

ELLIS HORWOOD PUBLISHERS

an introduction to
Nuclear Physics
with Applications in
Medicine and Biology

N. A. DYSON



2

AN INTRODUCTION TO NUCLEAR PHYSICS, WITH APPLICATIONS IN MEDICINE AND BIOLOGY

1

N. A. DYSON, M.A., Ph.D.

Department of Physics,
University of Birmingham



ELLIS HORWOOD LIMITED

Publishers · Chichester

Halsted Press: a division of

JOHN WILEY & SONS

New York · Brisbane · Chichester · Toronto

First published in 1981 by

ELLIS HORWOOD LIMITED

Market Cross House, Cooper Street, Chichester, West Sussex, PO19 1EB, England

The publisher's colophon is reproduced from James Gillison's drawing of the ancient Market Cross, Chichester.

Distributors:

Australia, New Zealand, South-east Asia:

Jacaranda-Wiley Ltd., Jacaranda Press,

JOHN WILEY & SONS INC.,

G.P.O. Box 859, Brisbane, Queensland 40001, Australia

Canada:

JOHN WILEY & SONS CANADA LIMITED

22 Worcester Road, Rexdale, Ontario, Canada.

Europe, Africa:

JOHN WILEY & SONS LIMITED

Baffins Lane, Chichester, West Sussex, England.

North and South America and the rest of the world:

Halsted Press: a division of

JOHN WILEY & SONS

605 Third Avenue, New York, N.Y. 10016, U.S.A.

© N. A. Dyson/Ellis Horwood Limited 1981

British Library Cataloguing in Publication Data

Dyson, N. A.

An introduction to nuclear physics, with applications in medicine and biology. –

(Ellis Horwood series in physics in medicine and biology)

1. Nuclear physics

I. Title

539.7'02461 QC776

Library of Congress Card No. 81-6720 AACR2

ISBN 0-85312-265-2 (Ellis Horwood Limited, Publishers – Library Edn.)

ISBN 0-85312-376-4 (Ellis Horwood Limited, Publishers – Student Edn.)

ISBN 0-470-27277-5 (Halsted Press)

Typeset in Press Roman by Ellis Horwood Limited, Publishers

Printed in the U.S.A. by Eastern Graphics Inc., Old Saybrook, Connecticut

COPYRIGHT NOTICE –

All Rights Reserved. No part of this publication may be reproduced, stored in a retrieval system, or transmitted, in any form or by any means, electronic, mechanical, photocopying, recording or otherwise, without the permission of Ellis Horwood Limited, Market Cross House, Cooper Street, Chichester, West Sussex, England.

Table of Contents

Table of Contents	5
Preface	9
Glossary of Terms	11
Chapter 1 Interactions between Radiaton and Matter	17
1.1 Introductory	17
1.2 Energy-loss of charged particles	18
1.3 Energy-loss of α -particles	19
1.4 Energy-loss from electron beams	23
1.5 Radiative losses for electrons.	25
1.6 Electron scattering.	27
1.7 Interaction between γ -radiation and matter-introduction	31
1.8 The Photoelectric process	32
1.9 The Compton effect.	35
1.10 Thomson and Rayleigh scattering	38
1.11 Pair production.	42
1.12 Processes involving nuclear energy levels	44
Further Reading	47
References	48
Chapter 2 Nuclear reactions and the production of radioisotopes	49
2.1 Introduction — nuclear stability	49
2.2 Neutron and proton capture	54
2.3 Compound nucleus formation	57
2.4 Direct interaction	60
2.5 Fission	60
2.6 Spallation and heavy ion bombardment	63
2.7 Quantitative aspects of radioisotope production	64
2.7.1 Charged particle bombardment by accelerator-produced beams	64

