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THEORY OF COMPLEX NUCLEI

ABSTRACT

THIS monograph is an introduction to the contemporary theory of complex nuclei. The experimental data characterizing the ground and low-lying excited states of medium and heavy nuclei are systemized and compared with the results of calculations. The achievements and the possibilities of the new methods used for description of the nuclear structure are demonstrated.

The necessary introduction to the theory of complex nuclei is given in Chapters 1 and 2. The choice of the nuclear model Hamiltonian and the Hartree–Fock–Bogolyubov variational principle are discussed in Chapter 3. The independent quasiparticle model is described in Chapters 4–7. Its application to the calculations of the nuclear spectra, nuclear transitions, nuclear equilibrium forms, and nuclear moments of inertia is also described in Chapters 4–7. Chapters 8–10 contain the exposition of the semimicroscopic nuclear vibration theory and the application of the theory to the deformed and spherical nuclei.

FOREWORD

THIS monograph was written with the aim of providing a course in nuclear theory. Main emphasis is given to the description of properties of ground and low-lying states of medium and heavy nuclei.

The scope of nuclear theory is so extensive that it cannot be fully described in a single book. Such parts of the nuclear theory as the formal scattering theory, problems of the two-nucleon interaction, the theory of the interaction with electromagnetic radiation, the theory of α- and β-decays, and several others are sufficiently explained in many nuclear physics textbooks. Special monographs are devoted to the explanation of specific parts of nuclear theory, such as the theory of nuclear matter, the fission theory, the application of group theory in nuclear physics, etc. Naturally, it is unnecessary to repeat here the content of those parts of the nuclear theory which are either sufficiently fully described in textbooks and monographs or which are not directly connected with the main content of this book. If the title of this monograph is to correspond as closely as possible to its content, it should be called "Introduction to certain aspects of the theory of medium and heavy nuclei".

Investigation of the atomic nuclei has two goals: the investigation of the nuclear structure *per se* and the investigation of the elementary interactions manifested in the properties of atomic nuclei. This monograph treats the nuclear structure as such; only the decisive interactions are included in the calculations. Described problems of the α- and β-decay theory and of the nuclear reaction theory are directly related to the nuclear structure, i.e. these processes are used as sources of information about the structure of complex nuclei.

Nuclear theory has reached such a level that the intrinsic unity of our ideas about nuclear structure is sufficiently evident. This allows the use of the deductive method of explanation in the book. It is necessary to note that the monograph describes basic methods of the nuclear many-body problem, which cannot yet form a closed theory. However, these nuclear theory methods form a basis, which makes it possible to perform scientific investigations and to analyze original nuclear physics works.

The general mathematical methods of the nuclear theory are treated in the monograph separately (Chapter 3, § 2; Chapter 4, § 1; and the whole Chapters 5 and 8). Readers not interested in the mathematical basis of the described methods may skip § 2 of Chapter 3, the whole of Chapter 5, and §§ 1 and 3 of Chapter 8. This will not cause any interruption in the continuity of the explanation.

Particular emphasis is given to the systemization of experimental material and to its comparison with the results of calculations. The majority of the theoretical results in tables and figures was recalculated using a unified basis.

The monograph does not contain a full bibliography of the discussed nuclear physics problems. References are given to the more important papers and books and to those works, the results of which are used in the monograph.

This book was writen in 1966–9. Part of the material is included in lectures, given since 1961 in the Dubna branch of the Physics Department of Moscow State University. Some parts were described in lecture courses, given in the IAEA summer school on nuclear theory in Czechoslovakia, 1962; in the JINR school on the structure of complex nuclei in Telavi, Georgia, 1965; in the all-union summer schools in Obninsk, 1966, and Khumsan, 1967, and in lectures given in Hungary, GDR, Italy, Romania, and Japan.

The monograph is intended for theoretical physicists, for the experimentalists working in nuclear physics, and for graduate and upper class students. It is assumed that the reader is familiar with the basic methods of quantum mechanics, statistical and nuclear physics.

