Rewarding Learning

Advanced Extension Award
2005

Physics

Advanced Extension Award

H7651

THURSDAY 30 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 30 minutes on this question.*

Read the passage and then answer the questions which follow.

The behaviour of gases

(Freely adapted from *The Structure of Matter*, by R. W. Christy and Agnar Pytte)

The three variables pressure p, molar volume V_m and temperature T, which describe the state of a gas cannot all be chosen independently. They are linked by an equation called the equation of state for the gas. For many gases under ordinary conditions this equation of state approximates to an equation called the ideal gas law:

$$pV_m = RT$$

where R is a constant. If V_m is in $m^3\,mol^{-1}$, p in Pa and T in K, then $R = 8.31\ J\,K^{-1}\,mol^{-1}$. It seems incredible that for very many real gases the constant in the equation linking p, V_m and T has approximately the same value, namely R.

The ideal gas law gives a macroscopic description of the various states of a hypothetical gas called an ideal gas. The molecules of an ideal gas are assumed to be point masses that exert no forces on the other molecules in the gas, move at random, and make perfectly elastic collisions with the walls of the container. An important property of an ideal gas is stated in Joule's law: the internal energy of an ideal gas depends only on temperature.

For gases under conditions which are abnormal, i.e. in which the ideal gas law no longer gives a good approximation to the behaviour of the gas, an equation of state due to Clausius may be used:

$$p(V_m - b) = RT$$

where p, V_m, R and T have their previous meanings and b is a constant. In the Clausius model the molecules are assumed to be hard spheres rather than point masses.

(a) Explain briefly what is meant by each of the following phrases **as they are used in the passage:**

(i) molar volume (*line 1*),

(ii) macroscopic (*line 9*),

(iii) hypothetical (*line 9*),

(iv) a perfectly elastic collision (*line 12*). [4]

(b) The passage states that for very many real gases under ordinary conditions the constant in the equation linking p, V_m and T has approximately the same value (*line 8*).

(i) Suggest what is meant by ordinary conditions, making reference to typical values of pressure and temperature (*line 3*). [1]

(ii) State a conclusion that can be drawn from the observation that for many gases the constant in the p, V_m, T equation is approximately the same. [1]

(iii) State a condition under which the agreement between the behaviour of real gases and that predicted by the ideal gas equation might be expected to break down. Explain why this might happen. [3]

(c) Joule's law (*lines 13–14*) relates to the internal energy of an ideal gas.

(i) State the origin of the internal energy of a sample of an ideal gas. [1]

(ii) Explain whether Joule's law applies to a real gas. [3]

(d) The Clausius equation (*lines 15–20*) may be used to describe the behaviour of a gas under abnormal conditions.

(i) State a unit for the constant b in the Clausius equation. [1]

(ii) A student is asked to obtain an expression for b in terms of the diameter d of a molecule and the Avogadro constant N_A. His answer is $b = \frac{1}{6}\pi d^3 N_A$. Suggest how he arrived at this result. [2]

(iii) The student's answer in **(ii)** is, in fact, wrong. The correct relation is $b = \frac{2}{3}\pi d^3 N_A$, i.e. four times his result. Explain how the factor of four arises. [3]

(iv) Describe what happens when the gas is compressed until V_m approaches b. Explain why this behaviour would be expected. [2]

[Total: 21 marks]

2 *You are advised to spend about 30 minutes on this question.*

The beam from a laser pen is slightly divergent with divergence angle θ, and is directed horizontally in a darkened laboratory. At any point along the beam the cross-section of the beam is circular. Because of the beam divergence, the radius r of the beam increases uniformly with the distance x from the laser, which is regarded as a point source. The divergence angle is shown in **Fig. 2.1**.

