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Centre number

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Candidate number

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Surname

StemUp Model Solution

Forename(s)

Candidate signature

I declare this is my own work.

A-level PHYSICS

Paper 3

Section B Turning points in physics

Monday 17 June 2024

Morning

Time allowed: The total time for both sections of this paper is 2 hours. You are advised to spend approximately 50 minutes on this section.

Materials

For this paper you must have:

- a pencil and a ruler
- a scientific calculator
- a Data and Formulae Booklet
- a protractor.

Instructions

- Use black ink or black ball-point pen.
- Fill in the boxes at the top of this page.
- Answer **all** questions.
- You must answer the questions in the spaces provided. Do not write outside the box around each page or on blank pages.
- If you need extra space for your answer(s), use the lined pages at the end of this book. Write the question number against your answer(s).
- Do all rough work in this book. Cross through any work you do not want to be marked.
- Show all your working.

Information

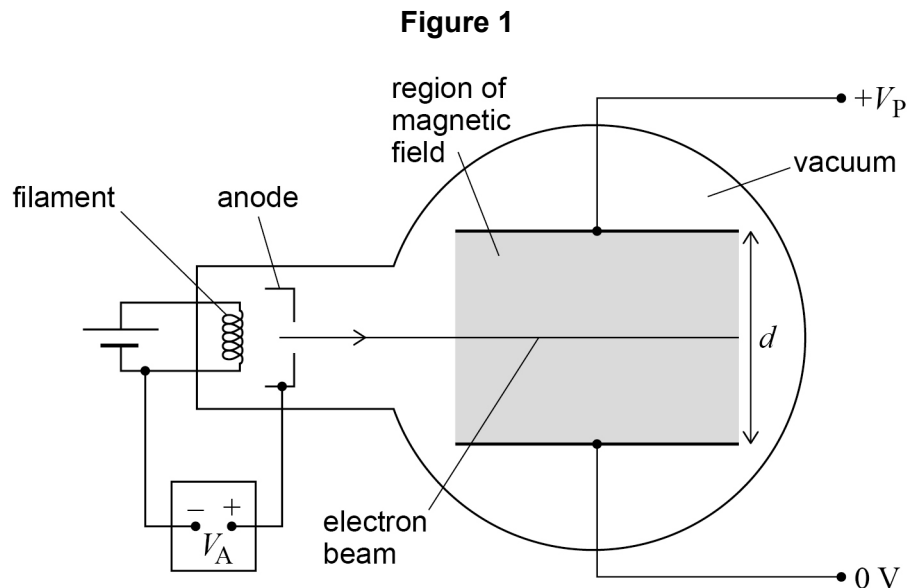
- The marks for questions are shown in brackets.
- The maximum mark for this paper is 35.
- You are expected to use a scientific calculator where appropriate.
- A Data and Formulae Booklet is provided as a loose insert.

For Examiner's Use

Question	Mark
1	
2	
3	
4	
TOTAL	



J U N 2 4 7 4 0 8 3 B D 0 1

Section BAnswer **all** questions in this section.**0 1 . 1****Figure 1** shows apparatus used in an experiment to measure the specific charge of the electron.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]

The electric force on each electron (from the field between the plates, eV_P/d , upwards) and the magnetic force (Bev , downwards) are equal in magnitude and opposite in direction.

So the forces are balanced and the resultant force is zero: there is no vertical acceleration, so the electrons travel in a straight line (Newton's first law).



