



Oxford Cambridge and RSA

Wednesday 21 October 2020 – Morning

A Level Physics A

H556/03 Unified physics

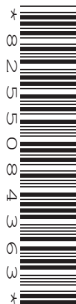
Time allowed: 1 hour 30 minutes

You must have:

- the Data, Formulae and Relationships Booklet

You can use:

- a scientific or graphical calculator
- a ruler (cm/mm)



Please write clearly in black ink. **Do not write in the barcodes.**

Centre number

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Candidate number

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First name(s)

Last name

StemUp Model Solution

INSTRUCTIONS

- Use black ink. You can use an HB pencil, but only for graphs and diagrams.
- Write your answer to each question in the space provided. If you need extra space use the lined pages at the end of this booklet. The question numbers must be clearly shown.
- Answer **all** the questions.
- Where appropriate, your answers should be supported with working. Marks might be given for a correct method, even if your answer is wrong.

INFORMATION

- The total mark for this paper is **70**.
- The marks for each question are shown in brackets [].
- Quality of extended response will be assessed in questions marked with an asterisk (*).
- This document has **20** pages.

ADVICE

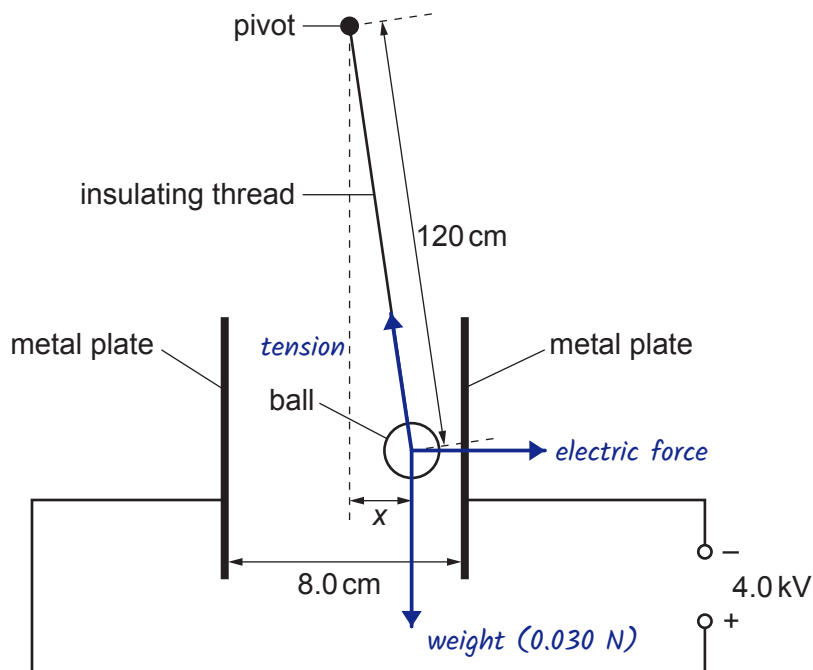
- Read each question carefully before you start your answer.

Answer **all** the questions.

- 1 A ball coated with conducting paint has weight 0.030 N and radius 1.0 cm . The ball is suspended from an insulating thread. The distance between the pivot and the centre of the ball is 120 cm .

The ball is placed between two vertical metal plates. The separation between the plates is 8.0 cm . The plates are connected to a 4.0 kV power supply.

- (a) The ball receives a positive charge of 9.0 nC when it is made to touch the positive plate. It then repels from the positive plate and hangs in equilibrium at a displacement x from the vertical, as shown below. The diagram is **not** drawn to scale.



- (i) Show that the electric force acting on the charged ball is $4.5 \times 10^{-4}\text{ N}$.

$$E = V/d = 4.0 \times 10^3 / 8.0 \times 10^{-2} = 5.0 \times 10^4 \text{ V m}^{-1}$$

$$F = QE = 9.0 \times 10^{-9} \times 5.0 \times 10^4$$

$$F = 4.5 \times 10^{-4} \text{ N}$$

[2]

- (ii) Draw, on the diagram above, arrows which represent the **three** forces acting on the ball. Label each arrow with the name of the force it represents. [2]

- (iii) By taking moments about the pivot, or otherwise, show that $x = 1.8 \text{ cm}$.

taking moments about the pivot (small angle):

$$\text{weight} \times x = \text{electric force} \times 120 \text{ cm}$$

$$0.030 \times x = 4.5 \times 10^{-4} \times 120$$

$$x = 0.054 / 0.030 = 1.8 \text{ cm}$$

[2]

- (b) The ball is still positively charged.