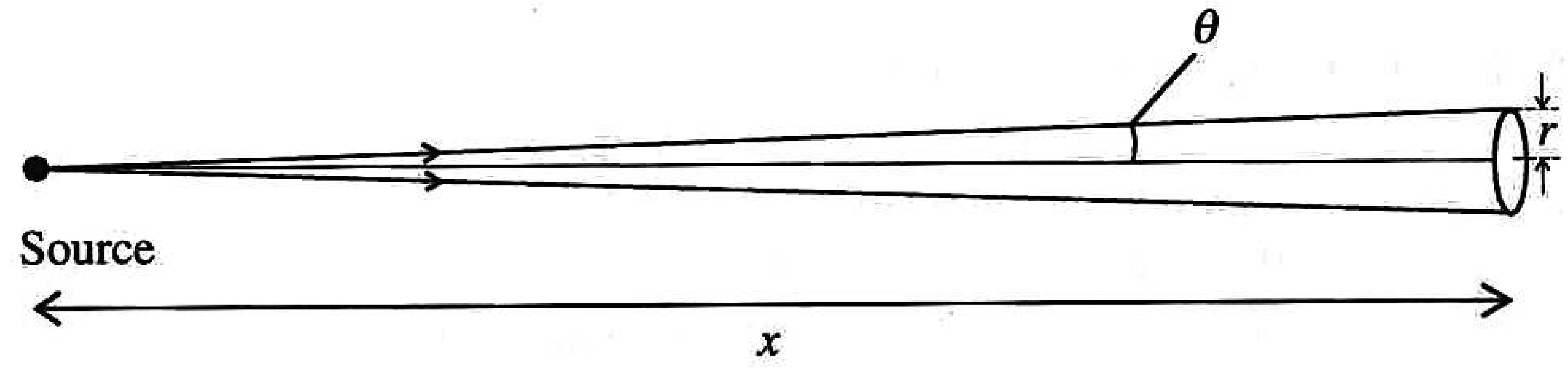

Fig. 2.1

A circular detector of diameter D is mounted on a long optical bench which runs parallel to the axis of the laser beam. The detector is placed so that it always intercepts the beam with its centre at the axis of the beam and its plane normal to the axis. The detector is connected to an output display which gives the intensity of the beam at that position. In this case, the intensity is taken as the total power incident on the detector divided by the detector area.

In **Fig. 2.2** experimental values of the measured signal from the detector are plotted as a function of distance x from the laser source. The vertical axis gives the signal as a fraction F of the maximum measured value.

(a) The graph in **Fig. 2.2** shows a straight line parallel to the x-axis at low values of x and a downward-curving region at higher values. Explain the shape of this graph in the two regions. [3]

(b) Extrapolate the lines on **Fig. 2.2** to determine the intersection of the straight and curved regions of the graph. Use the value of x at the intersection to find a value for θ. The diameter D of the detector is 10.0 mm.

Estimate the uncertainty in your value of θ. Explain how you arrive at this estimate. [4]

(c) Use the information in the first two paragraphs of the question to confirm the relation

$$F = \frac{D^2}{4x^2 \tan^2\theta}$$

which describes the downward-curving region of the graph. [3]

(d) Read off appropriate experimental values from **Fig. 2.2** and use them to plot a suitable graph to obtain a more precise value of θ.

Determine this value of θ. [8]

[Total: 18 marks]

