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excitation mechanisms of the nucleus

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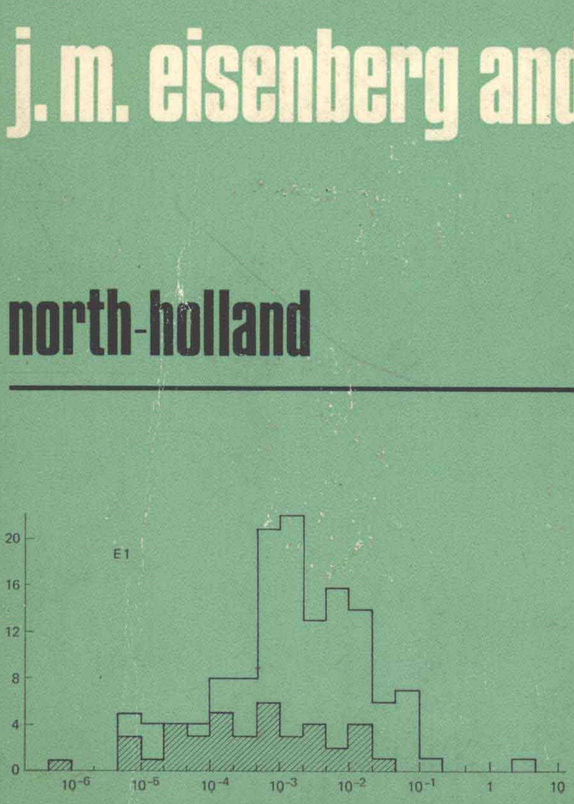

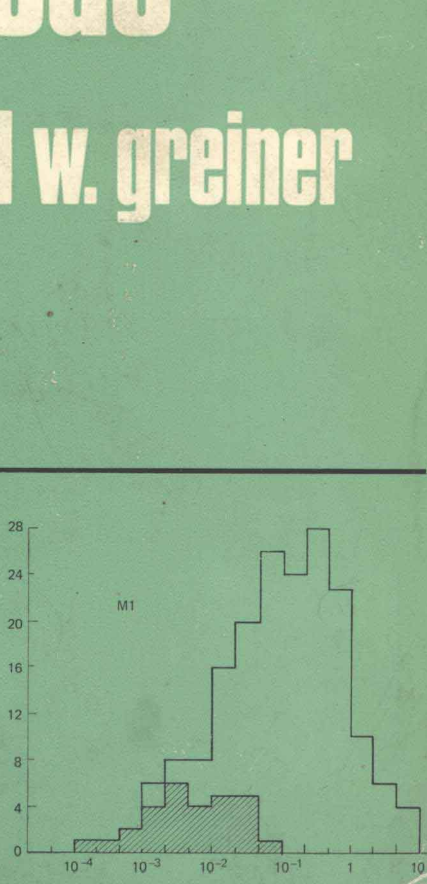

EXCITATION MECHANISMS OF THE NUCLEUS

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EXCITATION MECHANISMS
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NUCLEAR THEORY

VOLUME 2

Three books by J. M. EISENBERG and W. GREINER published by North-Holland Publishing Company:

VOLUME 1
NUCLEAR MODELS

VOLUME 2
EXCITATION MECHANISMS OF THE NUCLEUS

VOLUME 3
MICROSCOPIC THEORY OF THE NUCLEUS

Preface to the First Edition

Nuclear structure theory has long been one of the most difficult areas of physics to learn. This situation has existed largely because the techniques which have been used in the study of the nucleus have been of such diversity as to make it impossible to find extensive common themes among them. For example, nuclear experiments have involved phenomena as different as (d, n) reactions and muon capture. Even those experimental probes which are connected in their conceptual basis, such as Coulomb excitation, photonuclear reactions, and muonic atoms – all of which are basically electromagnetic in character – have focused upon quite different features of nuclear dynamics or statics. As a consequence, experimental information has, to a certain degree, tended towards fragmentation rather than integration. A similar picture emerges in nuclear theoretical work. Attempts at description by phenomenological models have drawn upon a variety of specialized areas which have often been quite far removed from each other: classical hydrodynamics, rotational molecules, shell structure, superconductivity, dispersion relations, and so forth.