I would like to express my deep gratitude to academician N. N. Bogolyubov for his constant interest, which has helped me in writing the monograph.

I would like to acknowledge many helpful discussions with my colleagues in the nuclear theory division of the Joint Institute for Nuclear Research. I am particularly obliged to D. A. Arsenev, V. B. Belyaev, R. V. Jolos, R. A. Eramzhyan, S. I. Fedotov, F. A. Gareev, S. P. Ivanova, I. Khristov, V. K. Lukyanov, L. A. Malov, I. N. Mikhailov, N. I. Pyatov, V. Rybarska, I. Sh. Vashakidze, and A. I. Vdovin, for their help in the explanation of particular problems. I am thankful to my wife, G. M. Solovieva, for her help in preparing the monograph for printing.

CONTENTS

INTRODUCTION

NUCLEAR physics is one of the youngest disciplines of science. Up to the second half of the nineteenth century, the atom was believed to be the smallest, nondivisible part of matter. The history of nuclear physics begins with the discovery of the Mendeleyev periodic law. The Mendeleyev table reflects the laws of atomic structure and the existence of nuclear mass number A and nuclear charge Z. The Mendeleyev periodic law played a principal role in the development of nuclear physics.

The development of nuclear physics can be divided into three periods. The first one (1896–1932) is the period in which the most general facts related to the atomic nucleus were discovered. H. Bequerel found radioactivity of uranium in 1896. P. Curie and M. Sklodowska-Curie found new radioactive elements—radium and polonium. Afterwards, three types of radioactive radiation were found: α-, β-, and γ-rays.

In 1904, J. J. Thomson suggested an atomic model, according to which the atom is a positively charged sphere, with electrons moving inside it. The Thomson model was disproved by Rutherford's experiments on α-particle scattering on thin foils. These experiments led to the discovery of atomic nuclei. The atomic planetary model was introduced by E. Rutherford in 1911. According to this model, an atom consists of a positively charged nucleus, with a radius of the order 10^{-12} cm and of electrons distributed around the nucleus with radii 10^{-8} cm. Almost all atomic mass is concentrated in the nucleus. Later, using quantum theory, N. Bohr justified and developed further Rutherford's atomic model. The nuclear transmutations of stable nuclei were discovered by E. Rutherford in 1919. At the same time, F. Aston found stable isotopes and established the basis for the development of mass spectroscopy.

The first quarter of the twentieth century is characterized by great development in physics. The most important achievements were the formulation of the relativity theory and quantum mechanics. These theories radically changed the ideas prevailing at the turn of the twentieth century about the basic laws of nature. They had important revolutionizing impact not only in physics but also in other natural sciences. The establishment of the relativity theory and of quantum mechanics formed the basis for the development of nuclear physics.

The second period in the history of nuclear physics (1932–49) can be described as the prehistory of modern nuclear physics. In 1932, J. Chadwick discovered the neutron, and J. Cockroft and E. Walton made the first nuclear transmutations using artificially accelerated particles. The discovery of the neutron led to the formulation of the proton–neutron model of an atomic nucleus by W. Heisenberg and D. D. Ivanenko. I. Curie and F. Joliot-Curie discovered artificial radioactivity and positron β-decay. These discoveries led to the synthesis of new elements. I. V. Kurchatov discovered nuclear isomerism, and L. Alvarez found nuclear transmutation caused by the capture of the orbital electrons.

The discovery of the fission of uranium nuclei bombarded by neutrons, made in 1938 by Hahn and Strassmann, was very important. G. N. Flerov and K. A. Petrzhak found spontaneous fission of uranium somewhat later. The first nuclear reactor was built and operated in the United States under the guidance of E. Fermi in December 1942. The intensive studies of nuclear fission and neutron interaction with matter formed the scientific basis of nuclear energy production.

