BRITISH PHYSICS OLYMPIAD 2004
COMPETITION

Paper 2 - 7th November 2003

3 hours plus 15 minutes reading time.

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

- FOUR questions must be attempted to obtain full marks. Formulae sheets can be used.
- QUESTION 1 IS COMPULSORY. It is expected that students will spend 75 minutes on this question. The total mark allocated to the question is 90. 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 eight 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

Useful data:

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
Acceleration of free fall	g	9.81	m s^{-2}
Gas constant	R	8.31	J mol^{-1} K^{-1}
Radius of the Earth	R_E	6.38×10^{6}	m
Earth to Sun distance	R_{ES}	1.50×10^{11}	m
Earth to Moon distance	R_{EM}	3.83×10^{8}	m

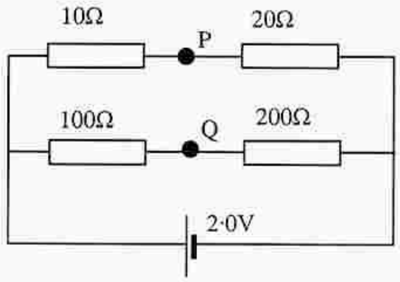
Formulae

Energy of a photon of frequency of f	$E = hf$
Momentum of a photon	$p = E/c$

Q1

a)

Figure 1.1



(i) Determine the p d between P and Q in Figure 1.1.

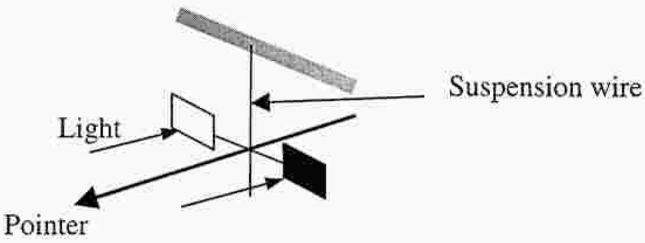
(ii) If the 10Ω resistance is replaced by an unknown resistor of XΩ, how could this circuit, with additional components, be modified to determine X?

[6]

b) (i) A red, 100 mW, laser beam, wavelength 650 nm, is incident normally on a perfectly black disk. Calculate the force on the disk.

(ii) If the disk is replaced by a mirror that reflects 95% of the incident light, deduce the force exerted on the mirror.

Figure 1.2



(iii) Two rectangular metal vanes are suspended by a wire, Figure 1.2. One is highly reflecting and the other is black. Both vanes are illuminated by identical, high intensity, laser beams normal to their surface. The system is contained in an evacuated chamber. The results observed, looking down the suspension wire, are:

Good vacuum	Anti-clockwise rotation
Ultra high vacuum	Very small clockwise rotation

How will the velocities of molecules in the chamber be affected by collisions with the vanes? Explain the observations.

[10]

c) The period of oscillation, T, of a simple pendulum, length l, with a bob of mass m oscillating along the x-axis with a small amplitude, is given by

$$T = 2\pi\sqrt{\frac{l}{g}}$$

An electric field of constant magnitude E is applied to the bob which has a charge Q. Determine T if:

(i) E is vertically downwards
(ii) E is horizontal along the x-axis
(iii) E is horizontal, perpendicular to the x-axis [6]

d) Two stations on the equator communicate by sending, and receiving, radio signals that undergo a single reflection from a layer 10 km above the surface of the Earth. What is their maximum separation in terms of the difference in their degrees of longitude? In practice they can communicate when they are considerably further apart, though there may be certain bands of longitude where reception is poor. Give a plausible explanation for this. [6]

e) Van der Waals proposed modifications to '$PV=RT$', the equation of state for an ideal gas. The modified equation is

$$\left(P + \frac{a}{V^2}\right)(V - b) = RT,$$

where a and b are constants.

(i) What are the units, or dimensions, of a and b?
(ii) What is the physical meaning of b and a?
(iii) Calculate the pressure of 2.00 mol of nitrogen at 200 K contained in a volume of $6.00\times10^{-3}\,\mathrm{m}^3$ if $a = 0.140$ SI units and $b = 3.90\times10^{-5}$ SI units.
(iv) What would be the pressure of the gas if it were ideal?

