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93103



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SCHOLARSHIP



Mana Tohu Mātauranga o Aotearoa
New Zealand Qualifications Authority

Scholarship 2025 Physics

Time allowed: Three hours
Total score: 32

Check that the National Student Number (NSN) on your admission slip is the same as the number at the top of this page.

You should answer ALL the questions in this booklet.

For all 'describe' or 'explain' questions, the answers should be written or drawn clearly with all logic fully explained.

For all numerical answers, full working must be shown and the answer must be rounded to the correct number of significant figures and given with the correct SI unit.

Formulae you may find useful are given on page 3.

If you need more room for any answer, use the extra space provided at the back of this booklet.

Check that this booklet has pages 2–28 in the correct order and that none of these pages is blank.

Do not write in the margins (✂). This area will be cut off when the booklet is marked.

YOU MUST HAND THIS BOOKLET TO THE SUPERVISOR AT THE END OF THE EXAMINATION.

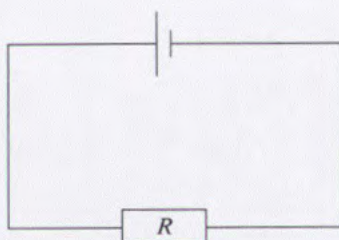
The formulae below may be of use to you.

$v_f = v_i + at$ $d = v_i t + \frac{1}{2} at^2$ $d = \frac{v_i + v_f}{2} t$ $v_f^2 = v_i^2 + 2ad$ $F_g = \frac{GMm}{r^2}$ $F_c = \frac{mv^2}{r}$ $\Delta p = F \Delta t$ $\omega = 2\pi f$ $d = r\theta$ $v = r\omega$ $a = r\alpha$ $W = Fd$ $F_{\text{net}} = ma$ $p = mv$ $x_{\text{COM}} = \frac{m_1 x_1 + m_2 x_2}{m_1 + m_2}$ $\omega = \frac{\Delta\theta}{\Delta t}$ $\alpha = \frac{\Delta\omega}{\Delta t}$ $L = I\omega$ $L = mvr$ $\tau = I\alpha$ $\tau = Fr$ $E_{K(\text{ROT})} = \frac{1}{2} I\omega^2$ $E_{K(\text{LIN})} = \frac{1}{2} mv^2$ $\Delta E_p = mg\Delta h$ $\omega_f = \omega_i + \alpha t$ $\omega_f^2 = \omega_i^2 + 2\alpha\theta$ $\theta = \frac{(\omega_i + \omega_f)}{2} t$ $\theta = \omega_i t + \frac{1}{2} \alpha t^2$	$T = 2\pi\sqrt{\frac{l}{g}}$ $T = 2\pi\sqrt{\frac{m}{k}}$ $E_p = \frac{1}{2} ky^2$ $F = -ky$ $a = -\omega^2 y$ $y = A \sin \omega t$ $y = A \cos \omega t$ $v = A\omega \cos \omega t$ $v = -A\omega \sin \omega t$ $a = -A\omega^2 \sin \omega t$ $a = -A\omega^2 \cos \omega t$ $\Delta E = Vq$ $P = VI$ $Q = CV$ $C_T = C_1 + C_2$ $\frac{1}{C_T} = \frac{1}{C_1} + \frac{1}{C_2}$ $E = \frac{1}{2} QV$ $C = \frac{\epsilon_0 \epsilon_r A}{d}$ $\tau = RC$ $\frac{1}{R_T} = \frac{1}{R_1} + \frac{1}{R_2}$ $R_T = R_1 + R_2$ $V = IR$ $F = BIL$ $V = BvL$ $F = Bqv$ $F = Eq$ $E = \frac{V}{d}$	$\phi = BA$ $\epsilon = -\frac{\Delta\phi}{\Delta t}$ $\epsilon = -L \frac{\Delta I}{\Delta t}$ $\frac{N_p}{N_s} = \frac{V_p}{V_s}$ $E = \frac{1}{2} LI^2$ $\tau = \frac{L}{R}$ $I = I_{\text{MAX}} \sin \omega t$ $V = V_{\text{MAX}} \sin \omega t$ $I_{\text{MAX}} = \sqrt{2} I_{\text{rms}}$ $V_{\text{MAX}} = \sqrt{2} V_{\text{rms}}$ $X_C = \frac{1}{\omega C}$ $X_L = \omega L$ $V = IZ$ $f_0 = \frac{1}{2\pi\sqrt{LC}}$ $v = f\lambda$ $f = \frac{1}{T}$ $n\lambda = \frac{dx}{L}$ $n\lambda = d \sin \theta$ $f' = f \frac{V_w}{V_w \pm V_s}$ $E = hf$ $hf = \phi + E_K$ $E = \Delta mc^2$ $\frac{1}{\lambda} = R \left(\frac{1}{S^2} - \frac{1}{L^2} \right)$ $E_n = -\frac{hcR}{n^2}$
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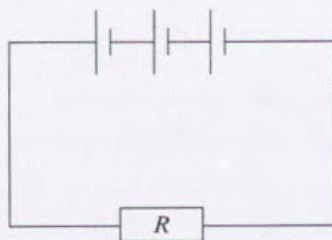
QUESTION ONE: INTERNAL RESISTANCE

