# Grade 12 Physics Model Paper 1

**ANSWER KEY**

Full marks 75 · 3 hours

Give the marks for the points in the marking scheme; an answer in other words that says the same is right.

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## Group A Multiple choice — 11 marks

### Question 1 — 11 × 1 = 11

**a.** **(ii)** kg m²/s

**b.** **(iii)** The angle of contact of water with glass is less than 90°, and that of mercury is more than 90°.

**c.** **(iii)** 1.6 s

**d.** **(iii)** 500 J, because its internal energy does not change

**e.** **(ii)** 40%

**f.** **(iii)** The waves in front of the moving siren are crowded together, so more of them reach her each second.

**g.** **(iii)** 1.8 mm

**h.** **(iv)** a straight line, at the same speed

**i.** **(iii)** Its susceptibility is small and negative, so it is weakly repelled by a magnet.

**j.** **(ii)** 31.4 Ω

**k.** **(iv)** the work function

## Group B Short answers, each on one content area — 40 marks

### Question 2 — 5 marks

**a.** The **angular momentum** of a body turning about an axis is the moment of its linear momentum about that axis; for a rigid body it is the product of its moment of inertia and its angular velocity, $L = I\omega$. **[1]**

**Marking scheme**

- Angular momentum defined as the moment of linear momentum about the axis, $L = I\omega$.

**b.** Once she has left the board, gravity acts through her center of mass, so there is no external torque about it, and her angular momentum $L = I\omega$ stays constant. **[2]**

Tucking brings her mass closer to the axis of rotation, which makes her moment of inertia $I$ smaller. With $I\omega$ constant, a smaller $I$ means a larger $\omega$: she spins faster. Straightening out makes $I$ large again, so $\omega$ becomes small and she enters the water almost without turning.

**Marking scheme**

- No external torque in the air, so angular momentum $I\omega$ is conserved.
- Tucking reduces $I$ (mass nearer the axis), so $\omega$ increases.

**c.** **The disc reaches the bottom first.** **[2]**

Rolling down through a height $h$, each body's loss of potential energy $Mgh$ is shared between kinetic energy of moving forward, $\frac{1}{2}Mv^2$, and kinetic energy of turning, $\frac{1}{2}I\omega^2$. The ring has all its mass at the rim, $I = MR^2$; the disc has $I = \frac{1}{2}MR^2$. So more of the ring's energy goes into turning and less into moving forward: at each point on the slope it moves more slowly. (From $Mgh = \frac{1}{2}Mv^2(1 + K^2/R^2)$: $v = \sqrt{gh}$ for the ring and $v = \sqrt{4gh/3}$ for the disc.) The result does not depend on the mass or the radius, only on the shape.



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**Marking scheme**

- The disc reaches the bottom first.
- Reason: the ring's larger moment of inertia ($MR^2$ against $\frac{1}{2}MR^2$) puts more of the energy into turning, so it moves forward more slowly.

## Question 3 — 5 marks

**a.** The viscous drag on a small sphere moving slowly through a fluid is directly proportional to the coefficient of viscosity η of the fluid, the radius r of the sphere and its velocity v: $F = 6\pi\eta r v$. **[1]**

**Marking scheme**

- $F = 6\pi\eta r v$, with the meaning of η, r and v.

**b.** Terminal velocity: $v = \dfrac{0.10\ \text{m}}{10\ \text{s}} = 0.010$ m/s. **[2]**

At the terminal velocity the drag and the upthrust balance the weight, which gives $v = \dfrac{2r^2(\rho - \sigma)g}{9\eta}$, so

$$\eta = \frac{2r^2(\rho-\sigma)g}{9v} = \frac{2 \times (1.0\times10^{-3})^2 \times (8000 - 1250) \times 9.8}{9 \times 0.010} = \frac{0.1323}{0.09} = \mathbf{1.47}\ \text{Pa s}$$

**Marking scheme**

- Terminal velocity 0.010 m/s and the formula $\eta = \dfrac{2r^2(\rho-\sigma)g}{9v}$.
- η = 1.47 Pa s (or N s/m²).

