Rewarding Learning

Advanced Extension Award
2004

Physics

Advanced Extension Award

100/1544/9

THURSDAY 1 JULY, 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.

Attempt **all seven** questions.

1 You are advised to spend about 45 minutes on this question.

Read the passage and then answer the questions which follow.

The Hall Effect

(Freely adapted from *Solid State Physics*, by N. W. Ashcroft and N. D. Mermin)

In 1879 the American physicist Edwin Herbert Hall tried to determine whether the force experienced by a current-carrying metal wire in a magnetic field was exerted on the whole wire or only upon what we would now call the moving electrons in the wire. He suspected it was the latter, and his experiment was based on the argument that

> "If the current of electricity in a fixed conductor is itself attracted by a magnet, the current should be drawn to one side of the wire, and therefore the resistance experienced should be increased."

Hall's efforts to detect this extra resistance were unsuccessful, but he did not regard this as conclusive.

> "The magnet may *tend* to deflect the current without being able to do so. It is evident that in this case there would exist a state of stress in the conductor, the electricity pressing, as it were, toward one side of the wire."

This "state of stress" should appear as a transverse potential difference, known today as the Hall potential difference, which Hall was able to observe.

Hall's experiment is illustrated in **Fig. 1.1**.

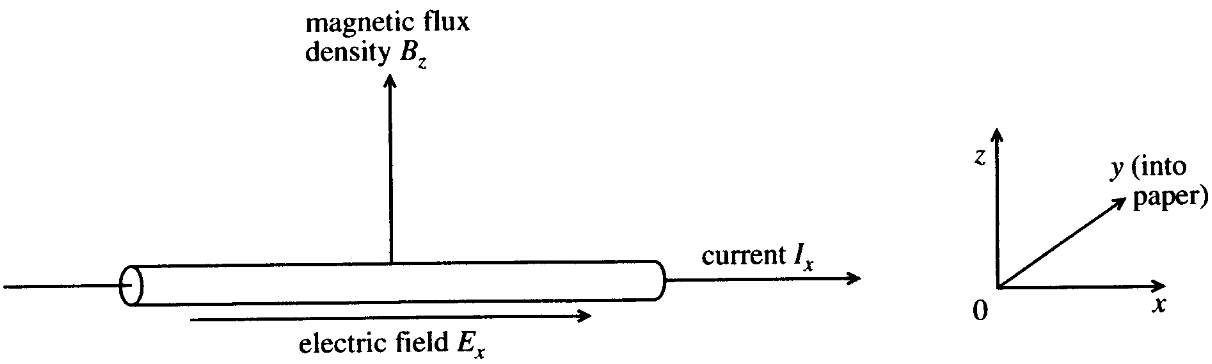

Fig. 1.1

An electric field E_x, applied to a wire extending in the x-direction, produces a current I_x in the wire. The average velocity of the electrons in this current is v_x. In addition, a magnetic field of flux density B_z is applied in the positive z-direction. As a result, an electromagnetic force of magnitude $B_z e v_x$ acts in a direction which is perpendicular to both the magnetic field and the electron velocity, and deflects electrons in the negative y-direction. This force is called the Lorentz force. However, the electrons cannot move very far in the negative y-direction before running up against the side of the wire. As they accumulate there, an electric field builds up in the y-direction that opposes their motion and their further accumulation. In equilibrium the force on the electrons due to this transverse field, called the Hall field E_y, will balance the Lorentz force.

The magnitude of the transverse field, the Hall field E_y, is an important quantity. Since the force on the electron due to the Hall field balances the Lorentz force, one might expect the Hall field to be proportional both to the applied magnetic flux density B_z and to the current I_x. For a wire of cross-sectional area A, one therefore defines a quantity called the *Hall coefficient* R_H by

$$R_H = \frac{E_y A}{I_x B_z}.$$

Answer the following questions

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

(i) state of stress (*lines 11, 13*),

(ii) transverse (*lines 13, 25, 27*),

(iii) electric field (*lines 16, 23*),

(iv) flux density (*lines 18, 29*),

(v) Lorentz force (*lines 21, 26, 28*),

(vi) proportional to (*line 29*). [6]

(b) **Fig. 1.2** shows an enlarged portion of the wire in **Fig. 1.1** using the same reference axes.

