BRITISH PHYSICS OLYMPIAD 2008

COMPETITION

Paper 2

9th November 2007

A three hour paper, plus 15 minutes reading time

There are EIGHT questions.
The marks for each question are given on the right hand side of the page.
Graph paper is available.

FOUR questions are to be attempted. Formulae sheets may be used.

QUESTION 1 IS COMPULSORY. It is expected that students will spend 75 minutes on this question. The total mark allocated is 79. Students can attempt any, or all, of the sections. However the maximum total mark to be awarded will be 40.

THREE of the remaining six questions should be attempted. Students are recommended to spend 35 minutes on each of these questions. The maximum mark for each of these questions is 20.

Important Constants

Speed of light	c	3.00×10^{8}	ms^{-1}
Planck constant	h	6.63×10^{-34}	Js
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}	$Nm^{2} kg^{-2}$
Acceleration of free fall	g	9.81	ms^{-2}
Molar gas constant	R	8.31	$JK^{-1}mol^{-1}$
Radius of the Earth	R_E	6.83×10^{6}	m
Mass of the Earth	M_E	5.97×10^{24}	kg
Sun – Earth distance	R_{SE}	1.50×10^{11}	m
Radius of the Sun	R_S	6.96×10^{8}	m
Mass of the Sun	M_S	1.99×10^{30}	kg

Q1

(a) A cricket ball of mass 0.167 kg is thrown vertically upwards with an initial speed of 25.0 ms^{-1}. If the ball reaches a maximum height of 20.0 m, determine the percentage loss of energy caused by air resistance. [3]

(b) An earthquake off the coast of Sumatra, Indonesia, at A produces mechanical P and S waves that travel through the mantle of the Earth at speeds, respectively, of 5.50 kms^{-1} and 3.00 kms^{-1}. If the S wave arrives at the coastal station B, across the Indian ocean near Mombasa , Kenya, 15 mins 17 s after the P wave , determine:

(i) the distance, D, of B from A

(ii) the time, T, taken by a tsunami, produced by the earthquake, to arrive at B if it travels at 800 kmh^{-1}.

(iii) On what principle could a tsunami warning system be established ? [6]

(c) A class of 11 students each determined a value for g using a simple pendulum. The following values were obtained:

9.80, 9.84, 9.72, 9.74, 9.87, 9.75, 9.28, 9.86, 9.81, 9.79, 9.82

(i) What is your best estimate for g ?
(ii) Estimate the accuracy , based on the deviation from the best value of g in (i). [4]

(d) A man in a boat, floating on a pond of area A, has with him a stone bolder, of mass M_B and density ρ_B, and a timber block, of mass M_T and density ρ_T . The water has density ρ_W . By how much does the level of the water in the pond change if he throws into the pond:

(i) the bolder ?
(ii) the timber block ?

Give a full explanation in each case. [6]

(e) An open cylindrical container, radius 18 cm, contains water of density 1000 kgm^{-3}. It has a hole in the base connected to a horizontal exit tube, Figure 1.e. The container is suspended by a spring, spring constant k, from a support, a vertical distance, H, from the water surface. As the water drains out of the container, what value of k is required to maintain the surface of the water at its initial distance H below the support ? [4]

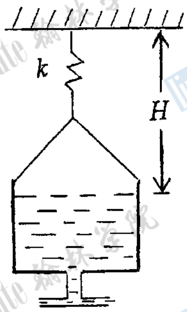

Figure 1.e

(f) A vehicle is travelling at 60 mph along a straight road, without slipping. What are the velocities at the 'compass points', N, S, E, and W, of the rim of the wheel? [7]

(g) A pulsed source of microwaves produces bursts of 20 GHz (20×10^9 Hz) radiation. Each burst has a duration of 1.0 ns. A parabolic reflector, radius 6.0 cm, is used to produce a parallel beam of radiation. The average power output of each pulse is 25 kW. Determine:

(i) the wavelength, λ, of the radiation
(ii) the total energy, E, of each pulse
(iii) the energy density, U, propagated by the reflector
(iv) the momentum density, P, propagated by the reflector [6]

(h) A constant horizontal acceleration is applied to a box, initially at rest, of mass 1.2 kg for 10.0 s. Its final speed is 0.40 ms^{-1}. What is the force, F, required?

