Form № 24

**MICROSCOPIC MODELS FOR EXOTIC NUCLEI AND NUCLEAR ASTROPHYSICS**

**THEME: “THEORY OF NUCLEAR SYSTEMS”**

**BLTP JINR**

NAME OF THE PROJECT LEADER: Voronov V.V., Dzhioev A.A.

DATE OF SUBMISSION OF THE PROJECT TO DSOA \_\_\_06.04.2023\_

DATE OF DECISION OF THE LABORATORY'S STC: \_\_\_22.12.2022\_\_\_ DOCUMENT NUMBER \_\_\_9\_\_\_\_\_

YEAR OF THE PROJECT OPENING: \_\_\_2024\_\_\_\_\_\_\_\_\_\_\_

(FOR RENEWABLE PROJECTS) -- PROJECT START YEAR: \_\_\_\_\_\_\_

**APPROVED
JINR DIRECTOR**

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**Block “Theoretical Physics”
Project name in the theme “Theory of Nuclear Systems”**

**Microscopic models for exotic nuclei and nuclear astrophysics**

**Dates of the projects: 2024-2028**

**1. General information on the project**

**1.1. Theme code 01-3-1136-2019**

**1.2. Laboratory BLTP**

**1.3. Scientific field Theoretical Physics**

**1.4. Project name Microscopic models for exotic nuclei and nuclear astrophysics**

**1.5. Project Leader(s): Voronov V.V., Dzhioev A.A.**

**2. Scientific rationale and organizational structure**

**2.1. Annotation**

The scientific project aims to solve a fundamental task of contemporary nuclear physics - development and improvement of a self-consistent microscopic approach to describe the structure of ground and excited states of exotic and superheavy atomic nuclei, as well as to predict their decay properties. On the one hand, such an approach is necessary for planning the research program of modern heavy ion accelerator facilities (SHE-Factory at JINR, SPIRAL 2 at GANIL, FAIR at GSI, RIBF at RIKEN) and for interpretation of their results. On the other hand, the need for reliable theoretical nuclear data is also relevant for modeling various astrophysical processes. For example, the study of rapid nucleosynthesis (r-process) requires precise nuclear data for about two thousand neutron-rich isotopes that are synthesized in astrophysical environments, and most of which will never be available in terrestrial laboratories. In addition, several astrophysical processes involving exotic nuclei occur at extreme densities and temperatures that also cannot be reproduced under terrestrial conditions and therefore require theoretical modelling.

**2.2. Scientific justification (purpose, relevance and scientific novelty, methods and approaches, methodologies, expected results, risks)**

The construction and upgrade of large-scale scientific nuclear physics facilities and the activity of experimental groups both in Russia and in research centers around the world are stimulating theoretical research on the structure of exotic nuclei and nuclear astrophysics. The main objective of such research is to unravel the mechanism of nuclei formation from their building blocks, strongly interacting protons and neutrons, determination the limits of nuclear stability, prediction the properties and structure features of exotic and superheavy nuclei, and to study nuclear reactions under astrophysical conditions. Based on close coordination with the experimental programs at the JINR basic facilities and taking into account existing links with international projects, theoretical research in the framework of the Project will aim at answering the following questions:

- How can self-consistent approaches for describing nuclear structure be improved so that they become universal?

- Where are the limits of proton and neutron stability of nuclei?

- What is the structure and how do exotic nuclear systems decay in the region of superheavy and light nuclei?

- How does the structure of nuclei change as a function of temperature and angular momentum?

- How does the astrophysical environment affect the properties of nuclei and nuclear reactions?

Thus, the Project plays an important role in the development of theoretical methods for the self-consistent description of nuclear structure and their application to the study of exotic and superheavy nuclei, as well as in predicting their decay properties for the planning of experiments and for astrophysical applications.

Until recently the prediction of masses, energy- and decay-characteristics of superheavy and neutron-excess nuclei was carried out within the framework of macro-microscopic models based on the Strutinsky shell-correction method. This is, first of all, a phenomenological finite-range liquid-droplet model (FRLDM) [1]. But it is well known that macro-microscopic models with parameters found near the beta-stability line cannot provide a reliable extrapolation of nuclear properties at distances of even a few mass units from the last experimentally studied nuclei, not to mention nuclides near far from the stability line. Only fully microscopic, self-consistent models based on the use of realistic effective interactions between nucleons, combined with energy density functional (EDF) theory, can provide a more reasonable extrapolation. Such models have recently been extensively applied to global calculations [2,3,4] and their application to the study of exotic nuclei provides us with a valuable tool to develop a new approach to constructing EDFs and to establish a link between microscopic and phenomenological nuclear models. To this end, and to ensure reliable predictions, the form and the parameters of the energy density functional need to be extrapolated well beyond the valley of nuclear stability.