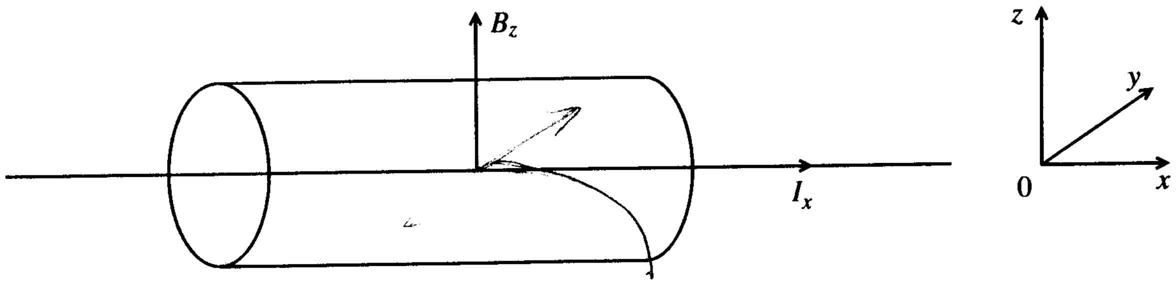

Fig. 1.2

(i) Copy **Fig. 1.2** in your answer booklet. The current I_x is initially in the positive x-direction. On your diagram, indicate the movement of an electron in the current in a region in which the uniform magnetic field of flux density B_z has been applied in the positive z-direction. [2]

(ii) With reference to your sketch in **(i)** and to the passage explain the origin of the Hall field in a current-carrying metal wire in a transverse magnetic field. [3]

(iii) After the Hall field has been established, how does the motion of the electron differ from your sketch in **(i)**? [1]

(c) **(i)** Making reference to information in the passage about the directions of fields and deflections, deduce the sign of the Hall coefficient (*lines 30–32*) for a metal. Assume that the charge carriers are free electrons. Explain your reasoning. [3]

(ii) **Table 1.1** gives values of the Hall coefficient R_H for six metals. Comment on these values.

Table 1.1

Metal	$R_H/\Omega\,m\,T^{-1}$
aluminium	+3.3
gold	−0.7
lithium	−1.3
magnesium	+2.5
silver	−0.8
sodium	−0.8

[2]

(d) It is easier to develop a simple quantitative theory of the Hall effect if one considers a strip of conductor instead of a cylindrical wire. **Fig. 1.3** shows such a strip, of rectangular cross-section, with dimensions a, b and c.

