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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

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.

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.

For Examiner's Use	
Question	Mark
1	
2	
3	
4	
TOTAL	



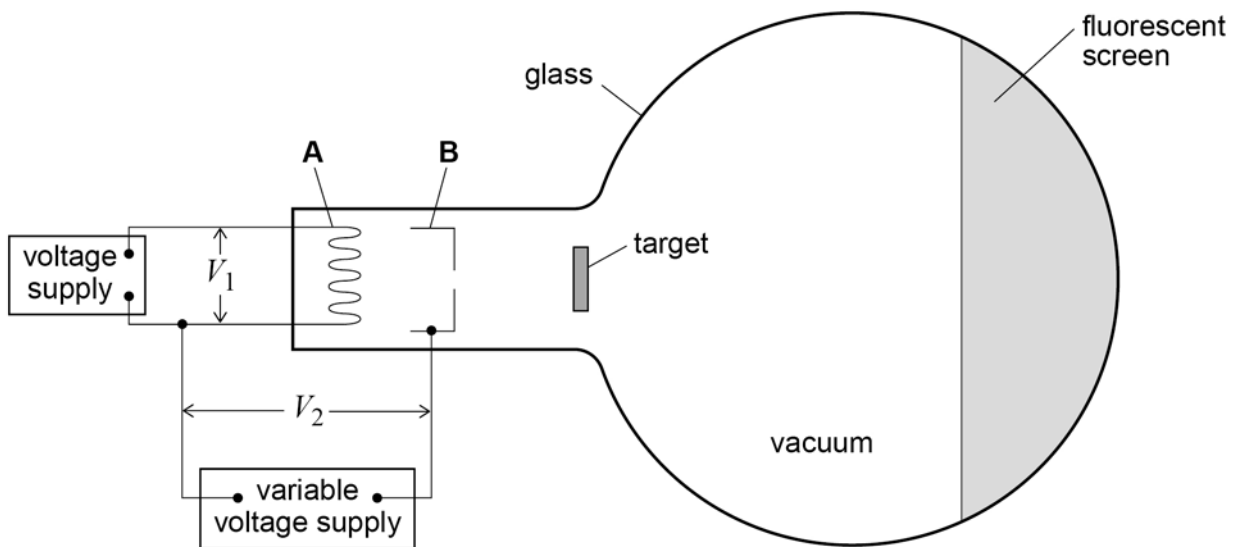
Section B

Answer **all** questions in this section.

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]

A is the filament (heated cathode). B is the anode, which has a small hole in it.

V_1 is the pd across the filament: it drives a current through A which heats it, supplying energy so that electrons are released from the hot metal surface by thermionic emission.

V_2 is the large pd between A and B: it produces an electric field that accelerates the emitted electrons towards the anode, and the high-speed electrons pass through the hole in B as a beam.



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]

Atom diameter $\approx 0.1 \text{ nm}$, so $\lambda \approx 50\%$ of this $\approx 0.05 \text{ nm} = 5.0 \times 10^{-11} \text{ m}$

$\lambda = h / p = h / \sqrt{2meV}$ (since $eV = p^2 / 2m$)

Rearranging: $V = h^2 / (2me\lambda^2)$

$V = (6.63 \times 10^{-34})^2 / (2 \times 9.11 \times 10^{-31} \times 1.60 \times 10^{-19} \times (5.0 \times 10^{-11})^2)$

$V = 603 \text{ V} \approx 600 \text{ V}$

$V_2 = \underline{\quad 600 \quad} \text{ V}$

Question 1 continues on the next page

Turn over ►



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]

The de Broglie hypothesis states that $\lambda = h / p$, so the wavelength of the electrons is inversely proportional to their momentum: if the momentum increases, the wavelength decreases.

Measure V_2 : this determines the kinetic energy of the electrons ($eV_2 = \frac{1}{2}mv^2$) and therefore their speed and momentum, $p = \sqrt{2meV_2}$.

Measure the diameter of the rings on the screen. The rings are a diffraction pattern, and the angle of diffraction depends on wavelength, so a larger ring diameter means a longer wavelength.

