



Oxford Cambridge and RSA

Tuesday 17 June 2025 – 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 page 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 using 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.

- 1 The Earth's aurora is an atmospheric effect visible in the polar regions.

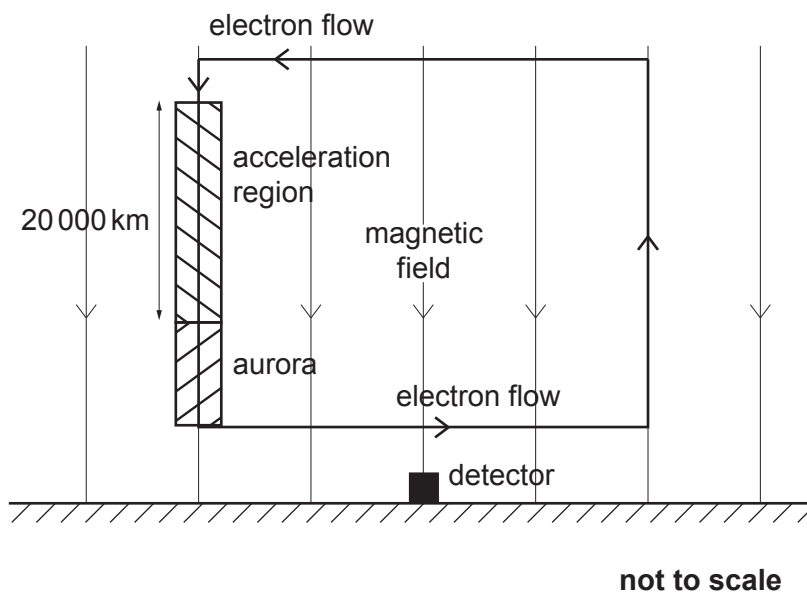
Electrons in the upper atmosphere initially move vertically downwards along one of the Earth's **magnetic** field lines. They are accelerated by an **electric** field.

These electrons collide with oxygen atoms causing atomic electrons to be excited to higher energy levels. The atomic electrons then return to lower energy levels, releasing photons of green light, red light and ultraviolet.

The accelerated electrons then travel horizontally through the atmosphere, before travelling vertically along a different magnetic field line, and then completing the circuit by travelling horizontally back to their starting point.

The situation is shown in **Fig. 1.1**.

Fig. 1.1



- (a) The accelerated electrons are accelerated by electric fields parallel to the magnetic field lines.

The length of the acceleration region is 20 000 km and the electric field value is 0.2 mV/m. The electric field can be assumed to be uniform.

- (i) Calculate the kinetic energy gained by the electrons as they pass through the electric field, in joules.

$$V = Ed = 0.2 \times 10^{-3} \times 20\,000 \times 10^3 = 4000 \text{ V}$$

$$W = QV = 1.60 \times 10^{-19} \times 4000$$

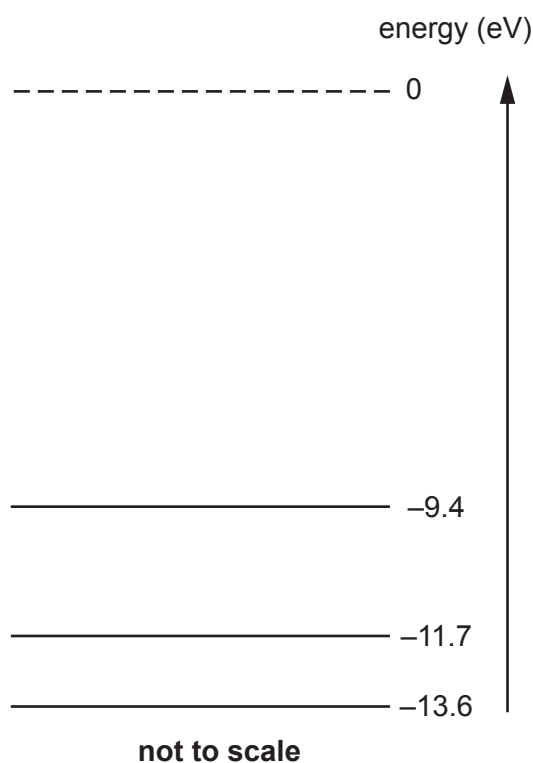
$$\text{kinetic energy} = \dots\dots\dots 6.4 \times 10^{-16} \dots\dots\dots \text{J [3]}$$

- (ii) State and explain the direction of the electric field required to accelerate the electrons **downwards**.

*Electrons are negatively charged, so the force on them is in the opposite direction to the electric field (the field is the direction of force on a positive charge).
To accelerate the electrons downwards, the electric field must be upwards.*

[2]

- (b) A simplified energy level diagram for atomic oxygen is shown below.



