

No part of the candidate's evidence in this exemplar material may be presented in an external assessment for the purpose of gaining an NZQA qualification or award.

SUPERVISOR'S USE ONLY

S

93103



931030

Draw a cross through the box (X) if you have NOT written in this booklet

☐

+

SCHOLARSHIP EXEMPLAR



Mana Tohu Mātauranga o Aotearoa
New Zealand Qualifications Authority

Scholarship 2024 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 2–24 in the correct order and that none of these pages is blank.

Do not write in any cross-hatched area (⚡). 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.

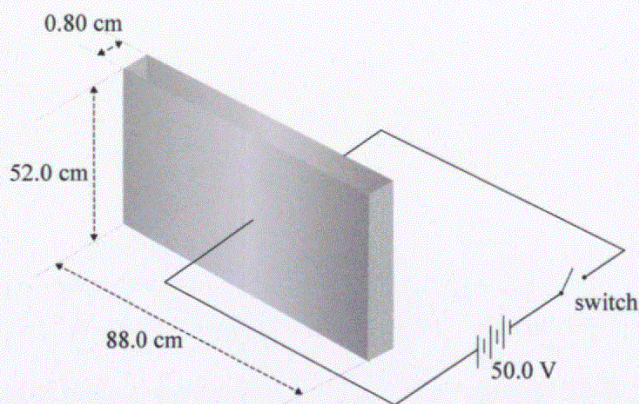
The formulae below may be of use to you.

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

QUESTION ONE: CAPACITOR TANK

Permittivity of free space = $8.85 \times 10^{-12} \text{ F m}^{-1}$
 Relative permittivity of air = 1.0

Hannah uses a rectangular tank, as shown in the diagram, to carry out a series of experiments investigating the behaviour of a parallel plate capacitor. The front and back of the tank are made of conducting metal plates 88.0 cm wide and 52.0 cm high. The sides and bottom of the tank are 0.80 cm wide, and are made of thin, non-conducting plastic.



- (a) (i) For her first experiment, Hannah closes the switch to connect the plates to the 50.0 V power supply.

Show that the charge stored on the plates is $2.5 \times 10^{-8} \text{ C}$.

Explain why this value should be stated to two significant figures.

$$C = \frac{\epsilon_0 A}{d} = \frac{8.85 \times 10^{-12} \times 0.52 \times 0.88}{0.008} = 5.06 \times 10^{-10} \text{ F}$$

$$Q = CV = 5.06 \times 10^{-10} \times 50 = 2.5311 \times 10^{-8} \text{ C}$$

$$= 2.5 \times 10^{-8} \text{ C (2sf)}$$

This value should be stated to 2 significant figures because, ~~the~~ of the measured values (0.80 cm, 52.0 cm, 88.0 cm, 50.0 V), the lowest accuracy given is 2 significant figures - for 0.80 cm.

The calculated charge value can only be as accurate as the lowest accuracy measurement in order to reflect ^{limited} accuracy of measuring equipment.

- (ii) Explain why the amount of energy stored in the charged capacitor is only half of the total energy provided by the power supply.

Of the total energy provided by the power supply, half is lost to heat in the wires*, so only half can be stored in the charged capacitor.

* and across the internal resistance of the battery.

- (b) The tank can be filled with a non-conducting oil with a relative permittivity of 2.1. No charge is transferred from the plates to the oil. There is a valve in the bottom of the tank that can be opened to drain the oil from the tank.

For her second experiment, Hannah starts with the tank empty, the plates uncharged, and the switch open. She then carries out the following steps in sequence to achieve a potential difference between the plates that is greater than 50.0 V:

- Step 1: Close the switch.
 Step 2: Fill the tank with oil.
 Step 3: Open the switch.
 Step 4: Drain the oil from the tank.

* (By conservation of charge)

- (i) Explain the effect of each of these steps, and how this sequence results in a potential difference that is greater than 50.0 V between the plates.

Step 1: Closing the switch initiates the capacitor's charging process. By $V = V_{\max}(1 - e^{-t/\tau})$, the capacitor charges by storing charge from electrons, thus building voltage. After sufficient time has passed ($\approx 5\tau$), the maximum voltage of 50.0 V and the maximum charge of $2.5 \times 10^{-8} \text{ C}$ is reached.