2.7.2	Reactor irradiation — ‘burn-up’ of target material	65
2.8	Practical aspects of radioisotope production	66
2.8.1	The target material	67
2.8.2	Specific activity	68
2.8.3	Radionuclidic purity	68
2.8.4	Preparation for medical or biological use	69
2.8.5	Production from a ‘generator’	70
	Further Reading	71
	References	71
Chapter 3 Instrumentation — an introduction to α, β, and γ-radiation detectors		72
3.1	Introductory	72
3.2	Geiger and Proportional counters	73
3.3	The Scintillation counter	82
3.4	Solid-state semiconductor detectors	89
3.5	Radiation dosimetry	91
	Further Reading	101
	References	101
Chapter 4 The radiation from nuclear decay		102
4.1	α -decay	103
4.2	β -decay	104
4.3	γ -radiation	108
4.4	Internal conversion	110
4.5	X-rays from electron capture and internal conversion	111
4.6	Positron annihilation	115
4.7	The absolute activity of radioactive sources	117
4.7.1	β^- -emitters	118
4.7.2	2 γ -photons in cascade	122
4.7.3	Electron capture and β^+ emitters	122
4.8	External dosimetry of radioactive sources	123
4.8.1	α -sources	123
4.8.2	β -sources	124
4.8.3	γ -ray sources	125
	Further Reading	129
	References	129
Chapter 5 Applications of radioisotopes in medicine and biology		130
5.1	Introduction — general behaviour of radioisotopes in the body	130
5.2	Determination of compartment volumes and pool masses by the isotope dilution method	131
5.3	Compartment theory	133

5.4	Total body water and its subdivisions	141
5.5	Behaviour of certain elements in the body	142
5.5.1	Sodium	142
5.5.2	Potassium	143
5.5.3	Calcium and Strontium.	143
5.5.4	Iron	144
5.5.5	Iodine	146
5.6	Scanning and imaging techniques	148
5.7	Radiotherapy with radioisotopes	152
5.8	Gaseous radioisotopes	153
5.8.1	Introduction.	153
5.8.2	Preparation	154
5.8.3	Physiological principles and clinical applications	155
5.8.4	Techniques of measurement	160
5.8.5	Other aspects of radioactive gases	162
5.9	Internal dosimetry of radioisotopes.	164
	Further Reading	171
	References	171

Chapter 6 Neutrons in biology and clinical medicine 173

6.1	Interactions with matter	173
6.1.1	Elastic scattering	173
6.1.2	Neutron capture	175
6.1.3	Inelastic scattering.	175
6.1.4	Fission, spallation and other nuclear processes	175
6.1.5	Energy loss and linear energy transfer	178
6.2	Production of neutrons.	182
6.2.1	Laboratory neutron sources	182
6.2.2	Nuclear reactors	184
6.2.3	Accelerator sources of neutrons	185
6.3	Neutrons in radiobiology and radiotherapy.	186
6.3.1	The Role of oxygen.	193
6.4	Neutron detection and dosimetry	195
6.4.1	Detectors based on elastic scattering	195
6.4.2	Use of nuclear reactions	196
6.4.3	Pulse shape discrimination.	197
6.4.4	Threshold detectors	198
6.4.5	Neutron dosimetry	198
6.5	Neutron activation analysis	199
	Further Reading	201
	References	201

Chapter 7 Other accelerator-based applications in medicine and biology . .	203
7.1 <i>X</i> -rays induced by protons and other heavy particles, for analysis . . .	203
7.2 Analysis by Rutherford back-scattering.	214
7.3 Analysis by nuclear reactions.	216
7.4 Muons and π -mesons in radiobiology and medical physics	220
Further Reading	223
References	223
Appendices	225
A1 The Bethe–Bloch expression for energy-loss	225
A2 The Klein–Nishina formula	229
A3 The Semi-empirical mass formula	231
A4 The Breit–Wigner formula	233
A5 Radioactive transformations — growth and decay.	234
List of Symbols	238
Index	242

**AN INTRODUCTION TO NUCLEAR PHYSICS,
WITH APPLICATIONS IN MEDICINE AND BIOLOGY**



ELLIS HORWOOD SERIES IN MEDICINE AND BIOLOGY

Series Editor:

E. H. GRANT, Professor of Experimental Physics, Queen Elizabeth College, University of London

This series aims to cover ionising radiation and its hazards, the medical and biological effects of radiowaves and microwaves, ultrasonics in medicine and biology, medical imaging, lasers in medicine and biology, and medical electronics. Other books will later be added to the series.

