arrow on axis only if no arrows on other axes Credit writing over poor diagram	3	3.12.1.3 AO1 1b
Total			10	

Question	Answers	Additional Comments/Guidance	Mark	ID details
	(All matter particles) have a wave-like nature/wave-like properties✓	Condone named particle e.g. electron Condone 'particles have a wavelength		



02.1	$c = \frac{1}{\sqrt{\mu_0 \epsilon_0}}$ seen AND μ_0 ϵ_0 substituted separately from data booklet ✓ To give value of c AND compared with c in booklet ✓	For MP1 condone formula seen AND answer given to at least 5 sf ($2.9986 \times 10^8 \text{ ms}^{-1}$) For MP2 need to see a valid comment that compares calculated value with data booklet value with units to at least 3sf	2	AO2.1b
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Question	Answers	Additional comments/Guidance	Mark	AO
02.2	Maxwell's model as varying perpendicular E and B fields (transmitting through space) ✓ (Oscillating) current in T indicates presence of (oscillating) E field ✓ Oscillating current in T produces (horizontal) B field ✓ Varying (horizontal) B field induces varying emf in loop OR Varying (vertical) E field creates a varying emf in loop ✓	For MP2 allow idea of distribution of charge in T giving rise to electric field For MP3 allow moving electrons produces a (varying) magnetic field For MP4 allow idea of magnetic field applying force on (moving) charges in the receiver (which is an emf) OR Idea of electric field causing change in charge distribution within the loop (which is an emf)	4	1× AO1.1a 3× AO2.1g

Question	Answers	Additional comments/Guidance	Mark	AO
02.3	In order to determine speed, need to measure wavelength/ distance between nodes OR antinodes in stationary wave ✓ From frequency of 75 MHz and $c = f\lambda$, wavelength = 4 m OR nodes/antinodes are 2 m apart ✓ Which is less than separation of transmitter and reflector so YES ✓ Answer refers to nodes ✓	For MP3 and MP4 allow for correct calculation leading to idea that three waves will fit between transmitter and detector so YES In MP3 allow ecf for incorrect wavelength	4	AO3.1a
Total			10	

Question	Answers	Additional comments/Guidance	Mark	AO
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01.1	Light consists of corpuscles that travel in straight lines ✓ (which means that) shadows are formed with sharp edges ✓	Condone ‘particles’ for ‘corpuscles’ Accept description of travelling in straight lines. In MP2 accept: no diffraction, only/just 2 lines/fringes seen, sharp shadows, lines are distinct Treat references to interference as neutral.	2	1 x AO1 1 x AO2
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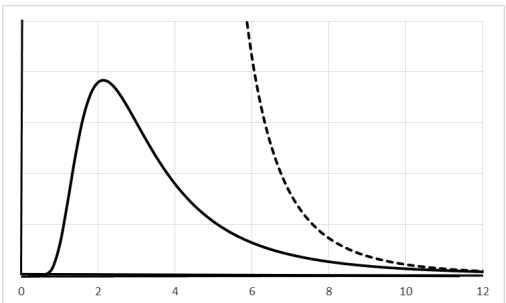
Question	Answers	Additional comments/Guidance	Mark	AO
01.2	The mark scheme gives some guidance as to what statements are expected to be seen in a 1 or 2 mark (L1), 3 or 4 mark (L2) and 5 or 6 mark (L3) answer. Guidance provided in section 3.10 of the 'Mark Scheme Instructions' document should be used to assist in marking this question.		6	2 x AO3 4 x AO1
	Mark	Criteria		
	6	All three areas covered well. 6 marks can be awarded even if there is an error and/or parts of one aspect missing.		
	5	A fair attempt to cover all 3 areas, but one area may only be covered partially.		
	4	Two areas successfully covered, or one covered and two others covered partially. Whilst there will be gaps, there should only be an occasional error.		
	3	One area covered and one covered partially, or all three covered partially. There are likely to be several errors and omissions in the discussion.		
	2	One area covered, or two covered partially		
	1	Only one area partially covered.		
	0	No relevant analysis.		
		Accept information seen in an appropriate diagram. The following statements are likely to be present. A alterations to experiment Slits separation / width should be closer to wavelength of wave. Make slits narrower and closer together. Use monochromatic (red) light use a single slit (to make the light coherent) Use a laser as it is coherent/ monochromatic B description of Huygens' theory Light is a wave. The theory uses the idea of (secondary) wavelets. Every point on wavefront acts as source of secondary wavelets. C explanation in terms of Huygens (When wave reaches slit) each point at slit produces secondary wavelets. Wavelets overlap on screen. Path difference due to different distances between a point on the screen and the two slits. Path difference introduces phase differences. Bright fringes form where path difference is whole number of wavelengths/waves arrive in phase. Dark fringes where path difference is odd number of half wavelengths/waves arrive in antiphase. Do not accept 'out of phase'. The mention of destructive/constructive interference or diffraction on its own does not gain credit.		



