An Introduction to Nuclear Physics

This clear and concise introduction to nuclear physics provides an excellent basis for a 'core' undergraduate course in this area.

The book opens by setting nuclear physics in the context of elementary particle physics and then shows how simple models can provide an understanding of the properties of nuclei, both in their ground states and excited states, and also of the nature of nuclear reactions. The book includes chapters on nuclear fission, its application in nuclear power reactors, and the role of nuclear physics in energy production and nucleosynthesis in stars.

This new edition contains several additional topics: muon-catalysed fusion, the nuclear and neutrino physics of supernovae, neutrino mass and neutrino oscillations, and the biological effects of radiation.

A knowledge of basic quantum mechanics and special relativity is assumed. Appendices deal with other more specialised topics. Each chapter ends with a set of problems for which outline solutions are provided.

Noel Cottingham and Derek Greenwood are theoreticians working in the H. H. Wills Physics Laboratory at the University of Bristol. Noel Cottingham is also a visiting professor at the Université Pierre et Marie Curie, Paris.

They have also collaborated in an undergraduate text, *Electricity and Magnetism*, and a graduate text, *An Introduction to the Standard Model of Particle Physics*. Both books are published by the Cambridge University Press.

An Introduction to
Nuclear Physics

Second edition

W. N. COTTINGHAM
University of Bristol

D. A. GREENWOOD
University of Bristol

CAMBRIDGE
UNIVERSITY PRESS

PUBLISHED BY THE PRESS SYNDICATE OF THE UNIVERSITY OF CAMBRIDGE
The Pitt Building, Trumpington Street, Cambridge, United Kingdom

CAMBRIDGE UNIVERSITY PRESS
The Edinburgh Building, Cambridge CB2 2RU, UK
40 West 20th Street, New York, NY 10011-4211, USA
10 Stamford Road, Oakleigh, VIC 3166, Australia
Ruiz de Alarcón 13, 28014 Madrid, Spain
Dock House, The Waterfront, Cape Town 8001, South Africa

http://www.cambridge.org

First published 1986
Reprinted 1987 (with corrections and additions), 1988, 1990, 1992, 1998
Second edition 2001

Typeface Times 10/13pt 3B2 [KB]

A catalogue record for this book is available from the British Library

Library of Congress Cataloguing in Publication data

Cottingham, W. N.
An introduction to nuclear physics / W.N. Cottingham and
D.A. Greenwood – 2nd ed. p. cm.
Includes bibliographical references and index.
ISBN 0 521 65149 2 (hardback) – ISBN 0 521 65733 4 (paperback)
1. Nuclear physics. I. Greenwood, D. A. II. Title.
QC776.C63 2001
539.7–dc21 00-059885

ISBN 0 521 65149 2 hardback
ISBN 0 521 65733 4 paperback

Transferred to digital printing 2002

Cambridge University Press
0521651492 - An Introduction to Nuclear Physics, Second Edition
W. N. Cottingham and D. A. Greenwood
Frontmatter
More information

Contents

Preface to the second edition

The main structure of the first edition has been retained, but we have taken the opportunity in this second edition to update the text and clarify an occasional obscurity. The text has in places been expanded, and also additional topics have been added. The growing interest of physics students in astrophysics has encouraged us to extend our discussions of the nuclear and neutrino physics of supernovae, and of solar neutrinos. There is a new chapter devoted to neutrino masses and neutrino oscillations. In other directions, a description of muon-catalysed fusion has been included, and a chapter on radiation physics introduces an important applied field.

We should like to thank Dr John Andrews and Professor Denis Henshaw for their useful comments on parts of the text, Mrs Victoria Parry for her secretarial assistance, and Cambridge University Press for their continuing support.

W. N. Cottingham
D. A. Greenwood
Bristol, March 2000

Preface to the first edition

In writing this text we were concerned to assert the continuing importance of nuclear physics in an undergraduate physics course. We set the subject in the context of current notions of particle physics. Our treatment of these ideas, in Chapters 1 to 3, is descriptive, but it provides a unifying foundation for the rest of the book. Chapter 12, on β-decay, returns to the basic theory. It also seems to us important that a core course should include some account of the applications of nuclear physics in controlled fission and fusion, and should exemplify the role of nuclear physics in astrophysics. Three chapters are devoted to these subjects.

Experimental techniques are not described in detail. It is impossible in a short text to do justice to the ingenuity of the experimental scientist, from the early discoveries in radioactivity to the sophisticated experiments of today. However, experimental data are stressed throughout: we hope that the interdependence of advances in experiment and theory is apparent to the reader.

We have by and large restricted the discussion of processes involving nuclear excitation and nuclear reactions to energies less than about 10 MeV. Even with this restriction there is such a richness and diversity of phenomena that it can be difficult for a beginner to grasp the underlying principles. We have therefore placed great emphasis on a few simple theoretical models that provide a successful description and understanding of the properties of nuclei at low energies. The way in which simple models can elucidate the properties of a complex system is one of the surprises of the subject, and part of its general educational value.

