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TOP SCHOLAR



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.

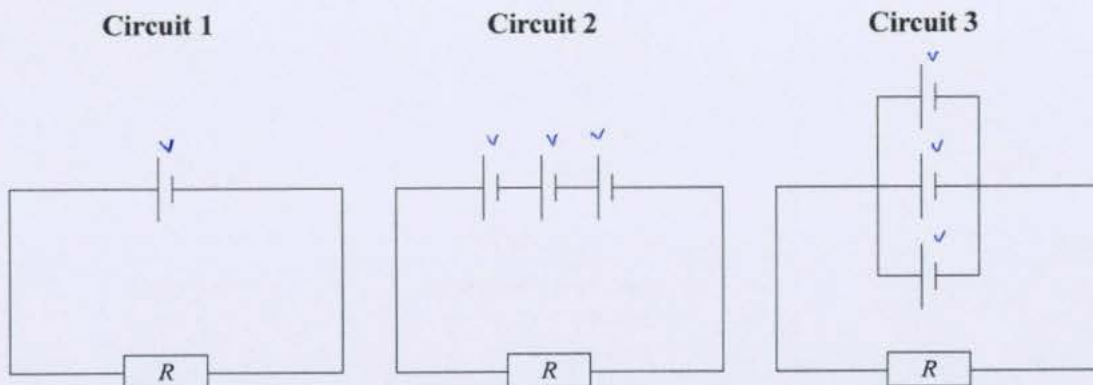
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The assessment starts on page 4.**

The formulae below may be of use to you.

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



- (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.

$$P = \frac{V^2}{R}$$

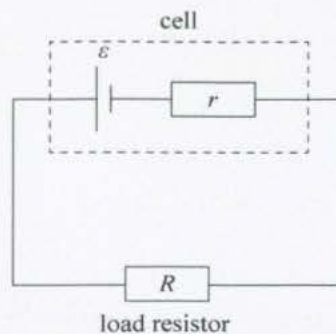
~~Max voltage cell~~

• In circuit 1 the resistor voltage equals the cell voltage V and the total power dissipated is given by $P = \frac{V^2}{R}$.

• In circuit 2, the resistor voltage equals $3V$. $P = \frac{(3V)^2}{R} = \frac{9V^2}{R}$ so the voltage dissipated by the resistor will be 3 times that in circuit 1.

• In circuit 3, as the voltages in a loop must sum to zero by Kirchhoff's law, if we consider the loop with a single cell and the resistor, then the voltage across the resistor must equal the voltage across one of the cells V . $P = \frac{V^2}{R}$.
Therefore the power dissipated by the resistor in circuit 3 is the same as the power dissipated by the resistor in circuit 1.

- (b) A real cell produces an emf ε 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:

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

Finding current:

$$I = \frac{\varepsilon}{(R+r)}$$

$$P_R = IV \quad \text{and} \quad V = IR$$

$$\Rightarrow P_R = I^2 R$$

substituting for I gives

$$P_R = \left(\frac{\varepsilon}{R+r} \right)^2 R$$

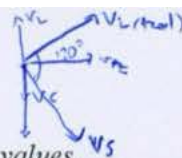
$$P_R = \frac{\varepsilon^2 R}{(r+R)^2}$$

- (ii) For a cell with constant ε 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 .

- When R is extremely large, so is the total resistance of the circuit. A larger resistance will result in a very small current ($V=IR$). $P=IV = I^2 R$, so despite the large R , the ~~decrease~~ decrease in I will result in a small amount of power dissipated since the I term is squared.
- When R is extremely small, the resistance of the circuit is ~~then~~ effectively just the internal resistance of the cell, and so the voltage drop across the internal resistance will be large and therefore the voltage drop across the load resistor will be incredibly small. $P=IV = \frac{V^2}{R}$, although R is small, so is the V term which is also squared*, meaning the power dissipated by the load resistor will ~~also be very small~~.

* (Note: a very small number squared results in an even smaller value).