Increasing V_2 increases the momentum of the electrons and the ring diameter is observed to decrease (decreasing V_2 makes the rings larger).

This shows the wavelength decreases as momentum increases, which is consistent with (supports) the de Broglie hypothesis.



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.
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Moving electrons can cross a potential barrier.	Moving electrons can cross a potential barrier.



13

Turn over for the next question

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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]

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

$$c = 1 / \sqrt{(4\pi \times 10^{-7} \times 8.85 \times 10^{-12})}$$

$$c = 1 / \sqrt{(1.112 \times 10^{-17})}$$

$$c = 2.9986 \times 10^8 \text{ m s}^{-1}$$

This agrees with the accepted value $c = 3.00 \times 10^8 \text{ m s}^{-1}$ in the Data Booklet (to 3 sf).

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 . 2

T is switched on so that an oscillating current is produced in the metal rods. An emf is detected in the conducting loop aerial.

Explain this experiment with reference to Maxwell's model of electromagnetic waves.

[4 marks]

In Maxwell's model an electromagnetic wave consists of oscillating (varying) electric and magnetic fields that are perpendicular to each other and in phase, and which travel (propagate) through space at speed c .

The oscillating current in the vertical rods of T means there is an oscillating distribution of charge on the rods, which gives rise to an oscillating (vertical) electric field.

The oscillating current in T also produces an oscillating (horizontal) magnetic field, perpendicular to the electric field. These varying fields travel as a radio wave from T to D.

At D the varying horizontal magnetic field passes through the conducting loop, so the magnetic flux linkage through the loop changes and a varying emf is induced in the loop (Faraday's law). This detected emf shows that electromagnetic waves were transmitted from T, supporting Maxwell's theory.

Question 2 continues on the next page

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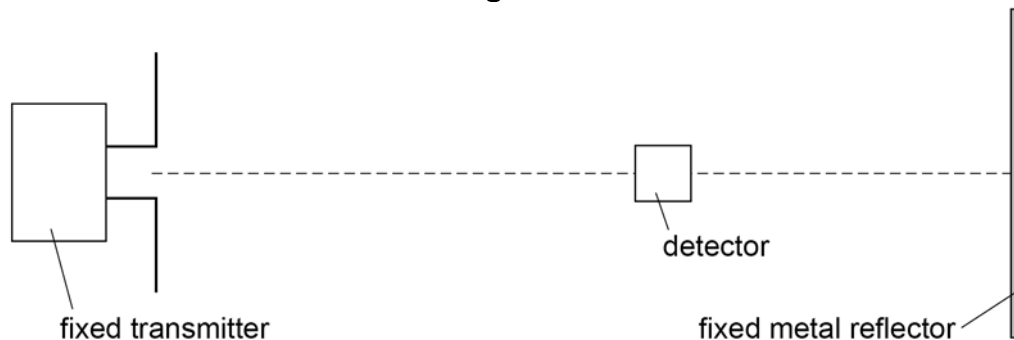


0 2 . 3

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]

To find the speed, the wavelength must be measured: move the detector between T and the reflector to locate nodes (minimum signal); adjacent nodes (or antinodes) are half a wavelength apart.

$$\text{Expected } \lambda = c / f = 3.00 \times 10^8 / 75 \times 10^6 = 4.0 \text{ m}$$

so nodes (and antinodes) are 2.0 m apart.

Separation of T and reflector $\approx 12 \text{ m}$, which is greater than this:

12 m = 3 wavelengths, so about 6 node separations (several nodes) fit between transmitter and reflector. The detector can be moved to measure the distance between several nodes, giving λ , then $c = f\lambda$.

So YES, this arrangement can be used to measure the speed.



