British Physics Olympiad

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British Physics Olympiad

BPhO Physics Challenge — Mark Scheme

September/October 2024

Instructions

Give equivalent credit for alternative solutions which are correct physics. Generally allow leeway of ± 1 significant figure.

This is not the tight marking scheme of a competitive exam paper. It is to allow students to engage in problem solving and develop their physics by working through problems requiring explanations, and developing ideas or models. Mark generously to encourage ideas, determination and the willingness on their part to have a go.

Qu 1.

As these are estimates the calculations below simply show one way to tackle the task; a good deal of latitude is needed in the marking to allow equivalent credit for other sensible approaches and degrees of approximation.

i) Alexandria lies 7° of latitude north of Syene. ✓
Hence, as 1 rad is approximately equal to 57°, ✓

$$\text{radius of Earth} = 800\text{ km} \times \frac{57^\circ}{7^\circ} \qquad \left[= \frac{800\text{ km}}{2\pi} \times \frac{360^\circ}{7^\circ}\right]$$
$$= 6500\text{ km.} \quad ✓$$

(3 marks)

ii) Assuming uniform atmosphere (variants possible!)

$$h = \frac{P}{\rho g}$$
$$= \frac{1 \times 10^5\text{ Pa}}{1.3\text{ kg m}^{-3} \times 10\text{ m s}^{-2}}$$
$$= 7.7\text{ km.} \quad ✓$$

The volume of the atmosphere can be approximated as, (surface area $\times$ [thin] height) (so value of g constant over this height and we have made this volume of atmosphere of constant density,

$$V = 4\pi r^2 h. \quad ✓$$

We can use this approximation for volume to find the number of molecules in the atmosphere,

$$\text{number of moles} = \frac{4\pi r^2 h}{0.022} \qquad 1\text{ mole occupies } \approx 22\text{ dm}^3$$
$$\text{number of molecules} = \frac{6 \times 10^{23} \times 4\pi r^2 h}{0.022}$$
$$= \frac{6 \times 10^{23} \times 4\pi \times (6500\text{ km})^2 \times 7.7\text{ km}}{0.022}$$
$$= 1 \times 10^{44}. \quad ✓$$

Or we can instead multiply the volume by $1.3\,\mathrm{kg\,m^{-3}}$ to obtain the mass of the atmosphere, and then divide by ≈ 0.030, which is the mass of a mole of air (about $30\,\mathrm{g}$), and then multiply by N_A. (3 marks)

iii) Argon is monatomic. This means there is only translational kinetic energy.

$$v = \sqrt{\frac{2E_k}{m}} \quad ✓$$
$$= \sqrt{\frac{2 \times 3700\,\mathrm{J}/N_\mathrm{A}}{0.04\,\mathrm{kg}/N_\mathrm{A}}}$$
$$= 430\,\mathrm{m\,s^{-1}}. \quad ✓$$

(2 marks)

[Total 8 marks]

Qu 2.

i) Light reflected from the bottom of the wedge travels further than that reflecting from the top. ✓
Leads to a path difference between rays that changes uniformly with distance along wedge. ✓
Therefore positions of constructive / destructive interference occur at regular spacings. ✓
Owtte

(3 marks)

ii) Transverse waves undergo a π phase shift at a more dense boundary, hence destructive interference at the tip of the wedge where the gap is λ but there is still a gap between the plates. ✓
Owtte

(1 mark)

iii) As the dark (or bright fringes) occur at equal intervals of thickness (every $\frac{\lambda}{2}$ of thickness or λ of path difference) they are analogous to cartographical contours. ✓
Owtte
If the gap has variations of a modest number of wavelengths, this will be apparent as a contour map formed of interference fringes. ✓
Owtte

(2 marks)

iv) At any given position, different colours (i.e. different wavelengths), will all have different phase differences. ✓
Therefore they will constructively / destructively interfere to different extents. ✓
At any position **only one wavelength** will disappear completely leaving “subtraction colours” (i.e. white minus one particular colour and a diminution of others). ✓
(3 marks)

[Total 9 marks]

Qu 3.

a) i) Marble oscillates to and fro across the slope. Maximum speed at lowest point and the marble is at rest at the highest points at the extremes. E_k is maximised at the lowest point and is minimised at the highest points. E_p is maximised at the highest points and is minimised at the lowest point. ✓✓✓

ii) Assuming no energy loss, same horizontal level as starting point. ✓

iii) Three different starting positions shown as different colour balls on **Figure 1,** each having the maxima of their motion in a horizontal line. The minima for all balls is the same point, shown in green.