In the face of this situation, most efforts to present nuclear structure physics in a more or less global way have done so by surveying key results in a large number of areas and leaving to the reader the hard job of finding out how the basic theoretical concepts were welded into detailed quantitative predictions about nuclear properties. This job is becoming increasingly difficult as the already vast and indigestible literature of nuclear physics is augmented at a frightening rate, while some of the very fundamental concepts in the area continue to be found only in the rather sketchy original accounts of the research journals. It appeared to us that the time was ripe to attempt a consolidation of this material.

Accordingly, we have tried to set forth a self-contained description of nuclear structure physics which would seek out the main lines of theoretical advances and develop them in a closely-reasoned fashion. It has been our goal to present this material so that very nearly all of the results which we include are derived here equation by equation. We have felt that a physicist who has these main lines of theoretical thinking well under control will find it relatively easy to explore the use of these essential techniques in other nuclear applications. This whole program is very much aided by advances in recent years which have led to a greater understanding of the ways in which apparently dissimilar accounts of nuclear properties are in fact closely related when one works out the implications of the fundamental concepts in a systematic fashion.

This description of nuclear structure theory has been constructed as a series of three volumes, each of which is intended to stand alone, but all of which are mutually complementary. The subject matter is organized by volume as follows:

1. *Nuclear models* (*collective and single-particle phenomena*), dealing with the phenomenological approaches to the depiction of collective rotational and vibrational features of nuclei, as well as the empirically based aspects of the spherical and deformed shell models.

2. *Excitation mechanisms of the nucleus* (*electromagnetic and weak interactions*), which treats those major techniques used in studying the nucleus which do not introduce the complications of a strongly interacting probe.

3. *Microscopic theory of the nucleus*, a volume concerned with how one describes nuclear properties beginning with the fundamental nucleon-nucleon interaction; it includes discussions of two- and three-nucleon systems, nuclear matter, Hartree-Fock approaches, the particle-hole formalism, pairing, and the relationship of these to the more phenomenological approaches.

These books have been written at a level which makes them usable for anyone who has had a conventional one-year course in quantum mechanics and who is slightly acquainted with nuclear phenomena. They may thus serve as texts in an intermediate graduate-level course in nuclear theory, in which case each volume would occupy approximately one semester. Of course, this would require that some of the material in each volume be omitted in classroom discussion. We feel this is as it should be: In the past, instructors of nuclear physics have borne the burden of elaborating on the somewhat skimpy theoretical material given in standard texts. To us it makes better sense at this level for the instructor to focus on the essential physics which is of interest for his course, leaving to the textbook the task of filling out the student's information and preparing him for reading in the nuclear research journals. We hope that these books may also serve a similar purpose for research workers in nuclear physics, providing them with background material in areas relating to their primary research interests. In particular, we would anticipate that many nuclear experimentalists will feel more at home with a book which puts in the intermediate steps than they will with one which leaves them out – the details are left out ostensibly to simplify the account, but their omission usually only succeeds in mystifying.

The present volume is the second in this series. It develops the basic formalism of multipole fields and quantization of the electromagnetic field, and then applies these techniques to describing the phenomena of photo- and electro-excitation, Coulomb excitation, and muonic atoms. It then presents weak interaction theory as it is relevant to nuclear physics, with special emphasis on the relation between this and nuclear electromagnetic processes. This volume thus serves as a natural transition between general quantum theory and its application in nuclear structure physics.

