

A Level Physics B (Advancing Physics)

H557/02 Scientific literacy in physics

Time allowed: 2 hours 15 minutes



You must have:

- a clean copy of the Advance Notice Article (inside this document)
- 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 page at the end of this booklet. The question numbers must be clearly shown.
- Answer **all** the questions.
- **Use the Insert to answer questions in Section C.**
- Where appropriate, your answer should be supported with working. Marks might be given for using a correct method, even if your answer is wrong.

INFORMATION

- The total mark for this paper is **100**.
- 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 **28** pages.

ADVICE

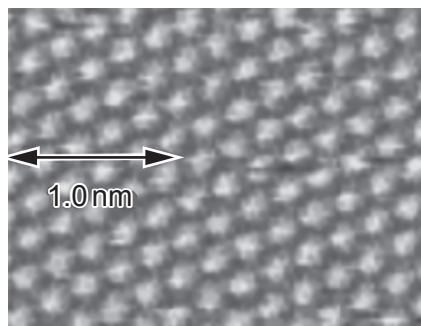
- Read each question carefully before you start your answer.

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SECTION A

- 1 This question is about measuring the sizes of atoms and using the structure of materials on a microscopic scale to explain large-scale properties.
- (a) **Fig. 1** shows an image of a sheet of gold atoms. Use the image to determine the radius of a gold atom. Explain your choice of the number of significant figures in your answer.

Fig. 1



scale arrow 1.0 nm = 2.3 cm on the image

8 atom diameters along a row = 4.4 cm, so one diameter = 0.55 cm

diameter = $0.55 / 2.3 \times 1.0 \text{ nm} = 0.24 \text{ nm}$, so radius = 0.12 nm

radius = 1.2×10^{-10} m

2 s.f. because the image is blurred and the atoms are not circular (gaps between them), and the ruler only reads to $\pm 1 \text{ mm}$. [3]

- (b) An estimate of the radius of a gold atom can be calculated from the density of gold.

One mole of gold contains 6.02×10^{23} atoms.

The mass of one mole of gold is 0.197 kg. The density of gold is $19\,320 \text{ kg m}^{-3}$.

- (i) Show that there are approximately 6×10^{28} gold atoms m^{-3} .

number of moles per $\text{m}^3 = 19\,320 / 0.197 = 98\,071 \text{ mol}$

atoms per $\text{m}^3 = 98\,071 \times 6.02 \times 10^{23}$

= $5.90 \times 10^{28} \text{ atoms m}^{-3}$, which is about 6×10^{28}

[2]

- (ii) The manner in which the gold atoms are packed together means that only 74% of the volume of a sample of gold is taken up by the atoms themselves. Use this percentage and your answer from (i) to calculate the radius of a gold atom.

Assume that gold atoms are spherical.

$$\text{volume of one atom} = 0.74 / 5.9 \times 10^{28} = 1.25 \times 10^{-29} \text{ m}^3$$

$$(4/3)\pi r^3 = 1.25 \times 10^{-29}$$

$$r = (3 \times 1.25 \times 10^{-29} / 4\pi)^{1/3} = 1.44 \times 10^{-10} \text{ m}$$

radius of atom = 1.44×10^{-10} m [2]

- (c) Images of arrangements of atoms in a metal sometimes reveal **dislocations** in the microscopic structure. Describe what dislocations are and how the presence of dislocations changes the properties of the metal.

Dislocations are places where atoms are missing (gaps or an extra half plane) in the regular crystalline structure of the metal. They make the metal less brittle, more ductile and tough, because planes of atoms can slip over each other at a dislocation, breaking only one bond at a time.

[3]

- 2 An alpha particle of kinetic energy 5.4 MeV produces 4.4×10^6 ions per metre in dry air. It transfers all its kinetic energy over 0.035 m.

(a)

- (i) Show that the average energy to remove an electron from a molecule (ionisation energy) in air is less than 6×10^{-18} J.

$$\text{number of ions per alpha particle} = 4.4 \times 10^6 \times 0.035 = 1.54 \times 10^5$$

$$\text{energy per ionisation} = 5.4 \times 10^6 \times 1.6 \times 10^{-19} / 1.54 \times 10^5$$

$$= 8.64 \times 10^{-13} / 1.54 \times 10^5 = 5.6 \times 10^{-18} \text{ J}$$

$$5.6 \times 10^{-18} \text{ J} < 6 \times 10^{-18} \text{ J}$$

[2]

- (ii) A free electron in air travels about 700 nm between collisions with molecules. Use your answer to (a)(i) to calculate the strength of a uniform electric field required to give an electron sufficient kinetic energy to ionise molecules in air.

