Rewarding Learning

Advanced Extension Award

2006

Physics

Advanced Extension Award

H7651

H7651

THURSDAY 29 JUNE, AFTERNOON

TIME

3 hours.

INSTRUCTIONS TO CANDIDATES

In the boxes on the answer booklet, write your centre number, candidate number and subject title.
Answer **all seven** questions.

INFORMATION FOR CANDIDATES

The total mark for this paper is 100.
The mark for each part of a question is shown in brackets and the total mark is given at the end of the question.
The values of physical constants and relationships you may require are given on a separate information leaflet which is an insert to the paper. Any additional data are given in the appropriate question.
The approximate time which you should spend on any one question is given at the start of the question.
You are reminded of the need to organise and present your answers clearly and logically and to use specialist vocabulary where appropriate.

Materials required for examination – Answer booklet, Graph paper, Calculator.

Items included with question paper – Information Leaflet (insert).

ADVICE TO CANDIDATES

In calculations you are advised to show all the steps in your working, giving your answers at each stage. Give final answers to a justifiable number of significant figures.

1 *You are advised to spend about 35 minutes on this question.*

Read the passage and then answer the questions which follow.

Fusion seen in table-top experiment!

(Freely adapted from *Physics World*, April 2005)

Physicists in the United States have generated nuclear fusion in a simple miniature device operating at room temperature. The device causes deuterium nuclei to collide with each other producing alpha-particles and neutrons and generating energy. The device could have applications as a portable neutron generator or in the propulsion systems for very small spacecraft, but will not be useful as an energy source because it consumes more energy than it produces.

The experimental set-up consists of a centimetre-size cylindrical crystal of lithium tantalate surrounded by deuterium gas. The lithium tantalate is pyroelectric, which means that, when the crystal is heated, positive and negative charges build up on opposite ends of the cylinder; the effect is bigger the greater the temperature change. A sharp tungsten tip is attached to the positively-charged end of the pyroelectric crystal. The temperature change creates an electric field that is large enough to ionise any deuterium atoms that stray near the tip. These deuterium ions get repelled from the tip and are accelerated by the electric field towards the flat surface of an earthed target rich in deuterium-containing compounds, where the fusion takes place.

“What they have made is a cute little neutron generator”, says Michael Saltmarsh, a physicist who has retired from the Oak Ridge National Laboratory in the United States. “You can imagine having one of those in your pocket – but don’t get it too warm!”

(a) **(i)** Write down nuclear equations to show how collisions of deuterium (^2_1H) nuclei could cause the generation of alpha-particles and neutrons (*line 3*). [3]

(ii) Sketch the graph of mean binding energy per nucleon against nucleon number for stable nuclei.

Collisions of deuterium nuclei also generate energy (*lines 2–3*). Describe how values of the mean binding energy per nucleon can be used to calculate the energy generated by the collision described in one of the equations you have listed in **(i)**. [5]

(iii) How does the process of generation of nuclear energy from uranium differ from that from the collision of deuterium nuclei? [2]

(b) Making use of the information in *lines 7–15*, draw a schematic diagram to illustrate the experimental arrangement. Include in your sketch the pattern of the electric field between tip and target. Describe the motion of deuterium ions in this region. [5]

(c) Why does Michael Saltmarsh call the device a neutron generator, and not a fusion energy generator (*line 16*)? Suggest why he expresses concern that the device should not be too warm in someone's pocket (*line 18*). [4]

(d) Explain why it is particularly exciting that the device demonstrates that fusion is possible close to room temperature (*lines 1–3*). Make reference to the forces between nuclei. [4]

[Total: 23 marks]

2 (*You are advised to spend about 25 minutes on this question.*)

A radioactive rubidium nucleus $^{87}_{37}Rb$ may decay to a stable strontium $^{87}_{38}Sr$ nucleus by the emission of a beta-particle.

