# ABSTRACT

for the dissertation work of Shalkar Muratovich Kazhykenov entitled "Exotic states of nuclei with 1 p shell", submitted for the degree of Doctor of Philosophy (PhD) in the educational program 8D05308 – Nuclear Physics

**General characteristics of the dissertation work.** Light nuclei with 1p shells are of interest due to the combination of single-particle, collective, and cluster manifestations. Scattering reactions serve as an effective tool for studying their structure and testing theoretical models of nuclear interactions.

In this paper, we investigate the interactions of protons and deuterons with $^{13}C$, $^{14}C$, and $^{7}Li$ nuclei in the energy region close to the Coulomb barrier. In this energy range, the characteristics of differential cross sections are highly sensitive to the features of the nuclear structure and interaction parameters. This allows the use of scattering reactions to study the distribution of nuclear density and structural effects in light nuclei.

The analysis is based on published experimental data and modern theoretical approaches. An optical model and a microscopic folding approach are used to construct the interaction potentials.

To describe the reaction dynamics, we used the partial-wave method, the distorted-wave Born approximation, and coupled-channel formalisms, taking into account the influence of excited states and multichannel processes on the scattering characteristics.

This paper analyzes the angular distributions of differential cross sections, phase shifts, and scattering amplitudes for the reactions $^{13}C(p,p)^{13}C$, $^{14}C(p,p)^{14}C$, $^{7}Li(p,p)^{7}Li$, as well as the corresponding reactions with deuterons. A comparison of calculated and experimental data was used to determine the parameters of the optical potentials, radial interaction characteristics, and the properties of low-lying excited states of the nuclei under study.

An analysis of the obtained results reveals the influence of microstructural effects on the formation of elastic and inelastic scattering cross sections and allows us to refine the interpretation of experimental data for nuclei with an open 1p shell. This paper is devoted to studying the structure of light nuclei and the specific features of nuclear reaction mechanisms.

**The relevance of this dissertation topic** stems from the need to further develop modern theoretical methods for analyzing nuclear reactions, allowing for a more complete description of experimental data and obtaining reliable information on the structure of light nuclei with an open 1p shell. Despite the large number of experimental studies performed, a number of questions related to scattering processes, nucleon transfer, and the influence of excited states on the characteristics of nuclear reactions remain open. Therefore, the need remains for the use of modern microscopic and multichannel methods to investigate the influence of nuclear structure on the characteristics of nuclear reactions at energies close to the Coulomb barrier.

**The purpose of the dissertation work** is to establish the influence of the microstructure of light nuclei $^{13}C$, $^{14}C$, and $^{7}Li$, including possible exotic states, on

the differential cross sections of the reactions $^{13}C(d,p)^{14}C$, $^{14}C(p,p)^{14}C$, and $^{7}Li(p,p)^{7}Li$.

**Research tasks:**

– to establish the influence of the structural features of $^{13}C$, $^{14}C$, and $^{7}Li$ nuclei on the characteristics of elastic and inelastic scattering of protons and deuterons in the energy region close to the Coulomb barrier;

– to construct and substantiate the parameters of microscopic and optical interaction potentials for $p+^{7}Li$, $d+^{13}C$, and $p+^{14}C$ systems based on a comparison of calculated and experimental data;

– determine the characteristics of low-lying excited states of the nuclei under study, including deformation parameters and features of their spatial structure;

– establish the relationship between phase shifts, partial scattering amplitudes, and structural characteristics of the nuclei under study.

**The object of the study** comprises the angular distributions of differential cross sections for proton and deuteron scattering on the nuclei $^{13}C$, $^{7}Li$, and $^{14}C$ in the energy range of 3.7-12.5 MeV, including the reactions $^{13}C(d,d)^{13}C$, $^{13}C(d,p)^{14}C$, $^{14}C(p,p)^{14}C$, and $^{7}Li(p,p)^{7}Li$.

**The subject of the study** includes differential cross sections, phase shifts, scattering amplitudes, the structure of excited states, and the parameters of nuclear interaction potentials for the $^{13}C$, $^{7}Li$, and $^{14}C$ systems at low energies.

