2024 H2 Physics Preliminary Examination Solution

Paper 3

1 **(a)** The internal energy of an ideal gas is just the sum of the microscopic kinetic energy, due to the random motion of its molecules since the microscopic potential energy of an ideal gas is zero.

Its internal energy depends only on its state (pressure, volume, temperature) and amount of gas.

(b) **(i)** **1.** $\Delta U = Q + W$

Since volume is constant, $W = 0$.

$$
\begin{aligned}
Q &= \Delta U \\
&= \frac{3}{2}p_2V - \frac{3}{2}p_1V \\
&= \frac{3}{2}V\left(p_2 - p_1\right) \\
&= \frac{3}{2}\left(2.0\times10^{-2}\right)\left(1.5\times10^{5} - 1.0\times10^{5}\right) \\
&= 1500.0 = 1500 \text{ J (shown)}
\end{aligned}
$$

2. Since

$$E_k = \frac{3}{2}kT_1 = 6.2\times10^{-21} \text{ J}$$

$$T_1 = \frac{2}{3}\left(\frac{6.2\times10^{-21}}{1.38\times10^{-23}}\right) = 299.52 \text{ K}$$

From $p = \frac{nR}{V}T$, since volume is constant,

$$\Delta p = \frac{nR}{V}\Delta T = \frac{p_1}{T_1}\Delta T$$

$$
\begin{aligned}
\Delta T &= \frac{\Delta p}{p_1}T_1 \\
&= \frac{0.5\times10^{5}}{1.0\times10^{5}}\left(299.52\right) \\
&= 149.76 = 150 \text{ K}
\end{aligned}
$$

OR

$$E_k = \frac{3}{2}kT_1$$

$$T_1 = \frac{2}{3}\frac{E_k}{k}$$

Since volume is constant,

$$\frac{p_1}{T_1} = \frac{p_2}{T_2}$$

$$T_2 = \frac{p_2}{p_1}T_1 = \frac{p_2}{p_1}\left(\frac{2}{3}\frac{E_k}{k}\right)$$

$$\begin{aligned}
T_2 - T_1 &= \frac{p_2}{p_1}\left(\frac{2}{3}\frac{E_k}{k}\right) - \frac{2}{3}\frac{E_k}{k} \\
&= \frac{2}{3}\frac{E_k}{k}\left(\frac{p_2}{p_1} - 1\right) \\
&= \frac{2}{3}\left(\frac{6.2\times10^{-21}}{1.38\times10^{-23}}\right)\left(\frac{1.5\times10^{5}}{1.0\times10^{5}} - 1\right) \\
&= 149.76 = 150\ \text{K} = 150\ {}^\circ\text{C}
\end{aligned}$$

OR

$U_1 = NE_k$ where N is the number of gas molecules

$$N = \frac{U_1}{E_k}$$

$$\begin{aligned}
\Delta U &= U_2 - U_1 \\
&= \frac{3}{2}NkT_2 - \frac{3}{2}NkT_1 \\
&= \frac{3}{2}Nk\left(T_2 - T_1\right)
\end{aligned}$$

$$\begin{aligned}
T_2 - T_1 &= \frac{2}{3}\frac{\Delta U}{Nk} \\
&= \frac{2}{3}\frac{\Delta U}{\left(U_1/E_k\right)k} \\
&= \frac{2}{3}\frac{E_k\Delta U}{\left(\frac{3}{2}p_1V\right)k} \\
&= \frac{4}{9}\frac{\left(6.2\times10^{-21}\right)\left(1500\right)}{\left(1.0\times10^{5}\right)\left(2.0\times10^{-2}\right)\left(1.38\times10^{-23}\right)} \\
&= 149.76 = 150\ \text{K} = 150\ {}^\circ\text{C}
\end{aligned}$$

(ii) The first law of thermodynamics states that the increase in internal energy ΔU is equal to the sum of the work done on the system *W* and the heat supplied to the system *Q*, i.e. $\Delta U = Q + W$. Hence $Q = \Delta U - W$.

When a unit mass of the gas, heated under constant volume or under constant pressure, experiences a unit rise in temperature, ΔU will be the same since $\Delta U \propto \Delta T$.

When the gas is heated at constant volume, there is no work done. *W* is zero and $Q_V = \Delta U$.

When the gas is heated at constant pressure, work is done by the gas as it expands. *W* is negative and $Q_p > \Delta U$.

The specific heat capacity of a gas is the heat supplied to a unit mass of the gas to cause a unit rise in its temperature i.e. $c = \dfrac{Q}{m(\Delta T)}$. Since $Q_p > Q_V$ the specific heat capacity at constant pressure is higher than that at constant volume.

