ABSTRACT

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Effects of cluster structure of stable boron and lithium isotopes to form the outputs of nuclear reaction in the interaction with deuterium and helium isotopes

The dissertation is devoted to the experimental study and theoretical analysis of the differential cross sections of nuclear processes ^{7}Li(d,d)^{7}Li, ^{7}Li(d,t)^{6}Li, ^{11}B(d,d)^{11}B, ^{11}B(d,t)^{10}B, ^{11}B(α,α)^{11}B, ^{11}B(α,t) ^{12}C at energies of 7-10 MeV/nucleon within the framework of various theoretical models.

The relevance of research. Experimental studies of the interaction process in nuclear reactions, carried out using accelerator technology, remain the main source of direct information on the structure of nuclei and the mechanism of nuclear reactions. In this case, a special place is occupied by the process that is the simplest in nuclear dynamics — elastic scattering, and the relatively large cross section allows one to extract information of fundamental importance for the physics of the nucleus about the effective interaction potential of colliding systems. In this case, physically reliable values of the potential are necessary for calculating the yields of the products of nuclear reactions with the participation of particles of different types in the input and output channels of the reactions.

At the same time, in the case of scattering of complex particles, the potential parameters are subject to significant ambiguities.Despite the numerous attempts made by experimenters and theoreticians, the task of determining the interaction potential of composite particles with nuclei is far from complete and belongs to one of the urgent and open problems of nuclear physics.

The set of accumulated data on the interaction of complex particles (hydrogen and helium nuclides, heavy ions) with light nuclei at energies above 10 MeV / nucleon indicates that scattering cross sections in the full angular range are formed by two mechanisms: potential scattering and exchange processes.In this case, the contribution of metabolic processes is directly related to the structure of interacting systems.A comprehensive examination of potential scattering with exchange processes makes it possible to use the nature of the reaction cross section at large angles to study the effects of clustering in various states of nuclei and to study their structural features. Obviously, the most favorable objects of such a study are lithium and boron nuclei, which have a pronounced cluster structure.

At present, the scattering of helium ions on ^{6}Li and ^{7}Li nuclei, which have a pronounced cluster structure, has been systematically studied. The observed “anomalous” rise in the cross section at large angles can be described taking into account the contribution of the exchange mechanism of cluster transfer, which is physically indistinguishable from potential scattering. Therefore, taking into

account this mechanism in a number of works made it possible not only to obtain more reliable parameters of optical potentials, but also to extract cluster spectroscopic factors from the analysis of cross sections at large angles.

An additional criterion for the reliability of the obtained spectroscopic factors for the "^{3}He + t" cluster configuration of the ^{6}Li nucleus can be the extraction of these quantities from an alternative approach, namely, from the transfer of the t - cluster in nuclear reactions.

For example, the reaction (d,t) on ^{7}Li nuclei was previously studied at energies of 12 MeV, 15 MeV, 18 MeV, 20 MeV, and 28 MeV. Only at E_d = 12 MeV were measurements taken in the full range of angles. In other cases, they were carried out in the region of the anterior hemisphere. A significant increase in the cross section for the reaction *(d,t)* at 12 MeV could be explained by the exchange of the *t* – cluster, but only the contribution of the direct neutron detachment mechanism, which describes the behavior of the cross sections at the front scattering angles, was taken into account. At other energies (15, 20, 28 MeV), only a qualitative analysis was carried out based on the approximation of a plane wave. The values of spectroscopic factors were not extracted.

Of no less interest is the study of elastic and inelastic scattering of α particles and deuterons on ^{11}B nuclei. This is due to the presence of «α-α-t" cluster structure of this nucleus. A study of the states of the ^{11}B nucleus, where both the cluster configuration (2α + t) and the structure of the shell model can coexist, it is useful for determining the characteristics of excited neutron halo states of a this nucleus. Indeed, in a number of works it was assumed that the low-lying states of 11B mainly have a shell structure, while cluster structures are well traced in states with negative parity above or near the threshold of the breakup into clusters. In addition, in recent experiments on resonance scattering on ^{7}Li nuclei, a new band of negative parity was confirmed, which includes the following excited states: 8.56 MeV ($3/2^-$), 10.34 MeV ($5/2^-$), 11.59 ($7/2^-$) and 13.03 MeV ($9/2^-$). Since these states have large alpha decay widths, this band can be formed on the basis of cluster structures. In addition, the analogy of the cluster structure of the ^{11}B nucleus with the three ^{12}C cluster structure is of particular interest for study.In particular, it was suggested in a number of works that the $3/2^-_3$ state can have a structure consisting of three clusters in the form of "2α + t" configuration, and can be an analog of the ^{12}C excited state with spin 0^+_2, which has a structure consisting of three alpha particles. However, it was assumed that the state of 8.56 MeV ($3/2^-$) cannot correspond to the state of ^{12}C (0^+_2). The analogy between 8.56 MeV ($3/2^-$) and ^{12}C (0^+_2) is controversial and requires further study of this problem.