**Research methods.** The study used modern methods of nuclear reaction theory: the optical model with a complex potential, the microscopic folding approach with the effective CDM3Y6 nucleon-nucleon interaction, the distorted wave Born approximation (DWBA), the partial-wave method, and the coupled-channel formalisms CC, CDCC and CRC. The imaginary part of the optical potential was defined by the Woods-Saxon potential. The calculations were performed using FRESCO, Python and Wolfram Mathematica, and the results were compared with experimental data from the EXFOR database and published works.

**Provisions submitted for defense.**

1. For the $^{13}C+^{12}C$ reaction in the energy range $E_{c.m.s}$=7.8-49.1 MeV, it was established by the OM+DWBA method that reproduction of the experimental differential cross sections at large scattering angles is achieved when one-step neutron transfer is taken into account; for the $^{13}C\rightarrow^{12}C+n$ configuration, the spectroscopic amplitude SA=0.87±0.10, weakly dependent on energy, was obtained.

2. For the $^{13}C(d,d)^{13}C$ reaction at deuteron energies $E_d$=14-16 MeV, the shape of the angular distributions is determined by the combined influence of virtual deuteron breakup and one-nucleon transfer processes. Reproduction of the experimental data requires inclusion of the $^{13}C(d,p)^{14}C$ and $^{13}C(d,n)^{14}N$ channels.

3. Based on data on inelastic scattering of deuterons by the $^{13}C$ nucleus at $E_d$=14.5 MeV, it was established that the excited state with energy E=3.09 MeV has predominantly a single-particle structure of the $^{12}C+n$ configuration, whereas the excited states with energies E=8.86 and 9.89 MeV are characterized by the dominant contribution of the $^{9}Be+\alpha$ cluster configuration with a negligibly small contribution of the $^{12}C(0_2^+)+n$ configuration.

4. The applicability of microscopic folding potentials (M3Y for $^{7}$Li and CDM3Y for $^{14}$C) based on their cluster densities (α+t and $^{12}$C+2n) has been established for the quantitative description of differential elastic proton scattering cross sections at energies of 3.0-7.0 MeV.

**Scientific novelty of the work.**

1. In the low-energy region, elastic and inelastic scattering processes were studied for $^{13}$C, $^{7}$Li, and $^{14}$C nuclei using the partial-wave method, the distorted-wave Born approximation, and coupled-channel formalisms for systems with an open 1p shell.

2. For light nuclei, the dependence of the calculation results on the structure of excited states was traced using microscopic folding potentials. Features of the angular distributions of differential cross sections are associated with the manifestation of single-particle and cluster configurations in $^{13}$C and $^{14}$C nuclei.

3. Differences in the level structure were obtained for the excited states of the $^{13}$C nucleus. For the 3.09 MeV state, the single-particle configuration predominates, while the 8.86 and 9.89 MeV levels are characterized by a dominant contribution from the $^{9}$Be+α cluster configuration.

4. When considering the $^{13}$C+$^{12}$C reaction within the cluster folding approach, the influence of single-step neutron transfer on the behavior of differential cross sections in the large-angle scattering region is demonstrated. Taking this mechanism into account ensures the reproduction of the features of anomalous large-angle scattering characteristic of the refractive interaction mode.

5. For the $^{7}$Li(p,p)$^{7}$Li system in the low-energy region, the application of the microscopic folding approach is considered. When describing the experimental angular distributions, a significant contribution is made by the imaginary part of the optical potential.

**The theoretical and practical significance of the study** lies in clarifying the relationship between the structures of light nuclei with an open 1p-shell ($^{13}$C, $^{14}$C, and $^{7}$Li) and the characteristics of nuclear reactions at low energies. The work demonstrates the role of single-particle and cluster configurations, transfer processes, and channel coupling in shaping phase shifts, scattering amplitudes, and differential cross-sections.

The practical significance of the study stems from the potential to use the derived potential parameters, phase characteristics, and differential cross-sections to analyze experimental data, plan new measurements, and refine nuclear interaction models. The results obtained can also be applied to supplement nuclear physics data regarding reactions involving light nuclei.

**The reliability of the results** is ensured by the consistent use of experimental data and modern theoretical approaches to describing nuclear reactions. An optical model, a microscopic folding approach, DWBA formalisms, and the partial-wave method were used in the analysis of the systems under study. Numerical calculations were performed using the FRESCO software suite.

