ABSTRACT

of the dissertation work of Kalzhigitov Nursultan Kuvandikovich on the topic of «Microscopic two- and three-cluster model of light atomic nuclei ^{6}Li and ^{8}Be», submitted for the degree of Doctor of Philosophy (PhD) in the educational program «8D05308 - Nuclear Physics»

General description of work. The dissertation is devoted to a detailed study of the structure and resonance states of the ^{6}Li and ^{8}Be nuclei in the two-cluster and three-cluster approximations. Much attention in this work is paid to the study of the influence of various effects on the structure of nuclei and their resonances, taking into account more realistic conditions for the wave function of interacting clusters.

The relevance of the dissertation topic. In nuclear physics, as well as in related fields of science today, many questions remain open and unresolved, affecting both the structure of atomic nuclei and the form of nuclear nucleon-nucleon interaction within them. In the theory of the atomic nucleus, a unified model has not yet been created that could include and take into account all the characteristics and properties of nuclei obtained from experiments. Experiments currently underway at low energies are also difficult to carry out and have a large error in the results, differing two or more times from the available theoretical calculations. In theories and nuclear models, the exact type of nuclear interaction potential that could include all the information available from experiments has not yet been determined. In this regard, despite many previously made discoveries, the theory of the atomic nucleus continues to develop, acquiring new experimental and theoretical data. When conducting research in this area, both new models for studying the structure of atomic nuclei and interactions between them are created, and existing ones are improved, taking into account the new data obtained.

The nature of many resonance states of both light and heavier nuclei, the formation of which directly affects fundamental issues of both nuclear physics itself, which may concern nuclear and thermonuclear reactions, and related areas such as astrophysics, where the manifestation of these resonance states is of great interest in understanding the evolution of matter in the universe, continues to remain unclear. Such open problems, which are widely known to everyone today, include: the Hoyle state and the cosmological lithium problems, the understanding and solution of which are also inextricably linked with the phenomena occurring inside the studied atomic nuclei and their interactions.

There are several theoretical methods that are most often used to study light nuclei. This is the many-particle shell model, the Hartree-Fock method, and various versions of the cluster model, which can be both macroscopic, which do not take into account the internal structure of the studied clusters, and microscopic, which, when considering the interaction between clusters, also describe their internal structure. In the studies carried out within the framework of this dissertation, preference was given to the microscopic method of the cluster model, namely the algebraic version of the resonant group method.

The studies carried out on the topic of the dissertation were aimed at studying the nature of resonance states in the nuclei of ^{6}Li and ^{8}Be, which play a key role in many issues of both nuclear physics and astrophysics. Having unique features in their structure, these nuclei were considered using both standard approaches for studying nuclear resonances (S-matrix, scattering phases, cross-section of elastic and inelastic processes) and advanced analysis methods (weight of the wave function in the inner region, average distance between clusters and spectroscopic factor in continuous spectrum states), which allowed us to look at the nature of the resonances under study, their occurrence and the effects behind them in a broader sense. For this reason, when performing research on the topic of the dissertation, a cluster model was chosen, or more precisely, an algebraic version of the resonating group method. Further, an algorithm for a newer and more advanced method was developed and proposed, which includes taking into account several binary reaction channels. The use of the selected methods of the cluster model made it possible to touch upon more complex and less studied issues related to the influence of cluster polarization effects on the structure, shape and manifestations in nuclear resonances, as well as very little studied effects caused by a more realistic description of the wave functions of interacting clusters within the framework of the model used.

The aim of the dissertation research is to study the influence of cluster polarization and the Pauli principle on the spectrum of light nuclei.

Research Tasks:

1. To conduct a step-by-step study of the structure of ^{6}Li and ^{8}Be nuclei using a two-cluster and then a three-cluster model, based on calculations within the framework of the RGM approach.

2. To analyze the main properties and characteristics of the studied nuclei, as well as the nature of their resonance states using both standard description methods and extended methods.

3. To generalize (expand) the cluster model to the possibility of taking into account several three-cluster configurations, as well as the polarizability of clusters when they approach each other.

4. To study the effects of cluster polarization and their influence on the structure of bound and resonance states in the ^{6}Li nucleus.

5. To study the structure and causes of artifactual Pauli resonances in a wide range of calculations of the structures of light nuclei and to find a scheme for their elimination.

The objects of the study: light nuclei ^{6}Li, ^{8}Be.

The subject of the study is the bound and resonance states of the nuclei ^{6}Li and ^{8}Be, wave functions, spectra, scattering phases, as well as the effects and phenomena acting on them in the two-cluster and three-cluster models.

Research methods: the resonance group method, two- and three-cluster models of atomic nuclei.

A microscopic two-cluster model was used to study the elastic alpha-alpha scattering and the resonance structure of the ^{8}Be nucleus. This model is an algebraic version of the resonant group method, which is based on the expansion of the wave function of a two-cluster system over a full set of basis functions of a harmonic oscillator or, in other words, oscillatory functions. To determine the interaction of nucleons within each of the clusters and the interaction between clusters, three known paired, semi-realistic, nucleon-nucleon potentials were used: the modified Hasegawa-Nagata potential, the Volkov V2 potential and the Minneota potential. Each of them has its own unique characteristics and differs in the core size at small distances between nucleons, which well implements strong, moderate and weak cores. This allows us to study the dependence of the calculated values on the shape of the nucleon-nucleon potential. A detailed analysis of the wave functions of the resonance states was carried out in the oscillatory, coordinate and momentum spaces.