[8]

f) The experimental values of two quantities, X and Y, are thought to satisfy one of the following two theoretical equations:

(i) $X = aY^b$ (ii) $X^3 = (cY + d)^2$

a, b, c and d are constants. How would you plot each relationship as a straight line graph? Explain how to determine the associated constants a, b, c and d.

[8]

g)

Figure 1.3

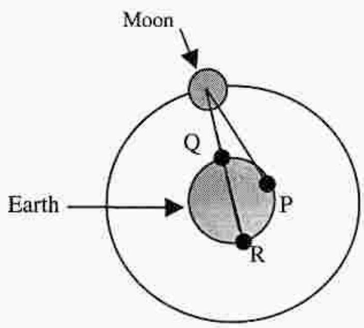


Figure 1.3 shows the Moon orbiting the Earth. Why do most sea ports experience two high tides every 24 hours? Explain which sea ports, of those indicated by Q,P, and R, have a high tide and which have a low tide. [6]

h) According to the special theory of relativity a mass, m, with velocity v, relative to an observer, is given by:

$$m = m_o \left(1 - \frac{v^2}{c^2}\right)^{-\frac{1}{2}}$$

where m_0 is the mass measured when $v = 0$. c is the speed of light.

A $^{238}_{92}U$ nucleus, mass of 2.21×10^5 Mev/c^2, stationary with respect to an observer, undergoes fission and breaks into two equal parts with a total kinetic energy of 200 Mev (1ev =1.60×10^{-19}J). If the two parts are brought to rest, what is the total decrease in mass in kg? What speed did the two masses have?

[8]

i) A lady ice skater, mass 60 kg, is moving at 12 m s^{-1} in a straight line. She decelerates by standing on one skate, and comes to rest in 40 m. Neglecting air resistance, calculate:

(i) her deceleration
(ii) the coefficient of friction between the skate and the ice
(iii) her loss of kinetic energy
(iv) the maximum mass of ice melted
The specific latent heat of melting of ice is 330 kJ kg^{-1}. [8]

k)

Figure 1.4

Figure 1.4 shows the Moon seen against the dark sky on a clear winter night. A narrow crescent of the Moon shines brightly, the rest of the Moon can just be seen.

(i) Why is the crescent bright?
(ii) How is it that the rest of the Moon can just be seen?
(iii) What factors determine the ratio of the brightness of the crescent to that of the rest of the Moon? [6]

l)

Figure 1.5

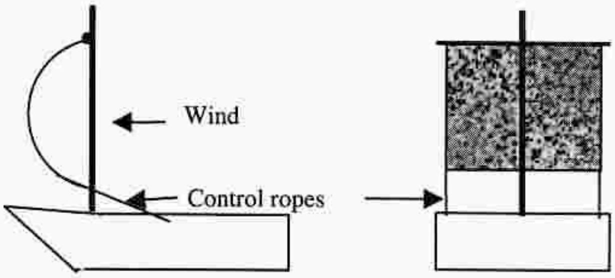


Figure 1.6

Figure 1.5 shows a side view of a simple sailing boat. Figure 1.6 is the same boat seen from the rear. The area of the sail is A. The wind velocity is v.

(i) Show that the force on the sail is kv^2, where k is a constant.
(ii) What are the dimensions of k?
(iii) How does k depend on the density of the air, ρ?
(iv) Explain why doubling the speed of the wind does not quadruple the speed of the boat.

[8]

m) A cyclist is travelling with constant velocity along a straight road. The wheels of the bicycle roll, without slipping, along the road. Why is it easier to photograph, with clarity, those parts of the spokes nearest the ground?

[4]

n) During a thunder storm a student sets his stopwatch to zero at the time of a lightening strike. He records the time, t, of a subsequent lightening strike, from the same direction, and the time interval, Δt, between each strike and the following thunder clap. His results are given in the table below.

t /s	Δt /s
0	32.5
49.1	18.0

(i) Why does the lightening strike occur before the thunder clap?
(ii) Determine the speed u at which the storm is approaching.

Assume the speed of sound is 334 m s^{-1}.