2 **(a)** Since <u>k and m are constant</u>, $a \propto -x$.
This implies that the block's <u>acceleration is proportional to its displacement from</u> the <u>equilibrium position</u>.

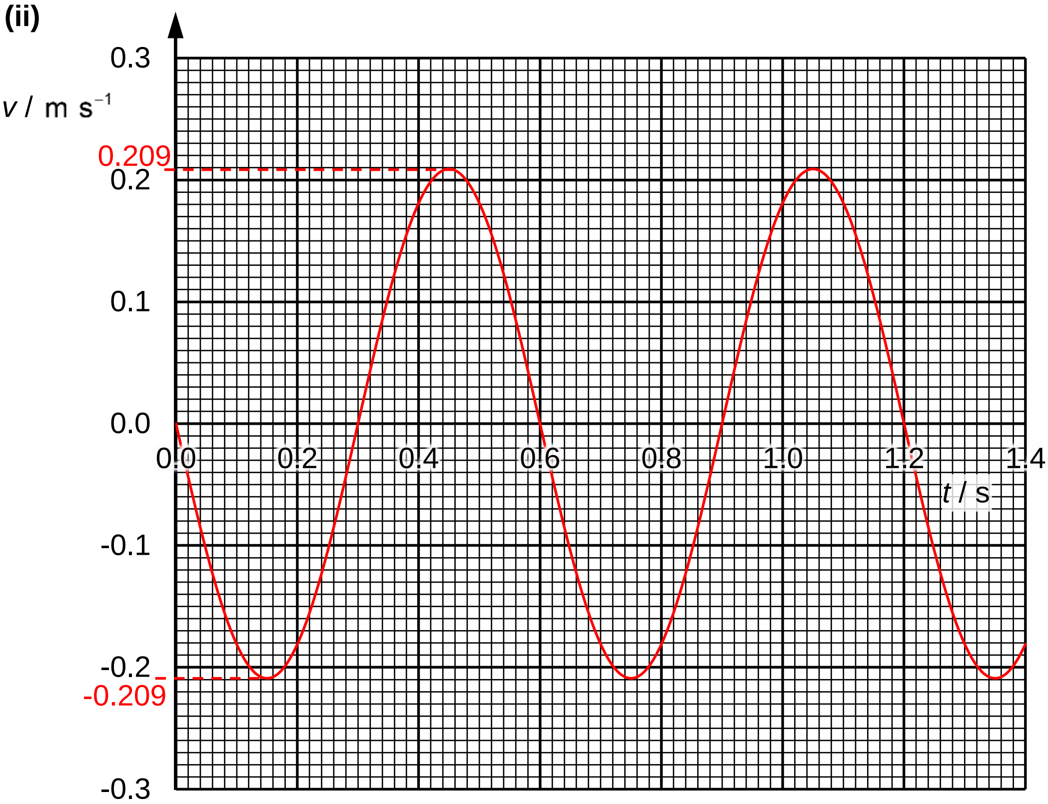
The <u>negative sign</u> implies that the <u>direction of its acceleration is always opposite to its displacement</u>, pointing towards the equilibrium position.

This satisfies the definition for simple harmonic motion.

(b) **(i)** From the graph, $T = 0.60$ s , $x_0 = 2.0 \times 10^{-2}$ m

$$\begin{aligned} v_0 &= \omega x_0 \\ &= \frac{2\pi}{T} x_0 \\ &= \frac{2\pi}{0.60}\left(2.0 \times 10^{-2}\right) \\ &= 0.20944 = 0.209 \text{ m s}^{-1} \end{aligned}$$

(ii)



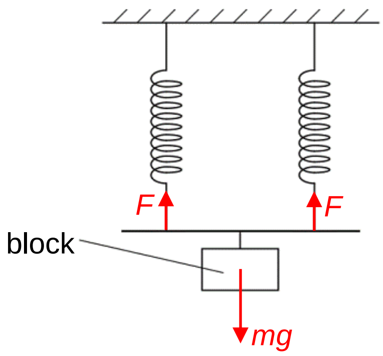
(iii) $E_K = \frac{1}{2}mv^2 = \frac{1}{2}m\left(\pm\omega\sqrt{x_0{}^2 - x^2}\right)^2 = \frac{1}{2}m\omega^2\left(x_0{}^2 - x^2\right)$