It is very humbling to realize how many people have helped us in this present enterprise, and we would like to take this opportunity to express to them our deep gratitude. We are much indebted to many physicists for useful discussions which have led to a clarification of the material in this book and its companion volumes. Among them are Drs. H. L. Acker *, M. V. Barnhill, M. Danos, B. Finck, B. Fricke, L. P. Fulcher, R. Guy, H. P. Kelly, J. LeTourneux, J. Nilsson, H. Pietschmann, R. C. Ritter, W. Scheid, E. Schopper, S. E. Sobottka, E. Spamer, B. M. Spicer, O. Tietze, H. J. Weber, and W. D. Whitehead. One of us (W.G.) would like to thank Dr. N. Cabrera for the hospitality extended to him at the University of Virginia. We would also like to express special thanks to Dr. W. D. Whitehead, and through him to the Center for Advanced Studies of the University of Virginia, for solving many difficult administrative problems, thereby making our collaboration possible. The Deutsche Forschungsgemeinschaft, the Bundesministerium für wissenschaftliche Forschung, and the Hessiches Kultusministerium are also deserving of thanks in this regard.

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* Deceased.

Our task in preparing the manuscript for press was substantially lightened by the unfailing cheerfulness and patience with which a number of people undertook to type this material. Chief among these were Mmes. E. Löhlein, M. Knolle, B. Paup, P. Walker, and S. Wigent. Mrs. C. Dadakis helped with obtaining library materials, and Mmes. L. Urbanek and S. Springwald drew the figures. We express here our very sincere thanks for all of this assistance.

Charlottesville, Virginia
April, 1969.

J. M. Eisenberg
W. Greiner

Preface to the Second Edition

Many of the topics covered in the first edition of this volume have subsequently been gathered into the general subject heading of "medium-energy nuclear physics" in response to the new development of accelerators which are copious sources of either electrons and photons or nucleons, pions, muons and neutrinos, and which function in the energy range of roughly 100 MeV to 1000 MeV. It therefore seemed desirable in this second edition to round out the coverage of material by including a chapter on strong interactions at medium energies. We hope that this can serve as an introduction to what promise to be very exciting developments in the coming years in this area.

Our thanks are once again extended to the many physicists who have influenced the presentation of material in this book, and who have pointed out errors which we have tried to correct in this second edition.

Charlottesville, Virginia
Frankfurt am Main, Germany
August, 1975

J. M. Eisenberg
W. Greiner

Contents

CHAPTER 1

Introduction

The present volume is concerned with the theoretical description of various mechanisms for probing nuclear structure. From the point of view of nuclear theory, two essential considerations must be brought to bear on the selection of a particular reaction mechanism for the study of nuclei. The first of these is the reliability with which current theoretical techniques can be used to describe the process in question; the second is the nature of the nuclear structure features to which a given mechanism is sensitive. The reactions discussed here will, for the most part, be drawn from amongst the electromagnetic and weak interactions so that the major unknown parts of the problems under discussion will relate to nuclear structure rather than to the reaction mechanism. Furthermore, these reactions have the property that they often tend to excite nuclear modes of a particular character. The levels in question generally correspond to a situation in which many of the nucleons take part in a given motion on an equivalent basis. This kind of collective nuclear motion can be described on the basis of semi-phenomenological theories using collective parameters to characterize the models of the nucleus which is viewed as a continuous distribution of matter. On the other hand, and perhaps more surprisingly, collective motion can also be satisfactorily treated using the shell model which takes as its initial point of departure the fact that the nucleus is an aggregate of interacting particles. The exploration and reconciliation of these two alternative viewpoints is one of the pivotal questions in nuclear structure theory, and so one must expect that the mechanisms which excite the collective modes will play a particularly important role in this theory.