The muons were found in cosmic rays in 1938, π-mesons in 1947; K-mesons and hyperons were found somewhat later. The technique of particle acceleration was further developed, and several low-energy accelerators were built. The proton 330 MeV accelerator was built in Berkeley (USA) in 1947, and a 440 MeV proton accelerator was built in Dubna (USSR) in 1949. The nucleon interactions at these energies were studied, and π-meson production caused by the proton-nucleus interaction was discovered. The construction of high-energy particle accelerators and the discovery of many new elementary particles led to the separation of a new discipline from nuclear physics—the physics of elementary particles.

Recent systematic study of nuclear structure and nuclear reaction mechanism can be considered as the third era in the development of nuclear physics. New technical development allowed physical studies on a large scale. New transuranium elements and a large number of new isotopes throughout the periodic system were produced. Experimental facts were accumulated in large numbers, and that brought about the determination of many nuclear properties and quantum characteristics of the ground and excited states of light, medium, and heavy nuclei. The various mechanisms of the nuclear reactions were studied. The development of the α-, β-, and γ-spectroscopy was also significant. The importance of nuclear reactions in the nuclear structure studies is ever-growing. The developed theoretical concepts helped to understand the basic nuclear processes and properties of ground and excited nuclear states.

The contemporary period of the development of nuclear physics is a period of intensive accumulation of experimental facts and their analysis. It is necessary to note, however, that quantitative experimental nuclear structure information is still rather limited.

Figure 1.1 shows the nuclear neutron-proton diagram. Nuclei in the region between the lines $B_n = 0$ and $B_p = 0$ should exist in nature (with lifetimes considerably larger than the characteristic nuclear time interval). These nuclei have positive neutron and proton separation energies. It is seen that the experimentally known nuclei form less than a quarter of all the possible nuclei. Physicists are trying to solve the problem of superheavy nuclei. In particular, it is possible that relatively long-lived nuclei exist in the region of $Z = 114$ or 126 and $N = 184$.

The low-lying excited states have been experimentally studied in only about 10% of the existing nuclei. Experimental information about the intermediate region of excitation energies is rather poor.

The methods of neutron spectroscopy give information about the average characteristics of compound states close to the neutron binding energy. Explanation of the nature of such states (How different is the structure of levels with the same spin and parity? What is the

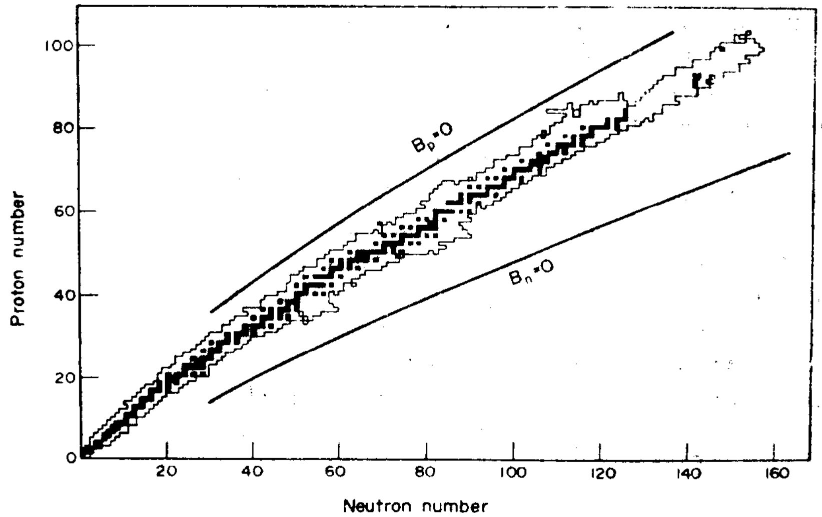

FIG. I.1. Neutron-proton diagram of the atomic nuclei. Dark areas: stable and long-lived nuclei. Light areas: known radioactive nuclei.

manifestation of shell effects? What is the role of the few quasiparticle components of the wave functions?, etc.) is very important. The most useful results are obtained from studies of the $n\gamma$ and $n\alpha$ reactions on resonance states. The study of the analog states and of different giant resonance states provides interesting information about the quasicontinuous part of the spectrum. It is not necessary to stress that the study of the analog states and giant resonance fine structure is only beginning.

