British Physics Olympiad 2006

Paper 3

Monday 27th February 2006.

Time allowed 3hrs plus 15 minutes reading time.

All questions should be attempted. All questions carry 20 marks each.

Question 4 of the examination should be handed in with each script. The candidates name should be written on Question 4.

Speed of light in free space	c	3.00×10^{8}	$m\,s^{-1}$
Elementary charge	e	1.60×10^{-19}	C
Mass of a proton (rest mass)	m_p	1.67×10^{-27}	kg
Acceleration of free fall at Earth's surface	g	9.81	$m\,s^{-2}$
Planck's constant	h	6.62×10^{-34}	J s
Specific heat capacity of water	c_v	4.20×10^{3}	$J\,kg^{-1}\,K^{-1}$
Stefan-Boltzmann constant	σ	5.67×10^{-8}	$Wm^{-2}K^{-4}$
Radius of the Sun	R_{Sun}	6.96×10^{8}	m
Radius of Earth orbit around the Sun	R_o	1.50×10^{11}	m
Radius of the Earth	R_{Earth}	6.37×10^{6}	m
Boltzmann constant	k	1.38×10^{-23}	$J\,K^{-1}$

Formulae

$P = A\sigma T^4$: P is the power radiated by a black body. A is the surface area of the body, σ is the Stefan-Boltzmann constant and T is the absolute temperature of the body.

At temperature T the energy of a particle is (number of degrees of freedom)$\times \frac{1}{2}kT$.

Q1 *In this question you are asked to make reasoned estimates and assumptions. These must be clearly stated*

a)

Figure 1.1

Figure 1.2

Figure 1.1 shows a photograph of the ice in a birdbath made of stone. Figure 1.2 shows a detailed picture of the pillar of ice shown in Figure1.1. The birdbath was in the open air and no water fell from above. Suggest an explanation.

b) A recent item of the national news reported "Scientists say that magnetic bracelets fail to cure aches and pains ". Outline the difficulties in performing a double blind test to settle this question.

c) Figure 1.3

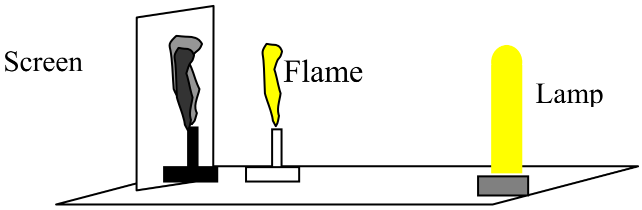


Figure 1.3 shows a demonstration of the dark shadow of a gas flame that has particles of salt in it. The lamp is a bright *low pressure* sodium lamp. Without the salt there is little shadow. Replacing the lamp with a tungsten filament lamp and a yellow filter destroys the black shadow. Explain.

d) On a clear day in summer the normal incident radiation on the surface of the Earth from the Sun is about 1000 Wm^{-2}. By making suitable simplifying assumptions, determine (i) the power per square metre of radiation emitted from the surface of the Sun and (ii) the pressure on the surface of the Sun due to this radiation. You may assume that the energy of a photon is hf, frequency f, and its momentum is hf/c. Calculate how many photons of wavelength 590 nm would be needed to accelerate a proton to a speed equivalent to a temperature of 10^6 K.

Q2

A heat pump is a device that pumps heat from a body at a temperature T_{cold}, to a body at a temperature T_{hot}. An example of a heat pump is a domestic refrigerator. The heat is pumped from the inside of the refrigerator to the outside. The pump will cool the inside of the refrigerator until a predetermined temperature is reached.

In some countries a heat pump is used as a domestic heater in winter and as an air conditioner in summer, i.e. cooling the air in the room and pumping the heat to the outside.

Figure 2.1

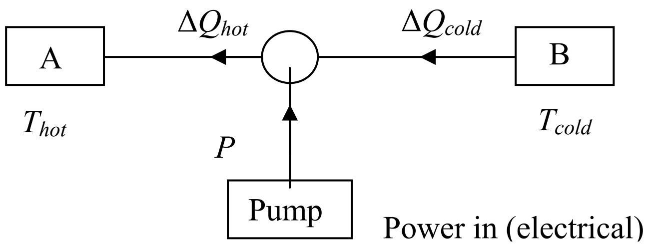


Figure 2.1 is a block diagram of the heat pump/refrigerator. A is the hot body at temperature T_{hot}. B is the cold body at temperature T_{cold}. ΔQ_{hot} and ΔQ_{cold} are the quantities of heat per second absorbed by A, and extracted from B. The pump delivers power P to achieve this.

a) Write down an equation relating $\Delta Q_{hot}, \Delta Q_{cold}$ and P. In addition it can be shown that an ideal heat pump satisfies the equation:

$$\frac{\Delta Q_{hot}}{\Delta Q_{cold}} = \frac{T_{hot}}{T_{cold}}.$$

b) Find the heating power that can be delivered into a room by an ideal heat pump if the pump power, P, is1.0 kW, when the outside temperature is 280K and the temperature of the room is 293K. Comment on your answer.

