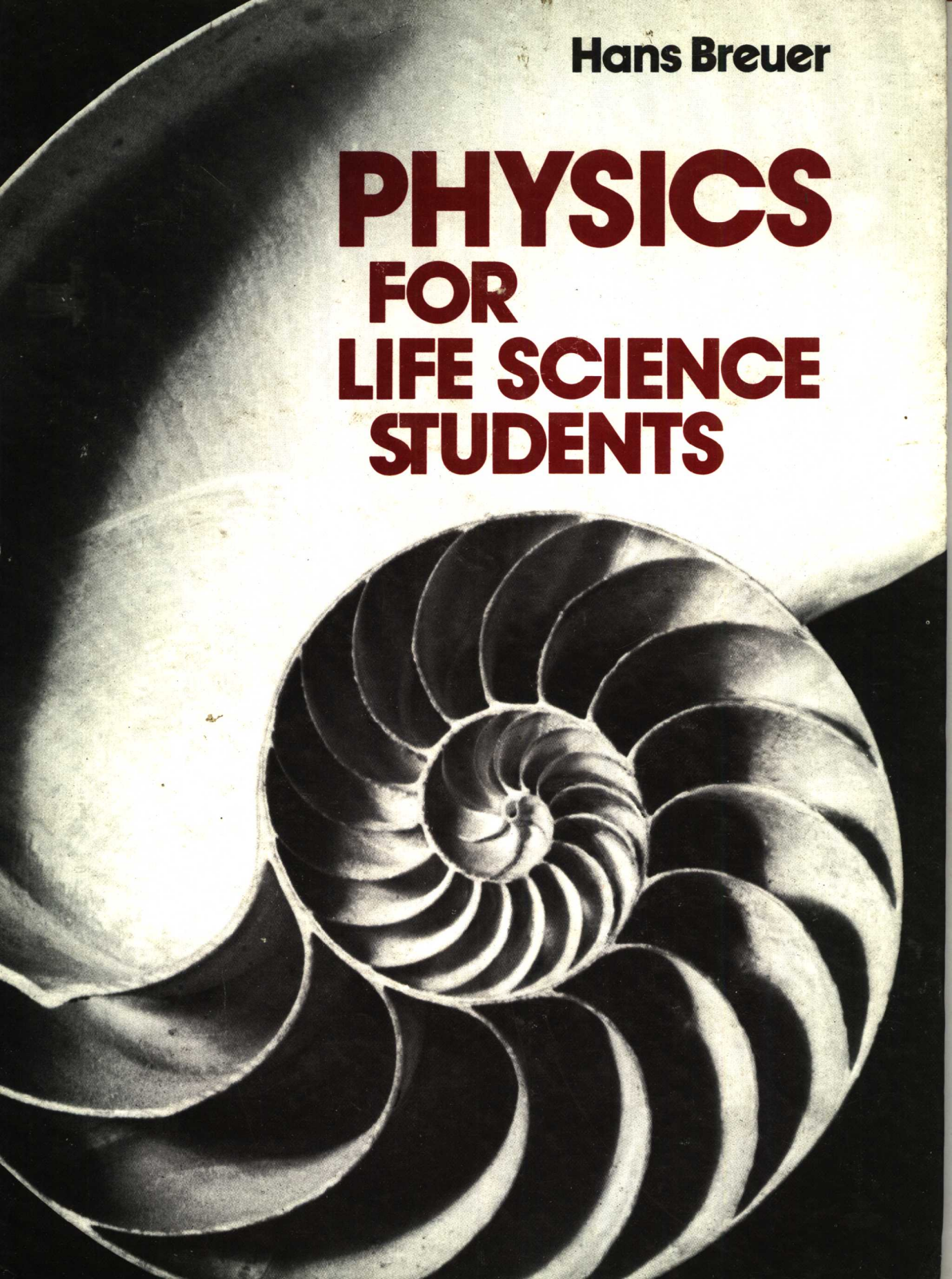


Hans Breuer

**PHYSICS
FOR
LIFE SCIENCE
STUDENTS**



PHYSICS FOR LIFE SCIENCE STUDENTS

HANS BREUER

PRENTICE-HALL, INC. / Englewood Cliffs, N.J.

