Cambridge Assessment International Education

Cambridge International AS & A Level

CANDIDATE NAME

CENTRE NUMBER

CANDIDATE NUMBER

0306447304

PHYSICS **9702/41**

Paper 4 A Level Structured Questions **May/June 2020**

2 hours

You must answer on the question paper.

No additional materials are needed.

INSTRUCTIONS
- Answer **all** questions.
- Use a black or dark blue pen. You may use an HB pencil for any diagrams or graphs.
- Write your name, centre number and candidate number in the boxes at the top of the page.
- Write your answer to each question in the space provided.
- Do **not** use an erasable pen or correction fluid.
- Do **not** write on any bar codes.
- You may use a calculator.
- You should show all your working and use appropriate units.

INFORMATION
- The total mark for this paper is 100.
- The number of marks for each question or part question is shown in brackets [ ].

This document has **28** pages. Blank pages are indicated.

DC (LK/CB) 180507/2

Data

speed of light in free space	$c = 3.00 \times 10^{8}\,\mathrm{m\,s^{-1}}$
permeability of free space	$\mu_0 = 4\pi \times 10^{-7}\,\mathrm{H\,m^{-1}}$
permittivity of free space	$\varepsilon_0 = 8.85 \times 10^{-12}\,\mathrm{F\,m^{-1}}$
	$(\frac{1}{4\pi\varepsilon_0} = 8.99 \times 10^{9}\,\mathrm{m\,F^{-1}})$
elementary charge	$e = 1.60 \times 10^{-19}\,\mathrm{C}$
the Planck constant	$h = 6.63 \times 10^{-34}\,\mathrm{J\,s}$
unified atomic mass unit	$1\,\mathrm{u} = 1.66 \times 10^{-27}\,\mathrm{kg}$
rest mass of electron	$m_e = 9.11 \times 10^{-31}\,\mathrm{kg}$
rest mass of proton	$m_p = 1.67 \times 10^{-27}\,\mathrm{kg}$
molar gas constant	$R = 8.31\,\mathrm{J\,K^{-1}\,mol^{-1}}$
the Avogadro constant	$N_A = 6.02 \times 10^{23}\,\mathrm{mol^{-1}}$
the Boltzmann constant	$k = 1.38 \times 10^{-23}\,\mathrm{J\,K^{-1}}$
gravitational constant	$G = 6.67 \times 10^{-11}\,\mathrm{N\,m^{2}\,kg^{-2}}$
acceleration of free fall	$g = 9.81\,\mathrm{m\,s^{-2}}$

Formulae

uniformly accelerated motion	$s = ut + \frac{1}{2}at^2$ $v^2 = u^2 + 2as$
work done on/by a gas	$W = p\Delta V$
gravitational potential	$\phi = -\frac{Gm}{r}$
hydrostatic pressure	$p = \rho gh$
pressure of an ideal gas	$p = \frac{1}{3}\frac{Nm}{V}\langle c^2 \rangle$
simple harmonic motion	$a = -\omega^2 x$
velocity of particle in s.h.m.	$v = v_0 \cos \omega t$ $v = \pm \omega\sqrt{(x_0^{\,2} - x^2)}$
Doppler effect	$f_o = \frac{f_s v}{v \pm v_s}$
electric potential	$V = \frac{Q}{4\pi\varepsilon_0 r}$
capacitors in series	$1/C = 1/C_1 + 1/C_2 + \ldots$
capacitors in parallel	$C = C_1 + C_2 + \ldots$
energy of charged capacitor	$W = \frac{1}{2}QV$
electric current	$I = Anvq$
resistors in series	$R = R_1 + R_2 + \ldots$
resistors in parallel	$1/R = 1/R_1 + 1/R_2 + \ldots$
Hall voltage	$V_H = \frac{BI}{ntq}$
alternating current/voltage	$x = x_0 \sin \omega t$
radioactive decay	$x = x_0 \exp(-\lambda t)$
decay constant	$\lambda = \frac{0.693}{t_{\frac{1}{2}}}$

Answer **all** the questions in the spaces provided.

1 **(a)** State what is meant by a *gravitational force*.

....

.... [1]

(b) A binary star system consists of two stars S_1 and S_2, each in a circular orbit.

The orbit of each star in the system has a period of rotation T.

Observations of the binary star from Earth are represented in Fig. 1.1.

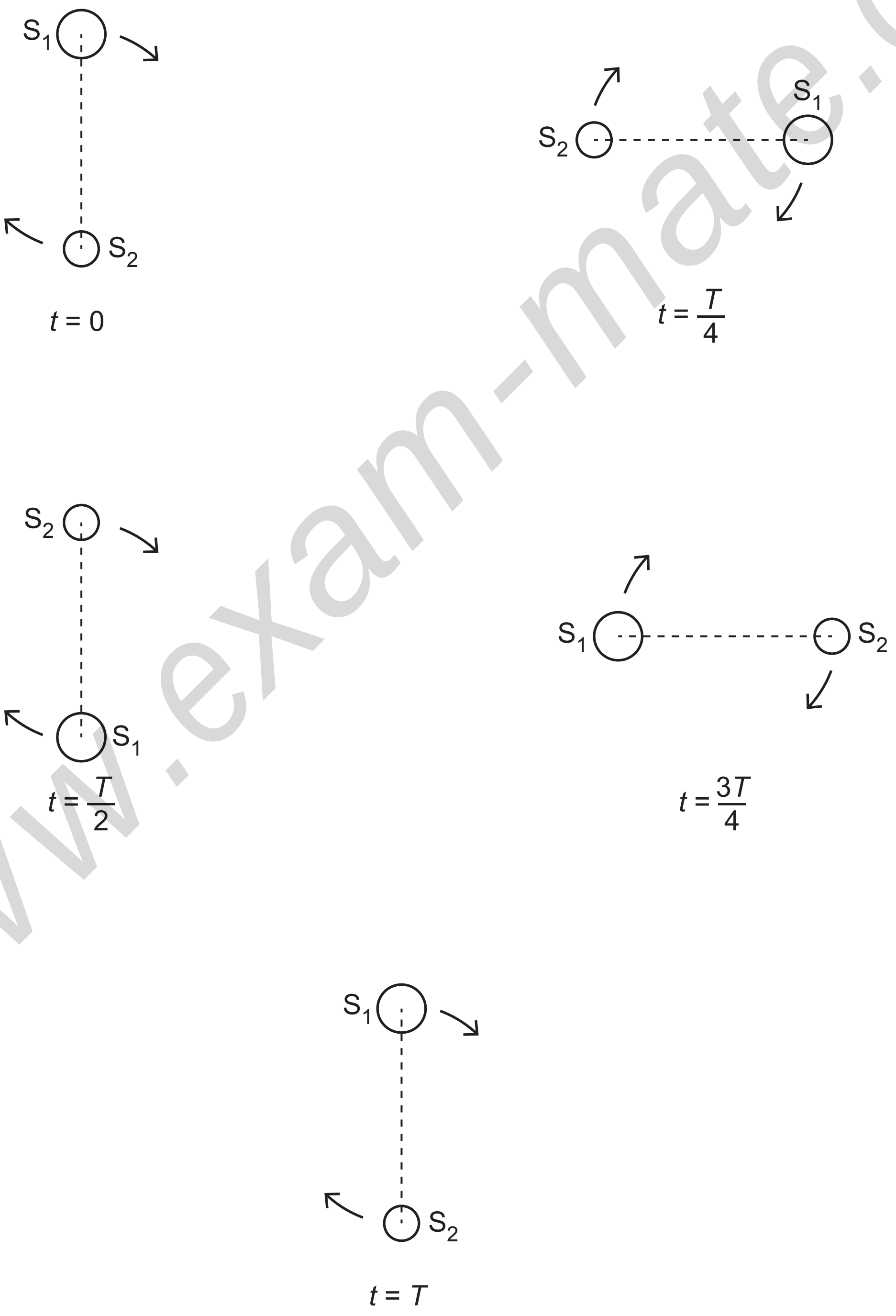

Fig. 1.1 (not to scale)

Observed from Earth, the angular separation of the centres of S_1 and S_2 is 1.2×10^{-5} rad. The distance of the binary star system from Earth is 1.5×10^{17} m.

Show that the separation d of the centres of S_1 and S_2 is 1.8×10^{12} m.

[1]

(c) The stars S_1 and S_2 rotate with the same angular velocity ω about a point P, as illustrated in Fig. 1.2.