The plates are now moved slowly towards each other whilst still connected to the 4.0 kV power supply. The plates are stopped when the separation is 5.0 cm.

Explain the effect that this has on the deflection of the ball and explain why the ball eventually starts to oscillate between the plates.

$E = V/d$, so as d decreases (V constant) the electric field strength increases

and the electric force on the ball $F = QE$ increases.

So the ball is deflected further from the vertical (to the right) until it touches the negative plate.

When it touches, the ball acquires the charge of the plate (becomes negative), so it is now repelled by the negative plate and attracted to the

positive plate. At the positive plate it becomes positive again and is repelled

back, so this cycle keeps repeating and the ball oscillates.

[4]

Question 1 continues on page 4

- (c) When the ball oscillates between the plates, the current in the external circuit is $3.2 \times 10^{-8} \text{ A}$.

A charge of 9.0 nC moves across the gap between the plates each time the ball makes one complete oscillation.

Calculate the frequency f of the oscillations of the ball.

$$I = Qf \text{ (charge } 9.0 \text{ nC transferred per oscillation)}$$

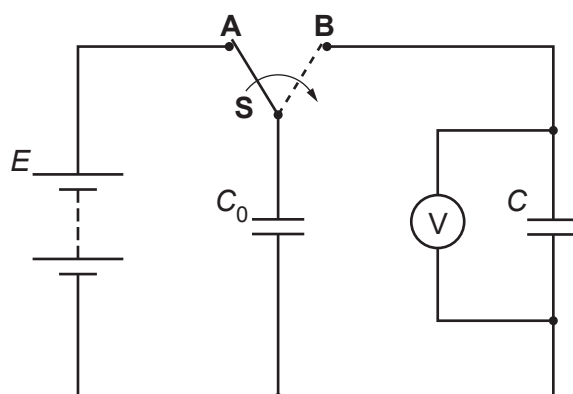
$$f = I/Q = 3.2 \times 10^{-8} / 9.0 \times 10^{-9}$$

$$f = 3.6 \text{ Hz}$$

$$f = \dots\dots\dots 3.6 \dots\dots\dots \text{ Hz [2]}$$

- 2 The diagram below shows a circuit containing two capacitors which are both initially uncharged. The battery has e.m.f. E and negligible internal resistance.

The switch **S** is first moved to position **A** until the capacitor of capacitance C_0 is fully charged.



The switch **S** is then moved to position **B**. The initial charge stored by the capacitor of capacitance C_0 is shared between the two capacitors. The final reading on the voltmeter is V .

- (a) Show that $V = \frac{C_0}{C + C_0} E$.

initial charge $Q = EC_0$; charge is conserved and the capacitors

are in parallel (same p.d. V), so final $Q = V(C + C_0)$

$EC_0 = V(C + C_0)$, so $V = C_0 E / (C + C_0)$

[2]

- (b) A student wants to determine the values of E and C_0 by repeating the experiment above and measuring the potential difference (p.d.) V for a selection of capacitors of capacitance C .

The student decides to plot a graph of $\frac{1}{V}$ against C .