Determine the wavelength of the green light emitted.

Fully justify your answer.

Red, green and UV: green has the middle wavelength, so it has the middle photon energy, so it comes from the middle-sized transition, -9.4 to -11.7:

$$\Delta E = 11.7 - 9.4 = 2.3 \text{ eV} = 2.3 \times 1.60 \times 10^{-19} = 3.68 \times 10^{-19} \text{ J}$$

$$\lambda = hc \div \Delta E = (6.63 \times 10^{-34} \times 3.00 \times 10^8) \div (2.3 \times 1.60 \times 10^{-19})$$

$$\lambda = 5.4 \times 10^{-7} \text{ m} \quad (\text{UV: } 4.2 \text{ eV, } 296 \text{ nm; red: } 1.9 \text{ eV, } 654 \text{ nm})$$

wavelength = ... 5.4×10^{-7} m [4]

- (c) The horizontal current closest to the Earth produces a magnetic field which can be detected at ground level.

With reference to **Fig. 1.1**, state and explain the direction of this magnetic field.

*The electrons flow to the right, so the conventional current is from right to left
(opposite to the electron flow).
By the right-hand grip rule, below this current at the detector the magnetic field
is out of the page.* [2]

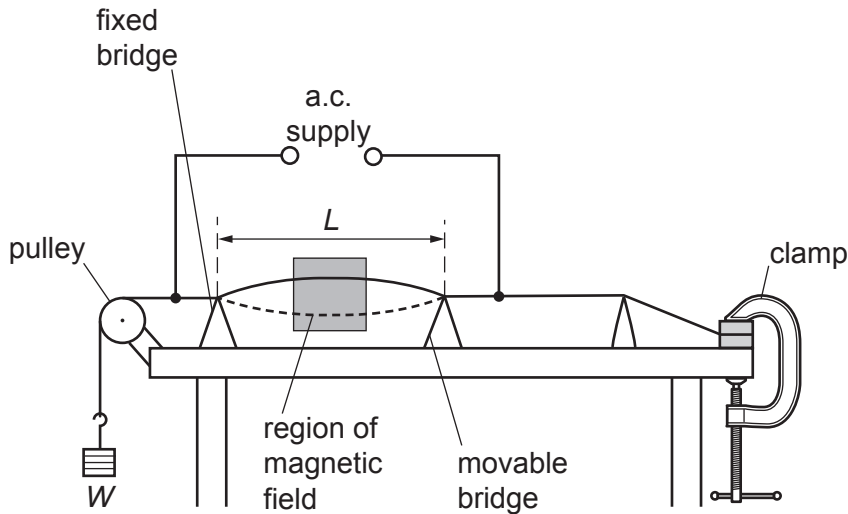
- (d) Suggest **two** ways that the horizontal current may affect the atmosphere.

- 1 *Heating effect: the current heats the atmosphere (gas).*
 - 2 *Ionisation of atoms (gas) in the atmosphere, e.g. lightning strikes.*
- [2]

5
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- 2 A student carries out an experiment to measure the frequency, f , of the mains electricity supply, using the apparatus shown in the diagram.



The wire passes between the poles of a magnet. It is held in tension by the weight W of the mass hanger. The fixed bridge and the movable bridge are separated by distance L .

Mains frequency current is passed through the wire. The student adjusts the movable bridge until the wire vibrates at its fundamental frequency. The weight W and the length L are recorded. This is repeated for several different weights.

- (a) Explain how a stationary wave is formed on the wire.

The alternating current in the wire in the magnetic field produces an oscillating force on the wire ($F = BIL$).

This produces waves travelling in opposite directions along the wire (reflected at the bridges) which superpose (interfere) to form nodes and antinodes. [2]

- (b) It can be shown that the fundamental frequency f_0 of a wire of length L under tension W is given by the equation

$$f_0 = \frac{1}{2L} \sqrt{\frac{W}{\mu}}$$

where μ is the mass per unit length of the wire, and has a value of $8.0 \times 10^{-4} \text{ kg m}^{-1} \pm 2\%$.

- (i) Suggest why the magnetic flux density, B , of the magnet does not appear in this equation.

B only affects the size of the force on the wire, so only the amplitude of the stationary wave. [1]

- (ii) Suggest a method to determine the mass per unit length, μ , of the wire.