[6]

Q2

a) A stone is dropped into a deep canyon. After 10.2 s it is heard to strike bottom. Estimate approximately:

(i) the depth of the canyon, h, neglecting the time taken by the sound wave to return to the top of the canyon

(ii) the time t_2 taken by the returning sound wave to reach the top of the canyon, assuming the speed of sound is 334 m s^{-1}

(iii) the accuracy of the result in (i)

[6]

b) If t_1 is the time taken for the stone to reach the bottom of the canyon and t_2 is the time for the sound wave produced to reach the top of the canyon:

(i) write down the equations that determine t_1 and t_2, neglecting air resistance

(ii) calculate the exact value of t_1

(iii) calculate the exact value of t_2

(iv) deduce the depth of the canyon

[10]

c) If the stone is initially thrown with velocity u horizontally into the canyon, what differences will arise in the answers to question (b)(i)?

[2]

d) If the stone is thrown vertically upwards with velocity u, how will this alter the answers to question (b)(i)?

[2]

Q3

A 2.00 m light rigid rod is suspended from the ceiling by two vertical wires, A and B, each having a natural length of $\ell = 1.00$ m, attached to each end of the rod. A is a copper wire with a Young's modulus $Y_A = 12.4 \times 10^{10}$ Pa, diameter 1.60 mm, and B is a brass wire with a Young's modulus $Y_B = 9.00 \times 10^{10}$ Pa, diameter 1.00 mm.

a) An 80 kg mass is attached to the midpoint of the rod, calculate:

(i) the tension in each wire, assuming the rod is horizontal
(ii) the consequent extension of A
(iii) the consequent extension of B
(iv) the angle the rod makes with the horizontal

[8]

b) The attachment of the 80 kg mass is moved to a point D, a distance x from A, along the rod.

Calculate:

(i) the extension of A
(ii) the extension of B
(iii) the distance x for the rod to be horizontal.

[12]

4.

a) Figure 4.1

Figure 4.1 shows the solar car that won the 2001 World Solar Challenge race. The maximum speed, using solar power only, was 108 kmhr^{-1}. The electrical power produced by the solar panels, efficiency 25%, was 1.35 kW. The efficiency of the motor was 97%. There was no wind.

(i) Calculate the total resistive force, R, of the car at maximum speed.
(ii) Why was the tyre pressure much greater than that in conventional vehicles?
(iii) Calculate the incident radiant power, P, of the Sun on the panels.
(iv) The car has three wheels. What advantage does this give?

[8]

b) A series circuit consits of an electrical cell, of p d V and negligable resistance, and a simple small d c motor consisting of a rotating coil, resistance r, and permanent magnets. The motor rotates at angular frequency ω when the average current is I.

(i) Explain why I decreases as the motor speeds up.
(ii) Derive the equation relating I and ω, introducing any appropriate constant.

[4]

c)

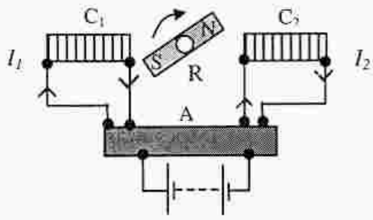


Figure 4.2

Figure 4.2 is a diagram of a brushless d c motor used to propel the solar car. The electrical cells are connected to a "black box" A, which supplies currents I_1 and I_2 to the coils. The rotor R is a magnet connected to the wheels.

(i) What is the purpose of A?
(ii) Sketch, on the same graph, the currents in the coils C_1 and C_2 as a function of time t.

[4]

(d) Why do solar cells overheat if the car is stationary and the batteries are not charging?

[4]

Q5

a) In 1600, Galileo attempted to measure the velocity of light, c, by sending a light signal from one hill top to another, a distance of 3 km. He was only able to measure time intervals to an accuracy of 0.1 s. Comment on the likely outcome of his measurement and the likely conclusion he reached. What is the minimum accuracy of the time measurement required to determine an estimate of the velocity of light in this experiment?