Assume that the electron accelerates from rest for 700 nm.

$$\text{energy gained from field} = \text{force} \times \text{distance} = Eqd$$

$$Eqd = 5.6 \times 10^{-18} \text{ J}$$

$$E = 5.6 \times 10^{-18} / (1.6 \times 10^{-19} \times 700 \times 10^{-9})$$

$$E = 5.0 \times 10^7 \text{ V m}^{-1}$$

$$\text{field strength} = 5.0 \times 10^7 \text{ V m}^{-1} \quad [2]$$

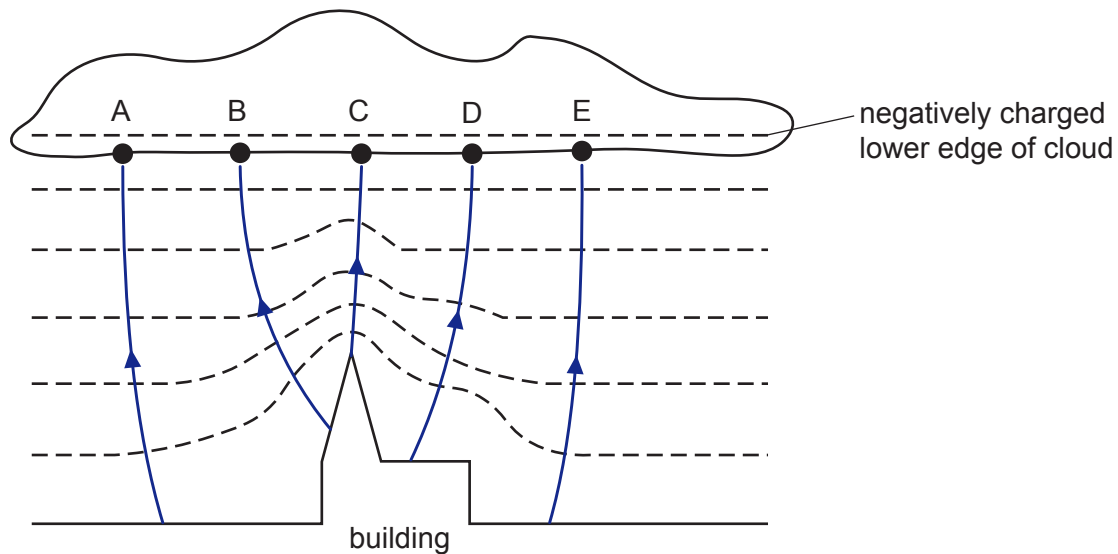
- (iii) Explain why the number of ions formed per second will initially rise at increasing rate after the first ionisation event.

The electrons freed by each ionisation are themselves accelerated by the field and gain enough k.e. to ionise more molecules. This increases the number of liberated electrons, which accelerate and produce more ions, so the number of ions formed per second rises at an increasing rate (an avalanche).

[2]

- (b) Fig. 2 is a representation of a thundercloud above a flat landscape with a tall building. The dotted lines represent equipotential lines with equal potential differences between each line.

Fig. 2



The surface of the ground and the building are at zero potential.

- (i) Draw field lines linking the points on the bottom of the cloud marked A to E to points of zero potential. [2]
- (ii) State and explain where the force on free electrons will be the greatest in the region between the zero potential surface and the lower edge of the cloud.

Greatest near the top of the spire of the building (just above its point).

Here the equipotential lines are closest together (smallest spacing), so the potential gradient and field strength E are greatest, and $F = eE$ is greatest.

..... [2]

- 3 This question is about radioactive decay and time-dilation when bodies move at near-light speeds.

A radioisotope thermal generator (RTG) uses the decay of plutonium-238 (Pu-238) to generate electrical power.

In a science fiction story, an RTG provides $3.50 \times 10^4 \text{ W}$ to the living quarters of a spaceship when the spaceship is launched.

(a)

- (i) Show that the initial activity of the plutonium source is about $4 \times 10^{16} \text{ Bq}$.

Energy released in one decay of Pu-238 = $8.96 \times 10^{-13} \text{ J}$

$$\begin{aligned} \text{activity} &= \text{power} / \text{energy per decay} = 3.50 \times 10^4 / 8.96 \times 10^{-13} \\ &= 3.9 \times 10^{16} \text{ Bq, which is about } 4 \times 10^{16} \text{ Bq} \end{aligned}$$

[1]

- (ii) Calculate the initial mass of Pu-238 in the generator.

Decay constant of Pu-238 = $2.48 \times 10^{-10} \text{ s}^{-1}$

Mass of one plutonium-238 atom = $3.95 \times 10^{-25} \text{ kg}$

$$\begin{aligned} A &= \lambda N, \text{ so } N = 3.9 \times 10^{16} / 2.48 \times 10^{-10} = 1.58 \times 10^{26} \text{ atoms} \\ \text{mass} &= 1.58 \times 10^{26} \times 3.95 \times 10^{-25} = 62 \text{ kg} \end{aligned}$$

mass = ..62..... kg [2]

(b)

- (i) Show that the power output of a **stationary** RTG will have fallen to about 72% of its original value after 42 years.

Initial power of RTG = $3.50 \times 10^4 \text{ W}$

$$P / P_0 = e^{-\lambda t}, \quad t = 42 \times 3.16 \times 10^7 \text{ s} = 1.33 \times 10^9 \text{ s}$$

$$P / P_0 = \exp(-2.48 \times 10^{-10} \times 42 \times 3.16 \times 10^7) = e^{-0.329} = 0.720$$

$$\text{so about 72\% } (P = 0.72 \times 3.50 \times 10^4 = 2.5 \times 10^4 \text{ W})$$

[2]

When the spaceship is launched a radio signal is sent to WST-A, a planet 30 light years away. The spaceship arrives at WST-A 12 years after the radio signal is detected at the planet.