Question	Answers	Additional comments/Guidance	Mark	AO
01.3	(Most of the screen dark) Newton's theory predicts: (bright) central spot surrounded by partial shadow ✓ Huygens' theory predicts: (bright region with) fringes around the edge ✓ edge of bright region/fringes coloured ✓	Credit labelled additions to diagram Condone MP1 for any suggestion of gradual decrease in brightness moving out from central region, e.g. suggestion it resembles a central maximum with no other maxima. Do not accept fringe.	3	1 x AO2 2 x AO3
Total			11	

Question	Answers	Additional comments/Guidance	Mark	AO
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02.1	Spectrum with peak depending on temperature (or emitter alone). ✓	(Em) radiation given off by perfect absorber/emitter. Condone light for radiation		
02.2	(Description of ultraviolet catastrophe) Intensity similar at long wavelengths, ✓ (But rather than peak) theory predicts intensity increases at shorter wavelengths/infinite at very short wavelengths ✓	If no other mark awarded, 1 mark can be given for idea that there is 'no peak'. Allow correct line on graph for either for 1 mark But some correct description needed for both  Condone any line that goes to infinity at short wavelengths for MP2.	1 1	AO1.1b AO2.1b

02.3	EM radiation emitted in quanta ✓ Energy of quantum is related to a single frequency OR $E = hf$, where h is Planck's constant. ✓	Do not condone photon or packet for quanta in MP1	2	AO1.1b
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2.4	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		The following statements are likely to be present. A main outcomes of experiments. No photoelectric emission if incident light below threshold frequency Photoelectric emission is instantaneous/occurs as soon as light is incident on metal surface (Photoelectrons have a range of KE from zero to max value, depending on type of metal and frequency of incident light. Number of photoelectrons per second is proportional to intensity of incident radiation) B problems of classical wave theory Intensity of wave (brightness of light) should determine whether photoelectron emitted/KE of photoelectron OR light of any frequency should cause emission. Wave energy spread over surface should mean time needed to for electrons to accumulate enough energy to be emitted/lower intensity the longer the time. C Aspects of Einstein's theory Light is made of photons Photoelectrons due to one photon interacting with one electron in surface of metal. Minimum energy (work function of metal) needed for electron to be emitted related to a threshold frequency by $\phi = hf_0$ Remaining energy of photon ($hf - hf_0$) becomes (max) KE of photoelectron. Brighter source means more photons (per second) and therefore more photoelectrons (per second).	AO3.1b X2 AO2.1a X2 AO1.1a X2
	Mark	Criteria		
	6	All 3 areas covered with at least two aspects of photoelectric effect covered in some detail. 6 marks can be awarded even if there is an error and/or parts of one aspect missing.		
	5	A fair attempt to analyse all 3 areas. If there are several errors or missing parts then 5 marks should be awarded.		
	4	Two areas successfully discussed, or one discussed and two others covered partially. Whilst there will be gaps, there should only be an occasional error.		
	3	One area discussed and one discussed partially, or all three covered partially. There are likely to be several errors and omissions in the discussion.		
	2	Only one area discussed, or makes a partial attempt at two areas.		
	1	None of the three areas covered without significant error.		
	0	No relevant analysis.		

Total			12
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Question	Answers	Additional Comments/Guidance	Mark	ID details
	Electrons (in surface) have to overcome the potential/coulomb barrier✓ Electrons have insufficient energy so (due to wave properties of electrons) there is a probability of electrons crossing from sample to tip OR a fraction of electrons will move from sample to tip. ✓	Credit diagram of high amplitude wave, barrier and lower amplitude transmitted wave for second mark Eg electron 'wave' in tip	2	AO2.1a



01.1	A is filament ✓ B is the anode ✓ V_1 is the p.d. to supply energy/ drive current to heat A. ✓ V_2 is the p.d./produces accelerating electric field to accelerate electrons.	Allow heated cathode	4	2 × AO1b 2 × AO2.1g
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Question	Answers	Additional comments/Guidance	Mark	AO
01.2	(Atom diameter about 0.1 nm) So wavelength should be about 0.05 nm ✓ $\lambda = \frac{h}{\sqrt{2meV}}$ seen ✓ Rearranged with substitutions of h, m, e to give $V = \frac{h^2}{2me\lambda^2}$ ✓ = 600 V ✓	Allow 0.05 nm to 0.1 nm for wavelength Ecf for wavelength for MP 2, 3, 4 Allow 1 sf answer	4	4 × AO3.2a

