ABSTRACT

of the thesis for the degree of Doctor of Philosophy (PhD)
at specialty 6D060500 – «Nuclear Physics» by Tkachenko Alessya Sergeevna
on the topic: **«Phase shift analysis of nuclear processes with the spin structure 1+1/2, 1+1, 1/2+3/2 and astrophysical applications»**

General description of the thesis. The work is dedicated to the development of a formalism for the phase shift analysis of processes with high channel spin values $(S > 1/2)$, in order to apply obtained results for precise solutions to a wide range of problems, such as low-energy processes in astrophysics and plasma physics, or the scattering of hadrons and mesons in intermediate-energy physics. Analytical estimates of the reduction of the exact method of phase shifts analysis in the framework of the modified potential cluster model (MPCM) are presented, when the inverse problem of reconstructing the interaction potentials from the experimental observables for the asymptotic normalization coefficients (ANC), the position and width of the corresponding resonances in the continuous spectrum, and binding energies is solved. In the framework of MPCM the reactions ${}^{3}\mathrm{He}({}^{2}\mathrm{H},\gamma){}^{5}\mathrm{Li}$ and ${}^{10}\mathrm{Be}\left(n,\gamma\right){}^{11}\mathrm{Be}$ at astrophysical energies are considered in the research.

Relevance of the research. It is believed that the evolution of the Universe after the Big Bang began with a chain of synthesis of chemical elements, the first link of which was the reaction $p(n,\gamma)d$. The problem of describing the synthesis of chemical elements during the evolution of the Universe served as an impetus for the development of the theory of nucleon-nucleon (*NN*) interaction. At present, several dozens of different *NN*-potentials have been built, but the universal one that able to describe any processes does not exist. This a priori does not allow the construction of a unified theory of the atomic nucleus more complex than *d*.

The study of the subsequent synthesis of heavier chemical elements is based on microscopically justified models of the atomic nucleus from the point of view of quantum-mechanical principles. In the modern scientific world, one of the most widely recognized is the model known as the "resonant group method" (RGM). Thus, in order to solve practical problems in the context of discussing the *NN*-potential, some approximations are inevitable.

One of the possible options lies in the fact that relying on the experimental data of elastic scattering, the observed energy spectra and asymptotic constants for the bound states of particles, as well as measured geometric characteristics such as charge and mass radii *etc*. one able to reconstruct the interaction potentials in a fixed binary cluster channel. This approach is known today as the potential cluster model (PCM).

In the context of PCM, there are two ways to account for the fundamental Pauli principle. The first one involves the introduction of repulsion in the nuclear potential at small distances, i.e. a low probability of clusters overlapping or, in other words, their isolation.is simulated. The second method is based on the introduction of a deep attraction potential, which implies the presence of Forbidden by the Pauli principle states (FSs) in both discrete and continuous spectra. PCM with the use of FSs is called the modified potential cluster model (MPCM).

This approach was previously used to describe the total cross sections and *S*-factors for astrophysical and thermal energies of nucleon capture processes in the following *nucleon-nucleus* channels: n^2H, p^2H, p^3H, n^6Li, p^6Li, n^7Li, p^7Li, n^8Li, p^9Be, n^9Be, n^{10}Be, p^{10}B, n^{10}B, p^{11}B, n^{11}B, n^{12}C, p^{12}C, n^{13}C, p^{13}C, n^{14}C, p^{14}C, n^{14}N, n^{15}N, p^{15}N, n^{16}O, and p^{16}O. The implementation of MPCM allows one to explain experimental data, and in some cases *reliably* predict the behavior of astrophysical *S*-factors at low and ultra-low energies.

In this research, for the first time, $^{3}\mathrm{He}(^{2}\mathrm{H},\gamma)^{5}\mathrm{Li}$ and $^{10}\mathrm{Be}(n,\gamma)^{11}\mathrm{Be}$ reactions are investigated at low and astrophysical energies.

