FORCES AND PARTICLES

**A Title in the Nature–Macmillan
Physics Series**

FORCES and PARTICLES

An Outline of the Principles of Classical Physics

A. B. Pippard, Sc.D., F.R.S.

*Cavendish Professor of Physics and President
of Clare Hall in the University of Cambridge*

Macmillan Education

© A. B. Pippard 1972

Softcover reprint of the hardcover 1st edition 1972 978-0-333-10681-5

All rights reserved. No part of this
publication may be reproduced or
transmitted in any form, or by any
means, without permission.

First Published 1972

THE MACMILLAN PRESS LTD
London and Basingstoke
Associated companies in New York
Toronto Melbourne Dublin
Johannesburg and Madras

ISBN 978-1-349-81597-5

ISBN 978-1-349-81595-1 (eBook)

DOI 10.1007/978-1-349-81595-1

Preface

This book is an expanded version of a lecture course given for several years to first-year Cambridge undergraduates reading physics as one of three experimental sciences for the Natural Sciences Tripos, Part 1A. For reasons of space the course had to be duplicated, with two lecturers covering the same material, though at different levels of difficulty. It was my task to lecture to those who wanted the more searching treatment; surveys afterwards showed a substantial fraction to be sympathetic, though there were always those who found the approach pointlessly unconventional. Recognizing the impossibility of pleasing everyone, I have now addressed myself, as I did when giving the course, to the more adventurous who are prepared to work out for themselves congenial patterns of thought that will make sense of what can so easily remain a disorderly assembly of observations and ideas.

Every practising physicist develops his own favourite modes of thought, and no one can, or should wish to, pass on to others all the details of his private system. Indeed, the more original his mode, the harder it is to transmit. Nothing in this book, however, is original; in so far as I reveal my own ways of thinking about physics, it is my hope that they will seem perfectly ordinary—for this offers the best chance that they will prove acceptable to others and will play some part in leading other imaginations into paths where genuine intellectual satisfaction is to be found.

A.B.P.

Contents

Note: Certain rather advanced sections of the discussion are distinguished by square brackets [].

	<i>Page</i>
1 Introduction	3
A brief exposition of the purpose and plan of the book; what background knowledge is assumed.	
2 Kinematics	9
Vectors and their time-derivatives; complex number representation of vectors; tangential and radial components of acceleration; rotating coordinate frames; Coriolis and centrifugal accelerations in complex and vector representations.	
3 Newton's laws of motion	20
Laboratory experiments to clarify definitions of force and mass; centroid; examples of third law; linear and angular momentum; apparent violations of momentum conservation. Relative motion and Galilean transformation; Coriolis and centrifugal forces; Foucault's pendulum [including analysis of an imperfect pendulum]; bathtub vortex; atmospheric motion. Work and energy; conservative forces; grad; basic theorems in the kinetic theory of matter.	
4 · The inverse-square laws (Newton, Michell, Coulomb)	47
Relative magnitudes of Coulomb and gravitational forces between fundamental particles; potential; Gauss' theorem; field lines; attraction of spheres; polarization of sphere; 'Cavendish' experiment; 'Eötvös' experiment.	

5 Dynamics of particles

60

Central orbits; general equation derived; numerical solution; algebraic laws of force, especially inverse-square; [simple pendulum with finite amplitude]; centrifugal potential; elliptical inverse-square orbits; Kepler's laws; planetary test of inverse-square law; hyperbolic inverse-square orbits; Rutherford scattering; Bohr atom; [adiabatic invariants and quantization; W.K.B. method]; tunnel effect and uncertainty principle as examples of the limitations of classical mechanics; tides.

6 Analysis of complex dynamical systems

86

General principles and examples (collision of spheres; centre of mass coordinates; chain falling on table; effect of atmospheric friction on a satellite; tidal friction and the Moon; dissection of a complex system). Continuous systems; wave on a string; the wave equation; internal stresses (tension, shearing stress, bending moment, stresses in membrane and solid); loaded membrane; Laplace's equation; soap film; [non-viscous fluid (compressional wave, Bernoulli's theorem)]. Dynamics of a rigid body; basic equations; statics; inertia tensor; two-dimensional problems (rolling cylinder, centre of percussion); gyroscope; precession of the equinoxes; [nutation; stability of extremal axes of inertia].

7 Units and dimensions

122

Attaching numbers to observations; measuring and ordering; the meaning of an algebraic equation; units and definition of dimensions; how many basic units? Dimensional analysis; physical laws and rules of thumb; velocity of waves; flow of fluid in a pipe; incomplete dimensional analysis illustrated by ship models and the critical point of He^3 .

8 The electrostatic field: charges and conductors in free space

145

Field of charge, dipole, quadrupole; synthesis of field patterns (charged spherical conductor, charge near earthed plane, charge in conducting wedge, conducting sphere in uniform field, charged pear-shaped conductor); concentration of field at a point; field-ion microscope; Poisson's and Laplace's equations; irrotational and rotational fields; curl; use of analogues. Capacitance, mutual and self; capacity coefficients and conventional circuit representation of capacitance; reciprocity; energy in a Coulomb field; different expressions; illustration of techniques available for simple problems. The voltaic cell; electrons in a metal; contact potential; potential distribution in a voltaic cell; comparison of energy in cell with other forms of storage; force on a conductor.

