

ABSTRACT

of the dissertation for the degree of Doctor of Philosophy (PhD)
in the specialty "6D060500 – Nuclear Physics"

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Investigation of emission of light charged particles from the interaction of stable isotopes of hydrogen and helium with ^{27}Al and ^{59}Co nuclei

General characteristics of the work.

This dissertation is devoted to the experimental study and theoretical analysis of double-differential and integral cross-sections of the (p,xp) and (p,x α) reactions for incident protons with energies $E_p = 7$ and 22 MeV, as well as (α ,xp) and (α ,x α) reactions for α -particles with energy $E_\alpha = 29$ MeV interacting with ^{27}Al and ^{59}Co nuclei.

Relevance of the topic.

At present, new precise experimental data on double-differential cross-sections of charged particle reactions at intermediate energies are of great importance. This is due to the key role of modern nuclear experiments in forming a nuclear data base and advancing theoretical models in line with contemporary approaches, both in fundamental and applied research. For example, the production of various radioisotopes increasingly relies on experimental data concerning the formation of final isotopes.

Additionally, there are challenges associated with the accumulation of radioactive waste with long half-lives, which can potentially be addressed by the development of promising Accelerator Driven Systems (ADS), consisting of high-energy proton accelerators and deeply subcritical nuclear reactors. The main concept involves using high-energy charged particle accelerators to produce neutrons in heavy element targets. Such systems can generate high neutron fluxes for power generation, transmutation of radiotoxic isotopes, or tritium production for fusion sources. These installations meet IAEA safety requirements. Stopping the accelerator immediately halts neutron emission from the target into the subcritical reactor, causing the nuclear chain reaction to cease rapidly.

The successful operation of such systems critically depends on experimental data regarding key interaction parameters of nuclides cross-sections, energy spectra, and angular distributions of secondary particles ($^{1,2,3}\text{H}$, $^{3,4}\text{He}$, etc.) that can serve as neutron-inducing agents.

A crucial requirement for experimental studies of pre-equilibrium nuclear decay is the use of methods enabling simultaneous measurement of continuous angular distributions across all open channels. The development of the concept of intermediate nuclear decay as an indicator of the emergence and evolution of the excited nuclear state is one of the fundamental challenges in nuclear reaction theory.

From a practical perspective, the study of interactions of light charged particles ($^1,^2,^3\text{H}$, $^3,^4\text{He}$, etc.) with matter, including knowledge of their differential cross-sections, is of great importance not only in nuclear and fusion research but also in fields such as dosimetry, radiation therapy, production of medical radionuclides, astrophysics, and cosmochemistry. Today, this is directly linked to the need to address the lack of accurate experimental data on double-differential reaction cross-sections influenced by charged particles at intermediate energies. Therefore, the improvement and validation of computational codes based on phenomenological and quantum-mechanical approaches remain a primary objective.

Objective of the work.

To obtain new experimental data on double-differential and integral cross-sections of reactions with hydrogen and helium nuclides on ^{27}Al and ^{59}Co nuclei, followed by theoretical analysis within the framework of the exciton model of pre-equilibrium decay.

To achieve this objective, the following tasks must be performed.

- Development and optimization of an experimental automated system for registration and identification of nuclear reaction products, including measurement and data analysis software;
- Experimental determination of double-differential and integral cross-sections for (p,xp) and (p,x α) reactions on ^{27}Al and ^{59}Co isotopes at proton energies of $E_p = 7$ and 22 MeV, and for (α ,xp) and (α ,x α) reactions at $E_\alpha = 29$ MeV;
- Optimization of the TALYS nuclear reaction code for cross-section calculations; identification of the contribution of different nuclear reaction mechanisms to the formation of the integral spectra for (p,xp), (p,x α) on ^{27}Al and ^{59}Co nuclei at $E_p = 7$ and 22 MeV, and (α ,xp), (α ,x α) at $E_\alpha = 29$ MeV.

Object of study. ^{27}Al and ^{59}Co nuclear isotopes.

Subject of study. Double-differential and integral cross-sections of (p,xp) and (p,x α) reactions on ^{27}Al and ^{59}Co nuclei at proton energies of 7 and 22 MeV, and of (α ,xp) and (α ,x α) reactions at an α -particle energy of 29 MeV.

Methodology of the research.

Detection and identification of secondary particles using an automated multidimensional programmable analysis system on extracted beams from the U-150M cyclotron at the Institute of Nuclear Physics, RK. Theoretical analysis of experimental results using computational codes based on modern theoretical approaches.