Therefore, the study of the interaction of charged particles with lithium and boron nuclei is of great interest. On the one hand, lithium and boron are one of the most important elements of the fuel cycle in the most promising projects of fusion reactors using deuterium-tritium plasma or alternative neutron-free fuel cycles. Another aspect is related to the issues of nucleosynthesis of light nuclei at an early stage of the evolution of the Universe and reactions proceeding with the formation of beryllium, lithium, and boron nuclei in a stellar medium.

The purpose of the dissertation research

The main aim of the work is an experimental and theoretical study of the influence of cluster structures of stable lithium and boron isotopes on the formation of yields of nuclear reactions in interactions with deuterons and α-particles.

The objectives of the study. To achieve the goals it was necessary to solve the following tasks:

- Measurements of differential cross sections for scattering of deuterons, α particles and reactions (d, t), (α, t) at ^{7}Li and ^{11}B nuclei at energies of 7-10 MeV/nucleon at the isochronous cyclotron U150M of the Institute of Nuclear Physics (Almaty, Kazakhstan);

Determination of global parameters of optical and folding potentials for the interaction of nuclear systems "d + ^{7}Li", "d + ^{11}B" and "α + ^{11}B" from the analysis of experimental data on elastic scattering;

- Extraction of deformation parameters for the excited states of ^{7}Li and ^{11}B nuclei from the analysis of experimental data on inelastic scattering;

- Determination of the values of spectroscopic factors of cluster configurations ^{7}Li → "α + t" and ^{11}B → "2α + t";

Object of study. The processes ^{7}Li(d,d)^{7}Li, ^{7}Li(d,t)^{6}Li, ^{11}B(d,d)^{11}B, ^{11}B(d,t)^{10}B, ^{11}B(α,α)^{11}B and ^{11}B(α,t)^{12}C at energies of 7-10 MeV/nucleon.

Subject of study. Differential cross sections for scattering of d and α particles, reactions (d, t) and (α, t) on light nuclei in a beam of the U150M accelerator. Mechanisms for the formation of cross sections for elastic and inelastic scattering of d and α-particle ions, reactions (d, t) and (α, t) on ^{7}Li and ^{11}B nuclei. Parameters of the potentials of nucleus-nucleus interactions. Spectroscopic characteristics of the states of ^{7}Li and ^{11}B nuclei.

Research Methods. To conduct an experimental study at the U-150M isochronous cyclotron of the Institute of Nuclear Physics (Almaty, Kazakhstan), the E-E method of registration and identification of nuclear interaction products was used. The essence of this technique is to simultaneously measure the specific energy loss of the products of nuclear reactions in a material (dE/dx) and their total kinetic energy (E). Theoretical analysis was carried out using the FRESCO computer program, which allows theoretical calculations using the following models: the standard optical model, the folding model, distorted wave method and coupled reaction channel method.

The main provisions to be defended:

1. Differential cross sections of nuclear reactions ^{7}Li(d,d)^{7}Li and ^{7}Li(d,t)^{6}Li at energies of 14.5 and 25 MeV, ^{11}B(d,t)^{10}B at an energy of 14.5 MeV and ^{11}B (α,t)^{12}C at an energy of 40.0 MeV and their analysis according to the optical model of the nucleus and the method of distorted waves, eliminates the discrete ambiguity of the real part of the potential for the systems "d+^{7}Li", "d+^{11}B" and "α+^{11}B" in a wide energy range.

2. The established values of the quadrupole deformation parameters of the ^{7}Li nuclei (β_2=1.1±0.3) and 11B (β_2=-0.80±0.2), taking into account the channel coupling between the ground and excited states of the studied nuclei, reduce the

deviations of the calculated cross sections from experimental ones in the range of average angles to 20– 30%.

3. The established values of the spectroscopic factors of the cluster configurations ^{7}Li→“d + t” (*SF*=1.19) and ^{11}B→“2α+t” (*SF*=1.0) correctly reproduce the rise of the reaction cross sections (d, t) and (α, t) under reverse angles on the studied nuclei and justify their cluster structures.

Scientific novelty.