The interest to the radiative capture reactions in the isobar-analogue channels $^{3}\mathrm{He}(^{2}\mathrm{H},\gamma)^{5}\mathrm{Li}$ and $^{3}\mathrm{H}(^{2}\mathrm{H},\gamma)^{5}\mathrm{He}$ is primarily due to the following two reasons: these reactions are parts of nucleosynthesis chain of the processes occurring in the early stages of a stable star formation, as well as possible candidates for the overcoming of the well-known problem of the $A = 5$ gap in the synthesis of light elements in the primordial Universe. In addition, a possible scenario for the formation of ^{6}Li in astrophysical processes involving the short-lived ^{5}Li isotope was considered. The two-step process $^2\mathrm{H} + {}^3\mathrm{He} \rightarrow {}^5\mathrm{Li} + \gamma$ and $n + {}^5\mathrm{Li} + \gamma \rightarrow {}^6\mathrm{Li} + \gamma$ is proposed as an alternative way of ^{6}Li formation at the BBN.

Present-day studies of stellar dynamics on the synthesis of neutron-rich beryllium isotopes are based on the only modelless calculations for the reaction rate $<\sigma \mathrm{v}>$ of radiative neutron capture on ^{10}Be, obtained by Rauscher in 1993. The evaluation of the reaction rate $^{10}\mathrm{Be}(n,\gamma)^{11}\mathrm{Be}$ obtained in the present work using modern data on ^{10}Be nucleus spectra and its spectroscopic characteristics show a radically different energy dependence $<\sigma \mathrm{v}>$. As a result, new estimates of the evolution chains of the early Universe according to the “beryllium” or “boron” scenarios are required.

Research purpose: is a development of the formalism for the phase shift analysis of high-spin scattering processes, as well as approbation and analytical evaluation of methods for constructing interaction potentials in binary cluster channels, applicable for solving astrophysical problems.

Research objectives:

1. To develop a formalism of the phase shift analysis for the systems with spin structures 1+1/2, 1+3/2 and 1+1; To develop a computer program for calculating the scattering phase shifts;
2. To analyze alternative methods for obtaining the scattering phase shifts and building interaction potentials in binary cluster channels;
3. To construct the binary interaction potentials at low and astrophysical energies within the modified potential cluster model approach for the reactions $^{3}\mathrm{He}(^{2}\mathrm{H},\gamma)^{5}\mathrm{Li}$ and $^{10}\mathrm{Be}\left(n,\gamma\right)^{11}\mathrm{Be}$;
4. To calculate the total cross sections, astrophysical *S*-factors and rates of the reactions $^{3}\mathrm{He}(^{2}\mathrm{H},\gamma)^{5}\mathrm{Li}$ and $^{10}\mathrm{Be}\left(n,\gamma\right)^{11}\mathrm{Be}$.

Research objects are the continuous and discrete spectra of binary cluster systems of light nuclei.

Research subjects are the scattering processes of spin particles in binary channels and radiative capture reactions at astrophysical energies.

Research methods: quantum theory of the angular momentum, partial waves method, numerical methods for solving differential equations and systems of algebraic equations, numerical methods for solving the Schrödinger equation.

Defense Provisions:

1. The differential scattering cross sections for processes with channel spin $S > 1/2$ are *universal* in the framework of the quantum theory of collisions taking into account spin-orbit and spin-spin interactions without restrictions on the number of partial waves and the channel spin value.

2. The two-step mechanism for the synthesis of ^{6}Li nuclei in the Big Bang, which consists of the reactions ^{2}H + ^{3}He $\rightarrow$ ^{5}Li + γ and n + ^{5}Li + $\gamma \rightarrow$ ^{6}Li + γ, calculated on the basis of total cross sections, astrophysical *S*-factor, and $^3\text{He}(^2\text{H},\gamma)^5\text{Li}$ reaction rate for energies up to 5 MeV in the framework of the modified potential cluster model using forbidden states, explains the ^{6}Li/^{7}Li ratio in the Universe.

3. The modified potential cluster model with forbidden states reproduces the available experimental data on the total cross sections for radiation capture of neutrons on a ^{10}Be nucleus in the energy range from 25.3 meV to 10.0 MeV.

Scientific novelty

1. A universal mathematical formalism is developed for constructing elastic scattering cross sections for multiplet states (from singlet with 2*S*+1=1 to sextet with 2*S*+1=6), which consider the spin-orbit and spin-spin interactions and allows one to perform the phase shift analysis taking into account any number of partial waves.

2. The experimental total cross sections of the $^3\text{He}(^2\text{H},\gamma)^5\text{Li}$ process at energies up to 5 MeV is reproduced in the framework of the modified potential cluster model. The role of the $^3\text{He}(^2\text{H},\gamma)^5\text{Li}$ process for the formation of ^{6}Li in the Big Bang nucleosynthesis (BBN) via its participation in a two-step mechanism ^{2}H + ^{3}He $\rightarrow$ ^{5}Li + γ; n + ^{5}Li + γ $\rightarrow$ ^{6}Li + γ has been established.