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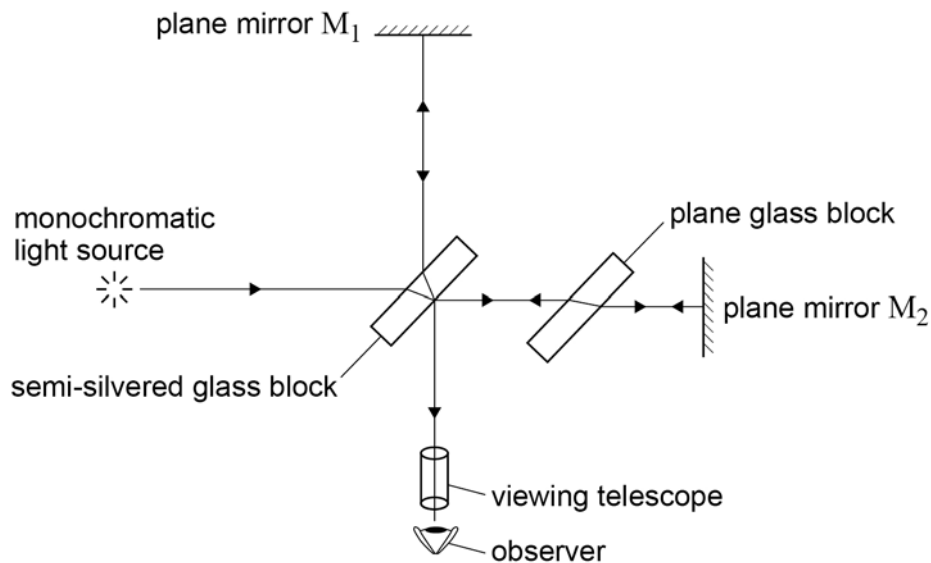
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0 3

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]

Procedure: monochromatic light from the source is split into two beams by the semi-silvered glass block. One beam travels to mirror M_1 and the other, at right angles, to mirror M_2 . The plane glass block makes sure both beams pass through the same thickness of glass and air. The beams are reflected back and recombine at the semi-silvered block and enter the telescope with a path difference, so the observer sees an interference pattern of bright and dark fringes. The position of the fringes is noted, then the whole apparatus is rotated through 90° and the fringe pattern is observed again for any shift.

Expected result: it was thought that light travelled through a stationary ether and that the Earth moved through the ether. The speed of light



relative to the apparatus would then depend on the direction of the beam relative to the Earth's motion, so the two beams would take different times to travel along the two arms. Rotating the apparatus through 90° swaps the arms' orientation relative to the Earth's motion, changing the time difference (path difference) between the beams, so the fringe pattern was expected to shift by a measurable amount (about 0.4 of a fringe). This shift would show that the ether exists and allow the absolute motion of the Earth through the ether to be detected and measured.

Actual result: no shift in the fringe pattern was observed, at any orientation or time of year (a null result).

Significance: this meant the absolute motion of the Earth could not be detected and there was no evidence for the ether. It showed that the speed of light in a vacuum is invariant (the same for all observers) and that all motion is relative, so there is no absolute motion. This later became one of the postulates of Einstein's theory of special relativity.

Turn over for the next question



0 4 . 1

State what is meant by an inertial frame of reference.

[1 mark]

An inertial frame of reference is one which is moving at constant velocity (not accelerating), so that Newton's first law of motion holds in it.

0 4 . 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]

In the frame of the particles the detector separation is length-contracted:

$$L = L_0 \sqrt{1 - v^2/c^2} = 45 \times \sqrt{1 - 0.97^2} = 10.9 \text{ m}$$

Time between detectors in particle frame:

$$t = 10.9 / (0.97 \times 3.00 \times 10^8) = 3.76 \times 10^{-8} \text{ s}$$

$$12.5\% = 1/8 = (1/2)^3, \text{ so the time taken is 3 half-lives}$$

$$\text{half-life} = 3.76 \times 10^{-8} / 3 = 1.25 \times 10^{-8} \text{ s} \approx 1.3 \times 10^{-8} \text{ s}$$

$$\text{half-life} = \underline{1.3 \times 10^{-8}} \text{ s}$$

0 4 . 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]

The proper time is the time ($3.8 \times 10^{-8} \text{ s}$) taken for the particle beam to travel between the detectors as measured in the reference frame of the particles.

END OF QUESTIONS



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