Library of Congress Cataloging in Publication Data

Breuer, Hans, date
Physics for life science students.

Includes bibliographies.

1. Physics. I. Title.

QC23.B817 530 74-18388

ISBN 0-13-674150-9

© 1975 by PRENTICE-HALL, INC., Englewood Cliffs, N.J.

All rights reserved. No part of this book
may be reproduced in any form or by any means
without permission in writing from the publisher.

10 9 8 7 6 5 4 3 2 1

Printed in the United States of America

Prentice-Hall International, Inc., *London*
Prentice-Hall of Australia, Pty. Ltd., *Sydney*
Prentice-Hall of Canada, Ltd., *Toronto*
Prentice-Hall of India Private Limited, *New Delhi*
Prentice-Hall of Japan, Inc., *Tokyo*

ACKNOWLEDGMENTS

Among those who contributed directly or indirectly to this text, I am especially indebted to my teachers P. Brix, W. Pohlit, and B. Rajewsky. The suggestions and support of William H. Grimshaw and Nicholas Romanelli of Prentice-Hall were invaluable. The close cooperation with J. Warren Blaker of Vassar College is appreciated as are the comments of Arthur Walters. I also remember with pleasure the long discussions with my friends and colleagues John Rawlins and William Hallidy. And, for their stimulating influence, I thank my students.

Appreciation is also expressed to the following publishers for permission to reproduce illustrations: Fig. 1-19, D'Arcy W. Thompson, *On Growth and Form*, Macmillan Publishing Co., Inc., New York; Fig. 2-11, *Nature*, vol. 229, Feb. 1971, Macmillan Journals Ltd., London; Fig. 4-13, Theodore von Karman, *Aerodynamics*, Cornell University Press, Ithaca, N.Y.; Fig. 9-39, Picker Corporation, North Haven, Conn.; Fig. 14-21, Diane M. Ramsey, ed., *Image Processing in Biological Science*, University of California Press, Berkeley, Ca.; Fig. 14-22, Rheinisches Landesmuseum, Bonn, West Germany.

TO THE STUDENT

Teaching physics to life science students is a difficult and challenging undertaking. If the physics becomes too abstract or too far removed from topics in biology and medicine, the student may lose interest. On the other hand, if the physics becomes so diluted that its clarity and overall consistency are submerged, then the intellectual rigor has been removed but the book does not fill the student's needs. The organization of this book has been dictated by the objective of avoiding both of these extremes. A careful determination of the relative importance of the various branches of physics for life science students was required. As a result some topics are treated only briefly while others are more detailed, this book being an introduction to physics and not to the life sciences.

You may wonder how much mathematics is used and whether it is necessary to know calculus. From my experience working with students of biology, medicine, and physics in Germany, Canada, and the United States, I know that it is not so much the calculus but the algebra that causes mathematical difficulties for the student. Therefore I have shown, in general, every intermediate step in calculations and derivations. You do not need to know calculus when you first open this book. You are introduced to elementary differential and integral calculus "as we go." This is surely simpler for you than surrounding formulas and phenomena with excessive wordiness and confusing analogies when a single line of calculus suffices. The same approach applies to vector notation when introduced. The use of graphical representation also helps to clarify topics—a method that is indispensable to the modern scientist.

Although the use of mathematics underlines and emphasizes the exactness and internal consistency of physics, do remember that the laws of physics are not necessarily the ultimate truth. They are only approximations, even where applied to pure physics. You must, therefore, take a critical stance: "What is the scope of that law?" "Are the basic assumptions fulfilled for these specific applications?" "What limits the accuracy of this particular formula?" Those are some of the questions you should ask yourself constantly. In this text I have stressed such limitations where they are not obvious.