Among recent approaches to the study of excited states of exotic nuclei, we note the following: 1. The quasiparticle random phase approximation (QRPA) based on the relativistic Hartree-Bogoliubov model [5]. 2. Self-consistent QRPA c with the Skyrme effective interaction extended to deformed nuclei [6]. 3. Large-scale shell-model calculations of strength functions of allowed and forbidden beta-transitions [7]. 4. In [8] for superheavy nuclei, based on the microscopic analogue of the Grodzins relation, for the first time an estimate for the energy of the first 2+ state was obtained, the value of which can serve as a criterion of closeness of the nucleus to (semi-)magic. The listed approaches, however, to dated have their limitations. In particular, microscopic calculations based on effective nuclear forces do not take into account simultaneously two factors: self-consistency and interaction with complex configurations. Shell-model calculations, although carried out on a very large configuration space, but use a strongly restricted single-particle basis, so they are poorly applicable to highly excited and resonant states. Estimations [8] of the energy of the first 2+ state for nuclei with small deformation give only lower energy limit and need further improvement.

Another important direction of modern research is the development of models to predict the rates and cross sections of various nuclear reactions under astrophysical conditions, in which thermal effects play an important role. The nuclear data used to date in computer simulations of various astrophysical processes are obtained either within the framework of the nuclear shell-model [9] (for pf-shell nuclei) or on the basis of simplified parameterizations [10] (for heavy neutron-rich nuclei). But as shown in [11], such calculations often underestimate the role of thermal effects and, as a consequence, lead to lower values of rates and cross sections than predicted by thermodynamically consistent estimates.

The approach that the participants of the Project intend to develop should overcome these limitations and provide a qualitative leap in describing the structure of exotic and superheavy nuclei, including for astrophysical applications, on the basis of the EDF method. It should be emphasized that an essential feature of the developed approach is its self-consistent nature, which allows one to describe with good accuracy the properties of both ground and excited states of exotic nuclei while considering the coupling of simple and complex configurations. Being microscopic, the approach should have a reliable predictive power, be applicable to nuclei with even and odd numbers of nucleons, and allow a natural generalization to the case of hot nuclei.

The proposed approach is largely based on the nuclear models developed at BLTP and well proven both in the study of low-energy nuclear states and in the description of the properties of giant resonances. This refers first of all to the quasiparticle-phonon nuclear model (QPM) [12]. The generalization of the QPM to realistic effective nucleon-nucleon interaction within the framework of the EDF method increases the predictive power of the approach and makes it fully self-consistent. Moreover, the use of the superoperator method makes it relatively easy to proceed from considering the coupling between simple and complex configurations in cold nuclei to the studying similar effects in hot nuclei.

[1] P. Möller et al., At. Data Nucl. Data Tables **125** (2019) 1.

[2] P.N. Stoitsov, et al., Phys. Rev. C **68** (2003) 054312.

[3] N. Schunck and J.L. Egido. Phys. Rev. C **78** (2008) 064305.

[4] S. V. Tolokonnikov et al., J. Phys. G **42** (2015) 075102.

[5] N. Paar et al., Phys. Rev. C **67** (2003) 034312.

[6] K. Yoshida and N. V. Giai. Phys. Rev. C **78** (2008) 064316.

[7] Q. Zhi, et al., Phys. Rev. C **87** (2013) 025803.

[8] N.Yu. Shirikova et al., Phys. Rev. C **105** (2022) 024309;

[9] K. Langanke and G. Martinez-Pinedo, At. Data Nucl. Data Tables **79** (2001) 1.

[10] K. Langanke et al., Phys. Rev. Lett. **90** (2003) 241102.

[11] A.A. Dzhioev and A.I. Vdovin, Phys. Part. Nucl. **53** (2022) 885, 939, 1051.

[12] V. G. Soloviev “Theory of atomic nuclei. Quasiparticles and phonons”, Institute of Physics Publishing, Bristol and Philadelphia, 1992.

The self-consistent microscopic approach used in the Project to describe ground and excited nuclear states is based on the combination of the energy density functional method and the quasi-haptic-phonon nuclear model. The EDF method has been successfully used in condensed matter theory and quantum chemistry. It has also proven itself in global calculations of nuclear characteristics and in astrophysical applications.