Question	Answers	Additional comments/Guidance	Mark	AO
01.3	State inverse relationship between wavelength and momentum ✓ Identify link between V_2 and momentum of electrons. ✓ Identify how ring diameter is related to wavelength. ✓ State change in ring diameter due to change in V_2 (which is consistent with de Broglie hypothesis) ✓	De Broglie hypothesis suggests that λ will decrease/increase if the momentum increases/decreases Allow qualitative statements. Measure V_2 to determine (KE of electrons and therefore) momentum/speed of electrons Measure ring diameter as increased/decreased diameter indicates increased/decreased wavelength (De Broglie hypothesis therefore supported by) increasing/decreasing V_2 resulting in decreased/increased ring diameter.	4	1 × AO2.1g 3 × AO3.2a

Question	Answers	Additional comments/Guidance	Mark	AO										
01.4	<table><tr><th>STM</th><th>TEM</th></tr><tr><td>Moving electrons can cross a potential barrier.</td><td>Moving electrons can be deflected by a magnetic field.</td></tr><tr><td>Moving electrons can be deflected by a magnetic field.</td><td>Moving electrons can be deflected by a magnetic field.</td></tr><tr><td>Moving electrons can be deflected by a magnetic field.</td><td>Moving electrons can cross a potential barrier.</td></tr><tr><td>Moving electrons can cross a potential barrier.</td><td>Moving electrons can cross a potential barrier.</td></tr></table>	STM	TEM	Moving electrons can cross a potential barrier.	Moving electrons can be deflected by a magnetic field.	Moving electrons can be deflected by a magnetic field.	Moving electrons can be deflected by a magnetic field.	Moving electrons can be deflected by a magnetic field.	Moving electrons can cross a potential barrier.	Moving electrons can cross a potential barrier.	Moving electrons can cross a potential barrier.	Only answer	1	AO1.1a
	STM	TEM												
	Moving electrons can cross a potential barrier.	Moving electrons can be deflected by a magnetic field.												
	Moving electrons can be deflected by a magnetic field.	Moving electrons can be deflected by a magnetic field.												
	Moving electrons can be deflected by a magnetic field.	Moving electrons can cross a potential barrier.												
	Moving electrons can cross a potential barrier.	Moving electrons can cross a potential barrier.												
☒														
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Tick in first box ✓														
Total			13											

Question	Answers	Additional comments/Guidance	Mark	AO
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05	Conversion of $3.7 \times 10^9 \text{ eV}$ to $5.9 \times 10^{-10} \text{ J}$ ✓ Correct use of $E = mc^2 = \frac{m_0 c^2}{\left(1 - \frac{v^2}{c^2}\right)^{\frac{1}{2}}}$ including correct substitution ✓ 0.97(c) ✓	Accept substitution of $3.7 \times 10^9 \times 1.6 \times 10^{-19}$	3
Total			3



04.1	(for Proper time, $t_0 = 31,536,000$ s / 365 days) Dilated time, $t = 31,561,259$ s ✓ Time dilation is 25,259 s / 421 minutes / 7.0 hours / 0.29 days ✓ The recorded time will be longer (as predicted) ✓ The recorded time will be less than several days longer (as predicted) ✓	Accept answers in other units (e.g. 365.3 days) Accept an answer of 31582876 seconds / 365.5 days where a proper time of 365.25 days has been used.	4
04.2	Theory of Special Relativity requires no acceleration ✓ (The spacecraft/frame of reference is) accelerating ✓ Alternative answer: Theory of Special Relativity requires inertial reference frame ✓ (The spacecraft/frame of reference is) not an inertial reference frame ✓	Accept change in direction / speed / velocity as alternatives for accelerating.	2
Total			6