**c.** **She is not right.** The terminal velocity is $v = \dfrac{2r^2(\rho-\sigma)g}{9\eta}$, so it is proportional to $r^2$, not to $r$: the weight less the upthrust goes as $r^3$, while the drag goes as $r$. Half the radius gives a quarter of the speed: **[2]**

$$v' = \frac{0.010}{4} = 0.0025\ \text{m/s}$$

Time between the marks: $t = \dfrac{0.10}{0.0025} =$ **40 s**, not 20 s.

**Marking scheme**

- Not right: $v \propto r^2$, so half the radius gives a quarter of the terminal velocity.
- Time = 40 s.

**OR**

**a.** **Simple harmonic motion** is the periodic motion of a body in which its acceleration is directly proportional to its displacement from the mean position and is always directed towards that position: $a = -\omega^2 x$. **[1]**

**Marking scheme**

- Acceleration proportional to the displacement and directed towards the mean position ($a = -\omega^2 x$).

**b.** **[2]**

$$T = 2\pi\sqrt{\frac{l}{g}} = 2\pi\sqrt{\frac{2.45}{9.8}} = 2\pi\sqrt{0.25} = 2\pi \times 0.5 = \pi \approx \mathbf{3.14}\ \text{s}$$

**Marking scheme**

- $T = 2\pi\sqrt{l/g}$ with the values.
- T = 3.14 s.

**c.** **It will lose time** (run slow). **[2]**

The period of the pendulum is $T = 2\pi\sqrt{l/g}$. With a smaller g, T is longer, so the pendulum makes fewer swings in an hour. The clock counts swings, so it shows less time than has really passed.

**Marking scheme**


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- The clock loses time.
- Reason: smaller g makes $T = 2\pi\sqrt{l/g}$ longer, so fewer swings are counted in a given time.

## Question 4 — 5 marks

**a.** When heat $dQ$ is given to a system, it is used partly to increase the internal energy of the system ($dU$) and partly to do external work ($dW$): $dQ = dU + dW$. It is the law of conservation of energy for processes that involve heat. **[1]**

**Marking scheme**

- $dQ = dU + dW$, with the meaning of each term.

**b.** When a gas is heated at constant volume, it does no external work ($dW = P\,dV = 0$), so all the heat goes to raising its internal energy, and so its temperature. **[2]**

When it is heated at constant pressure, it expands and does external work $P\,dV$ as well. To raise its temperature by the same 1 K (the same rise in internal energy), extra heat is needed for that work. So $C_P > C_V$; for one mole of an ideal gas the extra heat is exactly $R$: $C_P - C_V = R$.

**Marking scheme**

- At constant volume no work is done, so all the heat raises the internal energy.
- At constant pressure the gas also does work in expanding, so more heat is needed for the same temperature rise.

**c.** **[1]**

$$C_P = C_V + R = 20.8 + 8.3 = \mathbf{29.1}\ \mathrm{J/(mol\ K)}$$

**Marking scheme**

- $C_P = C_V + R = 29.1$ J/(mol K).

**d.** Pushed in quickly, the air has no time to give heat to the cylinder walls, so the compression is nearly **adiabatic** ($dQ = 0$). Then $dU = -dW$: the work done **on** the air goes entirely into its internal energy, and its temperature rises. **[1]**

**Marking scheme**

- Quick compression is nearly adiabatic, so the work done on the air raises its internal energy and temperature.

## Question 5 — 5 marks

**a.** The **grating element** is the distance $d = a + b$ between the corresponding points of two neighboring slits (the width of a slit plus the width of the opaque line next to it). It is $d = 1/N$, where N is the number of lines per unit length. **[1]**

**Marking scheme**

- $d = a + b$, the distance from a slit to the next ($d = 1/N$).

**b.** **[2]**

$$d = \frac{1}{N} = \frac{1}{5000\ \mathrm{per\ cm}} = 2 \times 10^{-4}\ \mathrm{cm} = 2 \times 10^{-6}\ \mathrm{m}$$

For the first order, $d\sin\theta_1 = \lambda$:

$$\sin\theta_1 = \frac{600 \times 10^{-9}}{2 \times 10^{-6}} = 0.3 \qquad \theta_1 = \mathbf{17.5}^\circ$$

**Marking scheme**

- $d = 2 \times 10^{-6}$ m and $d\sin\theta = n\lambda$.
- $\sin\theta_1 = 0.3, \theta_1 = 17.5^\circ$.

