REVIEW

on the PhD dissertation of Alessya Tkachenko entitled "Phase shift analysis of nuclear processes with the spin structure 1+1/2, 1+1, 1/2+3/2 and astrophysical applications" and submitted for the degree of Doctor of Philosophy (PhD) in the specialty "6D060500 – Nuclear Physics"

The dissertation of Alessya Tkachenko is dedicated to the development of a formalism for the phase shift analysis of processes with channel spin values $S > 1/2$. Part of the research is devoted to analytical estimates of the reduction of the exact method of phase shifts analysis in the framework of the modified potential cluster model (MPCM). In the framework of MPCM the reactions $^{3}\mathrm{He}(^{2}\mathrm{H},\gamma)^{5}\mathrm{Li}$ and $^{10}\mathrm{Be}(n,\gamma)^{11}\mathrm{Be}$ at astrophysical energies are considered as astrophysical applications examples.

1 Relevance of the research topic and its connection with general scientific and national programs

The PhD dissertation of Alessya Tkachenko lays the foundation for the consistent, sequential phase shift analyses for different integer and half-integer channel spins. Formalism, presented in the Section 1, allows one to find corresponding nuclear phase shifts using experimental data for a nucleon-nucleus and nuclear-nuclear reaction cross sections.

In addition to the direct methods of the phase shift analysis, the dissertation research also considers the cases of the lack of experimental data on the elastic scattering differential cross sections. In such cases MPCM is involved. For the first time, in the frameworks of MPCM, $^{3}\mathrm{He}(^{2}\mathrm{H},\gamma)^{5}\mathrm{Li}$ and $^{10}\mathrm{Be}(n,\gamma)^{11}\mathrm{Be}$ radiative capture reactions are investigated at low and astrophysical energies.

The reaction $^{3}\mathrm{He}(^{2}\mathrm{H},\gamma)^{5}\mathrm{Li}$ is involved in the nucleosynthesis chain of the processes occurring in the early stages of a stable star formation. Interest in this reaction stems from the fact that it can contribute to the Lithium problem solving.

The work is carried out in accordance with the research programs: "Study of the thermonuclear processes in the Universe" (0073-8/ПЦФ-15-МОН/1-16-ОТ, 2015-2017) and "Study of thermonuclear processes in stars and the primordial nucleosynthesis of the universe" (IRN: BR05236322-OT-19, 2018-2020);

2 Scientific results and the level of their validity

The following brand new reliable scientific results that correspond to the stated purpose of the research are presented in the dissertation:

1. The mathematical formalism for the differential cross sections for elastic scattering is developed. The total differential cross sections are expressed in terms of the corresponding independent partial amplitudes for each channel spin. These expressions are parametrized with respect to the arbitrary orbital angular momentum ℓ and can be applied for channels with an integer $(S = 1, 2)$ and half-integer $(S = 3/2, 5/2)$ spin values.

2. Based on MPCM, the theoretical results in general agreement with the available experimental data for the *S*-factor or total cross section of the radiative $^{3}\mathrm{He}(^{2}\mathrm{H},\gamma)^{5}\mathrm{Li}$ capture is obtained. Moreover, the possible contribution of the neutron capture on ^{5}Li to the formation of a stable ^{6}Li in the temperature range of the order of $1.0T_9$ at the BBN is considered.

3. In the framework of MPCM, all available experimental data are reproduced properly for the process $^{10}\mathrm{Be}(n,\gamma)^{11}\mathrm{Be}$ in the energy range from 25.3 meV to 10.0 MeV and the analytical approximation of the theoretical cross section allows one to predict its behavior at the energies less than 10 eV.

3 **The degree of validity and reliability of each scientific result (scientific provision) and conclusions, formulated in the dissertation** is provided by the fact that 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 (ACs), cross sections and astrophysical *S*-factors. Moreover, the analytical speculations from the Subsection 1 use the well-known algebraic methods of the quantum theory of angular momentum. The main results of the dissertation were published in local and Russian scientific journals recommended by the Committee for Control of Education and Science of the Ministry of Education and Science of the Republic of Kazakhstan or equivalent to them: International Journal of Mathematics and Physics (1), Russian Physics Journal (2), News of NAS RK (1). In scientific journals indexed in Scopus and Web of Science databases applicant has 3 publications, namely in Nuclear Physics A (2 publications) and in Astroparticle Physics (1 publication). The total number of international conferences proceedings equals 7. Alessya Tkachenko has a total of 14 scientific publications.