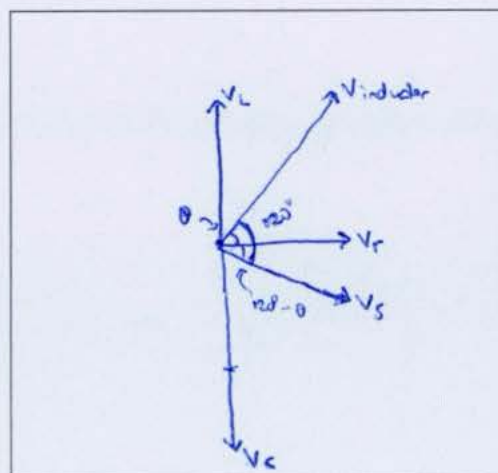
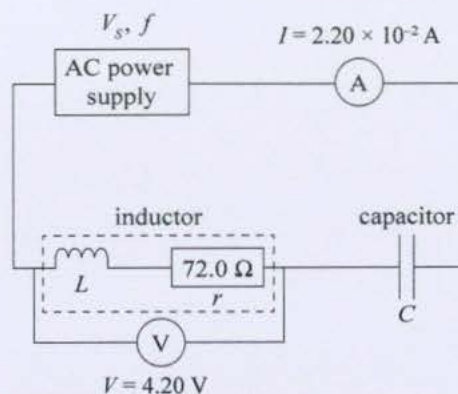
All voltages and currents referred to in parts (c) and (d) of this question are rms values.

- (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° .



$$V_r = I r = (2.20 \times 10^{-2}) (72) = 1.584 \, \text{V}$$

$$\cos \theta = \frac{V_r}{V_{\text{inductor}}} = \frac{1.584}{4.20}$$

$$\theta = \cos^{-1} \left(\frac{1.584}{4.20} \right) = 67.8^\circ$$

$$\cos(120^\circ - \theta) = \frac{V_r}{V_S}$$

$$V_S = \frac{V_r}{\cos(120^\circ - \theta)} = \frac{1.584}{\cos(52.16^\circ)} = 2.58 \, \text{V} \quad (3 \text{ s.f.})$$

- (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.

$$V_L = IX_L \quad V_C = IX_C \quad V_S = IZ$$

Impedance (Z) is given by the vector sum of X_L , X_C and R . X_L and X_C are in antiphase, so have the ability to cancel each other out, which could result in an impedance which is lower than the reactances of the capacitor and inductor.

If $X_C > Z$, then $V_C > V_S$. Likewise if $X_L > Z$, then $V_L > V_S$.

This works because the energy is not being dissipated by the inductor or capacitor, ~~energy~~ energy is only being dissipated as heat due to the resistance.

However the capacitor and inductor are still losing and gaining energy in antiphase to each other (i.e. ~~when~~ ^{when} the capacitor has a large store of charge, the inductor has a weak magnetic field and vice versa). ~~Therefore~~ This energy is not dissipated though, it is simply recycled through the circuit.

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.

- A shorter ~~stick~~ string, and hence shorter stick could be used. A string with a slander length will produce a fundamental note with a shorter wavelength. ($v = f\lambda$), so the frequency of the sound will be higher. (since v is constant)
- A thinner string could be used, ($\mu \downarrow$). This would increase the speed of the sound wave in the string. ($v = f\lambda$), so the frequency of the sound produced will be higher, (since λ is constant)

- (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.

The open end of the pipe effectively acts as a free moving boundary due to the differences in air pressure inside the pipe and outside the pipe. This means that a wave will reflect off the open end with no phase change. ~~the~~ Therefore the reflected wave will be in phase with the incident wave, ^{at the open end} and so they will constructively interfere, to produce an antinode at the open end.

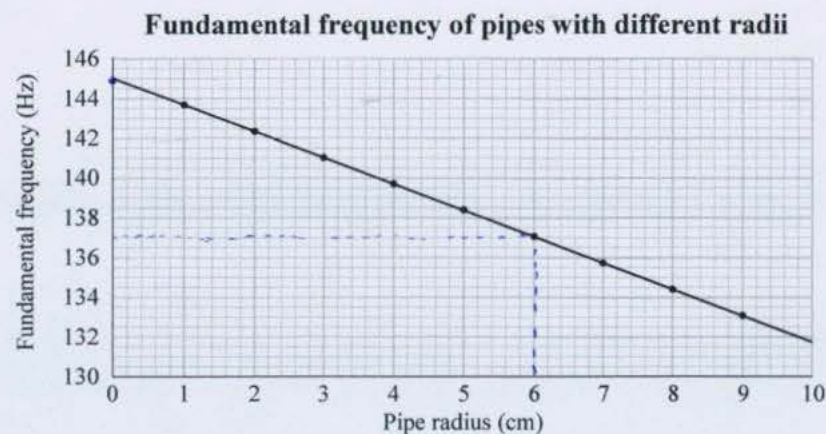
- (c) For an open end, the oscillation of air particles extends beyond the end of the pipe, making the pipe behave as if it is slightly longer than it really is. The larger the radius of the pipe, the more significant this effect becomes.