(a) A sample contains a large number of radioactive rubidium nuclei. At time $t = 0$, there are no strontium nuclei. At a later time t, there are n_{Rb} undecayed rubidium nuclei and n_{Sr} stable strontium nuclei.

Show that

$$n_{Sr} = n_{Rb}(e^{\lambda t} - 1), \qquad \textbf{Equation 2.1}$$

where λ is the decay constant. [3]

(b) Geologists use the decay of the radioactive rubidium nuclide as one method of dating rocks. In this method, values of n_{Sr} and n_{Rb} are obtained by chemical analysis of a rock sample. **Equation 2.1** is then used to find the age of the sample.

In a geological survey, samples of a particular type of rock were obtained from a number of places in a region. All samples had the same mass. **Table 2.1** shows the values of n_{Sr} and n_{Rb} obtained by the analysis of each sample.

Table 2.1

Sample	1	2	3	4	5
n_{Sr} /10^{18}	1.16	1.50	1.72	2.18	2.50
n_{Rb} /10^{18}	3.10	9.50	14.0	22.9	29.1

(i) According to a geologist's theory, the rock in the places from which the samples were taken was all formed at the same time. Explain how, by plotting a graph of n_{Sr} against n_{Rb} and comparing the result with that predicted from **Equation 2.1**, this idea could be checked. [3]

(ii) Plot this graph. You should find that it is not entirely as would be predicted from **Equation 2.1**. Suggest a reason for the discrepancy. [5]

(iii) In spite of the discrepancy in **(ii)**, it is still possible to estimate the age of the rock. Use your graph to obtain a value for its age. The decay constant λ for the decay of the rubidium nuclide is $4.50 \times 10^{-19}\,s^{-1}$. Give your answer in years.

(1 year = 3.16×10^{7} s) [3]

[Total: 14 marks]

3 (*You are advised to spend about 25 minutes on this question*)

(a) A body of mass m accelerates uniformly from rest to a speed v.

Sketch a graph of the speed of the body against time.

Write down equations representing Newton's second law of motion and the definition of work.

Write these equations in terms of gradient and area under the graph respectively. Hence show that the kinetic energy gained by the body is $\frac{1}{2}mv^2$. [5]

(b) (i) Other expressions for energy also include a factor of $\frac{1}{2}$; for example, the energy of a capacitor carrying a charge q with a potential difference V between its plates is $\frac{1}{2}qV$. Starting from a description of the process of charging a capacitor, explain how this factor arises. [4]

(ii) A feature of circuits containing charged capacitors is that there is often a spark at the contacts when a switch is opened or closed. In the circuit of **Fig. 3.1**, the capacitors are initially uncharged and both switches are open.

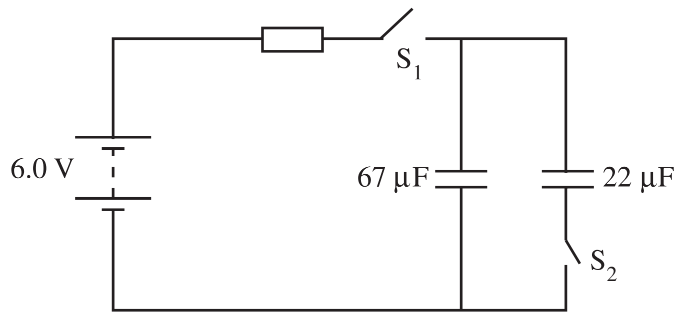

Fig. 3.1

Initially, switch S_1 is closed, charging the 67 μF capacitor from the battery. S_1 is then opened, leaving the 67 μF capacitor fully charged and the 22 μF capacitor still uncharged. When switch S_2 is closed, a spark occurs at the contacts of this switch. Estimate the energy dissipated in this spark. Is your value likely to be an over-estimate or an under-estimate? Give a reason. [8]

[Total 17 marks]

4 (*You are advised to spend about 25 minutes on this question.*)

In this question you are asked to estimate certain quantities. Some data and assumptions are given in the relevant part of the question, but you will also need to make use of your general knowledge of Physics.