11

Question	Answers	Additional Comments/Guidelines	Mark



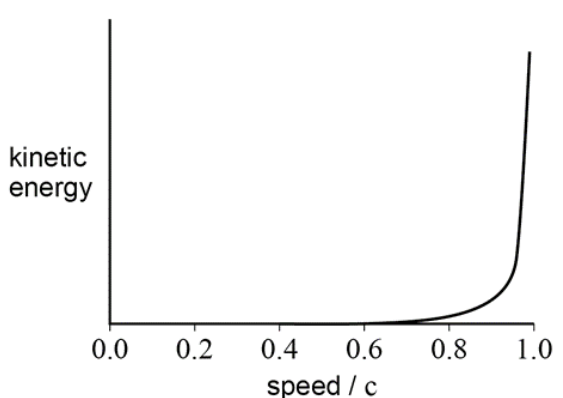
03	The mark scheme gives some guidance as to what statements are expected to be seen in a 1 or 2-mark (L1), 3 or 4-mark (L2) and 5 or 6-mark (L3) answer. Guidance provided in section 3.10 of the 'Mark Scheme Instructions' document should be used to assist in marking this question.		The following statements are likely to be present. A – outline of experimental procedure Semi-silvered glass block splits the beam of monochromatic light into two beams (The plane block ensures that both beams pass through the same thickness of glass and air) (Beams travel at right angles, to M_1 and M_2, and return to) combine at telescope with a path difference Observer sees interference pattern from two beams Apparatus rotated 90 degrees and pattern observed B – expected result Pattern would shift As path length/speed of light different depending on (orientation relative to) motion of apparatus So ether exists/absolute motion of Earth detected C – actual result and significance No shift in pattern No evidence of ether Speed of light is invariant/all motion is relative/no absolute motion	6	AO1.1a × 6
	Mark	Criteria			
	6	All three areas covered with at least two aspects covered in some detail. 6 marks can be awarded even if there is an error and/or parts of one aspect missing.			
	5	A fair attempt to analyse all three areas. If there are several errors or missing parts then 5 marks should be awarded.			
	4	Two areas successfully discussed, or one discussed and two others covered partially. Whilst there will be gaps, there should only be an occasional error.			
	3	One area discussed and one discussed partially, or all three covered partially. There are likely to be several errors and omissions in the discussion.			
	2	Only one area discussed, or makes a partial attempt at two areas.			
	1	None of the three areas covered without significant error.			
	0	No relevant analysis.			
Total				6	

Question	Answers	Additional comments/Guidance	Mark	AO
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04.1	One which moves at constant velocity	Allow: a reference frame in which Newton's laws / Newton's first law holds.	1	AO1.1a
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Question	Answers	Additional comments/Guidance	Mark	AO
04.2	In frame of particle beam Distance between detectors = $45\sqrt{1 - \frac{(0.97c)^2}{c^2}} = 10.9 \text{ m} \checkmark$ Time = $10.9 / 0.97c = 3.8 \times 10^{-8} \text{ s} \checkmark$ Half-life = time/3 $\checkmark = 1.3 \times 10^{-8} \text{ s} \checkmark$	MP1 is for determination of distance between detectors in ref frame of particles MP2 is for determining the time between detectors in the ref frame of particles MP3 is for use of reduction to 12.5% is equivalent to 3 half-lives MP4 is for correct final answer Allow alternative route from ref frame of detectors	4	AO2.1f

Question	Answers	Additional comments/Guidance	Mark	AO
04.3	The time taken for particle beam to travel between detectors 'measured' in the reference frame of particle beam $\checkmark$	Accept: shortest observable time for a particle passing between detectors. Accept $3.8 \times 10^{-8} \text{ s}$	1	AO2.1e
Total			6	

04.1	C ✓	Only answer	1	AO1
				

Question	Answers	Additional comments/Guidance	Mark	AO
04.2	KE = total energy – rest energy ✓ $m_0 c^2 = \frac{m_0 c^2}{\sqrt{1 - \frac{v^2}{c^2}}} - m_0 c^2 \quad \checkmark$ To give $v = 0.87c$ OR $2.6 \times 10^8 \text{ m s}^{-1} \quad \checkmark$	MP2 requires the use of the idea that the KE is equal to the rest energy. (calculator values are 0.8660 and 2.59808×10^8)	3	3 x AO2

Question	Answers	Additional comments/Guidance	Mark	AO
04.3	mass is related to energy through $E = mc^2$ ✓ When an object stores energy this appears as an increase in observed mass. OR A spring gains (elastic potential) energy so observed mass must also increase. ✓	Treat any idea that 'the difference in observed mass is negligible' as neutral.	2	2 x AO3
Total			6	

04.1	$L_0 = 2500 \text{ m}$ Length = $2500 \times (1 - 0.95^2)^{1/2}$ ✓ length = 781 (780) m ✓		2	AO2.1f
04.2	Number of muons passing through detector per second measured at top of mountain/in upper atmosphere AND Number of muons passing through detector per second measured on ground. ✓ Measurements show far fewer muons decay than expected in time taken (in observer's frame of reference) for muons to travel from upper atmosphere to ground (as the clock in muons frame of ref runs slower than observer so half-life appears longer). ✓	Allow "intensity of muons" Allow number decayed/difference in numbers at upper atmosphere and ground Allow more muons reach the ground than expected	2	AO1a
04.3	Lower velocity means Take longer to travel to ground (in either frame of reference) ✓ And time dilation effect less (in Earth frame of reference)/length contraction effect less (in muon frame of reference) (as not so close to c) ✓ More muons decay before reaching ground so rate of detection reduced ✓	If there is no reference to frame of reference or relativistic effects award Max 1. Answer needs to be consistent with the implicit frame of reference being discussed	3	AO3.1a
Total			7	



