

ABSTRACT

of the dissertation submitted for the degree of Doctor of Philosophy (PhD)
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Structural characteristics of $^{10,11}\text{B}$ nuclei in interactions with light charged particles at low energies.

The dissertation presents the results of a comprehensive study of the structural characteristics of $^{10,11}\text{B}$ nuclei. The processes of their interaction with light charged particles occurring in the low-energy range are considered based on experimental observations and theoretical analysis.

Relevance of the research topic. The study of the structure of light nuclei and the mechanisms of their interaction with deuterons and alpha particles remains an important and unresolved problem of modern nuclear physics and astrophysics. Particular interest is associated with exotic phenomena such as neutron halo and pronounced clustering, observed both in neutron-rich and stable nuclei. The nuclei of boron isotopes ^{10}B and ^{11}B are characterized by well-developed cluster configurations, which significantly affect the dynamics of scattering and transfer reactions, manifesting themselves in an anomalous increase of cross sections at large angles.

Practical significance of the study is related to the role of boron isotopes in thermonuclear technologies, nuclear medicine, and astrophysics. Refinement of interaction parameters and spectroscopic factors for these nuclei contributes to improving the accuracy of modeling processes relevant to the development of new technologies and understanding nucleosynthesis in stars. The ^{10}B nucleus is actively used in applied technologies, in particular in boron neutron capture therapy (BNCT), where the efficiency of interaction with neutrons depends on the structure and properties of the nucleus.

The phenomenon of the nuclear rainbow in the scattering of α -particles on boron nuclei provides a unique opportunity for a detailed investigation of optical potentials, minimizing ambiguities inherent in traditional approaches. Modern methods of theoretical analysis, including the consideration of cluster exchange and coupled channels, make it possible to reveal more deeply the structure and reaction mechanisms involving light nuclei.

Thus, the study of interactions of deuterons and α -particles with boron isotopes is a relevant direction combining fundamental interest and applied problems of nuclear physics.

The aim of this dissertation is a comprehensive experimental and theoretical study of the influence of cluster structures of stable $^{10,11}\text{B}$ isotopes on the formation of nuclear reaction yields in interactions with deuterons and alpha particles at low energies (in the range of 7–10 MeV per nucleon), including the determination of spectroscopic characteristics of the nuclei under study through measurements of

differential cross sections of the processes.

Research objectives:

- to perform experimental measurements of reaction yields accompanying the interaction of deuterons and α -particles with the ^{10}B nucleus in the energy range of 7–10 MeV per nucleon;
- to carry out a computational analysis of differential cross sections of deuteron and α -particle scattering on ^{10}B and ^{11}B nuclei in the low-energy region and to extract deformation parameters of the studied nuclei;
- to analyze the influence of cluster configurations – $\langle\langle {}^9\text{B} + n \rangle\rangle$, $\langle\langle {}^6\text{Li} + \alpha \rangle\rangle$ and ${}^8\text{Be}$ on the behavior of cross sections at large angles and to determine their spectroscopic amplitudes.

Object of research: differential cross sections of angular distributions of the processes $^{10}\text{B}(\text{d},\text{d})^{10}\text{B}$, $^{10}\text{B}(\text{d},\text{t})^{10}\text{B}$, $^{10}\text{B}(\alpha,\alpha)^{10}\text{B}$, $^{11}\text{B}(\alpha,\alpha)^{11}\text{B}$ in the energy interval of 7–10 MeV per nucleon.

Subject of research: experimental measurement of differential cross sections of deuteron and α -particle scattering, as well as (d,t) reactions on ^{10}B and ^{11}B nuclei using the U150M accelerator beam. Investigation of the dynamics of processes forming the cross sections of elastic and inelastic scattering in order to determine reliable parameters of optical potentials providing realistic modeling of inter-nuclear interactions for the systems $\langle\langle \text{d} + {}^{10}\text{B} \rangle\rangle$ and $\langle\langle \alpha + {}^{10}\text{B} \rangle\rangle$. Obtaining spectroscopic data on the energy levels of ^{10}B and ^{11}B nuclei.