A good example of these considerations is provided by the photonuclear giant resonance. In 1947, it was observed (Ba-47, Ba-48) that nuclei exhibit strong resonances in photon-induced reactions at energies of the order of 15 to 20 MeV. These resonances are now known to be a general feature found in all nuclei, and to correspond to excitation by the electric dipole component of the incident photon. Now the fact that electromagnetic waves favor electric dipole excitation when the wavelength is greater than the dimension of the excited system is well known and very general, so that the dominance of this component in photo-excitation at these energies does little more than to confirm that nuclei are small. On the other hand, the fact that the levels reached preferentially in the dipole transition are all in the same general energy region and that this region is similarly located in various nuclei has profound consequences for our understanding of nuclear structure. It emerges that the excitations in question correspond to the oscillation of protons and neutrons against each other, and for this reason they are labeled isospin modes. This motion can be characterized phenomenologically in terms of a sphere of protons oscillating against a sphere of neutrons, or alternatively in terms of oscillations in interpermeating proton and neutron fluids contained in a spherical or ellipsoidal box. However, it is also possible to describe the giant dipole resonance using the shell model. In that case, the relevant levels involve the promotion of a particle from the last filled shell of the core into the next shell. The connections between these two different manners of handling the giant resonance can be explored in considerable detail.

The photonuclear giant resonance mode can also be excited by inelastic electron scattering. At low momentum transfer, this process is essentially equivalent to photo-excitation and therefore produces as its dominant feature the same characteristic proton–neutron oscillations. As the momentum transferred by the electron to the nucleus is increased, a new kind of collective motion comes into play. The probing electron begins to be sensitive to the magnetization part of the nuclear current, and as a result levels are excited which we shall designate as spin–isospin modes. These modes correspond to a situation in which protons with spin up and neutrons with spin down oscillate against protons with spin down and neutrons with spin up (see fig. 1). As was the case with photo-excitation and the isospin modes, when one makes a detailed examination of the electro-excitation mechanism it is not surprising that these spin–isospin modes should appear preferentially at moderately high momentum transfer. What is surprising is that when one looks for these levels experimentally they appear localized in a fairly restricted range of excitation energies, and that range coincides rather closely with the photonuclear giant resonance region. Once again, the reasons for these special features lie in the nuclear structure description of these collective modes, and in particular relate to the fact that nuclear forces are relatively weakly dependent on the spin and isospin states of the interacting nucleons.

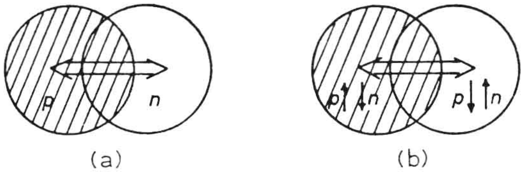

Fig. 1. Pictorial representation of isospin modes (a), and spin–isospin modes (b) of nuclear excitation. The vertical arrows denote spin direction.

The isospin and spin–isospin modes of nuclear excitation also play a crucial role in the muon capture reaction. Thus this reaction can be used to study them, and alternatively a precise understanding of their character is especially important in order to carry out a complete program for the description of weak interactions. The use of muon capture for nuclear structure studies is somewhat difficult because one can not observe the outgoing neutrino experimentally so that in order to obtain an excitation spectrum it becomes necessary to observe the nucleons emitted after the capture. This in turn drags in all the complications of the strong interaction physics in nuclear reaction theory. The situation is redeemed somewhat by the fact that it is possible to relate muon capture to radiative pion absorption. This latter process is one in which a bound negative pion is absorbed by the nucleus with the emission of a high-energy photon which takes up most of the pion rest mass energy. It excites a variety of spin–isospin modes very readily, and since the outgoing photon is observable, one can obtain a direct measurement of the distribution of nuclear excitation energies for spin–isospin levels.

The present volume confines itself in the main to a discussion of those aspects of nuclear interactions which can be understood without the introduction of detailed models of nuclear structure. Some examples of very simple nuclear models are used for illustrative purposes, but more extensive treatments of nuclear structure models are reserved for the two other volumes in this series. In particular, Volume 1 deals with phenomenological models appropriate to the treatment of collective modes of nuclear motion, and Volume 3 will deal with microscopic approaches to nuclear structure theory.