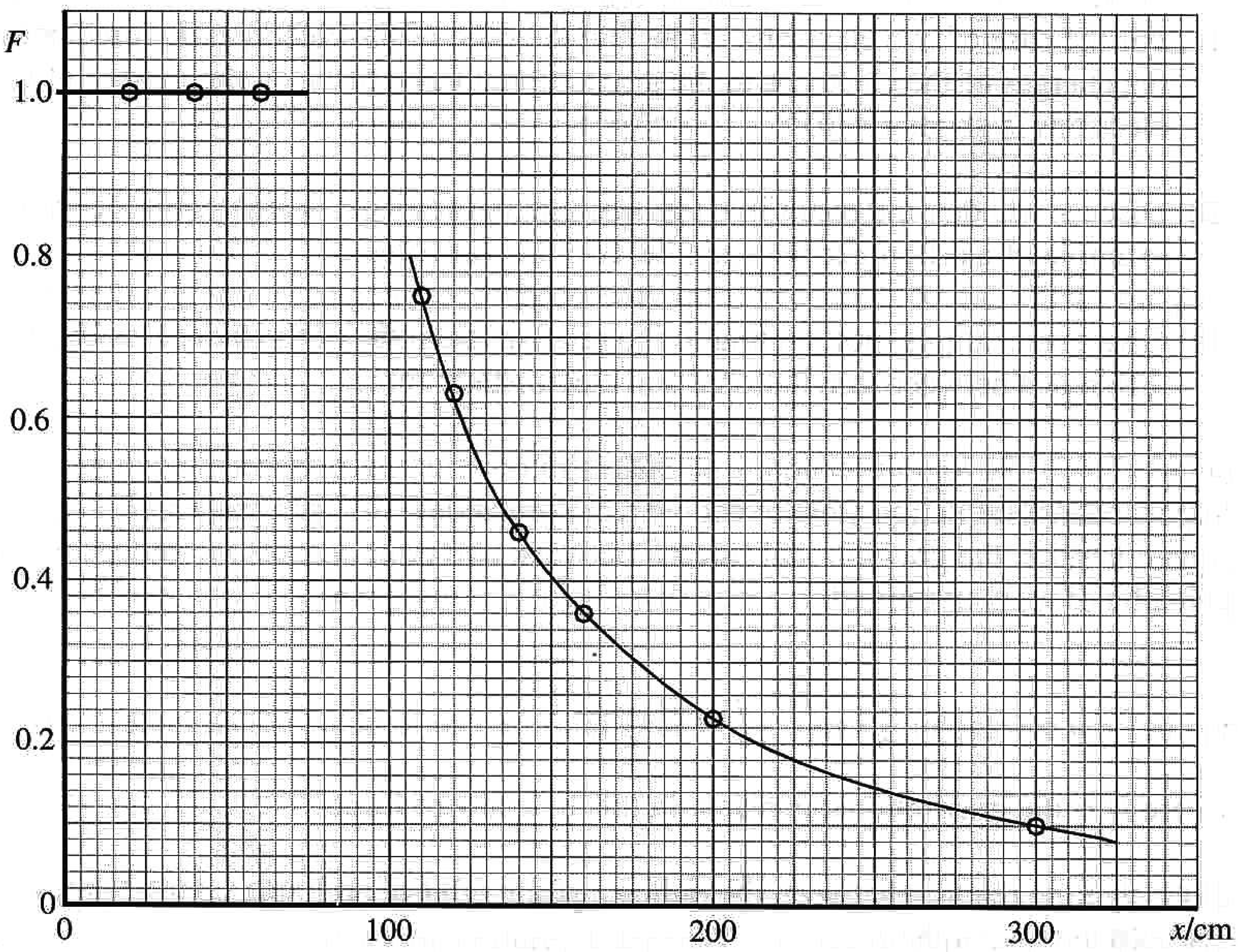

Fig. 2.2

3 *You are advised to spend about 20 minutes on this question.*

The gravitational force between two point masses, and the electrostatic force between two point charges, both follow an inverse square law of distance.

(a) Although there are similarities between the law in the two cases, there are also differences. A student, asked to give an example of a difference, says "the electrostatic force is very much stronger than the gravitational force".

(i) For the case of two electrons, show that the ratio of the electrostatic force between the charges of the electrons to the gravitational force between the masses of the electrons is about 4×10^{42}. [4]

(ii) Discuss whether the result in **(i)** proves that the student's statement is a correct example of a difference between the two laws of force. [2]

(iii) Give one example, not relating to the relative strengths of the forces, of another difference between gravitational and electrostatic forces. [1]

(b) Suppose that gravitation were to follow a reciprocal law of force, rather than an inverse square law, i.e. the gravitational force F between two point masses m_1 and m_2 would be given by

$$F = H\frac{m_1 m_2}{r}$$

where H is the gravitational constant in this new law of force.