- (i) Use the expression in (a) to show that the graph should be a straight line of gradient $\frac{1}{C_0 E}$ and y-intercept $\frac{1}{E}$.

$$1/V = (C + C_0) / C_0 E = (1/C_0 E) \times C + 1/E$$

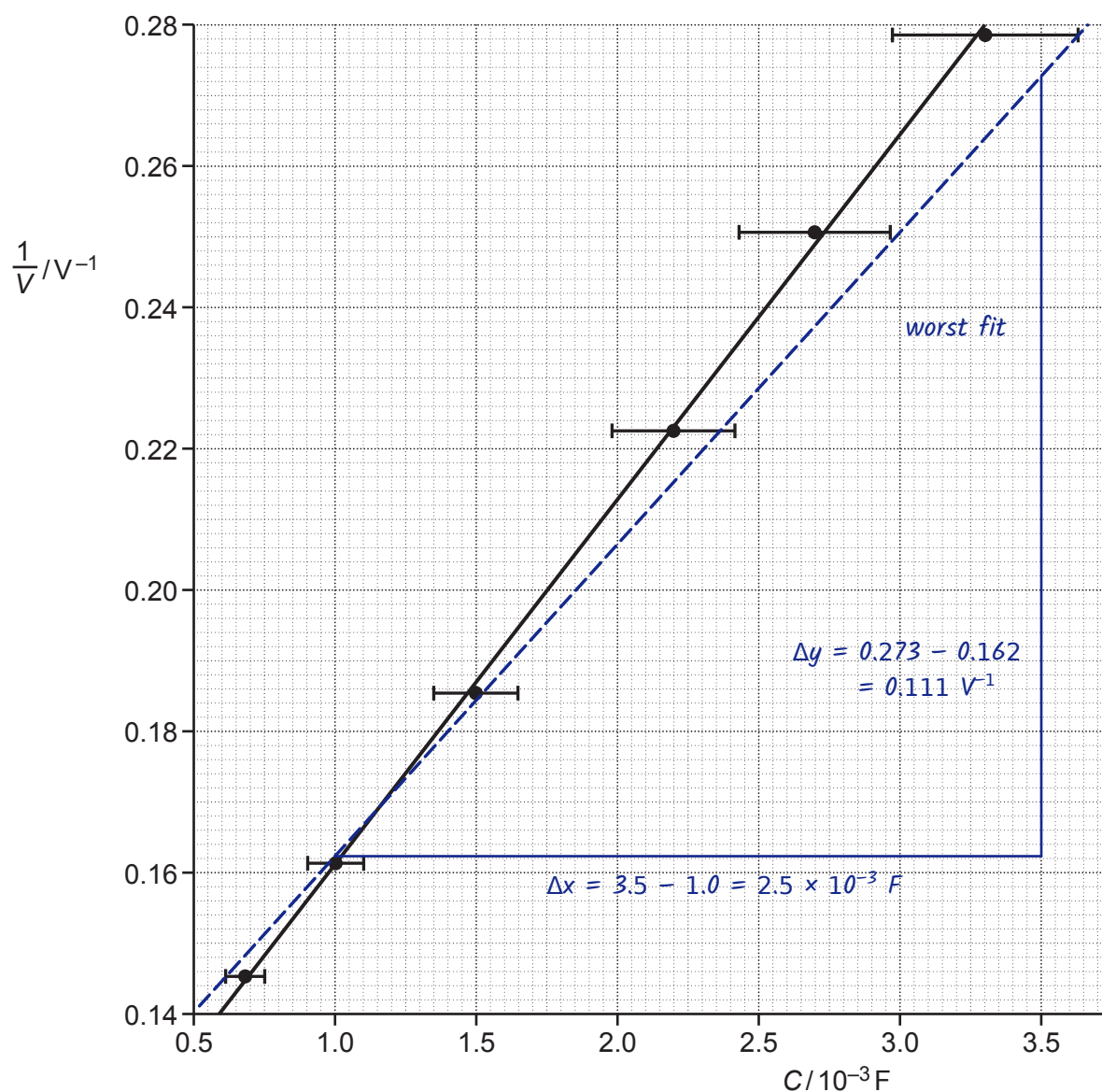
compare with $y = mx + c$: straight line, gradient = $1/C_0 E$,

y-intercept = $1/E$

[1]

Question 2 continues on page 6

- (ii) The data points, error bars and the line of best fit drawn by the student are shown in the graph below.



The gradient of the line of best fit is $51 \text{ V}^{-1} \text{ F}^{-1}$. The value of E is 9.1 V .