Step 2: Filling the tank with non-conducting oil acts as the addition of a dielectric medium between the plates. This is a non-conductive substance that can easily polarise. This increases the capacitance of the capacitor, and assuming the tank is entirely filled with the oil, $C_F = \epsilon_r C_i$, so that $C_F = 1.06 \times 10^{-9} \text{ F}$. By $Q = CV$, for constant supply voltage, the capacitor gains more charge due to its increased capacitance, now storing $Q_F = 1.06 \times 10^{-9} \times 50 = 5.3 \times 10^{-8} \text{ C}$ after sufficient charging time.

Step 3: By opening the switch, the power supply no longer controls the voltage across the capacitor, so that it is now dependent on the charge stored on the capacitor and its capacitance by $V = \frac{Q}{C}$.

Step 4: Draining the oil from the tank removes the dielectric medium from the capacitor, thus reducing its capacitance back to $C_i = \frac{C_F}{\epsilon_r}$ (back to $5.06 \times 10^{-10} \text{ F}$). As the charge stored on the plates is constant (if discharge has yet to occur), the voltage now increases across the capacitor, so that $V = \frac{Q}{C} = \frac{5.3 \times 10^{-8}}{5.06 \times 10^{-10}} = 105 \text{ V}$, greater than 50 V.

- (ii) Calculate the value of the potential difference between the plates that results from following the sequence of steps described on page 5.

Calculations on page 5.

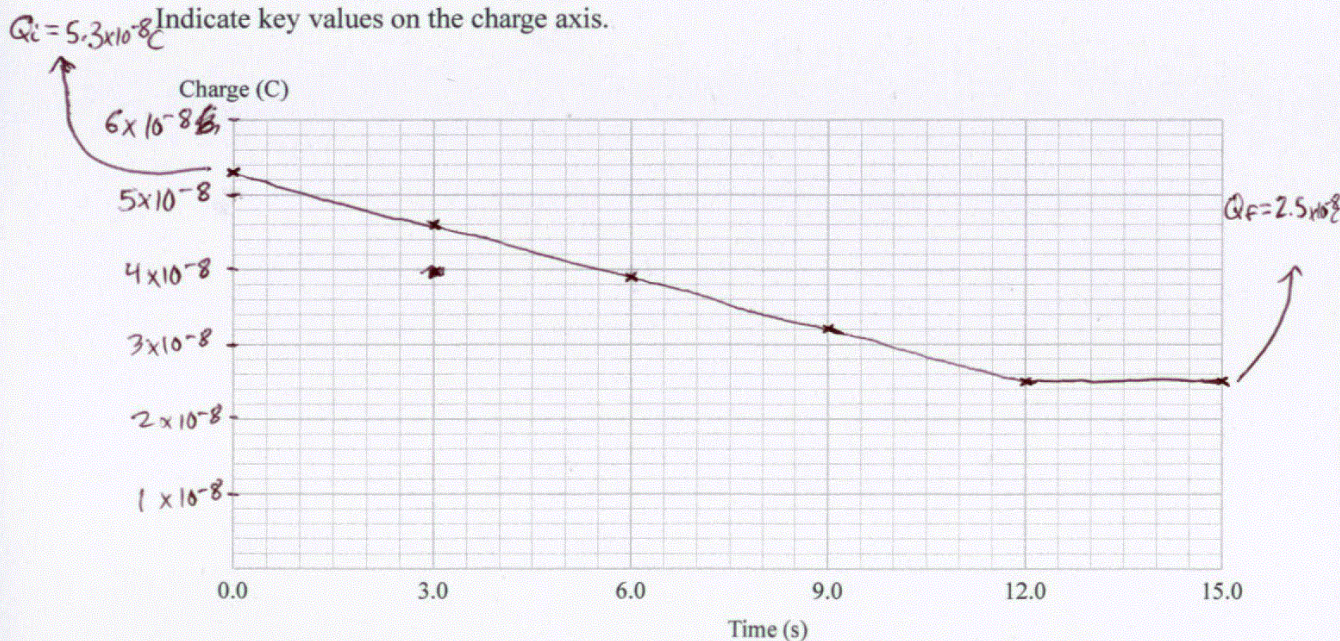
- (c) For her third experiment, Hannah fills the tank with oil and closes the switch so that the potential difference across the plates is 50.0 V. At time $t = 0.0$ s, she opens the valve and oil drains from the tank while the switch remains closed. The tank is completely empty after 12.0 s. Assume the oil flows from the tank at a constant rate.