The reliability of the selected interaction parameters was confirmed by comparing the calculated angular distributions with experimental data presented in the EXFOR database and published papers. The obtained results demonstrate

consistent agreement with the measured differential cross sections in the energy range under study.

**Relationship of this work to other research.** This dissertation presents materials and results obtained during the execution of research projects and program, specifically: AP14972391 "Investigation of exotic states of 1p-shell nuclei" (2022–2024); AP13067742 "Investigation of the Coulomb breakup of the $^{11}$Be halo nucleus using a non-stationary quantum approach" (2022–2024); AP19678586 "Production of exotic nuclei in fragmentation reactions at 10 MeV/nucleon: Estimation of yields and longitudinal momentum distributions" (2023–2025); and BR24992891 "Comprehensive research in nuclear and radiation physics and technology, high-energy physics, and cosmology for the development of competitive technologies" (2024–2026). These studies are thematically linked to the investigation of the structure of light and exotic nuclei and nuclear reaction mechanisms, as well as the development of computational and theoretical methods in nuclear physics.

**Author's contribution.** The author's personal contribution includes independently formulating the research objectives, selecting the theoretical approaches, performing calculations using the partial-wave method and the distorted-wave Born approximation, analyzing and interpreting the results, comparing theoretical data with experimental measurements, and preparing publications on the topic of the dissertation.

**Publications related to the dissertation topic.** The study resulted in five published research papers, including two articles in journals recommended by the Committee for Quality Assurance in Science and Higher Education of the Ministry of Education and Science of the Republic of Kazakhstan, and three publications in international journals indexed in Scopus and with a non-zero impact factor:

1. Urazbekov B.A., Karakozov B.K., Burtebayev N.T., Janseitov D.M., Nasrulla M., Alimov D., Valiolda D.S., **Kazhykenov Sh.**, Denikin A.S., Demyanova A.S., Danilov A.N., Starastcin V.A. Single-particle and cluster modes of $^{13}$C excited states of 3.09, 8.86 and 9.89 MeV // International Journal of Modern Physics E. – 2022. – Vol. 31, No. 4. – 2250031. DOI: https://doi.org/10.1142/S0218301322500318

2. Janseitov D.M., Alimov D., Valiolda D.S., **Kazhykenov Sh.**, Zhaugasheva S.A., Mauyey B., Hamada Sh. Cluster folding analysis of the $^{13}$C+$^{12}$C system at energies near the Coulomb barrier // Indian Journal of Physics. – 2025. – Vol. 99, No. 10. – P. 3891–3897. DOI: https://doi.org/10.1007/s12648-025-03585-1

3. **Kazhykenov Sh.M.**, Janseitov D.M., Yerbolatova G.U. Study of elastic scattering of protons on $^{7}$Li in the energy range of 3–5.3 MeV // Physical Science and Technology. – 2025. – Vol. 12, No. 1–2. – P. 134–141. DOI: https://doi.org/10.26577/phst202512113

4. Janseitov D.M., Alimov D., Valiolda D.S., **Kazhykenov Sh.**, Mauyey B., Kemper K.W., Hamada Sh. Observation of nucleon transfer and deuteron breakup on d+$^{13}$C system // Revista Mexicana de Física. – 2025. – Vol. 71, No. 3. – 031204. DOI: https://doi.org/10.31349/RevMexFis.71.031204

5. **Kazhykenov Sh.M.**, Janseitov D.M., Valiolda D.S., Altukhov I.V. Verification of the consistency between theoretical and numerical methods using

elastic proton scattering on $^{14}C$ in the energy range 3.7–7.0 MeV as an example // Bulletin of the NNC RK. – 2025. – No. 4. – P. 198–208. DOI: https://doi.org/10.52676/1729-7885-2025-4-198-208

**Approbation of the work.** The materials of the dissertation work were presented and discussed at the international scientific school-conference "Atom. Science. Technologies" (Kazakhstan, 2020). The results were also presented at a scientific seminar at the Institute of Nuclear Physics (2026). Some results formed the basis of a research project within the framework of the Bolashak program (2026).

**The dissertation consists** of an introduction, eight sections, a conclusion, and a list of references. The list of references consists of 192 sources. The research findings are presented on 95 pages and include 9 tables and 28 figures.