Rewarding Learning

Advanced Extension Award

2002

Physics

Advanced Extension Award

100/1544/9

FRIDAY 28 JUNE, AFTERNOON

TIME

3 hours.

INSTRUCTIONS TO CANDIDATES

In the boxes on the answer book, 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 book, Graph paper, Calculator, Drawing compasses.

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.

Attempt **all seven** questions.

1 (You are advised to spend about 40 minutes on this question.)

Read the passage and then answer the questions which follow.

Identifying atoms on solid surfaces

[Freely adapted from *Physics at Surfaces* by Andrew Zangwill (Cambridge University Press, 1988)]

One method of analysing the chemical composition of the surface of a solid is Auger electron spectroscopy (AES). In this technique, a beam of electrons of energy about 2 keV is directed at a sample. The electrons backscattered from the surface are collected and their energy spectrum is determined. **Fig. 1.1** shows a typical spectrum.

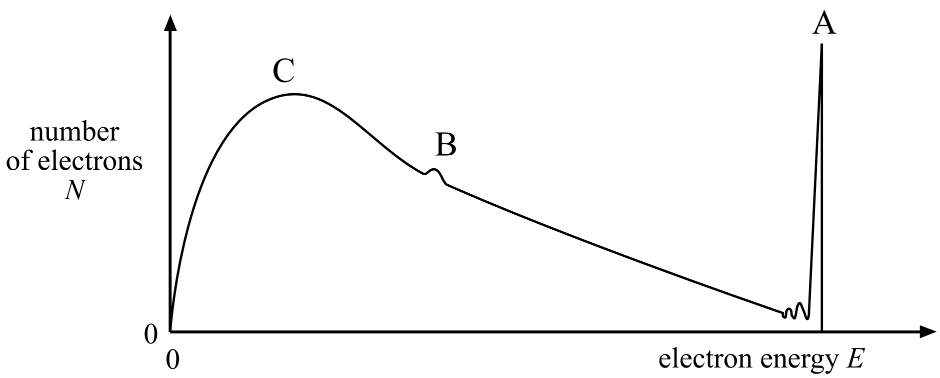

Fig. 1.1

The main features are an elastic peak (A in **Fig. 1.1**), due to electrons that are reflected directly from the surface of the solid, and a long tail of electrons that have lost energy to atoms of the solid. Two classes of electrons contribute to this tail. In the first, an electron leaves the solid as a result of a single, well-defined inelastic event between a bombarding electron and an atom of the surface. Such interactions show up as tiny blips in the energy spectrum (B in **Fig. 1.1**). Other electrons lose energy through multiple inelastic collisions, giving a broad, structureless peak (C in **Fig. 1.1**) extending down to zero energy.

The precise energies of the blips in the spectrum give the elemental signature of the surface. To understand this, consider the energy level diagram for one of the surface atoms (**Fig. 1.2.1**). Suppose that a bombarding electron, colliding with this surface atom, causes the ejection of an electron from level K, and its complete removal from the solid, as in **Fig. 1.2.2**. The vacant place in the K level is then filled by an electron from level L_1. A definite amount of energy is released in this transition. This energy may in turn eject an electron in the L_2 level from the atom. This process is called Auger electron emission, and the ejected electron is called an Auger electron. This is illustrated in **Fig. 1.2.3**.