In the life sciences we must be aware of the pitfalls of straightforward application of physical principles. The simplest biological systems have more parameters than the most complex ones in physics. There are also aspects intrinsic to living systems that elude the purely physical approach. For example, one obvious way to calculate a mutation rate is to estimate the radiation damage done by ever-present cosmic radiation to the carriers of genetic information, DNA. Knowing the structure of those double-helix molecules and the flux of cosmic radiation, we could then predict the rate of evolution. The calculation is simple enough, but it leads to an incorrect result. Why? Because there is a biological factor that has been overlooked: whenever one of the identical strands of the double helix is broken by radiation, a mechanism is triggered to repair the damaged strand by using information available from another strand.

Keeping such limitations in mind, you can then use physics as a means of gaining insight into life science phenomena; e.g., why man can see better than the anatomical structure of the retina seems to allow. You can observe conservation principles at work and may even enjoy understanding odd questions such as what an electron, waterbug, and supersonic aircraft have in common.

Some organizational aspects of this book: I have not pretended that you are completely ignorant of physics when you turn to the first page. We all live in a technical world that is largely governed by physical laws, and you are certainly aware of some of them. Besides, you had some introduction to science in high school, some rudimentary knowledge that remains. Therefore, I have used similarities and analogies with material that is covered in detail later in the book; of course, that has to be very basic material.

Throughout the book, the metric convention is used. If space-age organizations like NASA and conservative countries like England "go metric," we should not pretend that inch, pound, slug, and fortnight are still up-to-date units of measurement. However, conversions are given for metric versus nonmetric units. The general style and notation follows the *Style Manual* of the American Institute of Physics and the *Council of Biology Editors Style Manual*.

If you study the table of contents you will find the topics usually covered in an introductory physics text. However, the emphasis is different. Some subjects such as point mechanics, rigid bodies, thermodynamics, magnetostatics, and electrostatics are treated rather briefly. More space and time is devoted to topics that are pertinent for the student of life sciences: deformable media, phases of matter, transport phenomena, and radiation. You will also encounter chapters on unconventional topics such as graphical representation and information handling and processing. Most chapters include a flow chart to serve as a guidepost so that you are always aware of the general structure of the chapter and the interrelationship of topics, even when working at a

seemingly small detail. The additional reading material cited at the end of each chapter will serve to give you further insight or more detailed explanations of special features of the chapters. Do not overlook the appendices: part A should be especially useful to you.

It is my hope that you will discover, once having finished this book, that physics is not by nature dry and indigestible to a student of the life sciences.

HANS BREUER

Dakar, Africa

CONTENTS

Chapter 1	GRAPHICAL REPRESENTATION	1
1.	Coordinate graphs	
1.1	Terminology	2
1.2	Two-dimensional graphs	3
1.2(a)	Linear graphs	4
1.2(b)	Semilogarithmic graphs	6
1.2(c)	Double-logarithmic graphs	9
1.2(d)	Polar graphs	10
1.2(e)	Probability graphs	12
1.2(f)	Other graphs	13
1.3	Three-dimensional graphs	14
1.4	Interpolation and extrapolation	14
1.5	D'Arcy Thompson principle	15
2.	Vectors	16
2.1	Terminology	17
2.2	Addition and subtraction	17
2.3	Resolution into components	20
2.4	Vector multiplication	21
2.4(a)	Multiplication by a scalar	21
2.4(b)	Scalar product	21
2.4(c)	Vector product	21
3.	Flow charts	22
	Summary	25
	Problems	25
	Further Reading	27
Chapter 2	TIME AND LENGTH MEASUREMENTS	28
1.	Measurements and their evaluation	28
1.1	Terminology	28
1.2	Errors	30
1.2(a)	Error sources	30
1.2(b)	Agreement within error limits	33
1.2(c)	Significant figures	33
1.3	Error calculation	33
1.3(a)	Addition and/or subtraction	34
1.3(b)	Multiplication and/or division	34
1.3(c)	Exponentiation	35