The box is maintained at this constant velocity on a frictionless track whilst a continuous vertical stream of sand is deposited on it at the rate of 5.0 gms^{-1}, impacting at 10 ms^{-1}. Determine the vertical force, F_V, on the box due to the falling sand and the horizontal force, F_H, required to maintain the constant velocity of the box. [7]

(j) In the circuit in Figure 1.j all the resistors have resistance r and the cells have emfs E. Calculate the current, I, flowing through each cell. [5]

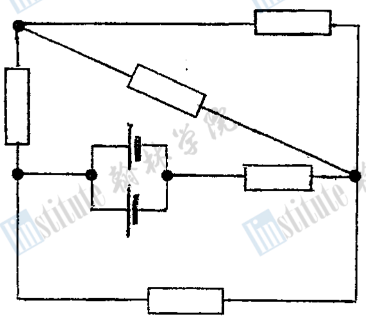

Figure 1.j

(k) Determine the energy released when a deuterium, D, and a tritium, T, nucleus are fused together to yield a neutron, n, and a helium, He, nucleus. The masses of these particles are given in Table 1.j.

Particle	Mass
D	2.01410u
T	3.01605u
n	1.00867u
He	4.00260u

Table 1.k

u = 1.66050×10^{-27} kg. [4]

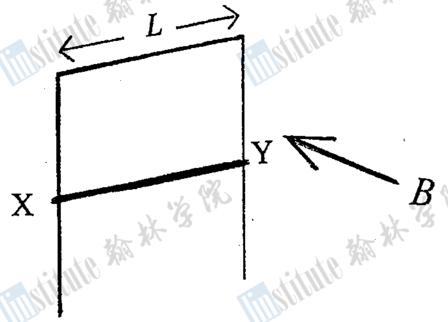

Figure 1.1

(l) An inverted U-shaped metal rod, with negligible electrical resistance, is erected in a vertical plane on a bench, Figure 1.1 . A horizontal rod XY , length L, equal to the distance between the arms of the U, mass m and electrical resistance R, can slide freely down the arms of the U. A homogeneous magnetic field of flux density B is perpendicular to the plane of the U.

(i) If the horizontal rod falls from rest, under gravity, it will reach a terminal velocity. Explain why this occurs.

(ii) Calculate the magnitude and direction of the current, I, produced after the terminal velocity, v, of the rod is attained.

(iii) By considering the terminal motion during a small time interval , Δt, show that the loss in gravitational potential energy is equal to the heat dissipated.

[10]

(m) A source of sound, emitting a note of frequency 500 Hz, starts from a stationary observer and travels directly towards a wall at speed v. The speed of sound is $c_s = 340\ \text{ms}^{-1}$. v is much less than c_s. Derive an expression for the frequency received by the stationary observer :

(i) directly from the source

(ii) after reflection from the wall

(iii) Determine the value of v, which is small compared with c_s, if the observer detects a beat frequency of 30 Hz. [10]

(n) The present day abundances of the isotopes U^{238} and U^{235} are in the ratio 140:1. They have half lives, respectively, of 4.5×10^9 and 7.1×10^8 years. Estimate the age of the Earth assuming that equal amounts of each isotope existed at the formation of the Earth.

[7]

Q2

Six resistors with resistances, in ohms, of r_1 ,r_2 ,r_3 ,r_4 , r_5 , and r_6 are connected as indicated in Figure 2.1.

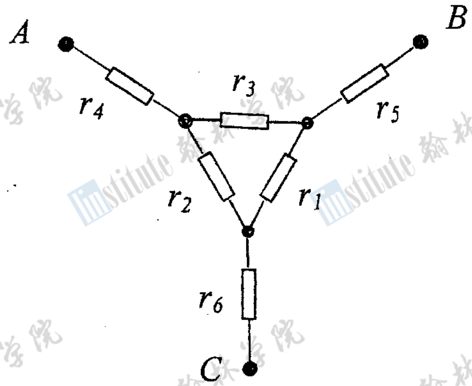

Figure 2.1

(a) If all the resistances have the value r determine the resistance:

(i) R_1 across AB
(ii) R_2 across AB when r_2 is short circuited
(iii) R_3 across AB when AC is short circuited [5]

(b) The resistors in Figure 2.1 have resistances, of 1,2,3,4,5 and 6 ohms, with no two resistors having the same value. Initially all resistors are unspecified.

(i) Obtain an algebraic expression for the resistance, R_{AB} , across AB. Express it as a rational fraction i.e. in terms of an algebraic numerator and denominator.
(ii) If $13R_{AB} = 94$, deduce the value of $(r_1 + r_2 + r_3)$.
(iii) Show that R_{AB} can be expressed as

$$R_{AB} = n_1 + n_2 + p,$$

where $p = n_3\,(13 - n_3)\,/13$

and n_1, n_2 , and n_3 are integers.