**c.** **He is not right.** Since $\sin\theta$ can be at most 1, $n\lambda \le d$, so $n \le \dfrac{d}{\lambda} = \dfrac{2 \times 10^{-6}}{600 \times 10^{-9}} = 3.33$. **[2]**


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The highest order he can see is the largest whole number below 3.33, the **third**. The fourth order would need $\sin\theta_4 = 4 \times 0.3 = 1.2$, which is impossible.

**Marking scheme**

- $n \le d/\lambda = 3.33$, since $\sin\theta \le 1$.
- Highest order 3, so he is not right (the fourth would need $\sin\theta = 1.2$).

## Question 6 — 5 marks

**a.** When four resistances P, Q, R and S are joined to form a Wheatstone bridge and no current flows through the galvanometer, the bridge is balanced and $\dfrac{P}{Q} = \dfrac{R}{S}$. **[1]**

**Marking scheme**

- At balance (no current in the galvanometer), $P/Q = R/S$.

**b.** She should take out a resistance close to the expected value of the wire, about 5 Ω, from the resistance box. That brings the balance point near the **middle** of the bridge wire, where a small error in reading the balance length makes the smallest error in the result. **[1]**

**Marking scheme**

- Use R close to the expected value (about 5 Ω) so the balance point is near the middle, where the error is least.

**c.** **Method.** She connects the nichrome wire X in the left gap and the resistance box R in the right gap, the galvanometer between the middle strip and the jockey, and the cell and key across the ends of the bridge wire. With a resistance taken out of the box, she slides the jockey along the wire, touching it gently, until the galvanometer shows no deflection, and reads the balance length l from the left end. **[3]**

**Formula.** The wire is uniform, so the resistances of its two parts are in the ratio $l : (100 - l)$. By the Wheatstone bridge principle,

$$\frac{X}{R} = \frac{l}{100 - l} \qquad \Rightarrow \qquad X = \frac{l}{100 - l}\,R$$

**Result.**

$$X = \frac{55.0}{100 - 55.0} \times 4 = \frac{55}{45} \times 4 = \mathbf{4.89\ \Omega}$$

She can repeat it for other values of R, and with X and R interchanged, and take the mean.

**Marking scheme**

- The circuit set up and the jockey moved until the galvanometer shows no deflection.
- $X = \dfrac{l}{100 - l}R$ from the Wheatstone bridge principle.
- X = 4.89 Ω.

## Question 7 — 5 marks

**a.** **First law:** whenever the magnetic flux linked with a closed circuit changes, an e.m.f. is induced in it; it lasts only as long as the flux is changing. **[2]**

**Second law:** the magnitude of the induced e.m.f. is directly proportional to the rate of change of the magnetic flux linkage, $\varepsilon = -N\dfrac{d\phi}{dt}$.

**Marking scheme**

- First law: a changing flux linked with a circuit induces an e.m.f. in it.
- Second law: the e.m.f. is proportional to the rate of change of flux linkage.

**b.** The changing flux in the core induces **eddy currents** in the iron, which waste energy as heat. Thin, insulated sheets (laminations) stop an eddy current from flowing across from sheet to sheet, so each **[1]**


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one is confined to a thin sheet where its e.m.f. is small and its path's resistance is large: the eddy currents, and the heat lost, become small.

**Marking scheme**

- Laminations reduce the eddy currents, and so the energy lost as heat.

**c.** As the magnet falls, the magnetic flux through each ring of the pipe below it grows and through each ring above it shrinks. This changing flux induces **eddy currents** in the copper. By **Lenz's law**, these currents flow so as to oppose their cause, the magnet's motion: the ring below repels the magnet and the ring above attracts it, so there is an upward force on it. It soon falls at a small, steady speed, and its lost potential energy becomes heat in the pipe. **[2]**

With a slit along the pipe, the currents can no longer flow all the way round the pipe, so the eddy currents and the opposing force become much smaller, and the magnet falls much faster.

**Marking scheme**

- The changing flux induces eddy currents in the pipe which, by Lenz's law, oppose the motion: an upward force on the magnet.
- A slit breaks the paths round the pipe, so the currents and the braking are much smaller and the magnet falls faster.

