BRITISH PHYSICS OLYMPIAD 2015-16

BPhO Round 1

Section 2

13th November 2015

Instructions

Time: 1 hour 20 minutes on this section (approximately 40 minutes on each question).

Questions: Only TWO of the five questions in *Section 2* should be attempted.

Working: Working, calculations and explanations, properly laid out, must be shown for full credit. The final answer alone is not sufficient.

Marks: The maximum mark for each of these questions is 20.

Solutions: Answers and calculations are to be written on loose paper or examination booklets. Graph paper and formula sheets should also be made available. Students should ensure their **name** and their **school** is clearly written on all answer sheets.

Setting the paper: There are two options for setting BPhO Round 1:

- *Section 1* and *Section 2* may be sat in one session of 2 hours 40 minutes.
- *Section 1* and *Section 2* may be sat in two sessions on separate occasions; with 1 hour 20 minutes allocated for each section. If the paper is taken in two sessions on separate occasions, *Section 1* must be collected in after the first session and *Section 2* handed out at the beginning of the second session.

Important Constants

Speed of light	c	3.00×10^{8}	m s^{-1}
Planck constant	h	6.63×10^{-34}	J s
Electronic charge	e	1.60×10^{-19}	C
Mass of electron	m_e	9.11×10^{-31}	kg
Gravitational constant	G	6.67×10^{-11}	N m^{2} kg^{-2}
Acceleration of free fall	g	9.81	m s^{-2}
Permittivity of a vacuum	ε_0	8.85×10^{-12}	F m^{-1}
Avogadro constant	N_A	6.02×10^{23}	mol^{-1}

Q2.

Electrons are accelerated through a potential V_1, producing a horizontal beam along the x-axis. The beam enters a perfectly uniform electric field parallel to the y-axis, produced by a parallel plate capacitor with potential difference, V_2 between the plates, which have separation d and are of length, s, as shown in Figure 2.1.

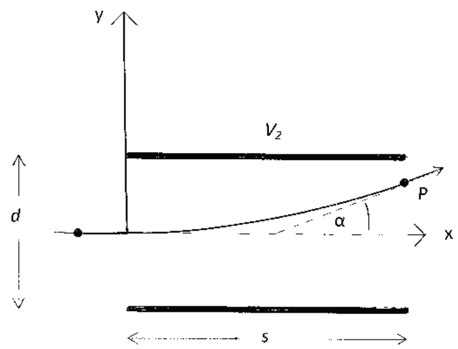

Figure 2.1

(a) Determine an expression for:

(i) the initial velocity, v_0 of the electrons entering the electric field.

(ii) the deflection angle, α , of the beam emerging from the electric field in terms of V_1 and V_2.

(iii) the displacement at P, y_e, of the emerging beam from the x-axis in terms of V_2

[8]

(b) Calculate the transition time, T, of an electron through the electric field, given that V_1 = 2,000 V, V_2= 50.0 V, s = 4.00 cm and d = 1.50 cm.

[2]

(c) On emerging from the parallel plates, the beam enters an identical electrostatic field that is at right angles to the initial field, perpendicular to the x-axis and the y-axis, along the z-axis. Determine an algebraic expression for the final speed of an electron exiting the second field and the angles it makes with the Cartesian coordinate axes.

[10]

Q3.

A force, F, resisting the motion of a cyclist travelling along a straight level road at speed v, in the absence of a wind, is given by

$$F = Av^2 + B$$

where A and B are constants.

Table 3 lists data on the power, P, developed by the cyclist as a function of v.

v / m s^{-1}	1.40	3.20	4.70	6.50	8.50	9.80	11.2	12.1
P/W	6.00	19.0	37.0	82.0	149	224	298	373

Table 3

(a) Draw a graph of F against v^2. Determine the constants A and B with an estimate of their accuracy.

[8]

(b) Suggest the physical significance of the terms Av^2 and B.

[2]

(c) The cyclist can sustain a power of 60 W over long periods. Deduce the equation for the maximum speed, v_C, he can maintain for long periods on a level road.

[5]

(d) By superimposing a graph on the sheet used in (a) determine v_C.

[5]

Q4.

(a) A square wave, positive voltage pulse with peak value 5.0 V and duration 0.020 s is applied across a series combination of a 2.0 kΩ resistor and a 5.0 μF capacitor.

Sketch, on the same graph, the voltages across the resistor, V_R, using a full curve, and across the capacitor, V_C, using a dashed curve. Add the two voltages using a dotted curve. No numerical calculation is required.

