ABSTRACT

for thesis submitted for the degree of Doctor of Philosophy (PhD) of the educational program «8D05308 - Nuclear Physics»

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Radiative capture reactions on light nuclei in stellar and interstellar plasma

General characteristics of the work.

The thesis presents model calculations of the reaction rates of radiative capture of neutrons on ^{8}Li, ^{9}Be and ^{13}B nuclei and protons on the ^{15}N isotope to assess scenarios for the evolution of light elements in stellar and interstellar plasma.

Relevance of research.

Modern Nuclear Astrophysics is a field of theoretical and experimental research covering the most extensive aspects of fundamental and applied physics. One of the directions is associated with the study of nuclear reactions on light nuclei with $A \leq 16$ at low energies. This direction is a path for solving various astrophysical problems. Let us list only some of the most actual ones:

• *the early Universe's formation and evolution theory* is building and developing. So, one of the most critical questions that have not yet found an unambiguous solution is whether the primary cosmological environment is homogeneous or whether the *proton* and *neutron* components delamination occurred.

• *models for the synthesis of chemical elements* in the post-Big Bang Nucleosynthesis (BBN) period are developing based on the definition and study of temperature conditions relevant to the formation of various chains of nuclear reactions.

• based on well-founded nuclear chains, various versions of *networks* are building, which ultimately make it possible to calculate the mass fractions of both stable nuclei and radioactive isotopes, as well as justify different scenarios for the formation and, very importantly, the *accumulation of heavy isotopes*.

In the context of the above, the reactions of radiative capture of nucleons on light nuclei (N,γ) play a distinctive, mainly determining role in nuclear astrophysics since hydrogen (i.e., protons) serves as the primary environment for natural thermonuclear processes, as a result of which secondary neutrons can be produced in significant quantities.

Laboratory studies of nuclear reactions of radiation capture are significantly limited in their capabilities due to objective reasons. The cross sections for reactions with protons (p,γ) are strongly suppressed by the Coulomb barrier in the energy range specific for nuclear processes in stars. The known ratio 1eV ~ $1.16 \cdot 10^4$ K makes it possible to estimate the range of energies and temperatures of interest for astrophysical problems. For example, the temperature of the Sun is $T_6 \sim 1$ $(T_6 = 10^6\,\text{K})$. However, it is extremely difficult to measure the total reaction cross sections (p,γ) at energies of ~100 keV and below. The experimental base, which provides direct and indirect measurements of cross sections for radiative neutron (n,γ) capture reactions, is today

represented by many projects and modern installations equipped with contemporary techniques. However, when dealing with short-lived isotopes, one faces a problem. For example, for the reaction $^{8}Li(n,\gamma_{0+1})^{9}Li$, only four experimental points are known at two energy values. Measurements of cross sections for the reaction $^{13}B(n,\gamma_{0+1})^{14}B$ are extremely uninformative.

It should be emphasized that the most reliable data are those obtained using different installations and methods, mutually confirmed. Otherwise, they are considered *preliminary* and require additional verification. Consequently, theoretical calculations of (N,γ) reaction characteristics are becoming extremely in demand. The level of reliability of theoretical calculations also increases if they are mutually confirmed in different model approaches.

Purpose of research is model calculations of the reaction rates of radiative neutron capture on ^{8}Li, ^{9}Be, and ^{13}B nuclei and protons on isotope ^{15}N for evaluation of light elements evolution scenarios in stellar and interstellar plasma.

Research goals:

1.To calculate the total cross sections and $^{8}Li(n,\gamma_{0+1})^{9}Li$ reaction rate.

2.To calculate the total cross sections $^{9}Be(n,\gamma_{0+1+2+3+4+5})^{10}Be$ reaction with formation of ^{10}Be in GS and five excited states, as well as corresponding reaction rates.

3.Develop substantiated model approach for the investigation of $^{13}B(n,\gamma_{0+1})^{14}B$ reaction at astrophysical energies. Calculate the total cross section and reaction rate.

4.Re-estimation of the astrophysical S-factors of $^{15}N(p,\gamma)^{16}O$ in MPCM including the interference effects and non-resonance magnetic dipole $M1$ transition. Evaluate the impact of these factors on the corresponding reaction rate.

Research objects are the binary cluster systems of light nuclei and mechanisms of radiative nucleon capture reactions at low and ultra-low energies.

Research methods: algebraic methods of the quantum theory of angular momentums, methods of quantum scattering theory, numerical methods for solving the Schrödinger equation of continuum and bound states, numerical integration.