04.1		calculation that shows $\ddot{K}E \neq \frac{1}{2}mv^2$ ✓	2	AO2 1h AO3 1b
	Calculation of at least three data sets and conclusion to the effect that as the constants differ, the classical prediction is not true ✓	If more than 3 calculations shown, reward any three correct		



Question	Answers	Additional Comments/Guidance	Mark	ID details
04.2	v has upper limit as E_k increases ✓ Explanation: As v increase mass increases ✓ As v approaches c, mass approaches infinity/increase in mass significant ✓ Near c, increases in E_k are due to increase in mass/E_k tends to infinity ✓	For MP1 allow comment on their calculations from 4.1 e.g. E_k/v^2 increases Do not reward references to 'constant increases' Treat 'exponentially' as neutral Condone energy/total energy for E_k	4	AO3 1b
04.3	$E_0 = m_0 c^2 = 8.2 \times 10^{-14} \text{ J}$ $E = \frac{m_0 c^2}{\left(1 - \frac{v^2}{c^2}\right)^{\frac{1}{2}}} = 2.6 \times 10^{-13} \text{ J} \checkmark$ $E_k (= E - E_0) = 2.6 \times 10^{-13} - 8.2 \times 10^{-14} \checkmark$ $1.8 \times 10^{-13} \text{ J} \checkmark$	If no marks are scored 1 mark can be given for <i>seeing</i> $8.2 \times 10^{-14} \text{ J}$ Allow ecf from MP1 for incorrect m_0 eg use of proton Give all 3 marks for correct answer	3	2 × AO1 1a 1 × AO2 1c
Total			9	

04.1	t_0 or t or l_0 or l identified and substituted into $t = \frac{t_0}{\sqrt{1-\frac{v^2}{c^2}}}$ or $l = l_0 \sqrt{1-\frac{v^2}{c^2}}$ ✓ Substitution using $v = \frac{s}{t}$ with their substituted values in the same reference frame ✓ All correct shaded value(s) from any row seen ✓	$l_0 = 1.4 \times 10^{14}$, $t_0 = 10$ (days) or 864000 (s), l or t from the result of $v = \frac{s}{t}$ for their v (allow t in days) Identification can be explicit or inferred from substitution. Condone missing squares on v and c in MP1. v: either $s = 1.4 \times 10^{14}$ or $t = 8.64 \times 10^5$ s with their answer from a relativistic calculation (but not with each other). Do not allow $v = \frac{1.4 \times 10^{14}}{10(\times 24 \times 60 \times 60)}$ or use of $v = c$ for MP2 and MP4. s or t: $v = 0.5c$ and one of $s = 1.4 \times 10^{14}$, $t = 8.64 \times 10^5$ s or their answer from a relativistic calculation	4	AO3
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		MP3 implies MP1 and MP2. If multiple values are seen, mark values used in conclusion. If there is no conclusion, all values must be correct. <table><tr><th colspan="3">Either reference frame</th></tr><tr><td>minimum v</td><td></td><td>actual v</td></tr><tr><td>$1.4 \times 10^8 \text{ m s}^{-1}$</td><td><</td><td>$1.5 \times 10^8 \text{ m s}^{-1}$</td></tr><tr><th colspan="3">Spaceship reference frame</th></tr><tr><td>time taken</td><td></td><td>maximum time</td></tr><tr><td>9.4 or 9.3 d</td><td><</td><td>10 d</td></tr><tr><td>$8.1 \text{ or } 8.0 \times 10^5 \text{ s}$</td><td><</td><td>$8.6 \times 10^5 \text{ s}$</td></tr><tr><td>distance travelled</td><td></td><td>maximum distance</td></tr><tr><td>$1.2 \times 10^{14} \text{ m}$</td><td><</td><td>$1.3 \times 10^{14} \text{ m}$</td></tr><tr><th colspan="3">Planet's reference frame</th></tr><tr><td>time taken</td><td></td><td>maximum time</td></tr><tr><td>10.8 d</td><td><</td><td>11.5 d</td></tr><tr><td>$9.3 \times 10^5 \text{ s}$</td><td><</td><td>$9.9 \times 10^5 \text{ s}$</td></tr><tr><td>distance travelled</td><td></td><td>maximum distance</td></tr><tr><td>$1.4 \times 10^{14} \text{ m}$</td><td><</td><td>$1.5 \times 10^{14} \text{ m}$</td></tr></table> Do not award MP4 unless MP1 and MP2 are awarded.	Either reference frame			minimum v		actual v	$1.4 \times 10^8 \text{ m s}^{-1}$	<	$1.5 \times 10^8 \text{ m s}^{-1}$	Spaceship reference frame			time taken		maximum time	9.4 or 9.3 d	<	10 d	$8.1 \text{ or } 8.0 \times 10^5 \text{ s}$	<	$8.6 \times 10^5 \text{ s}$	distance travelled		maximum distance	$1.2 \times 10^{14} \text{ m}$	<	$1.3 \times 10^{14} \text{ m}$	Planet's reference frame			time taken		maximum time	10.8 d	<	11.5 d	$9.3 \times 10^5 \text{ s}$	<	$9.9 \times 10^5 \text{ s}$	distance travelled		maximum distance	$1.4 \times 10^{14} \text{ m}$	<	$1.5 \times 10^{14} \text{ m}$		
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| | Comparison for their value(s) from using $v = \frac{s}{t}$ **and** a relativity equation **and** a consistent conclusion ✓ Consistent reference frame must be used for comparison but does not have to be identified. | | |