Determine the value of C_0 in millifarads (mF). Write your answer to 2 significant figures.

$$\text{gradient} = 1/C_0 E, \text{ so } C_0 = 1/(\text{gradient} \times E)$$

$$C_0 = 1/(51 \times 9.1) = 2.15 \times 10^{-3} \text{ F}$$

$$C_0 = 2.2 \text{ mF (2 s.f.)}$$

$$C_0 = \dots\dots\dots 2.2 \dots\dots\dots \text{ mF [2]}$$

- (iii) Draw on the graph a straight line of worst fit.

Use this line to determine the absolute uncertainty in your value of C_0 . Write your answer to an appropriate number of significant figures.

$$\text{worst fit gradient} = 0.111 / 2.5 \times 10^{-3} = 44 \text{ V}^{-1} \text{ F}^{-1}$$

$$C_0 (\text{worst}) = 1/(44 \times 9.1) = 2.5 \times 10^{-3} \text{ F} = 2.5 \text{ mF}$$

$$\text{absolute uncertainty} = 2.5 - 2.2 = 0.3 \text{ mF}$$

absolute uncertainty = ... 0.3 mF [4]

- (c) The experiment is repeated with a resistor of resistance $10 \text{ k}\Omega$ placed in series between S and the capacitor of capacitance C_0 .

State with a reason what effect, if any, this would have on the experiment.

..... No effect on the results; the resistor only slows the charging and discharging
 of the capacitors, so the final charges and the values of V are unchanged
 (the experiment just takes longer).

..... [1]

3 This question is about the Sun and its radiation.

- (a) (i) Use the data below to show that the luminosity of the Sun is about 4×10^{26} W.
- radius of Sun = 7.0×10^8 m
 - surface temperature of Sun = 5800 K

$$L = 4\pi r^2 \sigma T^4$$

$$L = 4\pi \times (7.0 \times 10^8)^2 \times 5.67 \times 10^{-8} \times 5800^4$$

$$L = 3.95 \times 10^{26} \text{ W} \approx 4 \times 10^{26} \text{ W}$$

[1]

- (ii) Sirius, the brightest star in the night sky, has a luminosity 25 times greater than that of the Sun. It has diameter 1.7 times greater than that of the Sun.

Calculate the surface temperature T of Sirius.

$$L \propto r^2 T^4; 25 = 1.7^2 \times (T/5800)^4$$

$$(T/5800)^4 = 25/2.89 = 8.65$$

$$T^4 = 8.65 \times 5800^4 = 9.8 \times 10^{15}$$

$$T = 9950 \text{ K}$$

$T = \dots\dots\dots 9950 \dots\dots\dots$ K [3]

***(b)** A student attends a lecture about the Sun and makes the following notes.

1. The Sun loses more than 4×10^9 kg of its mass every second to maintain its luminosity.
2. Treating hydrogen nuclei (protons) as an ideal gas, a temperature of 10^{10} K provides a kinetic energy of about 1 MeV, which is necessary for fusion.
3. However, the Sun's core temperature is only 10^7 K, so the chance of protons fusing on collision is very small. This explains why the Sun has such a long lifetime.

Explain the principles of physics which are involved in each of the three points.
You should include relevant formulae, but no numbers or calculations are required.

[6]

1. Fusion: in the core hydrogen nuclei fuse to form helium. The products have less mass than the reactants and this mass is released as energy, $\Delta E = \Delta mc^2$. Luminosity is energy released per second, so the mass lost per second $= L/c^2$.

2. For an ideal gas the mean kinetic energy of a proton is $\frac{1}{2}m\langle c^2 \rangle = \frac{3}{2}kT$, so high T means fast protons. Protons repel electrostatically and must get close enough to fuse (about 3 fm, within range of the strong force), so their kinetic energy must exceed the potential energy $e^2/4\pi\epsilon_0 r$, i.e. $\frac{3}{2}kT > e^2/4\pi\epsilon_0 r$, which needs $T \approx 10^{10}$ K.