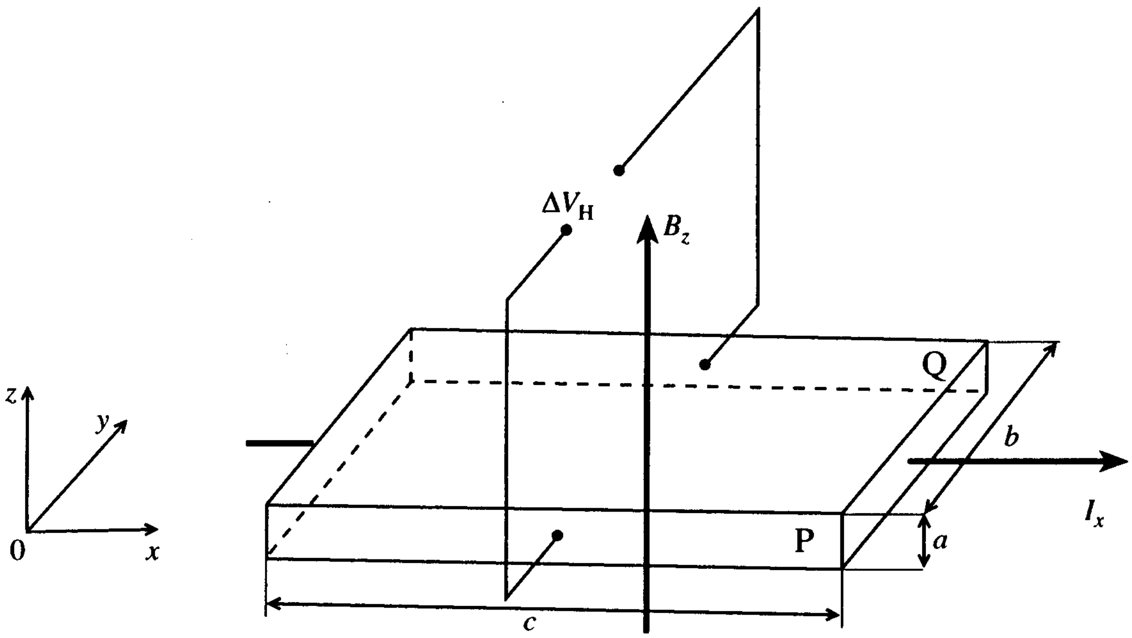

Fig. 1.3

The current I_x is in the positive x-direction, parallel to the long side of the strip. The uniform magnetic field of flux density B_z is applied in the positive z-direction, parallel to the side of length a. The Hall field E_y appears in the y-direction, parallel to the side of length b. The Hall field can be detected by the Hall potential difference ΔV_H between the sides P and Q of the strip.

The relation between I_x and the magnitude v_x of the average velocity of the charge carriers in the current is

$$I_x = nAv_xe,$$

where n is the number density of charge carriers in the conductor, A is the cross-sectional area of the strip and e is the elementary charge.

It is possible to determine the value of the number density n of charge carriers in a given conductor from information gained in a Hall effect experiment. Derive an equation linking n with measurable quantities shown in **Fig. 1.3**. [4]

(e) In talking about the Hall effect with friends, you find that several of them are puzzled by the explanation given in the passage (*lines 16–26*). They argue that because the force on the electrons caused by the Hall field is exactly counteracted by the Lorentz force, the case is a classic example of Newton's Third Law, which they state as "action and reaction are equal and opposite". They say

(1) that one of these forces, the Lorentz force, is the action, and the force caused by the Hall field is the reaction;

(2) there should be no force on the wire because of the equal and opposite forces on the electrons;

(3) it is an experimental fact that a current-carrying conductor in a magnetic field experiences a force.

(i) Give a full statement of the Third Law. [1]

(ii) Point out the error in **(1)**. [1]

(iii) Resolve the apparent contradiction between **(2)** and **(3)**. [2]

[Total: 25 marks]

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

Most Western Governments are looking seriously at renewable fuel sources for future power generation, because fossil fuel reserves are limited and carbon-based gas emissions are associated with global warming. Harnessing energy from the wind is an important possibility.

Consider a wind turbine with blades of length L.

(a) Show that the maximum power P_{max} that can be obtained from the turbine is given by

$$P_{max} = \frac{1}{2}\pi L^2 \rho v^3,$$

where ρ is the density of air and v is the wind speed. State any assumption made. [4]

(b) Find the maximum power that could be generated in a wind speed of 20 m s^{-1} by a turbine with blades of length 13 m. [2]

[Density of air = 1.2 kg m^{-3}.]

(c) Find the number of turbines considered in **(a)** that would be needed to replace a conventional fossil-fuel power station producing 100 MW when the wind speed is 10 m s^{-1}. [2]

(d) Sketch a graph to show how the maximum power P_{max} that can be obtained from a turbine depends on the speed v of the wind. Us your graph to explain why the number of turbines required when the wind speed is 20 m s^{-1} is much less than half your answer to **(c)**. [3]

[Total: 11 marks]

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

(a) The resistivity ρ of the simplest type of semiconductor varies with kelvin temperature T according to the equation

$$\frac{1}{\rho} = B\,e^{-(C/T)},$$ **Equation 3.1**

where B and C are constants for a given semiconductor.