~~$C = 1.06 \times 10^{-9} \text{ F}$~~

$\rightarrow C = 5.06 \times 10^{-10} \text{ F}$

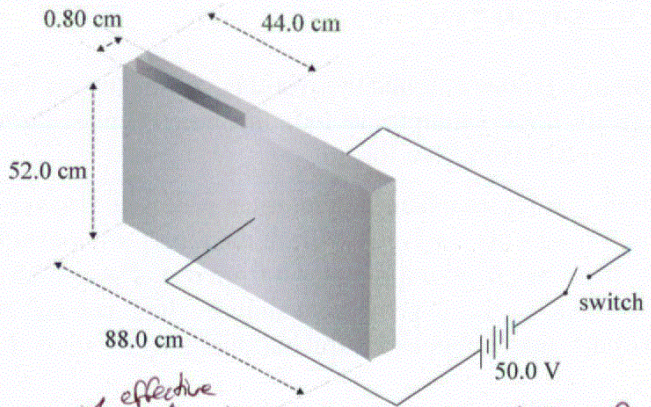
Sketch a graph on the axes below to show how the charge stored on the plates changes over the first 15.0 s.

Indicate key values on the charge axis.



- (d) For her last experiment, Hannah now adds a third parallel thin metal plate between the two original plates. The new plate is the same height as the two original plates, but is only half the width, and has negligible thickness.

Using appropriate physics concepts, explain the effect that adding the third plate will have on the total capacitance of the tank.



The third plate will decrease the ^{effective} distance between plates for that half of the capacitor. By $C = \frac{\epsilon_0 A}{d}$, the capacitor can be modelled in 2 ~~halves~~ halves, with the 2 plated half having $C_1 = \frac{\epsilon_0 \times 0.44 \times 0.52}{0.008} = 2.53 \times 10^{-10} \text{ F}$
 And the 3 plated half having $C_2 = \frac{\epsilon_0 \times 0.44 \times 0.52}{0.004} = 5.06 \times 10^{-10} \text{ F}$
 So that the total capacitance $C = C_1 + C_2 = 7.6 \times 10^{-10} \text{ F}$ (2sf)
 This increases total capacitance by 1.5x

(b) By referring to relevant physics principles, discuss the validity of these two statements:

- (i) **Statement 1:** For an object with fixed mass to have linear acceleration, it must experience a non-zero net force.

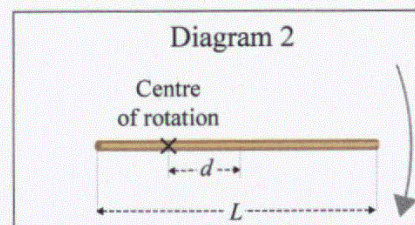
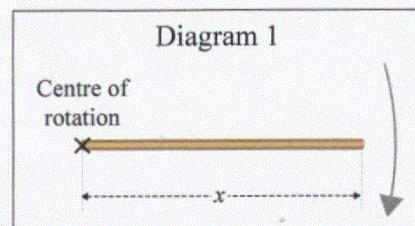
This statement refers to Newton's 2nd law that $F_{\text{net}} = ma$, or that a net force results in an acceleration on a mass.

- (ii) **Statement 2:** For an object with fixed mass to have angular acceleration, it must experience a non-zero net torque.

This statement ~~refers~~ refers to the law $\tau = I\alpha$. The fixed mass of the object is proportional to its rotational inertia I . Yet, this is also determined by the mass distribution of the object.

- (c) For a uniform thin rod with total length x and mass m rotating about one end, as shown in Diagram 1, the rotational inertia I is given by $I = \frac{1}{3}mx^2$.

While performing a sideways strike, a staff can be modelled as a thin, uniform rod rotating about a vertical axis through the centre of rotation, which is in a fixed position. The centre of rotation is closer to one end of the rod than the other, as shown in Diagram 2. The rotational inertia of a thin, uniform rod rotating about an axis part way along the rod can be found by adding the rotational inertias of the sections of the rod either side of the centre of rotation.



