introduction to nuclear physics

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ADDISON-WESLEY WORLD STUDENT SERIES

Introduction to

NUCLEAR PHYSICS

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ADDISON-WESLEY PUBLISHING COMPANY

Reading, Massachusetts

Amsterdam • London • Manila • Singapore • Sydney • Tokyo

THIS BOOK IS AN ADDISON-WESLEY WORLD STUDENT SERIES EDITION

NINTH PRINTING 1979

Library of Congress Catalog Card No. 66-21268

Preface

The main parts of this book have been developed from lecture notes for a course in Introduction to Nuclear Physics that I have given at Massachusetts Institute of Technology for a number of years. Prerequisite for this subject is a one-term course in atomic physics with wave mechanics. Some knowledge of elementary wave mechanics is therefore necessary for the full understanding of the major parts of this book. For those readers who feel uncertain about their proficiency in this subject, a brief review is given in Appendix 1.

It is difficult to define the level of this book as a third-year, fourth-year, or graduate text. Any student who has studied mechanics, electricity and magnetism, and elementary wave mechanics is ready for it. The students taking the course at Massachusetts Institute of Technology are indeed from the third and fourth year, as well as from the graduate school.

The book covers what I feel are the most important areas of nuclear-structure physics, or low-energy nuclear physics. Only one chapter out of fifteen has been devoted to the exciting field of elementary-particle physics, and one chapter covers nuclear energy. There are several reasons why elementary-particle physics or high-energy physics has not been covered more extensively in this book. The most obvious one is that it is not my own field of specialization, and in experimental nuclear physics, the low- and high-energy fields are pretty much separated now. Another reason is that the elementary-particle field is in a period of rapid development such that what is written now is very soon outdated. It is my hope that a specialist in the high-energy field will write an accompanying text.

In the organization of the material in this book, no attention whatsoever has been paid to the historical development of the subject. The experiments selected as examples are practically always typical, good, recent experiments rather than historical firsts. In each chapter, covering a given topic, the experimental facts are usually presented first. Thereafter, a theory is developed for this topic, and finally, experimental results and theory are compared. In this way, I hope to impress upon the student the fact that physics is an experimental science. Partly for reasons of mathematical complexity, theories of modern physics are most often derived by use of a number of approximations. Sometimes these theories can describe the physical processes with amazing precision, relatively speaking. Sometimes there is hardly any resemblance at all between the experimental facts and the theoretical results, and it becomes a matter of judgment whether the theoretical exercise has proved anything or not. Naturally, I have selected for this elementary text only simple, straightforward theories which have enjoyed a reasonable measure of success.

For a one-semester course, I have taken the material for my lectures mostly from Chapters 1, 2, 3, 6, 9, 10, 11, 13, and 15. The other chapters can be left out almost completely without loss of continuity.

Some of the problems given at the end of each chapter are marked with an asterisk. These are intended for use as "term problems"; that is, they require a considerable amount of work on the part of the student. Many of them have several sets of numerical parameters to be used. The instructor can then give one set to each student.

A number of people have helped in various phases of the development of this book. Without comparison, the person to whom I owe the greatest debt of gratitude is Mrs. Mary E. White, secretary, typist, language teacher, proofreader, indexer, and librarian and researcher for table material. My sincere thanks also go to Mr. James E. Spencer and Mrs. Helen J. Young for valuable help, particularly in the assimilation of the material for the Table of Nuclides (Appendix 6). Corrections and suggestions received from Professor H. A. Medicus, Professor P. R. Bevington, and Mr. K. Endre Toth have been extremely helpful. Finally, a project such as this, which has to be carried out mostly evenings and on weekends, becomes a family project. The encouragement and help received from my wife and boys are greatly appreciated.

H.A.E.

Winchester, Massachusetts
May 1966

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PART 1

Introduction

1 Brief Discussion of Nuclear Properties

1–1 *Objectives of Studying Nuclear Physics*

Rutherford established the fact that the atom consists of a nucleus surrounded by electrons. The diameter of the atom is roughly 10^{-8} cm, and that of the nucleus is of the order of 10^{-12} cm. Atomic dimensions are already much too small for direct visual observations, even if the most powerful microscopes are used. However, we can still "study" the atom or the nucleus by indirect methods. These involve performing certain experiments from which we obtain data that we can see or hear and arranging each experiment so that the observed data must have some bearing on what goes on inside the atom or the nucleus.