$E_P = E_T - E_K = \frac{1}{2}m\omega^2 x_0{}^2 - \frac{1}{2}m\omega^2\left(x_0{}^2 - x^2\right) = \frac{1}{2}m\omega^2 x^2$

$$E_P = E_K$$
$$\frac{1}{2}m\omega^2 x^2 = \frac{1}{2}m\omega^2\left(x_0{}^2 - x^2\right)$$
$$2x^2 = x_0{}^2$$
$$x = \pm\frac{x_0}{\sqrt{2}} = \pm\frac{2.0\times10^{-2}}{\sqrt{2}} = \pm 0.014142\text{ m} = \pm 1.4142\text{ cm}$$

At equilibrium, $L = 16.0\text{ cm}$.
When $E_P = E_K$,
$L = 16.0 + 1.4142 = 17.4142 = 17.4\text{ cm}$ (block is below equilibrium)
OR
$L = 16.0 - 1.4142 = 14.5858 = 14.6\text{ cm}$ (block is above equilibrium)

(c) $F_{eff} = 2F = mg$
$k_{eff}e = 2ke = mg$
$k_{eff} = 2k$



The <u>same mass results in half the extension</u> in each spring at equilibrium compared to a single spring in Fig. 2.1. Hence the <u>effective force constant is twice</u> the force constant of one spring ($k_{eff} = 2k$).

From $a = -\frac{k}{m}x$, angular frequency $\omega = \frac{2\pi}{T} = \sqrt{\frac{k}{m}}$. Hence period $\underline{T = 2\pi\sqrt{\frac{m}{k}}}$.

When the force constant is twice that in (a), the <u>period decreases to $\frac{1}{\sqrt{2}}$ the period in (a)</u>.

3 **(a)** amplitudes:
Particles in a progressive wave have the same amplitude.
Particles in a stationary wave have amplitudes ranging from zero at the nodes to maximum amplitude at the antinodes.

phases:
Particles within a wavelength in a progressive wave have different phases.
Particles in a stationary wave between adjacent nodes oscillate with the same phase and particles between adjacent segments oscillate π rad out-of-phase.
Particles at the node do not oscillate.

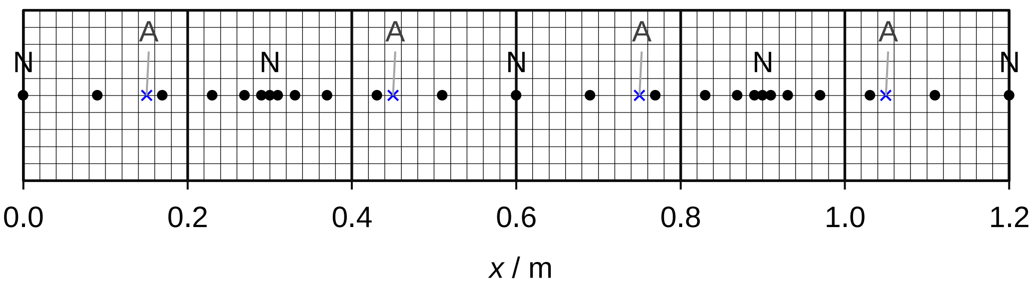
(b) **(i)** Wavelength is the distance between two adjacent particles that oscillate in phase.

$2\lambda = 1.20$ m (2 d.p.)
$\lambda = 0.600$ m (3 s.f.)

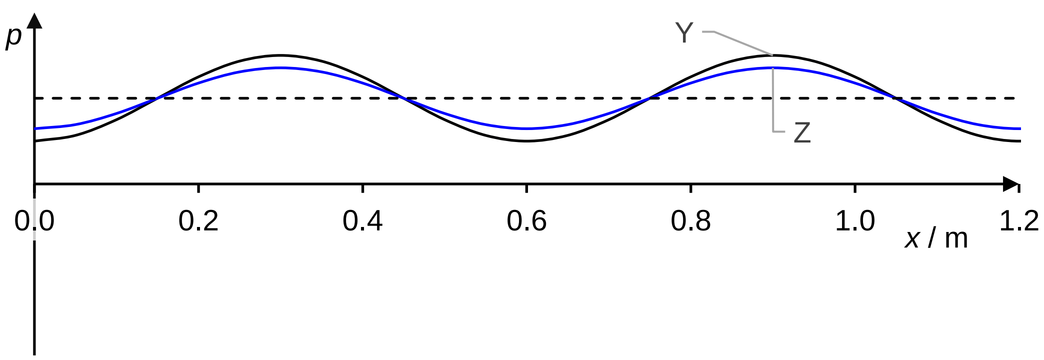
(ii) There are 6 intervals between 0.00 m and 0.30 m (1/2 wavelength) indicating that the separation between particles when they are at equilibrium is 0.05 m. The particle with equilibrium position at 0.15 m is at the amplitude position of 0.19 m at t_0 .