0 1 . 2

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

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

$$V_p = 1.51 \text{ kV}$$

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

$$V_A = 1.00 \text{ kV}$$

[4 marks]

$$\text{Undeflected: } Bev = eV_p/d, \text{ so } v = V_p/(dB)$$

$$v = 1.51 \times 10^3 / (5.0 \times 10^{-2} \times 1.59 \times 10^{-3}) = 1.90 \times 10^7 \text{ m s}^{-1}$$

$$\text{Accelerating pd: } \frac{1}{2}mv^2 = eV_A, \text{ so } e/m = v^2/(2V_A)$$

$$e/m = V_p^2 / (2V_A d^2 B^2)$$

$$e/m = (1.90 \times 10^7)^2 / (2 \times 1.00 \times 10^3)$$

$$e/m = 1.80 \times 10^{11} \text{ C kg}^{-1}$$

$$\text{specific charge} = \underline{1.80 \times 10^{11}} \text{ C kg}^{-1}$$

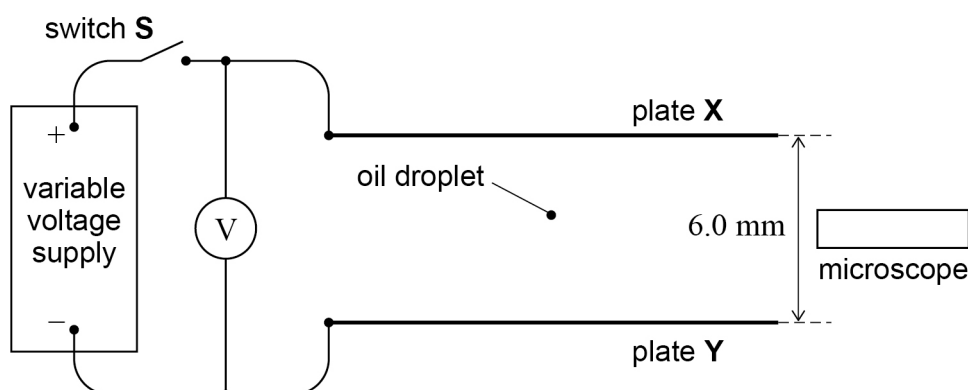
6

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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]

Procedure: with switch S open (no electric field between the plates), an oil droplet is sprayed into the region between plates X and Y and is observed through the microscope.

The droplet quickly reaches its terminal velocity. Using a stopwatch, measure the time t for it to fall a known distance s , using the scale (graticule) lines in the microscope eyepiece. Repeat and find a mean, then calculate the terminal velocity $v = s/t$.

Additional data needed: the density of the oil ρ , the viscosity of the air η and the gravitational field strength g .

Calculation: at terminal velocity the weight equals the viscous drag, so $mg = 6\pi\eta rv$ (Stokes' law). The mass of the droplet is $m = \rho V = (4/3)\pi r^3 \rho$.



So $(4/3)\pi r^3 \rho g = 6\pi \eta r v$, which rearranges to $r^2 = 9\eta v / (2\rho g)$, giving $r = \sqrt{(9\eta v / (2\rho g))}$, where ρ is the density of the oil and η is the viscosity of the air.

Principles and assumptions: the droplet falls at terminal velocity because the forces on it are balanced (weight = viscous drag force), so there is no acceleration (Newton's first law).

Air acts as a viscous fluid, so Stokes' law applies to the droplet. The droplet is assumed to be spherical, so $V = (4/3)\pi r^3$. The upthrust from the air is negligible and can be ignored.

Question 2 continues on the next page

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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]

$$\text{Volume: } V = \frac{4}{3}\pi r^3 = \frac{4}{3}\pi \times (1.20 \times 10^{-6})^3 = 7.24 \times 10^{-18} \text{ m}^3$$

$$\text{Mass: } m = \rho V = 880 \times 7.24 \times 10^{-18} = 6.37 \times 10^{-15} \text{ kg}$$

$$\text{Stationary: electric force} = \text{weight, } QV/d = mg$$

$$Q = mgd/V = 6.37 \times 10^{-15} \times 9.81 \times 6.0 \times 10^{-3} / 467$$

$$Q = 8.03 \times 10^{-19} \text{ C } (\approx 8 \times 10^{-19} \text{ C})$$



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]

$$\% \text{ uncertainty in } Q = 3 \times 4\% + 1\% + 0.1\% + 0.2\% + 2\% = 15.3\%$$

$$\text{Absolute uncertainty} = 0.153 \times 8.03 \times 10^{-19} = \pm 1.2 \times 10^{-19} \text{ C } (\approx \pm 1 \times 10^{-19} \text{ C})$$