4 The degree of novelty of each scientific result (provision), the conclusion of the applicant, formulated in the dissertation

1. For the first time, a universal mathematical formalism was developed for constructing elastic scattering cross sections from singlet ($2S+1=1$) to sextet ($2S+1=6$) states, which is not limited to summation over the orbital momentum ℓ. Analytical expressions are obtained for elements of the scattering matrix for systems with a spin structure of 1/2 + 1, 1+1, and 1/2 + 3/2, for both diagonal and none-diagonal matrix elements in the form of expansions in partial elementary amplitudes.

2. For the first time, in the framework of a modified potential cluster model, the role of the $^{3}\mathrm{He}(^{2}\mathrm{H},\gamma)^{5}\mathrm{Li}$ process for the synthesis of ^{6}Li in BBN has been established.

3. For the first time, experimental data for the process of radiative capture of neutrons on the ^{10}Be nucleus in the energy range from 25.3 meV to 10.0 MeV are properly reproduced in the framework of a modified potential cluster model.

5 Practical and theoretical significance of scientific results

The formalism presented for the scattering matrix of particles 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 research demonstrates

that with an increase of the channel spin value, the number of required independent amplitudes for a correct description of scattering processes increases. For solving modern astrophysical problems, *i.e.* considering low energy processes, whose description requires a small number of partial waves, general expressions for the partial amplitudes can be reduced to simple algebraic expressions. The research presents various nuclei, processes involving which can be described using the presented formalism, including isotopes of H, Li, Be, B, C and N. A detailed phase shift analysis further opens up the possibility of constructing binary interaction potentials of varying complexity – central, spin-spin, tensor, etc.

Opportunities of the reduction of the exact method of phase shifts analysis in the framework of the modified potential cluster model (MPCM) are presented in the research, and the calculations of the $^{10}\mathrm{Be}(n,\gamma)^{11}\mathrm{Be}$ reaction rate differ significantly from the available data and, thus, can change the idea of the role of the beryllium chain in the Big Bang Nucleosyntheses.

No less interesting results were obtained in the study of the process $^{3}\mathrm{He}(^{2}\mathrm{H},\gamma)^{5}\mathrm{Li}$ in the frameworks of MPCM, based on which a solution of the lithium problem was proposed, otherwise a mechanism for the accumulation of stable ^{6}Li was established. These results require **further clarification**; however, it is already possible to recommend these results for BBN network calculations.

The results, obtained by Alessya Tkachenko, undoubtedly contribute to solving a wide range of problems, such as low-energy processes in astrophysics and plasma physics, including the study of primordial nucleosynthesis of our Universe.

6 Comments, suggestions for the dissertation

1. It is desirable to discuss in the dissertation in some detail the requirements and conditions of the modified potential cluster model applicability.
2. For clarity and convenience, it would be appropriate to give an explicit form of interaction potentials, such as spin-spin, spin-tensor, spin-orbit, *etc.*, which are mentioned in the context of further use of scattering phases shits.
3. Figure 3.4 is illustrative and is used to qualitatively assess the contribution of the process $^{3}\mathrm{He}(^{2}\mathrm{H},\gamma)^{5}\mathrm{Li}$ to the formation of stable ^{6}Li. The work does not provide a relation that links time t and temperature T_9. The inclusion of such a relation could further clarify the contribution of the two-step mechanism involving the reactions $^{3}\mathrm{He}(^{2}\mathrm{H},\gamma)^{5}\mathrm{Li}$ and $^{5}\mathrm{Li}\ (n,\gamma)\ ^{6}\mathrm{Li}$ to the ^{6}Li accommodation.
4. The dissertation work contains a small number of typos.

7 Compliance of the content of the dissertation within the requirements of the "Rules for the award of academic degrees"

Despite the comments and remarks given above, the results and conclusions of the research are scientifically significant. The dissertation of Alessya Tkachenko **"Phase shift analysis of nuclear processes with the spin structure 1+1/2, 1+1, 1/2+3/2 and astrophysical applications"** is a completed scientific and qualification work. It demonstrates an internal unity and consistency of the content presentation. All

the sections, results, and conclusions are interrelated. The topic of the dissertation corresponds to the specialty "6D060500 – Nuclear Physics". By the volume and content, the dissertation meets the requirements of "Rules of awarding of academic degrees" of the Committee for Control of Education and Science of the Ministry of Education and Science of the Republic of Kazakhstan. I believe that Alessya Tkachenko deserves to be awarded the degree of Doctor of Philosophy (PhD).

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РАСТАЙМЫН: Абай атындағы ҚазҰПУ ПЕРСОНАЛДЫ БАСҚАРУ БӨЛІМІНІҢ БАСТЫҒЫ
ЗАВЕРЯЮ: НАЧАЛЬНИК ОТДЕЛА ПО УПРАВЛЕНИЮ ПЕРСОНАЛОМ
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