The principal importance of elementary particle studies is obvious. Many scientists believe that the fundamental problems of physics will be solved in this way. We shall try to answer the following question here: Is the study of atomic nucleus scientifically equally important? We think that the answer is yes for two reasons. First, the atomic nucleus is the basic and determining part of nature. Almost all the mass of matter is concentrated in nuclei. The nuclear mass and charge determine the structure of the electron cloud and thus the basic physical and chemical properties of atoms. The special features of nuclear structure and nuclear forces are very important in astrophysics because nuclear transmutations play the determining role in stars. The study of the nuclear structure must be of principal scientific importance when nuclei are so important in nature. It should not be forgotten that elementary particle physics was established in connection with the study of nuclear forces and the formulation of nuclear theory. The great variety of nuclear properties, which form an almost inexhaustible source of practical application, should also be mentioned. Thus the first argument is quite general. The second argument is the following one: the study of the elementary interaction process of two particles gives insufficient information about the particles themselves; additional information can be obtained from a study of the systems of interacting particles. The many-body problem gives complementary information about the involved forces. That part of the information, obtained from the solution of the many-body problem, cannot be obtained directly from the two-body problem.

Let us explain the second argument with two examples: the study of the deuteron and of nucleon–nucleon scattering cross-section below the meson production threshold did not lead to the unique determination of the nucleon–nucleon interaction potential (the very concept of the potential is only approximate). The experimental information can be explained using potentials with different forms (hard-core and soft-core potentials, velocity-dependent potentials, etc). However, when the properties of nuclear matter (when the Coulomb repulsion between protons is excluded, an arbitrary number of nucleons forms a stable system—so-called nuclear matter) and the properties of the finite nuclei are taken into consideration, the number of possible potentials is rather limited. The second example deals with the applicability of the independent particle model to the description of atomic nuclei. The interaction of nucleons bound in nuclei is considerably weaker than the interacton of the free nucleons. This difference is connected with the Pauli principle, i.e., we encounter peculiarities of the many-body problem in nuclei absent in the elementary interaction process. When the structure of atomic nuclei is studied, it is necessary to study not only the properties of the nuclear forces but also the conditions under which the forces are acting.

The development of nuclear physics in recent years did not lead to great discoveries; nevertheless, there has been important progress. There are two tendencies in nuclear structure studies. The first tendency is related to the full and detailed description of the ground-state properties of individual nuclei and to the expansion of such a description toward higher excitation energy. The second tendency is related to the description of larger and larger sets of nuclei, moving toward the superheavy nuclei and to nuclei further from the beta stability region.

Our study cannot be limited to one or several nuclei if the nuclear structure is to be understood. Many characteristic features of even–even nuclei are different from those of the neighboring odd–even or odd–odd nuclei. The structure of deformed nuclei is quite different from the structure of spherical nuclei, etc. There are important differences among the deformed nuclei. For example, actinide nuclei undergo fission, while deformed nuclei in the $150<A<190$ region do not. It is evident that fission cannot be studied using the properties of rare-earth isotopes. While nuclei in the $150 < A < 190$ and $228 < A < 254$ regions have a prolate ellipsodial form, nuclei in the $50 < Z, N < 82$ and $28 < Z < 50, 50 < N < 82$ have, possibly, oblate form, etc. We could mention other properties which are different for different nuclei. However, it is already clear that the structure of the different nuclei is different even if the forces are always the same. Thus it is necessary to study wide regions of nuclei.

Nuclear structure information, obtained in experiments with intermediate and high-energy particles interacting with nuclei, is ever-increasing. Thus the scattering of fast electrons shows that nuclear charge distribution may deviate from the Fermi distribution. Nuclear K-meson absorption suggests an existence of the neutron skin.