$x_0 = 0.19 - 0.15 = 0.04$ m (2 d.p.)

(c) **(i)**



(ii)



1. Pressure at the nodes is highest or lowest compared to the initial atmospheric pressure.
*Correct high and low pressure positions.

2. For stationary waves, energy is not transferred and the waveform does not progress forward. Positions of nodes and antinodes remain unchanged. Only the displacement of the particles between the nodes changes.
*Graph of smaller amplitude at $t_1 + \frac{T}{8}$ compared to at t_1.

(d) **(i)** Stationary wave is formed in the air column in the tube when an anitnode is at the mouth of the tube and a node is at the water surface.

When first loud note is heard,

$L_1 + c = \tfrac{1}{4}\lambda$

$$\begin{aligned} c &= \frac{1}{4}\lambda - L_1 \\ &= \frac{1}{4}(0.600) - 0.144 \\ &= 0.150 - 0.144 \\ &= 0.006 \text{ m} \quad \text{(3 d.p.)} \end{aligned}$$

(ii) When the next loud note is heard,

$L_2 + c = \tfrac{3}{4}\lambda$

$$\begin{aligned} L_2 &= \frac{3}{4}\lambda - c \\ &= \frac{3}{4}(0.600) - 0.006 \\ &= 0.444 \text{ m} \quad \text{(3 d.p.)} \end{aligned}$$

4 **(a)** **(i)** The electric field strength <u>due to each particle is directed towards the left</u>. As the <u>resultant electric field strength</u> at any point is the <u>vector addition</u> of the individual electric field strengths of A and B, it is always <u>towards the left</u>. Hence <u>there will be no point</u> where the electric field strength is zero.

(ii) The <u>electric potential due to A is negative</u> while that <u>due to B is positive</u>. The <u>total electric potential</u> at any point is the <u>scalar addition</u> of the individual electric potentials of A and B. Hence, <u>there will be a point</u> in between the charges where electric potential is zero.

(b) **(i)** By the principle of conservation of energy, considering energy changes of particle from the point it enters the electric field to the point it hits point P,

increase in kinetic energy = decrease in electric potential energy

$$\frac{1}{2}m\left(v_f^{\,2}-v_i^{\,2}\right)=q\left(\frac{1}{2}\Delta V\right)$$

$$\Delta V=\frac{m}{q}\left(v_f^{\,2}-v_i^{\,2}\right)$$

$$=\frac{\left(6.6\times10^{-27}\right)}{\left(3.2\times10^{-19}\right)}\left[\left(6.5\times10^{5}\right)^2-\left(4.1\times10^{5}\right)^2\right]$$

$$=5247=5250\text{ V}$$

Since the negatively charged particle accelerates towards plate Y which is at 0 V, plate X must be at a lower potential with respect to plate Y.

$V=-5250$ V

(ii)

$$F_E=ma$$

$$q\left(\frac{\Delta V}{d}\right)=ma$$

$$a=\frac{q\Delta V}{md}$$

$$=\frac{\left(3.2\times10^{-19}\right)\left(5250\right)}{\left(6.6\times10^{-27}\right)\left(3.6\times10^{-2}\right)}$$

$$=7.0707\times10^{12}=7.07\times10^{12}\text{ ms}^{-2}$$

(iii) Take direction to the right and downwards as positive.
consider horizontal motion,

$$s=-\left(u\sin\theta\right)t+\frac{1}{2}at^2$$

$$0.5\times3.6\times10^{-2}=-\left(4.1\times10^{5}\sin32^\circ\right)t+\frac{1}{2}\left(7.07\times10^{12}\right)t^2$$

$$t=1.0842\times10^{-7}\text{ s} \quad\text{or}\quad -4.6963\times10^{-8}\text{ s (NA)}$$

consider vertical motion,

$$d=\left(u\cos\theta\right)t$$

$$=\left(4.1\times10^{5}\cos32^\circ\right)\left(1.0842\times10^{-7}\right)$$

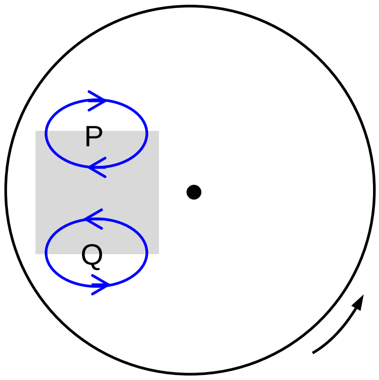
$$=0.037698=0.0377\text{ m}$$

5 **(a)** The sections of the disc moving towards or away from the magnets experience a change in magnetic flux linkage. There will be induced e.m.f. and induced currents in the conducting disc.