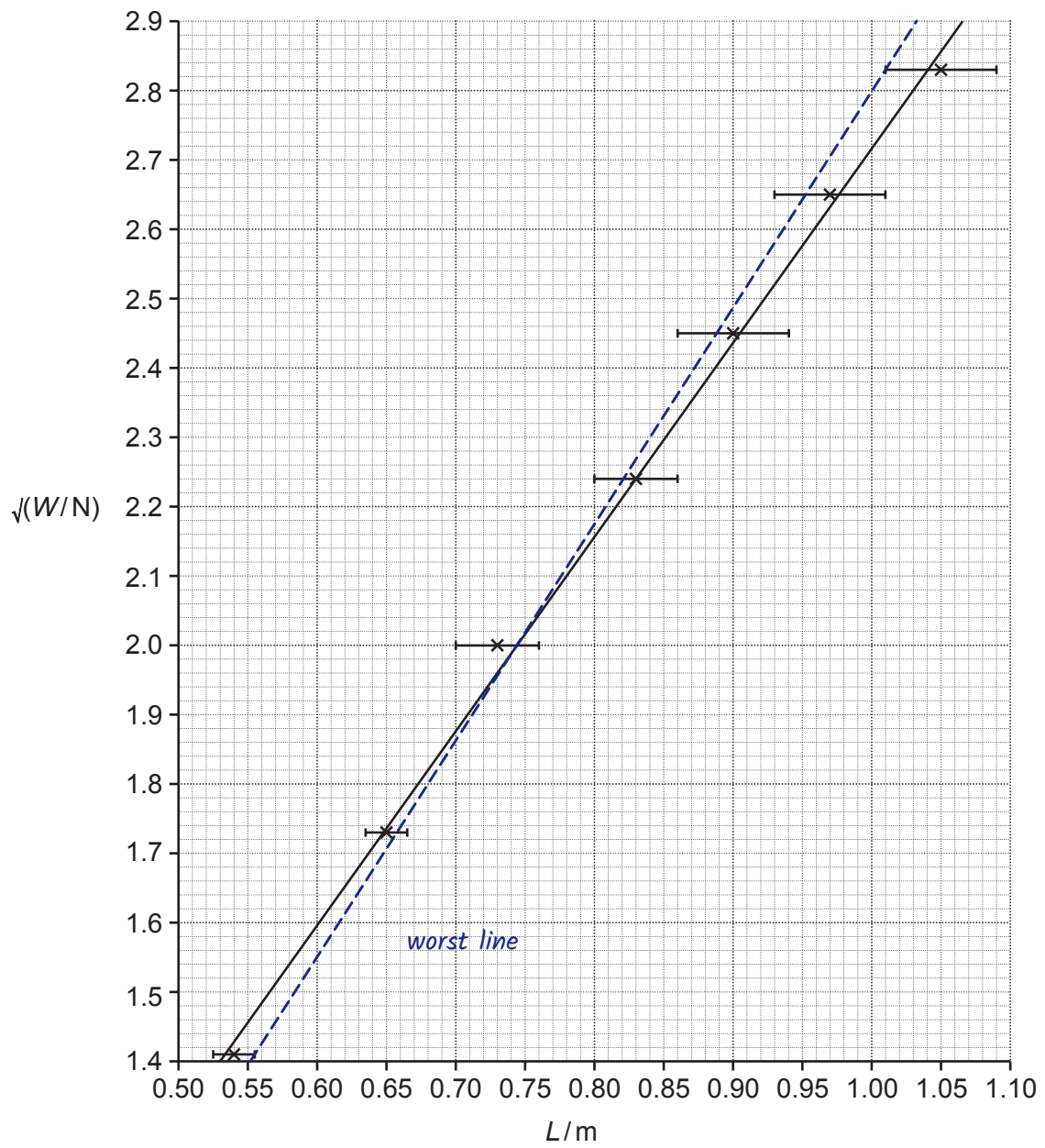
Measure the length of a sample of the wire with a metre ruler and measure its

mass using a (top-pan) balance.

Mass per unit length $\mu = \text{mass} \div \text{length}$.

[2]

(c) The graph shows the results of the experiment.



The student draws a best fit line on the graph. The gradient of the best fit line is $2.81 \text{ N}^{1/2} \text{ m}^{-1}$.

- (i) Draw a worst acceptable line on the graph. [1]
- (ii) Use your worst acceptable line to calculate the percentage uncertainty in the gradient of the best fit line.