- (ii) Calculate the average velocity of the spaceship during its 42-year journey.

signal takes 30 years to reach WST-A; ship arrives 12 years later

$$v = 30 \text{ light years} / 42 \text{ years} = (5/7)c = 0.714 \times 3.00 \times 10^8$$

$$\text{average velocity} = \dots 2.14 \times 10^8 \dots \text{ ms}^{-1} \text{ [1]}$$

- (iii) Explain by using relevant calculations, why the power output of the RTG when the spaceship lands on WST-A is approximately 79% of its value at launch. Assume that the spaceship travels at constant velocity throughout the journey.

$$\gamma = 1 / \sqrt{1 - v^2/c^2} = 1 / \sqrt{1 - (5/7)^2} = 1 / \sqrt{24/49} = 1.43$$

The RTG is at rest in the spaceship, so the time it experiences is

the proper time: $t = 42 / 1.43 = 29.4$ years (time dilation)

$$P / P_0 = e^{-\lambda t} = \exp(-2.48 \times 10^{-10} \times 29.4 \times 3.16 \times 10^7)$$

$$= e^{-0.230} = 0.794, \text{ so about 79\% of the launch value.}$$

This is higher than 72% because fewer years pass for the RTG.

[4]

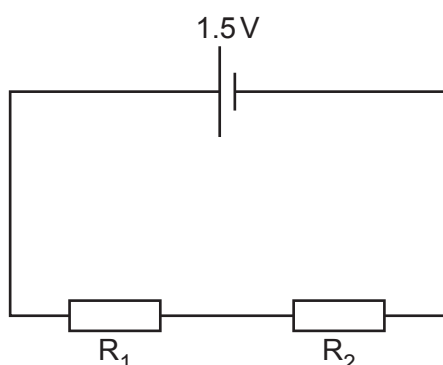
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9
SECTION B

- 4 This question is about a temperature sensor. Fig. 4.1 shows a potential divider circuit.

Fig. 4.1



- (a) The e.m.f. of the cell is 1.5 V. The cell has negligible internal resistance. The potential difference across R_1 is 0.4 V.

- (i) Explain the difference in the meaning of the terms *e.m.f.* and *potential difference*.

E.m.f. is the energy transferred per unit charge (per coulomb) to the charge in the cell.

P.d. is the energy transferred per unit charge (per coulomb) from the charge in a component, e.g. the resistor. [2]

- (ii) R_1 has a resistance of $30\ \Omega$. Calculate the resistance of R_2 .

p.d. across $R_2 = 1.5 - 0.4 = 1.1\text{ V}$; same current in both

$R_2 / R_1 = V_2 / V_1$, so $R_2 = 30 \times 1.1 / 0.4 = 82.5\ \Omega$

resistance = *83* Ω [2]

- (b) A student sets up the circuit shown in Fig. 4.2 to calibrate a thermistor to measure the temperature of a baby bath.

Fig. 4.2

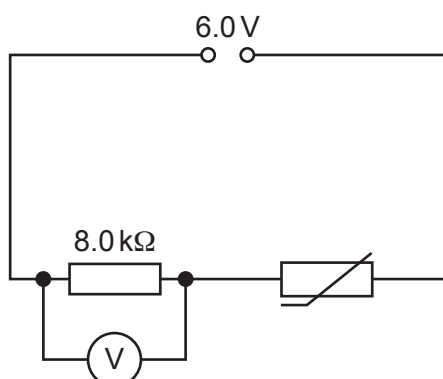
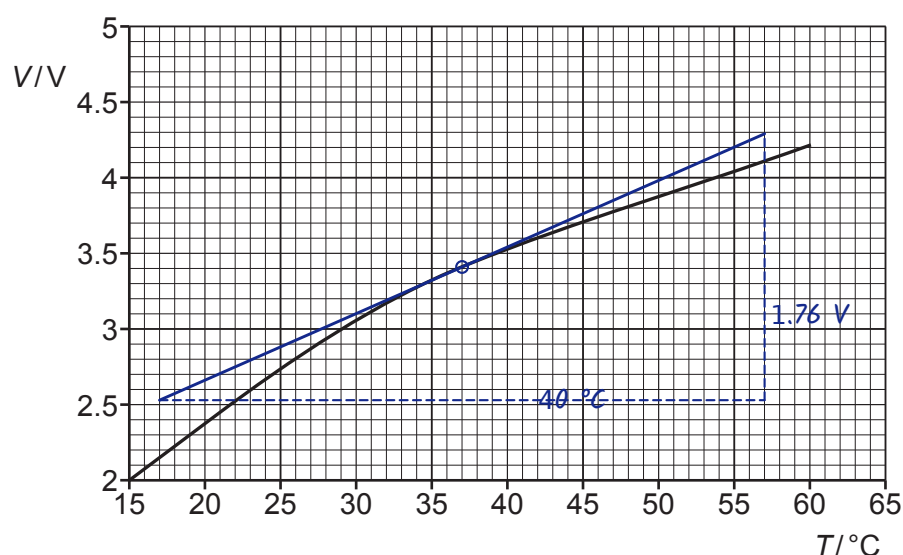


Fig. 4.3 shows how the p.d. across the $8.0\text{ k}\Omega$ resistor varies with the temperature of the thermistor.

Fig. 4.3



- (i) Describe an experimental method that could be used to obtain such a calibration curve. Give **one** possible source of experimental uncertainty and suggest how it can be reduced.

Put the thermistor in a beaker of water heated by a hot plate (water bath),
 with a thermometer next to it; record the voltmeter reading every 5°C as the
 water heats from 15°C to 60°C .
 Uncertainty: uneven temperature in the water (thermistor and thermometer not
 at the same temperature).
 Reduce it by stirring the water and waiting for the readings to settle. [3]

- (ii)* The ideal temperature for a baby bath is 37 °C. The voltmeter reads to the nearest 0.01 V. The resistance of the thermistor varies from approximately 13 kΩ to 3 kΩ over the temperature range.

