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Candidate signature

I declare this is my own work.

A-level PHYSICS

Paper 3

Section B Turning points in physics

Friday 5 June 2020

Afternoon

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.
- 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	
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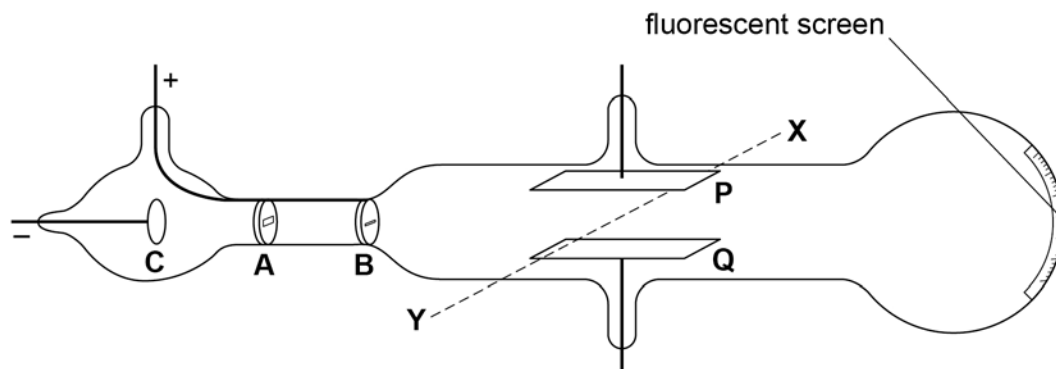
Section B

Answer **all** questions in this section.

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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.

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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]

The high pd produces a strong electric field which pulls electrons from the gas atoms, ionising the (low pressure) gas atoms.

The positive ions are accelerated towards the cathode C and strike its surface, releasing electrons from the cathode surface.

These electrons are accelerated towards the anodes A and B and pass through them as a narrow beam, forming the cathode ray.



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

Turn over ►



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 *Path is straight when electric force = magnetic force: $eE = Bev$, so $v = E/B$.*

Since v is greater, E must be increased (in proportion to v) so that the electric force eE increases to equal the larger magnetic force Bev .

magnetic flux density only *Again $v = E/B$ for an undeflected path, so for a greater v the magnetic flux density B must be decreased ($B = E/v$), so that the magnetic force Bev falls back to equal the unchanged electric force eE .*

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]

The specific charge of the cathode ray particles was much greater (about 2000 times greater) than the specific charge of the hydrogen ion, the largest known at the time.

Assuming the charges are similar in size, the cathode ray particles must have a much smaller mass than the hydrogen ion, so they are much smaller than an atom (and they are negatively charged).



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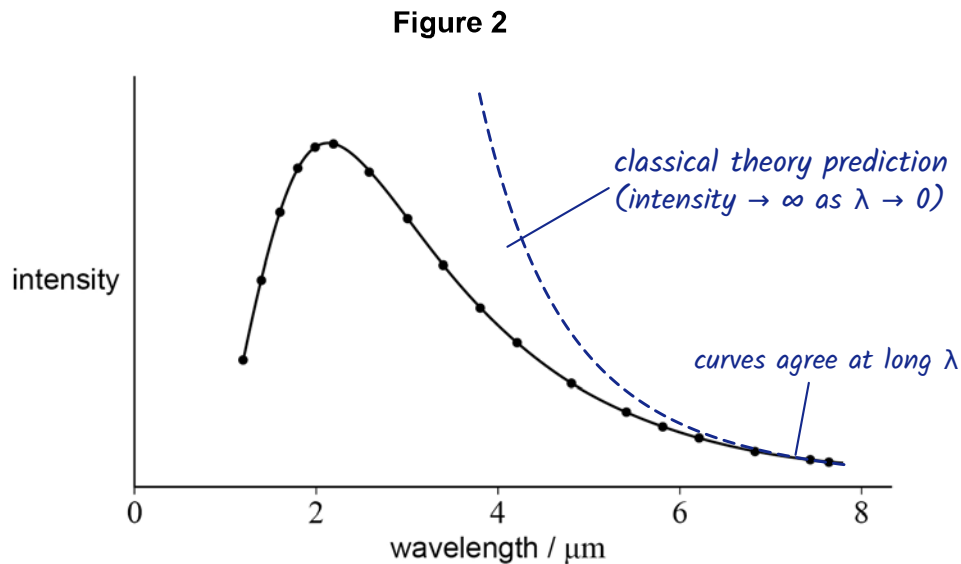
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0 2

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.



