ABSTRACT

to the dissertation work of Aknur Duisenbaykyzy Duisenbay
"Cluster systems interaction in nuclei", submitted for the degree of Doctor of Philosophy (PhD) in the specialty "6D060500-Nuclear Physics"

General description of work. The dissertation work is devoted to the study of the structure of light atomic nuclei and the dynamics of nuclear processes, as well as the theoretical analysis of the spectra of ^{8}Li and ^{8}B nuclei and the study of the influence of the Coulomb interaction on the spectrum of resonance states in two- and three-cluster continuums.

Relevance of the topic.

Nuclear physics is one of the fastest-growing areas of science in terms of theoretical and experimental research. Much in this field is still unclear and unexplored. Of particular interest are nuclear reactions involving light nuclei, which are responsible for the synthesis of atomic nuclei, the formation and evolution of the universe, the birth of stars, and related processes.

The analysis of astrophysical data on the propagation of light atomic nuclei in the universe stimulates new and more detailed experimental and theoretical studies of the properties of light nuclei and the reactions involved in them. Astrophysical applications of nuclear data require more detailed and accurate determination of the effective cross sections for nuclear reactions in the low energy range. There are no reliable experimental data in this energy range, and in this respect, nuclear astrophysics continues to require theoretical models.

Some energy levels of light nuclei studied experimentally in nuclear reactions sometimes cannot be explained by simple models such as the ordinary shell model or collective models of nuclei. For this reason, a combination of different models is often used. An important place is occupied by cluster models, in which nucleons are assumed to combine in most cases to form different, nearly stable structures, called clusters, which interact with each other.

The interacting clusters model allows to study in detail the properties of weakly bound light nuclei and their possible configurations. More specifically, the nucleus as a group of dynamically interacting clusters has its own unique internal cluster structure that is distinct from other nuclei.

The physics of clusters has historically been associated with the nucleus of the helium atom (α-particle), and the properties of the α-particle itself played a special role in this choice.

The models proposed for a given nucleus (and a similar mirror nucleus) usually consider only some of its main features. Since the formation of clusters strongly depends on correlations between nucleons and the properties of low-nucleon subsystems, the features of nuclear interactions are very specific and important for the study of nuclear cluster phenomena. The efficiency and reliability of cluster models is

confirmed by a large number of experimental data: the phenomenon of cluster radioactivity of nuclei, the compactness of α-clusters, and the formation of quasi-molecular states in nuclei and their isotopes.

At the same time, the use of cluster models greatly simplifies theoretical calculations by reducing the many-particle problem to an effective two-body problem when a two-cluster system is involved. Each cluster is considered as a stable group consisting of multiple nucleons interacting with other objects as a whole. The first and most rigorous formulation of the cluster model was by J. A. Wheeler. He introduced the concept of the "resonant group" and derived dynamical equations for the wave function describing the relative motion of clusters. Significant contributions to the understanding of nuclear structures were made by Wildermuth and Tang. They considered and developed a method that takes into account the cluster approximation and the Pauli principle for each of the clusters and the composite nucleus. Several microscopic methods were developed to solve the stationary Schroedinger equation based on the cluster model, and an antisymmetrization operator was introduced to implement the Pauli principle. The main difficulty of this approach is associated with calculations under the conditions of the antisymmetrization of nucleons. The development of the cluster model was carried out using microscopic methods to simplify the calculation taking into account the Pauli principle. One of these methods is the algebraic version of the method of resonating groups proposed by G.F. Filippov. The main ideas of the algebraic version are embedded in two packages of computational programs, with the help of which all calculations of this work were performed.

It should be emphasized that the cluster structure of the nucleus is also manifested in reactions with neutrons at low energies and with protons at energies above the Coulomb barrier. We note that in the reactions of neutron scattering from nuclei, the low energy region can be easily reached with the available experimental setups. However, when protons are scattered from light nuclei, Coulomb repulsion forces mask the effects of nuclear interactions at low energies. In such cases, it becomes difficult to determine the effective cross-sections for nuclear scattering based on experimental data. Similarly, for nuclear-nucleus scattering reactions at low energies. In these cases, theoretical research methods and calculations become important tools for evaluating reaction cross-sections and determining their properties.

Theoretical analysis shows that nuclei are not static entities that rigidly scatter neutrons and protons, but flexible structural configurations that respond to incident particles.

Many light nuclei are weakly bound and can also change configuration (i.e., size and shape) when they interact with nucleons or other nuclei at relatively short distances between interacting nuclei. This phenomenon is called nuclear polarization. To account for the polarizability of interacting clusters, a microscopic three-cluster model is formulated in this work. This model can be used to describe the so-called cluster polarization. Cluster polarization plays an important role in the formation of bound and resonant states in systems with seven nucleons.

Communication of this work with other research. This dissertation work was carried out in accordance with the coordination plan of research work on the following programs of basic research of the Ministry of Science and Higher Education of the Republic of Kazakhstan in the field of natural sciences: "Study of the excited states of light nuclei" (GF5).

The goal of the dissertation is a theoretical investigation of the properties of the ground and excited states of light atomic nuclei with distinct two- and three-cluster structures, including those with a large excess of neutrons or protons, the effects of the polarizability of interacting clusters on the structure of composite nuclei and on the course of nuclear reactions, and the influences of the Coulomb potential on the formation of resonance states in two- and three-nucleus continua.