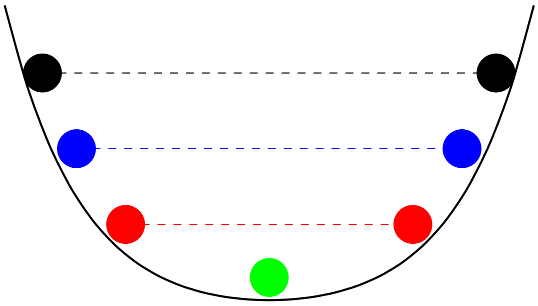

Figure 1: Smoothly curved **symmetrical** slope with three starting heights.

✓

iv) The midpoints of each ball starting height go vertically up as shown in **Figure 2.**

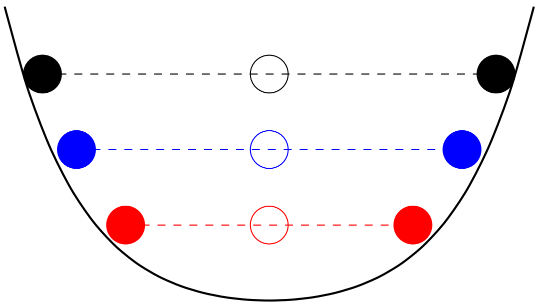

Figure 2: Smoothly curved **symmetrical** slope with midpoints of each ball shown.

There is no change in position with an increase of vibrational energy. ✓

(6 marks)

b) i) Same answer as part a)i) ✓

ii) Same answer as part a)ii) ✓

iii) Three different starting positions shown as different colour balls on **Figure 3,** each having the maxima of their motion in a horizontal line. ✓
The minima for all balls is the same point, shown in green.

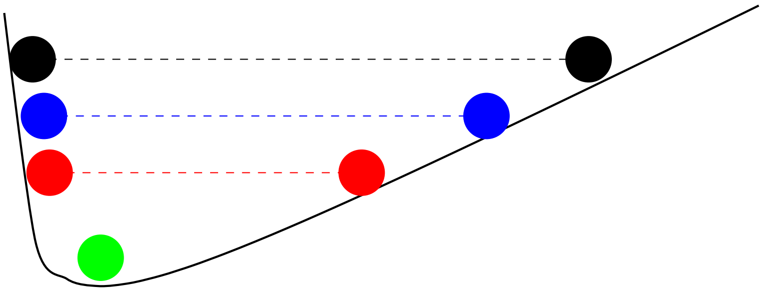

Figure 3: Smoothly curved **asymmetrical** slope with three starting heights.

iv) The midpoints of each ball starting height are this time not going vertically upwards as shown in **Figure 4.** ✓
Some comment that this system moves its mean position with increase in vibrational energy. ✓
(5 marks)

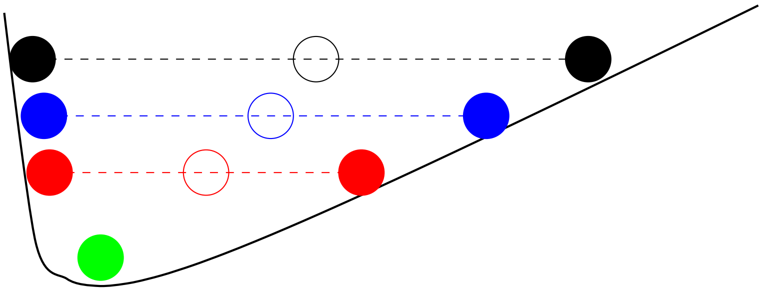

Figure 4: Smoothly curved **asymmetrical** slope with three starting heights and showing the midpoints.