Worst line (steepest) through (0.555, 1.41) and (1.01, 2.83):

$$\text{gradient} = (2.83 - 1.41) \div (1.01 - 0.555) = 1.42 \div 0.455 = 3.12 \text{ N}^{1/2} \text{ m}^{-1}$$

$$\text{absolute uncertainty} = 3.12 - 2.81 = 0.31 \text{ N}^{1/2} \text{ m}^{-1}$$

$$\text{percentage uncertainty} = 0.31 \div 2.81 \times 100 = 11\%$$

$$\text{gradient} = 2.81 \pm 0.31 (= 11\%) \text{ N}^{1/2} \text{ m}^{-1} \% \text{ [3]}$$

- (iii) Calculate a value for the mains frequency, f , including a percentage uncertainty.

$$\omega = 2f\sqrt{\mu} \times L, \text{ so } \text{gradient} = 2f\sqrt{\mu} \text{ and } f = \text{gradient} \div (2\sqrt{\mu})$$

$$f = 2.81 \div (2 \times \sqrt{8.0 \times 10^{-4}}) = 49.7 \text{ Hz}$$

$$\% \text{ uncertainty in } f = \% \text{ in gradient} + \frac{1}{2} \times \% \text{ in } \mu = 11 + \frac{1}{2} \times 2 = 12\%$$

$$f = 49.7 \text{ Hz} \pm 12\% \text{ [3]}$$

- (iv) Evaluate the accuracy of your value for f , given that the true value is 50.0 Hz .

$$\% \text{ difference} = (50.0 - 49.7) \div 50.0 \times 100 = 0.6\%$$

This is much smaller than the 12% uncertainty (upper bound $49.7 \times 1.12 = 56 \text{ Hz} > 50 \text{ Hz}$), so the true value lies within the range and the value is accurate.

..... [2]

3 This question is about comparing two methods for storing energy.

(a) A proposed method for storing energy uses trucks powered by electric motors.

The trucks carry sand up a mountain, storing surplus energy as gravitational potential energy.

When the energy needs to be released, they carry the sand back down the mountain, converting the gravitational potential energy into chemical energy stored in a battery.

Explain how an electrical generator in the truck could use **electromagnetic induction** to convert gravitational potential energy into chemical energy stored in a battery.

As the truck moves down the mountain, the weight (gravity) does work on it, and its motion turns (spins) a coil of wire in a magnetic field. The coil cuts magnetic flux, so there is a rate of change of flux linkage and an e.m.f. is induced, driving a current through the battery. Work is done on the charges by the magnetic field (electrical energy), and work done by the charge passing through the battery is stored as chemical energy. [3]

(b) A second proposed method for storing energy uses a tank of wax.

The wax is heated using an electrical heater, storing surplus energy as internal energy of the wax. The wax increases in temperature and melts as it is heated.

When the energy needs to be released, the wax is allowed to cool, converting the internal energy of the wax into thermal energy.

Explain, in terms of the particles in the wax, how energy is stored when it is heated.

Internal energy is the sum of the random kinetic and potential energies of the particles in the wax. As the solid wax heats up, the particles gain kinetic energy (vibrate faster); potential energy is constant. During melting, work is done against the intermolecular forces, increasing the particles' potential energy. As the liquid wax heats up, the particles' kinetic energy increases again. [3]

(c)* A gravitational potential energy storage system, as described in (a), is proposed as follows:

- height of mountain = 1 km
- overall efficiency = 70 %

A thermal energy storage system, as described in (b), is proposed as follows:

- lower operating temperature = 18 °C
- melting point of wax = 51 °C
- upper operating temperature = 70 °C
- specific heat capacity of solid wax = 2.6 kJ kg⁻¹ K⁻¹

- specific heat capacity of liquid wax = $3.0 \text{ kJ kg}^{-1} \text{ K}^{-1}$
- specific latent heat of fusion of wax = 160 kJ kg^{-1}
- overall efficiency = 95 %

Estimate the energy that can be stored by each system using 1 kg of sand or wax.

Discuss which system would be more appropriate for storing surplus electrical energy. Your answer should include an estimate of the energy that can be stored in each system using 1 kg of sand or wax.

Ignore any financial factors.

Sand: $\Delta GPE = mg\Delta h = 1 \times 9.81 \times 1000 = 9.8 \text{ kJ}$. Useful energy = $0.70 \times 9.8 = 6.9 \text{ kJ per kg}$.

Wax: heating solid from 18°C to 51°C : $E = mc\Delta\theta = 1 \times 2.6 \times (51 - 18) = 86 \text{ kJ}$. Melting: $E = mL = 1 \times 160 = 160 \text{ kJ}$. Heating liquid from 51°C to 70°C : $E = 1 \times 3.0 \times (70 - 51) = 57 \text{ kJ}$.

Total for wax = $86 + 160 + 57 = 303 \text{ kJ} \approx 300 \text{ kJ}$. Useful = $0.95 \times 303 \approx 290 \text{ kJ per kg}$.

So the thermal system stores about 40 times as much energy per kg ($290 \div 6.9 \approx 42$), i.e. a much higher energy density: far less material is needed.

GPE pros: sand is readily available, the energy stored in batteries is electrical/chemical, so it can be released directly to the grid, and it can be stored indefinitely. Cons: needs mountainous terrain, very large masses and a slow

Additional answer space if required

response time.

