ABSTRACT
of the dissertation work of Valiolda Dinara Salavatkyzy on the topic of "Coulomb breakup of exotic nuclei by quantum-mechanical approach", submitted for the degree of Doctor of Philosophy (PhD) in the specialty: "6D060500 - Nuclear Physics"

The relevance of the research topic

A characteristic feature of the physics of exotic nuclei is the close relationship between the mechanism of nuclear reaction and the structure of the nucleus. The most widely used reaction for studying halo nuclei is the Coulomb breakup reaction, which can be considered as the transition of a nucleon from a halo nucleus to a continuum due to varying Coulomb field between the nucleon and the target in collisions. Thus, the Coulomb breakup is one of the main tools in the study of halo nuclei. The breakup cross section provides useful information on the halo structure.

Within the framework of the dissertation work, for a more detailed study of the mechanism of the halo structure, it was planned to include low-lying resonances in various partial and spin states of the ^{11}Be nucleus in the calculation of the breakup cross section. The Coulomb breakup of the halo nuclei is studied numerically, by solving the time-dependent Schrödinger equation on an angular Lagrange and quasi-uniform radial grid. The developed computational scheme opens up new possibilities in the study of the Coulomb, as well as nuclear, breakup of halo nuclei on both heavy and light targets.

One of the relevant problems of the work is to study the contribution of low-lying resonances to the breakup cross section. Since in the previous calculations only two bound states of the ^{11}Be nucleus were taken into account (the ground state $½^+$ and the first excited state $½^-$), it is assumed that taking into account low-lying resonances will improve the theoretical description of the experimental data on the cross section for the breakup reaction ^{11}Be + ^{208}Pb → ^{10}Be + n + ^{208}Pb at intermediate energies and explain the appearance of visible peaks in the energy range 1.23, 2.78, and 3.3 MeV, which corresponds to the position of the peaks of resonances $5/2^+$, $3/2^-$ and $3/2^+$. Also, special attention should be paid to study of the influence of nuclear effects on the breakup cross section, which makes it possible to extract more detailed information on the structure of exotic nuclei.

Thus, the presented tasks of this dissertation work have priority directions not only in Kazakhstan, but also in the worldwide. Research on this topic is one of the rapidly developing fields of modern nuclear physics of all major scientific centers of the world. The obtained results are quite competitive on the international level. These studies are not only of academic interest, but also of great practical importance. The expected results are very important and relevant for the interpretation and planning of future experiments with exotic nuclei, since at the present time there is a substantial lag in the theoretical models from the needs of the experiment in this field. The key problem to be solved by the tasks of the dissertation work is the expansion of our approach to the low-energy area, since this area has hardly been studied both theoretically and experimentally. Thus, the obtained results will be important for testing existing theoretical models and for the practical application of theoretical calculations in experiments to investigate the breakup of halo nucleus at low-energy radioactive beams.

The goals of the research is an investigation of low-lying resonances in the Coulomb breakup of ^{11}Be halo nuclei on heavy target (^{208}Pb) from intermediate (70 MeV/nucleon) to low energies (5 MeV/nucleon) within non-perturbative time-dependent quantum-mechanical approach.

To achieve these goals, it is necessary to solve the following **objectives:**

– to select and analyse parameters of the potentials between the neutron and ^{10}Be core for description of different partial and spin states of the ^{11}Be nucleus;

– to investigate the influence of low-lying resonance states ($5/2^+$, $3/2^-$ and $3/2^+$) to the Coulomb breakup of ^{11}Be nucleus on a heavy (^{208}Pb) target within the semiclassical and quantum-quasiclassical time-dependent approaches;

– to study the contribution to breakup of nuclear interaction between projectile and target;

– to probe how good is the linear trajectory approach for projectile motion at low beam energies

– to explore the excitation of ^{11}Be in collision with ^{208}Pb target.

The objects of the research are a halo nucleus, ^{11}Be, low-lying resonances and breakup cross-section.

The subject of the research is quantum mechanics, the work is devoted to the numerical solution of the time-dependent Schrödinger equation, exact calculations of the breakup cross sections by quantum-mechanical approach.