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:

$$e = kr$$

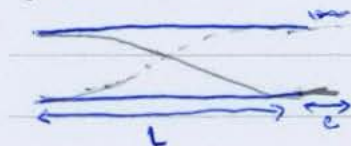
where r is the radius of the pipe and k is a constant.

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}



$$\lambda = 2(L + e) \quad f = 145, r = 0$$

$$\frac{v}{f} = 2L + 2e \quad 145 = \frac{343}{2L}$$

$$\frac{f}{v} = \frac{1}{2L + 2kr} \quad L = \frac{343}{2 \times 145} = 1.18 \text{ m (3sf)}$$

$$f = \frac{v}{2L + 2kr} \quad 137$$

$$f = \frac{343}{2.36 + 2kr} \quad r = 6.0 \times 10^{-2} \quad f = 137$$

$$137 = \frac{343}{2.36 + 2 \times 6.0 \times 10^{-2} k}$$

$$2.36 + 12.0 \times 10^{-2} k = \frac{343}{137}$$

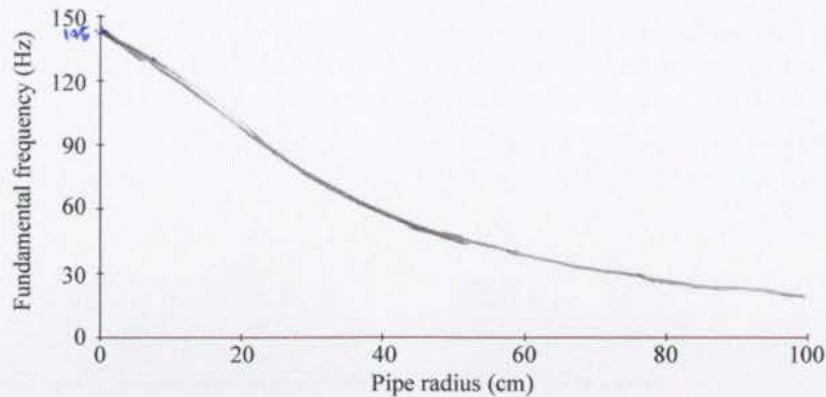
$$12.0 \times 10^{-2} k = 0.1433$$

$$k = 1.20 \quad (3\text{sf})$$

- (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 we increase the pipe radius, we increase the end correction, and hence the effective length of the pipe. A larger pipe length results in a larger wavelength for the fundamental note.

Considering the limit cases: As the radius of the pipe approaches infinity, so will the wavelength of the note approach infinity. $\star F = \frac{v}{\lambda}$, so therefore the fundamental frequency will tend towards zero as the radius of the pipe increases to large values. (Since v is constant). Thus, we will not get a linear trend.

QUESTION THREE: X-RAY PHOTOELECTRON SPECTROSCOPY

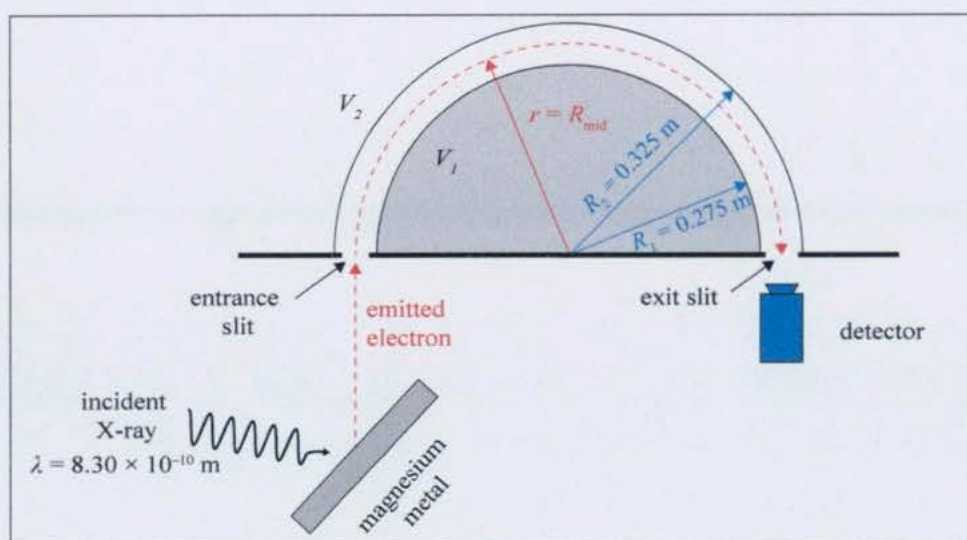
Charge of an electron = $-1.60 \times 10^{-19} \text{ C}$

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.