Equation 3.1 may be investigated experimentally by taking measurements of the resistance R of a sample of the semiconductor at a number of temperatures T, and plotting a suitable linear graph. The constants B and C may be obtained from this graph.

(i) Write down the equation relating resistance R and resistivity ρ. Identify any other quantities in this equation. [1]

(ii) Give the units of B and C. [2]

(iii) Using your answer to **(i)**, rewrite **Equation 3.1** in terms of R instead of ρ. [1]

(b) In an experiment, the following readings of the resistance R of a sample of a semiconductor were obtained at a sequence of temperatures T.

Table 3.1

T/K	833	800	769	714	625	500	455	400
R/mΩ	11.8	18.3	30.2	62.1	119	169	192	232

(1 mΩ = 1 milliohm)

(i) It is required to plot a linear graph to test whether the results in **Table 3.1** follow the relation expressed by your equation in **(a)(iii)**. State the axes of the graph you would plot. [1]

(ii) State how the value of C would be obtained from the graph in **(i)**. [1]

(iii) Process the readings in **Table 3.1** in preparation for plotting the graph indicated in your answer to **(i)**. Display the processed data in a suitable table. [3]

(iv) On graph paper, plot the points corresponding to the processed data from **(iii)**. Draw a graph through the points. This graph should show two approximately linear regions, joined by a curve, instead of the expected straight line. [4]

(v) From your graph, find the gradient of the linear region which corresponds to **lower** values of temperature. [3]

(vi) Suggest what may be happening to produce the shape of graph obtained in **(iv)**. Explain what features of the graph lead you to this suggestion. [3]

[Total: 19 marks]

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

This question is about the use of analogies to describe and explain phenomena in different areas of physics.

In logic, analogy is the process of arguing from parallel cases. Analogies are also used in physics, but the parallelism between the cases may not be exact.

(a) A physical analogy that is often used is the parallelism between the application of the inverse square law to electrostatics and to gravitation. It is particularly useful in comparing a simple model of the hydrogen atom with planetary motion. In the model, the electron is supposed to undergo circular motion about the proton. The centripetal force is provided by the electrostatic force between electron and proton. The momentum p_e of the electron in an orbit of radius r is

$$p_e = e\sqrt{\frac{m_e}{4\pi\varepsilon_0 r}}; \text{ alternatively, } p_e = e\sqrt{\frac{km_e}{r}},$$

where e is the elementary charge, m_e is the mass of the electron and ε_0 is the permittivity of free space; k is the Coulomb law constant. (You are **not** asked to derive this relation.) If the radius of the orbit is chosen so that its circumference is equal to one de Broglie wavelength of the electron, the radius turns out to be 5.3×10^{-11} m. This value is a realistic figure for the radius of a hydrogen atom.

(i) Derive the analogous expression for the momentum p_E of the Earth in its orbit about the Sun. Give your answer in terms of the mass M_E of the Earth, the radius r of its orbit, the mass M_S of the Sun, and the gravitational constant G. [3]

(ii) Determine whether it is realistic to follow the electrostatics/gravitation analogy so far as to state that the circumference of the orbit of the Earth is equal to one de Broglie wavelength of the Earth. [4]

[Reminder: the de Broglie wavelength λ of a particle moving with momentum p is given by $\lambda = h/p$, where h is the Planck constant.
Mass of Earth, $M_E = 5.98 \times 10^{24}$ kg;
mass of Sun, $M_S = 1.99 \times 10^{30}$ kg;
radius of Earth's orbit, $r = 1.49 \times 10^{11}$ m.]