The principal aim of nuclear physics studies is, then, by the aid of such indirect data, to understand how the nucleus is constructed and specifically to find the answers to the following questions.

(1) What are the building blocks of the nuclei?

(2) How do they move relative to each other?

(3) What is the law or laws governing the forces holding a nucleus together?

The answer to the first of these questions has long been known: the building blocks are neutrons and protons, each of which, however, has its own internal structure. Nuclear physics proper, also called low-energy nuclear physics or nuclear-structure physics, concerns itself with the questions of nuclear forces and nuclear structure. High-energy nuclear physics, or elementary-particle physics, deals with the particles of physics, their interactions, and their structure.

The expressions and concepts used in nuclear physics are mostly borrowed from macroscopic physics. We try to picture nucleons (protons and neutrons) moving around each other, subject to forces acting between them. This may be a very clumsy approach to the problem, but man is a creature who has not been provided with the proper senses to observe directly what is going on inside the nucleus. We shall continue to use borrowed expressions such as velocity, force, potential energy, etc., but we must always keep an open mind, and be very critical in using these classical concepts in nuclear physics.

Newton's laws are the accepted physical laws for describing motion of macroscopic particles at low and medium velocities. As amended by Einstein and others, these laws work for high velocities as well. By macroscopic particles, we mean particles with diameters of, say, more than 10^{-4} cm. Wave mechanics has had spectacular success in describing atomic and molecular phenomena which involve systems with diameters of the order of 10^{-8} cm. An important question now is: Can we extrapolate the proved validity of the wave-mechanics methods from atomic dimensions to the realm of the nucleus? The linear dimensions, as we have mentioned, decrease approximately by a factor of 10^4. Even more spectacular, perhaps, than the difference in linear dimensions is the difference in measurable *energy densities* between the macroscopic, atomic, and nuclear systems. A steel bar (or spring) under elastic tension may have a recoverable ("macroscopic") energy content of about 10^6 joules/m^3. The binding energy of all the electrons in heavy-element atoms amounts to about 10^{16} joules/m^3 of atomic matter (ordinary matter). The binding energy of the nucleons in an atomic nucleus amounts to about 10^{32} joules/m^3 of nuclear matter.

The answer to the question of whether or not wave mechanics can properly describe all important nuclear phenomena cannot yet be given with conviction. As we shall see later in this text, wave mechanics has been very successful, at least in some cases. In other instances, the extreme mathematical complexities of the problem make it difficult to decide whether it is the right approach.

In the following chapters we shall describe certain selected experiments in nuclear physics and try to understand, by means of elementary theories, how these experiments can further our understanding of nuclear forces and of nuclear structure. These experiments can be classified roughly as follows:

(1) measurement of static (unchanging) properties of nuclei, including measurements of size, mass, angular momentum, magnetic dipole moment, electric quadrupole moment, etc.;

(2) disintegration studies of radioactive nuclei (self-inflicted changes);

(3) studies of reactions of transmutation (forced changes).

This introductory chapter contains brief discussions of these topics to give the reader a quick glance at the subject matter that will be covered in the text and to introduce some of the terminology that will be used. On one topic, the size of nuclei, there is no further discussion in the text, and the treatment in this chapter is therefore somewhat more detailed than a mere introduction to concepts would warrant.

1–2 *Nomenclature*

Two nuclei with identical numbers of protons, Z, and identical numbers of neutrons, N, belong to the same nuclear species. A nuclear species is called a *nuclide*. It is identified by its chemical symbol and a superscript indicating the total number of nucleons, $A = Z + N$. Sometimes the number of protons (implied by the chemical symbol) is given as a subscript in front of the symbol. Examples are given in Table 1–1. Nuclides with identical Z are called *isotopes*,

Table 1–1

Symbol	Element	Z	N	A
C^{12} or ${}_6C^{12}$	Carbon	6	6	12
C^{13} or ${}_6C^{13}$	Carbon	6	7	13
Kr^{86} or ${}_{36}Kr^{86}$	Krypton	36	50	86
Hg^{192} or ${}_{80}Hg^{192}$	Mercury	80	112	192

a term which is often incorrectly used instead of "nuclide." For instance, Hg^{192} is often called a "radioactive isotope." It is a radioactive nuclide. Nuclides with identical A are called *isobars;* those with identical N are called *isotones.* Finally, an excited state (Section 1–12) of a given nuclide may be relatively long-lived, so that its decay time is directly observable. Such an excited state is called an *isomeric* (or metastable) state, and thus two nuclei of the same species but in different energy states, of which at least one is metastable, are called *isomers.*

1–3 The Nuclear Radius

Nucleons in the nucleus are confined to an approximately spherically symmetric structure. It is customary to talk about a nuclear radius, although a sharp spherical wall with a large density of nucleons everywhere inside and zero density outside does not exist.