Comparison for their value(s) from using $v = \frac{s}{t}$
and a relativity equation **and** a consistent conclusion ✓

Consistent reference frame must be used for comparison but does not have to be identified.

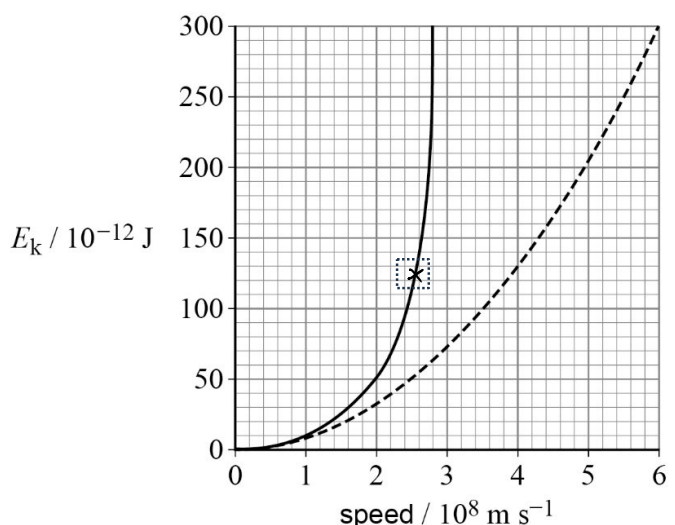
Question	Answers	Additional comments/Guidance	Mark	AO
04.2	Use of $\sqrt{1-0.5^2}$ or $\sqrt{1-\frac{0.5^2 c^2}{c^2}}$ or $\sqrt{1-\frac{(1.5 \times 10^8)^2}{(3 \times 10^8)^2}}$ or $\sqrt{1-0.25}$ $\sqrt{0.75}$ or 0.866 or $\frac{\sqrt{3}}{2}$ with lengths ✓ $l = 200$ (m) or $l_0 = 210$ (m) identified ✓ $(l_0 \text{ for ship}) = 231$ (m) or $(l \text{ for cargo}) = 182$ (m) ✓ Yes AND either $231 > 210$ OR $182 < 200$ ✓	Condone MP1 if L and L_0 are mixed up. Squares must be seen in substitution for MP1 but allow MP2 if missing. Correct substitution into $l = l_0 \sqrt{1-\frac{v^2}{c^2}}$ gains first 2 marks e.g. $l = 210\sqrt{1-0.5^2}$ or $200 = l_0\sqrt{1-0.5^2}$ or equivalent MP3 implies MP2 but not MP1 MP3 is cao and can be awarded if MP1 is withheld for missing squares in working but answer is correct. Allow ecf for MP4 for missing squares or calculation error provided a cargo length is compared to a ship length based on an attempted relativistic calculation.	4	AO3

Question	Answers	Additional comments/Guidance	Mark	AO
04.3	c	Speed of light is the same regardless of the speed of the observer or source	1	AO2
Total			9	

04.1	Either - Equation (for speed of light) only contains (universal) constants OR - Speed of light is invariant / constant / same in all reference frames / does not depend of speed of source or observer. ✓ Both bullet points above and one from - Constants don't depend on reference frame or speed of source / observer OR (refers to the) speed of light as being in free space / vacuum ✓	Speed of light is constant in equation is not enough for MP1. Do NOT allow speed of light is invariant in all <u>inertial</u> reference frames for MP2 but condone for MP1. Ignore calculations of speed of light	2	1 × AO1 1 × AO3
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Question	Answers	Additional comments/Guidance	Mark	AO
04.2	Use by manipulation or substitution of $l = l_0 \sqrt{1 - \frac{v^2}{c^2}} \quad \checkmark$ to give 69 m $\checkmark$	Condone substitution and working leading to 21 m e.g. $38 \sqrt{1 - \frac{2.5^2}{3^2}} = 21$ for 1 mark only. (mixes up l_0 and l) $l_0 = \frac{l}{\sqrt{1 - \frac{v^2}{c^2}}} = \frac{38}{\sqrt{1 - \frac{2.5^2 (\times 10^8)^2}{3.0^2 (\times 10^8)^2}}}$ Allow use of $v = \frac{s}{t}$ and $t = \frac{t_0}{\sqrt{1 - \frac{v^2}{c^2}}}$ for either route. 93 m comes from $\frac{38}{\sqrt{1 - \frac{2.5}{3.0}}}$ and gains 1 mark.	2	2 × AO2