(b) Describe two other aspects of physics that show some parallelism. You should identify the systems, compare any relevant equations if appropriate, and discuss the extent of the parallelism. [6]

[Total: 13 marks]

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

Two loudspeakers S_1 and S_2, which act as point sources, are connected to the same signal generator so that the sound waves emitted by them are in phase. The loudspeakers are 0.80 m apart. A sensitive, calibrated sound detector M is placed as shown in **Fig. 5.1**. If **Fig. 5.1** were drawn to scale, S_1M would be very nearly parallel to S_2M.

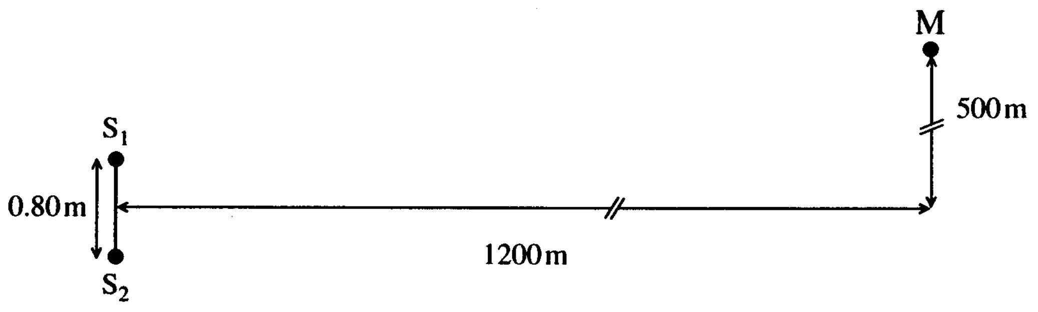

Fig. 5.1 (not to scale)

A student uses this apparatus to carry out an experiment to measure the speed of sound.

(a) First, the student increases the frequency of the signal generator from zero by turning the control by hand, in small increments. After each increment the student pauses at that frequency and notes the detector reading. The student plots a graph of detector reading against frequency, and finds that the reading first falls to a minimum when the frequency of the generator is 560 Hz.

By calculating the path difference between S_1M and S_2M, deduce the speed of sound in air. [5]

(b) The student plans to speed up the experiment by introducing automation. The student connects the frequency control of the generator to a motor which changes the frequency f at a constant rate with time t, starting with $f = 0$ at $t = 0$. The student records the time T at which the detector reading first falls to a minimum.

Formulate an equation which shows that this procedure leads to **two** possible values of the speed of sound. **Do not solve this equation.** [5]

[Hint: note that the sound waves take a measurable time to travel from the speakers to the detector. Thus, if the waves are out of phase at the detector at time T, they were out of phase at the speakers somewhat before T.

Note also that an equation of the form $ax^2 + bx + c = 0$ has two solutions for x.]

[Total: 10 marks]

6 You are advised to spend about 10 minutes on this question.

In this question you will need to recall the value of a commonly-used physical constant and to estimate values of other quantities. Credit will be given for making reasonable estimates.

Obtain an estimate of the mass of water that could be brought to the boil from room temperature if it were possible to apply all the energy dissipated when a car is brought to rest from a speed of 50 miles per hour. Quote your answer to an appropriate number of significant figures. [7]

[Total: 7 marks]

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

Put yourself in the following scenario.

> Your best friend is studying Classics, and often teases you about how physicists cannot do without his subject, pointing out that all the most important theories and particles have Latin or Greek names. One day he says:
>
> "What is this How-Much Theory? And why are amber particles so important to physicists?"
>
> You are at first puzzled, but soon realise that he is only making his point about the names of Physics theories and particles. By looking in a Latin dictionary you find that the word for "how much" is *quantum*. A Greek dictionary gives ηλεκτρον as the word for "amber". When you change the Greek letters to their English equivalents, you get *electron*.
>
> You decide not to be put down by a classicist, even if he is your friend.

Write a reply to your friend, explaining to him why his so-called How-Much Theory is important. Also explain why the particles which he calls amber pervade both Physics and everyday life. You may assume some scientific knowledge; your friend did well in Physics at GCSE, but has not studied it since.

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

[Total: 15 marks]