Important nuclear structure information is contained in the muon capture studies. The interaction of π-mesons with nuclei gives information about the short-range correlations of the nucleons in nuclei. The direct knock-out of certain light nuclei during interaction of fast protons with nuclei gives information about the nuclear cluster structure. The mechanisms of high-energy particle interaction with nuclei are very interesting.

Study of hypernuclei should be very useful in future nuclear structure research. In such nuclei, one or several nucleons are replaced by hyperons; the interaction between hyperons and between hyperons and nucleons can act without restrictions. Thus new features of the nuclear structure problem should be seen.

The contemporary period of the accumulation of experimental information is unavoidable. It is possible that it will lead to important discoveries. From the point of view of fundamental physical laws, the atomic nucleus problem is far from being exhausted.

Theoretical nuclear physics began more than 30 years ago after the discovery of the neutron and the realization that the nuclei are built from protons and neutrons. There are two basic difficulties in the formulation of nuclear theory. First: nuclear forces are very complicated and insufficiently known. Second, it is difficult to make a theory of systems composed of a large but finite number of particles when their interaction cannot be characterized by a small parameter (even for simple forces). Therefore the development of nuclear theory followed the line of a search for simple models. In the initial period of nuclear physics, the nucleus was compared to the charged drop or to the degenerate Fermi gas. Later, the word "model" got a wider meaning. Any set of the simplifying assumptions, both physical and mathematical, which allows calculation of nuclear properties with certain accuracy, is called a model. Thus the nuclear problem is transformed into the formulation of a model, which describes the real systems with the highest possible accuracy, on the one hand, and which is mathematically soluble, on the other. Each model stresses one particular aspect of the whole problem. If the model is used for the explanation of experimental facts, only those facts where this particular aspect is important are chosen.

Two basic types of nuclear models were developed. In models with strong interaction the nucleus is treated as an ensemble of tightly bound particles. Models of independent particles form the second type. Nucleons are moving approximately independently in the models of this type.

Two experimental facts were established in the initial period of the study of nuclear structure. The binding energy per particle is approximately constant for all nuclei (with the exception of the very light ones), and nuclear volume is proportional to the number of the nucleons. From these facts it follows that the proton and neutron density is constant in all nuclei. On the other hand, it was found that the interaction between nucleons is of short range and is strong. Therefore, a model with strong interaction, in which the nucleon mean free path is shorter than the nuclear dimensions, was formulated. N. Bohr and Ya. J. Frenkel suggested the charged liquid-drop model. It gave correct results when the stability against deformation was studied; it also established the limit of stability against fission.

N. Bohr has introduced the concept of the compound nucleus in the description of the interaction of incoming nucleons with nuclei. The model is based on the assumption that all nucleons are responsible in the same degree for the properties of a given nuclear state. According to this concept, the incoming nucleon interacts with one or two target nucleons and transfers to them (and through them to the whole nucleus) a large part of its energy. This happens before the particle penetrates the whole nucleus. The incoming particle, having lost most of its energy, is captured by the nucleus. The lifetime of the compound nucleus is long when compared with the time of flight through the nucleus. The compound nucleus has an energy excess—the energy brought in by the incoming particle. After a while, the energy excess (or its considerable part) can concentrate in one nucleon, which can leave the nucleus.

The success of the compound nucleus theory and the discovery and interpretation of the fission phenomenon suggested that the liquid-drop model describes well the real nuclei. However, it turned out that the liquid-drop model is inapplicable to the description of nuclear excited states. The dynamics of nuclear motion responsible for the properties of excited states is much more complicated than the motion of a liquid drop. Besides, the assumption that the mean free path is small was disproved. The mean free path is considerably larger than the distances between nucleons; it is comparable with nuclear dimensions. Nevertheless, the liquid-drop model played an important role in the history of nuclear theory.