c) In an experiment using 2.0 kW heat pump the cold body B is a tank with 10 kg of water initially at 290K. Ignore the thermal capacity of the empty tank. The rate of heat leakage into the tank from its surroundings only is 20θ W, where θ is the temperature difference between the tank and its surroundings that are at a constant 290K. Assume that T_{hot} is constant at 305K. Write down an equation for the rate of fall of temperature of the tank. Calculate the quantity of heat reaching the hot body per second:

(i) initially, when the tank is 290K
(ii) when the tank has reached 280K.

Calculate rate of fall of temperature of the tank:
(iii) initially
(iv) at 280K.

Q3

Figure 3.1

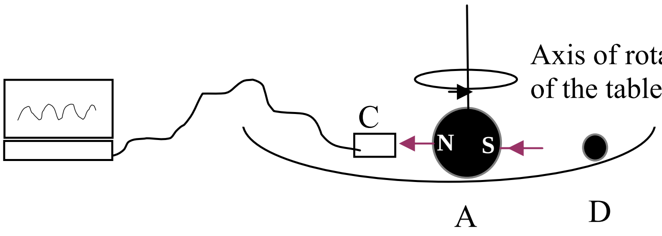
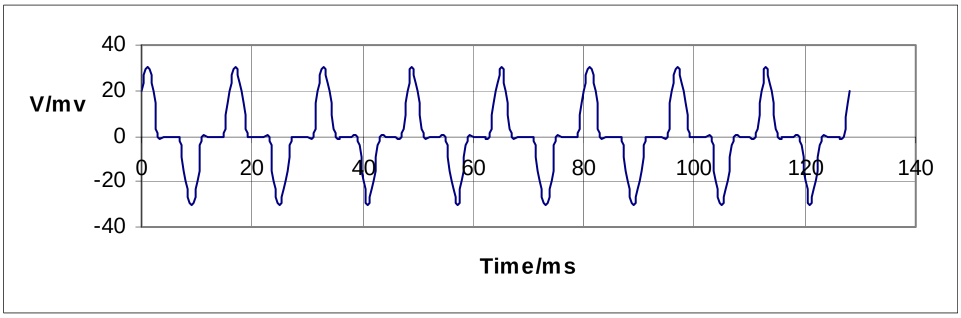


Figure 3.1 shows an experiment involving a rotational collision between two steel ball bearings, A and D. They rest in a very shallow spherical dish on a horizontal table. A has diameter of 5 mm and is permanently magnetised, but not strongly. D has a diameter of 2 mm and is not permanently magnetised. The probe C can be either a Hall effect probe with output p.d. V_{out} proportional to the magnetic field $\boldsymbol{B}$, or a small search coil. V_{out} has the form shown in Figure 3.2 . A line joining the North and South poles is parallel to the plane on which the dish is resting.

Figure 3.2



a) Use the data displayed in Figure 3.2 to calculate the angular velocity of the ball A.

b) Reproduce Figure 3.2 for a single period beginning at *Time* = 0 and superpose a sketch of the output expected from a search coil

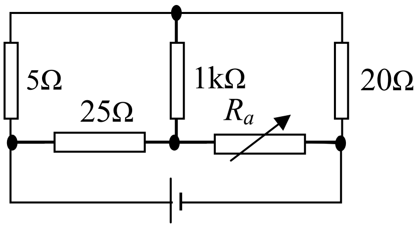
c) Initially the ball bearing A is given an angular velocity about a vertical axis when D is not present. After a short period of time ball D is placed in the dish and allowed to roll slowly towards A. Ignore the rotation of D about a horizontal axis. A collision takes place and D, which is not permanently magnetised, bounces away. Using the hint and the Table below, or otherwise, sketch, with numerical values, the trace observed on the computer, using the Hall probe, before and after the collision. Assume that no slippage occurs between the contact surfaces when the balls collide.

Linear motion	Rotational motion	Sphere
Mass m	Moment of inertia I	$I = 0.4mr^2$, r is the radius
Linear Momentum mv	Angular Momentum $I\omega$	
v is the linear velocity	ω is the angular velocity	

Hint: You may assume that the laws for angular motion are similar to those for linear motion. This results in similar equations of motion.