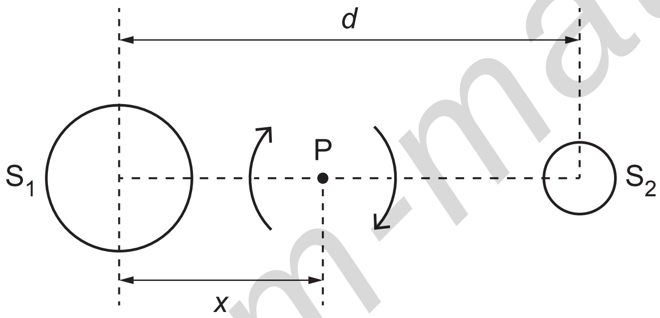

Fig. 1.2 (not to scale)

Point P is at a distance x from the centre of star S_1.
The period of rotation of the stars is 44.2 years.

(i) Calculate the angular velocity ω.

ω = ... rad s^{-1} [2]

(ii) By considering the forces acting on the two stars, show that the ratio of the masses of the stars is given by

$$\frac{\text{mass of S}_1}{\text{mass of S}_2} = \frac{d - x}{x}.$$

[2]

(iii) The mass M_1 of star S_1 is given by the expression

$$GM_1 = d^2 (d - x)\omega^2$$

where G is the gravitational constant.

The ratio in **(ii)** is found to be 1.5.

Use data from **(b)** and your answer in **(c)(i)** to determine the mass M_1.

M_1 = ... kg [3]

[Total: 9]

Question no. 1

(a) Gravitational force [1]

A **gravitational force** is a **force of attraction acting between two masses**. Equivalently, it can be described as **the force experienced by a mass due to the presence of another mass**, or **the force acting on a mass when it is in a gravitational field**.

(b) Separation of the two stars [1]

From Earth, the two stars subtend a **small angular separation** of 1.2×10^{-5} rad at a distance of 1.5×10^{17} m.

For small angles, the **linear separation** d is given by

distance × angle (in radians).

So,
$d = (1.5 \times 10^{17}) \times (1.2 \times 10^{-5})$

d = $\mathbf{1.8 \times 10^{12}}$ **m**

This shows that the separation of the centres of S_1 and S_2 is $\mathbf{1.8 \times 10^{12}}$ **m**, as required.

(c)(i) Angular velocity of the stars [2]

The stars complete one full circular orbit in a period of **44.2 years**.
Angular velocity ω is related to the period T by

$\omega = 2\pi / T$.

First, convert the period into seconds:

44.2 years = 44.2 × 365 × 24 × 3600
$= 1.39 \times 10^{9}$ s (to appropriate significant figures).

Now substitute:

$\omega = 2\pi / (1.39 \times 10^9)$

$\omega \approx$ **4.5×10^{-9} rad s^{-1}**

(c)(ii) Ratio of the masses [2]

The two stars rotate with the **same angular velocity** about point P.
The **gravitational force between the stars is the same on each star** (Newton's third law), and this force provides the **centripetal force** required for circular motion.

For star S_1 (mass M_1), distance from P is x:
centripetal force = $M_1 x \omega^2$

For star S_2 (mass M_2), distance from P is (d − x):
centripetal force = $M_2 (d - x) \omega^2$

Since the gravitational force is the same for both stars:

$M_1 x \omega^2 = M_2 (d - x) \omega^2$

The angular velocity cancels, giving:

$M_1 / M_2 = (d - x) / x$

This shows that the **ratio of the masses** is

mass of S_1 / mass of S_2 = $(d - x) / x$

(c)(iii) Mass of star S_1 [3]

We are told that the ratio of the masses is **1.5**, so:

$(d - x) / x = 1.5$

Rearranging:

$d - x = 1.5x$
$d = 2.5x$
$x = 0.4d$

Using the given expression:

$G M_1 = d^2 (d - x) \omega^2$

Substitute:

- $d = 1.8 \times 10^{12}$ m
- $d - x = 0.6d$
- $\omega = 4.5 \times 10^{-9}$ rad s^{-1}
- $G = 6.67 \times 10^{-11}$ N m^2 kg^{-2}

So,

$6.67 \times 10^{-11} \times M_1$
$= (1.8 \times 10^{12})^2 \times (0.6 \times 1.8 \times 10^{12}) \times (4.5 \times 10^{-9})^2$

Solving gives:

$M_1 \approx$ **1.1×10^{30} kg**

✅ Final Answers Summary

- (a) Gravitational force: **force of attraction between masses**
- (b) Separation d = **1.8×10^{12} m**
- (c)(i) Angular velocity ω = **4.5×10^{-9} rad s^{-1}**
- (c)(ii) Mass ratio = **(d − x) / x**
- (c)(iii) Mass of S_1 = **1.1×10^{30} kg**

2 **(a)** State what is meant by the *internal energy* of a system.

....

....

....

.... [2]

(b) By reference to intermolecular forces, explain why the change in internal energy of an ideal gas is equal to the change in total kinetic energy of its molecules.

....

....

.... [2]

(c) State and explain the change, if any, in the internal energy of a solid metal ball as it falls under gravity in a vacuum.

....

....

....

.... [3]

[Total: 7]

Question no. 2

(a) Internal energy of a system

The **internal energy of a system** is the **total energy associated with the random motion and positions of its particles**. It consists of two main components: the **total kinetic energy of the molecules or atoms due to their random motion**, and the **total potential energy arising from intermolecular forces between these particles**.

Importantly, internal energy does **not** include any macroscopic kinetic energy of the system as a whole or gravitational potential energy due to its position; it depends only on the **microscopic, random behaviour of the particles within the system**.

(b) Ideal gas and internal energy

For an **ideal gas**, it is assumed that there are **no intermolecular forces** between the gas molecules, except during collisions. As a result, the **intermolecular potential energy is zero** and remains constant.

Since there is **no potential energy associated with the separation of molecules**, the internal energy of an ideal gas depends **only on the total kinetic energy of its molecules**. Therefore, **any change in internal energy must be entirely due to a change in the kinetic energy of the molecules**.

Hence, the **change in internal energy of an ideal gas is equal to the change in the total kinetic energy of its molecules**.

(c) Solid metal ball falling under gravity in a vacuum

As a solid metal ball falls freely under gravity in a **vacuum**, its **gravitational potential energy decreases**, and this loss is converted into **macroscopic kinetic energy of the ball as a whole**.

However, there is **no change in the random motion of the atoms within the solid**, so the **random kinetic energy of the atoms does not change**. Additionally, the **interatomic spacing and structure of the solid remain unchanged**, meaning the **potential energy associated with the atomic bonds also remains constant**.

Because the ball falls in a vacuum, there are **no resistive forces**, so **no work is done on the ball that would cause heating**, and there is **no compression or deformation** of the solid. Therefore, **no energy is transferred into or out of the internal energy store**.

As a result, **the internal energy of the solid metal ball does not change** as it falls.

3 The piston in the cylinder of a car engine moves in the cylinder with simple harmonic motion. The piston moves between a position of maximum height in the cylinder to a position of minimum height, as illustrated in Fig. 3.1.

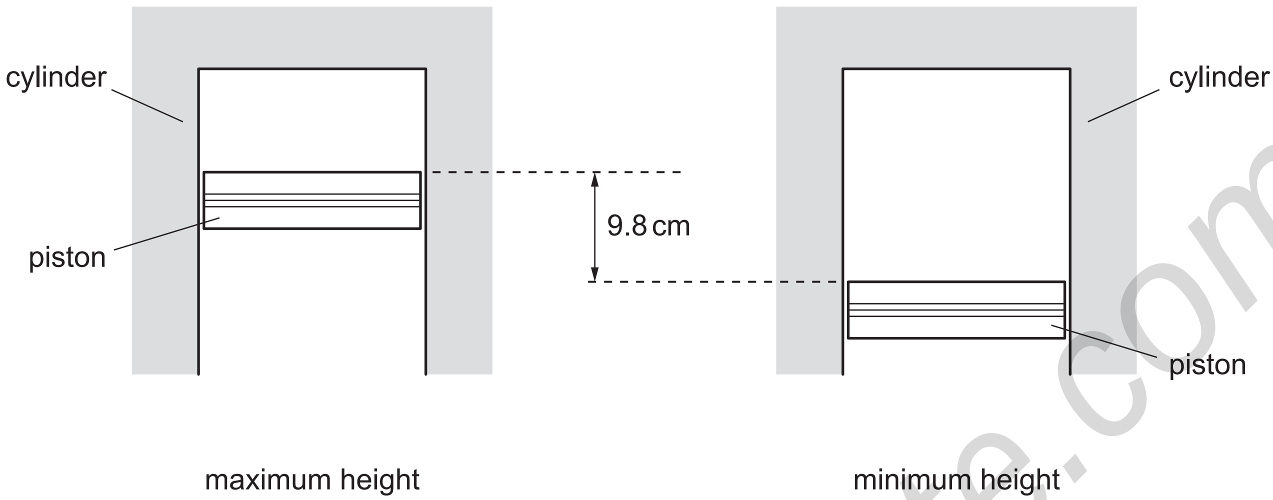

Fig. 3.1

The distance moved by the piston between the positions shown in Fig. 3.1 is 9.8 cm.