0 2 . 1

State what is meant by black-body radiation.

[2 marks]

Electromagnetic radiation emitted by a black body (a perfect absorber and emitter).

It has a continuous spectrum with a peak wavelength (intensity distribution) that depends only on the temperature of the emitter.



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]

At long wavelengths, classical theory predicts an intensity similar to the experimental results (the curves agree).

But rather than a peak, classical theory predicts that the intensity keeps increasing as wavelength decreases, becoming infinite at very short wavelengths (the ultraviolet catastrophe), as shown by the dashed line on Figure 2.

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]

Planck suggested that electromagnetic radiation is emitted in quanta (discrete amounts of energy), not continuously.

The energy of each quantum is related to a single frequency by $E = hf$, where h is the Planck constant.

Question 2 continues on the next page

Turn over ►



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]

Observations: (1) No photoelectrons are emitted if the frequency of the incident light is below a threshold frequency for that metal, however intense the light is. (2) Above the threshold frequency, photoelectric emission is instantaneous: electrons are emitted as soon as the light is incident on the surface, even for very weak light. Also, the photoelectrons have a range of kinetic energies from zero to a maximum, which depends on the metal and the frequency (not the intensity), and the number of photoelectrons emitted per second is proportional to the intensity.

Failure of classical wave theory: in wave theory the energy of a wave depends on its intensity (amplitude), not its frequency. So the intensity should determine whether electrons are emitted and their kinetic energy, and light of any frequency should cause emission if it is intense enough (or left on for long enough). This contradicts the threshold frequency. Also, wave energy is spread out evenly over the whole surface, so each electron would need time to absorb enough energy to escape, with weaker light needing a longer time. This contradicts the instantaneous emission that is observed.

Einstein's theory: Einstein extended Planck's idea and said that light itself is made of photons (quanta), each with energy $E = hf$. Each



photoelectron is produced by one photon interacting with one electron in the surface of the metal, transferring all its energy at once. This explains why emission is instantaneous.

An electron needs a minimum energy, the work function ϕ of the metal, to escape from the surface. This is related to the threshold frequency by $\phi = hf_0$. If $hf < \phi$, no single photon has enough energy to release an electron, so there is no emission below f_0 , however many photons arrive.

The remaining energy of the photon, $hf - \phi$ ($= hf - hf_0$), becomes the maximum kinetic energy of the photoelectron: $E_{k(max)} = hf - \phi$.

Electrons from deeper in the metal lose more energy escaping, giving the range of kinetic energies.

A brighter (more intense) source means more photons per second, and therefore more photoelectrons emitted per second, but it does not change the energy of each photon, so it does not change the maximum kinetic energy.

Significance: the photoelectric effect could only be explained if electromagnetic radiation behaves as particles (photons) rather than as continuous waves. Together with the wave behaviour shown by interference and diffraction, this showed that electromagnetic radiation has a dual wave-particle nature.

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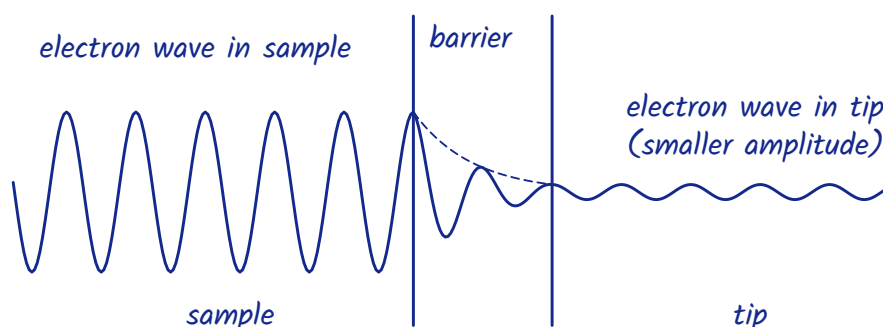


03.1

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]



Electrons in the surface of the sample must cross a potential (energy) barrier, the gap between the sample and the tip, but classically they have insufficient energy to overcome it.