Calculate the sensitivity **and** resolution of the temperature sensor at 37 °C. Explain the effect of changing the value of the fixed resistor to 80 kΩ on the sensitivity of the sensor. You may use calculations in your explanation.

Tangent at 37 °C (drawn on Fig. 4.3):

$$\text{sensitivity} = \text{gradient} = (4.29 - 2.53) \text{ V} / (57 - 17) \text{ °C} = 1.76 / 40$$

$$\text{sensitivity} = 0.044 \text{ V °C}^{-1}$$

$$\text{resolution} = 0.01 \text{ V} / 0.044 \text{ V °C}^{-1} = 0.23 \text{ °C}$$

$$80 \text{ k}\Omega: \text{ find } R_{th} \text{ from the graph, } R_{th} = 8.0 \times (6.0 - V) / V$$

$$20 \text{ °C: } V = 2.38 \text{ V, } R_{th} = 12.2 \text{ k}\Omega, \text{ new } V = 6.0 \times 80 / 92.2 = 5.21 \text{ V}$$

$$60 \text{ °C: } V = 4.21 \text{ V, } R_{th} = 3.4 \text{ k}\Omega, \text{ new } V = 6.0 \times 80 / 83.4 = 5.76 \text{ V}$$

$$35 \text{ °C: } V = 3.32 \text{ V, } R_{th} = 6.46 \text{ k}\Omega, \text{ new } V = 480 / 86.46 = 5.552 \text{ V}$$

$$39 \text{ °C: } V = 3.49 \text{ V, } R_{th} = 5.75 \text{ k}\Omega, \text{ new } V = 480 / 85.75 = 5.598 \text{ V}$$

$$\text{new sensitivity} = 0.046 \text{ V} / 4 \text{ °C} = 0.012 \text{ V °C}^{-1}$$

$$\text{new resolution} = 0.01 / 0.012 = 0.8 \text{ °C}$$

So using an 80 kΩ fixed resistor decreases the sensitivity of the sensor. The fixed resistor is always much greater than the thermistor (13 kΩ to 3 kΩ), and the ratio of the p.d.s. equals the ratio of the resistances, so most of the 6.0 V is always across the fixed resistor (5.2 V to 5.8 V). A change in thermistor resistance is now a small fraction of the total resistance, so V changes by only 0.55 V from 20 °C to 60 °C instead of 1.8 V: sensitivity falls from 0.044 to 0.012 V °C⁻¹ and the resolution worsens from 0.23 °C to 0.8 °C.

[6]

- (c) The resistance of the thermistor (a semiconductor) decreases when its temperature increases.

Explain this by considering the behaviour and number density of the mobile charge carriers in the semiconductor.

As temperature increases, more electrons gain sufficient energy to move into the conduction band (become free to move), so the number density n of mobile charge carriers (electrons and holes) increases greatly. $I = nAqv$, so the current is larger for the same p.d. and the resistance decreases. [3]

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Section B continues on page 14

5 This question is about gravitational and electrical fields.

(a)

- (i) The Earth orbits the Sun at a distance of 1.5×10^{11} m. Calculate the angular velocity and the orbital speed of the Earth.

Orbital period = 3.2×10^7 s (1 year)

$$\omega = 2\pi / T = 2\pi / 3.2 \times 10^7 = 1.96 \times 10^{-7} \text{ rad s}^{-1}$$

$$\text{angular velocity} = \dots 1.96 \times 10^{-7} \dots \text{ rad s}^{-1}$$

$$v = \omega r = 1.96 \times 10^{-7} \times 1.5 \times 10^{11}$$

$$\text{orbital speed} = \dots 2.95 \times 10^4 \dots \text{ m s}^{-1}$$

[2]

- (ii) Use your answer to (a)(i) to show that the centripetal acceleration of the Earth in its orbit is about $6 \times 10^{-3} \text{ m s}^{-2}$.

$$a = \omega^2 r = (1.96 \times 10^{-7})^2 \times 1.5 \times 10^{11} = 5.8 \times 10^{-3} \text{ m s}^{-2}$$

which is about $6 \times 10^{-3} \text{ m s}^{-2}$

[1]

- (iii) Use the value from (a)(ii) to calculate the mass of the Sun.

$$GMm / r^2 = ma, \text{ so } a = GM / r^2 \text{ and } M = ar^2 / G$$

$$M = 6.0 \times 10^{-3} \times (1.5 \times 10^{11})^2 / 6.67 \times 10^{-11}$$

$$M = 1.35 \times 10^{20} / 6.67 \times 10^{-11}$$

$$\text{mass} = \dots 2.0 \times 10^{30} \dots \text{ kg}$$

[3]

(b)

- (i) Calculate the ratio of the force due to the electric field (electrostatic force) between a proton and an electron and the gravitational force between the same particles at a separation r .

$$\text{ratio} = (ke^2 / r^2) / (Gm_p m_e / r^2) = ke^2 / Gm_p m_e \quad (r \text{ cancels})$$

$$= 8.99 \times 10^9 \times (1.6 \times 10^{-19})^2 / (6.67 \times 10^{-11} \times 1.67 \times 10^{-27} \times 9.11 \times 10^{-31})$$

$$= 2.30 \times 10^{-28} / 1.01 \times 10^{-67}$$

$$\text{ratio} \frac{\text{electrostatic force}}{\text{gravitational force}} = \dots\dots\dots 2.3 \times 10^{39} \dots\dots\dots [3]$$

- (ii) State why gravity is the dominant force in the large-scale structure of the Universe even though it is weaker than the electrostatic force on an atomic level.

