Fundamentals of nuclear physics

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To Jane, John and Tessa

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Preface

The aim of this textbook is to give a student a thorough understanding of the principal features of nuclei, of nuclear decays and of nuclear reactions. The properties of nuclei at low excitation and low angular momentum have been thoroughly studied and are now generally understood, and current research is on nuclei at high interaction energies, high angular momentum and far from the valley of stability. Several models have been developed to explain the observed wide variety of phenomena and I have attempted to describe and justify them, and also to explain the connections between them in some detail. This involves trying to give a microscopic description of nuclei, which is an intriguing many-body problem and forms an important part of this book. Besides this interest, parts of nuclear physics are of importance in the study of elementary particle physics and several nuclear phenomena have particular significance in other fields: for example, fission in nuclear power, fusion in astrophysics and radioactivity in biological tracer techniques. Consequently, nuclear physics is an important part of any physics undergraduate course.

In the first part of the book, several models are described and used to explain nuclear properties with many illustrative examples given. Sections follow on α-, β- and γ-decay, fission, thermonuclear fusion, reactions, nuclear forces and nuclear collective motion. In all of these, many examples are discussed and the student should gain a thorough grounding in our current knowledge of the nucleus. A lot of interesting experimental techniques have been developed to study nuclei and examples of these are also given.

The presentation is quantitative and short derivations are given in full to enable the student to make quantitative predictions about nuclear phenomena. The textbook is aimed at undergraduates in their final year, though the first part will be useful for a more introductory course and the latter chapters contain sections suitable for a first year graduate course. The level of the presentation is aimed at bridging the gap that exists between introductory undergraduate and graduate textbooks.

There are several questions after each chapter; those marked with an asterisk are taken from, or based on, Oxford University Physics Final Honour School questions. Several of the figures are taken from books, articles or papers, and the source is acknowledged in the figure caption.

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Physical constants and conversion factors

speed of light in vacuo	$c = (\mu_0 \varepsilon_0)^{-1/2}$	2.998×10^{8} m s^{-1}
Planck's constant	h	6.626×10^{-34} J s
	$\hbar = h/2\pi$	1.055×10^{-34} J s
		$= 6.582 \times 10^{-16}$ eV s
	$\hbar c$	197.3 MeV fm
elementary charge	e	1.602×10^{-19} C
	$e^2/4\pi\varepsilon_0$	1.440 MeV fm
fine structure constant	$\alpha = e^2/4\pi\varepsilon_0 \hbar c$	1/137.0
Bohr radius	$a_0 = \hbar/\alpha m_e c$	5.292×10^{-11} m
permittivity of vacuum	ε_0	8.854×10^{-12} F m^{-1}
permeability of vacuum	μ_0	$4\pi \times 10^{-7}$ H m^{-1}
Bohr magneton	$\mu_B = eh/2m_e$	9.274×10^{-24} J T^{-1}
nuclear magneton	$\mu_N = eh/2m_p$	5.051×10^{-27} J T^{-1}
Avogadro number	N_A	6.022×10^{23} mol^{-1}
Boltzmann constant	k	1.381×10^{-23} J K^{-1}
		$= 8.617 \times 10^{-5}$ eV K^{-1}
Fermi coupling constant	G_F	1.436×10^{-62} J m^3
Cabbibo angle	θ_c	0.224 rad
nuclear β-decay coupling	$G_\beta = G_F \cos \theta_c$	1.400×10^{-62} J m^3
constant	$G_\beta/(\hbar c)^3$	1.137×10^{-11} MeV^{-2}
gravitational constant	G	6.672×10^{-11} Nm^2 kg^{-2}
atomic mass unit (^{12}C)	u	1.661×10^{-27} kg
		$= 931.5$ MeV/c^2
neutron–H atom mass difference	$m_n - M_H$	0.782 MeV/c^2

masses (MeV/c^2): $m_e = 0.511$; $m_\mu = 105.7$; $m_{\pi^0} = 135.0$; $m_{\pi^\pm} = 139.6$; $m_p = 938.3$; $m_n = 939.6$
1 Å $= 10^{-10}$ m; 1 fm $= 10^{-15}$ m; 1 b $= 10^{-28}$ m^2; 1 eV $= 1.602 \times 10^{-19}$ J;
1 gauss (G) $= 10^{-4}$ tesla (T); 0 °C $= 273.15$ K