c) i) The graph of $y = \frac{1}{x}$ is shown in blue on **Figure 5.** The graph must pass through (1, 1). ✓

ii) The graph of $y = \frac{1}{x^2}$ is shown in red on **Figure 5.** The graph must pass through (1, 1). ✓

iii) As n increases, the part of the graph to left of (1,1) gets steeper. While the part of the graph to the right becomes closer to the horizontal axis. ✓
Owtte

iv) Shown in **Figure 6** are the two curves representing the two potential energies associated with this model of inter-atomic bond energies. ✓

v) Added to the graph the combined term shown in **Figure 7.** ✓

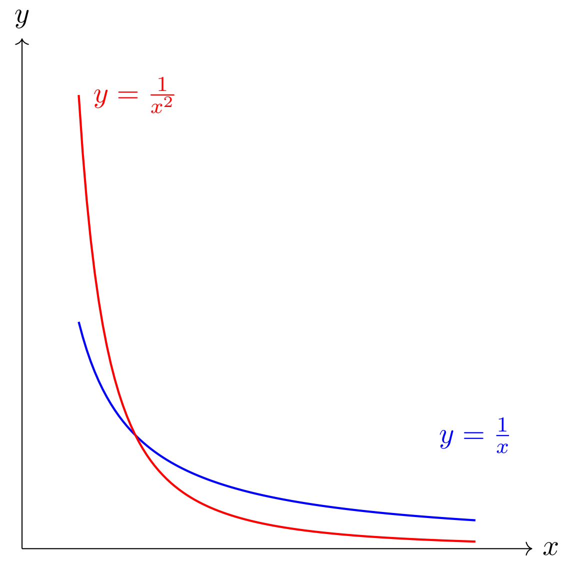

Figure 5: First quadrant showing the required graphs for question part i) and ii)

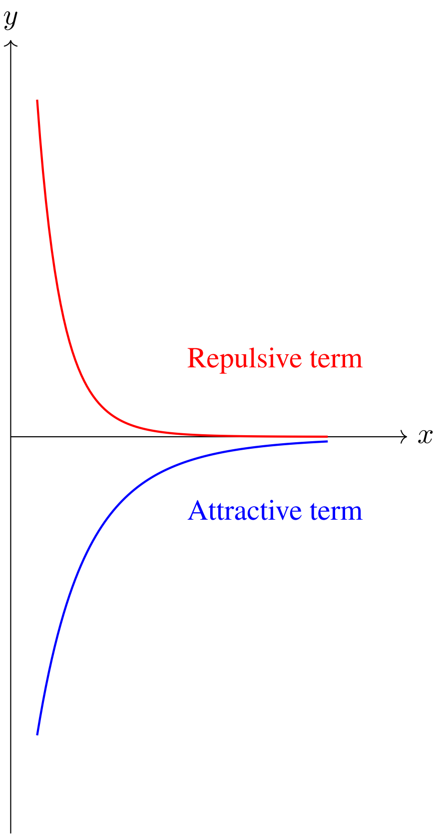

Figure 6: The repulsive term is shown in red and the attractive term is shown in blue.

vi) Asymmetrical ✓

vii) When at equilibrium, the graph of potential energy should have zero gradient. For stable equilibrium, this point should be a local minima. ✓
The equilibrium point is marked on **Figure 7** with an X. ✓

viii) When the bond is heated, the energy increases, allowing the atoms to oscillate around the

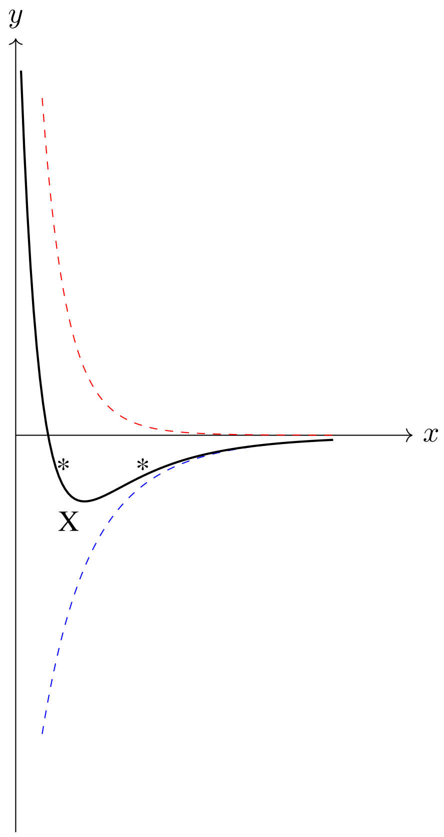

Figure 7: The combined term is shown in black

equilibrium position. The * shown in **Figure 7** indicate what could be acceptable, note the midpoint is not annotated but is required for the mark. For a more detailed view the annotations are similar to the graphs shown in **Figure 4** above. ✓