Electrostatic forces can be attractive or repulsive (gravity is always attractive).

The Universe has equal numbers of positive and negative charges, so on a large

scale the electrostatic forces cancel, but gravitational forces add up.

..... [2]

- (c) An early model of the hydrogen atom pictured the electron orbiting the proton in a similar manner to a planet orbiting the Sun. This is called the 'planetary model'.

- (i) Calculate the centripetal acceleration of an electron orbiting a proton at a separation of $0.5 \times 10^{-10} \text{ m}$.

$$F = ke^2 / r^2 = 8.99 \times 10^9 \times (1.6 \times 10^{-19})^2 / (0.5 \times 10^{-10})^2$$

$$F = 9.2 \times 10^{-8} \text{ N}$$

$$a = F / m = 9.2 \times 10^{-8} / 9.11 \times 10^{-31}$$

$$\text{centripetal acceleration} = \dots\dots\dots 1.0 \times 10^{23} \dots\dots\dots \text{ms}^{-2} [2]$$

- (ii) Accelerating charges emit electromagnetic radiation. Suggest and explain why this shows that the planetary model of the hydrogen atom is incorrect.

The orbiting electron is always accelerating (centripetally), so it would continuously radiate, transferring energy away. It would lose energy and spiral into the nucleus, so the atom would be unstable; atoms are stable, so the model is wrong. [2]

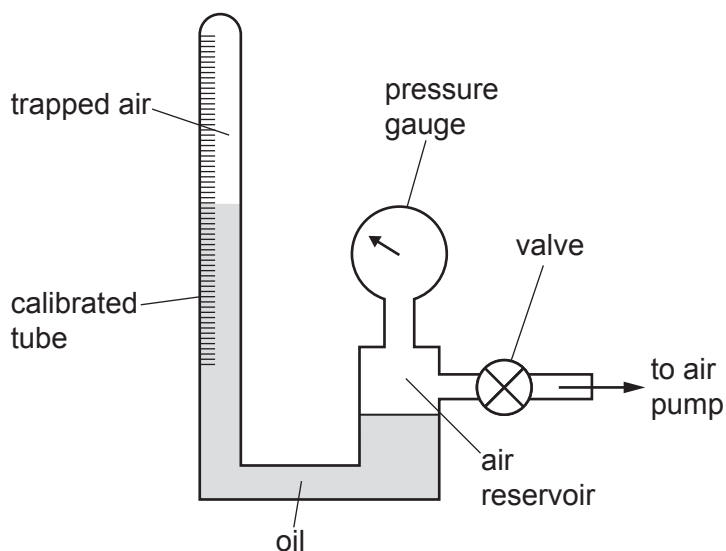
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Section B continues on page 18

- 6 This question is about Boyle's Law and ideal gas behaviour.

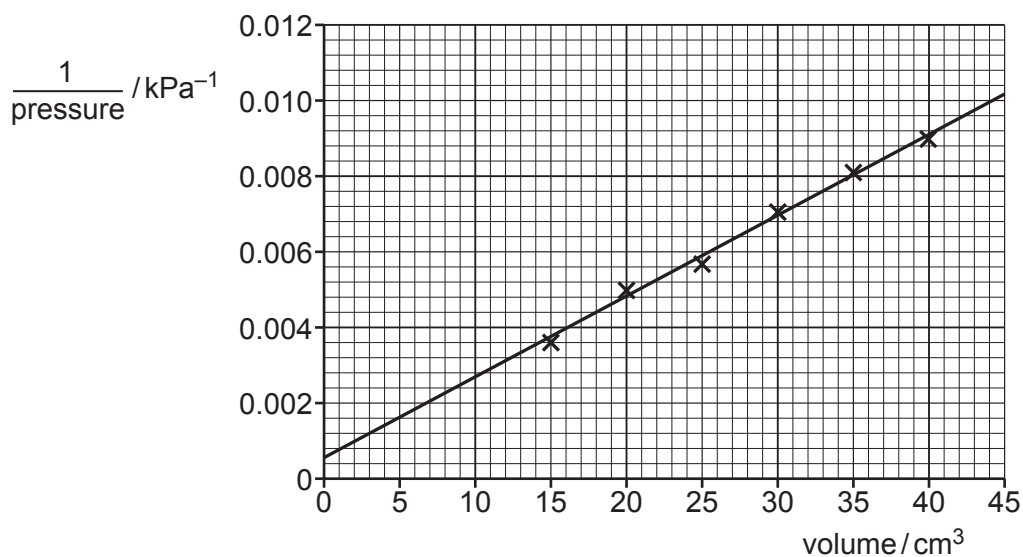
A demonstration is performed to show the relationship between the volume of a gas and the pressure it exerts. **Fig. 6.1** shows the apparatus used.

Fig. 6.1



Readings of pressure and volume are taken as the pressure of the trapped air is increased. The graph in **Fig. 6.2** is plotted using the results of the demonstration.

Fig. 6.2



(a)

- (i) Explain why it is necessary to keep the temperature of the air constant during the demonstration. Use ideas from kinetic theory to explain the effect of the temperature of the air increasing as the pressure increases.