Each book will act as an authoritative guide to its subject and will therefore be appropriate reading for postgraduate students entering its field or for workers in allied fields of research who require information. Practical applications and any attendant hazards will be emphasised and users of apparatus and workers exposed to radiations will therefore find the books a valuable source of knowledge.

Published and in preparation

AN INTRODUCTION TO NUCLEAR PHYSICS, WITH APPLICATIONS IN MEDICINE AND BIOLOGY

N. A. DYSON, University of Birmingham

IONISING RADIATION AND ITS HAZARDS

R. E. ELLIS, University of Leeds

MICROWAVES AND RADIOWAVES IN MEDICINE AND BIOLOGY

E. H. GRANT, Queen Elizabeth College, University of London

PHYSICAL PRINCIPLES OF MEDICAL ULTRASONICS

C. R. HILL, Institute of Cancer Research, Sutton

2
AN INTRODUCTION TO
NUCLEAR PHYSICS,
WITH APPLICATIONS IN
MEDICINE AND BIOLOGY

1
N. A. DYSON, M.A., Ph.D.

Department of Physics,
University of Birmingham



ELLIS HORWOOD LIMITED

Publishers · Chichester

Halsted Press: a division of

JOHN WILEY & SONS

New York · Brisbane · Chichester · Toronto

First published in 1981 by

ELLIS HORWOOD LIMITED

Market Cross House, Cooper Street, Chichester, West Sussex, PO19 1EB, England

The publisher's colophon is reproduced from James Gillison's drawing of the ancient Market Cross, Chichester.

Distributors:

Australia, New Zealand, South-east Asia:

Jacaranda-Wiley Ltd., Jacaranda Press,

JOHN WILEY & SONS INC.,

G.P.O. Box 859, Brisbane, Queensland 40001, Australia

Canada:

JOHN WILEY & SONS CANADA LIMITED

22 Worcester Road, Rexdale, Ontario, Canada.

Europe, Africa:

JOHN WILEY & SONS LIMITED

Baffins Lane, Chichester, West Sussex, England.

North and South America and the rest of the world:

Halsted Press: a division of

JOHN WILEY & SONS

605 Third Avenue, New York, N.Y. 10016, U.S.A.

© N. A. Dyson/Ellis Horwood Limited 1981

British Library Cataloguing in Publication Data

Dyson, N. A.

An introduction to nuclear physics, with applications in medicine and biology. –

(Ellis Horwood series in physics in medicine and biology)

1. Nuclear physics

I. Title

539.7'02461 QC776

Library of Congress Card No. 81-6720 AACR2

ISBN 0-85312-265-2 (Ellis Horwood Limited, Publishers – Library Edn.)

ISBN 0-85312-376-4 (Ellis Horwood Limited, Publishers – Student Edn.)

ISBN 0-470-27277-5 (Halsted Press)

Typeset in Press Roman by Ellis Horwood Limited, Publishers

Printed in the U.S.A. by Eastern Graphics Inc., Old Saybrook, Connecticut

COPYRIGHT NOTICE –

All Rights Reserved. No part of this publication may be reproduced, stored in a retrieval system, or transmitted, in any form or by any means, electronic, mechanical, photocopying, recording or otherwise, without the permission of Ellis Horwood Limited, Market Cross House, Cooper Street, Chichester, West Sussex, England.