The successful application of the Hartree–Fock method in atomic theory could explain interest in nuclear independent particle models. It is obvious that the Hartree–Fock method should give less accurate results in the nucleus than in the atom because the common source of force is missing and nuclear interaction is strong and has a short range. However, the nuclear shell model, formulated by Mayer and Haxel *et al.*,[1] was unexpectedly successful. The shell model assumed that a number of nuclear properties could be explained if individual nucleons move independently in an average field. The average field is formed by all other nucleons. The shell model explained not only the enhanced stability of the magic nuclei, but it explained many other experimental features of ground and excited nuclear states and many characteristics of their decay as well.

It should be noted that the average field of atomic electrons and the nuclear average field are substantially different. The nuclear field is induced by the nucleons only; therefore it must be less stable with respect to the deformations and surface vibrations.

Several experimental facts, unexplainable in the framework of the nuclear shell model, were known even in its early period. For example, in a large number of nuclei the intensity of the electrical $E2$ transition is up to one hundred times larger than the intensity of the one-proton transitions. Weakly excited states in even–even nuclei show even more clearly the existence of the collective effects. All these facts were observed in nuclei which have neutron and proton numbers very different from the magic numbers.

The pecularities of nuclei with many nucleons in the unfilled shells were explained by the unified nuclear model developed by Bohr and applied by Bohr and Mottelson.[2] The basic assumption of the unified nuclear model is the assumption of the ellipsoidal shape of these nuclei. The lowest excited states in this case are rotational states of the nucleus as a whole. The unified nuclear model takes explicitly into account the degrees of freedom related to the motion of one or several weakly bound nucleons. At the same time, the collective vibrations, related to the changes in the nuclear shape and orientation, were taken over from the liquid-drop model. The unified nuclear model is therefore an intermediate model between the shell and liquid-drop models. However, its basic physical assumptions are much closer to the shell model. All nucleons participate in the collective vibrations to a certain degree. The main role, however, is given to weakly bound nucleons, i.e. nucleons close to the Fermi level.

The unified nuclear model explained a large number of experimental facts and predicted a number of properties of deformed nuclei. The ideas of nuclear collective degrees of freedom were further developed by Davydov and coworkers,[3] who have discussed a more general case of nonaxially symmetric nuclei.

The scattering of particles on nuclei is sufficiently described by the nuclear optical model. This model is very similar to the independent particle model. The behavior of the incoming particle is described by its motion in the average nuclear field which has an imaginary (absorptive) part. If during the first collision of the incoming particle with the target nucleon one particle leaves the nucleus, we are dealing with a direct nuclear reaction. On the other hand, if the particles collide again and again, the chances that one particle will leave the nucleus are decreased, and the compound nucleus is formed. Thus, the independent nuclear model includes the two basic forms of nuclear reaction: direct interactions and formation of the compound nucleus.

Models using often contradicting assumptions were used in early nuclear theory. In recent years, however, the models used are complementary rather than contradictory. The properties of ground and low-lying excited states (up to 2 MeV) in medium and heavy nuclei are, at the present time, explained in the framework of the concept of average field plus residual interaction between nucleons.

The interaction between nucleons in the nuclei could be conditionally divided into two parts: the average, or selfconsistent nuclear field and the residual interaction. The average field is the nuclear potential which is formed by all nucleons. The residual interaction is that part of the interaction, which is not included in the average field. Note that some parts of the nucleon interaction cannot contribute to the average field in principle. The residual interactions play an important role in nuclei; they are not weak and cannot be treated by the perturbation method. They change smoothly and slowly when going from one nucleus to its neighbor. The average field determines certain nuclear properties directly. Besides, it governs the residual interactions, i.e., it defines the conditions for the materialization of their effects. The average field is responsible for a number of concrete features of individual nuclei and for the differences between them.