1.4 Powers of ten	35
1.5 Natural and man-made units	37
2. Time measurements	37
2.1 Definition	38
2.2 Various clocks	38
2.2(a) Biological clocks	38
2.2(b) Radioactive clocks	40
2.2(c) Magnetic clocks	41
3. Length measurements	41
3.1 Definition	41
3.2 Length of arc	43
3.3 Area and volume measurements	43
3.4 Signal travel time	45
Summary	46
Problems	47
Further Reading	48
Chapter 3 MOTION AND FORCES	49
1. Motion	50
1.1 Translatory motion	50
1.1(a) Velocity and Speed	50
1.1(b) Acceleration	52
1.2 Rotational motion	55
1.2(a) Velocity and acceleration	56
1.2(b) Angular acceleration detector in man	57
1.3 Irregular motion	59
2. Force	59
2.1 Newton's first and second laws	59
2.2 Mass	61
2.3 Force	62
2.4 Torque	63
2.5 Center of mass	65
2.6 Mechanical equilibrium	66
3. Various forces	68
3.1 Gravitational forces	68
3.1(a) Weight	68
3.1(b) Gravity detectors in organism	69
3.2 Buoyancy forces	70
3.2(a) Density	70
3.2(b) Density of water	70
3.2(c) Floating	72
3.3 Elastic forces	73
3.3(a) Hooke's law	73
3.3(b) Stress, strain and elasticity	74
3.3(c) Fatigue	77
3.3(d) Fine structure of bones	77
3.4 Frictional forces	78
3.4(a) External friction	78
3.4(b) Internal friction	80
3.4(c) Terminal (or sedimentation) speed	81
4. Applications	82
4.1 Weightlessness	82
4.2 Pressure	83

Summary	85
Problems	85
Further Reading	86
Chapter 4	CONSERVATION LAWS IN MECHANICS
	87
1. Work	87
2. Energy	90
2.1 Kinetic energy	91
2.2 Potential energy	92
2.3 Conservation of mechanical energy	94
3. Momentum	96
3.1 Definition	96
3.2 Momentum conservation	96
4. Efficiency	99
5. Power	101
5.1 Definition	101
5.2 Specific power	103
Summary	103
Problems	106
Further Reading	109
Chapter 5	DEFORMABLE MEDIA
	110
1. Statics	110
1.1 Internal forces	111
1.1(a) Surface tension	111
1.1(b) Contact angle	113
1.1(c) Capillarity	114
1.2 External forces	115
1.2(a) Static pressure	116
1.2(b) Pressure-volume relations	117
2. Dynamics	120
2.1 Streamlines	120
2.2 Ideal fluids	121
2.1(a) Equation of continuity	122
2.2(b) Bernoulli's theorem	123
2.3 Real fluids	124
2.3(a) Laminar flow	124
2.3(b) Turbulent flow	126
2.3(c) Transitions between laminar and turbulent flow	127
3. Applications	127
3.1 Hemodynamics	129
3.2 Lift and propulsion	130
3.3 Flight of birds	131
3.4 Magnus effect	132
Summary	133
Problems	134
Further Reading	135
Chapter 6	TEMPERATURE, HEAT AND THERMAL ENERGY TRANSFER
	136
1. Temperature	136
1.1 Temperature and thermometric scales	136

1.1(a) Customary temperature scales	136
1.1(b) Thermodynamic (or absolute) temperature scale	138
1.2 Temperature-dependent properties	139
1.2(a) Thermal expansion of matter	141
1.3 Thermometer	144
1.3(a) A biological temperature receptor	145
1.3(b) Paleotemperatures	145
2. Heat and associated quantities	146
2.1 Quantities	146
2.1(a) Heat	146
2.1(b) Specific heat capacity	146
2.1(c) Molar specific heat capacity	147
2.1(d) Latent heat	148
2.1(e) Heat capacity	148
2.2 Calorimetry	149
2.2(a) General	149
2.2(b) Food calories	151
2.3 Heat production	152
2.4 Heat pollution	152
2.4(a) Water	152
2.4(b) Fever	154
3. Thermal energy transfer	155
3.1 Temperature gradient	155
3.2 Temperature rate	156
3.3 Means of thermal energy transfer	157
3.3(a) Thermal conduction	157
3.3(b) Thermal convection	159
3.3(c) Thermal radiation	160
3.4 Thermal energy transfer during change of phase	161
Summary	162
Problems	163
Further Reading	164