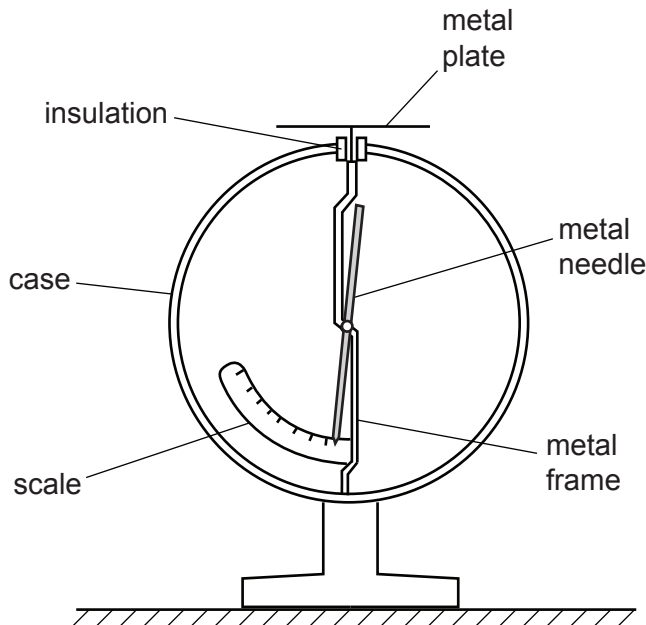
Thermal pros: high energy density, easily scaled up or automated and can be built anywhere. Cons: the thermal energy cannot readily be converted back into electrical energy for the grid, and the wax cools, so storage time is limited.

Conclusion: for storing surplus electrical energy to return to the grid, the GPE system is more appropriate despite its lower energy per kg, while the wax suits supplying heat.

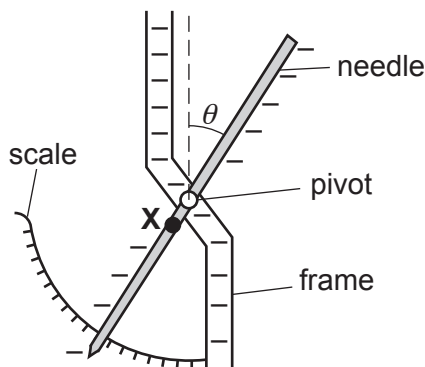
[6]

- 4 An electroscope is an instrument used to measure electric charge.

The diagram shows one type of electroscope.



The diagram below shows the needle of the electroscope when it is negatively charged. The centre of mass, **X**, of the needle has been marked on the diagram.



- (a) Suggest why the centre of mass of the needle is a **short** distance **below** the pivot.

With X below the pivot, the weight provides a restoring moment, so the needle rests vertically ($\theta = 0$) when there is no charge.

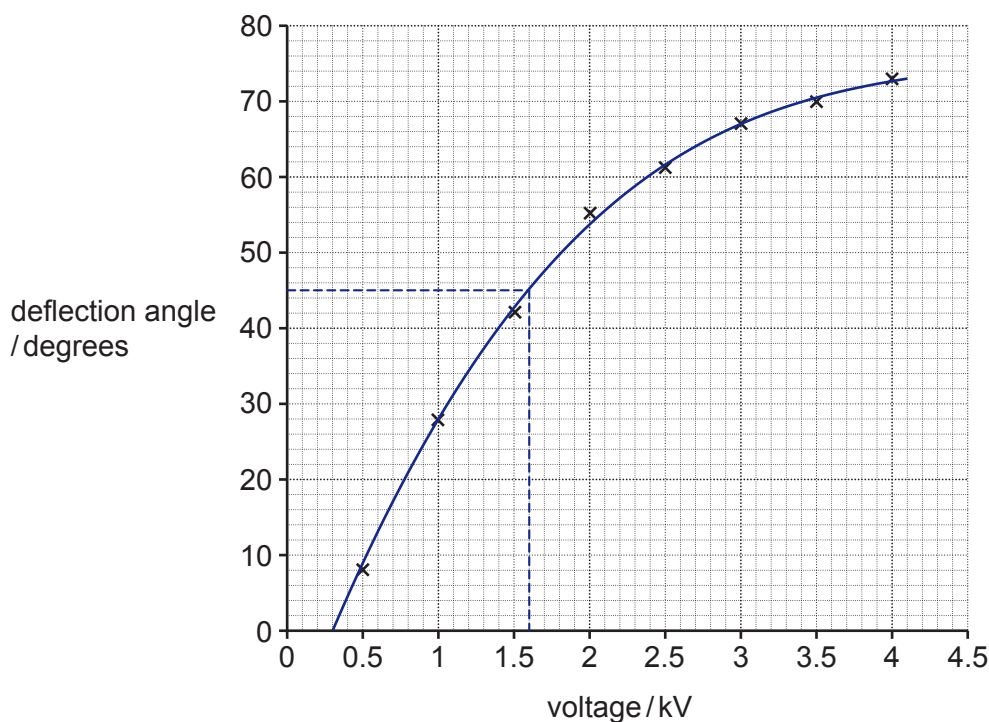
A short distance keeps the moment of the weight small, so a small charge gives a large deflection: this increases sensitivity (resolution).