Show that the rotational inertia of a thin, uniform rod of length L and mass m rotating about a point a distance d from the centre of mass is given by:

$$I = m \left(\frac{L^2}{12} + d^2 \right)$$

$$I = \frac{1}{3} m x^2$$

Considering the ^{smaller} section of the rod, its length $x_{\text{small}} = \frac{L}{2} - d$

$$\therefore I_{\text{small}} = \frac{1}{3} m \left(\frac{L}{2} - d \right)^2 = \frac{1}{3} m \left(\frac{L^2}{4} - Ld + d^2 \right)$$

Considering the larger section of the rod, its length $x_{\text{large}} = \frac{L}{2} + d$

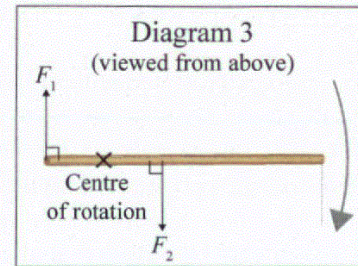
$$\therefore I_{\text{large}} = \frac{1}{3} m \left(\frac{L}{2} + d \right)^2 = \frac{1}{3} m \left(\frac{L^2}{4} + Ld + d^2 \right)$$

$$I_{\text{total}} = I_{\text{small}} + I_{\text{large}} = \frac{1}{3} m \left(\frac{L^2}{2} + 2d^2 \right) \\ = \frac{2}{3} m \left(\frac{L^2}{6} + \frac{2}{3} d^2 \right)$$

~~2/3~~

$$\left(\frac{\sqrt{2}}{\sqrt{3}} d \right)^2 = d^2 - \left(d + \frac{3-\sqrt{6}}{3} d \right)^2 \\ d^2 - \frac{12-2\sqrt{6}}{3} d + \frac{5-2\sqrt{6}}{3} d^2$$

- (d) Ben makes the staff rotate around a vertical axis by applying two horizontal forces F_1 and F_2 , one with each hand. These forces push the ends of the staff in opposite directions, as shown in Diagram 3 (viewed from above). The forces F_1 and F_2 produce a net torque that gives the staff an angular acceleration about the centre of rotation. The forces F_1 and F_2 are spaced equally from the centre of rotation and are applied perpendicular to the staff's length. The centre of rotation stays in the same position.



- (i) Discuss the relative sizes of the forces F_1 and F_2 needed to cause the staff to have an angular acceleration while the centre of rotation does not move. $\alpha = \frac{\tau}{I}$

~~The force applied to F_1~~ $\tau = I\alpha$. For angular acceleration that causes no rotational centre movement, the ^{angular} acceleration ^{caused} each force must be equal. Thus, as F_1 acts on a section of the staff with smaller I , the τ it produces must be smaller to compensate. $\tau_1 = F_1 d$, $\tau_2 = F_2 d$. As distance is constant, this means $F_1 < F_2$. Ben must apply a stronger force to F_2 than F_1 .

- (ii) A sideways strike can be blocked by holding a second staff vertically in front of the rotating staff.

Explain the position and direction that the blocking force should be applied to stop the rotating staff most effectively.

Explain the effect this blocking force has on the motion of the rotating staff.



~~which can occur with $F_{\text{block}} < |F_1| + |F_2|$~~

Source: www.reddit.com/r/martialarts/comments/13cdmpy/mau_rakau_and_wharetutaua/?rdt=43199

As F_2 is greater than F_1 , the blocking force should be applied to the end of the staff that F_2 is being applied to. It should be applied to the end of the staff to maximise d . It will apply a torque $\tau = F_{\text{block}} d$ that will be opposite to the direction of torque caused by F_2 . If $\tau_{\text{block}} > |\tau_2| + |\tau_1|$, the direction of rotation of the staff will change. This occurs by $\tau = I\alpha$, where the blocking torque causes a ^{change in acceleration} of the rotating staff. If the α induced is greater than initial α , direction change occurs. If not, the rotating staff will be slowed.

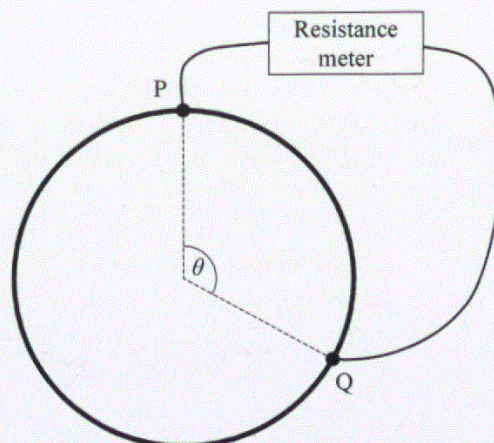
QUESTION THREE: LOOPS AND RINGS

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

A long, straight piece of thin resistive wire has a total resistance R between one end and the other. The piece of wire is now bent into a circular shape and the ends are connected together to make a single circular loop.