..Boyle's law is the relationship between p and V only: it requires constant.....
 ..temperature so that p and V are the only variables.....
 ..If T increases, the molecules gain speed (mean k.e. increases).....
 ..So there are more collisions per second with the walls (greater rate of.....
 ..collisions),.....
 ..and a greater momentum change per collision with the walls.....
 ..So p rises more than expected and V would not change in proportion to $1/p$:.....
 ..the graph would not be a straight line..... [4]

- (ii) Suggest and explain why the graph is a straight line with a positive y intercept.

..There is a systematic error on a proportional relationship ($V \propto 1/p$ should pass.....
 ..through the origin),.....
 ..e.g. a zero error on the pressure gauge, or volume of trapped air not shown on.....
 ..the scale..... [2]

(b)

- (i) The temperature of the trapped air is 293 K. Show that the root mean square speed of the air molecules is about 500 m s^{-1} .

Assume the mass of a molecule is $4.8 \times 10^{-26} \text{ kg}$.

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

$$\langle c^2 \rangle = 3 \times 1.38 \times 10^{-23} \times 293 / 4.8 \times 10^{-26} = 2.53 \times 10^5 \text{ m}^2 \text{ s}^{-2}$$

$$c_{\text{rms}} = \sqrt{(2.53 \times 10^5)} = 503 \text{ m s}^{-1}, \text{ which is about } 500 \text{ m s}^{-1}$$

[3]

- (ii) The movement of particles in an ideal gas can be described as a 'random walk'. State the meaning of 'random walk' in this context.

..Short straight paths between collisions with abrupt, random changes of.....
 ..direction at each collision..... [1]

(c)

- (i) The gradient of the graph is about $2 \times 10^{-4} \text{ kPa}^{-1} \text{ cm}^{-3}$.
Explain why this is equivalent to $0.2 \text{ Pa}^{-1} \text{ m}^{-3}$.

$$1 \text{ cm}^{-3} = 1 \times 10^6 \text{ m}^{-3} \text{ and } 1 \text{ kPa}^{-1} = 1 \times 10^{-3} \text{ Pa}^{-1}$$

$$\text{so } 1 \text{ kPa}^{-1} \text{ cm}^{-3} = 10^{-3} \times 10^6 = 1 \times 10^3 \text{ Pa}^{-1} \text{ m}^{-3}$$

$$2 \times 10^{-4} \text{ kPa}^{-1} \text{ cm}^{-3} = 2 \times 10^{-4} \times 10^3 = 0.2 \text{ Pa}^{-1} \text{ m}^{-3}$$

[2]

- (ii) Use the value in (c)(i) to calculate the number of moles of trapped air in the tube.

$$1/p = \text{gradient} \times V, \text{ so } 1/\text{gradient} = pV$$

$$pV = 1 / 0.2 = 5 \text{ Pa m}^3$$

$$pV = nRT: 5 = n \times 8.31 \times 293$$

$$n = 5 / (8.31 \times 293)$$

$$\text{number} = \underline{2.1 \times 10^{-3}} \dots \text{mol} \quad [3]$$

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Section C begins on page 22

SECTION C

This section is based on the Advance Notice Article, which is an insert.

- 7 A scan of a phonoautogram (lines 18–28) produces a signal variation of 2 mV and a noise level of 75 μ V.

Calculate the number of bits to best represent this sample. Make your reasoning clear.

Calculation:

$$\begin{aligned} \text{number of bits} &= \log_2((\text{signal} + \text{noise}) / \text{noise}) \\ &= \log_2(2.075 \text{ mV} / 0.075 \text{ mV}) = \log_2(27.7) = 4.79 \end{aligned}$$

number of bits = 5 (4.79)

Reasoning:

Round up to 5 bits to capture all the detail of the signal, even though some of the smallest steps will just be noise. [3]

8

- (a) Explain why the sensitivity of dynamic microphones falls at high frequencies and how this can affect the accuracy of recordings (lines 66–69).