Table of Contents

Table of Contents	5
Preface	9
Glossary of Terms	11
Chapter 1 Interactions between Radiaton and Matter	17
1.1 Introductory	17
1.2 Energy-loss of charged particles	18
1.3 Energy-loss of α -particles	19
1.4 Energy-loss from electron beams	23
1.5 Radiative losses for electrons.	25
1.6 Electron scattering.	27
1.7 Interaction between γ -radiation and matter-introduction	31
1.8 The Photoelectric process	32
1.9 The Compton effect.	35
1.10 Thomson and Rayleigh scattering	38
1.11 Pair production.	42
1.12 Processes involving nuclear energy levels	44
Further Reading	47
References	48
Chapter 2 Nuclear reactions and the production of radioisotopes	49
2.1 Introduction — nuclear stability	49
2.2 Neutron and proton capture	54
2.3 Compound nucleus formation	57
2.4 Direct interaction	60
2.5 Fission	60
2.6 Spallation and heavy ion bombardment	63
2.7 Quantitative aspects of radioisotope production	64
2.7.1 Charged particle bombardment by accelerator-produced beams	64

2.7.2	Reactor irradiation — ‘burn-up’ of target material	65
2.8	Practical aspects of radioisotope production	66
2.8.1	The target material	67
2.8.2	Specific activity	68
2.8.3	Radionuclidic purity	68
2.8.4	Preparation for medical or biological use	69
2.8.5	Production from a ‘generator’	70
	Further Reading	71
	References	71

Chapter 3 Instrumentation — an introduction to α , β , and γ -radiation detectors

3.1	Introductory	72
3.2	Geiger and Proportional counters	73
3.3	The Scintillation counter	82
3.4	Solid-state semiconductor detectors	89
3.5	Radiation dosimetry	91
	Further Reading	101
	References	101

Chapter 4 The radiation from nuclear decay

4.1	α -decay	103
4.2	β -decay	104
4.3	γ -radiation	108
4.4	Internal conversion	110
4.5	X-rays from electron capture and internal conversion	111
4.6	Positron annihilation	115
4.7	The absolute activity of radioactive sources	117
4.7.1	β^- -emitters	118
4.7.2	2 γ -photons in cascade	122
4.7.3	Electron capture and β^+ emitters	122
4.8	External dosimetry of radioactive sources	123
4.8.1	α -sources	123
4.8.2	β -sources	124
4.8.3	γ -ray sources	125
	Further Reading	129
	References	129

Chapter 5 Applications of radioisotopes in medicine and biology

5.1	Introduction — general behaviour of radioisotopes in the body	130
5.2	Determination of compartment volumes and pool masses by the isotope dilution method	131
5.3	Compartment theory	133

5.4	Total body water and its subdivisions	141
5.5	Behaviour of certain elements in the body	142
5.5.1	Sodium	142
5.5.2	Potassium	143
5.5.3	Calcium and Strontium.	143
5.5.4	Iron	144
5.5.5	Iodine	146
5.6	Scanning and imaging techniques	148
5.7	Radiotherapy with radioisotopes	152
5.8	Gaseous radioisotopes	153
5.8.1	Introduction.	153
5.8.2	Preparation	154
5.8.3	Physiological principles and clinical applications	155
5.8.4	Techniques of measurement	160
5.8.5	Other aspects of radioactive gases	162
5.9	Internal dosimetry of radioisotopes.	164
	Further Reading	171
	References	171

Chapter 6 Neutrons in biology and clinical medicine 173

6.1	Interactions with matter	173
6.1.1	Elastic scattering	173
6.1.2	Neutron capture	175
6.1.3	Inelastic scattering.	175
6.1.4	Fission, spallation and other nuclear processes	175
6.1.5	Energy loss and linear energy transfer	178
6.2	Production of neutrons.	182
6.2.1	Laboratory neutron sources	182
6.2.2	Nuclear reactors	184
6.2.3	Accelerator sources of neutrons	185
6.3	Neutrons in radiobiology and radiotherapy.	186
6.3.1	The Role of oxygen.	193
6.4	Neutron detection and dosimetry	195
6.4.1	Detectors based on elastic scattering	195
6.4.2	Use of nuclear reactions	196
6.4.3	Pulse shape discrimination.	197
6.4.4	Threshold detectors	198
6.4.5	Neutron dosimetry	198
6.5	Neutron activation analysis	199
	Further Reading	201
	References	201

