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Centre number

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Candidate number

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A-level PHYSICS

Paper 3

Section B Turning points in physics

Thursday 29 June 2017

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.

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.
- 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	
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5	
TOTAL	



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Section B

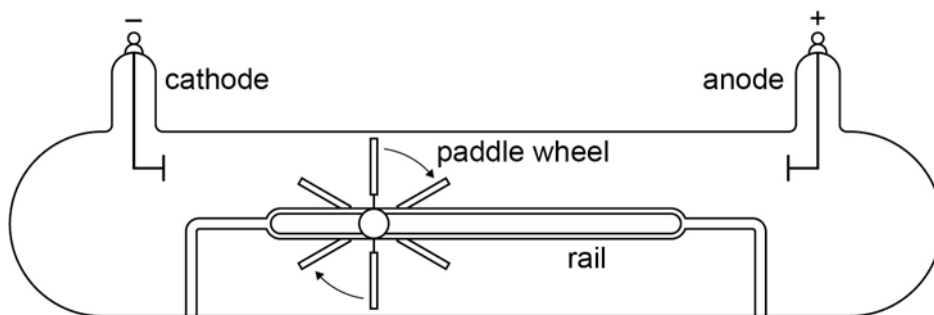
Answer **all** questions in this section.

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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



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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]

The paddle wheel moves from the cathode towards the anode, so the cathode rays must travel from the cathode towards the anode.

The paddle wheel gains kinetic energy (momentum) from the cathode rays, so they must be particles with mass that collide with the paddle and transfer momentum to it.



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]

The large potential difference pulls electrons out of the gas atoms near the cathode, so the gas atoms are ionised.

The positive ions produced are attracted to the cathode and collide with it, causing free electrons to be emitted from the cathode.

These electrons are accelerated towards the anode by the potential difference, forming a beam of cathode rays.

0 1 . 3

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]

Effect: the paddle wheel rotates more (faster).

Reason: with fewer air molecules in the tube, the electrons (cathode rays) make fewer collisions with molecules, so they reach the paddle with higher speed / energy / momentum.

7

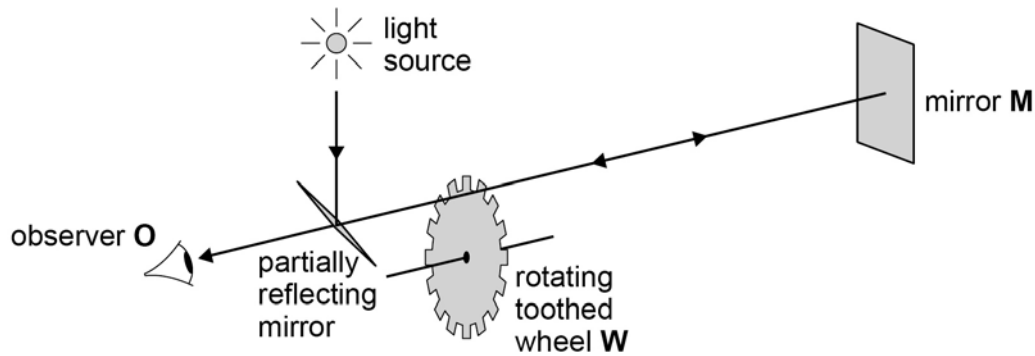
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0 2

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

When the rotation speed is low, the light passes through a gap, reflects off M and returns through the original gap before the wheel has turned enough to block it.

Observation B

At this speed, in the time the light takes to travel to M and back, the wheel turns so that the gap is replaced by the adjacent tooth, which blocks the returning light.



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]

$$c = 4dnf = 4 \times 8600 \times 720 \times 12 = 2.97 \times 10^8 \text{ m s}^{-1}$$

The accepted value is $3.0 \times 10^8 \text{ m s}^{-1}$, so the values are very similar and the data are consistent with it.

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]

The light must now pass a gap and then be blocked by the next tooth, so the wheel must turn three times as far in the same time.

$$f = 3 \times 12 = 36 \text{ rotations per second (36 Hz)}$$

Question 2 continues on the next page

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

[3 marks]

Maxwell's theory of electromagnetic waves predicted a value for the speed of electromagnetic waves in a vacuum, $c = 1/\sqrt{(\mu_0\epsilon_0)} \approx 3.0 \times 10^8 \text{ m s}^{-1}$.

Fizeau's result (about $3 \times 10^8 \text{ m s}^{-1}$) is very close to this predicted speed of electromagnetic waves.

This implies that light is an electromagnetic wave.