Research methods: numerical methods for solving the stationary and time-dependent Schrödinger equations: reverse iteration method, sweep method, the splitting up method, the discrete variable representation, finite-difference technique in quasi uniform radial grid.

The main statements for defense:

1. An account of the low-lying resonance states of ^{11}Be describes the experimental data on the breakup reaction ^{11}Be+^{208}Pb->^{10}Be+n+^{208}Pb cross sections at 69 MeV/nucleon with the accuracy of 1-2% and explains the appearance of visible peaks at energies of 1.23, 2.78, 3.3 MeV, which correspond to the positions of the $5/2^+$, $3/2^-$ and $3/2^+$ resonances, respectively.

2. The breakup cross sections of the halo nucleus ^{11}Be on a heavy (^{208}Pb) target at low collision energies (30-5 MeV/nucleon), demonstrate a visible peak due to the $5/2^+$ resonant state (E_r=1.23 MeV).

3. The differences between the linear and curvilinear (realistic) trajectories of the projectile in the analysis of the breakup reaction ^{11}Be+^{208}Pb->^{10}Be+n+^{208}Pb is about several percent in the energy range 30-20 MeV/nucleon, for 10 MeV/nucleon the discrepancy is 10% and reaches a value of more than 20% at 5 MeV/nucleon, which exceeds the effect of nuclear interaction.

Scientific novelty of the work. The novelty and originality of research lies in the fact that for the first time**:**

1. The low-lying resonant states ($5/2^+$, $3/2^-$ and $3/2^+$) of the ^{11}Be were included in the analysis of the breakup reaction $^{11}Be+^{208}Pb->^{10}Be+n+^{208}Pb$ by the numerical integration of the time-dependent Schrödinger equation.

2. The breakup cross sections of one-neutron halo nucleus of ^{11}Be on a heavy (^{208}Pb) target are calculated by solving the time-dependent Schrödinger equation with a non-perturbative algorithm in a wide range of beam energies (70-5 MeV/nucleon).

3. The inelastic cross sections for the excitation of the ½- state of ^{11}Be in a collision with ^{208}Pb target at low beam energies are evaluated with inclusion of Coulomb and nuclear interactions between the target and projectile. The influence of the curvilinear trajectory for projectile motion is analyzed with decreasing the collision energies.

The theoretical and practical significance of the research outcomes.

Theoretical significance of the study: exotic nuclei are one of the most intensively studied objects in modern few-nucleon nuclear physics. The theoretical study of halo nuclei within the framework of the non-stationary quantum-mechanical approach is relevant in connection with planning experiments on the study of light nuclei in radioactive beams.

The developed computational scheme in this dissertation work opens new possibilities in investigation of Coulomb, as well as nuclear, breakup of exotic nuclei on heavy, as well as, light targets. This theoretical model can potentially be useful for interpretation and planning of low-energy experiments in studying the halo structure of the nuclei. The obtained results at lower energies are important in connection with the research program in this area at HIE-ISOLD (CERN) and ReA12 (MSU).

The validity and reliability of the research results.

The results were successfully presented at high-level international scientific conferences and formed the basis of publications in high-ranking journals such as European Physical Journal A, Physics of Particles and Nuclei letters, Acta Physica Polonica B, Eurasian Journal of Physics and Functional Materials. The achieved scientific results are in good agreement with the existing works of other foreign authors in this field.

Personal contribution of the author. In the framework of the dissertation research, the author was directly involved in setting goals, in writing and debugging a computational program, processing and analyzing of obtained data, interpreting the results, preparing articles for publication as a full member of the scientific group. The contribution of the applicant to the results of the dissertation is essential.

Approbation of the dissertation. The materials of the dissertation work were reported at the following republican and international conferences:

1 "IV International Scientific Forum-Nuclear Science and Technology". RSE ME INP (Almaty, Kazakhstan, 2022).

2 The LXXI International conference "NUCLEUS – 2022. Nuclear physics and elementary particle physics. Nuclear physics technologies", Moscow State University, (Moscow, Russia, 2022).