A battery can be made by connecting a number of individual cells together. The cells can be connected either in series or in parallel.

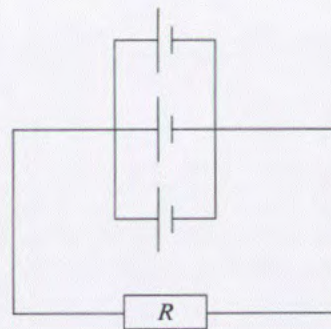
Circuit 1



Circuit 2



Circuit 3



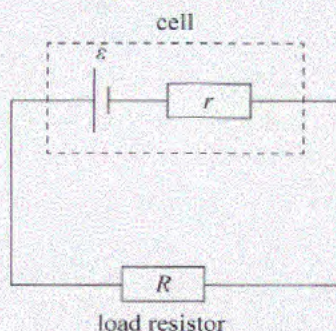
- (a) Compare the total power dissipated in the resistor R in the three circuits above: with a single cell, with three cells connected in series, and with three cells connected in parallel.

Assume the cells are all identical and ideal for this part of the question.

$$\cancel{R_1 = R_3 < R_2} \quad \cancel{P_1 = P_3 < P_2}$$

According to Kirchhoff's law, in any closed loop in ~~either~~ circuits 1 or 3, the voltage of the resistor is equal to the supply. The current through the resistor is also the same for 1 & 3, as in 3, the split paths join & cancel the effect. Circuit 2 has the supplies in series, whose voltage would be additive (& the resistance ~~is~~ unchanged).

- (b) A real cell produces an emf $\mathcal{E}$ and has internal resistance r . The cell is connected to a load resistor with resistance R .



- (i) Show that the power dissipated by the load resistor is given by the expression:

$$P_R = \frac{\mathcal{E}^2 R}{(r+R)^2}$$

$$P = I^2 R \qquad P = \mathcal{E}^2 R / (r+R)^2$$

$$V_r = \mathcal{E} - Ir$$

$$V_{\text{total}} = I_{\text{total}} R_{\text{total}}$$

$$\Rightarrow$$

$$IR_r = \mathcal{E} - Ir$$

$$R_r = \mathcal{E} / I - r$$

$$I = \mathcal{E} / (R_r + r)$$

- (ii) For a cell with constant $\mathcal{E}$ and constant r , the power dissipated by the load resistor is maximum when $R = r$.

Use appropriate physics concepts to explain why the power dissipated by the load resistor is small at extremely large and at extremely low values of R .

Power is proportional to the current squared, while only directly so for the resistance (i.e., $P \propto I^2$ but $P \propto R$), yet the current is inversely proportional to the resistance. Therefore, increasing the resistance would disproportionately decrease the current & hence the power; vice versa for decreasing the resistance.

All voltages and currents referred to in parts (c) and (d) of this question are rms values.

- (c) A real inductor has both inductance L and internal resistance r .

A real inductor with internal resistance $r = 72.0 \, \Omega$ is connected in series with a capacitor to an AC power supply with voltage V_S and frequency f .

Assume that both the capacitor and the power supply are ideal.

The current in the circuit is $I = 2.20 \times 10^{-2} \, \text{A}$. An AC voltmeter, connected as shown, measures the combined voltage of both the inductance and internal resistance of the real inductor as $V = 4.20 \, \text{V}$. The voltage V across the real inductor leads the voltage of the AC power supply V_S by 120° .