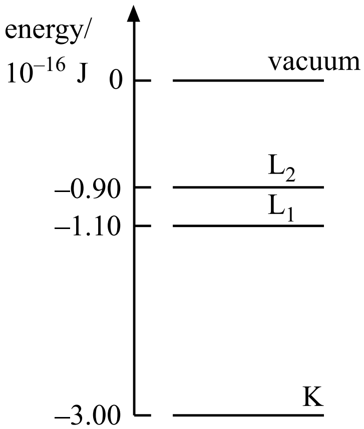

Fig. 1.2.1

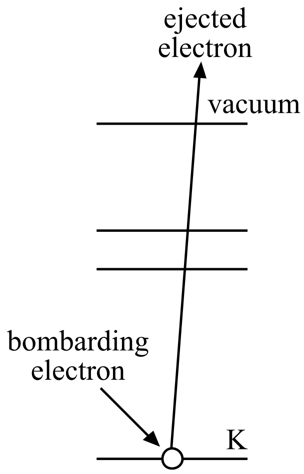

Fig. 1.2.2

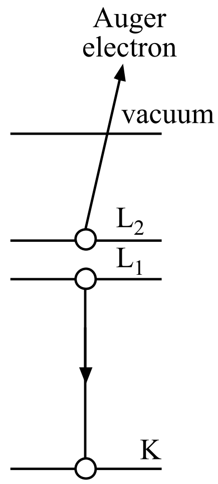

Fig. 1.2.3

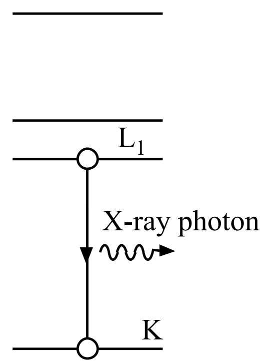

Fig. 1.2.4

Energy conservation gives the kinetic energy E_{kin} of the Auger electron as

$$E_{\text{kin}} = E_{\text{K}} - E_{\text{L}_1} - E_{\text{L}_2} \ ,$$

where E_{K}, E_{L_1} and E_{L_2} are the binding energies, relative to vacuum, of an electron in the K, L_1 and L_2 levels respectively. Note that the Auger electron's kinetic energy depends only on the energy level scheme of the atom from which it has been emitted. Every element exhibits at least one Auger process, and because the energy levels of atoms are well known and tabulated, the fingerprints left in the energy spectrum by every surface atom can be identified.

Alternatively, the energy released in the transition of the L_1 electron to the vacancy in the K level may appear as a photon of electromagnetic radiation in the soft X-ray region of the spectrum, as illustrated in **Fig. 1.2.4**. Detection of the threshold energy required for the incident electrons to initiate these X-rays also allows the identification of the surface atoms. This analysis technique is called Soft X-ray Appearance Potential Spectroscopy (SXAPS).

Answer the following questions

(a) What is meant by the **elemental signature of a surface** (*lines 13–14*)? [1]

(b) Explain what is meant by the terms **elastic** (*line 5*) and **inelastic** (*lines 8, 11*) in the context of electron interactions with atoms. [2]

(c) What feature of the bombarding electrons ensures that the AES and SXAPS techniques give information about only the outermost atomic layers of the surface?

If the energy of the bombarding electrons is increased to about 20 keV, the emitted X-rays give information about atoms in the bulk of the solid, instead of only in the surface. Why should changing the energy have this consequence? [3]

(d) **Fig. 1.3** is an enlargement of the blip at B in **Fig. 1.1**.

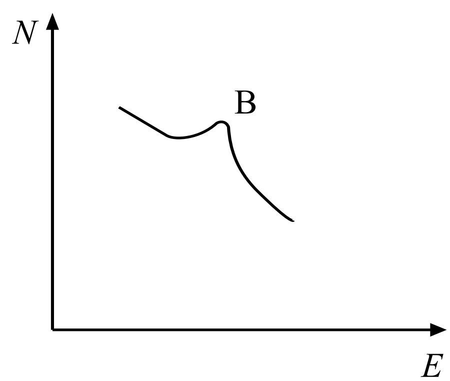

Fig. 1.3

(i) Explain how a measure of the number of surface atoms of a particular species might be obtained from this energy spectrum.

(ii) To identify Auger electron energies precisely, the equipment is arranged to provide a printout not of the energy spectrum (**Fig. 1.1**), but of the gradient of the energy spectrum in the region of interest.

Sketch a graph showing how the gradient G of **Fig. 1.3** depends on electron energy E. Mark on your graph the energy corresponding to the maximum of the blip (the energy of the Auger electron). [6]

(e) Refer to the energy level diagrams in **Figs 1.2.1–1.2.4**.

(i) Through what minimum potential difference must a bombarding electron be accelerated to cause the ejection of the K-electron from the atom (**Fig. 1.2.2**)?