The mass of the piston is 640 g.

At one particular speed of the engine, the piston completes 2700 oscillations in 1.0 minute.

(a) For the oscillations of the piston in the cylinder, determine:

(i) the amplitude

amplitude = ... cm [1]

(ii) the frequency

frequency = ... Hz [1]

(iii) the maximum speed

maximum speed = ... $m s^{-1}$ [2]

(iv) the speed when the top of the piston is 2.3 cm below its maximum height.

speed = ... $m s^{-1}$ [2]

(b) The acceleration of the piston varies.

Determine the resultant force on the piston that gives rise to its maximum acceleration.

force = ... N [3]

[Total: 9]

Question no. 3

(a) Motion of the piston

The piston executes **simple harmonic motion (SHM)** between a maximum and a minimum height in the cylinder.

The total distance between these two extreme positions is **9.8 cm**.

(a)(i) Amplitude

The **amplitude** of SHM is defined as the **maximum displacement from the equilibrium (mean) position**.

Since the piston moves symmetrically about the mean position, the total distance between the extreme positions is equal to **twice the amplitude**.

So,
distance between extremes = 2 × amplitude

9.8 cm = 2 × amplitude

amplitude = 9.8 ÷ 2 = **4.9 cm**

Amplitude = 4.9 cm

(a)(ii) Frequency

The piston completes **2700 oscillations in 1.0 minute**.

First convert time into seconds:
1.0 minute = 60 s

Frequency is the **number of oscillations per second**, so

frequency = number of oscillations ÷ time
frequency = 2700 ÷ 60

frequency = **45 Hz**

Frequency = 45 Hz

(a)(iii) Maximum speed

For simple harmonic motion, the **maximum speed** occurs as the piston passes through the **equilibrium position**.

The maximum speed is given by:
maximum speed = angular frequency × amplitude

First convert amplitude to metres:
4.9 cm = 4.9×10^{-2} m

Angular frequency is related to frequency by:
angular frequency = 2π × frequency

So,
angular frequency = 2π × 45

Now calculate the maximum speed:

maximum speed = $(4.9 \times 10^{-2}) \times (2\pi \times 45)$

maximum speed ≈ **14 m s^{-1}**

Maximum speed = 14 m s^{-1}

(a)(iv) Speed when the piston is 2.3 cm below maximum height

At maximum height, the piston is at **maximum displacement**, equal to the amplitude.

Amplitude = 4.9 cm

If the piston is **2.3 cm below the maximum height**, then its displacement from the mean position is:

displacement = 4.9 − 2.3 = **2.6 cm**

Convert to metres:
2.6 cm = 2.6×10^{-2} m

For SHM, the speed at displacement x is given by:
speed = angular frequency × √(amplitude² − displacement²)

Substitute values:

speed = $2\pi \times 45 \times \sqrt{[(4.9 \times 10^{-2})^2 - (2.6 \times 10^{-2})^2]}$

speed ≈ **12 m s^{-1}**

Speed = 12 m s^{-1}

(b) Resultant force giving rise to maximum acceleration

In simple harmonic motion, the **maximum acceleration** occurs at the **maximum displacement** (the extreme positions).

The maximum acceleration is given by:
maximum acceleration = angular frequency² × amplitude

The resultant force on the piston is given by **Newton's second law**:
force = mass × acceleration

Calculations

Mass of piston:
640 g = **0.64 kg**

Angular frequency:
$\omega = 2\pi \times 45$

Amplitude:
$x_0 = 4.9 \times 10^{-2}$ m

So,
maximum acceleration = $x_0 \times \omega^2$

Resultant force:
force = $0.64 \times (4.9 \times (2\pi \times 45)^2)$

force ≈ **2500 N**

Final Answers (as required in the exam)

- **Amplitude = 4.9 cm**
- **Frequency = 45 Hz**
- **Maximum speed = 14 m s^{-1}**
- **Speed at 2.3 cm below maximum height = 12 m s^{-1}**
- **Resultant force for maximum acceleration = 2500 N**

4 **(a)** **(i)** By reference to an ultrasound wave, explain what is meant by *specific acoustic impedance*.

....

....

.... [2]

(ii) An ultrasound wave is incident normally on the boundary between two media. The media have specific acoustic impedances Z_1 and Z_2.

State how the ratio

$$\frac{\text{intensity of ultrasound reflected from boundary}}{\text{intensity of ultrasound incident on boundary}}$$

depends on the relative magnitudes of Z_1 and Z_2.

....

....

....

.... [2]

(b) **(i)** State what is meant by the *attenuation* of an ultrasound wave.

....

.... [1]

(ii) A parallel beam of ultrasound is passing through a medium.
The incident intensity I_0 is reduced to $0.35I_0$ on passing through a thickness of 0.046 m of the medium.

Calculate the linear attenuation coefficient μ of the ultrasound beam in the medium.

μ = ... m^{-1} [2]

[Total: 7]

Question no. 4

(a)(i) Specific acoustic impedance

Specific acoustic impedance of a medium, when referring to an ultrasound wave, is a measure of how much the medium **resists the passage of the ultrasound wave**.

It is defined as the **product of the density of the medium and the speed of ultrasound in that medium**. In other words, it depends on:

- the **density of the medium**, and
- the **speed at which ultrasound travels through the medium**.

This means that different materials have different acoustic impedances because ultrasound travels at different speeds in materials of different densities.

(a)(ii) Reflection of ultrasound at a boundary

The ratio

intensity of ultrasound reflected / intensity of ultrasound incident

depends on how different the specific acoustic impedances **Z_1 and Z_2** of the two media are.

If the **difference between Z_1 and Z_2 is large**, then a **large fraction of the ultrasound is reflected**, so the ratio is **close to 1**.

If **Z_1 and Z_2 are very similar**, meaning the difference between them is small, then **very little ultrasound is reflected**, so the ratio is **close to 0**.

Therefore, the greater the mismatch in acoustic impedance at the boundary, the greater the proportion of ultrasound that is reflected.

(b)(i) Attenuation of an ultrasound wave

Attenuation of an ultrasound wave is the **loss of intensity (or amplitude or power)** of the wave as it travels through a medium.

This reduction occurs due to processes such as absorption and scattering within the medium.

(b)(ii) Linear attenuation coefficient

As the ultrasound travels through the medium, its intensity decreases according to an exponential relationship:

Intensity after distance x = initial intensity × e to the power (−μx)

We are told that:

- the intensity is reduced to **0.35 I_0**,
- the thickness of the medium is **0.046 m**.

Substituting these values gives:

0.35 = e to the power (−μ × 0.046)

Taking natural logarithms of both sides:

ln(0.35) = −0.046μ

Solving for μ:

μ = −ln(0.35) ÷ 0.046

This gives:

μ = 23 m^{-1}

✅ Final Answer:

μ = 23 m^{-1}

5 **(a)** State **one** similarity and **one** difference between the fields of force produced by an isolated point charge and by an isolated point mass.

similarity: ....

....

difference: ....

.... [2]

(b) An isolated solid metal sphere A of radius R has charge $+Q$, as illustrated in Fig. 5.1.

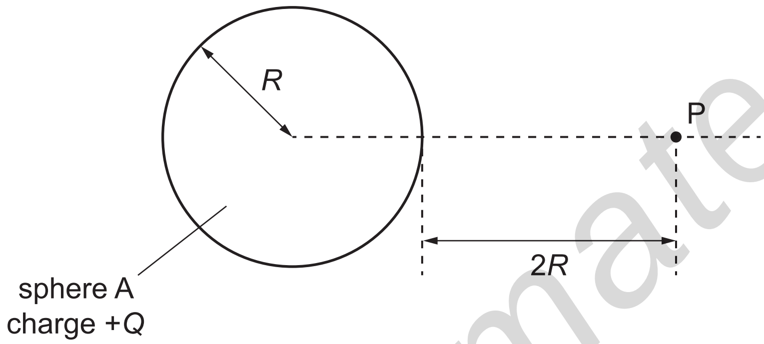

Fig. 5.1

A point P is distance $2R$ from the surface of the sphere.