Sketch a phasor diagram for the voltages, and use it to calculate the value of the power supply voltage V_S .

$$X = \frac{72}{2.2} \tan(\pi/6)$$

$$= 24\sqrt{3} \, \Omega$$

$$V = IZ$$

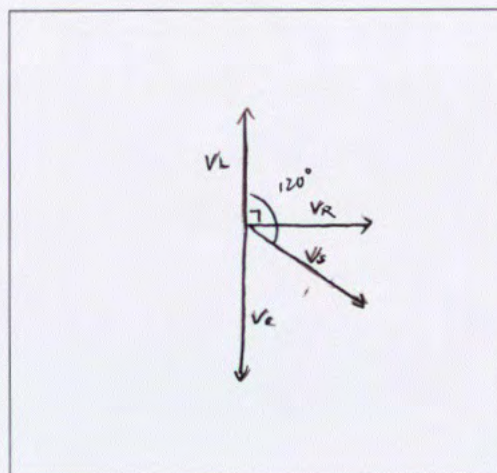
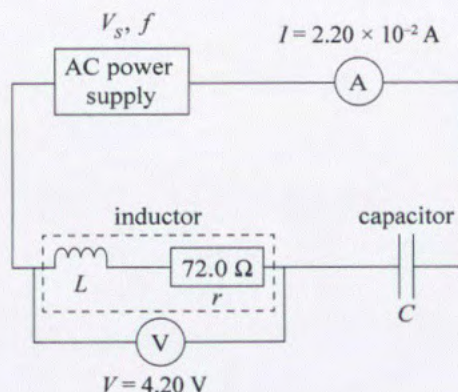
$$Z = |\vec{R} + \vec{X}|$$

$\Rightarrow$

$$V = I\sqrt{R^2 + X^2}$$

$$= 2.2 \times 10^{-2} \sqrt{72^2 + (24\sqrt{3})^2}$$

$$\approx 1.83 \, \text{V}$$



- (d) An ideal inductor, resistor, and capacitor are connected in series to an AC power supply. In certain conditions, the voltage across the inductor and the voltage across the capacitor can both exceed the voltage of the power supply.

Describe the conditions required for both V_L and V_C to exceed V_S .

Explain the energy transfers occurring in the circuit under these conditions.

The condition is being close to resonance, or specifically the inductive & capacitive reactance being roughly equal. The inductor & capacitor naturally oscillates, & the source merely "pushes" them. The energy in the inductor is effectively the magnetic field, ~~or sp~~, & that in the capacitor the electric field, or specifically for both, the electric potential energy of charge separation & the kinetic energy of the electrons. The energy transfers are between these two.

QUESTION TWO: TAONGA PŪORO

- (a) Te kū is a traditional Māori musical instrument that consists of a single string connected between the ends of a bent stick. The string is struck with a second stick to produce a sound.

A traditional Māori musician wants to make a second te kū that produces a sound with a higher frequency.

<https://www.haumanucollective.com/ku/>

Describe TWO separate changes that could be made to the design to increase the frequency of the sound produced.

Explain how each of these changes alters fundamental parameters that result in a higher frequency sound.

It could be made by shortening the string while keeping the tension ~~the~~ constant. This reduces the wavelength while keeping the wave speed constant, increasing the frequency. The tension could also be increased when the length is constant, which increases the frequency by increasing the wave speed.

- (b) A pōrutu is a traditional Māori musical wind instrument that is carved from wood or bone. A pōrutu is a hollow pipe that is open at both ends. It is played in a similar way to a flute, by blowing across one of the open ends and covering small holes with the fingers.

<https://collection.nelsonmuseum.co.nz/objects/G30429/porutu-long-flute>

Harmonic frequencies in a pipe occur when sound waves travelling along the pipe reflect from the end and interfere, forming a standing wave.

A simple model of this situation assumes that an antinode always occurs at an open end of a pipe.

Explain how a sound wave reflects from an open end of a pipe, and how this results in an antinode being formed.

A change in medium causes reflection. The air is limited in terms of movement inside the pipe, but not outside. When a wave front reaches the end of the pipe, the resultantly moving air particles outside produces a wave front more spread out in direction than inside the pipe, & ~~some~~ ~~to move~~ towards the pipe as a component, causing an apparent reflection.

