## "Three-body soft dipole mode and astrophysics applications"

Team of co-authors:

1. Grigorenko L. V. (FLNR, JINR)
2. Parfenova Yu. L. (FLNR, JINR)
3. Shulgina N. B. (BLTP, JINR)
4. Zhukov M. V. (CTH, Goteborg, Sweden)

The presented cycle of works includes 7 publications. The problem was formulated and approaches to its solution were outlined about 15 years ago [1]. Breakthrough results that allowed it to be completely resolved were obtained in the last 2-3 years [2-7].

Abstract:

The theoretical results are of particular importance in the problems of nuclear astrophysics. This is because not all the data required here have been obtained or verified experimentally. In particular, the studies of three-body radiative captures cannot rely on directly measured cross sections. They can be recalculated only from the reverse processes of three-body photodissociation. Various experimental methods are available for measuring the widths of three-particle (radioactive) decays. On the contrary, direct measurement of the cross sections for photo- or Coulomb dissociation in the low-energy region, from which it is possible to extract data on radiative capture for astrophysics in a model-dependent way, is not feasible either now or in any foreseeable future. The challenge facing the theory in this area is high-precision calculations without the possibility of direct experimental verification.

Three-body two-neutron and two-proton captures in nuclear astrophysics become relevant under conditions of high temperature and density. They are realized on the trajectories of astrophysical r- and rp-processes of explosive nucleosynthesis. This includes nucleosynthesis during the collapse of a supernova core, merging of neutron stars, explosive burning of accretion hydrogen on the surface of neutron stars, etc. "Classical" approaches to three-body nonresonant radiative captures were developed by the "founding fathers" [Fowler et al., Ann. Rev. Astr. Astroph. 5 (1967) 525] and are still used today [Angulo et al., Nucl. Phys. A 656 (1999) 3]. These methods are inherently semiclassical and in essentially quantum-mechanical real situations they can give an unpredictable result. The semiclassical method, universal in one dimension, has not yet been generalized for multidimensional problems, such as the problems of three-body radiative capture. In the presented study, a consistent quantum-mechanical approach to this class of problems was developed.

Exotic nuclei on the border of stability often have a structure with a neutron or proton halo. E1 dissociation of such nuclei has the character of the so-called "soft dipole mode" (SDM). SDM can be interpreted as a split off extremely low-energy part of the giant dipole resonance associated with the presence of different radial scales in nuclei with a halo. The first problem to be solved was that different methods and even approaches of different teams within the same method led to sharply differing strength functions E1 for three-body processes. It is still not possible to rely on an experiment in this area, since the study of reverse processes of Coulomb dissociation of nuclei with a two-nucleon halo is still at the forefront of the experiment and the existing results are unreliable and need interpretation themselves [2, 3]. At present, there are only two experiments on the Coulomb dissociation of 6He → a+n+n and 17Ne → 15O + p + p, from which it is possible to derive estimates of strength functions in a model-dependent way. The results presented here are of an "advanced" nature - several predictions have been made, which in recent years have been confirmed.

It is shown that the sharply oscillating character of the E1 strength functions obtained by various researchers over the past 25 years is an artifact of the convergence of various theoretical approximations. For this problem, the convergence is extremely poor. Thus, in the method of hyperspherical harmonics, a basis with Kmax> 100 is required [1]. Such calculations have become technically feasible relatively recently [6]. Even so, the problem of convergence from the energy range characteristic of the theory of nuclear reactions (E ~ 1-3 MeV) goes over to the energy range essential for astrophysics (E ~ 10-500 keV).

Under these conditions, to test three-body calculations, semi-analytical methods were developed based on simplified three-body Hamiltonians that admit exact solutions (that is, convergence was studied on problems with similar dynamics and exactly known convergence results) [1,3,4]. The same methods allow extrapolating the results to the low-energy region, which is relevant for astrophysical applications [1,4,5,7]. The problem of such extrapolation for radiative captures of core + n + n led to the understanding that the dynamics associated with the n-n interaction in the final state dominates these processes. In this case, the low-energy part of the strength function can be effectively described by a relatively simple dynamic dineutron model [4, 5]. The situation turned out to be much more complicated in the case of radiative captures of core + p + p. This problem is closely related to the "classical" unsolved problem of the three-body Coulomb continuum. It is shown that the dynamics associated with the interaction in the subsystem core + p, which is well described in the semi-analytic model with a simplified three-particle Hamiltonian [1,2,3], dominates here.

It was also confirmed in [3] that direct nonresonant processes make a significant contribution to the reaction rate of 15O (2p, γ) 17Ne. At the same time, careful consideration of all parameters, including the effects of three-body dynamics, made it possible to reduce by three orders of magnitude the uncertainty in the predicted rate of two-proton radiative capture in the temperature range important for astrophysics from 0.1 to 1.0 GK. In [5], the previously obtained calculation results of the 4He (2n, γ) 6He reaction rate are radically revised (by 1–2 orders of magnitude). In this case, it was found that most of the previous results have different low temperature asymptotics. This aspect of the problem was simply overlooked by other authors. New values of the reaction rates of three-body capture lead to a significant revision of some astrophysical scenarios.