Determine an expression that includes the terms R and Q for the electric field strength E at point P.

E = ... [2]

(c) A second identical solid metal sphere B is now placed near sphere A. The centres of the spheres are separated by a distance 6R, as shown in Fig. 5.2.

Fig. 5.2

Point P lies midway between spheres A and B.

Sphere B has charge –Q.

Explain why:

(i) the magnitude of the electric field strength at P is given by the sum of the magnitudes of the field strengths due to each sphere

....

.... [1]

(ii) the electric field strength at point P due to the charged metal spheres is not, in practice, equal to 2E, where E is the electric field strength determined in **(b)**.

....

....

.... [2]

[Total: 7]

Question no. 5

(a) Similarity and difference between the fields of force of an isolated point charge and an isolated point mass

Similarity:
The field produced by an isolated point charge and the field produced by an isolated point mass are **both radial fields**. In each case, the field lines are directed along straight lines that radiate symmetrically from (or towards) the point source, and the **magnitude of the field depends only on the distance from the source**. Equivalently, in both cases the field strength **varies with the inverse square of the distance** from the source.

Difference:
The **direction of the gravitational field due to a point mass is always towards the mass**, because gravity is always attractive. In contrast, the **electric field due to a point charge can be either towards or away from the charge**, depending on whether the charge is negative or positive.

(b) Electric field strength at point P due to sphere A

Sphere A is an **isolated conducting sphere**, so for points **outside the sphere**, its electric field is the same as that of a **point charge +Q located at its centre**.

Point P is a distance **2R from the surface of the sphere**, so its distance from the centre of the sphere is:

distance = R + 2R = 3R

The electric field strength due to a point charge Q at a distance x is given by:

field strength = $Q / (4\pi \varepsilon_0 x^2)$

Substituting **x = 3R**:

$$E = Q / (4\pi \varepsilon_0 (3R)^2)$$
$$E = Q / (36\pi \varepsilon_0 R^2)$$

This is the required expression for the electric field strength at P.

(c)(i) Why the magnitude of the electric field strength at P is the sum of the magnitudes of the fields due to each sphere

At point P, the electric field due to **sphere A (positive)** is directed **away from sphere A**, towards the right.
The electric field due to **sphere B (negative)** is directed **towards sphere B**, which is also towards the right.

Therefore, the **electric field vectors at P due to both spheres act in the same direction**. Since electric fields obey the principle of **superposition**, and the fields are in the same direction, the **resultant field magnitude is equal to the sum of the magnitudes of the individual fields**.

(c)(ii) Why the electric field strength at P is not, in practice, equal to 2E

Although each sphere is identical and P is midway between them, the electric field strength at P is **not exactly equal to 2E** because the spheres are **conducting and not point charges**.

When the two charged metal spheres are placed near each other, the **charges on their surfaces redistribute** due to electrostatic attraction between opposite charges. This causes the **charge distribution on each sphere to become distorted**, meaning the charge is no longer symmetrically distributed as it would be for an isolated sphere.

As a result, the electric field produced by each sphere at P is **not the same as the field that would be produced by an isolated sphere**, so the resultant field strength is **not exactly equal to twice the value E calculated in part (b)**.

6 **(a)** The transmission of signals using optic fibres has, to a great extent, replaced the use of coaxial cables.

Advantages of optic fibres include greater bandwidth and very little crosslinking.

(i) Suggest an advantage of greater bandwidth.

....

.... [1]

(ii) State what is meant by *crosslinking*.

....

....

.... [2]

(b) In telecommunications, a signal power of 1.0 mW is used as a reference power.
Signal powers relative to this reference power and expressed in dB are said to be measured in 'dBm'.

Show that a signal power of 13 dBm is equivalent to 20 mW.

[2]

(c) A signal of input power 20 mW is transmitted along an optic fibre for an uninterrupted distance of 45 km.

The optic fibre has an attenuation per unit length of 0.18 dB km^{-1}.

Calculate the output power *P* from the optic fibre.

P = ... mW [2]

[Total: 7]

Question no. 6

(a)(i) Advantage of greater bandwidth

An advantage of **greater bandwidth** is that the system can carry a **larger amount of information per second**.

In practical terms, a higher bandwidth allows **more data to be transmitted simultaneously**, which means **higher data transfer rates**. This enables faster communication and allows services such as high-quality video, audio, and large data files to be transmitted efficiently over optic fibres.

(a)(ii) Meaning of crosslinking

Crosslinking refers to the situation where **power or energy from a signal in one cable is radiated out and then picked up by a neighbouring cable**.

This causes **unwanted interference**, because part of the signal in one wire or fibre induces a signal in an **adjacent wire or fibre**, leading to distortion or corruption of the transmitted information.

(b) Showing that 13 dBm corresponds to 20 mW

Signal power in dBm is measured relative to a **reference power of 1.0 mW**, using the decibel relationship:

ratio in dB = 10 × log (P / Pref)

Here, the reference power Pref is **1.0 mW**, which is **1.0×10^{-3} W**.

Substituting the given value:

13 = 10 × log (P / 1.0 mW)

Dividing both sides by 10:

1.3 = log (P / 1.0 mW)

Taking the antilogarithm:

$P / 1.0\ mW = 10^{1.3} \approx 20$

Hence,

P = 20 mW

This shows that a signal power of **13 dBm is equivalent to 20 mW**.

(c) Output power from the optic fibre

The fibre has an **attenuation per unit length of 0.18 dB km^{-1}**, and the signal travels a distance of **45 km**.

First, calculate the **total attenuation**:

Total attenuation = 45 × 0.18
Total attenuation = **8.1 dB**

Using the decibel relationship for power loss:

attenuation = 10 × log (Pin / Pout)

Substituting the values:

8.1 = 10 × log (20 / P)

Dividing both sides by 10:

0.81 = log (20 / P)

Taking the antilogarithm:

$20 / P = 10^{0.81} \approx 6.46$

Rearranging:

P = 20 / 6.46 ≈ **3.1 mW**

Final Answer

Output power, P = 3.1 mW ✅

7 The output of a microphone is processed using a non-inverting amplifier. The amplifier incorporates an operational amplifier (op-amp).

(a) State, by reference to the input and output signals, the function of a non-inverting amplifier.

....

....

.... [2]

(b) The circuit for the microphone and amplifier is shown in Fig. 7.1.

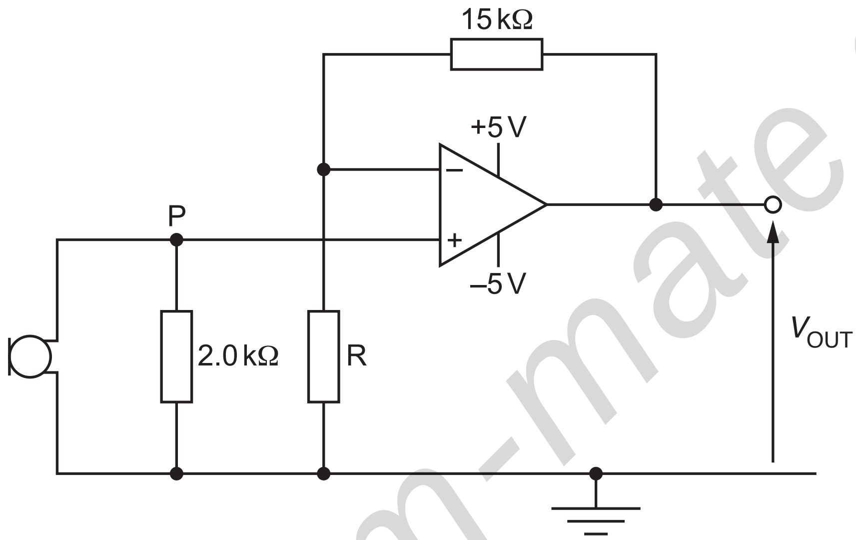

Fig. 7.1

The output potential difference V_{OUT} is 2.6 V when the potential at point P is 84 mV.

Determine:

(i) the gain of the amplifier circuit

gain = ... [1]

(ii) the resistance of resistor R.

resistance = ... Ω [2]

(c) For the circuit of Fig. 7.1:

(i) suggest a suitable device to connect to the output such that the shape of the waveform of the sound received by the microphone may be examined

.... [1]

(ii) state and explain the effect on the output potential difference V_{OUT} of increasing the resistance of resistor R.

....

....