Scientific novelty:

1.The total cross sections for radiative $n^{8}Li$ capture at energies in the range from 10 meV to 5 MeV are obtained, which generally agree with the results of experimental measurements. For the first time, a model-free criterion for evaluating the reliability of the calculated reaction rates is proposed due to the binding energy in the nucleon channels $^{6}Li(n,\gamma)^{7}Li$, $^{7}Li(n,\gamma)^{8}Li$, and $^{8}Li(n,\gamma)^{9}Li$. The same criterion allows us to estimate the permissible range of asymptotic constants in the bound state.

2.The partial and total cross-sections of $^{9}Be(n,\gamma_{0+1+2+3+4+5})^{10}Be$ reaction are calculated in the energy range from 10^{-5} to 5 MeV in the MPCM. The expansion of the energy range to 5 MeV allows to consider five resonances and estimate their signature in the total cross-section. The resonance of $E_x = 0.730$ MeV is proposed as $^{3}F_{2}^{1}$ state. Strong sensitivity of the cross sections on the asymptotic constant C_w provided the proper long-range dependence of radial bound S wave functions is proved. New results on the complete reaction rate are obtained. Impact of resonances on the reaction rate is demonstrated.

3.The total cross sections of $^{13}B(n,\gamma_{0+1})^{14}B$ reaction are calculated in MPCM based on $E1$ and $M1$ transitions from 10^{-2} eV to 5 MeV *for the first time*. Within the variation of the asymptotic constant, the interval for the thermal cross-section of 5.1−8.9 mb is proposed. Based on the theoretical total cross-sections at energies of 0.01 eV to 5 MeV, the reaction rate is calculated in the temperature range of 0.01 to $10T_9$. The ignition T_9 values of $^{13}B(n,\gamma_{0+1})^{14}B$ reaction depending on the neutron number density $\bar{n}_n$ of ~ 10^{22} cm^{-3} are determined.

4.For the first time the re-estimation of the astrophysical S-factor and reaction rate for the $^{15}N(p,\gamma)^{16}O$ reaction in the framework of MPCM includes interference of low-lying $^3S_1$ resonances and *magnetic non-resonance* $M1$ *transition*. The simulation of considering the experimentally observed cascade transitions is suggested.

Comparative analyses of the reaction rates for $^{12}N(p,\gamma)^{13}O$, $^{13}N(p,\gamma)^{14}O$, $^{14}N(p,\gamma)^{15}O$, $^{15}N(p,\gamma)^{16}O$ reactions involved into different branches of the CNO cycle obtained in the framework of the same model, MPCM is implemented. Temperature windows, prevalence, and significance of each process are determined. The comparison of the reaction rates indicates which slow reactions control the rate and time of cycles of oxygen isotopes nucleosynthesis at particular astrophysical temperatures.

5.For the first-time regularity "*the higher the channel threshold, the higher the reaction rate*" for neighbouring isotopes Li, B and, N is formulated.

Defense of Provisions:

1.Two criteria found for the evaluation of $^{8}Li(n,\gamma_{0+1})^{9}Li$ reaction rate allow to *narrow down* the range of reaction rates and *constrain* the choice of asymptotic constants: the values of thermal cross sections and *correlation* between the energy thresholds and order of reaction rates at low temperatures on lithium isotopes $^{6,7,8}Li$.

2.The partial and total cross-sections of $^{9}Be(n,\gamma_{0+1+2+3+4+5})^{10}Be$ reaction calculated in the energy range from 10^{-5} to 5 MeV *allows to consider* five $^3D_3^1$, $^3F_2^1$, $^3F_3$, $^3F_2^2$, and $^3D_3^2$ resonances and *estimate* their signature in the total cross-section. The inclusion of resonances shows their impact on the reaction rate within the factor 4-5 rising at $T_9 > 1$, comparing the modern results of Wallner *et al*., 2019 and Mohr *et al*., 2019.

3.The calculations of the total cross sections of $^{13}B(n,\gamma_{0+1})^{14}B$ reaction performed in MPCM from 10^{-2} eV to 5 MeV provide the proposal for new experimental measurements ISOLDE. The presented data on the reaction rates substantiate the role of $^{13}B(n,\gamma_{0+1})^{14}B$ reaction in the Boron-Carbon-Nitrogen chains, this is not the *break-point* of the Boron sequence.

The connection of the thesis with research programs.