Due to their wave properties, there is a probability of electrons crossing from the sample to the tip, so a small fraction of electrons tunnel through the barrier (see diagram).

Question 3 continues on the next page

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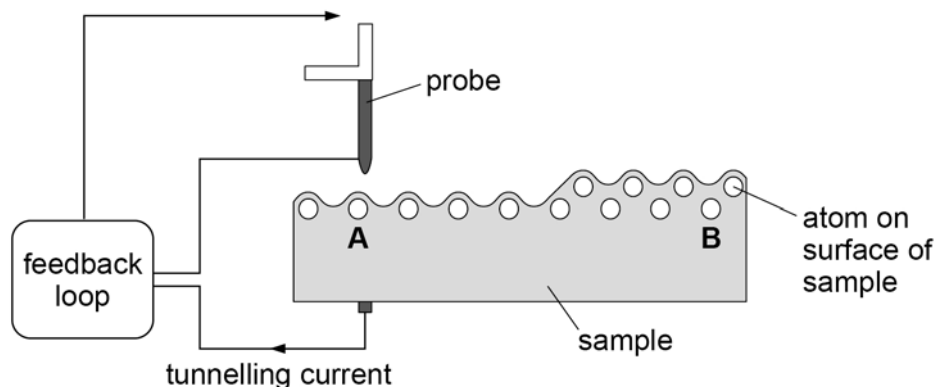


0 3 . 2

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]

A pd is applied between the tip of the probe and the sample, and the tip is held a fixed distance (about 1 nm) above the surface, so a tunnelling current flows from the surface to the probe.

The probe is scanned across the surface from A to B. When the tip moves over an atom (a higher layer of electrons), the gap decreases, so the tunnelling current increases.

Through the feedback loop, the tip is moved higher to reduce the current back to its original constant value (and lowered when the current falls).

The distance the tip moves equals the height of the surface above or below its original level.

So the vertical position of the tip at each point maps the positions of the atoms from A to B.



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]

$$E_k = 1.5 \text{ eV} = 1.5 \times 1.6 \times 10^{-19} = 2.4 \times 10^{-19} \text{ J}$$

$$\frac{1}{2}mv^2 = E_k: \frac{1}{2} \times 9.11 \times 10^{-31} \times v^2 = 2.4 \times 10^{-19}$$

$$v = \sqrt{(2 \times 2.4 \times 10^{-19} / 9.11 \times 10^{-31})} = 7.26 \times 10^5 \text{ m s}^{-1}$$

$$\lambda = h/mv = 6.63 \times 10^{-34} / (9.11 \times 10^{-31} \times 7.26 \times 10^5)$$

$$\lambda = 1.0 \times 10^{-9} \text{ m (1.0 nm)}$$

No: $\lambda = 1.0 \times 10^{-9} \text{ m}$ at 1.5 eV, and less energy means a longer

wavelength, so $\lambda > 1 \text{ nm}$, too long to resolve atoms (about 10^{-10} m), so

they are not suitable.

8

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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]

$$\text{Length contraction: } l = l_0 \sqrt{1 - v^2/c^2}$$

$$l_0 = 2.5 \times 10^3 \text{ m (distance in the observer's frame)}$$

$$l = 2500 \times \sqrt{1 - 0.95^2} = 2500 \times \sqrt{0.0975}$$

$$l = 2500 \times 0.312 = 781 \text{ m}$$

distance = 781 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]

Measure the number of muons passing through a detector per second at the top of a mountain (upper atmosphere), and the number per second at the ground (sea level).

Far more muons reach the ground than expected (far fewer decay) in the time taken in the observer's frame, because the muon clock runs slower so the half-life appears longer.



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]

With a lower velocity, the muons take longer to travel to the ground (in either frame of reference).

Also, as their speed is not so close to c , the time dilation effect is less in the Earth's frame (or the length contraction of the atmosphere is less in the muon's frame), so the half-life measured from Earth is less dilated.

So more muons decay before reaching the ground, and the rate of detection of muons on the surface of the Earth is reduced.

7

END OF QUESTIONS



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