Research methods: particle identification in the experiment was carried out using the ΔE – E technique. The theoretical analysis of the experimental data was performed using the SPI-GENOA and FRESCO codes within the framework of the optical model, the coupled channels method, and the distorted wave method.

Key provisions submitted for defense:

1. New angular distributions of differential cross sections for the nuclear processes $^{10}\text{B}(\text{d},\text{d})^{10}\text{B}$, $^{10}\text{B}(\text{d},\text{t})^{10}\text{B}$, and $^{10}\text{B}(\alpha,\alpha)^{10}\text{B}$ have been obtained in the low-energy range of 7–10 MeV per nucleon. Within the framework of their analysis, the structural characteristics of the ^{10}B nucleus were determined.
2. Physically justified parameters of optical potentials for inter-nuclear interaction have been determined for the $\langle\langle \text{d} + {}^{10}\text{B} \rangle\rangle$ system at an energy of 14.5 MeV and the $\langle\langle \alpha + {}^{10}\text{B} \rangle\rangle$ system at an energy of 29 MeV, providing a consistent description of experimental data and reliable extraction of nuclear deformation parameters and spectroscopic factors.
3. The quadrupole deformation parameters of the ^{10}B ($\beta_2 = 0.7$) and ^{11}B ($\beta_2 = 0.42$) nuclei have been established, obtained from the analysis of inelastic scattering within the coupled-channels model. These results refine the relationship between the ground and excited states of the nuclei and confirm the collective nature of their structure.
4. Spectroscopic factors of cluster configurations $^{10}\text{B} \rightarrow {}^9\text{B} + n$, ${}^9\text{B}$ ($3/2^-$) ($SA = 0.67$), ${}^9\text{B}$ ($5/2^-$) ($SA = 0.94$), ${}^8\text{Be}$ ($SA = 0.8$) и $^{10}\text{B} \rightarrow {}^6\text{Li} + \alpha$ ($SA = 1.4$) have been extracted. Their inclusion explains the rise in angular distributions of differential cross sections of elastic scattering at backward angles and substantiates the cluster structure of the studied nuclei.

Scientific novelty. The results obtained in this dissertation expand the experimental database on low-energy nuclear interactions, primarily due to measurements of interactions of deuterons and α -particles with ^{10}B and ^{11}B nuclei in the energy range of 7–10 MeV per nucleon, for which only fragmentary data were previously available. A comprehensive analysis of the experimental material was carried out using several theoretical approaches, which made it possible to trace how the features of the internal structure of the studied nuclei are reflected in the formation of cross sections of elastic and inelastic processes. Comparison of the obtained results with published data over a wider energy range made it possible to refine the interpretation of the observed effects and to specify the physical mechanisms determining the nature of interactions in the studied nuclear systems.

Within the framework of the coupled-channels method, the values of quadrupole deformation parameters of ^{10}B and ^{11}B nuclei (with negative sign) have been refined in the energy range of 7–10 MeV per nucleon.

Physically justified values of spectroscopic amplitudes for cluster configurations $^{10}\text{B} \rightarrow \langle \langle {}^6\text{Li} + \alpha \rangle \rangle$, $^{10}\text{B} \rightarrow \langle \langle {}^9\text{B} + n \rangle \rangle$ and ${}^8\text{Be}$ have been extracted from the description of scattering cross sections (α, α), (d,d), and (d,t) reactions on the ^{10}B nucleus in the backward hemisphere.

Theoretical and practical significance of the study. The performed research has high scientific and practical value. The newly obtained high-precision experimental data on the interaction of deuterons and α -particles with ^{10}B and ^{11}B nuclei in the low-energy range of 7–10 MeV significantly complement the existing nuclear data base, especially in terms of a wide angular range of measurements, previously poorly represented in world practice. Experimental cross sections of processes such as $^{10}\text{B}(\text{d},\text{d})^{10}\text{B}$, $^{10}\text{B}(\text{d},\text{t})^9\text{B}$, $^{10}\text{B}(\alpha, \alpha)^{10}\text{B}$, and $^{11}\text{B}(\alpha, \alpha)^{11}\text{B}$ constitute a new contribution to the global nuclear data base and may be included in international libraries such as EXFOR, maintained by the IAEA.