Q4

Figure 4.1



a) In the circuit shown in Figure 4.1 find the value of R_a that would give zero current in the 1kΩ resistor.

b)

Figure 4.2a

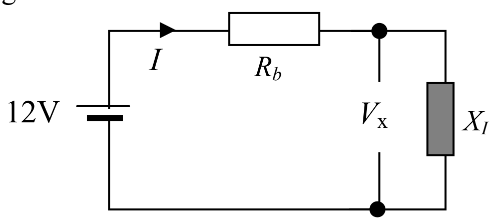
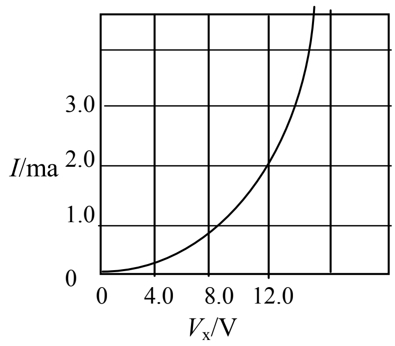


Figure 4.2b



Write down an expression for V_x in terms of the current I and the resistance R_b for the circuit in Figure 4.2a. Figure 4.2b shows the $V_x - I$ characteristics of X_I. In the case that $R_b = 6.0\text{k}\Omega$ plot this expression on the graph in Figure 4.2b and deduce the value of I.

c) Use Figure 4.2b to obtain four values of $\delta I/\delta R_b$ in the range $I = 0.5$ mA to $I = 1.1$ mA.

Figure 4.3

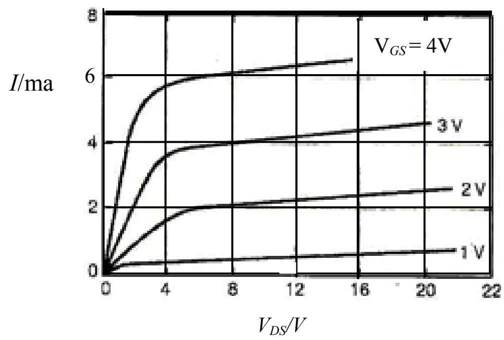
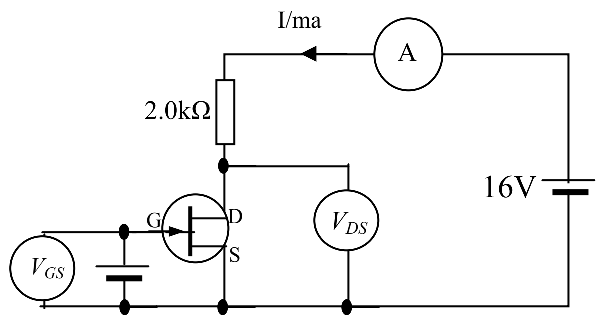


Figure 4.4



d) Fig 4.4.shows a circuit with a JFET transistor. It has three terminals D, S and G. No current flows in or out of G. The device is controlled by the electric field produced by electric potential of the gate G. Figure 4.3 shows the published characteristics of the device where the current I is plotted against the p.d. V_{DS} for different values of the p.d. V_{GS}. The circuit used for determining the characteristics does not contain the 2.0 kΩ resistor. Referring to the Figure 4.4 using the method of part b), or otherwise, determine:

(i) the value of I when V_{GS} is 2.5V

(ii) $\frac{\delta V_{DS}}{\delta V_{GS}}$ when $V_{GS} \approx 2.5\,\text{V}$. Why is this circuit found to be useful?

Q5

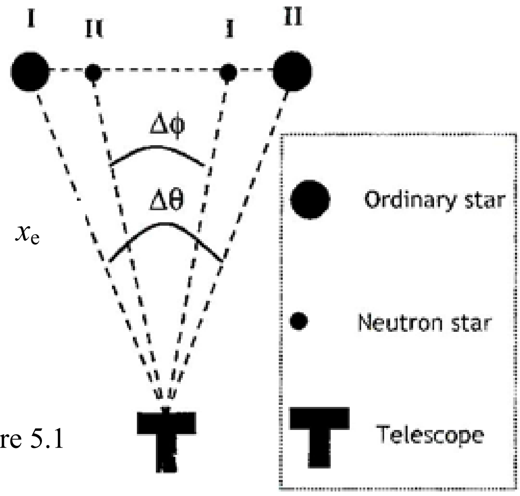


Figure 5.1

It is well known that most stars form binary systems. One type of binary system consists of an ordinary star with mass m_o and radius R, and a more massive, compact, neutron star with mass M, rotating around each other. In all the following ignore the motion of the Earth. Observations of such a binary system reveal the following information:

(i) The maximum angular displacement of the ordinary star is $\Delta\theta$, whereas that of the neutron star is $\Delta\varphi$ (see Figure 5.1).

(ii) The time it takes for these maximum displacements is τ.

(iii) The radiation characteristics of the ordinary star indicate that its surface absolute temperature is T and the radiated energy incident on a unit area on Earth's surface per unit time is E.

(iv) A calcium line in this radiation differs from its normal wavelength λ_o by an amount $\delta\lambda$, due only to the gravitational field of the ordinary star. For this calculation the photon can be considered to have an effective mass of $h/\lambda c$.

Find an expression for the distance x_e from Earth to this system in terms of the observed quantities and the universal constants.