A resistance meter is connected between two points on the loop, P and Q, which are separated by an angle θ around the loop as shown.

Point P remains fixed at the top of the loop, but point Q can be moved to any point around the edge of the loop.



- (a) By considering the resistance of the two sections of the circular loop (clockwise from P to Q, and anticlockwise from P to Q), show that R_{PQ} , the total resistance of the loop between the points P and Q, is given by the expression:

$$R_{PQ} = \frac{R\theta}{2\pi} \left(1 + \frac{\theta}{2\pi} \right)$$

*ratio of arc to whole
portion of circle*

$$R_{\text{clockwise}} = R \times \frac{\theta}{2\pi} = \frac{R\theta}{2\pi}$$

$$R_{\text{anticlockwise}} = R \times \frac{2\pi - \theta}{2\pi} = R \left(1 - \frac{\theta}{2\pi} \right) = R - \frac{R\theta}{2\pi}$$

Considering the 2 resistances in parallel:

$$\frac{1}{R_{PQ}} = \frac{1}{R_{\text{clockwise}}} + \frac{1}{R_{\text{anticlockwise}}} = \frac{2\pi}{R\theta} + \frac{2\pi}{R(2\pi - \theta)}$$

$$\frac{1}{R_{PQ}} = \frac{2\pi(2\pi - \theta) + 2\pi\theta}{R\theta(2\pi - \theta)} = \frac{4\pi^2 - 2\pi\theta + 2\pi\theta}{R\theta(2\pi - \theta)}$$

$$R_{PQ} = \frac{R\theta(2\pi - \theta)}{4\pi^2}$$

$$= \frac{R\theta}{2\pi} \left(\frac{2\pi - \theta}{2\pi} \right)$$

$$R_{PQ} = \frac{R\theta}{2\pi} \left(1 - \frac{\theta}{2\pi} \right)$$

as required

- (b) Explain, using physics concepts, where point Q should be placed to give the largest value of R_{PQ} , and determine the maximum value of R_{PQ} for a length of wire with resistance $R = 10 \Omega$.

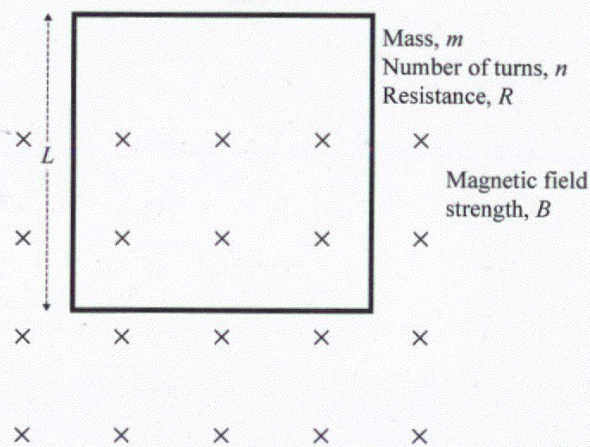
Point Q should be placed directly below point P so that $\theta = \pi \text{ rad} = 180^\circ$. This is because current flows ^{primarily} through the path of least resistance, so having a parallel path that has less resistance than the other will always reduce total resistance for constant source voltage as $R_T = \frac{V_s}{I}$, and current flows predominantly through the lower resistance path so that $I \rightarrow \frac{V_s}{R_{\text{lower}}}$. Thus for maximum resistance, both paths should be equally resistant.

$$\therefore R_{PQ} = \frac{R(\pi)}{2\pi} \left(1 - \frac{\pi}{2\pi}\right) = 2.5 \Omega$$

- (c) A square coil of wire with mass, m , resistance, R , and number of turns, n , falls freely into a uniform magnetic field as shown. The effects of air resistance can be ignored.

