SUPERVISOR'S USE ONLY

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

Mana Tohu Mātauranga o Aotearoa
New Zealand Qualifications Authority

Scholarship 2023
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 (DO NOT WRITE IN THIS AREA). This area may be cut off when the booklet is marked.

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

Question	Score
ONE	
TWO	
THREE	
FOUR	
TOTAL	

ASSESSOR'S USE ONLY

This page has been deliberately left blank.
The assessment starts on page 4.

The formulae below may be of use to you.

$v_f = v_i + at$

$d = v_i t + \frac{1}{2}at^2$

$d = \frac{v_i + v_f}{2}t$

$v_f^2 = v_i^2 + 2ad$

$F_g = \frac{GMm}{r^2}$

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

$\Delta p = F\Delta t$

$\omega = 2\pi f$

$d = r\theta$

$v = r\omega$

$a = r\alpha$

$W = Fd$

$F_{net} = ma$

$p = mv$

$x_{COM} = \frac{m_1x_1 + m_2x_2}{m_1 + m_2}$

$\omega = \frac{\Delta\theta}{\Delta t}$

$\alpha = \frac{\Delta\omega}{\Delta t}$

$L = I\omega$

$L = mvr$

$\tau = I\alpha$

$\tau = Fr$

$E_{K(ROT)} = \frac{1}{2}I\omega^2$

$E_{K(LIN)} = \frac{1}{2}mv^2$

$\Delta E_p = mg\Delta h$

$\omega_f = \omega_i + \alpha t$

$\omega_f^2 = \omega_i^2 + 2\alpha\theta$

$\theta = \frac{(\omega_i + \omega_f)}{2}t$

$\theta = \omega_i t + \frac{1}{2}\alpha t^2$

$T = 2\pi\sqrt{\frac{l}{g}}$

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

$E_p = \frac{1}{2}ky^2$

$F = -ky$

$a = -\omega^2 y$

$y = A\sin\omega t \qquad y = A\cos\omega t$

$v = A\omega\cos\omega t \qquad v = -A\omega\sin\omega t$

$a = -A\omega^2\sin\omega t \qquad a = -A\omega^2\cos\omega t$

$\Delta E = Vq$

$P = VI$

$V = Ed$

$Q = CV$

$C_T = C_1 + C_2$

$\frac{1}{C_T} = \frac{1}{C_1} + \frac{1}{C_2}$

$E = \frac{1}{2}QV$

$C = \frac{\varepsilon_o\varepsilon_r A}{d}$

$\tau = RC$

$\frac{1}{R_T} = \frac{1}{R_1} + \frac{1}{R_2}$

$R_T = R_1 + R_2$

$V = IR$

$F = BIL$

$V = BvL$

$F = Bqv$

$F = Eq$

$E = \frac{V}{d}$

$\phi = BA$

$\varepsilon = -\frac{\Delta\phi}{\Delta t}$

$\varepsilon = -L\frac{\Delta I}{\Delta t}$

$\frac{N_p}{N_s} = \frac{V_p}{V_s}$

$E = \frac{1}{2}LI^2$

$\tau = \frac{L}{R}$

$I = I_{MAX}\sin\omega t$

$V = V_{MAX}\sin\omega t$

$I_{MAX} = \sqrt{2}\,I_{rms}$

$V_{MAX} = \sqrt{2}\,V_{rms}$

$X_C = \frac{1}{\omega C}$

$X_L = \omega L$

$V = IZ$

$f_0 = \frac{1}{2\pi\sqrt{LC}}$

$v = f\lambda$

$f = \frac{1}{T}$

$n\lambda = \frac{dx}{L}$

$n\lambda = d\sin\theta$

$f' = f\frac{V_W}{V_W \pm V_S}$

$E = hf$

$hf = \phi + E_K$

$E = \Delta mc^2$

$\frac{1}{\lambda} = R\left(\frac{1}{S^2} - \frac{1}{L^2}\right)$

$E_n = -\frac{hcR}{n^2}$

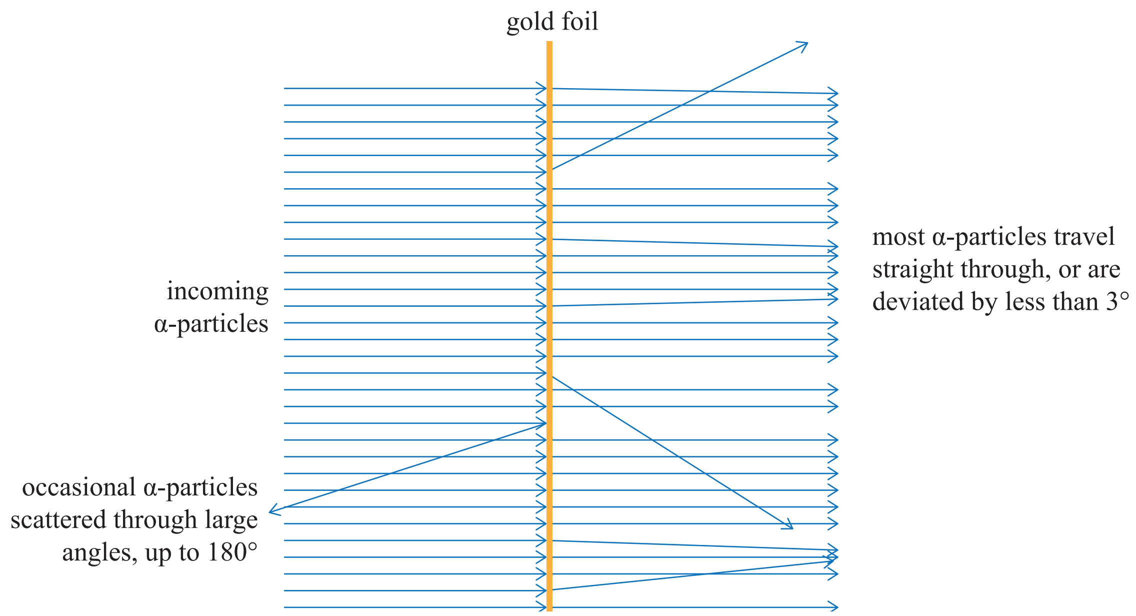
QUESTION ONE: THE DISCOVERIES OF ERNEST RUTHERFORD