[4]

b)

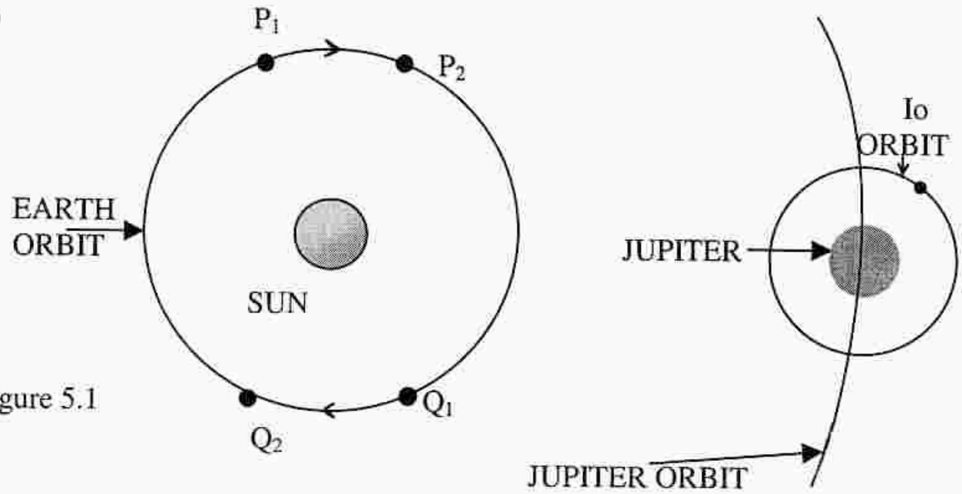


Figure 5.1

Roemer, in 1676, measured the period of rotation of Jupiter's moon Io around the planet, Figure 5.1. This period is much smaller than the period of rotation of the Earth around the Sun.

Explain how the period appears to vary as the Earth moves from:

(i) P_1 to P_2, towards Jupiter
(ii) Q_1 to Q_2, away from Jupiter

He found during one series of observations, assuming the period of Io is constant, that the time of appearance of Io, from behind Jupiter, varied by a maximum of 22 minutes during the course of a year. Explain this result and determine his value of c.

[8]

c) Fizeau, in 1849, devised a more accurate method of measuring c using a rotating, square toothed, wheel. Light travelled from a gap between two adjacent teeth to a mirror 8633 m away and was reflected back to the wheel. Meanwhile the adjacent tooth had replaced the gap and blocked out the returning beam. He used a wheel with 720 teeth and a rotation rate of 12.6 revolutions per second. Determine the value of c obtained.
If the rate of rotation was accurate to 4%, deduce the accuracy of his result.

[8]

Q6

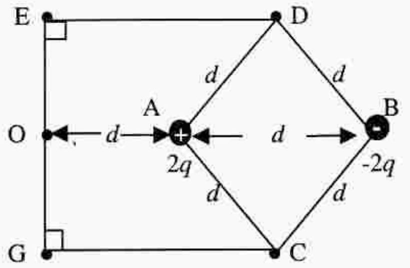


Figure 6.1

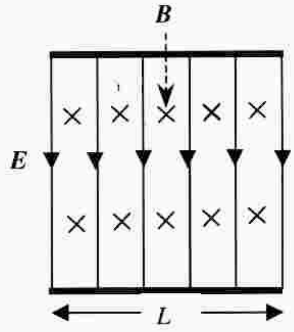


Figure 6.2

a) The charges $2q$ and $-2q$ are separated by a distance d and located at points A and B, Figure 6.1. d = AB = AD = DB = AO = AC = CB, where O is the mid-point of GE.

Determine:

(i) the vector forces $\boldsymbol{F_c}$ at C and $\boldsymbol{F_o}$ at O on a unit positive charge

(ii) the potential V_c at C and V_o at O

(iii) the work done in taking the charge $2q$ along the path ACGOED to D.

[10]

b) Figure 6.2 shows the plates, length L, of a CRO with a constant electric field $\boldsymbol{E}$ and a constant magnetic field of flux density $\boldsymbol{B}$ parallel to the plates and perpendicular to $\boldsymbol{E}$. A charge q, mass m, travelling horizontally with velocity v enters the region between the plates.