To travel round the hemisphere, the electron requires a centripetal force (a force towards the centre of its circular path). This centripetal force must be supplied by the electric force, caused by the potential difference $V_2 - V_1$. In order to have an electric force towards the centre of the electron's circular path, the potential difference $V_2 - V_1$ should be negative.

- (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.

$$F_c = F_e$$

$$\frac{mv^2}{r} = Eq$$

we know

$$r = R_1 + \frac{(R_2 - R_1)}{2}$$

$$= 0.275 + \frac{(0.325 - 0.275)}{2}$$

$$= 0.30 \text{ m}$$

$$\frac{mv^2}{r} = \frac{Vq}{R_2 - R_1}$$

$$mv^2 = \frac{Vq r}{R_2 - R_1}$$

$$= \frac{(160)(1.60 \times 10^{-19})(0.30)}{0.05}$$

$$= 5.76 \times 10^{-17}$$

$$E_k = \frac{1}{2} mv^2$$

$$= \frac{1}{2} (5.76 \times 10^{-17})$$

$$= 2.88 \times 10^{-17} \text{ J}$$

$$1 \text{ eV}$$

$$E = \frac{2.88 \times 10^{-17}}{1.60 \times 10^{-19}} = 180 \text{ eV}$$

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

$$E_k = 2.88 \times 10^{-17} \text{ J}$$

$$E_k = hf - \phi_{\min}$$

$$\phi_{\min} = hf - E_k$$

$$= \frac{hc}{\lambda} - E_k$$

$$= \frac{(6.63 \times 10^{-34})(3.00 \times 10^8)}{(8.30 \times 10^{-12})} - 2.88 \times 10^{-17}$$

$$= 2.11 \times 10^{-16} \text{ J}$$

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

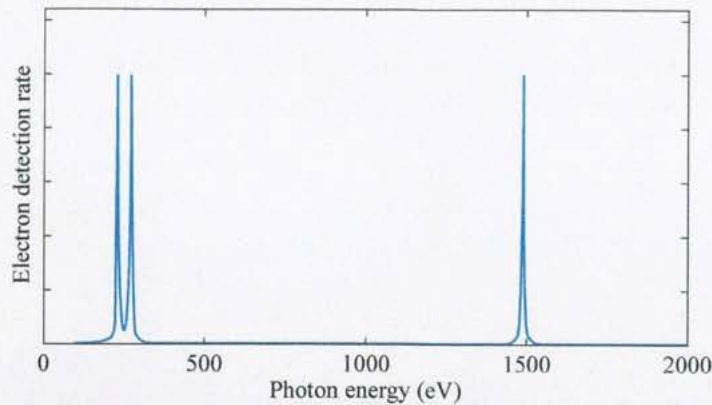
Explain why this is necessary, and discuss how the kinetic energy of a photoemitted electron would be affected if the magnesium was not electrically connected to ground.

If the magnesium is not electrically connected to the ground, then as electrons are released from the metal's surface, ~~there will~~ a charge separation will form within the magnesium metal, with the side the electrons are being released from becoming more positively charged. Therefore, further electrons that absorb a photon to be emitted, will require more energy than previously since the previous electrons now have to overcome the electrostatic attraction to the positive side of the magnesium metal. This means that the kinetic energy of an emitted photoelectron will decrease.

When the magnesium metal is electrically grounded, ~~there is~~ no charge separation will form, and so the electrons will maintain their kinetic energy needed for the experiment.

- (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 inside the magnesium metal is quantised^{atom} (restricted to a set order of possible values). Since only electrons were detected at specific photon energies, it implies that these photons had the exact amount of energy ~~that~~ needed to be absorbed by the electron, transferring its energy over to the electron so it can be emitted. Thus when light of the ~~right~~^{correct} frequencies was incident on the magnesium metal's surface, we detected a high emission of electrons, whereas if the frequency was not correct (i.e. the energy of the photons did not exactly match the energy difference required), then we got no electrons emitted. The double peak at ≈ 250 eV is likely the emission of Magnesium's two valence electrons.