Atomic number of gold = 79
Charge of an electron = -1.60×10^{-19} C

Ernest Rutherford won a Nobel Prize in 1908 for work on understanding radioactive decay and for discovering α-particles. Later, he and his fellow researchers used α-particles in two famous experiments.

Experiment 1: Scattering of alpha particles by gold foil

When Rutherford fired α-particles at a thin foil of gold, he observed that most went straight through or deviated by less than 3 degrees. However, the researchers were surprised to see occasional α-particles were scattered through large angles, some even returning in the direction from which they had come.



(a) Explain how these results were consistent with the model of the atom that Rutherford proposed.

(b) The electrostatic potential energy between two charges, of magnitudes q_1 and q_2, and separated by distance r, is given by $E_p = \frac{kq_1q_2}{r}$, where k = 8.99×10^9 N m^2 C^{-2}.

An α-particle of mass m, velocity v, and charge $2e$, travels directly towards a nucleus that remains stationary at all times. The charge on the stationary nucleus is Ze, where Z is the atomic number of the stationary nucleus, and e is the charge of an electron.

(i) Show that the distance of closest approach, D, is given by:

$$D = \frac{4kZe^2}{mv^2}$$

Explain your reasoning.

(ii) Calculate the distance of closest approach of a 4.78 MeV α-particle travelling directly towards a gold nucleus, which is fixed in position.

(c) If a nucleus of charge *Ze* were free to move, as would occur if it were in the gaseous state for example, would the distance of closest approach be the same, greater, or less than given by the equation in part (b)(i)?

Explain your answer using physical principles.

No calculation is required.

(d) **Experiment 2: Bombardment of nitrogen gas by high-energy alpha particles**

Rutherford and his fellow researchers fired high-energy, 7.70 MeV, α-particles at a container of nitrogen gas and were surprised to see that protons, ${}^{1}_{1}\mathrm{H}$, were emitted. At the time, the researchers knew that a nuclear reaction had occurred, but they did not know what the reaction was. Two possible nuclear reactions are:

$${}^{14}_{7}\mathrm{N} + {}^{4}_{2}\alpha \rightarrow {}^{17}_{8}\mathrm{O} + {}^{1}_{1}\mathrm{H} \qquad \text{Reaction 1}$$

$${}^{14}_{7}\mathrm{N} + {}^{4}_{2}\alpha \rightarrow {}^{13}_{6}\mathrm{C} + {}^{1}_{1}\mathrm{H} + {}^{4}_{2}\alpha \qquad \text{Reaction 2}$$

(i) Using your knowledge of binding energy per nucleon, explain which reaction, Reaction 1 or Reaction 2, is more likely.

(ii) Explain why it was necessary to use high-energy α-particles for this experiment.