(ii) How much energy is released when the L_1 electron moves to fill the vacancy in the K level (**Fig. 1.2.3**)?

(iii) Calculate the kinetic energy of the Auger electron emitted from the L_2 level (**Fig. 1.2.3**).

(iv) Calculate the wavelength of the X-rays emitted in the process illustrated in **Fig. 1.2.4**. [7]

(f) During the outbreak of Foot and Mouth Disease in 2001 the Government Chief Scientist was able to predict that the outbreak had passed its most serious point by referring to statistics on the rate of increase of new cases. He was able to make this statement before the number of new cases reported daily had reached its maximum. Making an analogy with the method of processing Auger electron spectra described in **(d)(ii)**, suggest why this approach was appropriate. [2]

[Total: 21 marks]

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

Early one morning, at two minutes thirty seconds past four (04:02:30), a meteorite struck an unknown location in Scotland. The impact generated a shock wave along the surface of the Earth. The wave was detected at five monitoring stations A, B, C, D and E.

Table 2.1 gives the positions of the stations, expressed as co-ordinates (x/km, y/km) relative to an arbitrary origin. Also tabulated are the times at which the shock wave was detected at the stations, and the intensity of the wave, expressed in arbitrary linear units.

Table 2.1

station	position (x/km, y/km)	time of detection (hr:min:s)	intensity of shock wave/ arbitrary units
A	(100, 90)	04:03:31	15.7
B	(10, 40)	04:03:45	12.7
C	(120, 10)	04:04:21	8.1
D	(240, 130)	04:04:51	6.1
E	(270, 295)	04:05:37	4.3

(a) The shock wave travelled outwards from the point of impact at a speed of 1.50 km s^{-1}. Using only the information associated with stations A, B and C, identify the co-ordinates of the point of impact of the meteorite. Give your answer to the nearest 10 km in both x and y. (You may wish to use drawing compasses and graph paper.) [6]

(b) Assume that no energy is lost from the wavefront as it travels outwards along the Earth's surface. Show theoretically that the intensity I of the surface shock wave at a distance r from the source of the wave is given by an equation of the form

$$I = \frac{K}{r}\,, \qquad \textbf{Equation 2.1}$$

where K is a constant. [2]

(c) Plot a suitable graph to demonstrate the extent to which the information from all five stations agrees with **Equation 2.1**. Briefly suggest an explanation for any difference between your graph and the function given by **Equation 2.1**. [6]

[Total: 14 marks]

3 (You are advised to spend about 30 minutes on this question.)

This question is about mechanical and electrical power.

(a) Define **power**.

A potential difference V is applied across a resistor, producing a current I. The power P dissipated in the resistor is given by $P = VI$. Show that this expression is consistent with your definition of power. [3]

(b) A battery of emf $\mathscr{E}$ and internal resistance r is connected to a variable load resistor, as shown in **Fig. 3.1**.

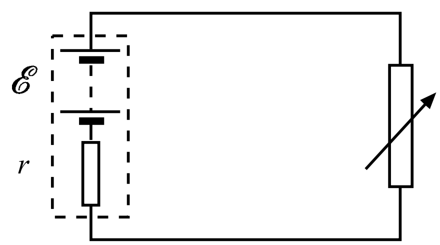

Fig. 3.1

(i) Consider the circuit when the resistance of the load resistor is R. Derive expressions for the total power P_{total} dissipated in the circuit, and the power P_{load} delivered to the load. Give your answers in terms of $\mathscr{E}$, R and r. [2]

(ii) The efficiency η of the circuit as a system for delivering power is defined as P_{load}/P_{total}. The condition for delivering maximum power to the load is $R = r$. (You are **not** asked to prove this result.)
What is the value of the efficiency of the circuit under this condition?
What is the value of the theoretical maximum efficiency?
Discuss whether this maximum efficiency can ever be achieved. [4]

(c) An inextensible chain of total mass M and length L is loosely coiled on a quayside. One end of the chain is attached to an inextensible rope of negligible mass. This is pulled vertically upwards at constant speed v by a crane. **Fig. 3.2.1** shows the situation at time t, when the top end of the chain is at a height y above the quay. A very short time Δt later the top of the chain is at a height $y + \Delta y$ (**Fig. 3.2.2**). Δy is very small compared with y.