Scientific Novelty.

1. For the first time, energy spectra of the (p,xp) and (p,x α) reactions for protons with energies $E_p = 7$ and 22 MeV, as well as of the (α ,xp) and (α ,x α) reactions for α -particles with energy $E_\alpha = 29$ MeV, were obtained on ^{27}Al and ^{59}Co nuclei in the angular range of $(30 \div 135^\circ)$ in the laboratory system).
2. For the first time, a theoretical analysis of the experimental data on the double-differential and integral cross sections of the (p,xp) and (p,x α) reactions on ^{27}Al and ^{59}Co nuclei was performed over a wide energy range.

3. For the first time, the experimental data on the double-differential and integral cross sections of the $(\alpha, x\alpha)$ and (α, xp) reactions on ^{27}Al and ^{59}Co nuclei at $E_\alpha = 29$ MeV were analyzed.

Main Provisions to be Defended.

1. The obtained set of new experimental data on the double-differential and integral cross sections of the (p, xp) and $(p, x\alpha)$ reactions at proton energies of 7 and 22 MeV, as well as of the (α, xp) and $(\alpha, x\alpha)$ reactions at α -particle energy of 29 MeV on ^{27}Al and ^{59}Co isotopes, is aimed at enriching nuclear data libraries for a wide range of applied purposes.

2. From the experimental and theoretical study of the double-differential and integral cross sections of the (p, xp) and $(p, x\alpha)$ reactions on ^{27}Al and ^{59}Co nuclei over a wide energy range, it has been established that as the energy increases, the contribution of pre-equilibrium processes to their formation grows and becomes dominant at about 30 MeV.

3. From the experimental and theoretical study of the double-differential and integral cross sections of the $(\alpha, x\alpha)$ and (α, xp) reactions on ^{27}Al and ^{59}Co nuclei at $E_\alpha = 29$ MeV, it has been established that the formation of secondary particles occurs mainly through equilibrium processes, since the large mass and charge of α -particles limit the possibility of complex pre-equilibrium processes and intranuclear cascades.

Author's personal contribution.

The author directly participated in planning, preparation, and conducting all experiments related to measuring the cross-sections of (p, xp) and $(p, x\alpha)$ reactions at $E_p = 7$ and 22 MeV, as well as (α, xp) and $(\alpha, x\alpha)$ reactions at $E_\alpha = 29$ MeV on ^{27}Al and ^{59}Co nuclei. The author played a key role in processing the experimental data and performing the theoretical analysis.

Reliability and validity of the results are ensured by the current methodology for detecting and identifying secondary particles using an automated multidimensional analysis system at the U-150M cyclotron of the Institute of Nuclear Physics, RK. The results are also supported by publications in international journals with non-zero impact factors and in journals recommended by the Science and Higher Education Quality Assurance Committee of the Ministry of Science and Higher Education of the Republic of Kazakhstan, as well as in proceedings of international scientific conferences.

Relevance to scientific research plans.

The dissertation was carried out within the framework of the grant project of the Committee of Science AP08955998 “Study of interaction cross-sections of hydrogen nuclides with nuclei of structural materials for advanced accelerator-driven systems”, and the targeted financing program BR09158499 of the Ministry of Energy of the Republic of Kazakhstan “Development of comprehensive scientific research in nuclear and radiation physics based on Kazakhstani accelerator complexes”.

Thesis defense presentations.

The results were reported and discussed at the following scientific forums:

- LXVIII International Conference "NUCLEUS 2018" (2018 y., Russia, Voronezh);
- II International Forum "NUCLEAR SCIENCE AND TECHNOLOGY" (2019 y., Kazakhstan, Almaty (INP));
- LXX International Conference "NUCLEUS-2020" (2020 y., Russia, Saint Petersburg);
- III International Forum "NUCLEAR SCIENCE AND TECHNOLOGY" (2021 y., Kazakhstan, Almaty (INP));
- International Conference "Modern Problems of Nuclear Power and Nuclear Technologies" (2021 y., Uzbekistan, Tashkent).

Publications. The main results of the dissertation have been published in 12 papers, including one in a journal recommended by the Science and Higher Education Quality Assurance Committee of the Ministry of Science and Higher Education of the Republic of Kazakhstan, five in international journals indexed in Scopus and Web of Science, and six in the proceedings of international scientific conferences.

Publications in international scientific journals indexed in Scopus / Web of Science.