Show that the relation between the radius r of the orbit of an Earth satellite and its period T would then be of the form

$$r^m T^n = A$$

where m and n are integers and A is a constant. Find numerical values for m and n. Find also the corresponding expression for A, in terms of the mass m_E of the Earth and the new gravitational constant H. [4]

[Total: 11 marks]

4 *You are advised to spend about 20 minutes on this question.*

The possibility of corrosion by oxidation when a metal is exposed to atmospheric air is an important factor in determining the fitness for purpose of components fabricated from the metal.

The process of oxidation can be thought of as the gradual growth of a film of the metal oxide on the surface of the metal. Experiments on a certain metal show that the relation describing how the thickness x of the oxide film depends on time t after the metal is exposed to atmospheric air is of the form

$$x = D\sqrt{t}$$

where D is a constant at a particular temperature.

(a) Sketch a graph of x against t. Suggest why the corrosion process follows the pattern of variation indicated by the graph. [5]

(b) In an experiment carried out with this metal at a temperature of 17 °C, it is found that the oxide film grows on a clean metal surface to a thickness of 2.5 μm in one week.

(i) Calculate how many more weeks it will take for the film to grow to a total thickness of 7.5 μm. [3]

(ii) Calculate the value of the constant D at 17 °C. Give your answer with an appropriate SI unit. [3]

(c) Experiments with this metal at a number of temperatures show that although D is a constant at a particular temperature, it depends strongly on temperature. The value of D might be expected to increase with increasing temperature. Explain why. [1]

[Total: 12 marks]

5 *You are advised to spend about 25 minutes on this question.*

(a) A mass m is suspended from a spring of force constant k. A simple derivation shows that the vertical oscillations of the mass are simple harmonic and of frequency f given by

$$f = \frac{1}{2\pi}\sqrt{\frac{k}{m}}.$$

Use SI base units to show that the units on both sides of the equation are the same. [2]

(b) Two light springs, each of unstretched length L and force constant k, are fastened between two clamps a distance $2L$ apart just above a horizontal, frictionless table. The springs obey the law $F = kx$ in both extension and compression. A mass M is clamped between the springs so that the mass rests on the table, as shown in **Fig. 5.1**.