QUESTION TWO: AXE THROWING

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

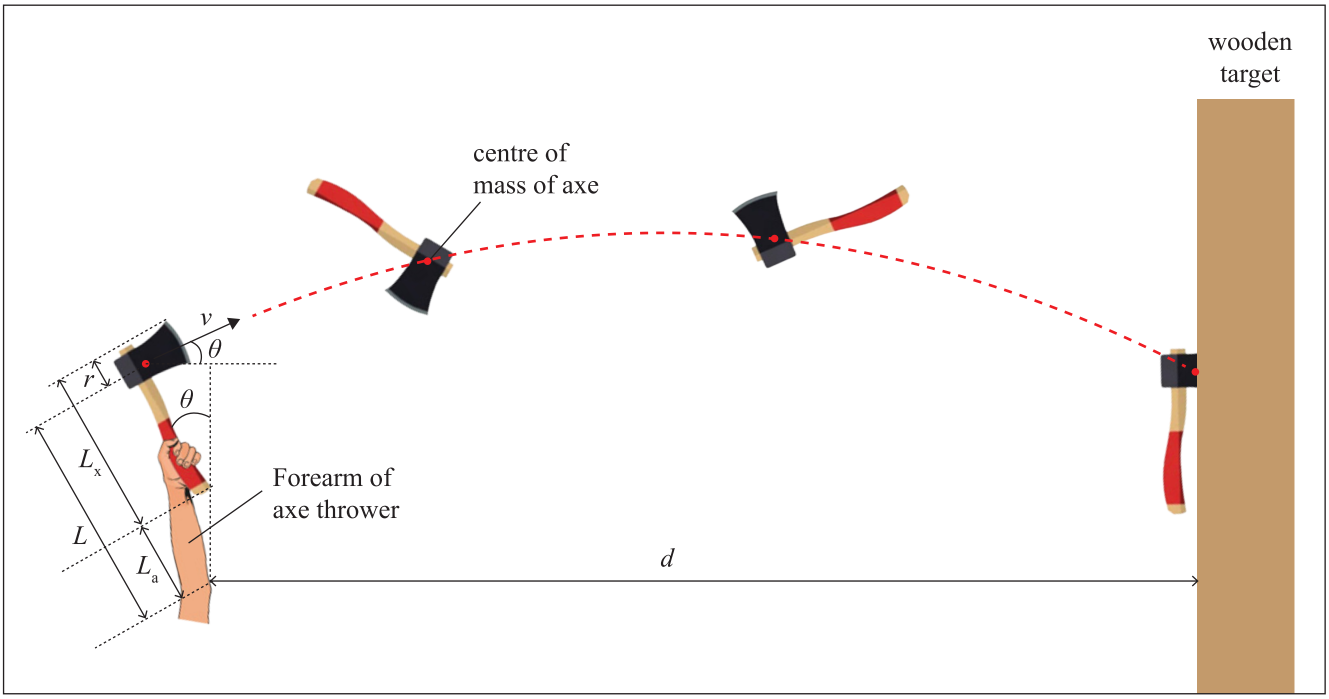
Axe throwing is a traditional sport that has become more popular recently. It involves throwing an axe at a wooden target. The path of the axe can be described with the physics of projectile motion and of rotational motion. If the axe is thrown correctly, it rotates after it is thrown so that it is vertical as it reaches the target, allowing the blade to stick in the target.

Source: www.sydney.com/destinations/sydney/sydney-west/penrith/attractions/throw-axe

Although everybody will throw the axe in a slightly different way, we can describe the throw as follows.

- The axe is held so that the forearm and the axe handle form a straight line, as shown in the diagram below.
- The throw is made by keeping the upper arm still and swinging the forearm from the elbow.

The axe is released at an angle θ, so that its centre of mass has a velocity, v. The axe is thrown from the same height as the target. The axe completes just over one full rotation as it travels from the release point to the target. The centre of mass of the axe finishes up level with the surface of the target, as shown in the diagram below.



The velocity of the centre of mass at release is v.

r = distance from the end of the axe to centre of mass

L_x = total length of axe

L_a = length of axe thrower's forearm

The length from the centre of mass to the elbow is, $L = L_a + L_x - r$

d = distance of axe thrower's elbow from the target

(a) An analysis of the projectile motion of the axe can be used to show that the time of flight of the axe, from the time it is released to when it strikes the target at exactly the same height, is $t = \dfrac{2v\sin\theta}{g}$.

Show that the initial velocity, v, required for the axe to strike the target successfully is given by:

$$v = \sqrt{\frac{g(d + L\sin\theta)}{2\sin\theta\cos\theta}}$$

Clearly show your working.