(i) If $\mathbf{B} = 0$, show that on emerging it will be deflected vertically by a distance y_1 given by

$$y_1 = \frac{qEL^2}{2mv^2} .$$

(ii) If $\boldsymbol{E} = 0$ and $\boldsymbol{B}$ is finite, show that the charge will emerge with a vertical deflection, y_2, in the opposite direction to y_1, given by

$$y_2 = R - \sqrt{R^2 - L^2} , \qquad \text{where } R = \frac{mv}{Bq} .$$

(iii) Show that if, during the motion through the plates, the fields are adjusted so that the forces on q balance,

$$\frac{q}{m} = \frac{2y_1 E}{B^2 L^2} .$$

[10]

Q7.

a) A square object is located in front of a plane mirror, in a plane perpendicular to that of the mirror, with one side parallel to the mirror. Draw rays of light reflected by the mirror, from the corners of the square, that enter an observer's eye in the same plane as the square. Indicate the location of the image.

[3]

b) A Young's double slit apparatus has a slit separation *d*. The distance between the plane of the slits and that of the screen is *L*, where *L*>>*d*, Figure 7.1.

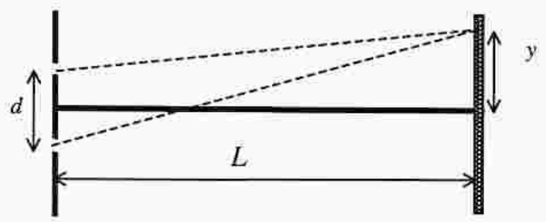


Figure 7.1

Show that constructive interference at a point a distance *y* along the screen, from the plane of symmetry of the apparatus, occurs if

$$y = \frac{n\lambda L}{d} ,$$

where *n* is an integer and λ is the wavelength of the light.

[3]

c)

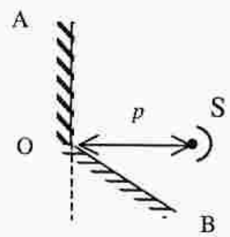


Figure 7.2

The angle AÔB between two adjacent mirrors, AO and OB, is 135°, Figure 7.2. AO is vertical. A shielded source, S, of monochromatic light, wavelength λ, a horizontal distance *p* from O, produces light incident on the two mirrors only.

(i) Where are the images of S located?
(ii) Why it is possible to produce an interference pattern on a screen?
(iii) In which direction would one place a screen?
(iv) What is the effective "*d*" for this system?
(v) What is the effective "*L*" if the screen is a distance *D* from O?
(vi) If AÔB increases gradually from 135° to 180°, how do the fringes change?

[14]

Q8

a) Fast neutrons, mass m_1, with a speed $v_1 = 2.0 \times 10^7$ ms^{-1}, are slowed down in a nuclear reactor by elastic collisions with the nuclei of a moderator. Calculate the speed v of a neutron after a single, head on, collision with (i) a hydrogen nucleus in water and (ii) a carbon nucleus in graphite by first deriving v in the general case of a collision with a nucleus of mass m_2. These nuclei are initially stationary.

After many collisions with atoms of a moderator at room temperature, what energy will the neutrons attain? The masses involved are:

neutron 1.0087 u; hydrogen nucleus 1.0073 u; carbon nucleus 11.9934 u

[12]

b) The ballistic pendulum is a device used to measure the speed v of a bullet. It consists of a stationary heavy rectangular wooden block of mass M suspended by vertical strings from the corners of the upper horizontal face. When a bullet of mass m strikes the block horizontally it undergoes an inelastic collision and embeds itself in the block. The block swings upwards. If the block rises a height h, obtain an expression for the speed of the bullet assuming h is small and the block moves initially with a horizontal velocity.
Comment on the motion of the block during its upward swing.

[8]

Q9

Time (min)	R (counts/s)
4·00	392.2
68·00	65.5
132·00	10.9
196·00	1.86

a) The table shows some measurements of the decay rate of a sample of ^{128}I, a radionuclide often used medically as a trace to measure the rate at which iodine is absorbed by the thyroid gland.
Determine the disintegration constant λ and the half-life $T_{1/2}$ for this radionuclide.

[13]

b) Element A is an alpha particle emitter with a half life of 1.0×10^8 years. The decay product B has a half life of 60 s. It decays by beta decay to element C, which is stable. It is thought that A was formed in the supernova that produced the solar system. A sample of rock on Earth contains all three elements.

(i) What will happen to the proportions of A, B, and C during a year?
(ii) The ratio of the number of atoms of C to those of A is 1.0×10^{11}.
When did the supernova occur?
(iii) What assumptions did you make to determine the date of the supernova?

[7]