3. As $k.e. \propto T$, at 10^7 K the mean $k.e.$ is only about 1/1000 of that needed. But the speeds follow a Maxwell-Boltzmann distribution, so a few protons in the high-energy tail have far more than the mean, and protons can quantum tunnel through the electrostatic barrier with a small probability. Fusing 4 protons into helium is a multi-step process, making it even less likely. The number of protons in the Sun is so huge that enough still fuse each second, but because the probability is so small the hydrogen is used up slowly, so the Sun has a long lifetime.

Additional answer space if required.

- 4 The International Space Station (ISS) orbits the Earth at a height of $4.1 \times 10^5 \text{ m}$ **above** the Earth's surface.

The radius of the Earth is $6.37 \times 10^6 \text{ m}$. The gravitational field strength g_0 at the Earth's surface is 9.81 N kg^{-1} .

- (a) Both the ISS and the astronauts inside it are in free fall.

Explain why this makes the astronauts feel **weightless**.

There is no contact (normal) force between the astronaut and the floor of the ISS, as both have the same acceleration (the floor falls away beneath the astronaut). [1]

- (b) (i) Calculate the value of the gravitational field strength g at the height of the ISS above the Earth.

$$\text{orbital radius } r = 6.37 \times 10^6 + 4.1 \times 10^5 = 6.78 \times 10^6 \text{ m}$$

$$g \propto 1/r^2, \text{ so } g r^2 = \text{constant}$$

$$g \times (6.78 \times 10^6)^2 = 9.81 \times (6.37 \times 10^6)^2$$

$$g = 9.81 \times (6.37/6.78)^2 = 8.66 \text{ N kg}^{-1}$$

$$g = \dots\dots\dots 8.66 \dots\dots\dots \text{N kg}^{-1} \text{ [3]}$$

- (ii) The speed of the ISS in its orbit is 7.7 km s^{-1} . Show that the period of the ISS in its orbit is about 90 minutes.

$$v = 2\pi r/T, \text{ so } T = 2\pi r/v$$

$$T = 2 \times \pi \times 6.78 \times 10^6 / 7.7 \times 10^3$$

$$T = 5.5 \times 10^3 \text{ s} = 92 \text{ minutes} \approx 90 \text{ minutes}$$

[2]

Question 4 continues on page 12

(c) Use the information in (b)(ii) and the data below to show that the root mean square (r.m.s.) speed of the air molecules inside the ISS is approximately 15 times smaller than the orbital speed of the ISS.

- molar mass of air = $2.9 \times 10^{-2} \text{ kg mol}^{-1}$
- temperature of air inside the ISS = 20°C

$$\frac{1}{2} m \langle c^2 \rangle = \left(\frac{3}{2}\right) kT, \text{ so } \langle c^2 \rangle = 3kT/m = 3RT/M$$

$$\langle c^2 \rangle = 3 \times 8.31 \times 293 / 2.9 \times 10^{-2} = 2.52 \times 10^5 \text{ m}^2 \text{ s}^{-2}$$

$$c_{\text{r.m.s.}} = \sqrt{(2.52 \times 10^5)} = 500 \text{ m s}^{-1}$$

$$\text{ratio} = 7.7 \times 10^3 / 500 = 15.4 \approx 15$$

so the r.m.s. speed is about 15 times smaller than the orbital speed

[3]

- (d) The ISS has arrays of solar cells on its wings. These solar cells charge batteries which power the ISS. The wings always face the Sun.

Use the data below and your answer to (b)(ii) to calculate the **average** power delivered to the batteries.

- The total area of the cells facing the solar radiation is 2500 m^2 .
- 7% of the energy of the sunlight incident on the cells is stored in the batteries.
- The intensity of solar radiation at the orbit of the ISS is 1.4 kW m^{-2} outside of the Earth's shadow and zero inside it.
- The ISS passes through the Earth's shadow for 35 minutes during each orbit.

$$\text{power incident on cells} = IA = 1.4 \times 10^3 \times 2500 = 3.5 \times 10^6 \text{ W}$$

$$\text{power stored} = 0.07 \times 3.5 \times 10^6 = 2.45 \times 10^5 \text{ W}$$

$$\text{time in sunlight per orbit} = 92 - 35 = 57 \text{ minutes}$$

$$\text{average power} = (57/92) \times 2.45 \times 10^5$$

$$\text{average power} = 1.5 \times 10^5 \text{ W}$$

$$\text{average power} = \dots\dots\dots 1.5 \times 10^5 \dots\dots\dots \text{ W [4]}$$

- 5 This question is about investigations involving an electromagnetic wave.