(a) Estimate the rate at which photons are emitted from a helium-neon laser, such as might be used in a school laboratory to demonstrate the superposition of light waves. Start by stating approximate values of the wavelength and power of such a laser. (Hint: the power is about 1×10^{-5} that of a domestic filament lamp.) [6]

(b) **(i)** Estimate the number of molecules in the Earth's atmosphere. Assume that the acceleration of free fall has a constant value of $10\,\text{m}\,\text{s}^{-2}$ throughout the height of the atmosphere. Take the radius of the Earth as $6 \times 10^{6}\,\text{m}$, the average mass of a molecule in the atmosphere as $5 \times 10^{-26}\,\text{kg}$, and atmospheric pressure at the Earth's surface as $1 \times 10^{5}\,\text{Pa}$. [4]

(ii) Discuss whether the assumption about the constancy of the acceleration of free fall throughout the height of the atmosphere in **(i)** is realistic. Start by stating an order-of-magnitude value for the height of the atmosphere. [5]

[Total 15 marks]

5 (*You are advised to spend about 20 minutes on this question.*)

(a) An electron moving with speed v is made to travel in a circular orbit of radius r by applying a uniform magnetic field of flux density B perpendicular to the plane of the orbit.

Show that the momentum p of the electron in the orbit is given by

$$p = Ber \qquad \textbf{Equation 5.1}$$

where e is the elementary charge. [3]

(b) In an electron accelerator called the betatron, electrons move in a circular orbit of constant radius r under the action of a magnetic field. The acceleration is achieved by increasing the total magnetic flux through the orbit. To keep the electrons moving in the same orbit it is necessary to use a non-uniform field, produced by shaped pole-pieces, and to increase the magnetic flux density at the orbit. The total flux Φ is increased at a rate $\Delta\Phi/\Delta t$, and the flux density B at the orbit at a rate $\Delta B/\Delta t$.

In parts **(b)(i)**, **(ii)** and **(iii)** the orbit is modelled as a circular loop of wire of radius r with a very narrow gap XY in it, as sketched in **Fig. 5.1.**

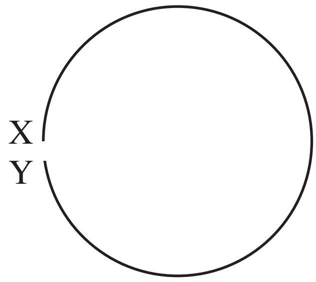

Fig. 5.1

(i) By considering the e.m.f induced between the ends X and Y of the wire as a result of changing the flux at a rate $\Delta\Phi/\Delta t$, obtain an expression for the work W done in taking an electron around the circle from X to Y while the flux is changing. Give your answer in terms of $\Delta\Phi/\Delta t$ and e. [2]

(ii) If work is done, a force must act on the electron. Write down another expression for W in terms of the tangential force F acting on the electron and the radius r of the orbit. [1]

(iii) By combining your answers to **(i)** and **(ii)**, relate F to e, r and $\Delta\Phi/\Delta t$. [1]

In parts **(b)(iv)** and **(v)** think of the electron as moving in its orbit of radius r.

(iv) Use **Equation 5.1** to obtain another expression for F in terms of the rate of change $\Delta B/\Delta t$ of the magnetic flux density. [2]

(v) Hence obtain the relation between $\Delta\Phi$, ΔB and r. [2]

[Total 11 marks]

6 (*You are advised to spend about 20 minutes on this question)*

Electrical circuits are normally two-dimensional. In the Physics laboratory, you connect up a circuit on the surface of the bench. In microelectronics, components are usually connected together on the surface of a single silicon wafer. Eventually, though, technology will change so that circuits become three-dimensional; this will increase their complexity.

(a) **Fig. 6.1** shows a two-dimensional circuit.