[2]

- (b) A student charges the electroscope by connecting the metal plate to the negative terminal of a high voltage power supply.

They record the deflection angle of the needle for a range of values of the voltage measured using a voltmeter.

Their results are shown in the graph below.



- (i) The student concludes that the voltmeter has a zero error of 300 V.

Explain their reasoning.

The curved line of best fit meets the voltage axis at 0.3 kV, so the voltmeter reads 300 V when there is zero deflection (no charge). [1]

- (ii) The capacitance of the electroscope is 20 pF.

Estimate the number of electrons stored on the electroscope when the deflection angle is 45°.

At 45°, V read from the curve = 1.60 kV; correcting for zero error:

$$V = 1.60 - 0.30 = 1.30 \text{ kV} = 1300 \text{ V}$$

$$Q = CV = 20 \times 10^{-12} \times 1300 = 2.6 \times 10^{-8} \text{ C}$$

$$N = Q \div e = 2.6 \times 10^{-8} \div 1.60 \times 10^{-19}$$

number of electrons = 1.6×10^{11} [4]

- 5 To control insect populations, sterilised male insects can be released into the wild.

They mate with females, who then produce no offspring, reducing the future population.

Sterilisation can be carried out using ionising radiation. The insects are placed in a canister about 10 cm across and then deliberately exposed to a known dose of ionising radiation.

- (a) Suggest why exposing an insect to ionising radiation may cause it to become infertile.

Ionising radiation damages (causes mutations in) the DNA in the cells, e.g. the gametes. [1]

- (b) Both gamma rays and X-rays can be used to sterilise the insects.

- (i) Suggest why alpha radiation is **not** suitable for irradiating large numbers of insects.

Alpha particles are not very penetrating; they have a short range in air (a few cm) and are easily absorbed.
So they would not reach insects on the far side of the 10 cm canister (or would be absorbed by the first insects). [2]

- (ii)* The sterilisation process may need to be carried out in laboratories that do not otherwise make use of ionising radiation.

Discuss the advantages and disadvantages of using gamma rays rather than X-rays for this purpose, including:

- descriptions of how gamma rays and X-rays are produced
- a comparison of any practical considerations relating to their use, including safety.

You may ignore any financial considerations.

Gamma rays come from the radioactive decay of unstable nuclei, e.g. Co-60: after alpha or beta decay the nucleus is left in an excited state and de-excites by emitting a gamma photon.

X-rays are produced in an X-ray tube: electrons are accelerated by a large p.d. (tens of kV) and hit a metal target (anode). As they decelerate, their kinetic energy is converted into X-ray photons, and electrons in the target atoms de-excite, giving characteristic X-rays.

Safety: gamma rays and high energy X-rays have similar penetration and ionisation, so similar shielding (thick lead or concrete) and short exposure times are needed in both cases.

Gamma advantages: the source is small, needs no electrical power and emits continuously and spontaneously, so it is simple to use in a laboratory.

Gamma disadvantages: it can never be switched off, so it must be stored and handled in shielded containers (tongs, remote handling) at all times, and its

Additional answer space if required

intensity decreases over time (half-life), so the source must be replaced regularly and exposure times recalculated.