A vertical transmitter aerial emits a **vertically polarised** electromagnetic wave which travels towards a vertical receiver aerial. The wavelength of the wave is 0.60 m.

Fig. 5.1 shows a short section of the oscillating electric field of the electromagnetic wave.

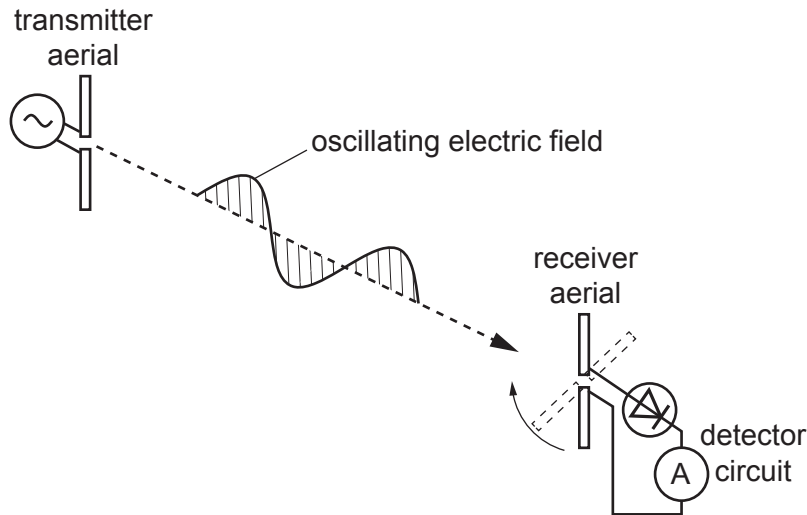


Fig. 5.1

- (a) Calculate the frequency f of the transmitted wave.

$$c = f\lambda, \text{ so } f = c/\lambda = 3.00 \times 10^8 / 0.60$$

$$f = 5.0 \times 10^8 \text{ Hz}$$

$$f = \dots\dots\dots 5.0 \times 10^8 \dots\dots\dots \text{ Hz [2]}$$

- (b) The electromagnetic wave is caused by electrons oscillating in the transmitter aerial. Each electron oscillates with simple harmonic motion.

Calculate the maximum acceleration a_{max} of an electron which oscillates with an amplitude of $4.0 \times 10^{-6} \text{ m}$.

$$a_{\text{max}} = \omega^2 A = (2\pi f)^2 A$$

$$\omega = 2\pi \times 5.0 \times 10^8 = 3.14 \times 10^9 \text{ rad s}^{-1}$$

$$a_{\text{max}} = (3.14 \times 10^9)^2 \times 4.0 \times 10^{-6} = 3.9 \times 10^{13} \text{ m s}^{-2}$$

$$a_{\text{max}} = \dots\dots\dots 3.9 \times 10^{13} \dots\dots\dots \text{ ms}^{-2} \text{ [3]}$$

- (c) Suggest why the diode in **Fig. 5.1** is necessary for an ammeter to detect a signal at the receiver aerial.

The current induced in the aerial is alternating (5×10^8 times a second), so its average is zero; the diode rectifies it to d.c. so the ammeter registers a reading. [1]

- *(d) A student carries out two investigations with these electromagnetic waves.

In **investigation 1**, the student rotates the receiver aerial about the horizontal axis joining the two aerals, as shown in **Fig. 5.1**.

In **investigation 2**, the student places a metal sheet behind the receiver aerial. The student moves the sheet backwards and forwards along the horizontal axis joining the two aerals, as shown in **Fig. 5.2**.