The QPM methods are based on the conception of elementary modes of nuclear excitations - quasiparticles and phonons. Quasiparticles define single-particle excitations in a nuclear system with pairing correlations and their structure is found by solving the Hartree-Fock-Bogolubov equations. Collective nuclear excitations are described as phonons whose energy and structure are found by solving QRPA equations. In the framework of QPM it is possible to take into account the coupling between quasiparticles and phonons, while taking into account the Pauli principle. The use of the coupling of simple and complex configurations in the framework of QPM is nowadays practically the only way allowing one to go beyond the harmonic approximation using a large configuration space and without violating the Pauli principle.

Essentially new in the proposed Project is the use of the superoperator method. This method, based on the possibility of treating the mixed state in Hilbert space as a pure state in Liouville space, allows one to study uniformly the properties of even, odd and hot nuclear systems. This, in turn, allows one to generalize to the case of hot nuclei in astrophysical conditions all standard methods and concepts used in theoretical nuclear physics (quasiparticles, phonons, the equation of motion method, etc.).

Let us list the results expected at the end of the Project:

1. To ensure reliable predictions, the form and parameters of the EDF will be extrapolated far beyond the stability valley. Special attention will be paid to isovector properties, which play a crucial role in nuclei with large neutron-proton asymmetry.
2. Using a unified set of EDF parameters, the effect of interaction between simple and complex configurations on the properties of charge-neutral and charge-exchange nuclear excitations will be investigated with respect to their resonance structure as well as on the decay characteristics of nuclei at the driplines.
3. The developed self-consistent EDF methods will be applied to the study of beta-decay in the context of astrophysical r-process and weak nuclear reactions with hot nuclei in various astrophysical scenarios (supernova explosions, stellar nucleosynthesis, and neutrino formation).
4. Topical questions to be answered by the Project: role of tensor interaction in describing the fragmentation of Gamow-Teller resonance; beta-decay of neutron-rich nuclei; multi-neutron emission; beta-delayed gamma-spectroscopy.
5. Neutrino interaction with matter is an important problem in various astrophysical phenomena, e.g., supernovae, neutron star mergers, formation of the crust of neutron stars. The role of inelastic neutrino scattering on nuclei and the magnetic field in the neutrino thermalization process must be elucidated.
6. Calculations of charge and matter distribution radii for long isotopic chains, including deformed nuclei. Theoretical analysis of isotopic behavior of radii and observed anomalies.
7. The magic numbers for stable nuclei are well known. However, to understand the stability of the heaviest nuclei with Z>118, it is necessary to study their shell structure. For this purpose it is planned to study the evolution of magic numbers as a function of the ratio of neutrons to protons in the nucleus and to predict new nuclei with closed (sub)shells near the proton and neutron driplines.
8. Prediction of alpha spectra of superheavy nuclei for planning future experiments. Alpha-decays from isomeric states as well as fission from these states will be considered.
9. In order to determine the competition between different modes of radioactive decay of superheavy nuclei, lifetime calculations concerning orbital electron capture and β+ decay will be carried out, taking into account the contribution of first-forbidden transitions and the effect of nuclear deformation

It should be emphasized that the scientific staff of the sector № 1 in the theme “Theory of Nuclear Systems” have long-term successful experience in the study of nuclear structure and annually they publish around 15 research papers in highly ranked international scientific journals.

Selected publications of the scientific staff of the sector № 2 in the theme “Theory of Nuclear Systems” (2019-2022)