The research work is carried out in accordance with the following programs:

1."Study of the rates of some thermonuclear reactions in solar cycles and BBN" (IRN: AP09259021-OT-23, 2021-2023);

2."Study of the processes of thermonuclear hydrogen combustion in the CNO cycle on the Sun and in stars" (IRN: AP19676483, 2023-2025);

Personal contribution of the author. Badigul Yeleusheva took part in all stages of research, including the development the MPCM implementation for studying astrophysical processes of reactions $^{8}Li(n,\gamma_{0+1})^{9}Li$, $^{9}Be(n,\gamma_{0+1+2+3+4+5})^{10}Be$, $^{13}B(n,\gamma_{0+1})^{14}B$ and $^{15}N(p,\gamma)^{16}O$.

Theoretical and practical significance.

The results of calculations of the reaction cross sections $^{8}Li(n,\gamma_{0+1})^{9}Li$ and $^{13}B(n,\gamma_{0+1})^{14}B$ within the framework of MPCM actually provide a justification for setting up new experimental measurements both at thermal energies and in an extended range up to 5 MeV . It should be noted that the R-matrix approach is in principle not applicable to these reactions. For the reaction $^{9}Be(n,\gamma_{0+1+2+3+4+5})^{10}Be$, energy regions for which refined experimental data are required are also determined.

Reaction rates $^{8}Li(n,\gamma_{0+1})^{9}Li$, $^{9}Be(n,\gamma_{0+1+2+3+4+5})^{10}Be$, $^{13}B(n,\gamma_{0+1})^{14}B$ and $^{15}N(p,\gamma)^{16}O$ are recommended include in databases.

Reaction rates are calculated by averaging particles over velocities in the plasma according to the Maxwell equilibrium distribution. This distribution assumes a homogeneous model of the Universe. The obtained reaction rates can be taken as a basis for conducting promising studies of the effects of taking into account the weak non-ideality of stellar plasma, using Tsallis statistics instead of Maxwell statistics.

It is important to continue research to test the hypothesis related to the pattern "*the higher the channel threshold, the higher the reaction rate*" using extended data for neighboring isotopes. This information is of great practical importance both for theoretical model calculations - clarification of model parameters, and for qualitative estimates of reaction rates at low temperatures.

The reliability of the results, first of all, is due to the fact that the calculations use the algebraic methods of the quantum theory of angular momentum. Moreover, the construction of interaction potentials and calculations of the characteristics of radiative capture reactions based on modern experimental data on level spectra, their width, ACs, cross sections and astrophysical *S*-factors. The reliability and validity of the results is also confirmed by publications in journals recommended by the Committee for Control of Education and Science of the Ministry of Education and Science of the Republic of Kazakhstan, as well as in the proceedings of international scientific conferences.

Research approbation and publications.

The main results from the thesis were published in foreign scientific journals with impact-factor: *Frontiers in Astronomy and Space Sciences*, *Chinese Physics C*; and also, were reported and discussed at the following conferences: *No. XXVII (2022) European Academic Science and Research*, *25th European Conference on Few-Body Problems in Physics* (EFB25) (30 July- 4 August 2023, Mainz, Germany).

Publication:

Publications in scientific journals included and indexed in the Scopus\Web of Science database:

– Dubovichenko S.B., **Yeleusheva B.M.**, Burkova N.A., Tkachenko A.S. The reaction rate of radiative $n^{8}Li$ capture in the range from 0.01 to $10T_{9}$ // Frontiers in Astronomy and Space Sciences. – 2023. – Vol. 10. – 1251743.

– Tkachenko A.S., Burkova N.A., **Yeleusheva B.M.**, Dubovichenko S.B. Estimation of radiative capture $^{13}B(n,\gamma_{0+1})^{14}B$ reaction rate in the modified potential cluster model // Chinese Physics C. – 2023. – Vol. 47. – 104103.

– Dubovichenko S.B., **Yeleusheva B.M.**, Burkova N.A., Tkachenko A.S. Radiative $^{9}Be(n,\gamma_{0+1+2+3+4+5})^{10}Be$ reaction rate in the potential cluster model // Chinese Physics C. – 2023. – Vol. 47. – 084105.

– Dubovichenko S.B., Tkachenko A.S., Kezerashvili R.Ya., Burkova N.A., **Yeleusheva B.M.** Astrophysical S-factor and reaction rate for $^{15}N(p,\gamma)^{16}O$ within the modified potential cluster model // Chinese Physics C. – 2024. – Vol. 48. – 044104.

Thesis structure and volume.

The thesis consists of Introduction, five sections, Conclusion, References. It contains 29 figures and 22 tables. References consists of 196 items. The thesis is set out on 105 pages of printed text.