(iv) Evaluate p for all six possible values of n_3 and deduce the value of r_3 . Similarly deduce the values of r_2 and r_1 if $13R_{AC} = 87$ and $13R_{BC} = 131$.
(v) Determine the possible values of n_1 and n_2, hence r_4 and r_5, for R_{AB} .
(vi) Similarly obtain the possible values of n_1 and n_2 for R_{AC} and R_{BC} . and deduce the values of r_4 ,r_5 , and r_6 . [15]

Q3

(a) A double star consists of two stars, each with the same mass as our Sun, M_S , separated by a distance d. They are observed to complete a full rotation about their centre of mass in one week. Determine, to two significant figures, the ratio (d/R_{SE}), where R_{SE} is the Sun-Earth distance, without assuming the numerical value of M_S .

[6]

(b) In this calculation light may be considered as a stream of particles, photons, each having a mass ($h/\lambda c$) and energy (hc/λ), where λ is the wavelength of the light. Light with $\lambda = 500$ nm is emitted from the surface of the Sun, radius R_S, and received on Earth , radius R_E , slightly shifted in wavelength by $\Delta\lambda$ after travelling a distance R_{SE} .

(i) Give an algebraic expression for the change in the gravitational potential energy of the photon, ΔU.

(ii) Estimate the relative order of magnitude of each term in the expression for ΔU in (i). Indicate which term/s can be neglected for the result to be correct to 2 significant figures.

(iii) Calculate ($\Delta\lambda / \lambda$) to 2 significant figures. [11]

These calculations give identical results to those involving a more rigorous calculation.

(c) Explain why the value of g at the Earth's equator differs from its value at the poles. Which has the greater value?

[3]

Q4

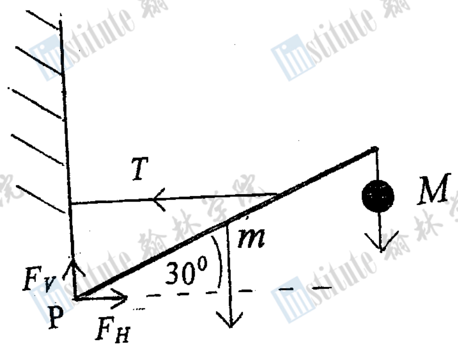

Figure 4.a

(a) A mass $M = 100$ kg hangs from one end of a uniform beam of length 3.00 m and mass $m = 2.00$ kg. The other end is hinged to a vertical wall at P. A horizontal cable, of negligible mass, is attached to the beam at a point 2.00 m from P to hold the beam in equilibrium at an angle of 30^0 to the horizontal, Figure 4.a.

Determine:

(i) the tension T in the cable

(ii) the horizontal and vertical components of the forces of the hinge on the beam, F_H and F_V respectively.

[8]

(b)

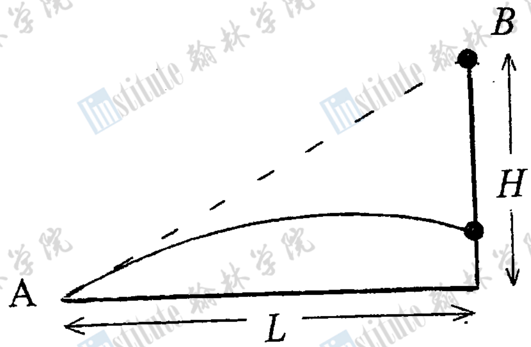

Figure 4.b

A marksman on the ground at A fires his rifle in the direction of a stationary clay pigeon located in a tower at B, height H, at a horizontal distance L from A, Figure 4b. At this instant the pigeon is released and falls vertically, under gravity. Verify that the bullet strikes the pigeon during its fall.

[12]

Q5

(a)

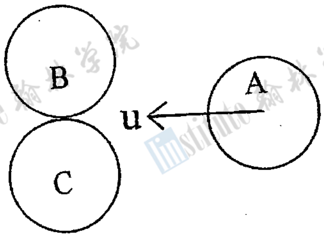

Figure 5.a

A sphere A travelling horizontally on a smooth table, with speed u, collides symmetrically, and elastically, with two stationary spheres, B and C, that are touching. All the spheres are identical and of mass m, Figure 5a. Determine the velocities of all the spheres after the collision.

C has a further collision with an identical sphere D, initially at rest and touching it. The centres of B, C and D lie on a straight line. Determine the outcome of this collision.

[12]

(b) Two identical cylindrical containers, A and B, Figure 5.b, both of volume V and negligible thermal capacity, are connected by a valve C, which is initially closed. Cylinder A contains n mols of a monatomic gas, at temperature T and with specific heat capacity per mol of $^3/_2 R$. It is fitted with a piston P which is initially fully withdrawn. B is a closed evacuated cylinder. The valve C is opened and the gas is driven into B by pushing home the piston at such a rate that the pressure, p, in A remains constant. It comes to rest after being displaced through a volume yV. The final temperature of the gas is T_f.

(i) Write down the initial and final gas equations for the system.

(ii) Determine the work done by the piston, W, and the internal energy gained by the gas, U.