## Question 8

**5 marks**

**a.** Decay constant: **[3]**

$$\lambda = \frac{0.693}{T_{1/2}} = \frac{0.693}{8.0\ \text{days}} = 0.0866\ \text{per day}\ (\approx 1.0 \times 10^{-6}\ \text{s}^{-1})$$

The activity is proportional to the number of undecayed nuclei, so it halves every half-life:

$$\frac{3.2}{0.4} = 8 = 2^3$$

That is 3 half-lives: $t = 3 \times 8.0 =$ **24 days**.

**Marking scheme**

- $\lambda = 0.693/T_{1/2}$.
- λ = 0.0866 per day (1.0 × 10⁻⁶ s⁻¹).
- 3.2 to 0.4 MBq is 3 half-lives: 24 days.

**b.** A short half-life means a high activity for a small amount: enough radiation for the scan or the treatment is given by a tiny mass of the isotope, and the activity then falls quickly (to 1/8 in 24 days), so the patient is not exposed for long. **[2]**

With a half-life of billions of years, a sample would hardly decay in a lifetime: for the same activity a huge amount would be needed, and what was taken in would keep irradiating the body for the rest of the patient's life.

**Marking scheme**

- Short half-life: high activity from a small amount, so a small dose gives enough radiation.
- It soon decays away, so the body is not irradiated for long; a long-lived isotope would stay active for a lifetime.

## Question 9

**5 marks**

**a.** Any three of these: **[3]**

1. They are electromagnetic waves of very short wavelength (about 0.06 Å to 100 Å), traveling in straight lines at the speed of light.
2. They are not deflected by electric or magnetic fields, as they carry no charge.


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3. They pass through materials opaque to light, such as flesh, wood and paper, but are stopped by bone and heavy metals such as lead.
4. They blacken a photographic plate.
5. They cause fluorescence in some substances.
6. They ionize the gas they pass through.
7. They can damage living cells.

**Marking scheme**

- One correct property.
- A second correct property.
- A third correct property.

**b.** The shortest wavelength comes from an electron that gives all its energy $eV$ to a single photon: **[2]**

$$\lambda_{\min} = \frac{hc}{eV} = \frac{6.62 \times 10^{-34} \times 3 \times 10^{8}}{1.6 \times 10^{-19} \times 31\,000} = \mathbf{4.0 \times 10^{-11}}\ \text{m}\ (0.40\ \text{Å})$$

**Marking scheme**

- $\lambda_{\min} = \dfrac{hc}{eV}$.
- $\lambda_{\min} = 4.0 \times 10^{-11}$ m.

**OR**

**a.** When the junction is made, free electrons diffuse from the n side, where they are many, into the p side, and holes diffuse from the p side into the n side; there they recombine. **[3]**

This leaves a thin region on each side of the junction with almost no free carriers: the **depletion layer**. In it are only the fixed ions, negative acceptor ions on the p side and positive donor ions on the n side.

These charges set up an electric field across the junction, from the n side to the p side, which opposes further diffusion. The potential difference across the layer is the **potential barrier**, about 0.7 V for silicon.

**Marking scheme**

- Electrons diffuse from n to p and holes from p to n, and recombine.
- A region with no free carriers, only fixed ions (negative on the p side, positive on the n side), is left: the depletion layer.
- The ions' field opposes further diffusion; its potential difference is the potential barrier (about 0.7 V for silicon).

**b.** **[2]**

| A | B | A + B | $Y = \overline{A + B}$ |
|---|---|---|---|
| 0 | 0 | 0 | 1 |
| 0 | 1 | 1 | 0 |
| 1 | 0 | 1 | 0 |
| 1 | 1 | 1 | 0 |

The output is 1 only when both inputs are 0: it is a **NOR gate**.

**Marking scheme**

- The truth table with Y = 1, 0, 0, 0.
- It is a NOR gate, $Y = \overline{A + B}$.

## Group C Long answers, each on one content area — 24 marks

### Question 10 — 8 marks

**a.** Speed of the transverse wave on the string, with $m = 5.0 \times 10^{-3}$ kg/m: **[2]**


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$$v = \sqrt{\frac{T}{m}} = \sqrt{\frac{72}{5.0 \times 10^{-3}}} = \sqrt{14\,400} = 120\ \mathrm{m/s}$$

In the fundamental mode the string's length is half a wavelength, $\lambda = 2l = 1.20$ m:

$$f_0 = \frac{v}{2l} = \frac{120}{2 \times 0.60} = \mathbf{100\ Hz}$$

**Marking scheme**

- $v = \sqrt{T/m} = 120$ m/s.
- $f_0 = v/2l = 100$ Hz.