.... [2]

[Total: 8]

Question no. 7

(a) Function of a non-inverting amplifier

A **non-inverting amplifier** produces an **output signal that is proportional to the input signal**, meaning that the output voltage increases linearly as the input voltage increases.

Crucially, the **output signal has the same sign (polarity) as the input signal**. This means that when the input voltage is positive, the output voltage is also positive, and when the input voltage is negative, the output voltage is negative. There is **no phase reversal** between the input and output signals.

(b) Microphone and amplifier circuit

(i) Gain of the amplifier circuit

The **voltage gain** of an amplifier is defined as the ratio of the output voltage to the input voltage:

Gain = output voltage ÷ input voltage

From the question:

- Output voltage, VOUT = **2.6 V**
- Input voltage at point P, VIN = **84 mV = 0.084 V**

So,

Gain = 2.6 ÷ 0.084
Gain ≈ **31**

Gain of the amplifier = 31

(ii) Resistance of resistor R

For a **non-inverting operational amplifier**, the voltage gain is given by:

Gain = 1 + (feedback resistance ÷ resistance to ground)

From the circuit:

- Feedback resistor = **15 kΩ**
- Resistor to ground = **R**

Substituting the known gain:

31 = 1 + (15 000 ÷ R)

Subtract 1 from both sides:

30 = 15 000 ÷ R

Rearranging:

R = 15 000 ÷ 30
R = **500 Ω**

Resistance of resistor R = 500 Ω

(c) Further considerations for the circuit

(i) Suitable device to examine the waveform

To examine the **shape of the waveform** of the sound signal at the output, a suitable device is a:

Cathode-ray oscilloscope (CRO)

An oscilloscope allows the voltage to be displayed against time, making it possible to observe the waveform shape, frequency, and amplitude of the sound signal.

(ii) Effect of increasing the resistance of resistor R

From the gain expression for a non-inverting amplifier:

Gain = 1 + (15 000 ÷ R)

If the resistance **R is increased**, the fraction (15 000 ÷ R) becomes smaller.

As a result:

- The **gain of the amplifier is reduced**
- Therefore, for the same input signal, the **output voltage VOUT becomes smaller**

So increasing R reduces the gain, causing a smaller output voltage.

8 **(a)** Define the *tesla*.

....

....

....

.... [3]

(b) A magnet produces a uniform magnetic field of flux density B in the space between its poles.

A rigid copper wire carrying a current is balanced on a pivot. Part PQLM of the wire is between the poles of the magnet, as illustrated in Fig. 8.1.

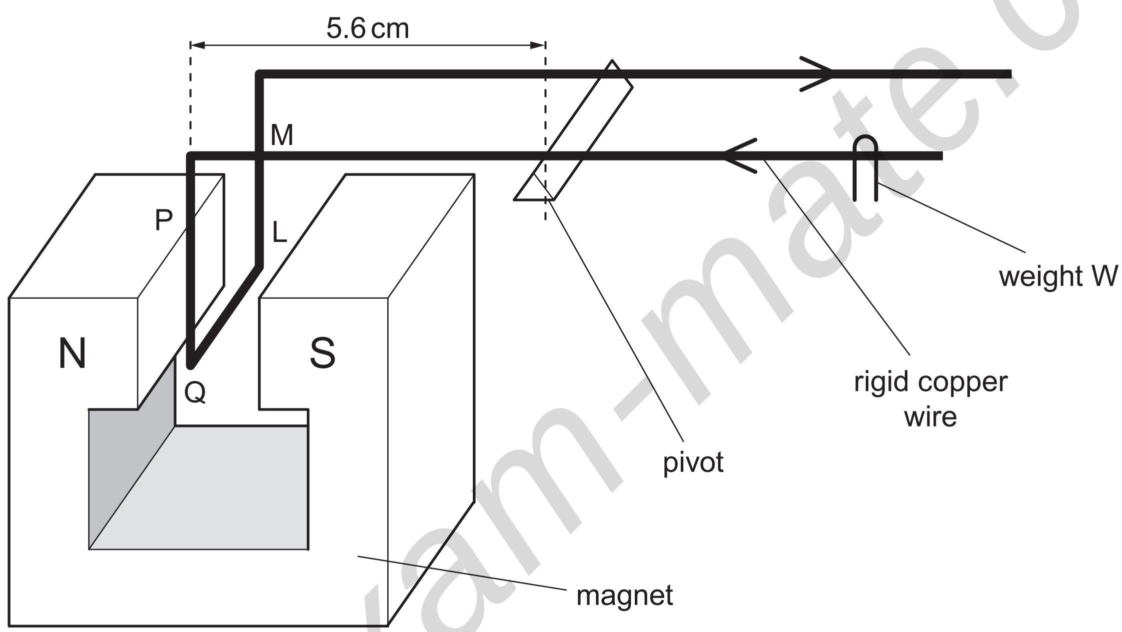

Fig. 8.1 (not to scale)

The wire is balanced horizontally by means of a small weight W.

The section of the wire between the poles of the magnet is shown in Fig. 8.2.

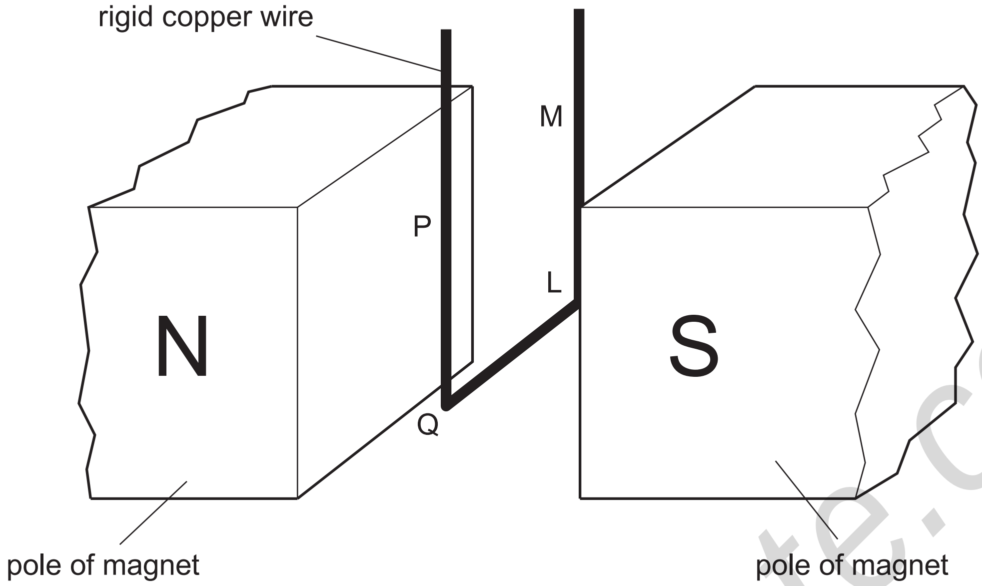

Fig. 8.2 (not to scale)

Explain why:

(i) section QL of the wire gives rise to a moment about the pivot

....

....

....

.... [3]

(ii) sections PQ and LM of the wire do not affect the equilibrium of the wire.

....

....

....

.... [2]

(c) Section QL of the wire has length 0.85 cm.

The perpendicular distance of QL from the pivot is 5.6 cm.

When the current in the wire is changed by 1.2 A, W is moved a distance of 2.6 cm along the wire in order to restore equilibrium. The mass of W is 1.3×10^{-4} kg.

(i) Show that the change in moment of W about the pivot is 3.3×10^{-5} N m.

[2]

(ii) Use the information in **(i)** to determine the magnetic flux density *B* between the poles of the magnet.

B = ... T [3]

[Total: 13]

Question no. 8

(a) Define the tesla.

The **tesla** is the SI unit of magnetic flux density.

It is defined as the magnetic flux density of a magnetic field which produces a **force of 1 newton per metre** on a straight conductor carrying a **current of 1 ampere**, when the **conductor is perpendicular to the magnetic field**.

Equivalently, **1 tesla = 1 newton per ampere per metre**, for a wire placed **normal to the field**.

(b)(i) Explain why section QL of the wire gives rise to a moment about the pivot.

The section **QL carries an electric current** and lies **perpendicular to the magnetic field** between the poles of the magnet. As a result, the magnetic field exerts a **force on the current-carrying wire**.

This magnetic force acts in a **vertical direction**, as determined by Fleming's left-hand rule. Importantly, the line of action of this force **does not pass through the pivot**.

Since a force acts at a perpendicular distance from the pivot, it produces a **turning effect (moment)** about the pivot. Therefore, section **QL gives rise to a moment** about the pivot.

(b)(ii) Explain why sections PQ and LM of the wire do not affect the equilibrium of the wire.