(iii) Deduce the numerical value of the ratio (T/T_f).

[8]

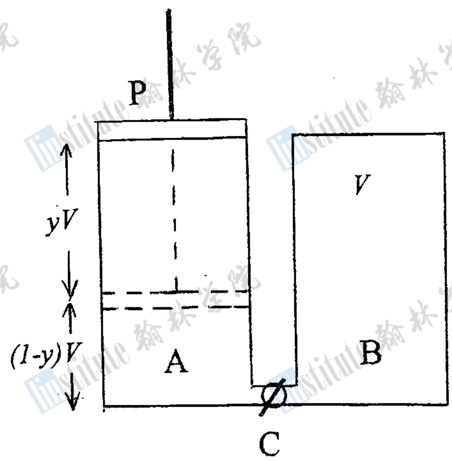

Figure 5.b

Q6

In an experiment to investigate the photoelectric effect, light of wavelength λ is incident on a metal surface and a current is produced. The current is suppressed by supplying a potential difference V between the metal surface and the collecting plate.

(a) (i) Derive, with a full explanation, an equation relating λ, V and the work function, W, of the metal.

(ii) Why does the classical explanation of the photoelectric effect fail to explain the experimental results ?

[6]

(b) The results obtained in the experiment are given in Table 6.b.

V/V	λ /10^{-9} m
1.0	200
2.0	196
3.0	158
4.0	144

Table 6.b

(i) Verify graphically that the results follow the relationship derived in (a) (i).
(ii) Determine h and W from the graph, specifying their accuracy.
(iii) Obtain the threashold frequency, ν_0, for photoelectric emission.
(iv) What is the effect of doubling the incident light intensity ? [14]

Q7

A radioactive source contains a mixture of two unrelated radioactive substances, A and B, with decay constants, λ_A and λ_B ; A has the larger decay constant. A counter which is 60% efficient at detecting all the decays of nuclei A, but only 11% efficient for those of substance B. At time t = 0, A and B produce N_A and N_B counts per minute, respectively. The results of the experimental measurements for the total counts are given in Table 7.1.

t Time / days	N Counts / min.
0.5	7000
2.0	620
5.0	142
9.0	76
15.0	28

Table 7.1

(a) (i) Write down the equation for N, the number of counts per minute detected by the counter.

(ii) Deduce the behaviour of N for large t.

(iii) Using (ii) plot a suitable graph in order to determine N_B and λ_B .

(iv) What is the initial number of B atoms present ?

[15]

(b)

(i) Extrapolate the graph to obtain a value of N at time $t = 0$ and hence determine N_A.

(ii) Using the first experimental result in Table 7.1, determine λ_A. [5]

Q8

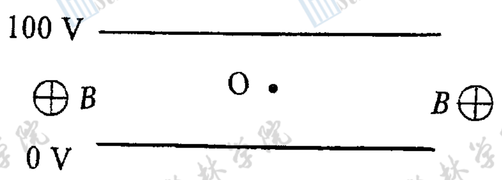

Figure 8.1 Side View

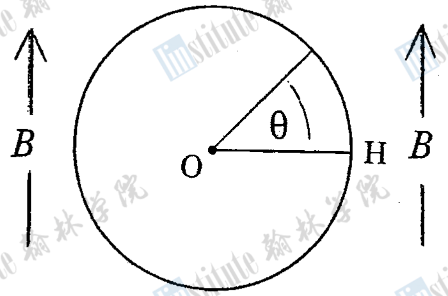

Figure 8.2 Plan

Two parallel circular conducting plates, 1.00 mm apart, are in an evacuated vessel. The plates are at a potential difference of 100 V and situated in a constant magnetic field of flux density B = 0.010 T parallel to the surface of the plates, Figures 8.1 and 8.2.

A radioactive source of beta particles , with maximum energy of 15.0 keV, is located, symmetrically, at the centre, O, of the gap between the plates.

(a) Determine using classical physics:

(i) the electric force on a beta particle
(ii) the order of magnitude of the ratio of the gravitational to the electric force on a beta particle
(iii) the maximum speed of the beta particle at O
(iv) the condition for beta particles, travelling in the horizontal plane through O, to emerge from the plates
(v) the range of speeds of the emerging beta particles from the plates
(vi) the angular range of θ, Figure 8.2, of the beta particles in (v) [15]

(b) (i) The calculations in (a) assume that the beta particles are not travelling with relativistic speeds. Is this assumption justified ? Give a quantitative answer.

The relativistic mass m of the electrons is given by

$$m = m_0 \ (1 - v^2 / c^2)^{-1/2},$$

where $m_0 = m_e$, the rest mass of the electron, and v is the speed of the electron.

(ii) How does the kinetic energy of a relativistic electron differ from that of a non-relativistic particle ?

[5]