Chapter 7 PHASES OF MATTER

165

1. Introduction and notation	165
1.1 Interrelating flow chart	165
1.2 Phase diagram	166
1.2(a) Application: ice skating	167
1.2(b) Principle of Le Chatelier	168
2. Phases of matter	168
2.1 Solid phase	168
2.2 Liquid phase	168
2.2(a) Glass	169
2.3 Gaseous phase	169
2.3(a) Vapor	169
2.4 Plasma	170
3. Temperatures and transition energies	170
3.1 Temperature ranges	170
3.1(a) Supercooling	171
3.1(b) Survival of life	171
3.2 Transition energies	172
4. Applications	172
4.1 Freeze-drying	172

4.2 How to make diamonds	174
4.3 Liquifying gases	175
4.4 Hygrometry	176
4.5 Mixtures of phases and materials	177
Summary	178
Problems	178
Further Reading	179
Chapter 8 TRANSPORT PHENOMENA	180
1. Introduction	180
1.1 Stationary and nonstationary transport	180
1.2 Gradient	181
1.3 Net transport	183
2. Passive transport	184
2.1 Diffusion	184
2.2 Osmosis	187
2.3 Application: separating uranium isotopes	190
3. Active transport	192
3.1 Transport by mechanical pumps	192
3.2 Transport by electrophoresis	194
3.3 Carrier-mediated transport	196
Summary	196
Problems	198
Further Reading	199
Chapter 9 OSCILLATIONS, WAVES, AND SPECTRA	200
1. Introduction	200
1.1 Oscillations	200
1.2 Period and frequency	201
1.3 Wavelength and wave number	202
1.4 Transverse and longitudinal waves	203
1.5 Polarization	204
2. Harmonic oscillations and waves	205
2.1 Free and damped oscillations	206
2.2 Energy and intensity	206
2.3 Forced oscillations	207
2.3(a) Eigenfrequency	207
2.3(b) Resonance	208
3. Superposition	208
3.1 General	208
3.1(a) Beat	209
3.1(b) Resonance	209
3.1(c) Cancellation	210
3.2 Wave packets	211
4. Waves at boundaries	212
4.1 Transmission	212
4.1(a) Refraction	212
4.1(b) Dispersion	213
4.2 Reflection	213
4.2(a) Reflectivity	213
4.2(b) Total reflection	213

Chapter 11 GEOMETRICAL OPTICS 255

1. Introduction	255
2. Rays at boundaries	256
2.1 Notation	256
2.2 Reflection	258
2.2(a) Law of reflection	258
2.2(b) Curved surfaces	259
2.2(c) Applications	261
2.3 Refraction	261
2.3(a) Law of refraction (Snell's Law)	261
2.3(b) Total reflection	263
2.3(c) Plane surfaces	265
2.3(d) Lenses	266
2.3(e) Lens aberrations	268
2.4 Applications	268
2.4(a) Lenses with variable focal length	268
2.4(b) Eyeglasses	270
3. Images	271
3.1 Notation	271
3.2 Images formed by curved optical elements	271
3.3 The pinhole	274
3.4 Image converter	275
4. Magnification and resolution	277
4.1 Magnification	277
4.2 Spatial resolution	277
4.3 Time resolution	279
5. Optical instruments	281
5.1 Simple devices	282
5.2 Telescope	284
5.3 Microscope	286
5.4 Projector	289
Summary	291
Problems	292
Further Reading	294