(b) The angular velocity of the axe is given by $\omega = \dfrac{v}{L}$. For a successful throw that ends up with the axe rotating and sticking in the target, as shown in the diagram opposite, show that the ratio of $\dfrac{d}{L}$ is given by:

$$\frac{d}{L} = (\theta + 2\pi)\cos\theta - \sin\theta$$

(c) In axe throwing, the angle θ is usually small.

Derive a simplified form of the equation in part (b), for a small angle θ.

Clearly show your working and state any assumptions made.

(d) Axe throwers have limited scope to vary their angle of release, and can throw from any distance, provided they stay behind a line marked on the ground.

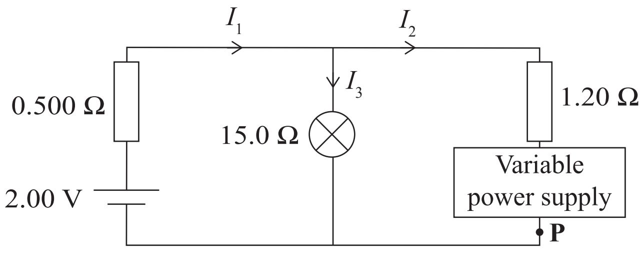
(i) Mika throws an axe with a larger total length, L_x.

What other adjustment can she make to ensure that her throw still hits the target successfully?

(ii) Giving reasons, explain which aspects of the axe's flight would change, and which would stay the same, if Mika were throwing an axe on the Moon, where the acceleration due to gravity is less than on Earth.

QUESTION THREE: DC AND DOPPLER

A circuit is set up with two power supplies. One supplies a constant EMF of 2.00 V, the other is a variable power supply that can provide a continuous range of EMFs.



(a) In addition to Ohm's Law, describe two other key circuit rules that could be applied to determine currents and potential differences in a circuit like this, and state the fundamental physics principles these rules are based on.

(b) The orientation and EMF of the variable power supply are adjusted until no current flows through the 15 Ω lamp, and it does not light up.

(i) Calculate the EMF of the variable power supply when the lamp does not light up, and clearly state whether point **P** shown on the diagram is the positive or negative end of the variable power supply.

(ii) With the variable power supply still set so the 15.0 Ω lamp does not light up, the lamp is replaced by another lamp with a lower resistance.

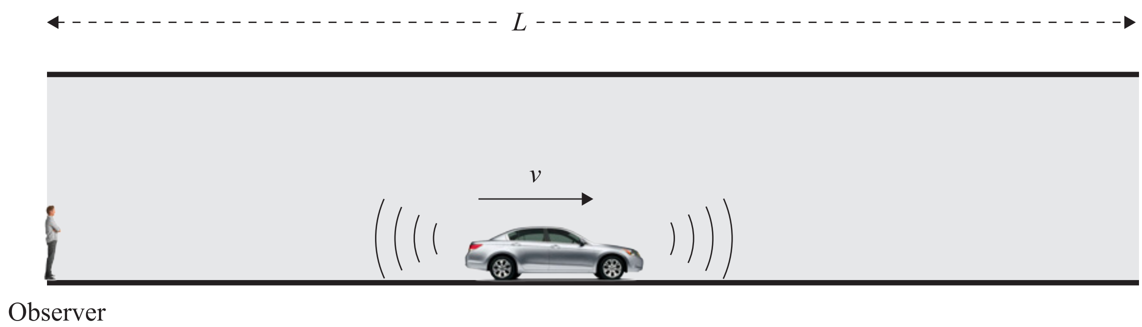
Explain whether the new lamp with lower resistance will light up or not.

(c) A moving car, with a horn emitting sound with frequency, f, starts from rest and accelerates with constant acceleration, a, towards a stationary observer a distance, d, away.

Show that the observer will eventually hear a frequency of $2f$ only if $d > \frac{v_w^2}{8a}$, where v_w is the speed of sound.

(d) A car travels through a tunnel at a constant speed. The car horn emits sound at a constant single frequency. When sound reaches one of the open ends of the tunnel it is reflected and travels back along the tunnel in the other direction.

The size of the car is small compared to the diameter of the tunnel, so that the presence of the car does not affect the sound travelling through the tunnel.



Sources: https://signalvnoise.com/posts/920-car-design-the-side-crease-is-in
https://www.istockphoto.com/photo/casual-man-side-view-gm183765770-15426060

An observer standing at one of the open ends of the tunnel will hear two distinct frequencies from the car horn.