In sections **PQ and LM**, the magnetic forces act **along the same horizontal line**, or equivalently the forces are **horizontal**.

These forces are **equal in magnitude and opposite in direction**, so they cancel each other out. Because their lines of action coincide, they produce **no resultant moment about the pivot**.

Hence, sections **PQ and LM do not affect the equilibrium** of the wire.

(c)(i) Show that the change in moment of W about the pivot is

3.3×10^{-5} N m

The change in moment is given by:

change in moment = weight × change in perpendicular distance

The weight of W is
mass × g = $1.3 \times 10^{-4} \times 9.81$ N

The weight is moved a distance of **2.6 cm**, which is **2.6×10^{-2} m**.

So the change in moment is:

$1.3 \times 10^{-4} \times 9.81 \times 2.6 \times 10^{-2}$

= **3.3×10^{-5} N m**

This confirms the required value.

(c)(ii) Determine the magnetic flux density B between the poles of the magnet.

The change in moment produced by the magnetic force on section QL is equal to:

magnetic force × perpendicular distance from the pivot

The magnetic force on a straight current-carrying conductor is proportional to:

B × current × length of conductor

Here:

- Change in current = **1.2 A**
- Length of QL = **0.85 cm = 0.85 × 10^{-2} m**
- Perpendicular distance from pivot = **5.6 cm = 5.6 × 10^{-2} m**

So,

change in moment = $B \times 1.2 \times 0.85 \times 10^{-2} \times 5.6 \times 10^{-2}$

Using the value from part (i):

$3.3 \times 10^{-5} = B \times 1.2 \times 0.85 \times 10^{-2} \times 5.6 \times 10^{-2}$

Solving gives:

B = 0.058 T

✅ Final Answer

Magnetic flux density, B = 0.058 T

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9 **(a)** A coil of wire is situated in a uniform magnetic field of flux density *B*.
The coil has diameter 3.6 cm and consists of 350 turns of wire, as illustrated in Fig. 9.1.

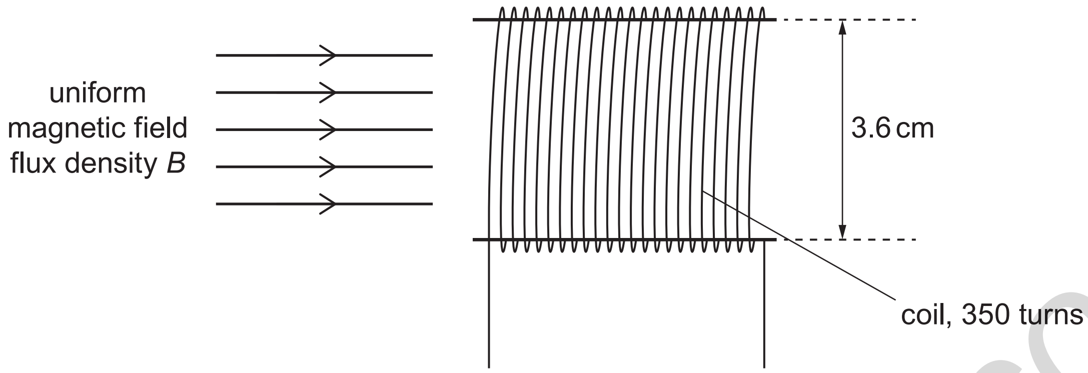

Fig. 9.1

The variation with time t of B is shown in Fig. 9.2.

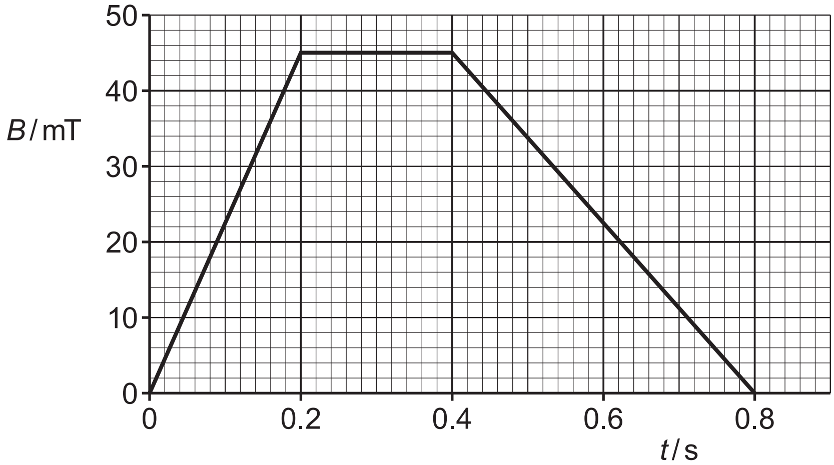

Fig. 9.2

(i) Show that, for the time $t = 0$ to time $t = 0.20$ s, the electromotive force (e.m.f.) induced in the coil is 0.080 V.

[2]

(ii) On the axes of Fig. 9.3, show the variation with time t of the induced e.m.f. E for time $t = 0$ to time $t = 0.80$ s.

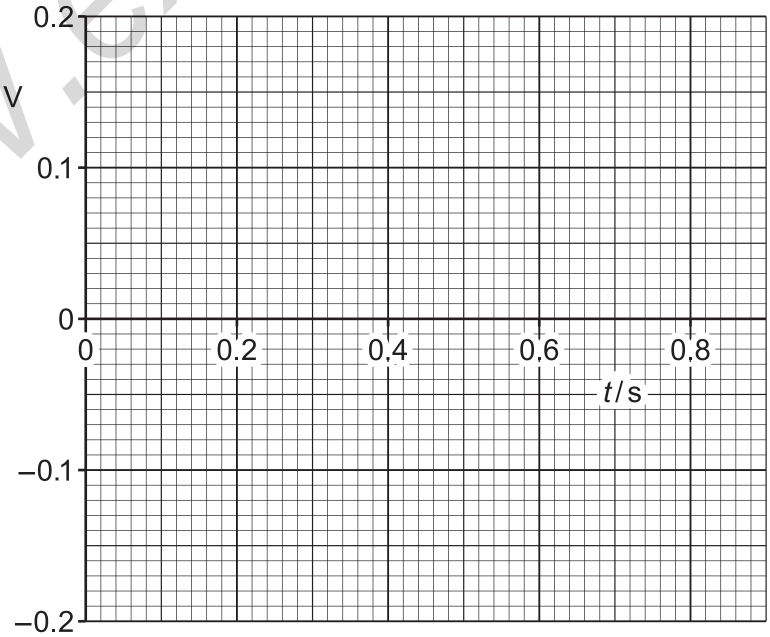

Fig. 9.3

[4]

(b) A bar magnet is held a small distance above the surface of an aluminium disc by means of a rod, as illustrated in Fig. 9.4.

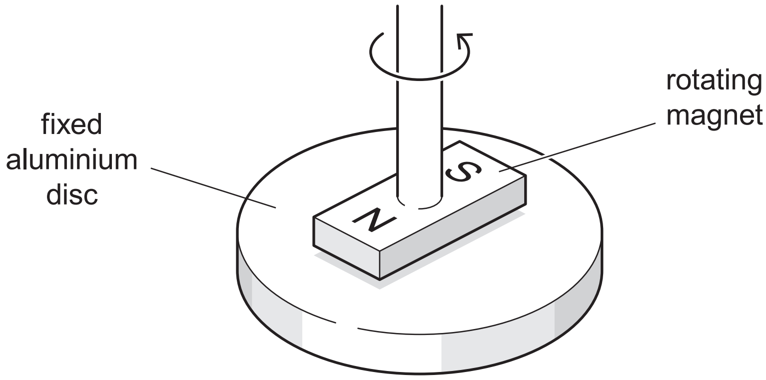

Fig. 9.4

The aluminium disc is supported horizontally and held stationary.

The magnet is rotated about a vertical axis at constant speed.

Use laws of electromagnetic induction to explain why there is a torque acting on the aluminium disc.

....

....

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....

.... [4]

[Total: 10]

Question no. 9

(a)(i) Showing that the induced e.m.f. is 0.080 V for $0 \le t \le 0.20$ s

The coil is placed in a **uniform magnetic field**, so the magnetic flux through **each turn** is given by

magnetic flux = magnetic flux density × area of the coil.

Since the field is perpendicular to the plane of the coil, the full area contributes.