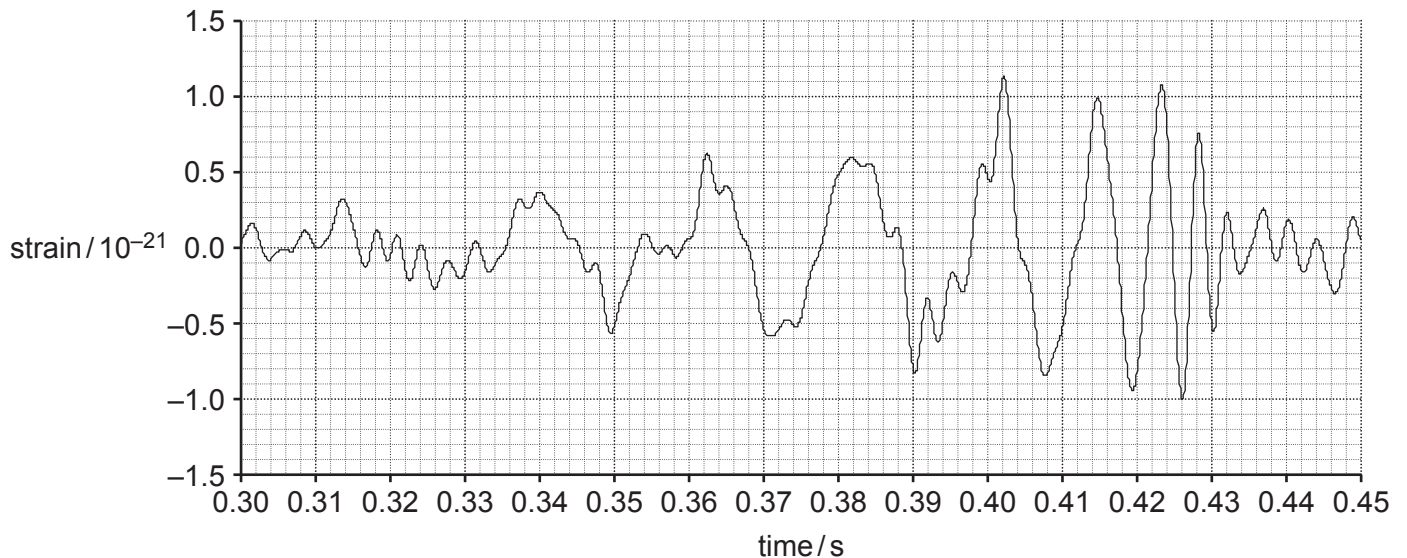
X-ray advantages: the machine can be switched off, so there is no radiation when off, and the X-ray energy can be controlled by the p.d. Disadvantages: needs large equipment and a large electrical power supply.

Overall, X-rays are safer for such a laboratory: there is no radioactive source to store.

[6]

- 6 Gravitational waves are disturbances in space-time that are produced by violent astrophysical events.
- (a) They are detected by measuring the change in length of a detector as the wave passes through. The change in length is reported as a strain.

The graph shows the variation in time of the strain due to the gravitational waves emitted by the collision of two black holes.



- (i) Define **strain**.

Strain = extension ÷ original length (extension per unit length). [1]

- (ii) The maximum strain shown on the graph is approximately 10^{-21} .

Calculate the force that would produce the same strain in a copper wire of diameter 2 mm.

Young modulus of copper = 130 GPa

$$A = \pi r^2 = \pi \times (1.0 \times 10^{-3})^2 = 3.14 \times 10^{-6} \text{ m}^2$$

$$F = E \times \text{strain} \times A = 130 \times 10^9 \times 10^{-21} \times 3.14 \times 10^{-6}$$

force = ... 4.1×10^{-16} N [3]

- (iii) By considering the answer to (ii), suggest why it is very difficult to detect the strain caused by gravitational waves.

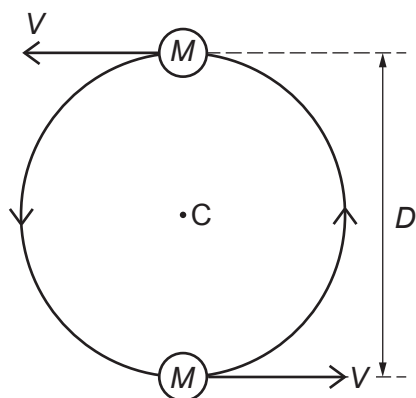
The strain is very small; a tiny force of only about 4×10^{-16} N would produce the same strain.

So the signal is difficult to distinguish from background noise; it is hidden by the effects of other forces (vibrations). [2]

- (b) In this part of the question you will use Newtonian physics to estimate the power output of the black hole collision.

The diagram shows two identical black holes, each of mass M , orbiting each other with period T .

Prior to colliding, the black holes move at speed V in identical circular orbits of diameter D about the central point C .



- (i) Write down an expression for the gravitational force, F , acting between the black holes in terms of M , D and the universal gravitational constant, G .

$$F = \dots\dots\dots -GM^2 \div D^2 \dots\dots\dots [1]$$

- (ii) The total orbital energy, E , of the black holes is the sum of their kinetic energy and gravitational potential energy. Show that E is given by the expression:

$$E = k (\pi^2 G^2 M^5)^{1/3} (1/T^{2/3})$$

where k is a numerical constant.

