BRITISH PHYSICS OLYMPIAD 2002

COMPETITION

Paper 2 - 9th November 2001

3 hours plus 15 minutes reading time.

There are SIX questions in this paper.
The marks for each section of the question are given on the right hand side of the page.

- FOUR questions must be attempted to obtain full marks.
- QUESTION 1 IS COMPULSORY. It is expected that students will spend 75 minutes on this question. The total mark allocated to the question is 80. Students can attempt any, or all, of the sections of the question but the maximum total mark awarded for answers will be 40.
- THREE of the remaining five 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.

Formulae sheets can be used.

Useful data:

Speed of light in free space	c	3.00×10^{8}	m s^{-1}
Elementary charge	e	1.60×10^{-19}	C
Mass of proton	m_p	1.67×10^{-27}	kg
Gravitational constant	G	6.67×10^{-11}	N m^{2} kg^{-2}
Acceleration of free fall at Earth's surface	g	9.81	m s^{-2}
Boltzmann constant	k	1.38×10^{-23}	J K^{-1}
Earth-Moon distance	R_{EM}	3.82×10^{8}	m
Radius of the Earth	R_E	6.37×10^{6}	m
Mass of the Earth	M_E	5.97×10^{24}	kg
Avogadro constant	N_A	6.02×10^{23}	mol^{-1}

The root mean square (rms) translational velocity, u, of a molecule, mass m, at temperature T is given by 🗁mu^2 = ☝kT.

Q1 *Emphasise the physical principles and make reasoned estimates where appropriate.*

a) Determine the current I through the ammeter A in each of the four circuits in Figure 1.1. The ammeter has zero resistance. The voltmeter, in (ii), has infinite resistance and a reading 8V. The resistance R has not been specified.

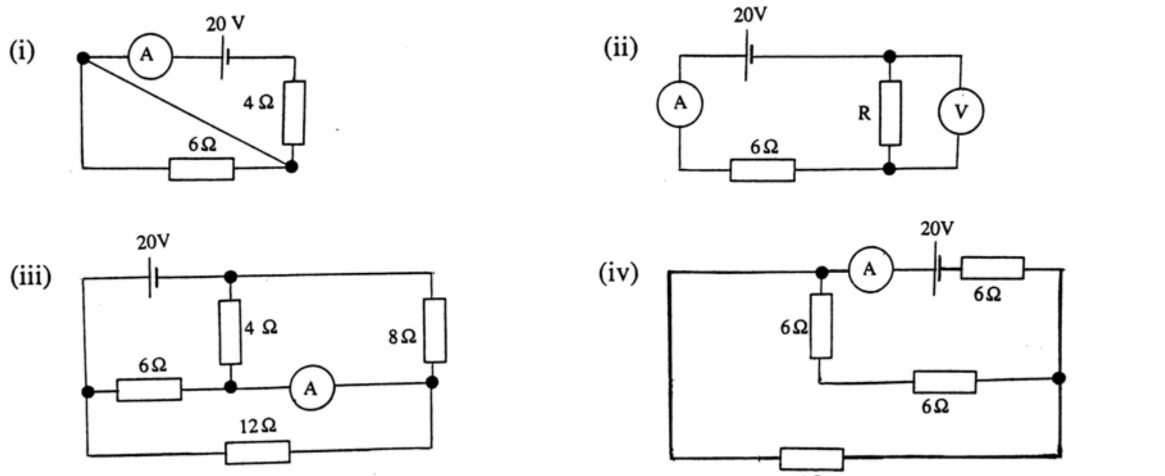

Figure 1.1 [8]

b) U_{92}^{238} has a very long half life and decays through a series of daughter products ending with a stable isotope of lead. Very old samples of U_{92}^{238} ore, which have not undergone physical or chemical changes, would be expected to show an equilibrium between the daughter elements provided that their half life was considerably shorter than that of U_{92}^{238}. Analysis of an ore of U_{92}^{238} shows that for each 1.00 g of U_{92}^{238} there is 0.300 μ g o Ra_{88}^{226} . The half life of Ra_{88}^{226} is 1602 years.
What is the half life of U_{92}^{238} ? [8]

c) A uniform beam AOB, O being the mid point of AB, mass M, rests on three identical vertical springs with stiffness constants k_1, k_2 and k_3 at A, O and B respectively. The bases of the springs are fixed to a horizontal platform. Determine the compression of the springs and their compressional forces in the case:

(i) $k_1 = k_3 = k$ and $k_2 = 2k$
(ii) $k_1 = k$, $k_2 = 2k$ and $k_3 = 3k$

[8]

d) A rocket, total mass 1.00×10^4 kg, is launched vertically; eighty per cent of the mass being fuel. At ignition, time $t = 0$, the thrust equals the weight of the rocket. The ejected exhaust gases have a speed of 9.00×10^2 ms $^{-1}$. Assuming the rate of fuel consumption and the acceleration due to gravity are constant, calculate:
(i) the mass, m, of gases ejected per second
(ii) the acceleration, a_e, of the rocket when the fuel is almost exhausted at time t_e

cont.

(iii) the mass, M, of the rocket at time t

(iv) the acceleration, a, of the rocket at time t, where $0 \le t \le t_e$

(v) Sketch a graph of the acceleration, a, of the rocket from $t = 0$ to $t = \infty$. [8]

e) It has been shown that the volume V of water in the Mediterranean Sea is approximately equal to the volume of a large raindrop multiplied by the number of molecules in the raindrop. Use this result to estimate V.

[8]

f) (i) Where are geostationary satellites located?

(ii) The square of the orbital period of a body in circular orbit around a planet is proportional to the cube of its orbital radius. Determine the orbital radius R of a geostationary satellite by applying this result to a geostationary satellite and the Moon.

(iii) Why is it difficult to receive satellite television programmes when living at latitudes close to the poles?

[12]

g) A neutron moving through heavy water strikes, head on, an isolated stationary deuteron.

(i) Assuming the mass m of the neutron is equal to half that of the deuteron, show that the ratio of the final speed of the deuteron, v_d, to the incident speed of the neutron, u_n, is (👌).

(ii) Determine the percentage of the initial kinetic energy acquired by the deuteron.

(iii) How many such collisions would be required to slow the neutron down from 10 Mev to 0.0l ev?

[16]

h) A white light shines vertically down on a horizontal CD ROM disc. The disc is viewed by a teacher whose eye is a horizontal distance 0.50 m from the disc and 0.35 m vertically above its horizontal plane, Figure 1.2. A yellow light of wavelength 590 nm is observed due to first order diffraction.

(i) Deduce the spacing d between adjacent tracks of the CD ROM.

(ii) The CD ROM is tilted, clockwise through an angle of 5^{o}. Determine the wavelength now observed.

[12]

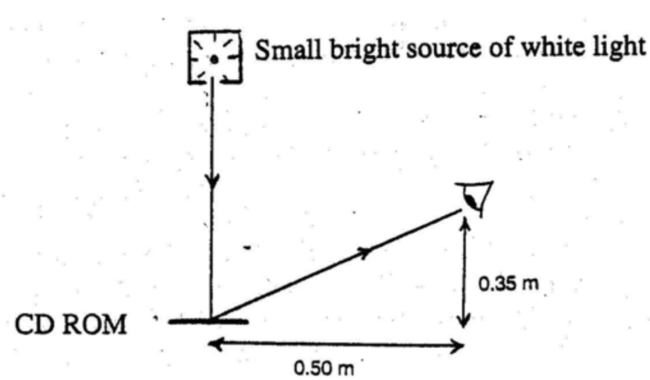

Figure 1.2

Q2

a) Write down an energy equation expressing the first law of thermodynamics. Define all the terms in the equation. [5]

b) Water in an electric kettle is brought to the boil in 180 s by raising its temperature from 20° C to 100° C. It then takes a further1200 s to boil the kettle dry. Calculate the specific latent heat of vaporisation of water, L, at 100° C. The specific heat capacity of water is 4200 J $kg^{-1}K^{-1}$.
State any assumptions made. [4]

c) A cylinder, with a weightless piston, has an internal diameter of 0.24 m. The cylinder contains water and steam at 100° C. It is situated in a constant temperature bath at 100° C, Figure 2.1. Atmospheric pressure is 1.01×10^{5} Pa. The steam in the cylinder occupies a length of 0.20 m and has a mass of 0.37 g.