- (i) By considering the forces acting on the coil, show that the terminal velocity of the coil as it falls into the field is given by:

$$v = \frac{mgR}{B^2 L^2 n^2}$$



$$F_g = mg$$

$$V = BvLn = IR$$

$$F = BILn = \frac{B^2 v L^2 n^2}{R}$$

$$\therefore I = \frac{BvLn}{R}$$

~~At~~ Terminal velocity is when $F_g = F_{\text{mag}}$

$$\therefore mg = \frac{B^2 v L^2 n^2}{R}$$

$$v = \frac{mgR}{B^2 L^2 n^2}$$

as required.

- (ii) By choosing realistic values for m , n , and L , estimate the terminal velocity of a small coil with resistance $R = 1.0 \Omega$ as it falls into a magnetic field of strength $B = 1.0 \times 10^{-3} \text{ T}$.

Discuss the motion of your coil as it enters the field.

A realistic value of m could be 100g , L could be 30cm , and n could be 5

$$\therefore V = \frac{mgR}{B^2 L^2 n^2} = \frac{0.1 \times 9.81 \times 1}{(1 \times 10^{-3})^2 \times 0.3^2 \times 5^2} = 436000 \text{ m s}^{-1}$$

The coil initially falls with an acceleration of $a = 9.81 \text{ m s}^{-2}$ due to gravity. As a voltage is induced in the wire, current begins to flow, creating a rather magnetic field that interacts with the first to produce a force opposing motion on the coil. This force is equivalent to the gravitational force so that $F_g = F_{\text{mag}}$. ~~Thus, the coil falls at a constant velocity.~~ As it slows from the initial speed to the terminal velocity once in the field, the induced voltage decreases by $V = BLv$. This decreases the current induced, which decreases the force acting to oppose motion by $F = BIL$.

- (d) A square coil is unwound, and the same piece of wire is used to make a second square coil with sides twice as long as the original coil.

Use physics concepts to explain how the terminal velocity of the new coil compares to that of the initial coil when dropped into the same magnetic field.

~~The terminal velocity should be equivalent~~ If sides are twice as long, the perimeter of the square coil has increased by $8\times$. Thus, n must have been reduced by a factor of 8. L is increased by a factor of 2. $\therefore$ velocity reduced by $\frac{1}{16}$ ($\frac{1}{8}^2 \times \frac{1}{2}^2$)

QUESTION FOUR: LASER COOLING

Planck's constant = 6.63×10^{-34} J s

Mass of a sodium atom = 3.82×10^{-26} kg

Speed of light = 3.00×10^8 m s⁻¹

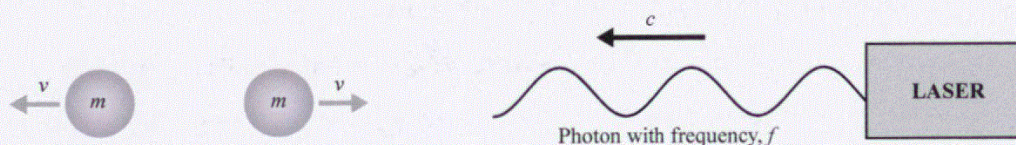
Physicists use lasers to transfer momentum and slow down gaseous atoms. This can cool a gas down to temperatures close to absolute zero.

The momentum of a photon is related to its wavelength by the relationship:

$$p = \frac{h}{\lambda}$$

A laser of frequency, f , is shone into a container holding gaseous sodium atoms. The energy of each photon is slightly less than the difference in energy between two electron energy levels in a sodium atom.

Gaseous sodium atoms can be moving in any direction, but for the purposes of Question Four, we will only consider one-dimensional motion – either towards or away from the laser.



- (a) Explain which sodium atom, the one moving towards the laser or the one moving away from the laser, can absorb a photon from the laser.

Considering the doppler effect, for the sodium atom moving towards the photon, it will have a higher apparent frequency than its actual frequency, because the atom encounters each successive wavefront at a shorter ^{time interval} ~~distance~~ apart than they actually are due to its motion, making the apparent wave length shorter than if the atom was stationary. Thus, by $f = \frac{c}{\lambda}$, where c is constant, the apparent frequency is higher. As $E = hf$, so $E \propto f$, this means the photon will have slightly higher relative energy. This will allow it to be absorbed, as it will now be able to match the difference in energy levels in a sodium atom, thus exciting an electron to a higher energy level. Thus, it is the atom moving towards the laser that can absorb the photon. The atom moving away will experience a lower frequency due to ^{higher} ~~lower~~ apparent wavelength of the laser, meaning the photon has lower energy than usual, which is already less than the difference in energy between 2 sodium electron energy levels, so it will not be absorbed by this atom.