We have tried to keep the mathematics as simple as possible. We assume a knowledge of the basic formulae of special relativity, and some basic quantum mechanics: wave-equations, energy levels and the quantisation of angular momentum. A few topics which may not be covered in elementary courses in quantum mechanics are treated in appendices. We consider the technicalities of angular momentum algebra, phase shift analysis and isotopic spin to be inappropriate to a first course in nuclear physics. Equations are written to be valid in SI units; results are usually expressed in MeV and fm. Each chapter ends with a set of problems intended to amplify and extend the text; some refer to further applications of nuclear physics. We have covered the bulk of the material in this book in 35 lectures of the core undergraduate curriculum at Bristol; these are given in the second and third years of the honours physics course.

We thank colleagues and students who read drafts of the text and drew our attention to errors and obscurities, which we have tried to eliminate. We are grateful to Margaret James and Mrs Lilian Murphy for their work on the typescript.

There is a less obvious debt: to the sometime Department of Mathematical Physics of the University of Birmingham where, under Professor Peierls, we first learned about physics.

W. N. Cottingham
D. A. Greenwood
Bristol, August 1985

Constants of nature, conversion factors and notation

Velocity of light	c	2.99792×10^{8} m s^{-1}
Planck's constant	$\hbar = h/2\pi$	1.05457×10^{-34} J s
Proton charge	e	1.60218×10^{-19} C
Boltzmann's constant	k_{B}	1.3807×10^{-23} J K^{-1}
		$= 8.617 \times 10^{-5}$ eV K^{-1}
Gravitational constant	G	6.67×10^{-11} m^3 kg^{-1} s^{-2}
Fermi coupling constant	G_{F}	$1.166 \times 10^{-11} (\hbar c)^3$ MeV^{-2}
Electron mass	m_{e}	9.1094×10^{-31} kg
		$= 0.51100$ MeV$/c^2$
Proton mass	m_{p}	1.007 276 amu
		$= 938.27$ MeV$/c^2$
Neutron mass	m_{n}	1.008 66 amu
		$= 939.57$ MeV$/c^2$
Atomic mass unit	(mass ^{12}C atom)/12	1.66054×10^{-27} kg
		$= 931.49$ MeV$/c^2$
Bohr magneton	$\mu_{\mathrm{B}} = e\hbar/2m_{\mathrm{e}}$	5.78838×10^{-11} MeV T^{-1}
Nuclear magneton	$\mu_{\mathrm{N}} = e\hbar/2m_{\mathrm{p}}$	3.15245×10^{-14} MeV T^{-1}
Bohr radius	$a_0 = 4\pi\varepsilon_0 \hbar^2/m_{\mathrm{e}}e^2$	0.529177×10^{-10} m
Fine-structure constant	$e^2/4\pi\varepsilon_0 \hbar c$	1/137.036

$\hbar c = 197.327$ MeV fm, $\quad e^2/4\pi\varepsilon_0 = 1.43996$ MeV fm
1 MeV $= 1.60218 \times 10^{-13}$ J
1 fm $= 10^{-15}$ m, $\quad$ 1 barn $= 10^{-28}$ m$^2 = 10^2$ fm^2
(Source: Review of Particle Physics (1998), *Eur. Phys. J.* **C3**, 1–794.)

Notation

r, **k**, etc., denote vectors (x, y, z), (k_x, k_y, k_z), and $r = |\mathbf{r}|$, $k = |\mathbf{k}|$,
$\mathrm{d}^3\mathbf{r} = \mathrm{d}x\,\mathrm{d}y\,\mathrm{d}z$, $\quad \mathrm{d}^3\mathbf{k} = \mathrm{d}k_x\,\mathrm{d}k_y\,\mathrm{d}k_z$.

$$\nabla^2 = \frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial y^2} + \frac{\partial^2}{\partial z^2} = \frac{1}{r}\frac{\partial^2}{\partial r^2} r + \frac{1}{r^2 \sin\theta}\frac{\partial}{\partial\theta}\sin\theta\frac{\partial}{\partial\theta} + \frac{1}{r^2\sin^2\theta}\frac{\partial^2}{\partial\phi^2},$$

$\mathrm{d}\Omega = \sin\theta\,\mathrm{d}\theta\,\mathrm{d}\phi$ denotes an infinitesimal element of solid angle.