3. Experimental data for the total cross sections of radiative capture of neutrons on the ^{10}Be nucleus are reproduced in the framework of the modified potential cluster model with forbidden states, and the rate of this reaction was calculated in the energy range from 25.3 meV to 10.0 MeV.

Theoretical and practical significance

The formalism presented for the scattering matrix of particles with a spin structure $\vec{s}_1 + \vec{s}_2 = \vec{1} + \vec{1}/2$, $\vec{s}_1 + \vec{s}_2 = \vec{1}/2 + \vec{3}/2$, and $\vec{s}_1 + \vec{s}_2 = \vec{1} + \vec{1}$ in the form of expansion in partial amplitudes allows one to carry out a sequential phase shift analysis of experimental data both in elastic and inelastic scattering. The same amplitudes are structural elements for calculating polarization characteristics such as asymmetry of the angular distribution, vector and tensor polarizations, and polarization transfer coefficients.

The application area of the obtained mathematical formalism is not limited only to astrophysical problems; it can be used, for example, in the study of low-energy processes in plasma physics, in particular, to take into account quantum-mechanical effects, as well as in problems of hadron and meson scattering in intermediate-energy physics.

A detailed phase shift analysis further opens up the possibility of constructing binary interaction potentials of varying complexity – central, spin-spin, tensor, etc. In the future, based on the presented analytics, it is possible to create program codes and software for the consistent phase shift analysis based on the modern experimental data.

In addition, in the framework of MPCM, the possibility of extracting the scattering phase shifts in an indirect way was demonstrated, namely, from experimental data on the spectra of light nuclei – excitation energies E_{cm}, level widths Γ, quantum characteristics J^{π}, and also asymptotic normalization constants.

The process of radiative capture of neutrons $^{10}\mathrm{Be}(n,\gamma)^{11}\mathrm{Be}$ in the energy range $25.3\ \mathrm{meV} \le E \le 10.0\ \mathrm{MeV}$ is studied. The calculation of the total cross sections shows good agreement with the experimental data reconstructed from the measurements of Coulomb dissociation. To date, studies of stellar dynamics have relied on the only modelless calculations of Rauscher (1993) for the reaction rate. Our $<\sigma v>$ calculations of the reaction $^{10}\mathrm{Be}(n,\gamma)^{11}\mathrm{Be}$ differ significantly from the Rauscher's data and, thus, can significantly change the idea of the role of the beryllium chain in the overall macroscopic picture of the fractions of the masses of light elements at an early stage of the evolution of the Universe.

In the framework of the MPCM, the cross sections of the ^{3}H^{3}He and n^{5}Li processes of radiative capture and their analytical parameterization were obtained, the reactions rates were calculated.

Based on comparisons of the rates of these reactions and the prevalence of light elements, it has been suggested that the two-step process $^{2}\mathrm{H} + {}^{3}\mathrm{He} \to {}^{5}\mathrm{Li} + \gamma$ and $n + {}^{5}\mathrm{Li} + \gamma \to {}^{6}\mathrm{Li} + \gamma$ can make contribution to the formation of ^{6}Li at BBN, especially at temperatures T_9 of the order of unity. In this temperature range, the number of neutrons has not yet begun to decrease, and the number of ^{2}H deuterium nuclei and ^{3}He isotope is already reaching its maximum, which leads to an increase in the yield of the $^{2}\mathrm{H} + {}^{3}\mathrm{He} \to {}^{5}\mathrm{Li} + \gamma$ reaction. Thus, additional quantitative calculations of the contribution of this reactions to the accumulation of the ^{6}Li nucleus at BBN, in stars, and other astrophysical processes are required.

Personal contribution of the author. Alessya Tkachenko took part in all stages of research, including the development of a formalism for phase shift analysis and the MPCM implementation for studying astrophysical processes $^{3}\mathrm{He}(^{2}\mathrm{H},\gamma)^{5}\mathrm{Li}$ and $^{10}\mathrm{Be}(n,\gamma)^{11}\mathrm{Be}$. Research work was carried out at Al-Farabi Kazakh National University, as well as during a foreign internship held at the City University of New York (CUNY, New York, USA).