Chapter 12 ELECTROSTATICS AND MAGNETOSTATICS 295

1. Introduction	295
2. Electrostatics	296
2.1 Electric charge	296
2.2 Conservation of charge	297
2.3 Coulomb's law	298
2.3(a) Formulation	298
2.3(b) Unit of charge	299
2.3(c) Electric permittivity	299
2.4 Electric field	300
2.4(a) Lines of force	300
2.4(b) Potential difference	302
2.4(c) Electric capacitance	305
2.5 Matter in electric fields	307
2.5(a) Polarization	307
2.5(b) Electric displacement	308
2.5(c) Applications	308

2.2 Rate of information	352
2.3 Speed of information	353
3. Information handling	353
3.1 General	353
3.2 Input	354
3.2(a) Transducer	355
3.2(b) Receptor	355
3.3 Transfer of information	356
3.3(a) Redundance	357
3.3(b) Amount transferred in man	357
4. Information processors	358
4.1 Feedback circuit	358
4.1(a) Negative feedback	359
4.1(b) Positive feedback	360
4.1(c) Application: control of blood pressure	360
4.2 Analog computer	362
4.2(a) Capillary flow	362
4.2(b) Deep freezing	363
4.2(c) Relative merits	364
4.3 Digital computer	364
4.3(a) General characteristics	364
4.3(b) Relative merits	366
4.3(c) Applications in the life sciences	367
4.3(d) Computers and the brain	367
Summary	369
Further Reading	369

Chapter 15 RADIATION

371

1. Wave-particle dualism	371
1.1 Waves as particles	372
1.2 Particles as waves	374
2. Electromagnetic radiation	375
2.1 General characteristics	375
2.1(a) Region	375
2.1(b) Absorption	376
2.2 Visible and ultraviolet light	377
2.2(a) Region	377
2.2(b) Sources	377
2.2(c) Detectors	377
2.2(d) Photometry	379
2.3 X rays	380
2.3(a) Region	380
2.3(b) Sources	381
2.3(c) Detectors	382
2.3(d) Dosimetry of x rays	383
3. Particle radiation	384
3.1 Sources	385
3.2 Detectors	385
3.3 Particle ranges	386
3.4 General dosimetry	387
4. Applications	388
4.1 X-ray diagnostics	388
4.2 Laser scalpel	389
4.3 Light absorption spectroscopy	389

Summary	391
Problems	392
Further Reading	394
Chapter 16	ATOMIC AND NUCLEAR PHYSICS
	395
1. The atom	395
1.1 Short history	395
1.2 Size and components	396
1.3 Systematics	397
1.3(a) Electron shells	397
1.3(b) Nuclear shells	399
1.4 Excitation and de-excitation	399
1.4(a) Atomic shell	399
1.4(b) Atomic nucleus	401
1.5 Terminology	402
2. Nuclear reactions	403
2.1 Terminology	403
2.2 Selected reactions	404
2.2(a) Reactions with photons	404
2.2(b) Reactions with neutrons	404
2.2(c) Reactions with protons	405
2.2(d) Nuclear fission	405
2.2(e) Nuclear fusion	405
2.3 Application: activation analysis	406
3. The unstable atom—radioactivity	406
3.1 Stable and unstable nuclides	406
3.2 Half-life	407
3.2(a) Physical half-life	407
3.2(b) Biological half-life	408
3.3 Activity	409
3.4 Mode of decay	410
3.4(a) Alpha decay	410
3.4(b) Beta decay	411
3.5 Reading a chart of nuclides	412
4. Applications	413
4.1 Tracer techniques	413
4.2 Nuclear power	414
4.3 A prehistoric nuclear reactor	416
Summary	416
Problems	418
Further Reading	419
APPENDICES	421
A. Information retrieval	421
B. Symbols for physical quantities used in the text	429
C. Prefixes for multiplying factors	431
D. Conversion factors	432
E. Important physical constants	434
F. Greek alphabet	435
Answers to odd-numbered problems	436
INDEX	441