So Q lies between about $6.8 \times 10^{-19} \text{ C}$ and $9.2 \times 10^{-19} \text{ C}$. The uncertainty, $1.2 \times 10^{-19} \text{ C}$, is larger than half of e ($1.60 \times 10^{-19} / 2 = 0.80 \times 10^{-19} \text{ C}$), so the range includes values that are not integer multiples of $1.60 \times 10^{-19} \text{ C}$ (it overlaps $5e$ and $6e$). Therefore this result cannot be used to confirm charge quantisation.

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0 3

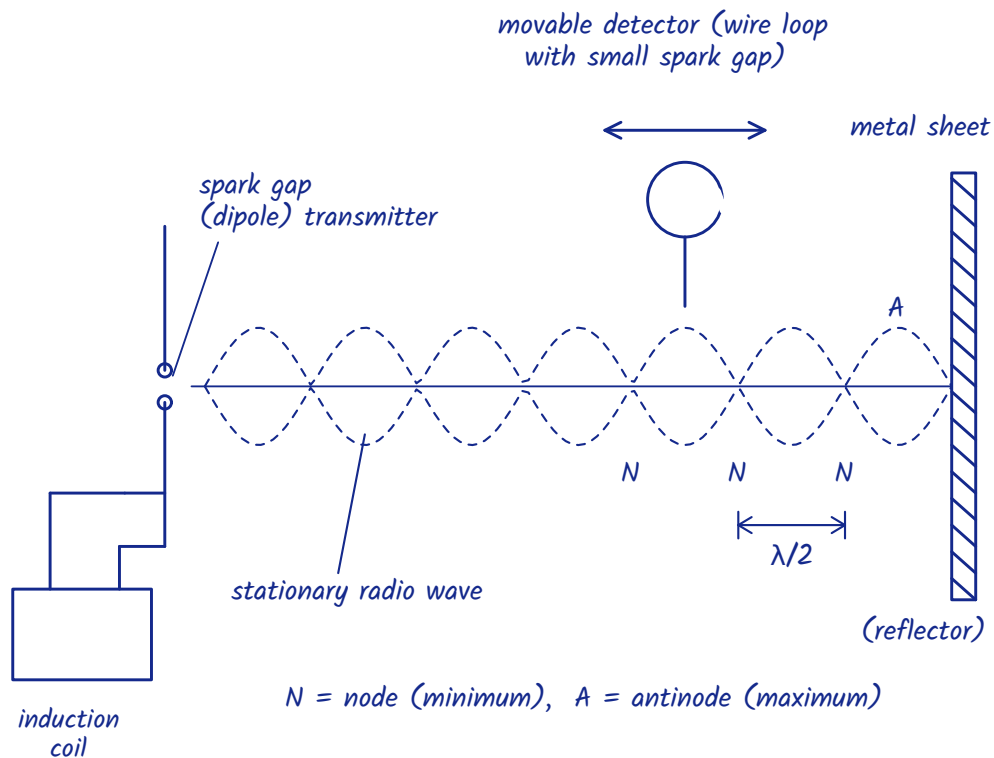
Hertz did an experiment to determine the speed of radio waves.

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]



A spark-gap (dipole) transmitter connected to an induction coil produces radio waves of known frequency f (from the resonant frequency of the



transmitter circuit). A flat metal sheet reflects the waves back towards the transmitter.

The incident and reflected waves superpose to form a stationary (radio) wave between the transmitter and the reflector, with nodes (minima) and antinodes (maxima).

A detector (a wire loop or dipole with a small spark gap) is moved along the line between transmitter and reflector. Sparks are strongest at maxima and absent at minima.