**b.** $f = \frac{1}{2l}\sqrt{\frac{T}{m}}$, so with the same length and string $f \propto \sqrt{T}$: **[2]**

$$\frac{T'}{T} = \left(\frac{f'}{f}\right)^2 = \left(\frac{150}{100}\right)^2 = 2.25 \qquad T' = 2.25 \times 72 = \mathbf{162\ N}$$

**Marking scheme**

- $f \propto \sqrt{T}$ (the law of tension).
- T' = 162 N.

**c.** A light touch forces a **node** at the middle of the string. The fundamental mode has an antinode there, so it cannot sound. The lowest mode with nodes at both ends and at the middle is the second harmonic, with the string vibrating in two loops ($\lambda = l$): **[2]**

$$f = \frac{v}{l} = \frac{120}{0.60} = 200\ \mathrm{Hz}$$

A note of **200 Hz** is heard, an octave above the fundamental.

**Marking scheme**

- The touch makes a node at the middle, so the fundamental (antinode at the middle) is stopped.
- The second harmonic, 200 Hz (an octave higher), is heard.

**d.** **No.** The mass per unit length of a wire is $m = \pi r^2 \rho = \frac{\pi d^2}{4}\rho$, so twice the diameter gives **four** times the mass per unit length (20 g per meter), not twice. **[2]**

By the law of mass, $f = \frac{1}{2l}\sqrt{\frac{T}{m}} \propto \frac{1}{\sqrt{m}}$ at the same length and tension, so the frequency is halved: $f = \frac{100}{\sqrt{4}} = \mathbf{50\ Hz}$, an octave below, not 71 Hz.

**Marking scheme**

- $m = \pi r^2 \rho$: twice the diameter gives four times the mass per unit length, not twice.
- $f \propto 1/\sqrt{m}$, so f = 100/2 = 50 Hz: he is not right.

## Question 11 — 8 marks

**a.** $X_L = 80\ \Omega$ is greater than $X_C = 40\ \Omega$, so the circuit is **more inductive**, and the current **lags** behind the supply voltage. The phase angle is **[2]**

$$\tan\phi = \frac{X_L - X_C}{R} = \frac{80 - 40}{30} = \frac{4}{3} \qquad \phi = 53^\circ$$

**Marking scheme**

- $X_L > X_C$: more inductive, so the current lags the voltage.
- $\tan\phi = (X_L - X_C)/R = 4/3$, φ = 53°.

**b.** **[2]**

$$Z = \sqrt{R^2 + (X_L - X_C)^2} = \sqrt{30^2 + (80 - 40)^2} = \sqrt{900 + 1600} = \mathbf{50\ \Omega}$$


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$$I = \frac{V}{Z} = \frac{200}{50} = \mathbf{4}\ \mathrm{A}$$

**Marking scheme**

- $Z = \sqrt{R^2 + (X_L - X_C)^2} = 50\ \Omega$.
- $I = V/Z = 4$ A.

**c.** The three voltages are not in phase, so they add as phasors (vectors), not as numbers. Draw the current along the x-axis. $V_R = 120$ V is in phase with the current, along it; $V_L = 320$ V leads it by 90°, straight up; $V_C = 160$ V lags it by 90°, straight down. **[2]**

$V_L$ and $V_C$ are opposite, so they partly cancel: $V_L - V_C = 160$ V up. This is at right angles to $V_R$, so

$$V = \sqrt{V_R^2 + (V_L - V_C)^2} = \sqrt{120^2 + 160^2} = \sqrt{40\,000} = 200\ \mathrm{V}$$

**Marking scheme**

- The voltages are out of phase: $V_R$ along the current, $V_L$ 90° ahead and $V_C$ 90° behind, so they add as phasors (diagram).
- $V = \sqrt{V_R^2 + (V_L - V_C)^2} = \sqrt{120^2 + 160^2} = 200$ V.