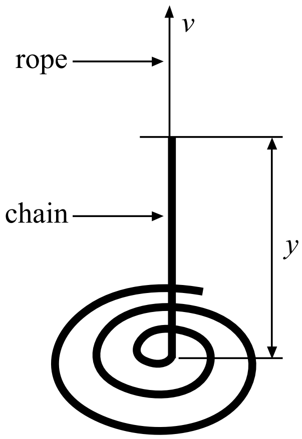

Fig. 3.2.1

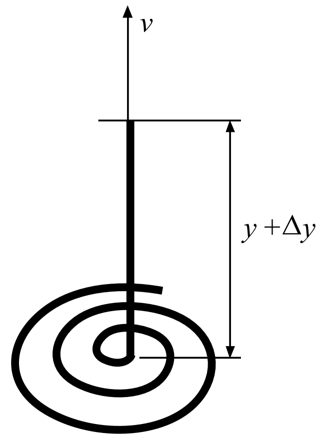

Fig. 3.2.2

(i) Obtain expressions for the change ΔE_{pot} in the potential energy of the chain that occurs in the time Δt, and the change ΔE_{kin} in its kinetic energy that occurs in the same interval. Assuming that ΔE_{pot} and ΔE_{kin} are the only changes that take place in the energy of the chain, show that the power P supplied by the crane at time t is given by

$$P = \frac{Mv}{L}(gy + \tfrac{1}{2}v^2)$$

[7]

[*Reminder:* since Δy is very small, terms like $(\Delta y)^2$ can be neglected.]

(ii) Taking $y = 0$ at time $t = 0$, sketch a graph to show how the power P depends on t from $t = 0$ to $t = 2L/v$. Assume that at $t = 2L/v$ the top end of the chain has not yet reached the crane. [3]

[Total: 19 marks]

4 (You are advised to spend about 15 minutes on this question.)

The storage of binary data is of crucial importance in modern information technology. Increasingly, capacitors are being considered for information storage. Capacitors can store data in the form of electric charge on their plates.

(a) In this application, measuring the amount of charge stored in a capacitor as a function of electric field is extremely important. Measurement systems based on the circuit shown in **Fig. 4.1** are often used.

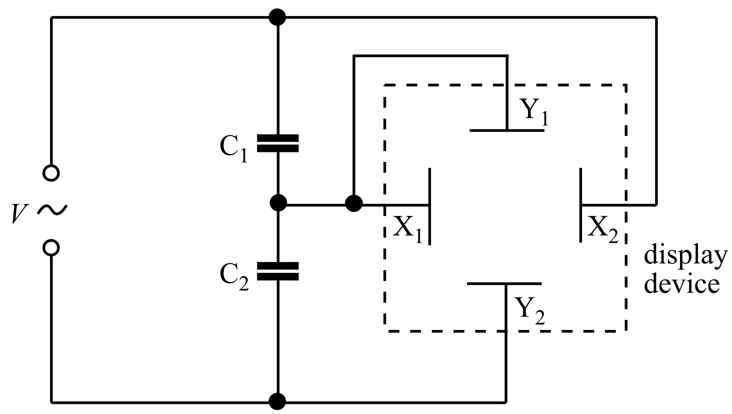

Fig. 4.1

In this circuit the data are stored on capacitor C_1. The capacitance of capacitor C_2 is known. A slowly-varying voltage V is applied. The voltages at various points in the circuit are applied to the plates X_1, X_2, Y_1 and Y_2 in the display device, and readings from the display allow determination of the relevant potential differences.

(i) By using the potential difference between X_1 and X_2, and that between Y_1 and Y_2, show how the circuit is capable of measuring the charge stored in capacitor C_1 as a function of the voltage dropped across this capacitor. [3]

(ii) Capacitor C_2 is chosen so that much the greater part of the applied voltage is dropped across capacitor C_1. What can you deduce about the magnitude of the capacitance of C_1 relative to that of C_2? Explain your reasoning. [2]

(b) So-called "thin film" capacitors have been developed for use in data storage applications. Such capacitors consist of a thin film of insulating material sandwiched between two parallel electrodes. Typically, the thickness of the insulator is about 50 nm. The capacitor operates at a potential difference of about 2 V.