By Lenz's law, the direction of the <u>induced currents</u> in the disc will oppose the change in the magnetic flux linkage. This <u>produces a force</u> that <u>opposes the direction of the spin of the disc</u>, causing it to slow down.

In slowing down, the <u>mechanical / kinetic energy of the disc is converted to electrical energy</u> as induced currents and eventually converted to thermal energy which is dissipated to the surroundings. This obeys the law of conservation of energy.

(b)



*At least one closed loop drawn at each region P and Q.
*Correct direction of eddy current for each loop.
*For each loop, part of loop in the magnetic field, part of it outside the magnetic field.

(c) As the disc is slowing down, its angular velocity is decreasing. This leads to a <u>rate of change of magnetic flux linkage that is decreasing which produces a decreasing induced e.m.f.</u>

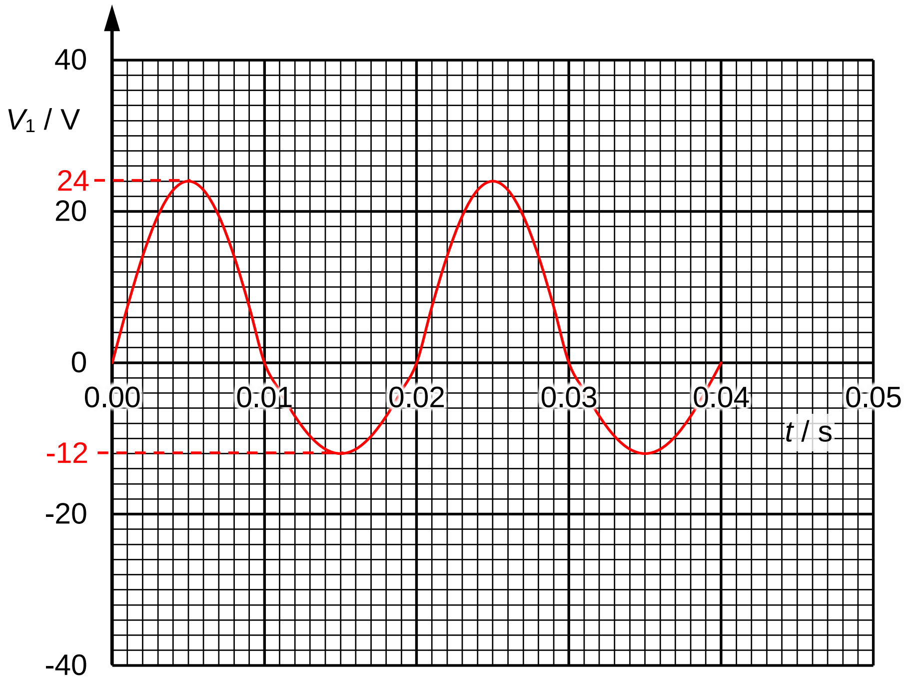
The <u>decreasing induced current produces an opposing / decelerating force that is decreasing in magnitude</u>.

This causes the <u>angular velocity of the disc to decrease at a decreasing rate</u>. Hence its decrease is not linear (does not decrease at a constant rate).

(Angular deceleration is decreasing in magnitude.)

6 **(a)** The root-mean-square value of an alternating current is that value of the direct current that would produce thermal energy at the same rate in the same resistor.

(b) **(i)**



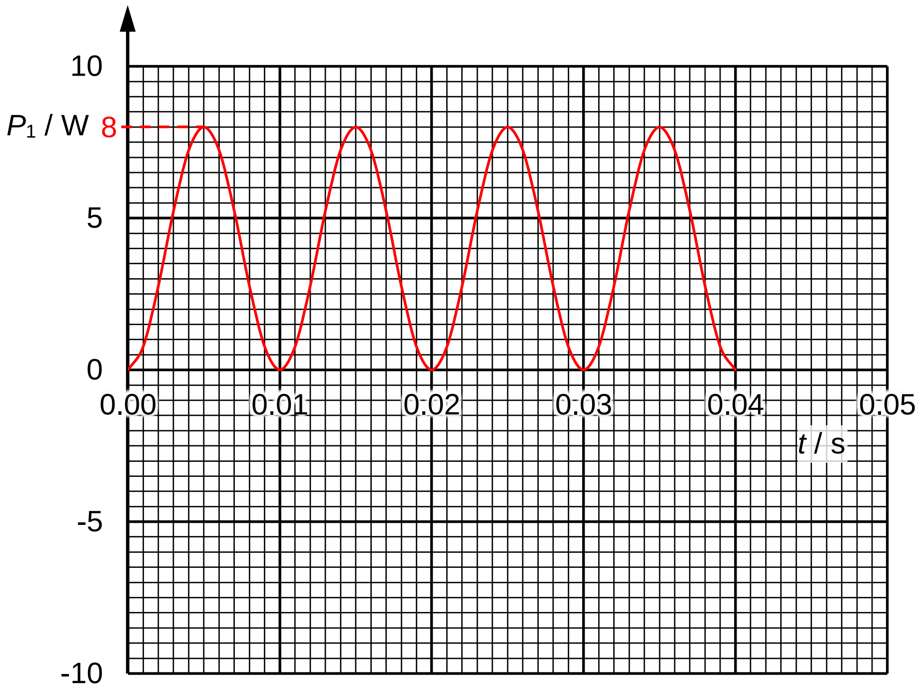
With S closed, current passes through the diode and R_1 in the forward bias direction. In the reverse bias direction, current passes through R_1 and R_2.