(b) Explain how the momentum of each of the sodium atoms, the one moving towards the laser and the one moving away from the laser, may be affected by the photon.

The atom moving towards the laser can absorb the photon, and with it its energy $E = hf$. The photon's momentum is $p = \frac{h}{\lambda} = \frac{h}{c} f$. Thus it's proportional to its frequency, ~~which is greater~~. As it ~~is~~ moving in the opposite direction to the photon travelling towards it, by $P_i = \overset{\leftarrow}{P}_{\text{photon}} + \vec{P}_{\text{sodium}}$, the total momentum ^{of the system} will be less than the sodium atom's initial momentum, though likely still in the same direction ($\rightarrow$) due to sodium atoms having immensely larger mass than a photon. Thus, upon ~~collision~~ ^{absorption}, by conservation of momentum, the final momentum of the sodium atom will be decreased.

The atom moving away from the laser has a momentum in the same direction as the laser & so that p_i is greater than the initial atom's momentum and in the same direction ($\leftarrow$). By conservation of momentum upon collision (not absorption), the total system's momentum will be equal to this. So that the atom's total momentum likely increases while the photon's decreases.

- (c) For an observer moving at speed v , where v is much less than the speed of light, the apparent change in frequency Δf of an electromagnetic wave of frequency f , due to the Doppler effect, can be approximated by:

$$\Delta f = \frac{fv}{c}$$

A transition between energy levels in a sodium atom occurs when a photon with wavelength $5.89 \times 10^{-7} \text{ m}$ is absorbed. The average speed of a gaseous sodium atom at room temperature is $5.70 \times 10^2 \text{ m s}^{-1}$.

Calculate the percentage change in momentum of a sodium atom caused by the absorption of a photon with wavelength $5.89 \times 10^{-7} \text{ m}$.

~~$$f_{\text{photon}} = \frac{c}{\lambda} = \frac{3 \times 10^8}{5.89 \times 10^{-7}} = 5.09 \times 10^{14} \text{ Hz}$$~~

~~The speed of the sodium atom = 5.7×10^2~~

~~$$\therefore \Delta f = \frac{f v}{c} = \frac{5.09 \times 10^{14} \times 5.74 \times 10^7}{3 \times 10^8} = 9.68 \times 10^8 \text{ Hz}$$~~

~~Relativ Energy $E = mc^2$ $F' = F + \Delta F = 5.09 \times 10^{14} + 9.68 \times 10^8$~~

~~$$T_{E_{rel}} = E_{rel} + E_{rec}$$~~
~~$$= 3.42 \times 10^{-19} \text{ J}$$~~

~~$E' = hf' = 3.377 \times 10^{-19} \text{ J}$~~

~~$$P_{\text{solidum}} = \rho v = 2.18 \times 10^{-25} \text{ kg m s}^{-1}$$~~

8. conservation of energy, ~~$E_{ki} = E_{kf} + E_{int} + E' = E_{kf}$~~

$$K_i = \frac{1}{2} m (v_i)^2 = 6.21 \times 10^{-21} \text{ J}$$

Physics 93103, 2024

Question Four continues
on the following page.

 ~~$\frac{\Delta P}{P_i} = 8.9\%$~~

844% change in momentum 00877

- (d) Despite being used for slowing atoms down, this process can sometimes result in an atom moving faster than it was originally. After absorbing a photon, the sodium atom can then emit a photon when the electron drops back down to its original energy level. The emitted photon can be emitted in any direction.

Explain how this process can result in the atom moving faster than its original speed if the photon is emitted in the same direction the original photon was travelling (away from the laser).