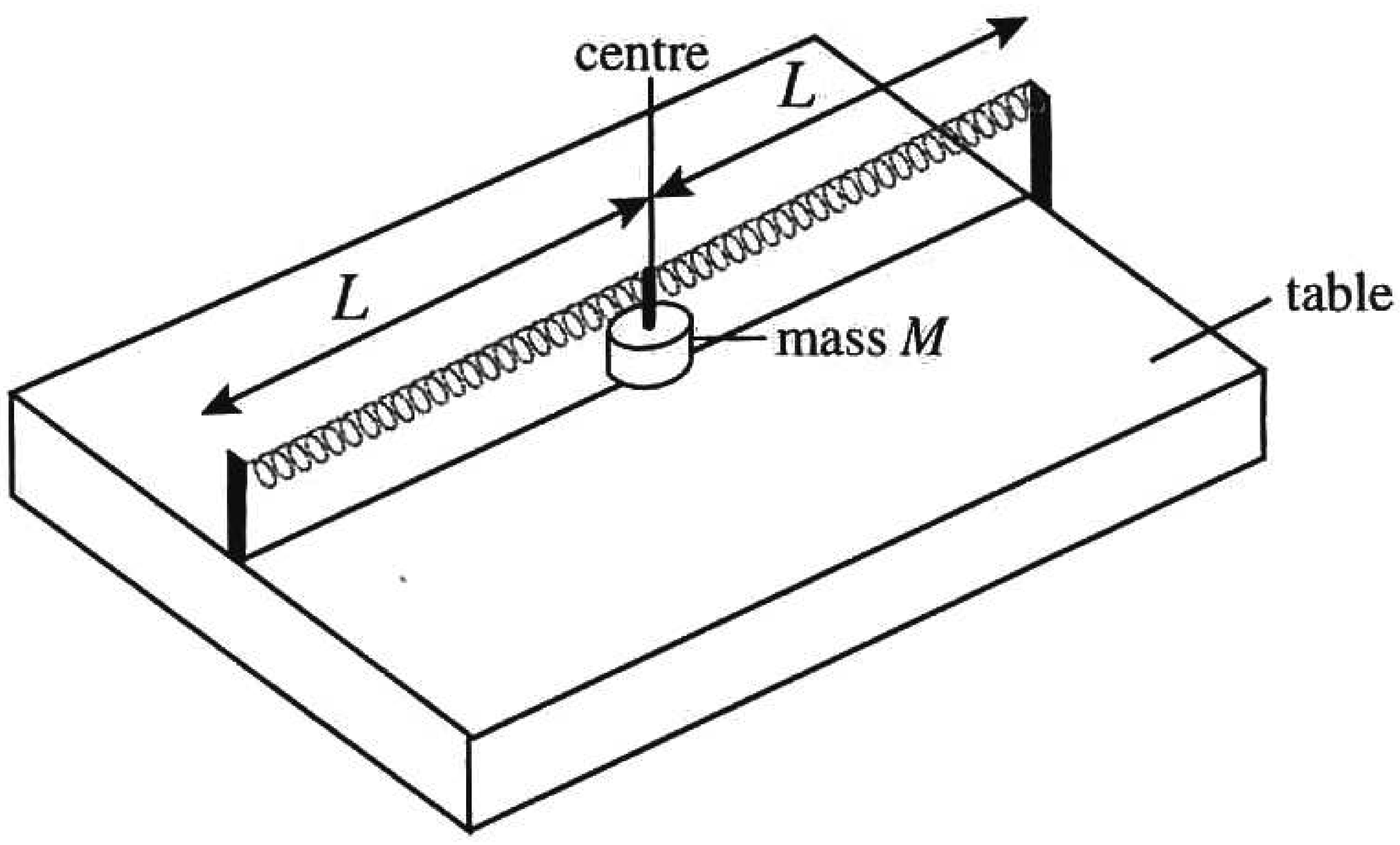

Fig. 5.1

(i) The mass is displaced by a small distance along the axis of the springs, as shown in **Fig. 5.2**.