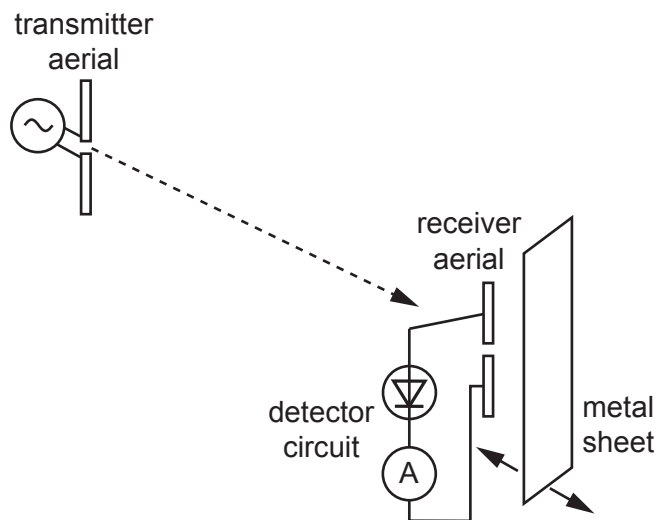


Fig. 5.2

For each of these two investigations:

- Explain why the ammeter sometimes gives a maximum reading and sometimes a zero (or near zero) reading.
- State the orientations of the receiver aerial in **investigation 1**, and the positions of the metal sheet in **investigation 2**, where these maximum and zero readings would occur.

[6]

Investigation 1: the electric field of the wave oscillates vertically and drives the free electrons in the aerial. With the receiver aerial vertical (0° or 180°), the electrons are driven up and down along the whole length of the aerial, giving maximum (a.c.) current, so the reading is a maximum. Rotated by 90° (or 270°) the aerial is horizontal; the field oscillates across the aerial, not

along it, so no current is induced and the reading is zero.

Investigation 2: the wave reflects off the metal sheet and the reflected wave

superposes with the incident wave at the receiver aerial. They are coherent

(same source), so they interfere. When the reflected wave has travelled an

extra $n\lambda$ the waves are in phase and interfere constructively: maximum

current when the sheet is $\lambda/2, 2\lambda/2 \dots$ (30 cm, 60 cm ...) from the receiver

aerial. When it has travelled an extra $(2n + 1)\lambda/2$ the waves are 180° (π

rad) out of phase and interfere destructively: zero current when the sheet is

$\lambda/4, 3\lambda/4 \dots$ (15 cm, 45 cm ...) from the aerial. The reflected wave weakens

with distance, so cancellation is incomplete and the reading is only near zero.

Additional answer space if required.

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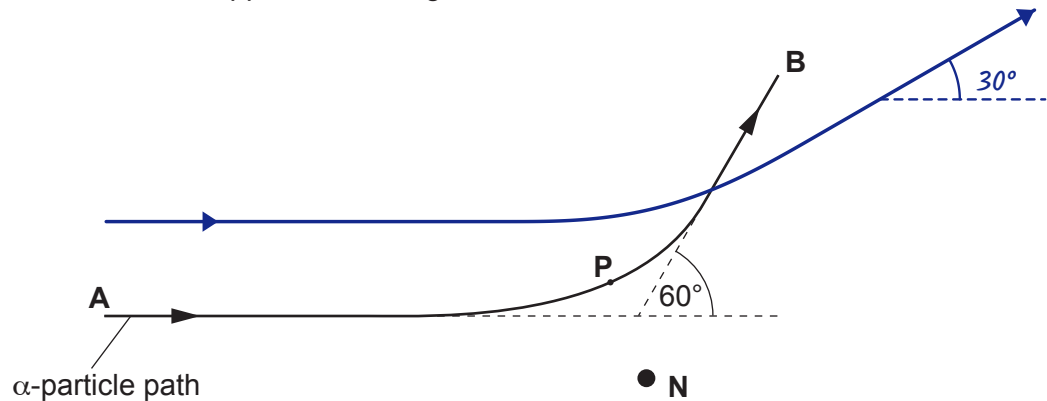
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- 6 A beam of α -particles is incident on a thin gold foil. Most α -particles pass straight through the foil. A few are deflected by gold nuclei.