If the photon is emitted in the same direction the original photon was travelling (away from the laser) it will have a momentum $p = \frac{h}{\lambda}$ that is in that same direction. Its momentum ~~at~~ before emission p_i ~~is~~ from left to right ($\rightarrow$) but p_{total} is equal to the final momentum of the sodium atom + p_{photon} $= |p_{\text{sodium}}| - |p_{\text{photon}}|$. As momentum is conserved, $p_{\text{sodium}} = |p_{\text{total}}| + |p_{\text{photon}}|$, thus momentum increases. ~~At~~ At constant mass, the sodium atom has increased momentum from when it had the photon absorbed, thus it has greater velocity. The velocity decrease upon absorption Δv_{abs} ~~depends on~~ p_{photon} . The velocity ~~decrease~~ ^{increase} upon emission depends on p_{photon} . $\Delta v_{\text{emission}} > \Delta v_{\text{absorption}}$, because the final momentum of the photon relative to the sodium atom is greater than the ~~initial~~ initial momentum of the photon relative to the sodium atom (preabsorption). This is due to the doppler shift that increases apparent frequency ~~pre~~ ^{pre} absorption and decreases it post absorption.

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

QUESTION
NUMBER

4(c) $p_{\text{photon}} = \frac{h}{\lambda} = \frac{1.13 \times 10^{-27} \text{ kgms}^{-1}}{(1.125636672 \times 10^{-27} \text{ kgms}^{-1})} \rightarrow \text{without doppler shift}$

$p_{\text{sodium}} = mv = 2.18 \times 10^{-23} \text{ kgms}^{-1} = (2.1774 \times 10^{-23})$

$p_{\text{total}} = \overleftarrow{p_{\text{photon}}} + \overrightarrow{p_{\text{sodium}}} = |p_{\text{sodium}}| - |p_{\text{photon}}|$

~~Wavelength~~ $p_{\text{photon}} = \frac{h}{c} f$

When f changes due to doppler effect,

~~$\Delta f = \frac{f v}{c} = 5.09 \times 10^8$~~

$\Delta f = \frac{f v}{c}$, $f = \frac{c}{\lambda}$, $\Delta f = \frac{v}{\lambda} = 9.68 \times 10^8 \text{ Hz}$

$f' = f + \Delta f = 9.68 \times 10^8 + \frac{c}{\lambda} = 5.09 \times 10^{14} \text{ Hz}$

$= 9.68 \times 10^8 + 5.093378608 \times 10^{14} = 5.093388285 \times 10^{14} \text{ Hz}$

$p_{\text{photon}} = \frac{h}{c} f' = 1.126 \times 10^{-27} \text{ kgms}^{-1}$ - with doppler shift
 $= (1.12563881 \times 10^{-27} \text{ kgms}^{-1})$ (negligible difference at 4sf)

$p_{\text{total}} = 2.18 \times 10^{-23} - 1.125 \times 10^{-27} = 2.177287436 \times 10^{-23}$
 $= 2.1773 \times 10^{-23} \text{ kgms}^{-1} (5sf)$

$= p_{\text{total}}$

by conservation of momentum
 $= p_{\text{sodium}} \text{ (due to absorption)}$

$\Delta p_{\text{sodium}} = 1.125 \times 10^{-27}$

$\% \Delta p = \frac{1.125 \times 10^{-27}}{2.18 \times 10^{-23}} \times 100 = 5.1696 \times 10^{-3}$

$= 0.0051696\%$

$= 0.00517\% \text{ change in momentum}$

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

QUESTION
NUMBER

4(b) For the atom moving towards the photon/laser, Its momentum is in the opposite direction to the photon's. $\therefore$

$$p_{\text{total}} = \overset{\rightarrow}{p_{\text{sodium}}} + \overset{\leftarrow}{p_{\text{photon}}}$$

As $|p_{\text{sodium}}| \gg |p_{\text{photon}}|$ (due to the photon's ~~very small~~ ~~momentum~~ ~~being~~ mass being very small ($m = \frac{E}{c^2}$))

$$\overset{\rightarrow}{p_{\text{total}}} = |p_{\text{sodium}}| - |p_{\text{photon}}|$$

Thus the momentum of the atom moving towards the laser will be reduced, but still act in the same direction as the initial momentum. It will only be reduced slightly by 1 photon.

Scholarship

Subject: Physics

Standard: 93103

Total score: 23

Q	Score	Marker commentary
1	7	High level scholarship understanding of a novel capacitance context.
2	4	Variable understanding across a range of situations involving mechanics concepts mainly relating to rotating systems.
3	6	Scholarship level understanding of a variety of electrical and mechanics concepts. Sound mathematical manipulation demonstrated.
4	6	Scholarship level understanding of modern physics in a unique and challenging context.