ix) Two further lines similar to what is shown in **Figure 4.** ✓

x) As the temperature and therefore the vibrational energy increases so does the mean separation. ✓

Bond length increasing throughout a sample of material implies expansion. ✓

(11 marks)

[Total 22 marks]

Qu 4.

a) Considering the potential dividers ACB, ADB, symmetry requires C and D to be at the same potential. ✓
DC has no p.d across it, therefore no current flows in it and so it is redundant. It may be removed without causing change. ✓
The system becomes 60 Ω, 30 Ω, 60 Ω in parallel, which by inspection is 15 Ω. ✓

(3 marks)

b) As every resistor has one end connected directly to A and the other end connected directly to B, the resistors are connected in parallel. ✓
$30\ \Omega$, $30\ \Omega$, $30\ \Omega$ in parallel, by inspection gives $10\ \Omega$. ✓

(2 marks)

c) Consider this annotated version of the network as shown in **Figure 8.**

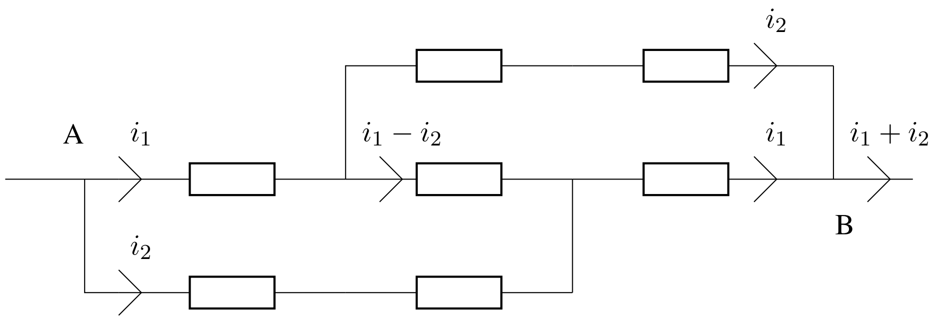

Figure 8: Annotated resistor network

Insert currents as shown beside point A; symmetry requires i_1 and i_2 beside point B and the remainder follow from Kirchhoff's first law. ✓
There are other similar starting points possible.

Consider the pd across the whole system:

$$V = (i\ \ + i\ \ )R \tag{1}$$

Or, following the uppermost route,

$$V = i\ \ R + 2i\ \ R \tag{2}$$

where R represents a single $30\ \Omega$ resistor.

Or, directly across the centre,

$$\begin{aligned} V &= i_1 R + (i_1 - i_2)R + i_1 R &(3)\\ &= (3i_1 - i_2)R &(4) \end{aligned}$$

Eliminating V from (2) and (4),

$$i_1 R + 2i_2 R = (3i_1 - i_2)R,$$

re-arranging for i_1,

$$\begin{aligned} i_1 + 2i_2 &= 3i_1 - i_2\\ 2i_1 &= 3i_2\\ i_1 &= \frac{3}{2} i_2. &(5) \end{aligned}$$

Eliminating V from (1) and (2),

$$(i_1 + i_2)R_{\text{total}} = i_1 R + 2i_2 R$$

We can substitute in the result from (5)

$$\frac{5}{2} i_2 R_{\text{total}} = \frac{7}{2} i_2 R$$

$$R_{\text{total}} = \frac{7}{5}R$$
$$R_{\text{total}} = 42\,\Omega.$$

✓

✓

✓

✓

✓

Whole calculation, by any route up to 5 marks depending on progress.

(6 marks)

[Total 11 marks]

END OF SOLUTIONS