The diagram shows the path of one α -particle which passes close to a gold nucleus **N** in the foil. The α -particle is deflected through an angle of 60° as it travels from **A** to **B**.

P marks its position of closest approach to the gold nucleus.



- (a) Another α -particle in the beam is deflected by the same gold nucleus **N** through an angle of 30° .

Sketch its path onto the diagram above.

[2]

- (b) The distance between **P** and **N** is $6.8 \times 10^{-14} \text{ m}$.

Calculate the magnitude of the electrostatic force F between the α -particle (${}^4_2\text{He}$) and the gold nucleus (${}^{197}_{79}\text{Au}$) when the α -particle is at **P**.

$$Q = 79e \text{ and } q = 2e$$

$$F = Qq / 4\pi\epsilon_0 r^2$$

$$F = 79 \times 2 \times (1.60 \times 10^{-19})^2 / [4\pi \times 8.85 \times 10^{-12} \times (6.8 \times 10^{-14})^2]$$

$$F = 7.9 \text{ N}$$

$$F = \dots\dots\dots 7.9 \dots\dots\dots \text{ N [4]}$$

Question 6 continues on page 18

- (c) The initial kinetic energy of each α -particle is 5.0 MeV.

Show that the magnitude of the initial momentum of each α -particle is about $10^{-19} \text{ kg m s}^{-1}$.
Take the mass of the α -particle to be $6.6 \times 10^{-27} \text{ kg}$.

$$E_k = 5.0 \times 10^6 \times 1.60 \times 10^{-19} = 8.0 \times 10^{-13} \text{ J}$$

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

$$p = \sqrt{2 \times 6.6 \times 10^{-27} \times 8.0 \times 10^{-13}}$$

$$p = 1.0 \times 10^{-19} \text{ kg m s}^{-1} \text{ (about } 10^{-19} \text{ kg m s}^{-1}\text{)}$$

[3]

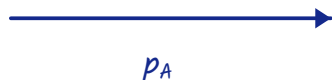
- (d) The **magnitude** of the final momentum of the α -particle at **B** is equal to its initial value at **A**.

The gold nucleus **N** is initially at rest. During the passage of the α -particle from **A** to **B**, no other forces act on the two particles.

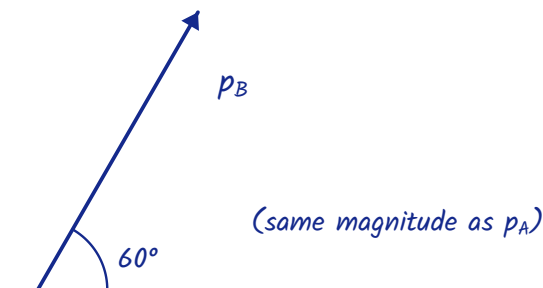
In the following questions label any relevant angles.

- (i) Draw two vectors in the spaces below to represent the initial momentum and the final momentum of the α -particle.

initial momentum at **A**

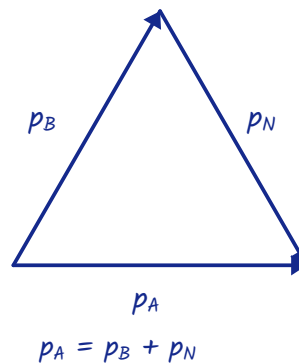
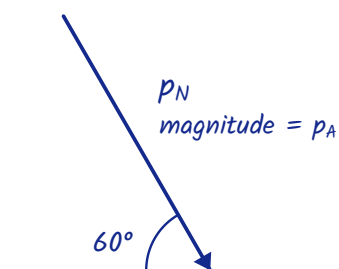


final momentum at **B**



[2]

- (ii) Draw a vector in the space below to represent the momentum of the nucleus **N** when the α -particle reaches **B**.



Explain how you determined this momentum.

By conservation of momentum (no external forces): $p_N = p_A - p_B$. As $|p_A| = |p_B|$ with 60° between them, the vector triangle is equilateral, so p_N has the same magnitude at 60° below the horizontal. [2]

END OF QUESTION PAPER

[illegible]

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