1. For the first time, the differential cross sections for nuclear reactions ^{7}Li(d,d)^{7}Li and ^{7}Li(d,t)^{6}Li were measured at energies of 14.5 and 25 MeV, ^{11}B(d,t)^{10}B at 14.5 MeV and ^{11}B(α,t)^{12}C energies of 40.0 MeV The analysis of these data in the framework of the optical model of the core and the distorted wave method made it possible to eliminate the discrete ambiguity of the real part of the interaction potential for the systems “d+^{7}Li”, “d+^{11}B” and “α+^{11}B”.

2. The values of the quadrupole deformation parameters of the ^{7}Li nuclei (β_2 =1.1±0.3) and ^{11}B (β_2=-0.80±0.2 with a negative sign) were determined, which made it possible to significantly improve the descriptions of the studied angular distributions in the region of average scattering angles.

3. The values of spectroscopic factors of cluster configurations ^{7}Li→“d+t” (*SF*=1.19) and ^{11}B→“2α+t” (*SF*=1.0), necessary for determining the reaction cross sections (d,t) and (α,t), are calculated at opposite angles.

Scientific and practical value of work

The results of the research are of high scientific and practical value. The obtained experimental cross sections of the ^{7}Li(d,d)^{7}Li,^{7}Li(d,t)^{6}Li,^{11}B(d,t)^{10}B and ^{11}B(α,t)^{12}C processes at energies of 7-10 MeV/nucleon in a wide angular range can significantly supplement world nuclear data bank; IAEA library (EXFOR) on the interaction of deuterons and α particles with lithium and boron nuclei.

Experimental data are also needed to refine the parameters of theoretical models of nucleus-nucleus interactions.The totality of the data obtained on the scattering cross sections of deuterons and α particles on ^{7}Li and ^{11}B nuclei at low energies and the structural characteristics of the studied nuclear systems will be useful for model calculations of the energy balance of promising nuclear power plants, as well as in theoretical calculations of nucleosynthesis reactions in stars and interstellar spaces.

The reliability of the results

In the dissertation, well-known experimental and theoretical methods and models were used: E-E particle registration and identification technique, optical model, folding model, distorted wave method and coupled channel method. The calculations were performed using a recognized, widely tested computer code: FRESCO. The obtained results are in good agreement with the works of other authors in this field.

The relationship of this work with other research projects. The dissertation was carried out as part of scientific research on the topics: “Study of the excited halo states of neutron-rich nuclei ^{9}Be, ^{11}B, ^{13}C in interactions with deuterons” No. GR 0115RK01006 (2015-2017) and “Study of radiation capture and peripheral nuclear transfer reactions of protons at energies near the Coulomb

barrier caused by heavy ions for astrophysical and thermonuclear applications, AR05132062/GF (2018-2020).

Personal contribution of the author. The results stated in the dissertation were obtained by the author together with the employees of the Research Center “Kurchatov Institute” (Moscow, Russian Federation), Saitama University (Saitama, Japan) and the laboratory of low-energy nuclear reactions of the Institute of Nuclear Physics (Almaty, Kazakhstan) and are reflected in joint publications. The author’s personal contribution is to participate in the formulation of research tasks and the design of the experiment, in conducting a set of experimental studies, in processing and analyzing experimental results.

Work approbation.

Materials of the thesis were reported at 6 republican and international conferences: 19 th International Workshop on Radiation Imaging Detectors iWoRID, Poland, Krakov, July 2–6, 2017; XXXVI Mazurian Lakes Conference on Physics», Piaski, Poland, September 3-9, 2017; Zakopane Conference of Nuclear Physics, "Extremes of the Nuclear Landscape", August 26- September 2, 2018, Zakopane, Poland; DREB2018 - 10th International Conference on Direct Reactions with Exotic Beams4-8 June 2018, Matsue, Japan; II International Scientific Forum «Nuclear Science and Technologies» Almaty, Kazakhstan, June – 24-27, 2019; Ninth International Conference «Modern Problems of Nuclear Physics and Nuclear Technologies” September 24-27, 2019, Tashkent, Uzbekistan.

Publications

Based on the dissertation materials, 19 works were published (10 articles, 8 theses and one patent), of which 3 articles in magazines recommended by the Committee for Quality Assurance in the field of education and science of the Ministry of Education and Science of the Republic of Kazakhstan, as well as 1 patent of the Russian Federation “Semiconductor detector with internal amplification”, 7 articles with a non-zero impact factor in journals indexed by Thomson Reuters and Scopus.

The structure and scope of the dissertation

The dissertation consists of an introduction, five sections, a conclusion and a list of references from 217 items. The total amount of work is 127 pages of text, including 16 tables and 51 figures.