Chapter 7 Other accelerator-based applications in medicine and biology . .	203
7.1 <i>X</i> -rays induced by protons and other heavy particles, for analysis . . .	203
7.2 Analysis by Rutherford back-scattering.	214
7.3 Analysis by nuclear reactions.	216
7.4 Muons and π -mesons in radiobiology and medical physics	220
Further Reading	223
References	223
Appendices	225
A1 The Bethe–Bloch expression for energy-loss	225
A2 The Klein–Nishina formula	229
A3 The Semi-empirical mass formula	231
A4 The Breit–Wigner formula	233
A5 Radioactive transformations — growth and decay.	234
List of Symbols	238
Index	242

Author's Preface

This book was written to provide a concise account of the applications of nuclear physics to medical and biological science. In order to do this, it seemed necessary to outline some rather basic aspects of nuclear and radiation physics and, in its final form, something approaching half the book is devoted to laying these foundations. The book will therefore be of interest not only to those undergraduates and postgraduates who are devoting their main effort to medical physics, but also to those students who are looking primarily for an introduction to nuclear physics together with an account of some of the ways in which it impinges on the work of other scientists.

The book, then, should appeal to many undergraduates, including those who, in their final year, have selected a biomedical type of option as a means of broadening their scientific interest and also perhaps in order to explore a possible career avenue. The book will also be of value to postgraduates in various disciplines—those who are pursuing post-graduate courses in medical or medically-oriented physics; those who are seeking to become radiobiologists (whether originally students of physics, biology or medicine); and those who, as undergraduates, sought to combine physics with other subjects such as biology or environmental science, and are now needing to develop their nuclear physics to a more useful level than they were able to prior to graduation. Finally, it is hoped that physicists and others who have already embarked on careers in medical physics or environmental science may find the book to be of value.

The *Further Reading* to which the student's attention is particularly drawn, lists those works which for the most part are standard texts in nuclear physics, medical physics, and other more specialised areas of medicine and biology. This book will fulfil one of its purposes if it successfully launches the physicist into a systematic study of the uses of radioisotopes in clinical medicine, or the environmental scientist into the study of the detection and measurement of nuclear radiation. Many of the works listed under this heading contain very extensive lists of references which will assist the reader in his quest for more specialised and detailed material.

I am greatly indebted to Mrs Z. Drolc of the Queen Elizabeth Hospital, Birmingham and to Dr R. G. Harris of the University of Birmingham for reading substantial sections of the text, and for helping me by discussion of the subject matter. Also, I owe a debt to the Series Editor, Professor E. H. Grant, Queen Elizabeth College, University of London, for reading the whole text, and for providing guidance at all stages of preparation. Needless to say, any errors, or infelicities of balance, remain the Author's responsibility. The bulk of the typing was carried out by Mrs Sue Yeomans and Mrs June Layton, to whom my sincere thanks are due.

I am indebted to the following publishers and institutions for permission to reproduce tables and illustrations from their copyright publications: Academic Press Inc., (Fig. 1.2); Cambridge University Press, (Fig. 1.6); Chapman and Hall Ltd., (Fig. 5.5); North Holland Publishing Co., (Figs. 3.9, 3.10, 4.10, 7.2, 7.3); Pergamon Press, (Fig. 4.16); Wiley and Sons, (Fig. 4.4); U.S. Government Printing Office, (Fig. 2.6); also The Institute of Physics (London), The American Institute of Physics. The American Physical Society, and the American Physiological Society. Other acknowledgements appear in the text, and in captions to tables and diagrams. If any acknowledgements have been inadvertently omitted, I shall be glad to be informed, in order to make amends in future printings.

Working on the premise that all ventures of this type can benefit from contact with those for whom the work is intended, the Author would welcome criticisms and suggestions, from readers, whether students, teachers, research workers, or others working in this field, towards improvement of the book in any future edition or reprinting.

N. A. Dyson
University of Birmingham,
April 1981