1. Gusseinova D., **Ussabayeva G.**, Zholdybayev T.K., Boztosun I., Kucuk Y., Koning A.J., Kerimkulov Zh., Sadykov B., Temirzhanov A., Canbula B. New measurements of (p,xp) and (p,x α) reactions on ^{27}Al at 7.0, 22.0 and 30.0 MeV // The European Physical Journal A. – 2025. – Vol. 61. – Article ID: 133. <https://doi.org/10.1140/epja/s10050-025-01603-8>
2. Zholdybayev T.K., Duisebayev B.A., Sadykov B.M., Nassurlla M., **Ussabayeva G.**, Ismailov K.M. Emission of light charged particles from reaction of ^3He ions of energy 50.0 MeV with ^{59}Co nucleus // Acta Physica Polonica B. – 2018. – Vol. 49, No. 3. – P. 693-698. <https://doi.org/10.5506/APhysPolB.49.693>
3. Zholdybayev T.K., Sadykov B.M., Nassurlla M., **Ussabayeva G.**, Duisebayev B.A., Ismailov K.M., Dyachkov V.V., Saduyev N.O. Inclusive spectra of protons and α particles from the interaction between α particles with an energy of 29 MeV and ^{27}Al and ^{59}Co nuclei // Bulletin of the Russian Academy of Sciences: Physics. – 2019. – Vol. 83, No. 9. – P. 1183-1186. <https://doi.org/10.3103/S1062873819090326>
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5. Zholdybayev T.K., **Ussabayeva G.A.**, Temirzhanov A.A., Mukan Zh.T., Sadykov B.M., Duisebayev B.A. Proton emission from the interaction of 7 MeV energy protons with ^{59}Co nucleus // Journal of Physics: Conference Series. – 2023. – Vol. 2642, Issue 1. – 012001. <https://doi.org/10.1088/1742-6596/2642/1/012001>

Publications in journals recommended by Science and Higher Education Quality Assurance Committee of the Ministry of Science and Higher Education of the Republic of Kazakhstan.

1. **Ussabayeva G.**, Duisabayev B.A., Zholdybayev T.K., Sadykov B.M., Nassurlla M. Inclusive spectra of protons from the interaction of alpha particles with 29 MeV energy with ^{27}Al and ^{59}Co // Recent Contributions to Physics. – 2018. – Vol. 65, No 2. – P. 33-41. (in Russian).

Publications in the proceedings of international scientific conferences.

1. Duisabayev B.A., Zholdybayev T.K., Sadykov B.M., **Ussabayeva G.**, Nassurlla M., Ismailov K.M., Dyachkov V.V. The inclusive cross sections for the formation of p, d, α from the interaction of α -particles of 29 MeV energy with nuclei ^{27}Al and ^{59}Co // LXVIII International conference «NUCLEUS 2018». Fundamental problems of nuclear physics, atomic power engineering and nuclear technologies. Russia, Voronezh, July 2-6, 2018. – P. 117.

2. Duisabayev B.A., Zholdybayev T.K., Sadykov B.M., Nassurlla M., Ismailov K.M., **Ussabayeva G.**, Boztosun I. Measurement of the (p,xp) reaction cross-section for proton energies of 7 MeV on the middle nuclei // LXVIII international conference «NUCLEUS 2018». Fundamental problems of nuclear physics, atomic power engineering and nuclear technologies. Russia, Voronezh, July 2-6, 2018. – P. 112.

3. **Ussabayeva G.**, Zholdybayev T.K., Sadykov B.M. Study of secondary emission of light charged particles during the interaction of ^3He ions with ^{27}Al , ^{59}Co , ^{112}Sn nuclei at an energy of 50 MeV // II International Forum “NUCLEAR SCIENCE AND TECHNOLOGY”. Kazakhstan, Almaty, June 24-27, 2019. – P. 38. (in Russian).

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5. **Ussabayeva G.**, Zholdybayev T.K., Sadykov B.M. Investigation of continues energy spectra of light charged particles from interaction of ^3He ions with ^{27}Al wide energy range // III International Forum “NUCLEAR SCIENCE AND TECHNOLOGY”. Kazakhstan, Almaty, September 20-24, 2021. – P. 25.

6. **Ussabayeva G.**, Sadykov B.M., Zholdybayeva S., Zholdybayev T.K. Light charged particles production from interaction of ^3He ions with ^{27}Al wide energy range // Modern problems of nuclear energetics and nuclear technologies. Tashkent, Uzbekistan, November 23-25, 2021. – P. 44.