(i) Calculate the electric field strength in such a capacitor and comment on its value. [2]

(ii) Such a capacitor has capacitance 9 pF. It is charged to a potential difference of 2 V, and is then discharged by connecting the two electrodes with a metal wire. Calculate the number of electrons transferred from one end of the wire to the other. [2]

[Total: 9 marks]

5 (You are advised to spend about 15 minutes on this question.)

Fig. 5.1 shows a loop of thin, light, very flexible, insulated wire lying in an irregular shape on a smooth, horizontal table.

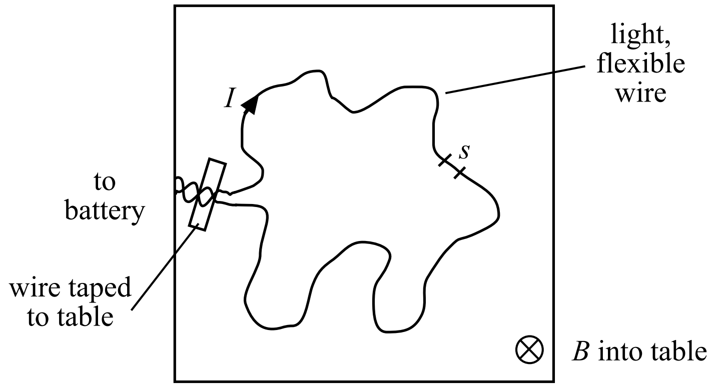

Fig. 5.1

The ends of the loop are twisted together, and this part of the wire is taped firmly to the table. The length of wire in the loop not fixed to the table is L. A steady, uniform magnetic field of flux density B is directed vertically downwards through the whole area of the table. The ends of the wire are then connected to a battery so that there is a large current I in the loop in the clockwise direction, as shown in **Fig. 5.1**.

(a) Consider the very short length s of the wire in **Fig. 5.1**. What is the magnitude and direction of the force acting on this length? Hence describe and explain what happens to the shape of the loop. [4]

(b) By considering the equilibrium of a small part of the loop, find an expression for the tension T in the loop when it carries the current I. Give your answer in terms of B, I and L. [5]

(c) The battery is disconnected and then reconnected so that the direction of the current is reversed. Describe and explain what happens to the loop. [2]

[Total: 11 marks]

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

(a) The units of all derived mechanical quantities can be expressed as products or quotients of the SI base units of mass, length and time. However, it is possible to set up alternative systems in which other quantities are taken as the base units.

A student has the idea of making his name by proposing a new set of mechanical units, with the newton (N), the joule (J) and the watt (W) as base units. In this system, the metre (m), kilogram (kg) and the second (s) will become derived units. Express the metre, kilogram and second as products or quotients of the proposed new base units.

Although the student's system meets the aim of being able to express all mechanical quantities in terms of its base units, it is not feasible. Why not?

Another student proposes a set of mechanical units with mass, volume and density as the base quantities. Why is this system bound to fail? [5]

(b) Using relevant physical arguments relating to pressure, estimate the following quantities:

(i) the area of a car tyre in contact with the road,

(ii) the number of air molecules taken into your lungs each time you draw a breath.

In each case, you will have to assume the values of some of the quantities you use, and credit will be given for choosing reasonable values. Make clear the physics principles and equations you use in arriving at your final answers. [9]

[Total: 14 marks]

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

You’re at a funfair, and you see a young boy accidentally letting go of his helium-filled balloon. To the child this is a catastrophe, and he is very upset. You try to take his mind off the event. You decide to use your knowledge of physics to describe and explain what you think might happen to the balloon and the gas inside it as it rises in the air. Write an account of this explanation. In your answer, you should refer to the balloon’s motion, to the balloon’s size, and to the gas in the balloon.

Apart from the content of your answer, you will also be assessed on the quality of your written communication. [12]

[Total: 12 marks]