$$\text{Each mass has radius } D/2: Mv^2 \div (D/2) = GM^2 \div D^2, \text{ so } v^2 = GM \div 2D$$

$$\text{Also } v = 2\pi(D/2) \div T = \pi D \div T$$

$$E = -GM^2 \div D + 2(1/2 Mv^2) = -GM^2 \div D + GM^2 \div 2D = -GM^2 \div 2D$$

$$\pi^2 D^2 \div T^2 = GM \div 2D, \text{ so } D^3 = GMT^2 \div 2\pi^2$$

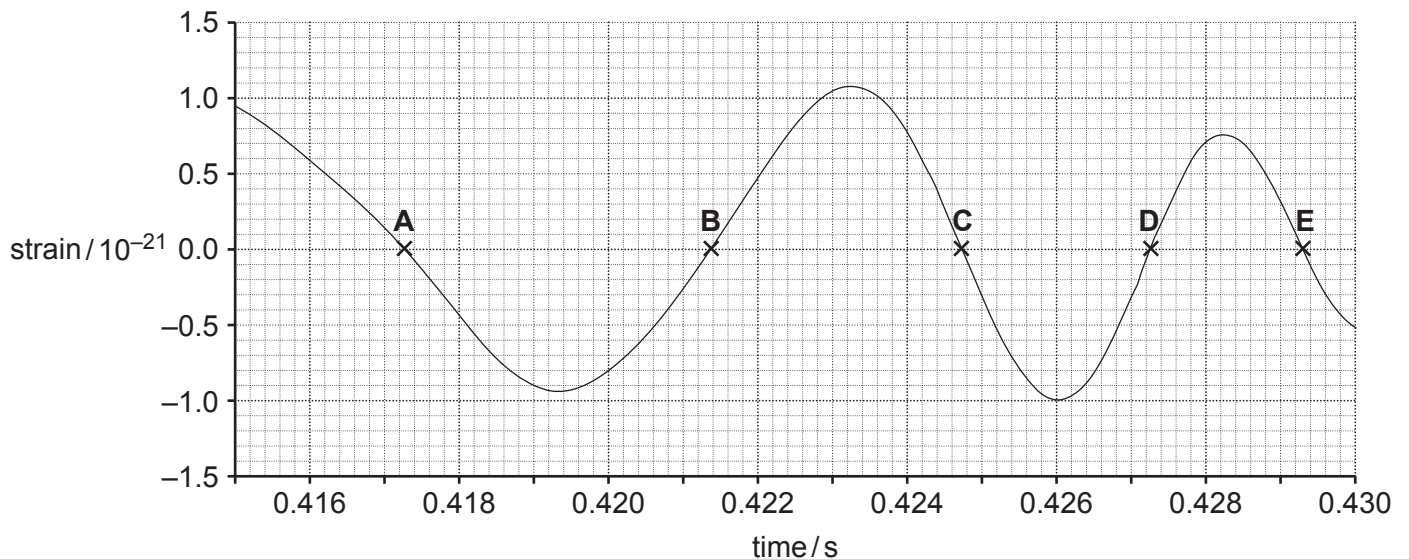
$$E^3 = -G^3 M^6 \div 8D^3 = -2\pi^2 G^3 M^6 \div 8GMT^2 = -\pi^2 G^2 M^5 \div 4T^2$$

$$E = -(1/4)^{1/3} (\pi^2 G^2 M^5)^{1/3} (1/T^{2/3}), \text{ so } k = -0.63 \quad [3]$$

- (iii) The graph below shows detail from the graph in (a).

The black holes spiral towards one another before colliding. As they do so their orbit period decreases.

The orbit period is equal to the period of the gravitational waves.



By considering the time periods **AC** and **CE**, estimate the orbital energy lost by the black holes between these two orbits.

Use $k(\pi^2 G^2 M^5)^{1/3} = -2.04 \times 10^{46}$

From graph: $A = 0.4173 \text{ s}$, $C = 0.4247 \text{ s}$, $E = 0.4293 \text{ s}$

$T_{AC} = 0.4247 - 0.4173 = 7.4 \times 10^{-3} \text{ s}$; $T_{CE} = 0.4293 - 0.4247 = 4.6 \times 10^{-3} \text{ s}$

$E_{AC} = -2.04 \times 10^{46} \times (7.4 \times 10^{-3})^{-2/3} = -5.37 \times 10^{47} \text{ J}$

$E_{CE} = -2.04 \times 10^{46} \times (4.6 \times 10^{-3})^{-2/3} = -7.38 \times 10^{47} \text{ J}$

$\text{energy lost} = (7.38 - 5.37) \times 10^{47} = 2.0 \times 10^{47} \text{ J}$

energy lost = ... 2.0×10^{47} J [3]

- (iv) By considering times **B** and **D**, use your answer to (iii) to estimate the power radiated as gravitational waves in this time interval.

$B = 0.4214 \text{ s}$, $D = 0.4273 \text{ s}$; $\Delta t = 0.4273 - 0.4214 = 5.9 \times 10^{-3} \text{ s}$

$P = E \div t = 2.01 \times 10^{47} \div 5.9 \times 10^{-3}$

power = ... 3.4×10^{49} W [2]

END OF QUESTION PAPER

[illegible]

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