[6]

(b) The current, I, through a rod is related to the voltage V across it by

$$I = 0.20\,V^3.$$

The rod is connected in series with a resistor, resistance R, and a 6.0 V battery.

What is the value of R if:

(i) the current in the circuit is 0.40 A?

(ii) the power dissipated in the rod is twice that dissipated in the resistor?

[7]

(c) In the circuit in Figure 4.c(i), show that the circuit can be reduced to that in Figure 4.c(ii). Determine the values of R_1, R_2, C_1 and C_2. Each time a simplification is made to the circuit elements, draw the modified circuit.

[7]

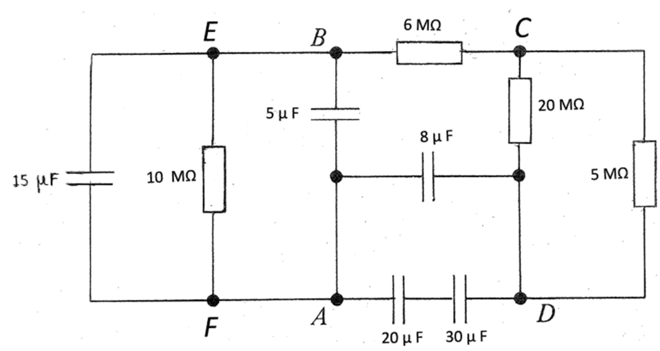

Figure 4.c(i)

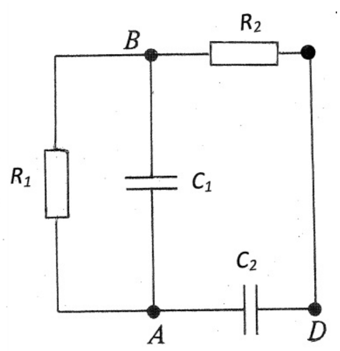

Figure 4.c(ii)

Q5.

A vertical glass tube, of height $2x_0$, is sealed at its lower end and open at the top end to the atmosphere. It contains *n* moles of air in the lower half (i.e. x_0) of volume V_0, and mercury of density, ρ, in the top half. As the air expands the mercury is expelled.

Atmospheric pressure, P_0, corresponds to length x_0 of mercury in a barometer.

(a) Air expands, occupying an additional length x of the tube, but with total volume V and pressure . Using the reduced volume, $V_R = V/V_0$, and the reduced pressure, $P_R = P/P_0$ of the air, express these quantities in terms of the reduced value of x, $x_R = x/x_0$. Deduce:

(i) the relation between P_R and V_R that is independent of temperature.

(ii) the general ideal gas law, for the air in the tube at temperature T, in terms of the reduced variables , V_R and T_R only , where $T_R = T/T_0$, and $T_0 = P_0V_0/nr$.

[4]

(b) Sketch on a $P_R - V_R$ graph for the system;

(i) the behaviour of the air in the physically admissible region.

(ii) the isotherms for the air, indicating which are at the higher temperatures by labelling using $T_{R1} > T_{R2} > T_{R3} >$ etc.

Comment on the symmetry of the curves in (i) and (ii).

Deduce the highest temperature reached by the air in the tube.

[8]

(c) When a small change in the reduced temperature, ΔT_R, and reduced volume, ΔV_R, takes place

$$5\Delta T_R/2 = s_R\Delta T_R - P_R\Delta V_R$$

where s_R is the specific heat per mole of the air in the tube.

Deduce that $$s_R = (21 - 12V_R)/(6 - 4V_R)$$

[4]

(d) Sketch a graph of s_R against V_R in the physically admissible region.

[4]

Q6.

Two identical spherical homogeneous stars A and B, each of mass M and radius r, have their centres $6r$ apart. The motion of the stars is to be ignored.

(a) Explain:
  (i) Why the surface of B is, or is not, a gravitational equipotential surface.
  (ii) With the aid of a diagram where, external to the surface of the stars, the gravitational potential is smallest and largest.
  (iii) Where on the surface of the stars is the potential a maximum?
  (iv) What is the potential mid-way between the stars?

[9]

(b) Sketch, on the same diagram, the equipotentials that have the values:

  (i) $V_1 = -10GM/3r$,

  (ii) $V_2 = -2GM/3r$ and

  (iii) $V_3 = -GM/3r$.

[4]

(c) If a body of mass m is ejected from B determine, with appropriate explanation, the minimum velocity, v_m , of launch required to enable it to reach A.

[7]

End of Questions