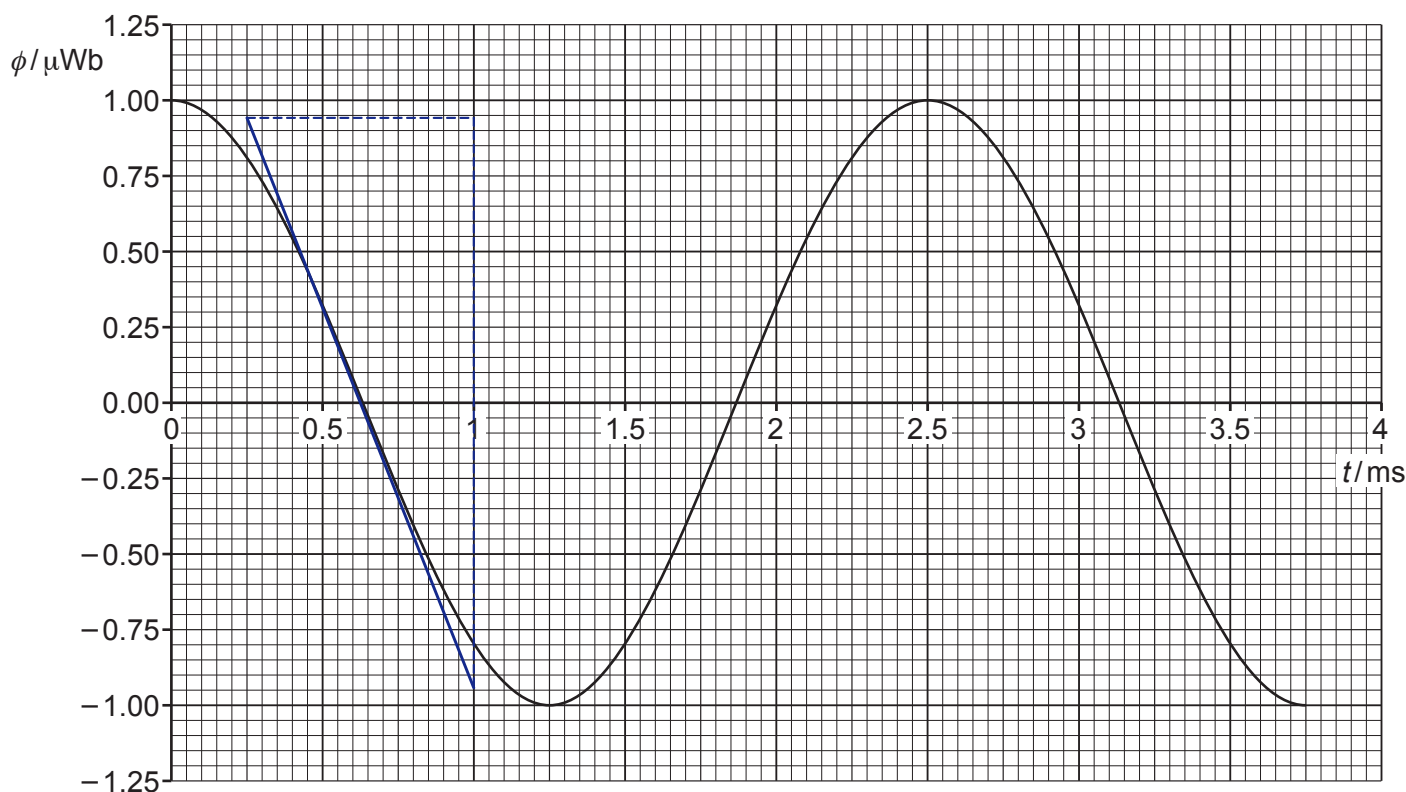
The diaphragm and coil have mass (inertia), which limits their acceleration for a given pressure force.

At high frequencies the force reverses before they move far, so the amplitude of oscillation is reduced and the sensitivity falls.

The diaphragm cannot respond quickly enough to the high-frequency components of complex waveforms, so the tone and timbre are not recorded accurately. [3]

- (b) Fig. 8 shows how the flux through a coil of 170 turns in a dynamic microphone oscillating in a magnetic field changes with time.

Fig. 8



Calculate the maximum emf induced during the cycle.

max emf where the gradient is steepest ($\phi = 0$): tangent at 0.625 ms

gradient = $1.88 \times 10^{-6} \text{ Wb} / 0.75 \times 10^{-3} \text{ s} = 2.5 \times 10^{-3} \text{ Wb s}^{-1}$

emf = $N d\phi/dt = 170 \times 2.5 \times 10^{-3}$

maximum emf = *0.43*..... V [2]

- 9 Data for a capacitor in a condenser microphone with air as the dielectric are given below:

Diameter of circular diaphragm = 1.80 mm

Equilibrium separation of diaphragm and back plate = $9.6 \mu\text{m}$

Relative permittivity of air = 1

Bias voltage = 12.0 V

A 340 Hz sine wave is incident on the diaphragm which oscillates at a frequency of 340 Hz with an amplitude of $0.1 \mu\text{m}$.

- (a) Use the equation given (line 76) in the article to show that the **maximum** value of capacitance during the oscillation is about 2.4 pF.

maximum C when d is smallest: $d = 9.6 - 0.1 = 9.5 \mu\text{m}$

$$A = \pi r^2 = \pi \times (0.90 \times 10^{-3})^2 = 2.54 \times 10^{-6} \text{ m}^2$$

$$C = \epsilon_0 \epsilon_r A / d = 8.85 \times 10^{-12} \times 1 \times 2.54 \times 10^{-6} / 9.5 \times 10^{-6}$$

$$C = 2.37 \times 10^{-12} \text{ F} = 2.37 \text{ pF, which is about } 2.4 \text{ pF}$$

[2]

- (b) Calculate the energy stored on the capacitor at this maximum value.

$$\frac{1}{2} CV^2 = \frac{1}{2} \times 2.37 \times 10^{-12} \times 12.0^2$$

$$\text{energy stored} = \dots 1.7 \times 10^{-10} \text{ J} \dots \dots \dots [1]$$

- (c) The capacitance at equilibrium position is 2.35 pF. Use this value and your value from (a) to calculate the mean current from the capacitor as the diaphragm moves from its position in (a) to the equilibrium position.

$$\Delta Q = \Delta C \times V = (2.37 - 2.35) \times 10^{-12} \times 12.0 = 0.24 \times 10^{-12} \text{ C}$$

$$\text{time from maximum displacement to equilibrium} = T/4$$

$$t = 1 / (4 \times 340) = 0.735 \times 10^{-3} \text{ s}$$

$$I = \Delta Q / t = 0.24 \times 10^{-12} / 0.735 \times 10^{-3}$$

$$\text{mean current} = \dots 3.3 \times 10^{-10} \dots \dots \dots \text{ A} [3]$$