Forward bias: peak V_1 = peak V = 24 V
Reverse bias: peak V_1 = 12 V

period $T = \dfrac{2\pi}{\omega} = \dfrac{2\pi}{314} = 0.02$ s

*Sine graph with correct period.

(ii)



With S opened, current passes through R_1 and R_2 all the time and does not pass through the diode.
Since V and I of the alternating supply is sinusoidal, power graph will be a sine^2 graph.

$$\text{peak } P_1 = \frac{(\text{peak } V_1)^2}{R_1} = \frac{(24/2)^2}{18} = 8 \text{ W}$$

*Correct shape (smooth curve, sine squared) with correct period.

7 **(a)** The emission line spectrum consists of a series of distinct lines of specific colours/ wavelengths/ frequencies on a dark background.

Each line is produced by the emission of photons of a specific quantum of energy. Since the photons have specific energy, they must be emitted when electrons in the atoms de-excites between discrete energy levels.

(b) **(i)** The characteristic K_α and K_β lines are due to X-ray photons produced from electron transitions from shell L to K and shell M to K, respectively (or from energy level n = 2 to n = 1 and n = 3 to n = 1, respectively).

Since shell L is nearer to shell K than shell M to shell K, K_α photons have smaller energy E than K_β photons. As energy E is inversely proportional to the wavelength λ, K_α photons have a longer wavelength than K_β photons.

(ii) X-ray photons are emitted when high speed electrons collide with the target atom and undergo many rapid decelerations. The kinetic energy lost by an incident electron is converted into the energy of an X-ray photon. The amount of energy lost varies since an electron can undergo multiple collisions resulting in X-ray photons of varying energies.

The most energetic X-ray photon is produced when an incident electron loses all its kinetic energy in one collision. Since the energy of a photon is given by $E = \dfrac{hc}{\lambda}$, this most energetic X-ray photon has the shortest wavelength.

8 **(a)** **(i)**

$$\phi = B_H A$$
$$= \left(5.2\times10^{-5}\cos70^\circ\right)\left(0.80\times0.55\right)$$
$$= 7.8254\times10^{-6} = 7.83\times10^{-6}\text{ Wb}$$

(ii) **1.** When the window is opening, the aluminium frame cuts the Earth's magnetic field lines and the magnetic flux through the window decreases. This causes a rate of change of magnetic flux linkage in the frame.

By Faraday's law, there will be an induced e.m.f. in the frame.

Since the frame is a closed loop, this induced e.m.f. produces an induced current in the frame.

By Lenz's law, the direction of the induced current is such as to produce an effect to oppose the decrease in the magnetic flux. Current will flow from ADCB to increase the magnetic flux.

2.

$$\Delta\phi = \phi_f - \phi_i$$
$$= 0 - 7.83\times10^{-6}$$
$$= -7.83\times10^{-6}\text{ Wb}$$

3.

$$|E| = \left|-\frac{\Delta\phi}{\Delta t}\right|$$
$$= \left|-\frac{-7.83\times10^{-6}}{0.30}\right|$$
$$= 2.61\times10^{-5}\text{ V}$$

(b) **(i)** Since the velocity of the charged particles is perpendicular to the magnetic field, the magnetic force acting on the charged particles is always perpendicular to their velocity. The magnetic force only changes the direction of the velocity while the speed remains constant.

As the magnitude of the magnetic force is constant, it points towards a fixed point, causing the particles to move in a circular motion about the fixed point with a constant radius.