The most direct studies of the density of nucleons in nuclei have been made by Hofstadter and coworkers at Stanford University.* The method is one of high-energy (e.g., 183 MeV) electron scattering or diffraction. Figure 1–1 shows the experimental arrangement in schematical form. The electron beam from a linear accelerator is momentum-analyzed and steered into a scattering chamber by two deflecting magnets.† In the center of the scattering chamber, the beam passes through a thin foil of the scattering material, for instance gold. Electrons scattered by deflections in the electric fields of the nuclei in the foil may pass through a thin window in the scattering chamber, a short distance through air, and thereafter through another window into the vacuum system of a magnetic spectrometer. The latter instrument momentum-analyzes the scattered electrons so that only elastic events in the target foil are recorded. The spectrometer can rotate about an axis through the target so that the intensity of scattered electrons can be observed as a function of the scattering angle θ.

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* See, for instance, R. Hofstadter, H. R. Fechter, and J. A. McIntyre, *Phys. Rev.* **92,** 978 (1953) and B. D. Hahn, D. G. Ravenhall, and R. Hofstadter, *Phys. Rev.* **101,** 1131 (1956). See also various papers in *Rev. Mod. Phys.* **30,** 142–584 (1958).

† Magnetic focusing of ion beams is discussed in Appendix 2.

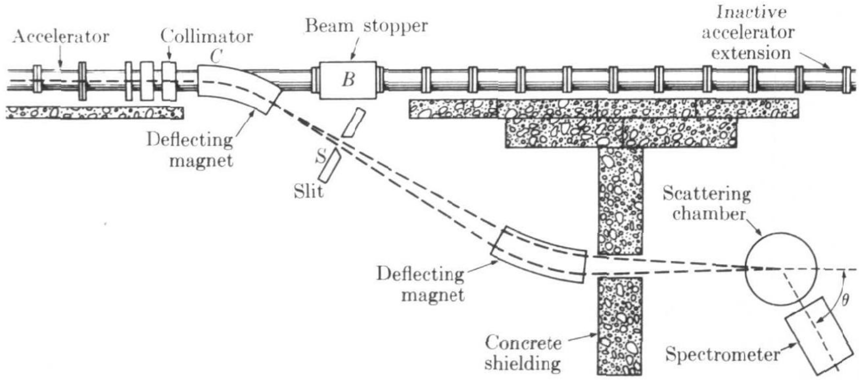

Fig. 1–1. Apparatus used by Hofstadter and coworkers for high-energy electron-scattering experiments of nuclei. (From R. Hofstadter *et al., op. cit.*)

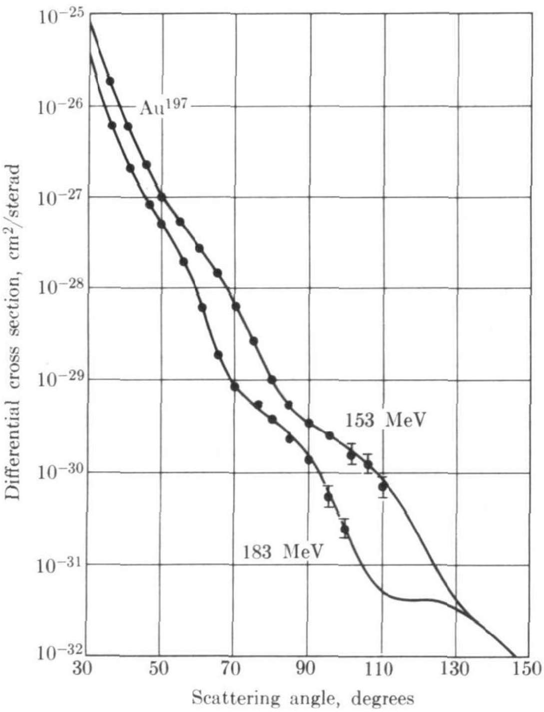

Fig. 1–2. Results of electron-scattering experiments performed on gold. (From B. Hahn *et al., op. cit.*)