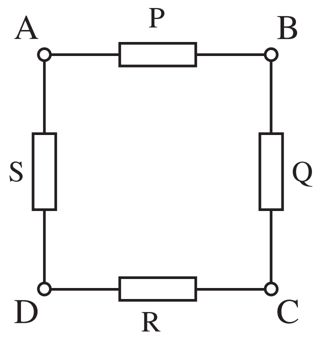

Fig. 6.1

Four resistors of value 1.0 Ω, 2.0 Ω, 3.0 Ω and 4.0 Ω are used to make this circuit.

The resistance is measured between pairs of terminals in turn, with the following results:

between terminals A and B	1.6 Ω
between terminals B and C	0.9 Ω
between terminals C and D	2.4 Ω
between terminals D and A	2.1 Ω

Deduce the resistance of each of the resistors P, Q, R and S. Show your reasoning clearly. [5]

(b) **Fig. 6.2** shows a three-dimensional network which consists of twelve equal resistors, each of resistance R connected to form a cube. A current I enters at X and leaves at Y.

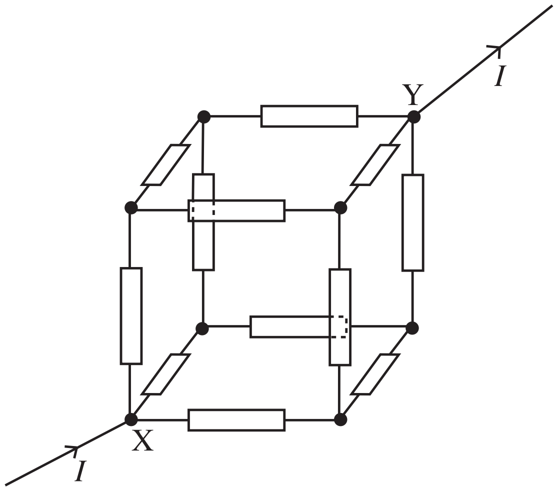

Fig. 6.2

Determine the resistance of the network between X and Y. (Hint: consider the symmetry of the network.) [5]

[Total 10 marks]

7 (*You are advised to spend about 20 minutes on this question*)

You meet an old friend who used to study Physics with you, but has since made a career in analysing sporting events. Interested in the unusual transition from Physics to sporting journalism, you ask him to tell you more.

"Well," he says, "let me give you an example. For most people, to predict the number of horses that will still be running in the Grand National, as a function of the number of fences that have been jumped, would seem impossible. You and I, however, as physicists, can clearly appreciate that it will probably conform to an exponential decay function."

You laugh and nod knowingly, despite being a little confused.

"Actually," your friend continues, "could I ask you to write an article for our *Monthly Sporting Journal* emphasizing the importance of the exponential function, both in Physics and in racing?"

Without thinking, you agree.

Write a short article for your friend's *Monthly Sporting Journal*. Describe briefly **two** examples from Physics. Remember that the readership will be much more interested in picking a winner for the Grand National than in learning the finer details of Physics. Hence, you should include in your article an explanation of how the exponential decay curve may come into predicting the number of horses that will finish the Grand National.

Apart from the content of your answer, you will be assessed on the quality of your written communication.

[Total: 10 marks]

THIS IS THE END OF THE QUESTION PAPER

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ADVANCED EXTENSION AWARD

PHYSICS

Information Leaflet

The following may be of use in answering some of the questions.