3 The International Workshop on Elementary Particles and Nuclear Physic, RSE ME INP (Almaty, Kazakhstan, 2022).

4 I International School-Conference “Atom. The science. Technology" RSE ME INP (Almaty, Kazakhstan, 2021).

5 The XXV International Scientific Conference of Young Scientists and Specialists (AYSS-2021), Joint Institute for Nuclear Research (JINR), (Almaty, Kazakhstan, 2021) and others. The results of the research were reported at the seminar of the N.N. Bogolyubov Laboratory of Theoretical Physics, Joint Institute for Nuclear Research on July 2020.

Publications.

Based on the results of the dissertation work, 6 printed works were published, 4 of that were published in journals included in the database indexed by SCOPUS scientometric databases, 2 - in the journals included in the list recommended by the Committee for Quality Assurance in the Sphere of Education of the Ministry of Science and Higher Education of the Republic of Kazakhstan.

Articles in journals indexed by scientometric databases SCOPUS and Web of Science:

1 Valiolda D., Melezhik V.S., Janseitov D. Investigation of low-lying resonances in breakup of halo nuclei within the time-dependent approach // The European Physical Journal A. – 2022. – Vol. 58. –P 341-3413.

2 Valiolda D., Melezhik V.S., Janseitov D. Study of bound and resonance states of ^{11}Be in breakup reaction // Eurasian Journal of physics and functional materials. –2022. –Vol. 6, № 3. –P. 165-173.

3 Valiolda D., Melezhik V.S., Janseitov D. Study of nuclear contribution to breakup cross section of ^{11}Be halo nuclei within time-dependent approach // Physics of Particles and Nuclei Letters. –2022. –Vol. 19, №5. –P. 477-480.

4 Valiolda D., Melezhik V.S., Janseitov D. Contribution of Low-lying Resonances in the Coulomb Breakup of ^{11}Be Halo Nuclei// Acta Physica Polonica B Proceedings Supplement. –2021. –Vol. 14, № 4. –P. 687-692.

Articles in scientific journals of the Republic of Kazakhstan:

1 Valiolda D.S., Zhaugasheva S.A., Janseitov D.M., Zhussupova N.K. The study of the neutron halo of the ^{11}Be nucleus taking into account the influence of an external field// NEWS of the National Academy of Sciences of the Republic of Kazakhstan. –2018. –Vol. 318, №2. –P. 12-20.

2 Valiolda D.S., Janseitov D.M., Zhaugasheva S.A., Zhussupova N.K. Investigation of the neutron halo of the ^{11}Be nucleus// Recent Contributions to Physics. –2018. –Vol. 64, №1. –P. 81-88.

The structure and volume of the thesis. The dissertation consists of an introduction, three sections, a conclusion, a list of references and 3 appendices. The volume of the dissertation is 90 pages, containing 34 figures and 11 tables, the number of used literature sources is 62.

In the introduction, the relevance of the dissertation topic and the problem statement are discussed, the goals and novelty of the obtained results, their practical and theoretical significance are presented. **The first section** is devoted to the determination of the exotic nuclei and the description of the ^{11}Be nucleus as a halo structure. The main features of the halo structure, such as nuclear density, large radii, and low binding energies and others are considered. **The second section** formulates the nonperturbative time-dependent approach in breakup reactions. In this model, the time-dependent Schrödinger equation for a halo-nucleon is integrated with a non-perturbative algorithm on a three dimensional spatial mesh. **The third section** is devoted to the discussion of obtained results: the calculation of breakup reactions. **The Conclusion** formulates the main results obtained in the dissertation and is devoted to concluding remarks.

The main results of the dissertation work. A considerable contribution of low-lying resonances ($5/2^+$, $3/2^-$ and $3/2^+$) and the nuclear interaction between the target and projectile into breakup of ^{11}Be on the ^{208}Pb target were found at low beam energies (5-30 MeV/nucleon). The satisfactory accuracy of the semiclassical approach with linear trajectories of the projectile was also demonstrated for the ^{11}Be breakup cross sections up to 30 - 20 MeV/nucleon. It is shown that this approach is also useful at lower energies, where, however, a more adequate description is provided by the quantum-quasiclassical approach. The convergence of the computational scheme and accuracy of research are demonstrated in the considered energy range (5-69 MeV/nucleon), including low-lying resonances in various partial and spin states of ^{11}Be.