**d.** The most power is taken at **resonance**, when $X_C = X_L = 80\ \Omega$: then Z = R = 30 Ω and the current is greatest (200/30 = 6.7 A). Since $X_C = \dfrac{1}{2\pi f C}$, a larger $X_C$ needs a **smaller** capacitor: **[2]**

$$C = \frac{1}{2\pi f X_C} = \frac{1}{2 \times 3.14 \times 50 \times 80} = 3.98 \times 10^{-5}\ \mathrm{F} \approx \mathbf{40}\ \boldsymbol{\mu}\mathbf{F}$$

That is half the present capacitor, which is about 80 μF ($1/(2\pi \times 50 \times 40)$).

**Marking scheme**

- Most power at resonance, $X_C = X_L = 80\ \Omega$, so a smaller capacitor ($X_C \propto 1/C$).
- C = 1/(2πf X_C) ≈ 40 μF.

**OR**

**a.** An ammeter is joined in series and must measure currents far larger than the galvanometer can take. A low resistance (a **shunt**) in parallel carries most of the current, leaving only a small, definite fraction, up to 1 mA, to flow through the galvanometer, so the meter can be read for a larger range. **[2]**

Because the shunt is small, the ammeter as a whole has a very low resistance, so putting it in series hardly changes the current it measures.

**Marking scheme**

- The shunt in parallel carries most of the current, leaving only up to the full-scale current in the galvanometer.
- Its low resistance keeps the ammeter's resistance low, so it hardly changes the current in the circuit.

**b.** A voltmeter is connected **in parallel** with the part of the circuit whose potential difference it measures. If its resistance were low, it would draw a large current, lowering the resistance of that part and so changing the very potential difference it is meant to measure. With a very high resistance it draws almost no current, and the circuit is left nearly as it was. **[2]**

**Marking scheme**

- A voltmeter is joined in parallel with the part being measured.
- A high resistance draws almost no current, so the potential difference measured is not changed.

**c.** The galvanometer and shunt have the same potential difference across them: $I_g G = (I - I_g)S$. **[2]**


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$$S = \frac{I_g G}{I - I_g} = \frac{0.001 \times 99}{0.100 - 0.001} = \frac{0.099}{0.099} = \mathbf{1\ \Omega}$$

**Marking scheme**

- $I_g G = (I - I_g)S$.
- S = 1 Ω.

**d.** For a full-scale deflection at 10 V the total resistance must be $\frac{10}{0.001} = 10\,000\ \Omega$, and the galvanometer already gives 99 Ω of it: **[2]**

$$R = \frac{V}{I_g} - G = 10\,000 - 99 = \mathbf{9\,901\ \Omega}$$

So the friend is **not exactly right**. With 10 kΩ the total is 10,099 Ω, and full scale would need 10.1 V: every reading would be about 1% low. That is close enough for rough work, but not for an accurate meter.

**Marking scheme**

- $R = V/I_g - G = 9{,}901\ \Omega$, so the friend is not exactly right.
- His 10 kΩ gives readings about 1% low (full scale at 10.1 V): near enough only for rough work.

## Question 12 — 8 marks

**a.** Light gives its energy to electrons in photons, each of energy $hf$, and one photon is absorbed by one electron. An electron can escape only if a single photon gives it at least the work function φ of the metal. Below the threshold frequency $f_0 = \phi/h$ each photon has too little energy. A brighter light only means more photons, each still too weak, so no electron escapes. **[2]**

**Marking scheme**

- Energy comes in photons of $hf$, one photon to one electron.
- Below $f_0 = \phi/h$ one photon cannot give the work function; brighter light only gives more such photons.

**b.** The stopping potential measures the maximum kinetic energy of the photoelectrons, $eV_0 = hf - \phi$. This depends only on the energy of one photon, $hf$, and on the metal, not on how many photons arrive. A more intense light gives more photons, so more electrons and a larger current, but each electron's maximum energy, and so $V_0$, stays the same. **[2]**

**Marking scheme**

- $eV_0 = hf - \phi$: the maximum kinetic energy depends on the photon's energy, not on the number of photons.
- Higher intensity gives more photoelectrons (more current), not faster ones.

**c.** From $eV_0 = hf - \phi$, $V_0 = \frac{h}{e}f - \frac{\phi}{e}$: the graph of $V_0$ against f is a straight line of slope $h/e$. From the first and last readings: **[2]**

$$\text{slope} = \frac{2.13 - 0.48}{(10.0 - 6.0) \times 10^{14}} = \frac{1.65}{4.0 \times 10^{14}} = 4.125 \times 10^{-15}\ \text{V s}$$

$$h = e \times \text{slope} = 1.6 \times 10^{-19} \times 4.125 \times 10^{-15} = \mathbf{6.6 \times 10^{-34}}\ \text{J s}$$

**Marking scheme**

- Slope of $V_0$ against f = h/e = 4.125 × 10⁻¹⁵ V s.
- h = 6.6 × 10⁻³⁴ J s.