Question	Answers	Additional comments/Guidance	Mark	AO
04.3	Evidence of idea that kinetic energy = total energy – rest energy ✓ $E_k = \frac{m_0 c^2}{\sqrt{1 - \frac{v^2}{c^2}}} - m_0 c^2$ with substitutions correct ✓ 1.21 or 1.22×10^{-10} (J) ✓	If no other mark awarded, give one mark for calculation of total energy (2.72×10^{-10} J) or rest energy (1.5×10^{-10} J) Use of $m = \frac{m_0}{\sqrt{1 - \frac{v^2}{c^2}}}$ with $E_k = \frac{1}{2}mv^2$ is 0 marks In MP2 allow use of γ from earlier 04.2 but value must be seen here. Allow rest energy = $931.5 \times 10^6 \times 1.60 \times 10^{-19}$ as part of calculation. At least 3 sf Allow 1.23×10^{-10} (J) A substitution missing the squares and showing 2.2×10^{-10} J is eligible for MP2.	3	3 × AO2

Question	Answers	Additional comments/Guidance	Mark	AO
04.4	Follows dashed line up to $v = 1$; condone divergence starting anywhere from $v = 0.3$ to $v = 1.1$ ✓ Increasing gradient passing within one grid square of (2.5, 122) ✓ Increasing gradient and does not go beyond $v = 3$ ✓ 	For MP3, if line reaches $v = 3$ must be asymptotic MP3 should not be awarded if continuing the line would clearly cross $v = 3$	3	3 × AO3.1a
Total			10	

04.1		render meaning clear. The text is legible.	reverse change,	6
	6. When rotated there would be a change in the phase difference between the waves (at each point in the fringe pattern) Bullet point 2 in the question (Results compared with prediction) 7. The apparatus was capable of detecting shifts of 0.05 fringe, 8. No shift was detected then or in later experiments when apparatus rotated Bullet point 3 in the question (Conclusions) 9. The experiment showed that there is no absolute motion 10. Ether did not exist so light travels without the need for a material medium, 11. The Earth was dragging the ether with it.			

	4	<u>The response includes a well presented discussion of two from bullets 1 and two from bullet 3 and one from bullet 2</u>	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.		Many responses fail to demonstrate an understanding that the shift pattern is there in the first place and the shift occurs due to rotation of the apparatus. They often imply that the shift is due to differences in the distance travelled	
	3	<u>The response includes a discussion of one comment from each bullet</u>				

	2	<u>The response makes comments about two bullet points (This is likely to be from bullets 2 and 3)</u>	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	Makes relevant comment from the list				
	0	No relevant coverage of the likely statements.	The student's presentation, SP&G seriously obstruct understanding.			



Question	Answers	Additional Comments/Guidance	Mark
04.2	Correct postulate invariance of the speed of light <u>in free space/vacuum</u> . speed of light the same in free space		1
04.3	Laws of physics have the same form in all inertial frames Laws of physics unchanged from one inertial frame to another	The <u>same</u> laws of physics are obeyed/apply/hold in (all) inertial frames of reference/non accelerating frames of reference/frames moving at a constant velocity Not Allowed All laws of physics Laws of physics are the same Laws of physics are constant Mention of Newton's laws being obeyed Allow 1 here if both 4.2 and 4.3 are correct but reversed	1

04.4	Time of flight is found to be $4.41 \times 10^{-6} \text{ s}$ ✓ $t_o = t \sqrt{1 - \frac{v^2}{c^2}}$ or $t_o = 4.41 \times 10^{-6} \sqrt{1 - 0.99^2}$ ✓ (Proper time t_0 is) $6.22 \times 10^{-7} \text{ s}$ ✓ Percentage remaining is (found from the graph) 82 ± 1 OR In muon reference frame $L = 1310 \sqrt{1 - 0.99^2}$ ✓ 185 m ✓ $t = \frac{185}{0.99 \times 3 \times 10^8} = 6.23 \times 10^{-7} \text{ s}$ ✓ allow ecf for incorrect length calculation $82 \pm 1\%$ ✓	May do Number of half lives = $6.22 \times 10^{-7} / 2.2 \times 10^{-6}$ fraction remaining = $0.5^{0.283} = 0.82$ 185 m seen scores 2 <u>Must see this stage with speed = $0.99 \times 3 \times 10^8$</u> Final answer in range can be awarded even if 0.99 omitted in MP3 Allow <u>minor</u> differences in time (3rd sf) due to rounding in processing	4
Total			12