1. E.T. Gregor, N.N. Arsenyev, M. Scheck, T.M. Shneidman, M. Thurauf, C. Bernards, A. Blanc, R. Chapman, F. Drouet, A.A. Dzhioev, G. de France, M. Jentschel, J. Jolie, J.M. Keatings, “Decay properties of the 3-1 level in 96Mo*”, J. Phys. G: Nucl. Part. Phys.* **49**, 075101 (2019).
2. H. G. Ganev, “E1 transitions in the extended proton-neutron symplectic model”, *Phys. Rev. C* **99**, 054304 [10 pages] (2019).
3. E.O. Sushenok, A.P. Severyukhin, N.N. Arsenyev, I.N. Borzov, “Effects of tensor interaction and neutron-proton pairing on beta-decay characteristics of 130,132Cd”, *Acta Physica Polonica B* **50**, 261-267 (2019).
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5. A. Repko, J. Kvasil, V.O. Nesterenko,”Elimination of spurious modes within quasiparticle random-phase approximation*”, Phys. Rev. C* **99**, 044307 [14 pages] (2019)
6. V. N. Kondratyev, Alan A. Dzhioev, A. I. Vdovin, S. Cherubini, M. Baldo, “Energy exchange in neutrino nuclear scattering”, *Phys. Rev. C* **100**, [5 pages] 045802 (2019)
7. V.O. Nesterenko, A. Repko, J. Kvasil, P.-G. Reinhard, “Individual dipole toroidal states: main features and search in (e,e’) reaction”, *Phys. Rev. C* **100**, 064302 [11 pages] (2019)
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9. H. G. Ganev, “Some U(d1+d2) > U(d1) x U(d2) isoscalar factors involving two-rowed initial and final representations”, *Int. J. Mod. Phys. E* **28**, 1950071 [10 pages] (2019)
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11. E. B. Balbutsev, I.V. Molodtsova, P. Schuck, “The nuclear spin scissors mode – theory and experiment”, *Acta Phys. Pol. B* **12**, 637-648 (2019)
12. A.A. Dzhioev, A. I. Vdovin, Ch. Stoyanov, “Thermal quasiparticle random-phase approximation calculations of stellar electron capture rates with the Skyrme effective interaction”, *Phys. Rev. C* **100**, 025801 [16 pages] (2019)
13. H. G. Ganev, “U(6) quasi-dynamical symmetry in 238U”, *Nucl. Phys. A* **987**, 112-127 (2019)
14. E.E. Suchenok, A.P. Severyukhin, N.N. Arsenyev, I.N. Borzov, “Effects of dynamical pairing on the beta-decay properties of neutron-rich nuclei”, *Physics of Atomic Nuclei* **82**, 120–127 (2019)
15. I.N. Borzov, S.V. Tolokonnikov, “Self-consistent description of isobaric analog resonances in neutron-rich nuclei with pairing”, *Physics of Atomic Nuclei* **82**, 560-572 (2019)
16. P.N. Usmanov, E.K. Yusupov. A.I. Vdovin, U.S. Salikhbaev, “Phenomenological analysis of characteristics of rotational bands in 158,160Gd isotopes”, *Physics of Particles and Nuclei Letters* **16**, 706-712 (2019)
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19. V.N. Kondratyev, A.A. Dzhioev, A.A., Vdovin, “Magnetic and thermal effects in neutrino scattering in hot and dense nuclear matter”, *Bull. Russ. Ac. Sc.* **84**, 962–967 (2020)
20. T. Fischer, G. Guo, A.A. Dzhioev, G. Martinez-Pinedo, Meng-Ru Wu, A. Lohs, Yong-Zhong Qian, “Neutrino signal from proto-neutron star evolution: Effects of opacities from charged-current–neutrino interactions and inverse neutron decay”, *Phys. Rev. C* **101**, 025804 [15 pages] (2020)
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23. I.N. Borzov, S.V. Tolokonnikov, “Fully self-consistent study of isobaric analog resonances”, *Phys. At. Nucl.* **83**, 567-576 (2020)
24. I.N. Borzov, “Global calculations of beta-decay properties based on the Fayans functional”, *Phys. At. Nucl.* **83**, 413–426 (2020)
25. S. Mishev, V.V. Voronov, “Matter density in a simple core-plus-particle model”, *Bull. Russ. Ac. Sc.* **84**, 1534-1536 (2020)
26. A.P. Severyukhin, N.N. Arsenyev, I.N. Borzov, R.G. Nazmitdinov, S. Åberg, “On statistical properties of the Gamow-Teller strength distribution in 60Ca”, *Phys. At. Nucl*. **83**, 171–178 (2020)
27. I.N. Borzov, S.V. Tolokonnikov, “Self-consistent calculation of the charge radii in the 58-82Cu isotopic chain”, *Phys. At. Nucl.* **83**, 482-494 (2020)
28. A. A. Dzhioev, S. V. Sidorov, A. I. Vdovin, T. Yu. Tretyakova, “Tensor interaction effects on stellar electron capture and beta-decay Rates”, *Phys. At. Nucl.* **83**, 143-160 (2020)
29. E. B. Balbutsev, I. V. Molodtsova, P. Schuck, “Triplet of nuclear scissors modes”, *Phys. At. Nucl.* **83**, 212-218 (2020)
30. P.N. Usmanov, E.K. Yusupov, A.I. Vdovin, “Analyzing the magnetic characteristics of 158,160Gd states using a phenomenological model”, *Bulletin of the Russian Academy of Science: Physics*  **84**, 968-973 (2020)
31. I.N. Borzov, S.V. Tolokonnikov, “Fayans functional: self-consistent description of isospin excitations”, *Physics of Atomic Nuclei* **83**, 24-32 (2020)
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40. D. A. Testov, A. P. Severyukhin, B. Roussiere, N. Arsenyev, F. Ibrahim, M. Lebois, I. Matea, Yu. Penionzhkevich, V. Smirnov, E. Sokol, I. Stefan, D. Susuki, D. Verney, Jh. Wilson,”Study of 123Ag beta-decay at ALTO”, *Eur. Phys. J. A* **57**, 59 [6 pages] (2021)
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44. H. G. Ganev, “Microscopic shell-model description of transitional nuclei”, *Eur. Phys. J. A* **58**, 182 [10 pages] (2022)
45. N.Yu. Shirikova, A.V.Sushkov, R.V.Jolos, “Coriolis mixing of the K=1 and K=0 mixed symmetry states in the well deformed even-even nuclei”, *Eur. Phys. J. A* **58**, 98 [6 pages] (2022)
46. N.Yu.Shirikova, A.V.Sushkov, L.A.Malov, E.A.Kolganova, R.V.Jolos, “Prediction of the excitation energies of the 2+1 states for superheavy nuclei based on the microscopically derived Grodzins relation”, *Phys. Rev. C* **105**, 024309 [6 pages] (2022)
47. H. G. Ganev, “Proton-neutron symplectic model description of 20Ne”, *Chinese Phys. C* **46**, 044105 [9 pages] (2022)
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55. A.A. Dzhioev, A.I. Vdovin, “Superoperator approach to the theory of hot nuclei and astrophysical applications: III – Neutrino-nucleus reactions in stars”, *Physics of Particles and Nuclei* **53**, 1051-1088 (2022)