(i) Explain why the observer hears two distinct frequencies from the car horn.

(ii) The car travels through the tunnel at a constant speed, v, while the horn emits sound at a constant frequency, f, so that both the 20th and 21st harmonics resonate in the tunnel. These harmonics cause a beat frequency of 4.76 Hz at the end of the tunnel.

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

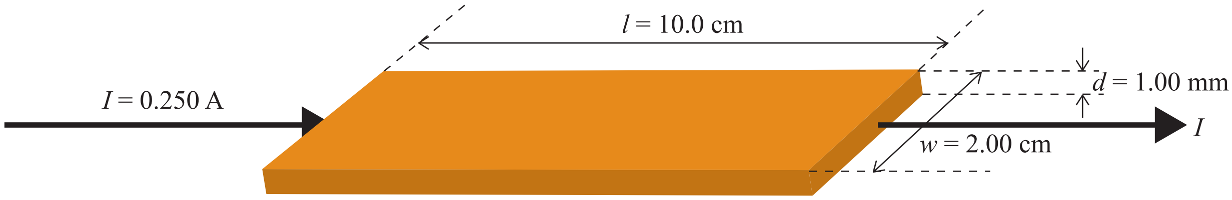
Calculate the speed of the car, v, AND the frequency of the horn, f.

QUESTION FOUR: HALL EFFECT

Charge of an electron = -1.60×10^{-19} C

When charge flows through a conductive material, e.g. a metal, only some of the electrons are free to move. A conductor has a fixed number of free electrons per unit volume, n.

For copper metal, $n = 8.49 \times 10^{28}$ electrons m^{-3}



(a) (i) A piece of copper metal 10.0 cm long, 2.00 cm wide, and 1.00 mm thick has a current of 0.250 A flowing through it.

By first calculating the amount of free charge in the piece of copper, determine the average speed of a free electron as it flows through the piece of copper.

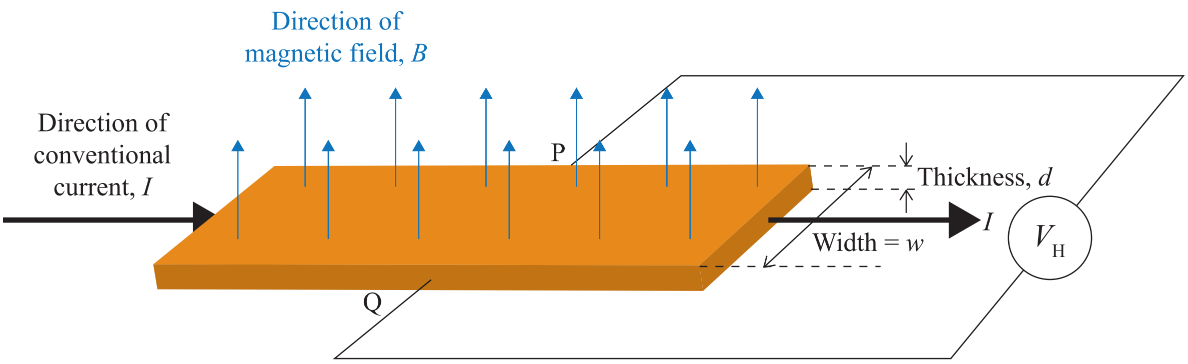
(ii) The current flowing through a conductor is given by the relationship:

$$I = neAv_d$$

where e is the charge of an electron, A is the cross-sectional area of the conductor, and v_d is the average drift velocity of a free electron.

Show that the relationship above is dimensionally consistent.

When charge flows through a conductor which is inside a uniform magnetic field, a sideways force is exerted on the moving electrons that pushes them to one side of the conductor. This makes one side of the conductor positively charged and the opposite side negatively charged. This separation of charge produces a potential difference, known as a Hall Voltage, V_H, across the two sides of the conductor.



(b) By considering the magnetic force acting on an electron moving through the conductor, state which side of the conductor, P or Q, is positively charged.

Your answer must include a description of how you made your selection.

(c) (i) When a steady current is flowing, the sideways forces acting on an electron moving through the conductor are balanced.

Explain the origin of the force that balances the magnetic force on a moving electron.

Question Four continues on the following page.

(ii) By considering the sideways forces acting on a moving electron, show that the Hall Voltage, V_H, is given by the expression:

$$V_H = \frac{BI}{nde}$$

(d) Measuring the Hall Voltage is a commonly used method for determining the strength of a magnetic field.

Describe the conditions necessary to achieve the most precise measurement of the strength of a magnetic field, and any practical limitations to achieving these conditions.

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