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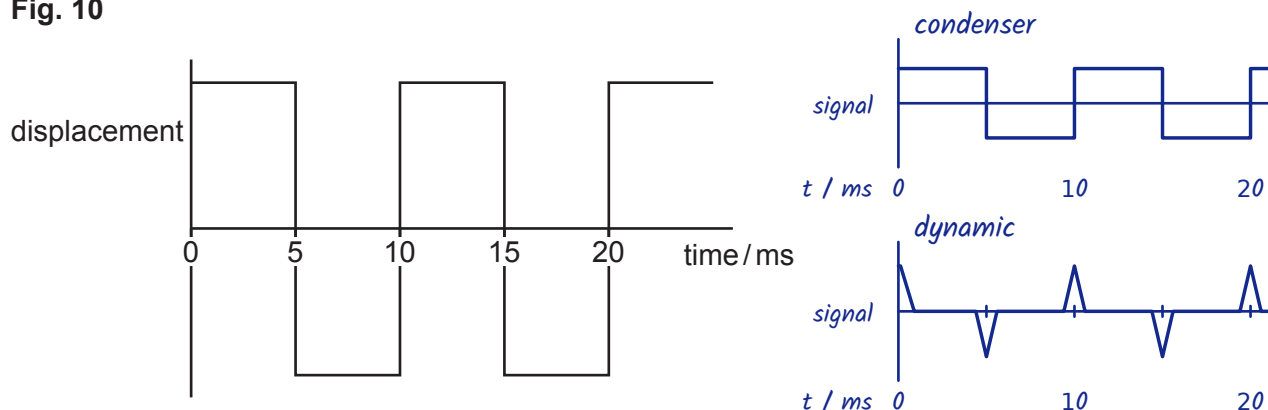
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Question 10 begins on page 26

- 10* Using appropriate equations, explain and compare how the phase of the output signal from dynamic and condenser microphones relates to the phase of the incident sound wave (lines 73–74 and lines 90–92).

Describe how each type of microphone would respond to an incident square wave sound, as shown in **Fig. 10**, and explain which microphone is best suited to recording such a wave. You may include sketch graphs of signal amplitude (no unit) against time/ ms from the two microphones in your answer.

Fig. 10



Dynamic: $\varepsilon = -N \frac{d\Phi}{dt}$. The coil moves with the diaphragm, so flux linkage $\propto$ displacement $x = A \sin \omega t$ and $\varepsilon \propto dx/dt = A\omega \cos \omega t$. The output leads the sound wave by $\pi/2$ rad (90°): it is greatest at zero displacement (coil moving fastest) and zero at maximum displacement.

Condenser: V is held constant, $Q = CV$ and $C = \varepsilon_0 \varepsilon_r A/d$, so $Q \propto 1/d$. As the pressure pushes the membrane in, d falls and C and Q rise at the same time, so the output is in phase with the incident wave (phase difference 0).

Square wave: the condenser output is a square wave (see sketch) changing at 5, 10, 15 and 20 ms, as the membrane is held at each separation.

The dynamic coil is pushed sharply in and out of the field at each edge, so $d\Phi/dt$ is very large for a short time: sharp peaks, alternately positive and negative, with zero output between, when the flux is constant.

So the condenser microphone is best suited: its output has the same shape as the wave, and its low-mass membrane responds quickly to the sudden changes; the dynamic output does not resemble the wave.

[6]

- 11 The total capacitance of two capacitors in series is given by:

$$\frac{1}{C_{\text{total}}} = \frac{1}{C_1} + \frac{1}{C_2}.$$

- (a) Using equations for the capacitance of the membrane and air-gap capacitors in an electret microphone (lines 100–105) to show that the total capacitance of the two capacitors in series is given by:

$$C_{\text{total}} = \frac{\epsilon_0 \epsilon_r S}{\epsilon_r d + h}$$

$$C_M = \epsilon_0 \epsilon_r S / h \text{ and } C_G = \epsilon_0 S / d$$

$$1/C_{\text{total}} = h / \epsilon_0 \epsilon_r S + d / \epsilon_0 S = h / \epsilon_0 \epsilon_r S + \epsilon_r d / \epsilon_0 \epsilon_r S$$

$$1/C_{\text{total}} = (\epsilon_r d + h) / \epsilon_0 \epsilon_r S$$

$$\text{so } C_{\text{total}} = \epsilon_0 \epsilon_r S / (\epsilon_r d + h)$$

[2]

Here are some data about an electret microphone capsule:

Surface area of membrane layer and metal backplate = $4.5 \times 10^{-6} \text{ m}^2$

Thickness of membrane layer = $1.9 \times 10^{-5} \text{ m}$

Relative permittivity of membrane layer = 1.8

Width of air gap = $3.8 \times 10^{-5} \text{ m}$

- (b) The total charge on the capacitors is $9.7 \times 10^{-11} \text{ C}$. Calculate the potential difference across the two capacitors.

$$C = 8.85 \times 10^{-12} \times 1.8 \times 4.5 \times 10^{-6} / (1.8 \times 3.8 \times 10^{-5} + 1.9 \times 10^{-5}) = 8.2 \times 10^{-13} \text{ F}$$

$$V = Q / C = 9.7 \times 10^{-11} / 8.2 \times 10^{-13} = 118 \text{ V}$$

potential difference = ..120..(118)..... V [2]

END OF QUESTION PAPER

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