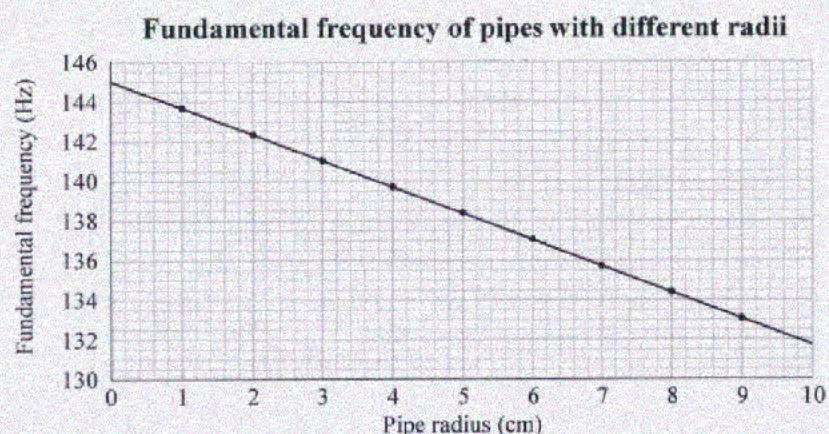
- (c) For an open end, the oscillation of air particles extends beyond the end of the pipe, making the pipe behave as if it is slightly longer than it really is. The larger the radius of the pipe, the more significant this effect becomes.

The apparent extra length at an open end of a pipe is called the end correction, e . For a cylindrical pipe, the end correction can be expressed as:

$$e = kr$$

where r is the radius of the pipe and k is a constant.

The fundamental frequency is measured for a range of uniform cylindrical pipes that are open at both ends. The pipes have the same length L , but different radii. The results and trend line are plotted on the graph below.



Use information from the graph above to determine the length of the pipes, L , and the value of the constant k .

Speed of sound in air = 343 m s^{-1}

$$v = f\lambda$$

$$\lambda = v/f$$

$$= 343/145 \text{ m}$$

$$L = \cancel{0.86/145} 343/290$$

$$\approx 1.18 \text{ m}$$

$$145(343/145 + 0.5k(0)) = 131.75(343/145 + 0.5k(0.1))$$

$$343 = 131.75(343/145) + 0.5875k$$

$$k = (343 - 131.75(343/145))/0.5875$$

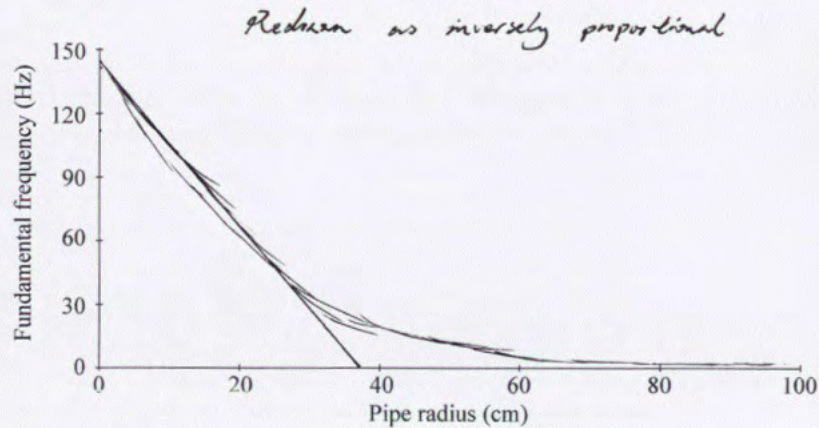
$$k \approx 4.757966368$$

$$= 4.76 \text{ (3 s.f.)}$$

- (d) The data on the graph on page 10 appears to show a linear trend between fundamental frequency and pipe radius within the range tested.

Sketch a trend line on the axes below to show how you expect the trend to continue if the pipe radius is increased significantly beyond the range tested.

Use relevant physics concepts to explain why you expect the trend to behave in this way.



~~As the radius increases, the pressure difference caused by the driving force decreases, apparently linearly, shown both by the graph & the equation.~~

According to the equation provided ($v = kr$), the radius linearly increases the wavelengths of the harmonics, which are inversely proportional to their respective frequencies.