The contemporary state of the nuclear theory is characterized by wide application of mathematical methods and physical ideas of the quantum field theory and of statistical physics. Works on superfluidity,[4] superconductivity,[5, 6] and Fermi-liquid theory[7] were particularly important for the development of nuclear theory. The mathematical methods of the superfluidity and superconductivity theory are very general. They allow one to solve the problem of residual fermion interaction, leading to pair correlations, in a rather general form. Bogolyubov[8] has suggested the possibility of the superfluidity of nuclear matter; later, Bohr *et al.*[9] discussed the existence of the superfluid states in atomic nuclei. The theory of pair correlations of the superconducting type in atomic nuclei was formulated independently by Belyaev[10] and Soloviev.[11, 12] The theory of pairing correlations explained many nuclear properties which were not understood before. Moreover, it gave a basis for broad studies of nuclear structure, based on the microscopical approach. From the large number of papers in this field we would like to mention the work of Migdal[13, 14] based on the Fermi-liquid theory.

Contemporary nuclear theory is not a theory of nuclear models if the term "model" is understood in its usual meaning. Physicists use the word "model" to characterize an approximate method used for the description of a certain restricted class of properties of a large number of nuclei. Only part of the nuclear forces, responsible for the discussed nuclear properties or processes, is taken into account. The remaining forces are either neglected completely or included in a crude way. Thus, the word "nuclear model" means that only part of the nuclear force, particularly important for a certain set of nuclear properties, is taken into account. Note that this part of nuclear force (which is taken into consideration) is changed when other nuclear properties or other nuclei are considered. Therefore, the approximate methods for the description of the main nuclear characteristics change as well, when different characteristics are considered, or when light or heavy nuclei are considered. This important peculiarity of the atomic nucleus is a consequence of its complexity and of the diversity of its properties.

Therefore, "model" in contemporary nuclear theory means an approximate method of description of nuclear properties, which takes into account the most important, i.e. determining for the given properties part of the nuclear force. This monograph is devoted to the description of nuclear models in this sense.

The problems of nuclear theory are so vast that they cannot be fully explained in one book, as Blatt and Weisskopf[15] did some 20 years ago. The experimental material about medium and heavy nuclei is quite rich and diverse. For example, a full description of all experimental facts about nuclei with the mass number $A = 182$, and their analysis[16] forms a book of appreciable volume. Thus a full description of nuclear theory needs several volumes. This problem has been solved, seemingly, by Bohr and Mottelson in their monograph; its first volume has already appeared in print.[17]

A number of the aspects of nuclear theory are fully described in textbooks (see refs. 18–20); some are explained in good monographs (see refs. 21, 22). For example, problems of nuclear matter and of the applications of methods, developed by Brueckner and others, to the finite nuclei, are described in detail in refs. 21–23. Obviously, it is not necessary to include them here.

The description of the theory of ground and excited (up to 2–3 MeV) states of medium and heavy nuclei forms the main content of this monograph. The semimicroscopic approach, based on the selection of interaction (which reflects the most important part of nuclear forces), is used. The nuclear many-body problem can be reduced to the problem of several degrees of freedom. This fact explains the success of the semimicroscopic approach, which is a natural extension of the phenomenological method.

The deductive method is used in this monograph. The interaction Hamiltonian, describing nuclear rotation, the average nuclear field, and residual interaction between nucleons is constructed. Approximate mathematical methods of solution of the nuclear many-body problem (with different parts of the forces, contained in the interaction Hamiltonian) are explained. The structure of ground and excited states of complex nuclei is studied. The interaction Hamiltonian has been chosen in its simplest possible form. We want to test how the large ensemble of the experimental facts can be explained by using a relatively simple interaction, and to see when and what kind of the effective forces must be added.

Large emphasis is given to the systematization of the experimental material and to its comparison with theoretical calculations. This has been done, however, in a rather general way. In this aspect, the book differs from, for example, ref. 24 where all available experimental material about odd-A deformed nuclei is carefully analyzed, systemized, and compared with theory (see also ref. 25).

In conclusion, let us make a few comments about terminology.