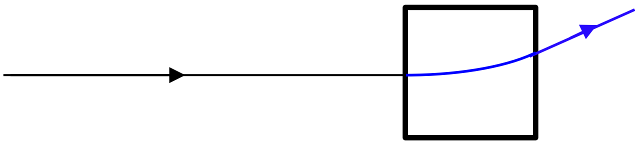
(ii) The magnetic force acting on the particle provides the centripetal force.

$$Bqv = m\frac{v^2}{r}$$
$$r = \frac{mv}{Bq}$$

Since the particles travel at the same speed in the field of the same magnetic flux density,

$$\frac{r_\alpha}{r_e} = \frac{m_\alpha}{m_e}\frac{q_e}{q_\alpha}$$
$$= \frac{\left(4\times1.66\times10^{-27}\right)}{9.11\times10^{-31}}\times\frac{1}{2}$$
$$= 3644.3$$
$$r_\alpha = 3.6\times10^3 r_e \qquad \text{(shown)}$$

(iii)



*Slight curve (due to large radius) in *B* field.
*Straight path after it exits *B* field from the right edge of the field.

(iv) **1.**

$$R = \frac{mv}{Bq}$$
$$= \frac{(9.11 \times 10^{-31})(1.2 \times 10^{6})}{(0.70 \times 10^{-3})(1.60 \times 10^{-19})}$$
$$= 9.7607 \times 10^{-3} = 9.8 \text{ mm} \quad \text{(shown)}$$

2.

$$T = \frac{2\pi R}{v}$$
$$= \frac{2\pi (9.8 \times 10^{-3})}{1.2 \times 10^{6}}$$
$$= 5.131 \times 10^{-8} = 5.13 \times 10^{-8} \text{ s}$$

3. The electron moves in a circular path in a clockwise direction (viewed from top).

From 0 ms to 1.2 ms, the radius of curvature of its path decreases and increases from 1.2 ms to 3.2 ms.

After 3.2 ms, the direction of its circular path will change to an anti-clockwise direction.

From 3.2 ms to 4.0 ms, the radius of curvature of its path decreases.

4. State any time from 2.4 ms to just before 3.2 ms (from $B = 0.70$ mT and decreasing to zero).

As the <u>magnetic flux density of the field decreases</u>, the <u>radius of curvature of the electron's path increases</u> and leaves the magnetic field due to the high speed of the electron.

9 **(a)** The maximum kinetic energy of the photoelectrons is dependent only on the frequency, but not on the intensity of the incident radiation.

In the particulate theory of light, electromagnetic radiation is made up of discrete quanta of energy known as photons. Each photon has energy $E_{photon} = hf$ where h is the Planck constant and f is the frequency. Emission of a photoelectron is only possible when a single photon is absorbed by an electron on the surface of the metal in a one-to-one interaction.

The maximum kinetic energy of the photoelectron is given by $\text{K.E.}_{\text{max}} = hf - \Phi$ where Φ is the work function of the metal. The equation shows that the maximum kinetic energy is a function of the photon's energy and hence frequency for the same metal with constant Φ.

Increasing the intensity of light only increases the rate of incident photons on the metal and has no effect on E_{photon} which is dependent only on frequency. Therefore, there is no effect of intensity on the maximum kinetic energy which provides evidence for the particulate nature of electromagnetic radiation.

OR

There is a threshold frequency below which there is no emission of photoelectrons regardless of the intensity of the incident radiation.

In the particulate theory of light, electromagnetic radiation is made up of discrete quanta of energy known as photons. Each photon has energy $E_{photon} = hf$ where h is the Planck constant and f is the frequency. Emission of a photoelectron is only possible when a single photon is absorbed by an electron on the surface of the metal in a one-to-one interaction.

The maximum kinetic energy of the photoelectron is given by $\text{K.E.}_{\text{max}} = hf - \Phi$ where Φ is the work function of the metal. The emission of a photoelectron is only possible if the maximum kinetic energy is greater than zero hence $hf \geq \Phi$. If the photon energy is less than Φ i.e. $f < f_0$ where $f_0 = \dfrac{\Phi}{h}$ is the threshold frequency, there will be no emission of photoelectrons.

Increasing the intensity of light only increases the rate of incident photons on the metal and has no effect on E_{photon} which is dependent only on frequency. Therefore, there is no effect of intensity on the threshold frequency which provides evidence for the particulate nature of electromagnetic radiation.