To study the resonance structure of the ^{6}Li nucleus and various processes inside it, by analogy with the ^{8}Be nucleus, a microscopic two-cluster model of the AVRGM was used. In addition, a more advanced microscopic multichannel model was used to study the ^{6}Li nucleus, including two three-cluster configurations, allowing for a better account of all the binary channels available in the nucleus. The applied method allowed us to study in more detail the spectrum of resonance states in a wide energy range of the ^{6}Li nucleus and come closer to identifying the effects that affect its shape and properties. A distinctive feature of the new method is the use of two types of basis functions at once to describe the state of the nuclear system: oscillatory and Gaussian, which made it possible to take into account a more realistic form of the wave function of the nuclear system under study.

Provisions made for the defense:

1) Resonance states have a compact form in space, and the smaller the resonance width, the more compact the state. Among all the states of the continuous spectrum, resonant states have minimal values of mass root-mean-square radii and average distance between clusters, so the mass root-mean-square radius of the 0+ resonance in the ^{8}Be nucleus is 3 times smaller than the similar radius of other states of the continuous spectrum.

2) Polarization of interacting clusters plays a significant role in the formation of the ground state of the ^{6}Li nucleus, as well as its low-lying resonant states. Bringing the calculated value of the spectral parameters closer to their experimental values. For the ground state 1^{+}, cluster polarization shifts the energy by 1.2 MeV (from -0.249 to -1.474), and also reduces the energy by 2.4 times and the width of the 3+ resonance by 10 times. Cluster polarization has a very weak effect on highly excited states of negative parity of the ^{6}Li nucleus. A method for visualizing cluster polarization is proposed.

3) A clear criterion for determining the conditions for the occurrence of artifact resonances (Pauli resonances) and an algorithm for their selection are formulated.

The novelty of the study and practical significance of the work

The study of the structure of atomic nuclei through the cluster representation is currently carried out by many research groups around the world: in Europe, Japan, the USA, in the countries of the near and far abroad. In Kazakhstan, studies of nuclear structures and their interactions with each other have a rich history and several scientific directions both in the field of theoretical physics and in the field of experimental nuclear physics.

The work carried out and the results obtained correspond to the current directions of scientific development both in Kazakhstan and around the world. The results obtained are absolutely new and contribute to the development of the cluster model of the nucleus, offering a new look at previously existing problems.

As part of the studies:

1) It was demonstrated how narrow and wide resonances of the ^{8}Be nucleus manifest themselves in various physical quantities: in standard ones, such as scattering phases, scattering cross-sections, as well as advanced analysis methods, such as the weight of the wave function in the inner region, the average distance between clusters, and the spectroscopic factor. The relationship between the wave functions of resonance states in the coordinate and oscillator spaces is clearly shown. It is shown how to correctly estimate the average between clusters.

2) The nature of resonances in light nuclei and the effect of the Pauli principle on the wave functions of resonance states are analyzed in detail. As a result, it was clearly shown that the smaller the resonance width, the stronger the effect of the Pauli principle on it.

3) Having carried out a systematic analysis of the properties of Pauli resonances in a large number of light nuclei, the threshold for the appearance of Pauli resonances was established. The boundary between almost forbidden Pauli states and allowed Pauli states was also established.

4) A new method for eliminating the influence of Pauli resonance effects is proposed.

5) The role of cluster polarization in the formation of bound and resonant states of the ^{6}Li nucleus.

Relationship of this work with other scientific studies.

This dissertation paper presents the materials and results that were obtained by completing the main tasks of the research work on the project: AP09259876 "Physics of Compact Stellar Objects" 2021-2023. Further tasks and research in the direction presented in this dissertation are already being carried out within the framework of the research work on the project Zhas Galym 24-26: AP22683187 "Structure of Light Nuclei and Hypernuclei in Multichannel and Multicluster Models".

The reliability and validity of the research results. All studies were carried out taking into account the principles and basic norms of scientific ethics. The obtained results and the main theses of the scientific research have been repeatedly presented and presented at many international scientific conferences, with the participation of world highly qualified specialists in the field of the research. The obtained results underwent thorough peer review and were published in highly rated, periodical, scientific publications indexed by Scopus and Web of Science databases, as well as in domestic journals recommended by CQASHE.

Personal contribution of the author. The doctoral student independently completed the following tasks: a literature review of sources on the topic of the dissertation research, conducting numerical and analytical calculations, analyzing the results obtained, constructing graphs of phase shifts of elastic and inelastic scattering, as well as wave functions of resonance states of the studied nuclei ^{6}Li and ^{8}Be. Writing and proofreading the text of publications published on the topic of the dissertation research. Also, the doctoral student submitted manuscripts of articles to the editors of both domestic and foreign scientific publications as an author for correspondence.