The pressure difference at the pipe opening decreases as the radius increase.

QUESTION THREE: X-RAY PHOTOELECTRON SPECTROSCOPY

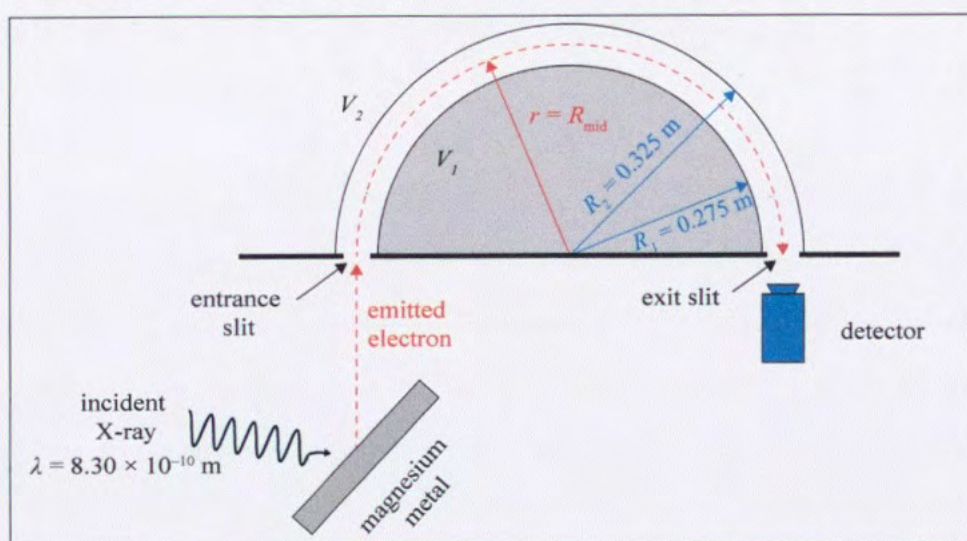
Charge of an electron = $-1.60 \times 10^{-19} \text{ C}$

Planck's constant = $6.63 \times 10^{-34} \text{ J s}$

Speed of light = $3.00 \times 10^8 \text{ m s}^{-1}$

X-ray photoelectron spectroscopy (XPS) is a technique used to determine the energy of electrons emitted by a material when it is illuminated with X-rays.

Electrons emitted by the illuminated material enter a hemispherical electron energy analyser, which consists of two concentric metal hemispheres with a narrow gap between them. The hemispheres have a potential difference of $V_2 - V_1$ between them, as shown in the diagram below.



In an experiment to measure the energy of electrons in magnesium, a sample of magnesium metal is illuminated by X-rays with a wavelength of $8.30 \times 10^{-10} \text{ m}$.

A narrow opening at the entrance ensures that the electrons enter the gap between the hemispheres midway between their surfaces, and that they enter at a tangent to the hemispheres. At the exit, on the other side of the analyser, a detector records any electrons that successfully travel around the semicircular path from the entrance to the exit.

The radii of the inner and outer hemispheres are $R_1 = 0.275 \text{ m}$ and $R_2 = 0.325 \text{ m}$ respectively. The potential difference between the hemispheres is varied, and the rate of electrons received by the detector is observed. Electrons are observed at the detector when the potential difference between the analyser plates is set to 60.0 V .

- (a) Explain whether the potential difference $V_2 - V_1$ should be negative or positive.

As the electrons experience a net force towards V_1 , V_1 is more positive & therefore $V_2 - V_1 < 0$.

- (b) (i) Show that the kinetic energy of electrons that reach the detector is 180 eV.

Assume the magnitude of the electric field between the hemispheres is uniform, and any relativistic effects can be ignored.

$$E = V/d$$

$$F = Eq$$

$\Rightarrow$

$$F = Vq/d$$

$$= -60 \times -1.6 \times 10^{-19} / (0.325 - 0.275)$$

$$= 1.92 \times 10^{-16} \text{ N}$$

$$F = mv^2/r$$

$$E_k = mv^2/2$$

$\Rightarrow$

$$E_k = Fr/2$$

$$= 1.92 \times 10^{-16} \times (0.325 + 0.275) / 4 = \frac{2.88 \times 10^{-17}}{\cancel{2.40 \times 10^{-17}}} \text{ J} = 180 \text{ eV}$$