Cambridge University Press
0521651492 - An Introduction to Nuclear Physics, Second Edition
W. N. Cottingham and D. A. Greenwood
Frontmatter
More information

Glossary of some important symbols

A	nuclear mass number $(= N + Z)$
$\mathbf{A}(\mathbf{r}, t)$	electromagnetic vector potential
a	§4.1 nuclear surface width; §4.5 bulk binding coefficient
$B(Z, N)$	binding energy of nucleus
$\mathbf{B}(\mathbf{r}, t)$	magnetic field
b	§4.5 surface tension coefficient; §14.1 impact parameter
$\mathbf{E}(\mathbf{r}, t)$	electric field
E	energy; E_n, E_p neutron energy, proton energy; E_n^F, E_p^F neutron, proton Fermi energy, measured from the bottom of the shell-model neutron potential well; E_G §8.3
$F(Z, E_e)$	§12.3 Coulomb correction factor in β-decay
$f(Z, E_0)$	§12.3 kinematic factor in total β-decay rate
G	§6.2 exponent in the tunnelling formula
G_w	§12.2 weak interaction coupling constant $(= G_F V_{ud})$
g	§8.1 statistical factor in Breit–Wigner formula
g_L, g_s	§5.6 orbital and intrinsic magnetic moment coefficients
g_A	§12.5 axial coupling constant
$\mathscr{G}(r_s/r_c)$	§6.2 tunnelling integral
$\mathbf{J}$	§C.3 total angular momentum operator
j	quantum number associated with $\mathbf{J}^2$
j_z	quantum number of J_z
$\mathbf{k}$	wave vector
k_F	value of $k = \|\mathbf{k}\|$ at the Fermi energy
$\mathbf{L}$	§C.1 orbital angular momentum operator
l	quantum number associated with $\mathbf{L}^2$; Chapter 9, Chapter 14 mean free path

m	quantum number of L_z; reduced mass
m_s	quantum number of s_z
m_α	mass of α-particle; m_a, m_{nuc} mass of atom, nucleus
N	number of neutrons in nucleus
$n(E)$	density of states
$\mathcal{N}(E)$	integrated density of states
$\mathbf{p}$	momentum
Q	§5.7 nuclear electric quadrupole moment; §6.1 kinetic energy release in nuclear reaction
q	§9.4 fission probability
R	§4.3 nuclear radius; §12.3 reaction rate
r_s, r_c	§6.2 potential barrier parameters
$S_n(N, Z)$	§5.2 neutron separation energy
$S(E)$	§8.3 parameter of nuclear reaction cross-section for energies below the Coulomb barrier
$S_0(E)$, $S_c(E)$	§12.3 electron (positron) energy spectrum without and with Coulomb correction
$\mathbf{s}$	§C.2 intrinsic angular momentum operator
s	quantum number associated with $\mathbf{s}$; §4.5 symmetry energy coefficient
T	kinetic energy
$T_{1/2}$	decay half life
t_{nuc}	§5.2 nuclear time scale
t_p	§9.4 prompt neutron life
U	potential energy; $\bar{U}$ mean proton–neutron potential energy difference in nucleus
$u_l(r)$	radial wave-function
V	normalisation volume; §3.3 $V(r)$ nucleon–nucleon potential
V_{ud}	§12.5 element of Kobayashi–Maskawa matrix
v	velocity
Z	atomic number (number of protons in nucleus)
Γ, Γ_i	width, partial width, of an excited state
γ	§14.1 relativistic factor $(1 - v^2/c^2)^{-\frac{1}{2}}$
δ	§4.4 coefficient of pairing energy
ε_0	permittivity of free space
ε_F	§11.1 Fermi energy of electron gas
θ	§13.3 neutrino mixing angle
θ_w	§13.1 Weinberg angle
$\boldsymbol{\mu}$	§5.5 magnetic dipole operator

μ_n, μ_p	neutron, proton magnetic moment
μ	§5.5 magnetic dipole moment; §11.1 stellar mass per electron; §14.3 photon linear attenuation coefficient
μ_0	permeability of free space
ν, ν_d	§9.3 mean number of prompt neutrons, delayed neutrons, per fission
ρ	§2.1 electric charge density; §14.1 mass density
ρ_{ch}	§4.1 electric charge density in units of e
ρ_0	§4.3 nucleon *number* density in nuclear matter
ρ_{nuc}, ρ_n, ρ_p	*number* density of nuclei, neutrons, protons
$\boldsymbol{\sigma}$	§C.2 Pauli spin matrices
σ	cross-section; σ_{tot}, σ_e, σ_f total, elastic, fission cross-section
τ	mean life; τ_{E1}, τ_{M1} electric, magnetic, dipole transition mean life; §7.4 $(\tau_i)^{-1}$ partial decay rate
Φ	§3.4 meson field
ϕ	electromagnetic scalar potential
$\psi(\mathbf{r})$	single particle wave-function
ψ_m	§D.1 general wave-function
Ω_{S0}, Ω_T	§3.3 angular terms in the nucleon–nucleon potential
ω	angular frequency