Figure 2.1

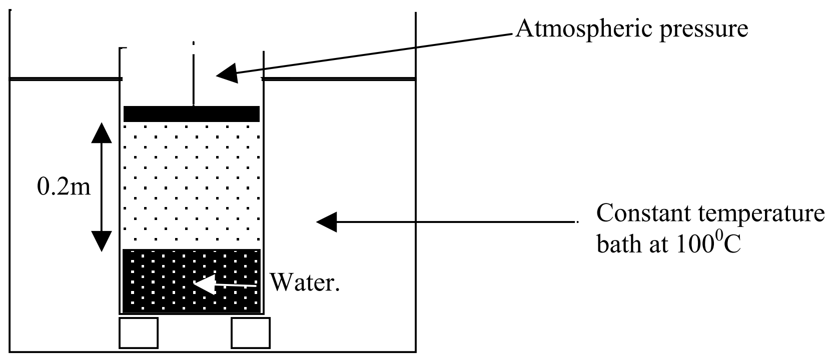

Figure 2.1

(i) What is the pressure P of the steam in the cylinder?
(ii) If the piston moves very slowly down a distance 0.10 m, how much work, W, will be done in reducing the volume of the system?
(iii) What is the final temperature, T_f, in the cylinder?
(iv) Determine the heat Q_c produced in the cylinder. [6]

d) A molecule of oxygen near the surface of the Earth has a velocity vertically upwards equal in magnitude to the root mean square (rms) value. If it does not encounter another molecule, calculate:

(i) the height H reached if the surface temperature is 283 K
(ii) the surface temperature T_s required for the molecule to escape from the Earth's gravitational field if the potential energy per unit mass at the Earth's surface is $(-GM_E/R_E)$.

The oxygen molecule has a molar mass of 0.032 kg. [5]

Q3

a) Two identical synchronously oscillating dippers separated by a horizontal distance $l = 3.0$ m, with a period of 1.00 s, produce waves on a smooth lake that travel at a speed of 1.2 ms^{-1}. The centres of the waves are at A and B. O is the mid point of AB.

(i) Draw a scale diagram of the wave fronts present after 4.00 s.

(ii) What conditions must be satisfied for constructive and for destructive interference of the water waves, at a point which is a distance x from A and distance y from B?

(iii) Mark, in the diagram, the regions where constructive and destructive interference occur.

(iv) P is a point at a large distance, compared with l, from A and B, at an angle $\theta =$ POB. What are the conditions for constructive and destructive interference at P?

[10]

b) A boat crosses a smooth lake at a speed of 5.0 m s^{-1}. Waves on the lake travel at 2.5 m s^{-1}. The waves generated by the boat produce a bow wave. This is tangential to the waves created by the boat. What angle, ϕ, does the bow wave make with the velocity of the boat? Give an explanation of the calculation.

[4]

c) Figure 3.1 shows a horizontal square ABCD with sides of length 2000 m. Coherent 10.0 MHz radio signals, wavelength λ, are transmitted from A and B.

(i) Calculate the value of λ.

(ii) What is the path difference p_B for the two signals, from A and B, received at B? Express it in terms of the product $n_B\lambda$ and deduce the value of n_B. Repeat the calculation for the point C and obtain the corresponding p_C and n_C.