- (ii) Calculate the minimum amount of energy that would be required to remove one of these electrons from the magnesium metal.

$$hf = \phi + E_k$$

$$v = f\lambda$$

$\Rightarrow$

$$\phi = h\nu/\lambda - E_k$$

$$= 6.63 \times 10^{-34} \times \frac{3 \times 10^8}{0.30 \times 10^{-10}} - 2.88 \times 10^{-17}$$

$$\approx 2.11 \times 10^{-16} \text{ J (3 s.f.)}$$

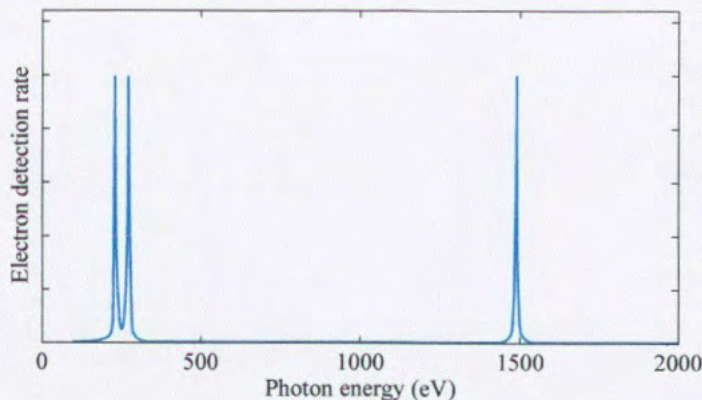
- (c) In this experiment, the magnesium must be electrically connected to ground.

Explain why this is necessary, and discuss how the kinetic energy of a photoemitted electron would be affected if the magnesium was not electrically connected to ground.

The ground is conductive enough to be treated as an infinite source of charge. If the magnesium was insulated, the E_k of an emitted electron would reduce with more time that the magnesium is exposed to the X-ray because the metal would be ionised (positively charged), attracting the electrons with greater force & hence more work would be required.

- (d) In this experiment, the photon wavelength can be varied to change the photon energy. The graph below shows the rate at which electrons are observed at the detector as photon energy is varied. The count rate displays three clear peaks.

Explain what this implies about the energy of the electrons inside the magnesium metal.



This implies that the energy of the electrons is quantised inside the ~~the~~ magnesium atoms; otherwise, a more continuous curve would be observed. The discrete energy levels are different electron shells. It also implies that the electrons only absorb their corresponding amount of energy, which is enough to ionise. The steep but nevertheless present gradient around the peaks are from atoms further away from the stone surface.

QUESTION FOUR: PENDULUMS AND SPRINGS

Acceleration due to gravity = 9.81 m s^{-2}

A simple pendulum, with a string of negligible mass, that is oscillating with a small angle θ , can be approximated as moving with simple harmonic motion.

- (a) (i) By considering the forces acting, show that the acceleration of the pendulum is given by the expression:

$$a = -\frac{gx}{L}$$

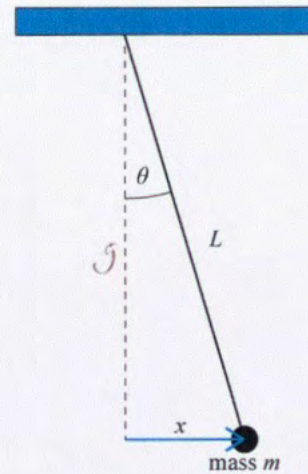
$$T \approx 2\pi\sqrt{L/g}$$

$$\omega = 2\pi/T \Rightarrow \omega = \sqrt{g/L}$$

$$a = -\omega^2 x$$

$\Rightarrow$

$$a = -gx/L$$

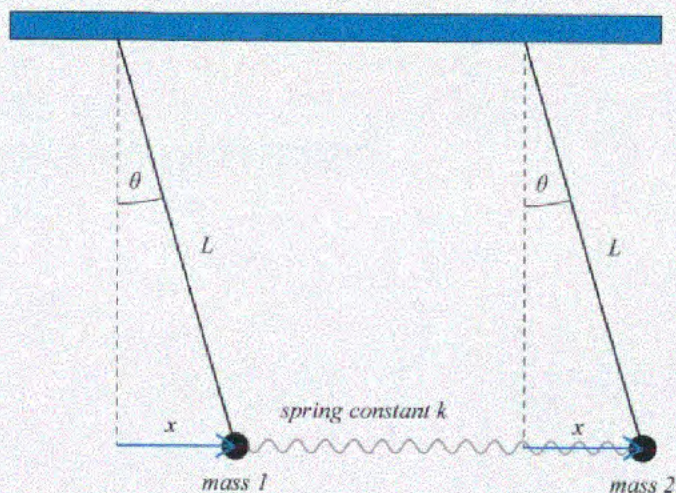


- (ii) Explain how this expression shows that when the angle θ is small, the motion of a simple pendulum can be approximated as simple harmonic motion.

The expression " $T = 2\pi\sqrt{L/g}$ " already assumes the angle to be small. A more precise expression would be $a = -g \cos \theta$; when θ approaches zero, a approaches $-g$ exactly, which is the case or $a = -g \cos(\sin^{-1}(x/L))$. $\cos \sin^{-1} \frac{x}{L}$ approaches one as x approaches zero.

- (b) Two identical pendulums are independently suspended from a fixed beam and connected by a spring with negligible mass. The spring has spring constant k , and the natural unstretched length of the spring is the same as the distance between the two points from which the pendulums are suspended.

The two pendulums can be independently moved either to the left or to the right before being released to investigate the motion of the pendulums with different initial conditions.



For the first investigation, the two pendulums are both moved to the right with the same initial displacement x , as shown in the diagram above. The pendulums are released at the same time so that they oscillate in phase.

The pendulums are set up with the following values:

- pendulum length = 0.560 m
- pendulum mass = 50.0 g
- initial displacement = 2.50 cm
- spring constant = 13.0 N m⁻¹

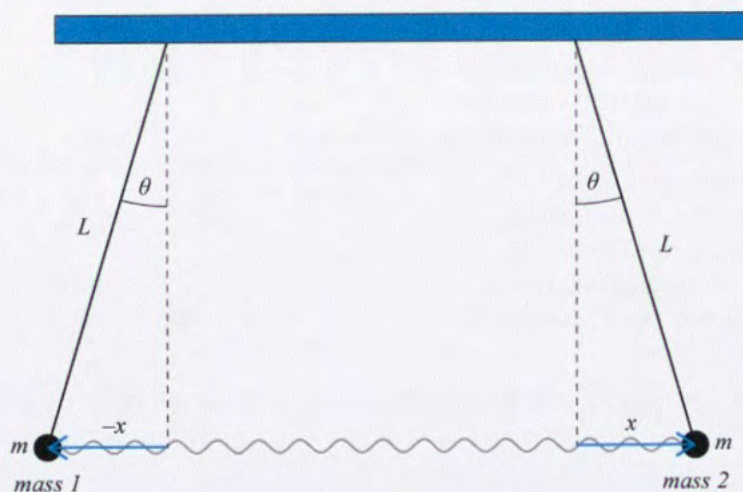
Calculate the period of the pendulums in this system.

Use appropriate reasoning to justify your answer.

$$\begin{aligned}
 T &= 2\pi\sqrt{L/g} \\
 &= 2\pi\sqrt{0.56/9.81} \\
 &\approx 1.50 \text{ s}
 \end{aligned}$$

The spring does not act, as it is never stretched nor compressed while the distance between the masses are always maintained.

- (c) For the second investigation, the two pendulums are moved the same initial distance x , but in opposite directions, as shown below. They are then released at the same time, so that they oscillate in opposite phase.



By considering the forces acting on one of the masses, show that the period of the opposite phase oscillations is given by:

$$T = \frac{2\pi}{\sqrt{\frac{g}{L} + \frac{2k}{m}}}$$

$$F = -kx$$

$$a = -\omega^2 x$$

$\Rightarrow$

$$\omega = \sqrt{k/m}$$

$$a = -kx/m$$

$$a = -gx/L$$

They can be added ~~but~~ because the directions & masses are both equal

$$a_{\text{net}} = -x(g/L + 2k/m) \quad a = -\omega^2 x$$

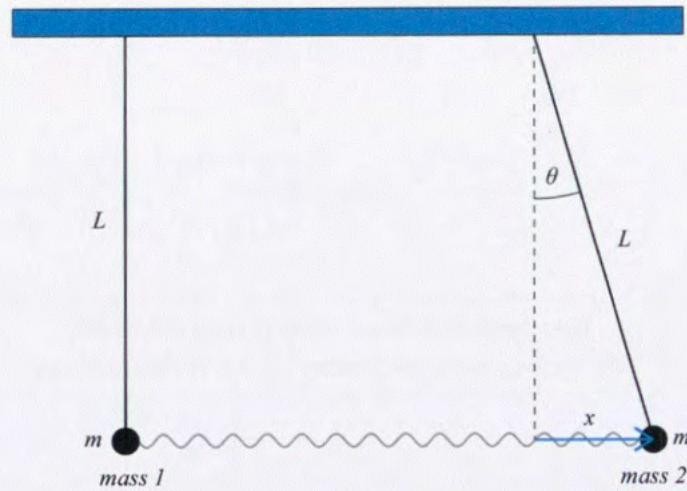
$$\omega^2 = k$$

$$T = 2\pi/\omega$$

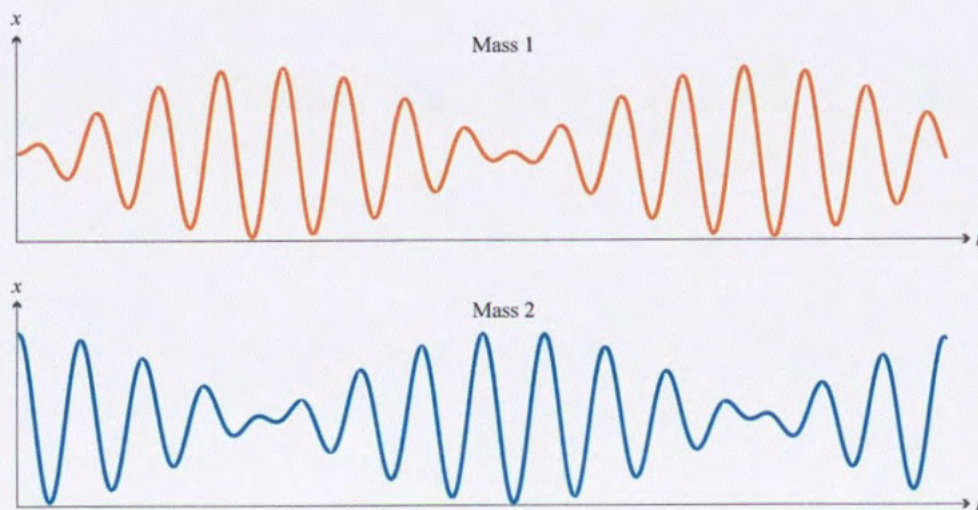
$\Rightarrow$

$$T = 2\pi/\sqrt{g/L + 2k/m}$$

- (d) For the third investigation, mass 1 is held at its equilibrium position, while mass 2 is displaced to the right, as shown below.



Both masses are released at the same time. The two pendulums oscillate with varying amplitude, and are neither purely in phase nor in opposite phase with each other. The displacement of the two masses over time is shown below.



By considering the forces acting on the two masses, explain why the oscillations vary in this way, and how energy in the system is transferred between the two masses.

The graphs show, each, the sum of two sinusoidal functions of similar but different frequencies. The energy is transferred sinusoidally between the two masses*, observed by their respective amplitudes. In no instance in this situation do both the spring & pendulums reach equilibrium; they are out-of-phase. The different frequencies in the components are caused by the initially different restorative forces (i.e., the spring acts equally on both masses but mass 2 initially experiences a greater F_w).

* by the potential energy in the spring.

Extra space if required.
Write the question number(s) if applicable.

QUESTION
NUMBER

$$F = -kx$$

$$a = -\omega^2 x$$

$$F = kx / \omega^2$$

Scholarship

Subject: Physics

Standard: 93103

Total score: 24

Q	Score	Marker commentary
1	5	Scholarship level understanding of a range of DC and AC electrical concepts.
2	6	High level understanding across a range of situations involving waves concepts mainly relating to open ended pipes.
3	8	Scholarship level understanding of modern physics in a unique and challenging context.
4	5	Scholarship level understanding of simple harmonic motion in a unique and challenging context.