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:

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

Forces



Acceleration

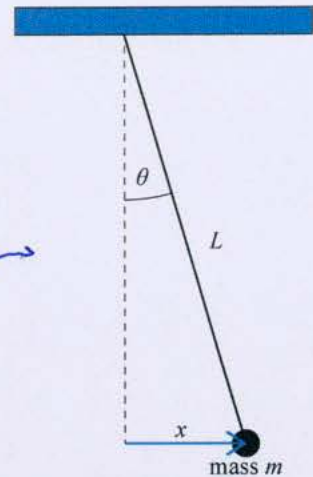
$$a = \frac{F}{m}$$

$$= \frac{-mg \tan \theta}{m}$$

$$= -g \tan \theta$$

$$\sin \theta = \frac{x}{L}$$

From here



For

$$\tan \theta = \frac{F_{\text{net}}}{F_g}$$

$$F_{\text{net}} = F_g \tan \theta$$

$$= -mg \tan \theta$$

$$\text{For small } \theta : \sin \theta \approx \tan \theta$$

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

- (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.

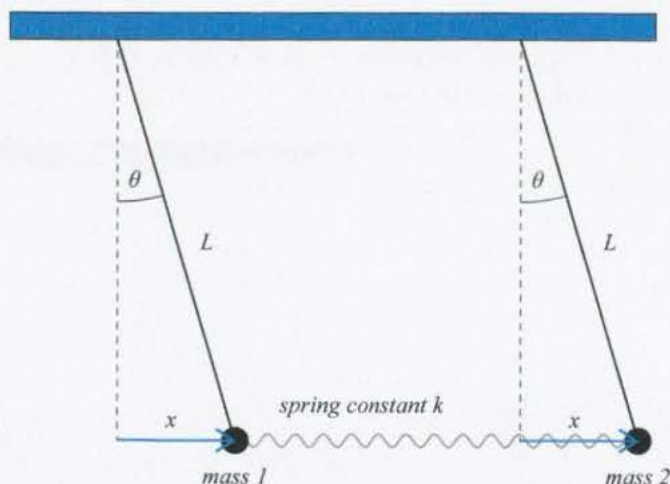
By when θ is small, we can use the small angle approximation ($\sin \theta \approx \tan \theta$)

to derive the equation: $a = -\frac{gx}{L}$

This shows that the motion of a simple pendulum can be approximated as simple harmonic motion, since: Acceleration is towards equilibrium (indicated by negative sign), and acceleration is proportional to displacement from equilibrium.

- (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.

Since the pendulums oscillate in phase, the spring will have no effect ~~on the period~~ ^{on the period}

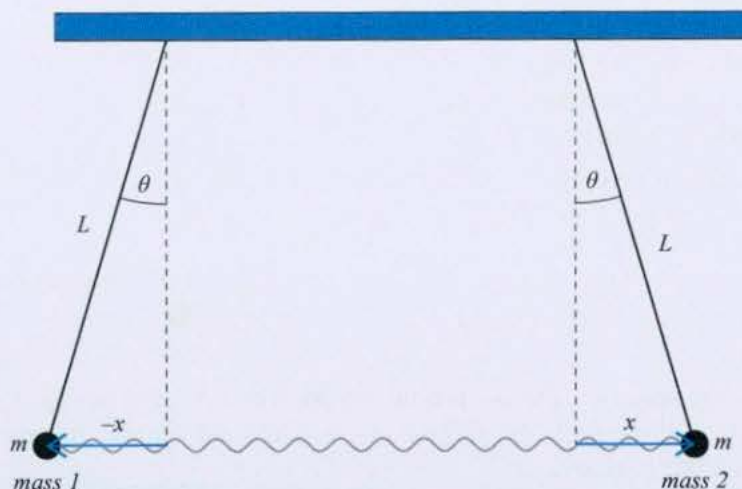
$$T = 2\pi \sqrt{\frac{L}{g}} = 2\pi \sqrt{\frac{0.560}{9.81}} = 1.50 \text{ s}$$

Both pendulums will have the period 1.50 s

As the constant distance between the balls does not change, the spring does not stretch.

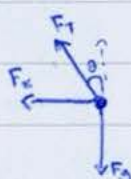
Therefore we can consider the pendulum system simply as its individual pendulum components.