**2.3. Estimated completion date 2024-2028**

**2.4. Participating JINR laboratories**

**BLTP in collaboration with FLNR, MLIT, DLNP**

**2.5. Participating countries, scientific and educational organisations**

**Given in the suggestion on the theme continuation**

**3. Staffing**

**3.1. Staffing needs in the first year of implementation**

|  |  |  |  |
| --- | --- | --- | --- |
| **№№****п/п** | **Category** **employee**  | **Core staff,** **Amount of FTE** | **Associated Personnel** **Amount of FTE** |
| 1. | scientific staff  | 15 | 1 |
| 2. | engineers  | 0 | 0 |
| 3. | professionals  | 5 | 0 |
| 4. | employees  | 0 | 0 |
| 5. | workers  | 0 | 0 |
|  | **Total:**  | **15** | **1** |

**3.2. Human resources available**

**3.2.1. JINR core staff, BLTP**

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **№**№**п/п** | **Category****employee** | **NAME** | **Position**  | **FTE** |
| 1. | scientific staff  | Arsenyev N. N.  | s.r. | 100% |
| 2. |  | Molodtsova I. V.  | s.r. | 100% |
| 3. |  | Severyukhin A. P.  | s.r. | 100% |
| 4. |  | Balbutsev E. B.  | l.r. | 100% |
| 5. |  | Borzov I. N.  | l.r. | 50% |
| 6. |  | Ganev H. G. | l.r. | 100% |
| 7. |  | Kuzmin V. A.  | l.r. | 100% |
| 8. |  | Malov L. A.  | l.r. | 100% |
| 9. |  | Nesterenko V. O. | l.r. | 100% |
| 10. |  | Vdovin A. I.  |  c.r. | 100% |
| 11. |  | Voronov V. V.  | c.r. | 100% |
| 12. |  | Stratan G.  | c.r. | 100% |
| 13. |  | Dzhioev A. A.  | h.s. | 100% |
| 14. |  | Vishnevskiy P. I.  | j.s. | 100% |
| 15. |  | Mardyban M. A.  | j.s. | 100% |
|  | **Total:**  | **14 p. – staff****1 p. - associated personal** |  |  |

**4. Financial support**

**Project will be funded within the theme “Theory of nuclear systems”**



**Project Leader \_\_\_\_\_\_\_\_\_/\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_/**

Form № 25

**APPROVAL SHEET FOR PROJECT**

**MICROSCOPIC MODELS FOR EXOTIC NUCLEI AND NUCLEAR ASTROPHYSICS**

**THEME: “THEORY OF NUCLEAR SYSTEMS”**

NAME OF THE PROJECT LEADER: Voronov V.V., Dzhioev A.A.



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| AGREED BY JINR DIRECTOR | SIGNATURE  | DATE |
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| CHIEF SCIENTIFIC SECRETARY  | SIGNATURE | DATE |
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| CHIEF ENGINEER  | SIGNATURE | DATE |
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| LABORATORY DIRECTOR  | SIGNATURE | DATE |
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| CHIEF LABORATORY ENGINEER  | SIGNATURE | DATE |
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| PROJECT LEADER | SIGNATURE | DATE |
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| DEPUTY PROJECT LEADER | SIGNATURE | DATE |
| APPROVED BY THE PAC  | SIGNATURE | DATE |