Values of constants

speed of light in free space	$c = 3.00 \times 10^{8}\ \mathrm{m\ s^{-1}}$
permeability of free space	$\mu_0 = 4\pi \times 10^{-7}\ \mathrm{H\ m^{-1}}$
permittivity of free space	$\varepsilon_0 = 8.85 \times 10^{-12}\ \mathrm{F\ m^{-1}}$
	$\left(\dfrac{1}{4\pi\varepsilon_0} = 9 \times 10^{9}\ \mathrm{F^{-1}\ m}\right)$
elementary charge	$e = 1.60 \times 10^{-19}\ \mathrm{C}$
the Planck constant	$h = 6.63 \times 10^{-34}\ \mathrm{J\ s}$
unified atomic mass unit	$1\ \mathrm{u} = 1.66 \times 10^{-27}\ \mathrm{kg}$
electron mass	$m_e = 9.11 \times 10^{-31}\ \mathrm{kg}$
proton mass	$m_p = 1.673 \times 10^{-27}\ \mathrm{kg}$
neutron mass	$m_n = 1.675 \times 10^{-27}\ \mathrm{kg}$
molar gas constant	$R = 8.31\ \mathrm{J\ K^{-1}\ mol^{-1}}$
the Avogadro constant	$N_A = 6.02 \times 10^{23}\ \mathrm{mol^{-1}}$
the Boltzmann constant	$k = 1.38 \times 10^{-23}\ \mathrm{J\ K^{-1}}$
gravitational constant	$G = 6.67 \times 10^{-11}\ \mathrm{N\ m^{2}\ kg^{-2}}$
acceleration of free fall on the Earth's surface	$g = 9.81\ \mathrm{m\ s^{-2}}$
normal atmospheric pressure	$p_{atm} = 1.01 \times 10^{5}\ \mathrm{Pa}$
electron volt	$1\ \mathrm{eV} = 1.60 \times 10^{-19}\ \mathrm{J}$

Formulae

The following equations may be useful in answering some of the questions in the examination:

Mechanics

equations for uniformly accelerated motion	$v = u + at$
	$s = \frac{1}{2}(u + v)t$
	$s = ut + \frac{1}{2}at^2$
	$v^2 = u^2 + 2as$

Momentum and Energy

force = rate of change of momentum	$F = \frac{\Delta(mv)}{\Delta t}$
power	$P = Fv$

Kinetic Theory

kinetic theory of gases	$pV = \frac{1}{3}Nm\overline{c^2}$
average kinetic energy of a molecule	$\frac{1}{2}m\overline{c^2} = \frac{3}{2}kT = \frac{3RT}{2N_A}$

Electricity

terminal potential difference	$V_{load} = \mathcal{E} - Ir$
discharge of capacitor	$Q = Q_0 e^{-t/RC}$
time constant	$\tau = RC$

Atomic and Nuclear physics

radioactive decay	$\frac{\Delta N}{\Delta t} = -\lambda N$
	$N = N_0 e^{-\lambda t}$
half-life	$T_{\frac{1}{2}} = \frac{\ln 2}{\lambda}$

Energy

mass-energy relationship	$E = mc^2$

Quantum Physics

energy-frequency relationship for photons	$E = hf$
de Broglie equation	$\lambda = \dfrac{h}{p}$

Waves and Oscillations

two-slit interference	$\lambda = ay/d$ **or** $\lambda = xs/D$
simple harmonic motion	$a = -(2\pi f)^2 x$
	$x = A \cos 2\pi ft$ $x = A \sin 2\pi ft$

Fields

gravitational fields	$g = \dfrac{F}{m}$
	$g = \dfrac{GM}{r^2}$
electric fields	$E = \dfrac{F}{q}$
	$E = \dfrac{1}{4\pi\varepsilon_0} \dfrac{q}{r^2}$
	$E = \dfrac{V}{d}$

Magnetic effect of currents

force on a current-carrying conductor	$F = BIl$
force on a moving charge	$F = Bqv$
magnetic flux	$\Phi = BA$
induced e.m.f.	$\mathcal{E} = -\dfrac{d(N\Phi)}{dt}$

Mathematical equations

areas and volumes	area of circle = πr^2
	surface area of cylinder = $2\pi rh + 2\pi r^2$
	volume of cylinder = $\pi r^2 h$
	surface area of sphere = $4\pi r^2$
	volume of sphere = $\frac{4}{3}\pi r^3$
radians	arc = $r\theta$
	$\sin\theta \approx \tan\theta \approx \theta$ and $\cos\theta \approx 1$ for small θ
logarithms	$\ln(x^n) = n \ln x$ $\ln(e^{kx}) = kx$