(iii) An observer at C moves towards B, a distance x, in the direction CB in order to receive the first signal of maximum strength. Determine x. [6]

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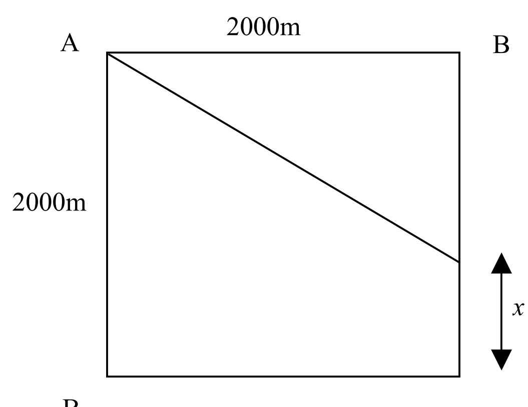

Figure3.1

Q4 Figure 4.1

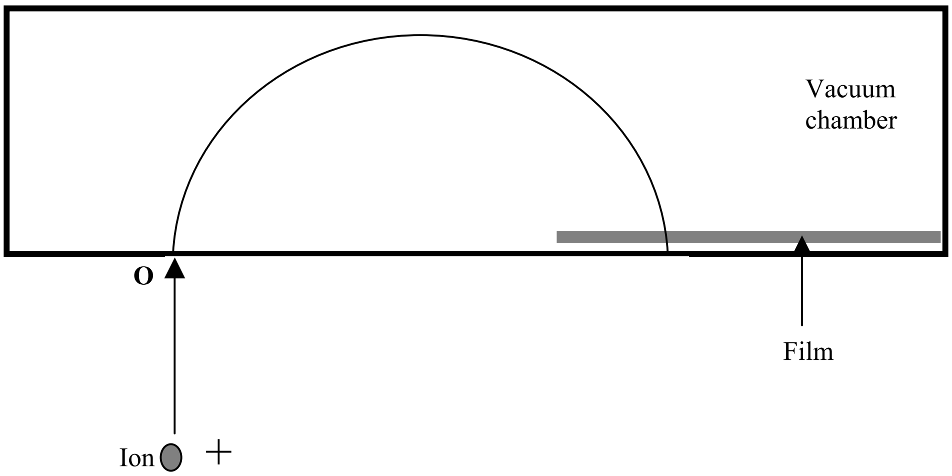

Figure 4.1

A mass spectrometer measures the mass m of ions. An ion, charge Q, is accelerated to a high speed v. It is injected at right angles to OP at O, Figure 4.1, into a region with a uniform magnetic field B which is perpendicular to the initial velocity of the ion. The ion will impact on the photographic film at P. By measuring the distance OP the mass of the ion can be determined. The spectrometer is contained in a vacuum chamber.

a) Show that:

(i) the path of an ion is circular and state the direction of the magnetic field
(ii) the radius R of the circle is given by

$$R = mv/(BQ).$$

[4]

b) Singly charged ions of K^{39}_{19} and K^{41}_{19} are accelerated through a p.d. of 500V and injected into the mass spectrometer with a magnetic flux density $B = 0.70$ T.

(i) What is the speed v_i of the ions injected into the spectrometer?
(ii) Determine the speed at which the ions hit the film, v_f.
(iii) Calculate the distance OP for each ion.

[7]

c) (i) If the accelerating voltage fluctuates within a range (500 ± 5) V, obtain the spread in OP for each ion.
Determine if the spectrometer can distinguish between the two ions.
(ii) How will a small variation in the incident direction of the ions, for constant v_i, affect their trajectories?

[9]

Q5

a)

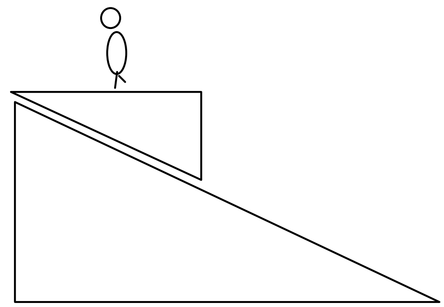

Figure 5.1

A student, mass 80 kg, stands on a horizontal set of bathroom scales, of negligible mass, attached to a massless platform that slides down a 30^{o} incline, Figure 5.1. The scales read 75 kg. Calculate:

(i) the vertical acceleration a_{v} of the student

(ii) the acceleration of the student down the slope a_{s}

(iii) the coefficient of dynamic friction μ between the platform and the slope, where μ is the ratio of the frictional force to the normal reaction.