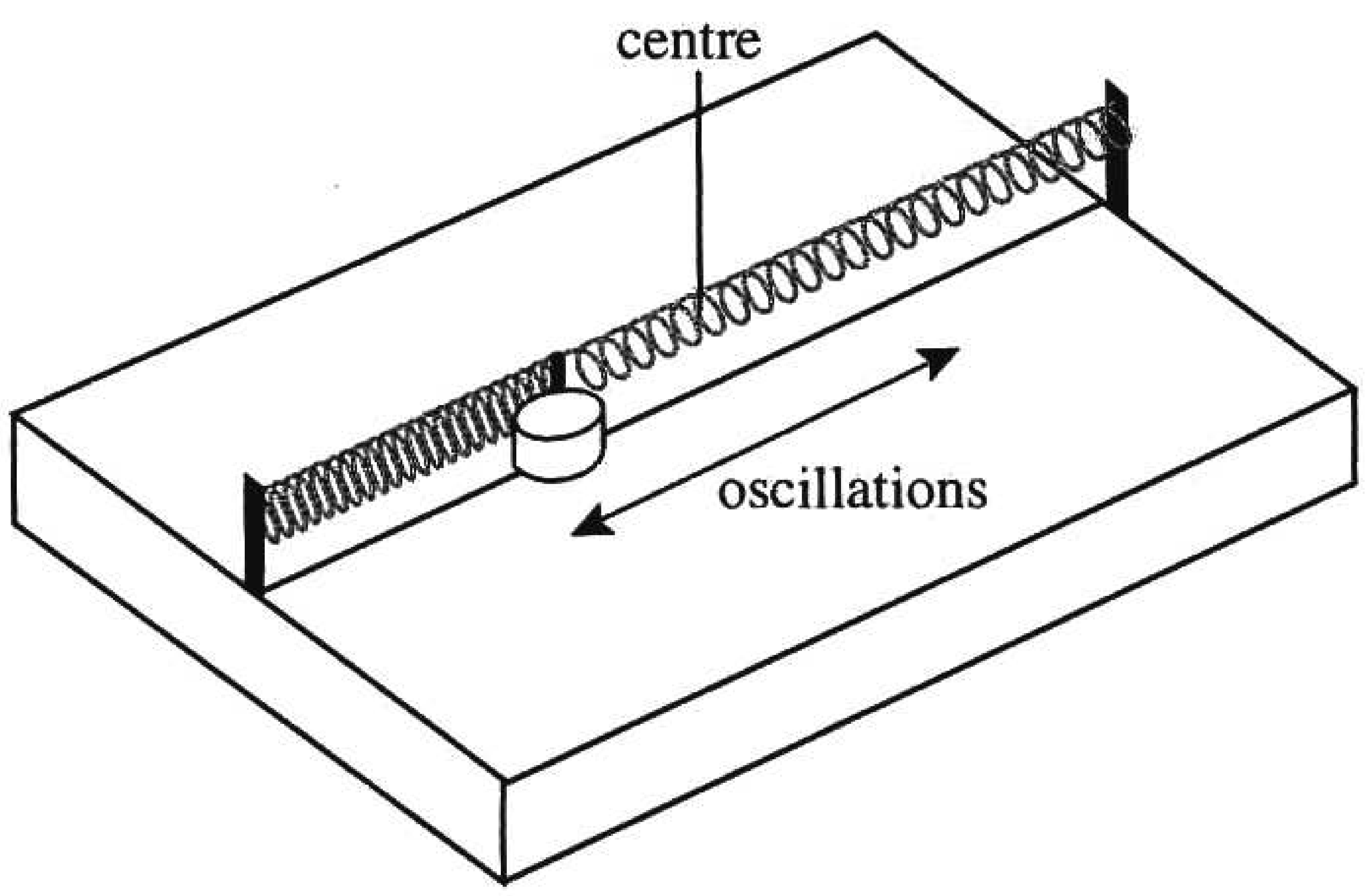

Fig. 5.2

The mass is then released. Show that it moves in simple harmonic motion. Find an expression for its frequency. [4]

(ii) The mass is brought to rest. It is drawn aside through a small distance, very much less than L, perpendicular to the original line of the springs, as shown in **Fig. 5.3**.