The **diameter of the coil is 3.6 cm**, so the radius is:

radius = 1.8 cm = 1.8×10^{-2} m

The area of one turn of the coil is therefore:

$A = \pi r^2 = \pi(1.8 \times 10^{-2})^2$ m^2

From the graph of magnetic flux density against time, between **t = 0 and t = 0.20 s**, the magnetic flux density increases **uniformly** from **0 to 45 mT**, so:

change in magnetic flux density, $\Delta B = 45 \times 10^{-3}$ T

The coil has **350 turns**, so the total change in flux linkage is:

$\Delta(N\Phi) = N \times A \times \Delta B$

Using **Faraday's law of electromagnetic induction**, the magnitude of the induced e.m.f. is:

e.m.f. = change in flux linkage ÷ time taken

Substituting the values:

- $N = 350$
- $A = \pi(1.8 \times 10^{-2})^2$
- $\Delta B = 45 \times 10^{-3}$ T
- $\Delta t = 0.20$ s

This gives:

e.m.f. = $(45 \times 10^{-3} \times \pi \times (1.8 \times 10^{-2})^2 \times 350) \div 0.20$

Evaluating this expression gives:

e.m.f. = 0.080 V

Hence, the induced electromotive force in the coil between **0 and 0.20 s** is **0.080 V**, as required.

(a)(ii) Variation of induced e.m.f. with time from 0 to 0.80 s

The induced e.m.f. depends on the **rate of change of magnetic flux**, not on the flux itself.

From 0 to 0.20 s

- Magnetic flux density increases **linearly**
- Rate of change of flux is **constant**
- Therefore, the induced e.m.f. is **constant**

So, the graph shows a **straight horizontal line** at:

+0.080 V or −0.080 V
(either polarity is acceptable, depending on chosen direction)

From 0.20 s to 0.40 s

- Magnetic flux density is **constant**
- There is **no change in flux**
- Therefore, **no e.m.f. is induced**

So, the graph lies **along the time axis at E = 0 V**.

From 0.40 s to 0.80 s

- Magnetic flux density decreases **linearly**
- Rate of change of flux is **constant but smaller than before**
- The time interval is **twice as long**, so the gradient is **half as steep**

Hence, the magnitude of the induced e.m.f. is **half of 0.080 V**, which is:

0.040 V

Because the flux is now **decreasing**, the induced e.m.f. has **opposite polarity** to that from 0 to 0.20 s.

So, the graph shows a **straight horizontal line** at:

−0.040 V or +0.040 V,
with **opposite sign** to the first section.

Summary of the graph (what must be drawn on Fig. 9.3)

- **0 to 0.20 s**: horizontal line at **±0.080 V**
- **0.20 to 0.40 s**: line at **0 V**
- **0.40 to 0.80 s**: horizontal line at **∓0.040 V** (opposite polarity)

This completes the correct e.m.f.–time graph.

(b) Explanation of why there is a torque acting on the aluminium disc

As the **magnet rotates**, the magnetic field pattern above the aluminium disc **changes with time**. This means that parts of the disc are **cutting magnetic field lines**, or equivalently, the magnetic flux through the disc is **continually changing**.

According to **Faraday's law of electromagnetic induction**, a **changing magnetic flux induces an e.m.f.** in a conductor. Since the aluminium disc is a continuous conductor, this induced e.m.f. causes **eddy currents** to flow within the disc.

These eddy currents flow in the presence of the **magnetic field produced by the magnet**. A current-carrying conductor in a magnetic field experiences a **magnetic force**.

The forces acting on different parts of the disc produce a **turning effect**, resulting in a **torque** on the aluminium disc. The direction of this torque is such that it tends to **oppose the relative motion** between the magnet and the disc, in accordance with **Lenz's law**.

Thus, the rotating magnet induces currents in the aluminium disc, and the interaction between these currents and the magnetic field produces a **torque on the disc**.

10 (a) White light passes through a cloud of cool low-pressure gas, as illustrated in Fig. 10.1.

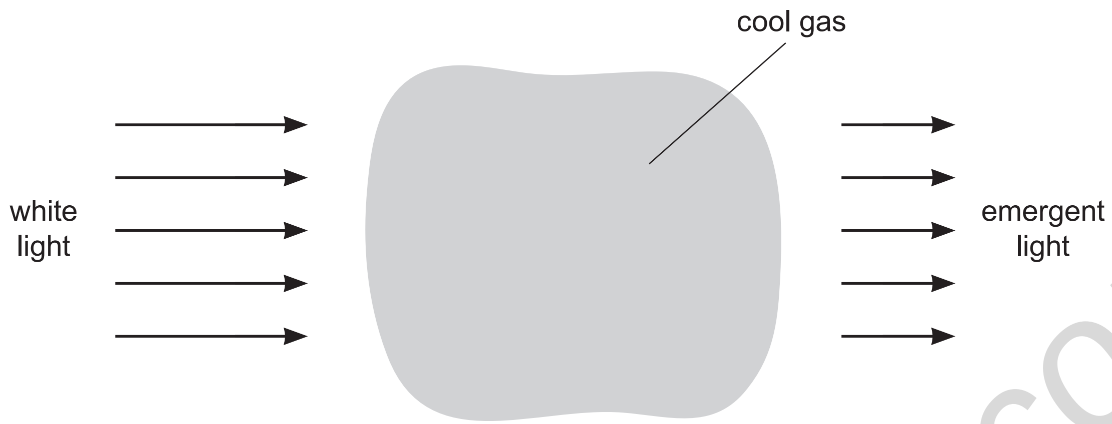

Fig. 10.1

For light that has passed through the gas, its continuous spectrum is seen to contain a number of darker lines.

Use the concept of discrete electron energy levels to explain the existence of these darker lines.

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.... [4]

(b) The uppermost electron energy bands in a solid are illustrated in Fig. 10.2.

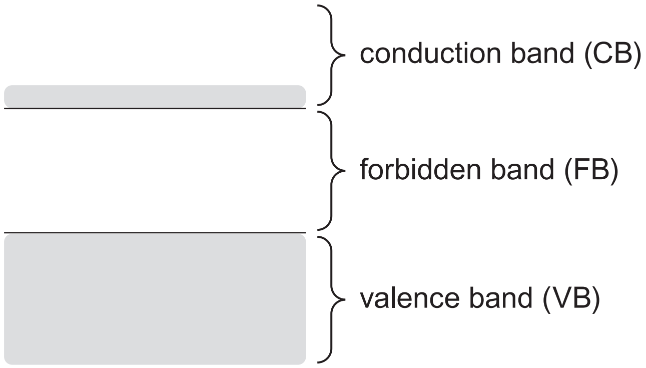

Fig. 10.2

Use band theory to explain the dependence on light intensity of the resistance of a light-dependent resistor (LDR).

....

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....

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....

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.... [5]

[Total: 9]

Question no. 10

(a) Explanation of the dark lines in the spectrum (absorption lines)

When **white light passes through a cool, low-pressure gas**, the atoms of the gas contain electrons that can only exist at **discrete (quantised) energy levels**.

As the white light travels through the gas, **photons of certain specific energies are absorbed by electrons** in the atoms of the gas. In particular, an **electron in a lower (inner) energy level absorbs a photon** whose energy exactly matches the **difference between two allowed energy levels**. This absorbed energy causes the electron to **move from a lower energy level to a higher energy level**.

Because electron energy levels are discrete, **only photons with very specific energies can be absorbed**. These energies correspond to particular wavelengths within the continuous spectrum of white light.

After a short time, the excited electron **de-excites back to a lower energy level**, emitting a photon of **the same energy** as the one originally absorbed. However, these emitted photons are released **in all directions**, not necessarily in the original direction of the light beam.

As a result, **photons of those specific energies are missing from the transmitted light** in the forward direction. This produces **dark absorption lines** at particular wavelengths within the otherwise continuous spectrum.

(b) Explanation of how the resistance of an LDR depends on light intensity (using band theory)

In a light-dependent resistor (LDR), electrons normally occupy the **valence band (VB)**, while the **conduction band (CB)** is separated from it by a **forbidden band (band gap)**.

When light falls on the LDR, **photons transfer energy to electrons in the valence band**, or equivalently, **electrons in the valence band absorb photons**. If the photon energy is sufficient, the electron gains enough energy to **cross the forbidden band and move into the conduction band**.

When an electron moves into the conduction band, it leaves behind a **positive hole in the valence band**. Both the **free electron in the conduction band** and the **hole in the valence band** act as **charge carriers**.

At **low light intensity**, there are relatively **few photons**, so only a **small number of electrons are promoted to the conduction band**. Most electrons remain in the valence band, meaning there are **few charge carriers**, and the resistance is **high**.