- (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:

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



$$\begin{aligned} F_{\text{net}} &= kx - \frac{mg}{L} \\ &= -x \left(k + \frac{mg}{L} \right) \end{aligned}$$

$$\begin{aligned} F_{\text{net}} &= -k(2x) - \frac{mgx}{L} \\ &= -x \left(2k + \frac{mg}{L} \right) \end{aligned}$$

$$a = \frac{F}{m} = -x \left(\frac{2k}{m} + \frac{g}{L} \right) \quad \text{we also know } a = -A\omega^2 = -x\omega^2$$

Equating accelerations:

$$-x \left(\frac{2k}{m} + \frac{g}{L} \right) = -x\omega^2$$

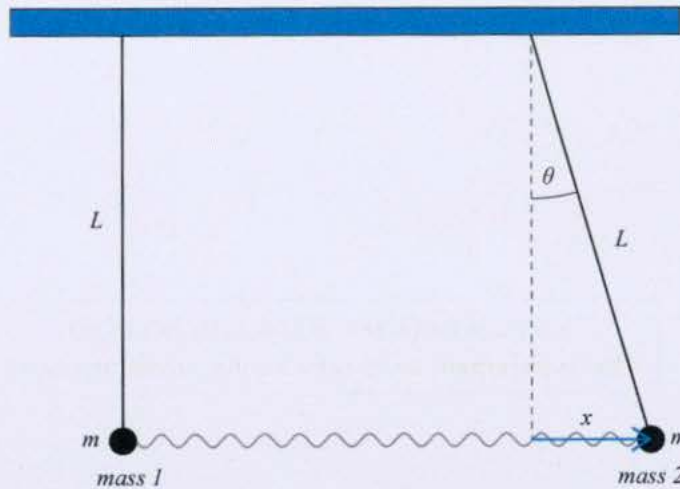
$$\left(\frac{2\pi}{T} \right)^2 = \left(\frac{2k}{m} + \frac{g}{L} \right)$$

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

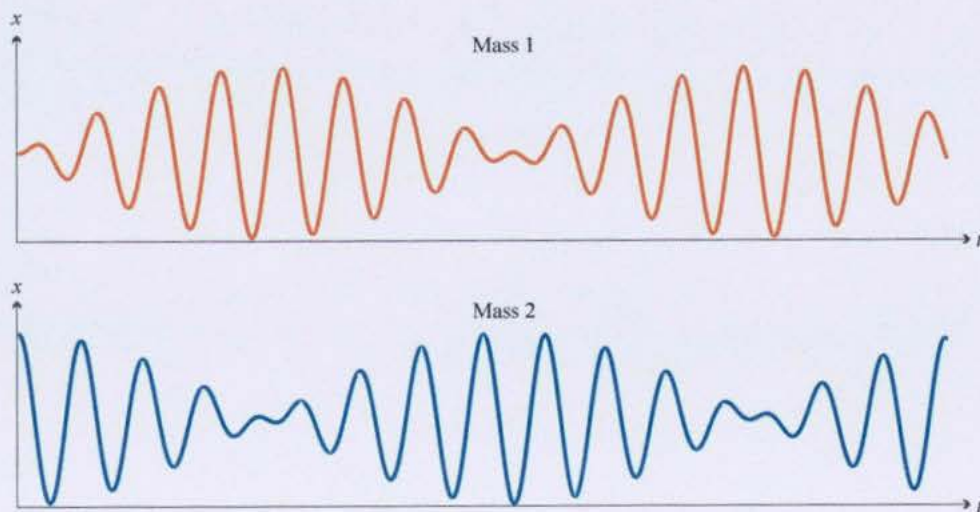
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*Question Four continues
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- (d) For the third investigation, mass 1 is held at its equilibrium position, while mass 2 is displaced to the right, as shown below.



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.

On mass 2 initially:

$$F_{\text{net}} = -kx - \frac{mgx}{L}$$

On mass 1 initially:

$$F_{\text{net}} = -kx$$

Initially we have m_2 is experiencing a large force so will experience a large acceleration, where the spring potential energy is converted to the kinetic energy of m_2 .

At

At equilibrium for both masses: $F_{\text{net}} = -kx$

~~Outwards~~ Outwards: $F_{\text{net}} = -kx - \frac{mgx}{L}$

~~Inwards~~ Inwards: $F_{\text{net}} = kx - \frac{mgx}{L}$

This shows the force is maximum ~~and~~ while the pendulums move outwards and is minimum when the pendulum swings outward. These changing forces result in the amplitude of the oscillation varying from large to small, and the period of the oscillations for m_1 and m_2 being out of phase by 90° . So when the amplitude of m_1 's oscillations are large, the amplitude of m_2 's oscillations are small. The masses transfer kinetic energy between each other, by transforming or going to or from the elastic potential energy within the spring, which they are both connected to.