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**d.** The threshold frequency is where $V_0 = 0$: from the line, $f_0 = 6.0 \times 10^{14} - \dfrac{0.48}{4.125 \times 10^{-15}} = 6.0 \times 10^{14} - 1.16 \times 10^{14} = 4.84 \times 10^{14}$ Hz. **[2]**

$$\phi = hf_0 = 6.6 \times 10^{-34} \times 4.84 \times 10^{14} = 3.2 \times 10^{-19}\ \text{J} = \frac{3.2 \times 10^{-19}}{1.6 \times 10^{-19}} = \mathbf{2.0}\ \text{eV}$$

Red light: $f = \dfrac{c}{\lambda} = \dfrac{3 \times 10^8}{650 \times 10^{-9}} = 4.6 \times 10^{14}$ Hz, which is **below** the threshold $4.84 \times 10^{14}$ Hz (each photon has only 1.9 eV). So red light **cannot** eject electrons, however bright.

**Marking scheme**

- $f_0 \approx 4.8 \times 10^{14}$ Hz and φ = 2.0 eV.
- Red light (4.6 × 10¹⁴ Hz, 1.9 eV) is below the threshold, so no electrons are ejected.

**OR**

**a.** By Bohr's theory, the electron in a hydrogen atom can only be in certain orbits, each with a definite energy. Light is emitted only when the electron jumps from a higher level to a lower one, as a photon of energy $hf = E_i - E_f$. Since only certain energy differences are possible, only certain frequencies are emitted, which appear as separate bright lines. **[2]**

**Marking scheme**

- The electron can have only certain definite energies (energy levels).
- A jump between levels emits a photon of $hf = E_i - E_f$: only certain frequencies, so separate lines.

**b.** The zero of energy is taken as the electron at rest at an infinite distance from the nucleus, that is, just free of the atom. A bound electron is held by the nucleus's attraction: energy has to be **given** to it to free it, so it has less energy than a free electron at rest, a negative energy. The more negative $E_n$, the more tightly the electron is bound (13.6 eV in the ground state). **[2]**

**Marking scheme**

- Zero energy is the electron free of the atom (at infinity, at rest).
- A bound electron needs energy to be freed, so its total energy is less than zero.

**c.** **[2]**

$$\Delta E = E_3 - E_2 = -\frac{13.6}{9} - \left(-\frac{13.6}{4}\right) = -1.51 + 3.40 = 1.89\ \text{eV} = 1.89 \times 1.6 \times 10^{-19} = 3.02 \times 10^{-19}\ \text{J}$$

$$\lambda = \frac{hc}{\Delta E} = \frac{6.62 \times 10^{-34} \times 3 \times 10^8}{3.02 \times 10^{-19}} = 6.57 \times 10^{-7}\ \text{m} \approx \mathbf{657}\ \text{nm}$$

This is the red line of the Balmer series.

**Marking scheme**

- ΔE = 1.89 eV (3.02 × 10⁻¹⁹ J).
- λ = hc/ΔE ≈ 657 nm (6.57 × 10⁻⁷ m).

**d.** A photon is absorbed only if its energy exactly equals the difference between the ground state and a higher level: **[2]**

- to n = 2: $13.6\left(1 - \frac{1}{4}\right) = 10.2$ eV
- to n = 3: $13.6\left(1 - \frac{1}{9}\right) = 12.09$ eV
- to n = 4: $13.6\left(1 - \frac{1}{16}\right) = 12.75$ eV

So the **10.2 eV** and **12.75 eV** photons can be absorbed (lifting the electron to n = 2 and n = 4). The 11.0 eV photon matches no difference and is less than the 13.6 eV needed to ionize the atom, so it passes through without being absorbed.

**Marking scheme**

- Absorbed only if the energy equals a level difference: 10.2 eV (n = 1 to 2) and 12.75 eV (n = 1 to 4).


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- 11.0 eV matches no difference (and cannot ionize), so it is not absorbed.


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