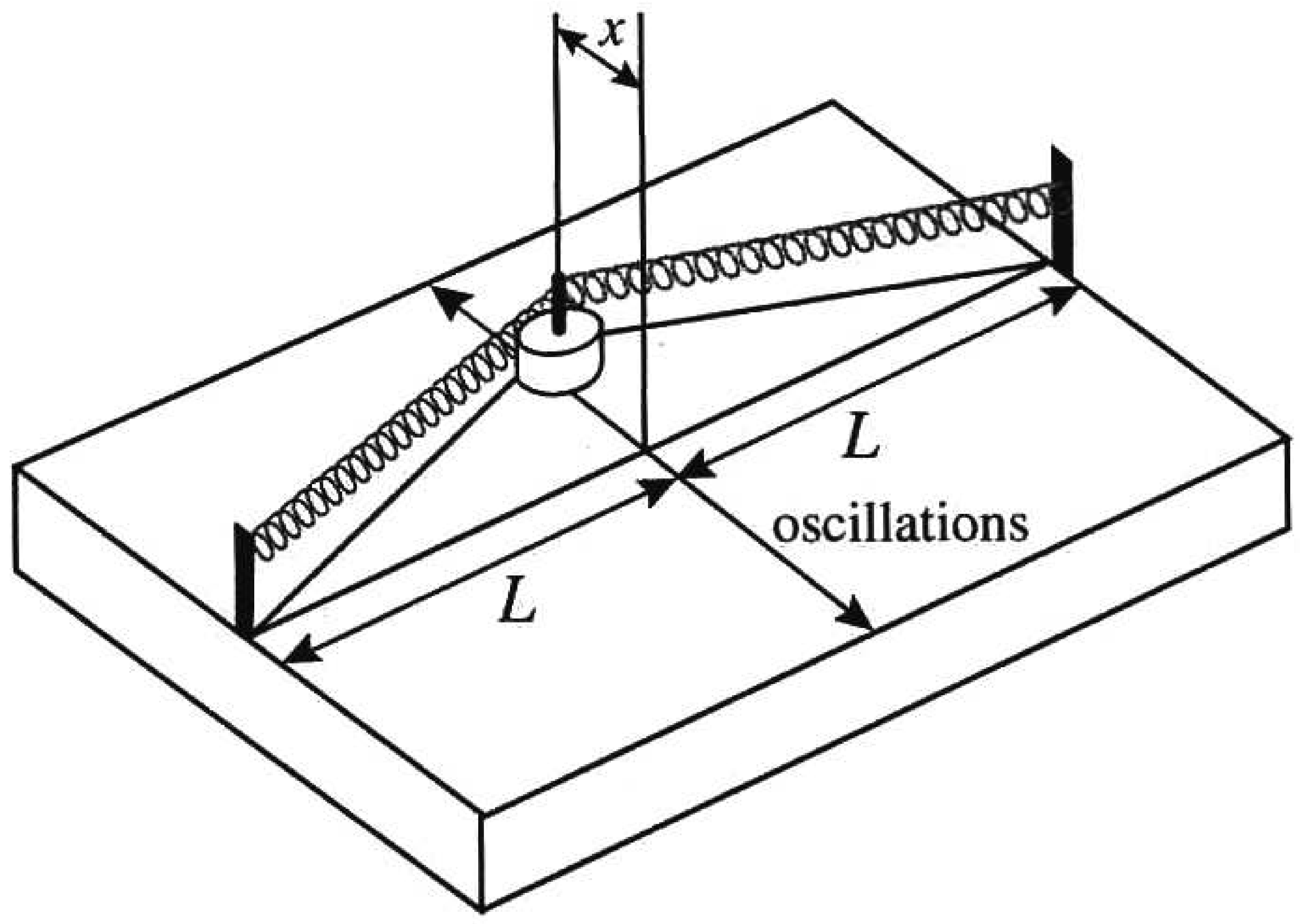

Fig. 5.3

The mass is then released so that it moves along the line perpendicular to the original axis of the springs.

1. Find the resultant force on the mass when the displacement from equilibrium is x. You will need to use the expansion $(1 + a)^n \approx 1 + na$, which applies for $a \ll 1$. [5]

2. What has the subsequent motion in common with that in **(i)**, and how does it differ? [2]

[Total: 13 marks]

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

(a) In ice each water molecule has four nearest neighbours. It takes about 3 MJ to convert 1 kg of ice into steam. The mass of a mole of water molecules, containing 6.0×10^{23} molecules, is 0.018 kg.

Estimate the energy required to break the bond between two water molecules in ice. [4]

(b) A tangled length of insulated copper wire has a mass of 0.2 kg. Its resistance is 5 Ω. Estimate, to the nearest order of magnitude, the length of the wire; i.e., is its length 1 m, 10 m, 100 m, . . . ? Ignore the mass of the insulation.

You will need to recall or estimate the values of relevant properties of copper. These estimates need to be only order-of-magnitude figures. [6]

[Total: 10 marks]

7 *You are advised to spend about 25 minutes on this question.*

Imagine that you are a scientific journalist for a national newspaper, specialising in physics-related stories.

For physicists, 2005 is a particularly important year. It marks exactly one hundred years since Einstein published his seminal research papers outlining, among other things, the quantum nature of electromagnetic radiation and mass-energy equivalence. You have persuaded your editor that the centenary should be marked by an article explaining, in an easily understandable way, these two facets of Einstein's work, and that you should be the person to write it.

Your readership will have only a limited knowledge of Physics and its language, and will be particularly interested in the importance of Einstein's work in the modern world.

Write the article you would like to publish.

Apart from the content of your answer, you will also be assessed on the quality of your written communication. [15]

[Total: 15 marks]