At **high light intensity**, there are **more photons incident on the LDR**, so **more electrons are excited into the conduction band**. This creates **more electron–hole pairs**, increasing the number of charge carriers available to conduct current.

Since **an increase in charge carriers leads to increased conductivity**, the **resistance of the LDR decreases as light intensity increases**.

11 An electron, at rest, has mass m_e and charge $-q$.

A positron is a particle that, at rest, has mass m_e and charge $+q$.

A positron interacts with an electron. The electron and the positron may be considered to be at rest.
The outcome of this interaction is that the electron and the positron become two gamma-ray (γ-ray) photons, each having the same energy.

(a) Calculate, for one of the γ-ray photons:

(i) the photon energy, in J

energy = ... J [2]

(ii) its momentum.

momentum = ... N s [2]

(b) State and explain the direction, relative to each other, in which the γ-ray photons are emitted.

....

....

....

.... [2]

[Total: 6]

Question no. 11

(a)(i) Photon energy

When an electron and a positron annihilate **at rest**, there is **no kinetic energy** before the interaction.
Therefore, **all of the energy of the photons comes from the rest-mass energy** of the particles.

The rest-mass energy of **one** electron (or positron) is given by Einstein's equation:

$\mathbf{E = mc^2}$

For an electron:

- mass $m_e = 9.11 \times 10^{-31}$ kg
- speed of light $c = 3.0 \times 10^{8}$ m s^{-1}

So the rest-mass energy of one particle is:

$E = 9.11 \times 10^{-31} \times (3.0 \times 10^{8})^2$
$E = 8.2 \times 10^{-14}$ J

Since **two identical γ-ray photons are produced** and they share the total energy equally, the energy of **one** γ-ray photon is:

energy = 8.2×10^{-14} J

(a)(ii) Momentum of one γ-ray photon

A γ-ray photon is a photon, so it has **no rest mass**. Its energy and momentum are related by:

$\mathbf{E = pc}$

Rearranging:

$\mathbf{p = E / c}$

Substituting the photon energy found in part (a)(i):

$p = (8.2 \times 10^{-14}) / (3.0 \times 10^{8})$
$p = 2.7 \times 10^{-22}$ N s

momentum = 2.7×10^{-22} N s

(b) Direction of emission of the γ-ray photons

Before the interaction, the electron and the positron are **both at rest**, so the **total momentum of the system is zero**.

Momentum must be conserved in all interactions.
Therefore, after annihilation, the **total momentum of the two photons must also be zero**.

Since each photon has the **same momentum magnitude**, their momenta must be **equal and opposite** in order to cancel out.

Hence, the two γ-ray photons are emitted:

in opposite directions

12 **(a)** The decay of a sample of a radioactive isotope is said to be random and spontaneous.

Explain what is meant by the decay being:

(i) *random*

....

.... [1]

(ii) *spontaneous*.

....

.... [1]

(b) A radioactive isotope X has a half-life of 1.4 hours.

Initially, a pure sample of this isotope X has an activity of 3.6×10^5 Bq.

Determine the activity of the isotope X in the sample after a time of 2.0 hours.

activity = ... Bq [3]

(c) The variation with time t of the actual activity A of the sample in **(b)** is shown in Fig. 12.1.

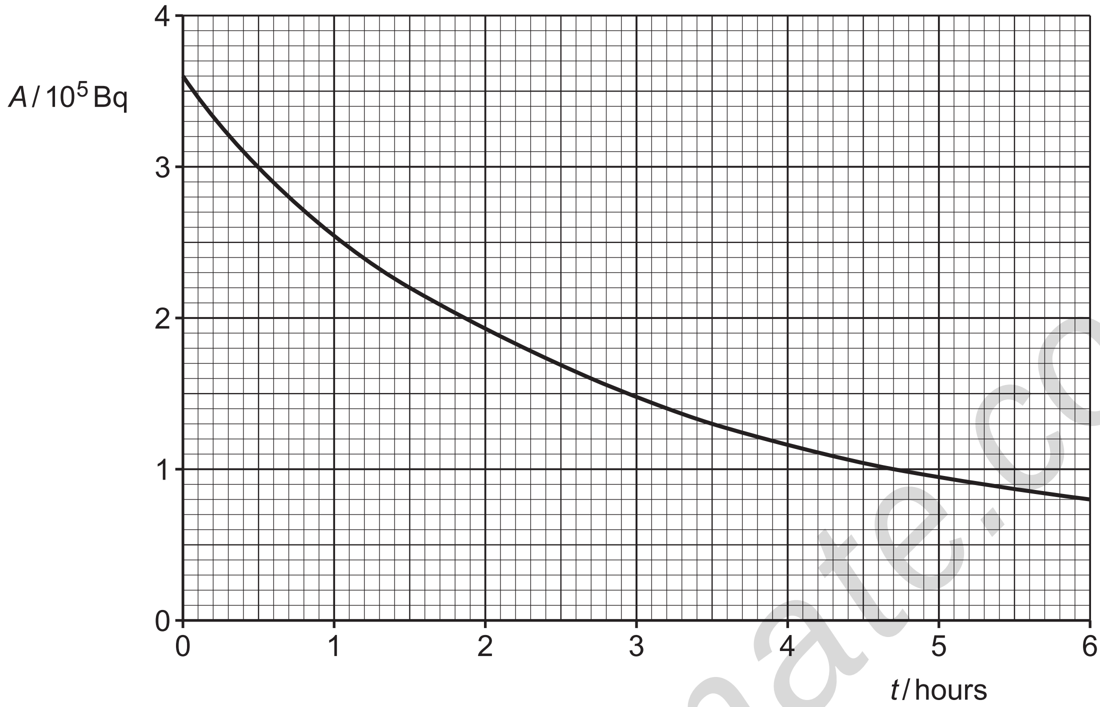

Fig. 12.1

(i) The initial activity of isotope X in the sample is 3.6×10^5 Bq.

Use information from **(b)** to sketch, on the axes of Fig. 12.1, the variation with time t of the activity of a pure sample of isotope X. [1]

(ii) Suggest an explanation for any difference between the actual activity of the sample shown in Fig. 12.1 and the curve you have drawn for the activity of isotope X.

....

....

.... [2]

[Total: 8]

Question no. 12

(a) Meaning of radioactive decay being random and spontaneous

(i) Random

Radioactive decay is described as **random** because it is **impossible to predict exactly when a particular nucleus will decay**. Even if two identical nuclei are observed under identical conditions, one may decay while the other does not. Each nucleus has a **constant probability of decaying per unit time**, but the exact moment of decay for an individual nucleus is unpredictable.

(ii) Spontaneous

Radioactive decay is **spontaneous** because it occurs **without any external trigger**. The decay of a nucleus is **not affected by environmental factors** such as temperature, pressure, chemical state, or electric and magnetic fields. The nucleus decays entirely due to internal nuclear processes.

(b) Determining the activity after 2.0 hours

The activity of a radioactive sample decreases exponentially with time. The decay constant depends on the half-life of the isotope.

The half-life of isotope X is **1.4 hours**, and the initial activity is **3.6×10^5 Bq**.

The number of half-lives elapsed in 2.0 hours is:

Number of half-lives
= 2.0 ÷ 1.4
≈ 1.43

Each half-life reduces the activity by a factor of 0.5, so the activity after time t is:

Activity = initial activity × (0.5)^(number of half-lives)

Activity
= $3.6 \times 10^5 \times (0.5)$^(2.0 / 1.4)
≈ $3.6 \times 10^5 \times 0.37$
≈ **1.3×10^5 Bq**

Activity after 2.0 hours = 1.3×10^5 Bq

(c)(i) Sketching the activity–time graph for isotope X

Using the information from part (b):

- At **t = 0**, the activity is **3.6×10^5 Bq**
- At **t = 1.4 hours** (one half-life), the activity is **1.8×10^5 Bq**
- At **t = 2.0 hours**, the activity is **1.3×10^5 Bq**

The required sketch is a **smooth exponential decay curve** that:

- Starts at **(0, 3.6×10^5)**
- Passes through **(1.4, 1.8×10^5)**
- Passes through **(2.0, 1.3×10^5)**
- Continues decreasing smoothly with time

This curve represents the decay of a **pure sample of isotope X only**.

(c)(ii) Explanation for the difference between the two curves

The curve shown in Fig. 12.1 lies **above** the curve for the pure isotope X. This means that the **actual activity of the sample is greater than the activity expected from isotope X alone**.

This indicates that there must be an **additional source of activity** in the sample. The most likely explanation is that the **decay product of isotope X is itself radioactive**, so its decay contributes additional activity to the total measured activity.

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