Research Tasks. To achieve this goal, it was necessary to solve the following tasks:

- Implement the algebraic version of the resonance group method to obtain analytical expressions for the matrix elements of the Hamiltonian for two- and three-cluster systems. Calculate the spectrum of the light atomic nuclei ^{5}He, ^{5}Li, ^{6}Li, ^{7}Li, ^{7}Be, ^{8}Be in the two-cluster approximation. Construct the wave functions of bound and resonant states in the coordinate, momentum, and oscillator spaces. Determine the phases and integral effective cross sections of elastic scattering α+n, α+p, α+d, α+t, α+^{3}He, α+α.
- Within the framework of the microscopic three-cluster model, which allows the polarization of binary subsystems to be taken into account, investigate the states of the discrete and continuous spectra of ^{8}Li and ^{8}B nuclei represented by the three-cluster configuration ^{4}He+^{3}H+n and ^{4}He+^{3}He+p, respectively. Calculate the phases of elastic and inelastic ^{7}Li+n and ^{7}Be+p scattering.
- Investigate the influence of the Coulomb interaction on the energy and width resonance states in pairs of mirror nuclei ^{8}Li and ^{8}B, ^{9}Be and ^{9}B.

The objects of the study are light nuclei such as ^{5}He, ^{5}Li, ^{6}Li, ^{7}Li, ^{7}Be, ^{8}Li, ^{8}B, ^{8}Be, ^{9}Be, ^{9}B and their cluster structures and related phenomena: cluster polarization, effects of Coulomb interactions.

The subject of study is cluster-cluster interactions in nuclei, bound and resonant states of light atomic nuclei, phase shifts and effective cross sections for elastic and inelastic scattering of clusters, Coulomb interaction effects in mirror nuclei.

Research Methods. The methods of non-relativistic quantum mechanics for many-particle systems and scattering theory were used in the work. The method of resonating groups and the many-body model of shells were also actively involved in the work.

The novelty of the work

- Within the framework of a microscopic two-cluster model, the structure of the light atomic nuclei ^{5}He, ^{5}Li, ^{6}Li, ^{7}Li, ^{7}Be, ^{8}Be was studied. The dependence of the spectrum of these nuclei on the shape and properties of the nucleon-nucleon potential is studied. The wave functions of bound and resonant states of nuclei were constructed for ^{5}He, ^{5}Li, ^{6}Li, ^{7}Li, ^{7}Be, ^{8}Be in coordinate, momentum and oscillator space. Common features of the wave functions of bound states and long-lived resonant states are established.

- The effect of polarization of ^{7}Li and ^{7}Be nuclei, considered as binary systems ^{4}He+^{3}H and ^{4}He+^{3}He, respectively, on the structure of ^{8}Li and ^{8}B nuclei and on the elastic and inelastic ^{7}Li+n and ^{7}Be+p scattering parameters. The calculated proton and neutron root-mean-square radii of the ^{8}Li and ^{8}B nuclei confirm the presence of a neutron halo in the ^{8}Li nucleus and a proton halo in the ^{8}B nucleus, which have been previously detected by experimental methods.
- The influence of the Coulomb interaction on the parameters of the resonance states of two pairs of mirror nuclei ^{8}Li and ^{8}B, ^{9}Be, and ^{9}B. Two very probable scenarios for the motion of the resonance states in the energy-width plane under the influence of Coulomb forces have been established.

Scientific and practical significance of the work. Theoretical research is fundamental to nuclear physics and nuclear astrophysics and is of great importance in the context of the study of the structure of light nuclei. From a practical point of view, the results obtained can be served as a basis for the development of other alternative methods, and some of the results can be used in educational practice to introduce new directions in nuclear physics, some data can be used as reference points for new experiments. A number of nuclear processes are considered that determine the synthesis of light atomic nuclei in the early universe and their distribution in stars.

Provisions made for the defense:

1. The shape of interaction potential for ^{5}He, ^{5}Li, ^{6}Li, ^{7}Li, ^{7}Be, and ^{8}B nuclei has little effect on compact two-cluster states, bound states, and long-lived (narrow) resonant states, but noticeably affects short-lived (wide) resonant states: The spin-orbit interaction strongly changes the parameters and wave function of resonant states, and the wave functions of long-lived resonant states are similar to the wave functions of bound states, which describe compact configurations when two clusters are very likely to be at small relative distances.

2. In the processes of elastic and inelastic ^{7}Li+n and ^{7}Be+p interactions, the ^{7}Li and ^{7}Be nuclei change size and shape as a result of cluster polarization, namely cluster polarization is found to significantly affect the structure of the bound and resonant states of these nuclei: a neutron halo exists in the ^{8}Li nucleus and a proton halo exists in the ^{8}B nucleus.

3. The Coulomb interaction of protons in pairs of mirror nuclei ^{8}Li and ^{8}B, ^{9}Be and ^{9}B has a strong, moderate and weak influence on the parameters of bound states and resonances, where ^{8}Li and ^{8}B decay into two fragments and ^{9}Be and ^{9}B decay into three fragments (clusters).

The author's personal contribution. The author has independently written the entire scope of the dissertation work, performed analytical calculations and selected the relevant literature. The task definition, choice of research methods and discussion of the results were done jointly with the supervisors.

The reliability and validity of the obtained results are confirmed by publications in foreign journals with high impact factor and in publications recommended by the Committee for Control of Education and Science of the Ministry of Science and Higher Education of the Republic of Kazakhstan, as well as in the proceedings of international scientific conferences in near and far abroad.

Publications. On the basis of the materials of the dissertation work 9 printed papers were published, including 1 in the journal included in the databases Scopus and Tomson Reuters, 3 in the journals included in the list recommended by the Committee for Quality Assurance in Education and Science of the MSHE RK, 5 in the materials of international conferences in the Republic of Kazakhstan and abroad.

The volume and structure of the dissertation. The dissertation work consists of an introduction, 3 chapters and a conclusion. The work is presented on 109 pages of a computer set, illustrated by 45 figures, 19 tables, 1 appendix and includes a bibliography.