Further development of analytical methods for estimating the three-body astrophysical reaction rates is related to the so-called method of asymptotic normalization coefficients. This method is widely used to estimate the rate of two-body radiative capture at low energies and is fully analytical.(LD.Blohintsev, A.Mukhamedjanov, N.K.Timofeyuk, Phys. Rev. Lett. **91** (2003) 232501). The method is applicable for peripheral reactions when the strength function depends only on two parameters - the binding energy and the coefficient at the asymptotic tail of the ground state wave function. The generalization of this method to the case of three-body radiative capture reactions is a nontrivial problem that has not yet been solved. The presented study shows how this method can be generalized to the case of two-proton radiative captures in the low-energy region [7]. It turned out that an important factor here is the influence of strong correlations in the capture process. In essence, this is a consequence of the multidimensional character of the problem, when the wave function of the continuum depends not only on the total energy above the threshold, but also on the distribution of this energy over two-body subsystems. It is this distribution that is highly correlated. Using 17Ne as an example, a compact and elegant analytical formula for the rate of three-body radiative capture at astrophysical energies is obtained for the first time. Comparison with accurate dynamic calculations showed excellent agreement at temperatures below or at the order of 0.4 GK and good agreement at temperatures below 1.0 GK.

Let us highlight the main results of the study:

1) Theoretical methods have been developed that make it possible to correctly describe soft dipole excitations in a wide range of energies: from very low ~ 10-500 keV, which are

important for nuclear astrophysics problems, to ~ 10 MeV, where dipole excitations are no longer soft (associated with three-body clustering ) [1,6,7].

2) Correct low-energy asymptotics for E1 strength functions of three-body radiative captures core + n + n and core + p + p and the corresponding correct low-temperature asymptotics of astrophysical rates are obtained for the first time. The results obtained for the studied cases of 6He and 17Ne differ sharply (by orders of magnitude) from all previously obtained results. The correctness of the results obtained is substantiated by comparing the results of direct three-body calculations with the results of exactly solvable models [1,5,7].
3) It has been demonstrated that for core + n + n radiative captures, the dynamics associated with the n-n interaction in the final state dominates. The low-energy part of the strength function can be effectively described by the dynamic dineutron model [4,5].
4) It has been demonstrated that for core + p + p radiative captures the dynamics of interaction in the subsystem core + p dominates, which is well described in a semi-analytical model with a simplified three-particle Hamiltonian [1,2,3].
5) A fully analytical generalization of the asymptotic normalization coefficients method for the case of nonresonant three-body proton captures [7] at astrophysical energies has been derived. The high accuracy of this approximation is substantiated.

The results of the research radically change the "landscape" in this area of nuclear theory. The calculated strength functions are qualitatively different from those previously obtained by other researchers. The rates of nonresonant astrophysical 2n and 2p captures differ by orders of magnitude from those obtained earlier.

The stages of this work were reported at the following international conferences on nuclear physics: EXON 2018 (Petrozavodsk, September 10-14, 2018), Few-Body Problems in Physics 2018 (9-13 July, Caen, France), ECT* workshop on “Probing exotic structure of short-lived nuclei by electron scattering”, (Trento, Italy, July 16-20, 2018), Workshop “The structure and dynamics of weakly-bound systems” (2018, 19-22 November, IPN Orsay, France), Technical Meeting on Novel Multidisciplinary Applications with Unstable Ion Beams and Complementary Techniques (IAEA Headquarters, Vienna, Austria, December 10-14, 2018), The 1st RAON Users Workshop (3-5 April, 2019, Institute for Basic Science, Daejeon, South Korea), International symposium on “Fundamentals of Nuclear Particle Decay” (August 28-30, 2019, Stockholm, Sweden), NUSTAR Annual Meeting 2020 (GSI, Darmstadt, Germany, 2-6 March 2020) and also at seminars at INP SB RAS, SINP MSU, NRC KI and JINR. In the presented list of publications there are 7 articles in the journals "Physics Letters B", "Physical Review C" and "Acta Physica Polonica B".

Chairman of STC BLTP ______________________

Secretary of STC BLTP ______________________

**Appendix**

## List of publications

## "Three-particle soft dipole mode and astrophysical applications "

1. L.V. Grigorenko, K. Langanke, N.B. Shul'gina, and M.V. Zhukov,

*"Soft dipole mode in $^{17}$Ne and the astrophysical 2p capture on $^{15}$O"*,

Physics Letters B **641** (2006) 254–259.

2. Yu.L. Parfenova for ACCULINNA-2 collaboration,

*"Study of exotic nuclei in the Flerov Laboratory of Nuclear Reactions at Joint Institute for Nuclear Research"*,

Acta Physica Polonica B **49** (2018) 495.

3. Yu.L. Parfenova, I.A. Egorova, L.V. Grigorenko, N.B. Shul'gina, J.S. Vaagen, M.V. Zhukov,

*"From Coulomb excitation cross sections to nonresonant astrophysical rates in three-body systems: The $^{17}$Ne case"*,

Physical Review C **98** (2018) 034608 [arXiv: 1804.02674].

4. L.V. Grigorenko, J.S. Vaagen, and M.V. Zhukov,

*"Exploring the manifestation and nature of a dineutron in two-neutron emission using a dynamical dineutron model"*,

Physical Review C **97** (2018) 034605 [arXiv: 1804.02674].

5. L.V. Grigorenko, N.B. Shulgina, M.V. Zhukov,

*"Three-body vs. dineutron approach to two-neutron radiative capture in $^{6}$He"*,

Physics Letters B **807** (2020) 135557 [arXiv: 2003.12374].

6. L.V. Grigorenko, N.B. Shulgina, M.V. Zhukov,

*"High-precision studies of the soft dipole mode in two-neutron halo nuclei: The $^{6}$He case"*,

Physical Review C **102** (2020) 014611 [arXiv: 2003.10701].

7. L.V. Grigorenko, Yu.L. Parfenova, N.B. Shulgina, M.V. Zhukov,

*"Asymptotic normalization coefficient method for two-proton radiative capture"*,

Physics Letters B Volume 811, 10 December 2020, 135852,
https://doi.org/10.1016/j.physletb.2020.135852 [arXiv: 2007.13139].