04.1	Either conversion of 1 MeV to J or $W = QV$ $1.60 \times 10^{-19} \times 1.30 \times 10^6 = 2.08 \times 10^{-13} \checkmark$ (J)	At least 2 sf required.	1	1 AO1
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Question	Answers	Additional comments/Guidance	Mark	AO
04.2	$Q = mc\Delta\theta = 1.5 \times 903 \times 68.0 (= 92\,106 \text{ J})$ OR $E_K \text{ of one electron} = \frac{92\,106}{4.50 \times 10^{17}} \checkmark (= 2.05 \times 10^{-13} \text{ J})$ Both calculations and correct conclusion, eg Yes, this is consistent with an accelerating voltage of 1.30 MV. $\checkmark$	Alternative route Total E_K for all electrons = $2.08 \times 10^{-13} \times 4.50 \times 10^{17} = (93\,600 \text{ J})$ OR $\Delta\theta = \frac{Q}{mc} = \frac{93600}{1.5 \times 903} \checkmark (= 69.1 \text{ K})$ which is consistent with the temperature rise observed. $\checkmark$ Can also compare total E_K with $mc\Delta\theta$ for MP2. Use of 2.0×10^{13} gives total E_K of 90 000 J and $\Delta\theta$ of 66 K which is consistent. Allow comparison of in eV or accelerating pd (1.28×10^6) with $1.3 \times 10^6 \text{ V}$ or MeV with MV.	2	2 AO3

Question	Answers	Additional comments/Guidance	Mark	AO
04.3	Correct calculation of non-relativistic E_K ✓_a Statement or attempted use of $E_K = mc^2 - m_0c^2$ ✓_b Correct calculation of relativistic E_K ✓_c Both calculations and comparison of with 2.1×10^{-13} or 2.0×10^{-13} J to conclusion consistent with idea that student B is correct ✓_d Alternative Calculation of speed using $v = \sqrt{\frac{2E_K}{m}}$ ✓_a Statement or attempted use of $E_K = mc^2 - m_0c^2$ ✓_b Calculation of speed from relativistic equation ✓_c Both calculations and comparison of results with 2.88×10^8 or 3×10^8 ✓_d Alternative for Max 2 Correct calculation of non-relativistic E_K ✓_a Calculation of relativistic mass, total energy or $\sqrt{1 - v^2/c^2}$ or $\frac{1}{\sqrt{1 - v^2/c^2}}$ AND comment that relativistic effects are significant (owtte) so B is correct. ✓_{bcd}	$E_K = \frac{1}{2}mv^2 = 3.78 \times 10^{-14}$ J $E = \frac{m_0c^2}{\sqrt{1 - \frac{v^2}{c^2}}} - m_0c^2 = 2.11 \times 10^{-13}$ J For ✓_d allow a comparison of $\Delta\theta$ from $m_{Al}c\Delta\theta = N(mc^2 - m_0c^2)$ with 68° Allow ecf for ✓_d for minor calculation error, rounding error or transcription errors but there must be a relativistic KE and non-relativistic calculation to award ✓_d. $v = 6.8 \times 10^8$ m s⁻¹ if using 2.08×10^{-13} $v = 2.88 \times 10^8$ m s⁻¹ if using 2.08×10^{-13} Allow calculations based on the total number of electrons and comparison with 04.2. If no other marks awarded max 1 for student B is correct because speed is greater than 3.0×10^7 m s⁻¹ or v is 96% of c (which is greater than 10%).	4	4 AO3



Question	Answers	Additional comments/Guidance	Mark	AO
04.4	< 29.8 ns ✓		1	1 AO2

Question	Answers	Additional comments/Guidance	Mark	AO
04.5	Max 4 • Gain/change in E_K is the same ✓_a • due to the same loss of potential energy OR gain in $E_K = e(\Delta)V$ and same potential difference ✓_b • Increase/change in speed is greater in stage 1 ✓_c • Idea that mass increases with speed ✓_d • Idea that energy is used to produce a large increase of mass and a small increase in speed in stage 13 (with a small increase in mass and a large increase in speed in stage 1) ✓_{e1} OR Idea that electron speed cannot increase much when close to the speed of light since electrons cannot travel faster than the speed of light ✓_{e2}	Only allow use of $\frac{1}{2}mv^2$ or $E_K \propto v^2$ if it is clear that this refers only to stage 1 for ✓_b or ✓_e. ✓_d Allow a correct sketch of relativistic mass and speed graph if c is labelled on speed axis. ✓_d Condone with reference to $E_K = \frac{1}{2}mv^2$ ✓_e must refer to relativity.	4	4 AO3
Total			12	