9



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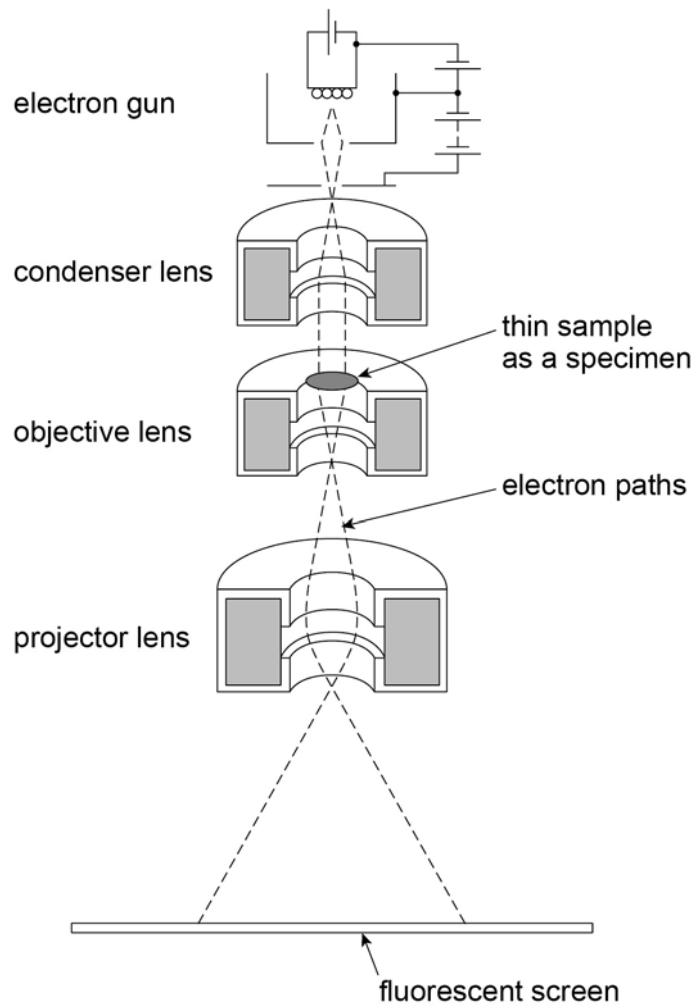
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0 3

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]

$$\lambda = h / p \quad \text{and} \quad E_k = p^2 / 2m, \quad \text{so} \quad \lambda = h / \sqrt{2mE_k}$$

$$\lambda = 6.63 \times 10^{-34} / \sqrt{2 \times 9.11 \times 10^{-31} \times 4.1 \times 10^{-16}}$$

$$\lambda = 6.63 \times 10^{-34} / 2.73 \times 10^{-23}$$

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

Atoms have a diameter of about 0.1 nm (1×10^{-10} m). The wavelength 2.4×10^{-11} m is less than the atomic diameter, so in principle individual atoms can be resolved.

Question 3 continues on the next page

Turn over ►



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]

Image formation: electrons from the electron gun are accelerated through a high potential difference. The magnetic lenses are coils of wire producing magnetic fields.

Electrons passing through the middle (along the axis) of a lens are undeviated, while electrons near the edges are deflected by the magnetic field towards the axis of the TEM.

The condenser lens deflects the electrons into a wide parallel beam that is incident uniformly on the sample.

The electrons pass through the thin sample; some are scattered or absorbed by the denser parts, so the transmitted beam varies in intensity. The objective lens then forms a (magnified) image of the sample.

The projector lens magnifies this further and casts a second image onto the fluorescent screen, where electrons striking it emit light so the image can be seen.

Quality and detail: the electrons behave as waves with de Broglie wavelength $\lambda = h/mv$, so the wavelength depends on the speed of the electrons. A higher accelerating voltage gives faster electrons, a shorter wavelength, less diffraction and so greater resolution (detail).

The emitted electrons come from a heated cathode (thermionic emission), so they have a spread (distribution) of speeds which depends on the temperature. Electrons of different speeds have



different wavelengths and are focused at different points, so they follow different paths through the lenses, causing aberration and blurring the image.

The sample must be very thin: electrons passing through the sample lose speed, which increases their wavelength and so decreases the detail. A thicker sample also scatters more electrons, reducing the quality of the image.

10

Turn over for the next question

Turn over ►



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]

$$t_0 = 1 \text{ year} = 31\,536\,000 \text{ s}, \quad v/c = 1.2 \times 10^7 / 3.0 \times 10^8 = 0.04$$

$$t = t_0 / \sqrt{1 - v^2/c^2} = 31\,536\,000 / \sqrt{1 - 0.04^2}$$

$$t = 31\,561\,259 \text{ s}$$

$$\text{Time dilation} = 31\,561\,259 - 31\,536\,000 = 25\,259 \text{ s, which is}$$

about 421 minutes, 7.0 hours or 0.29 days.

So the student is correct that the clock stationary relative to the observer records a longer time than the clock on the spacecraft (as predicted).

However, it is longer by only about 0.29 days (7 hours), much less than several days, so the prediction is wrong about the size of the difference.

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]

The theory of special relativity only applies to inertial frames of reference, i.e. frames that are not accelerating.

Because of the Sun's gravity and the change in direction, the spacecraft is accelerating, so its frame of reference is not an inertial frame.



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]

$$E = 3.7 \times 10^9 \times 1.6 \times 10^{-19} = 5.9 \times 10^{-10} \text{ J}$$

$$E = mc^2 = m_0 c^2 / \sqrt{1 - v^2/c^2}$$

$$m_0 c^2 = 1.67 \times 10^{-27} \times (3.0 \times 10^8)^2 = 1.50 \times 10^{-10} \text{ J}$$

$$\sqrt{1 - v^2/c^2} = 1.50 \times 10^{-10} / 5.92 \times 10^{-10} = 0.254$$

$$1 - v^2/c^2 = 0.0645$$

$$v^2/c^2 = 0.9355$$

$$v/c = \sqrt{0.9355} = 0.967$$

proton velocity = 0.97 c

3

END OF QUESTIONS



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