9 Dielectric materials

178

Atomic structure of molecule; dipole moment and polarizability; magnitude according to Bohr model; internal field correction; susceptibility and permittivity. Effect of fluid dielectric on capacitance and force between conductors; [pressure variations in a dielectric]; parallel plate capacitor with different arrangements of dielectric. Macroscopic field

equations and boundary conditions; dielectric sphere and ellipsoid in uniform field; depolarizing coefficient; cavity definitions of fields.

10 Magnetic fields due to currents 196

General description of phenomena, leading to plausible argument for Ampère's laws; magnetic shell; unit pole and μ_0 defined; law of Biot and Savart; field of finite solenoid. Distributed currents. Force on a current; validity of Newton's third law; attraction of current-carrying wires and coils. Current balance. Homopolar motor.

11 Charged particles in electric and magnetic fields 223

Lorentz force; electron gun; cathode-ray tube; e/m and the properties of the electron; helical path in uniform magnetic field; cyclotron frequency; oscillatory phenomena in metals (magnetoacoustic oscillations, Azbel-Kaner resonance). Spatially varying magnetic field (plasma containment, Van Allen belts); [flux as an adiabatic invariant; orbit quantization; de Haas-van Alphen effect]. Larmor's theorem; diamagnetism. Crossed electric and magnetic fields; Hall effect and magnetoresistance.

12 Electromagnetic induction 242

Galilean transformation of electric and magnetic fields; induction related to Lorentz force; moving circuits and magnets; sliding contacts; homopolar generator. Self and mutual inductance; reciprocity of mutual inductance. Electrical circuits; Kirchhoff's laws extended to inductive circuits; RC , LR and LCR circuits; use of complex algebra and vector diagram. Eddy currents and skin effect; [sphere rotating in transverse magnetic field]. Energy and forces in a magnetic field; $M^2 \leq L_1 L_2$.

13 Magnetic materials 272

Atomic diamagnetism, its origin and magnitude; susceptibility and permeability; B , H and M ; paramagnetism. Effect of magnetic fluid on forces between poles and currents. Spin of electron; ferromagnetism; domains; effect of magnetizable core on inductance; gaps in magnetic circuits; transformers.

14 Maxwell's displacement hypothesis and electromagnetic waves 286

Magnetic field produced by moving charge and changing electric field; the displacement current; the sodium doublet; the electromagnetic wave in free space as a self-sustaining field system; analytical derivation of wave equation; transmission lines; determination of $\mu_0 \epsilon_0$ (Rosa and Dorsey); Lorenz disc; Maxwell bridge. Examples of electromagnetic waves, from whistlers to γ -rays. An inconsistency in Galilean transformations; light does not obey the vector law of composition of velocities; Essen's form of the Michelson-Morley experiment; Relativity—a brief survey of its salient features.

Appendix Vector formulae 313

Index 317

Acknowledgements

The author acknowledges with thanks the courtesy of all who have kindly given permission for the reproduction of the following illustrations.

	<i>Page</i>
Weather Map, 16 Oct. 1970. Reproduced with the permission of the controller of Her Majesty's Stationery Office and <i>The Times</i>	41
Figure from Roll, Krotkov and Dicke, <i>Ann. Phys.</i> 26 (1964), p. 442. By kind permission of the author and editor. © Academic Press.	58
Figure 2.7.2 from Batchelor, <i>Introduction to Fluid Dynamics</i> , C.U.P., p. 106. By kind permission of the publishers.	101
Figure from Lamb, <i>Hydrodynamics</i> , C.U.P., p. 228. By kind permission of the publishers.	(upper figure) 106
Figure 125 from Prandtl, <i>Fluid Dynamics</i> , Vieweg, p. 149. By kind permission of the publishers.	141
Figure 18 from Jeans, <i>Electricity and Magnetism</i> , C.U.P., p. 51. By kind permission of the publishers.	(lower figure) 146
Figure 17 from Jeans, <i>Electricity and Magnetism</i> , C.U.P., p. 50. By kind permission of the publishers.	(left-hand figure) 151
Figure 64 from Jeans, <i>Electricity and Magnetism</i> , C.U.P., p. 193. By kind permission of the publishers.	(upper figure) 152

Figure 14 from Gomer, *Field Emission and Field Ionization*, Harvard, p. 33. By kind permission of the publishers. 153

Figure 3 from *The Fermi Surface* (ed. Harrison and Webb), Wiley, p. 149. By kind permission of the publishers. (lower figure) 231

Figure from *The Physics of Metals* (ed. Ziman), C.U.P., p. 65. By kind permission of the publishers. 236

The publishers have made every effort to clear and acknowledge all copyright material. They trust that anyone whose copyright has been infringed will accept sincere apologies.

‘Descartes put forward his conjectures as verities, almost as if they could be proved by his affirming them on oath. He ought to have presented his system of physics as an attempt to show what might be anticipated as probable in this science, when no principles but those of mechanics were admitted: this would indeed have been praiseworthy; but he went further, and claimed to have revealed the precise truth, thereby greatly impeding the discovery of genuine knowledge.’

CHRISTIAAN HUYGENS (1629–1695)