From a theoretical point of view, the obtained results are important for refining the structural characteristics of ^{10}B and ^{11}B nuclei and can be used for verification and calibration of modern nuclear models. Comparison of new experimental data with predictions of theoretical calculations will improve the accuracy of describing nuclear interaction mechanisms and cluster-type reactions over an extended energy range.

The practical significance of the results lies in their application to the modeling of physical processes in advanced nuclear energy systems, including thermonuclear and hybrid systems. In addition, the accumulated data can be used in calculations of nucleosynthesis reactions occurring under astrophysical conditions – in stars and the interstellar medium – where interactions of light nuclei play a key role in the formation of the chemical composition of the Universe.

Reliability of the results. It is ensured by the use of well-established and widely recognized experimental and theoretical methods in world scientific practice. In the experimental part, a reliable method for particle registration and identification – the ΔE –E technique – was applied, which has demonstrated high efficiency in the study of nuclear reactions. Theoretical modeling was performed using optical and folding models, as well as the distorted-wave and coupled-channels methods,

providing a comprehensive description of reaction mechanisms.

Numerical calculations were carried out using the FRESKO software package, which is widely accepted in nuclear physics and has been repeatedly validated for problems of this class.

The obtained results are in good agreement with literature data of other authors, which additionally confirms the correctness of the applied methodological approach and ensures a high degree of reliability of the conclusions drawn in this study.

Connection of the present research with other scientific projects. The dissertation work was carried out as part of a broader комплекс of scientific studies within several thematic areas: BR10965191 “Comprehensive studies in nuclear and radiation physics, high-energy physics and cosmology for the development of competitive technologies” (2021–2023), IRN AP14870964 “Investigation of interaction processes of protons and ^{10}B ions with ^{11}B nuclei for thermonuclear and astrophysical applications” (2022–2024), and BR21881941 “Experimental and theoretical studies in the field of high and ultra-high energies for solving актуальных problems of astrophysics and cosmic ray physics” (2023–2025).

Author’s contribution. The dissertation is based on studies carried out jointly with researchers of the NRC “Kurchatov Institute” (Moscow, Russian Federation) and the Laboratory of Low Energy Nuclear Reactions of the Institute of Nuclear Physics (Almaty, Kazakhstan), the final results of which were published collaboratively. The author’s contribution includes formulation of key scientific problems, participation in methodological approaches and experimental planning, direct execution of a wide range of experimental measurements, as well as comprehensive processing of the obtained experimental data and their subsequent interpretation within the framework of theoretical models.

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

- Abstracts of the V International Scientific Forum «Nuclear Sciences and Technologies» – Almaty, Kazakhstan, October 7–11, 2024.

- Abstracts of the IV International Scientific Forum «Nuclear Science and Technologies», dedicated to the 65th anniversary of the Institute of Nuclear Physics – Almaty, Kazakhstan, September 26–30, 2022.

- Abstracts of the III International Scientific Forum «Nuclear Science and Technologies», dedicated to the 30th anniversary of the Independence of the Republic of Kazakhstan – Almaty, Kazakhstan, September 20–24, 2021.(in Russian)

Publications on the dissertation topic. Within the framework of the dissertation research, the author has prepared 10 scientific publications. Among them, 3 articles have been published in peer-reviewed international journals of quartiles Q2–Q3 (Universe (Scopus – 74th percentile, WoS – Q3), Physics (Scopus – 55th percentile, WoS – Q2), Nuclear Physics A (Scopus – 71st percentile, WoS – Q2)), and 2 publications in the proceedings of international conferences (Conference Papers) indexed in the Scopus and Web of Science databases, as well as 5 publications in collections of international scientific conference proceedings.

Structure and scope of the dissertation. The dissertation consists of an introduction, four main sections, a conclusion, and a list of references comprising 101 sources. The total length of the work is 92 pages, including 4 tables and 39 figures.