Measurements: the distance between several adjacent nodes (minima) is measured with a metre rule, e.g. the distance across 5 node-to-node spacings, and divided by 5 to give the node to adjacent node distance.

Node to adjacent node distance = $\lambda/2$, so $\lambda = 2 \times (\text{min to adjacent min distance})$ (or $4 \times \text{max to adjacent min}$).

The speed of radio waves is then calculated from $c = f\lambda$. Hertz found a value close to the speed of light, about $3 \times 10^8 \text{ m s}^{-1}$.

5

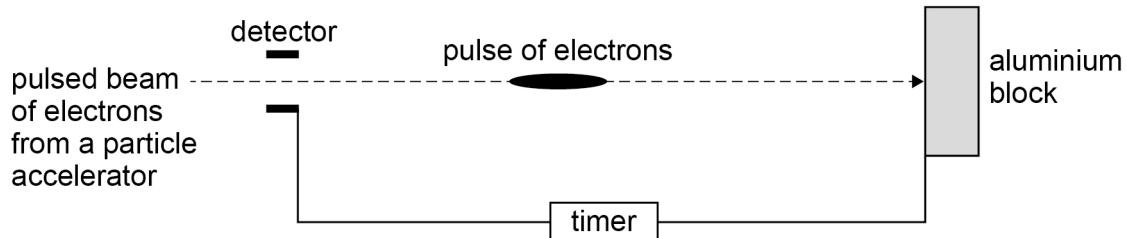
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0 4

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]

$$E_k = eV = 1.60 \times 10^{-19} \times 1.30 \times 10^6$$

$$E_k = 2.08 \times 10^{-13} \text{ J } (\approx 2 \times 10^{-13} \text{ J})$$

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]

$$Q = mc\Delta\theta = 1.50 \times 903 \times 68.0 = 9.21 \times 10^4 \text{ J}$$

$$E_k \text{ per electron} = 9.21 \times 10^4 / 4.50 \times 10^{17} = 2.05 \times 10^{-13} \text{ J}$$

$$2.05 \times 10^{-13} \text{ J} \approx 2.08 \times 10^{-13} \text{ J (equivalent to a pd of 1.28 MV), so}$$

yes, the temperature rise is consistent with 1.30 MV.



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]

$$\text{Non-relativistic: } E_K = \frac{1}{2}m_0v^2 = 0.5 \times 9.11 \times 10^{-31} \times (2.88 \times 10^8)^2$$

$$E_K = 3.78 \times 10^{-14} \text{ J}$$

$$\text{Relativistic: } E_K = mc^2 - m_0c^2 = m_0c^2(1/\sqrt{1 - v^2/c^2} - 1)$$

$$\sqrt{1 - v^2/c^2} = \sqrt{1 - 0.96^2} = 0.280$$

$$E_K = 9.11 \times 10^{-31} \times (3.00 \times 10^8)^2 \times (1/0.280 - 1)$$

$$E_K = 2.11 \times 10^{-13} \text{ J}$$

The relativistic value, $2.11 \times 10^{-13} \text{ J}$, agrees with the energy given to each electron by the accelerating pd ($2.08 \times 10^{-13} \text{ J}$, and the $2.05 \times 10^{-13} \text{ J}$ from the temperature rise).

The non-relativistic value, $3.78 \times 10^{-14} \text{ J}$, is about 5 times too small.

This is because v is 96% of c , so relativistic effects are significant.

So student A is wrong and student B is correct: the relativistic equation is required.

Question 4 continues on the next page

Turn over ►



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]

The gain in E_K is the same in both stages, since gain in $E_K = e\Delta V$ and each stage has the same pd (100 kV).

The increase in speed is much greater in the first stage than in the last stage.

By relativity, mass increases with speed. In stage 1 the energy gives a large increase in speed and a small increase in mass; in stage 13 the electron is close to c , which it cannot exceed, so there is a large increase in mass and only a small increase in speed.

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END OF QUESTIONS



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Question number	Additional page, if required. Write the question numbers in the left-hand margin.
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