Research approbation and scientific publications. The main results from the dissertation were published in local and Russian journals: *International Journal of Mathematics and Physics* (1 publication), *Russian Physics Journal* (2 publications), *News of NAS RK* (1 publication); in foreign scientific journals with impact-factors: *Nuclear Physics A* (2 publication) and *Astroparticle Physics* (1 publication); and also were reported and discussed at the following conferences: the 9th International Scientific Conference "*Modern Achievements of Physics and Fundamental Physical Education*" (October 12-14, 2016, Kazakhstan, Almaty), the International Conference of Students and Young Scientists "*Farabi Alemy*" (April 10-13, 2017 and April 9-12, 2018, Almaty, Kazakhstan), the International Scientific Forum "*Nuclear Science and Technology*" (September 12-15, 2017, Almaty, Kazakhstan), the *International Conference on Few-Body Problems in Physics* (FB22) (July 9-13, 2018, Caen, France).

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, asymptotic constants (*AC*s), 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.

The connection of the thesis with research programs. The research work is carried out in accordance with the following programs:

1. *"Study of the thermonuclear processes in the Universe"* («Исследование термоядерных процессов во Вселенной», 0073-8/ПЦФ-15-МОН/1-16-ОТ, 2015-2017);

2. *"Study of thermonuclear processes in stars and the primordial nucleosynthesis of the universe"* («Изучение термоядерных процессов в звездах и первичном нуклеосинтезе вселенной», IRN: BR05236322-OT-19, 2018-2020);

Thesis structure and volume. The thesis consists of Introduction, four Sections, Conclusion, References and two Appendixes. It contains 19 figures and 14 tables. References consists of 147 items.

Conclusions. In this dissertation, rather successful attempt to develop the scattering phase shift formalism for the high-spin nuclear processes relevant for the astrophysical applications was made.

Also, in the MPCM framework the possibility of obtaining the scattering phase shifts indirectly, based on experimental data (excitation energy E_{cm}, level widths Γ, quantum characteristics J^{π}, ANC), was demonstrated.

Based on the phase shifts obtained, the binary interaction potentials within the MPCM approach were constructed and the total cross sections, astrophysical *S*-factor and reaction rates for the radiative capture reactions $^{3}\mathrm{He}^{2}(\mathrm{H},\gamma)^{5}\mathrm{Li}$ and $^{10}\mathrm{Be}(n,\gamma)^{11}\mathrm{Be}$ were calculated.

As a result of the research, the following conclusions were formulated:

1. The analytical expressions obtained for the differential cross sections for elastic scattering taking into account the spin-orbit and spin-spin interactions are applicable for channels with an integer $(S=1, 2)$ and half-integer $(S=3/2, 5/2)$ spin value . The total differential cross sections are expressed in terms of the corresponding independent partial amplitudes for each channel spin. These expressions are presented for arbitrary

orbital angular momentum ℓ. It should be noted that due to this, these expressions can be used for any arbitrary number of partial waves ℓ.

2. MPCM implementation succeeded to obtain the theoretical results in general agreement with the available experimental data for the *S*-factor or total cross section of the radiative ^{3}He(^{2}H,γ)^{5}Li capture at astrophysical energies. Simple parametrizations of the considered radiative ^{5}Li(n,γ)^{6}Li and ^{3}H(^{3}He,γ)^{6}Li capture reactions cross sections and their rates are obtained. We also compared the rates of these two processes and the rates of the ^{3}He(^{2}H,γ)^{5}Li capture reaction, considered the possible contribution of neutron capture on the ^{5}Li nucleus to the formation of stable ^{6}Li.

It has been shown qualitatively that the neutron capture on ^{5}Li formed at ^{3}He(^{2}H,γ)^{5}Li capture in the temperature range of the order of 1.0T_9 at the BBN, can make a significant contribution to the processes of primary accumulation of a stable ^{6}Li.

3. In the framework of MPCM the potentials of n^{10}Be interaction were constructed. These potentials reproduce correctly the general trend of experimental data for the total cross-sections of the neutron radiative capture on ^{10}Be nucleus at low and ultralow energies in the range from 25.3 meV to 10.0 MeV.

The theoretical cross-sections have been calculated from the thermal energy 10.0 meV up to 10.0 MeV and approximated by the simple function of energy, which can be used for calculation of the cross-sections at energies less than 10 eV.