[10]

b) A metal ring of mass m, radius r with a small radius of the cross sectional area, and resistance R falls, symmetrically, from rest, at time $t = 0$, in a horizontal radial magnetic field of magnitude B, Figure 5.2. At time t it has a vertical velocity v, an acceleration a and a current I.

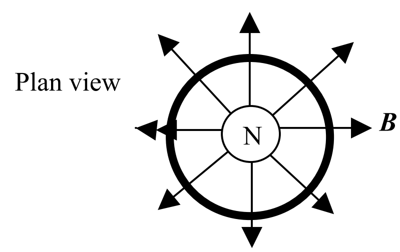

Figure 5.2

(i) Show that, due to the rate at which the magnetic flux is cut,

$$I = 2\pi rBv/R.$$

(ii) Deduce that

$$ma = mg - (2\pi rB)^2 v/R.$$

(iii) Derive the initial variation of v with t.
Deduce the terminal velocity of the ring.

(iv) Sketch graphically the variation of a and v with t. [10]

Q6

a) Figure 6.1 shows an ideal circuit with a battery, emf V, a switch S, an ammeter A of negligible resistance and a capacitor, capacitance C. The switch moves continuously from A to B, n times per second, where n is a large integer. Obtain an expression for the average current I registered by the ammeter.

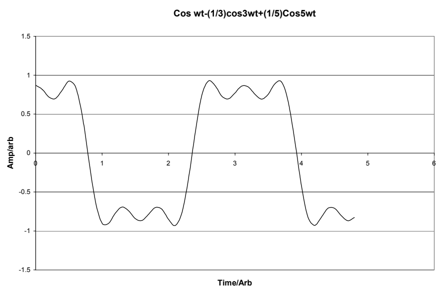

Figure 6.2

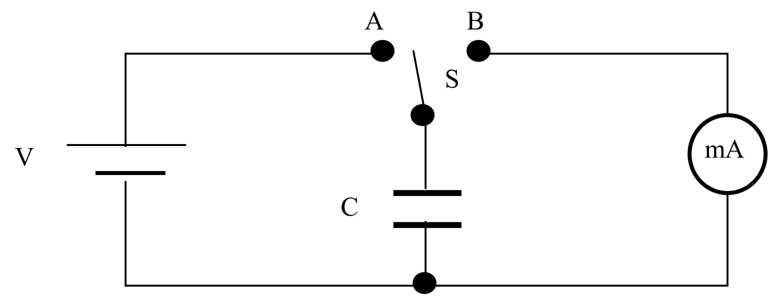

Figure 6.1

How would this current alter if a lead resistance R were included with the:

(i) battery? (ii) ammeter? [7]

b) The expression $F(t) = (4/\pi)\,[\cos(2\pi ft) - \tfrac{1}{3}\cos(6\pi ft) + \tfrac{1}{5}\cos(10\pi ft)]$
is an approximation to a *unit* square-wave of frequency f at time t, Figure 6.2.
For each cosine term give the

(i) amplitude (iii) phase
(ii) frequency (iv) period [4]

c) A square-wave voltage, with peak value V_o, is applied *separately* across a resistor with resistance R and a capacitor with capacitance C. Sketch graphs of the variation with time of;

(i) the current I through the resistor;
(ii) the charge Q on the capacitor.
(iii) Superimpose on these graphs I and Q resulting from the voltage $V_oF(t)$.

[4]

d) A signal generator, resistance $300\,\Omega$, produces a square-wave signal of frequency 1.0 MHz. The output of the generator is connected to an oscilloscope, with negligible capacitance, by a coaxial cable of capacitance 1.5×10^{-9}F and negligible resistance. Sketch the trace observed on the oscilloscope screen.
Give any necessary calculations. [5]