(b) **(i)**

$$\Phi = \frac{hc}{\lambda_0}$$

$$\lambda_0 = \frac{(6.63\times10^{-34})(3.00\times10^{8})}{(4.33)(1.60\times10^{-19})}$$

$$= 2.8709\times10^{-7} = 287 \text{ nm}$$

(ii) $E_{K,\max} = \frac{1}{2}mv_{\max}^2 = \frac{hc}{\lambda} - \Phi$

$$v_{\max} = \sqrt{\frac{2}{m}\left(\frac{hc}{\lambda} - \Phi\right)}$$

$$= \sqrt{\frac{2}{9.11\times10^{-31}}\left(\frac{(6.63\times10^{-34})(3.00\times10^{8})}{210\times10^{-9}} - (4.33)(1.60\times10^{-19})\right)}$$

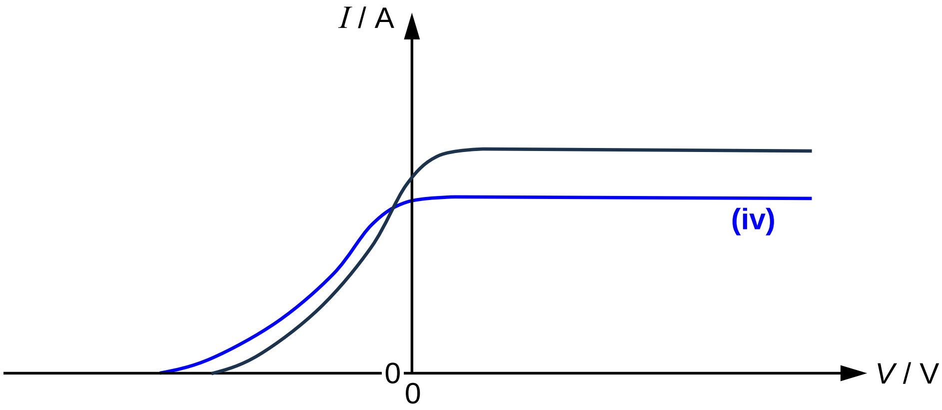
$$= 7.4725\times10^{5} = 7.47\times10^{5}\ \text{m s}^{-1}$$

(iii) When $V = 0$ V, there is no electric force on the emitted photoelectrons and they travel at a constant speed along a straight line perpendicular to the collector plate.

When $V = +3.0$ V, the electric force, $F_e = eE = \frac{eV}{d} = \frac{3e}{d}$, is the resultant force on the photoelectron and it acts in the same direction as its velocity.

Since the resultant electric force is constant, acceleration, $a = \frac{3e}{m_e d}$, is constant, and the speed of the emitted photoelectron increases at a constant rate as it moves along a straight line perpendicular to the collector plate.

(iv)



Shorter wavelength, higher photon energy, higher maximum kinetic energy, hence larger stopping potential.
Since intensity $i = \frac{hc}{\lambda A}\left(\frac{dN_p}{dt}\right)$ remains the same, the rate of incident photons $\frac{dN_p}{dt}$ decreases with a decrease in wavelength or an increase in photon energy. Hence the saturated photocurrent decreases.

(c) (i) The electrons behave as waves with de Broglie's wavelength λ which is related to its momentum p by $\lambda = \frac{h}{p}$. The graphite film, having atoms that are regularly spaced at distances comparable to the wavelength of the electrons, acts as a diffraction grating resulting in a diffraction pattern of concentric rings when the electrons pass through the graphite film.

The maximum and minimum intensities of the concentric rings are a result of electron waves undergoing constructive and destructive interference similar to how light waves interfere.

(ii) $E_k = \frac{1}{2}mv^2 = \frac{1}{2}\frac{(mv)^2}{m} = \frac{p^2}{2m} = \frac{(h/\lambda)^2}{2m} = \frac{h^2}{2m\lambda^2}$

increase in kinetic energy = decrease in electric potential energy

$$\frac{h^2}{2m\lambda^2} - 0 = q\Delta V$$

$$\lambda = \frac{h}{\sqrt{2mq\Delta V}}$$

$$= \frac{6.63\times10^{-34}}{\sqrt{2(9.11\times10^{-31})(1.60\times10^{-19})(5.0\times10^{3})}}$$

$$= 1.7366\times10^{-11} = 1.74\times10^{-11} \text{ m}$$

(iii) According to Rayleigh criterion, the <u>limiting angle of resolution $\theta_{\text{min}} \approx \frac{\lambda}{b}$</u> where b is the size of the aperture. For the electrons, <u>θ_{min} is approximately four orders of magnitude smaller</u> ($\theta_{\text{min}} \propto \lambda$) than for visible light.

Hence, an <u>electron microscope has a much higher resolving power compared to an optical microscope</u> allowing it to resolve structures at the atomic scale which the optical microscope is unable to.