Form № 24

**LOW-ENERGY NUCLEAR DYNAMICS AND PROPERTIES OF NUCLEAR SYSTEMS**

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

**BLTP JINR**

NAME OF THE PROJECT LEADER: Ershov S. N., Antonenko N. V.

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

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**APPROVED**

**JINR DIRECTOR**

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

**“Low-energy nuclear dynamics and properties of nuclear systems”**

**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 Low-energy nuclear dynamics and properties of nuclear systems**

**1.5. Project Leader(s): Ershov S. N. , Antonenko N. V.**

**2. Scientific rationale and organisational structure**

**2.1. Annotation**

The purpose of the project is to study the important dynamical nuclear processes such as fusion, quasi-fission,

multinucleon transfers, capture and breakup. The investigations of the near threshold effects demand an uniform description of the nuclear structure and reactions. Priority would be a development of the cluster models that allow us to understand peculiarities of the nuclear structure at extreme points in the neutron-proton landscape. It would have planned a further development of the completely quantum models for decays of the weakly bound nuclei. Study of the nuclear properties depending on an energy is necessary to reveal effects outside the mean field description. In the heated nuclei the potential energy surface is changed such a way that the height of the fission barrier for super heavy nuclei is decreasing. Investigation of the formation of super heavy nuclei with *Z*=119 and 120 in fusion reactions must be continued within a microscopic approach. The transport coefficients and nucleus-nucleus potentials calculated microscopically would be used in the double-folding model for a description of the nuclear fusion.

**2.2.**  **Scientific justification**

Our understanding of the nuclear properties is coming from experiments devoted to the nuclear reaction studies. It is necessary to scrutinize the important dynamical processes such as fusion, quasifission, multinucleon transfers, capture and breakup. Description of the transfer reactions can be improved by taken into account the nonlocal interactions and the pair or cluster transfers. The improvement of the energy density functional is demanded by a description of the nuclear properties including the calculation of the nucleus-nucleus interaction.

Every project participant will work in one of the following directions.

It is necessary to study in details the influence of an environment on the rate of the astrophysical reactions. It demands the further development for the theory of the open quantum systems. Thus it is necessary to consider the low-energy dipole excitations that play presumably a noticeable role in the stellar nucleosynthesis.

The potential energy surface with the energy increasing is changed such a way that the fission barrier height is decreasing for the superheavy nuclei. Therefore the investigations of the shell effects damping with the energy increasing are important for estimation of the stability of the excited heavy nuclei. The survival probability estimation of the excited heavy nuclei demands the density level calculations for the ground state and on the fission barrier.

Exploring the formation of superheavies with *Z*=119 and 120 in fusion reactions must be continued within a microscopic approach. The transport coefficients and nucleus-nucleus potentials calculated microscopically would be used in the double-folding model for a description of the nuclear fusion. Also peculiarities of the quasi-fission competing with the complete fusion would be considered. There are plans to compare the calculated mass distributions and TKE of the quasi-fission products with distributions of the fission products. The task is to find the reliable criteria for a separation of the fission products from the quasi-fission ones. New heavy ion isotopes that cannot be obtained in the complete fusion reactions may be formed by transfer reactions. Therefore it demands the further theoretical analysis of these reactions including the cluster transfer into description. Investigations of the new isotopes synthesis of super heavy nuclei must be continued in the evaporation channels of charged particles in order to search out the most suitable reactions for future experiments.

An advantage of the cluster approach is the simultaneous description of the α-decay and spontaneous fission from the ground state of both even-even and even-odd nuclei with the same set of parameters. The main model assumption is that the charge asymmetry as a collective coordinate is responsible for these processes. In the same approach it is necessary to investigate the fission from isomeric states and induced fission. A success of the experimental data descriptions will lead to a new look at the fission process.

There are many examples demonstrating the phase transitions in nuclei with increasing the excitation energy, angular momentum and with changing of the nucleon number. These phase transitions are associated with the change of symmetry. We are going to consider the peculiarities of symmetry breaking and symmetry transformation and also the related physical effects in finite quantum systems.

The nuclear theory applied in many research fields plays an important role in explanation of the experimental data and realization of the experimental programs, and also in search for the new applications. Large-scale nuclear physics facilities in the world support the theoretical research programs in the field of nuclear dynamics and nuclear astrophysics. Our theoretical efforts are addressed to the following questions:

- What are the limits of nuclear stability? Where are the positions of proton and neutron drip-lines? How can we detect proton shell closure beyond Pb? What is the best way to produce a certain isotope?

- How do the fusion and fission dynamics occur? Can we find observables to confirm the certain channels in fusion and fission?

- How do the astrophysical processes occur? What is the influence of the environment on astrophysical reactions?

- How does the nuclear structure change with the temperature and angular momentum? What is the role of cluster degrees of freedom in nuclear excitations? What are the properties of superheavies?

- What are the properties of nuclear systems beyond the nucleon stability? Does the multineutron radioactive decay exist?

Experiments on the complete fusion reactions of the 48Ca and different actinide nuclei have been successfully performed by FLNR (Dubna), GSI (Darmstadt) and LBNL (Berceley) with aim of synthesis of the super heavy nuclei with *Z* = 112–118.

Measurement and prediction of the reaction cross sections are the important task at studies of superheavy nuclei (SHN). Fusion cross sections and the structure properties of SHN are defined by competition between the mass properties and microscopic dynamics. The problem is to choose the optimal method for production of SHN with Z = 119, 120 and, possibly, 121 using the complete fusion reactions. If there are a few possibilities for formation of SHN with Z = 119 – 121 than for synthesis of the new isotopes there are a variety of the possible methods. Therefore it is necessary to choose the most effective reactions for a production of the new SHN isotopes with Z < 119. The number of the accessible actinide targets is small. Possibly, the largest Z for the nucleus-target is equal to 99. For the SHN production with Z = 119- 121 is necessary to use the beams with Z > 20, i.e. Ti or Cr ones. While for reactions with the 48Ca beam there are a lot of data and few excitation functions are measured, the reactions with Ti and Cr demand the theoretical analysis to define the optimal collision energies and evaporation channels.

Concerning the new isotopes production, there can be used both the complete fusion or transfer reactions. Theory is going to search for the most effective reactions to get the maximal yield for the isotope under consideration. Besides the choice of colliding nuclei in complete fusion reaction it is possible to change the collision energy and use the subbarrier energy leading to the (0 – 2)n evaporation channels and evaporation residuals with the large number of neutrons, and also the higher energies that lead to (5 – 8)n evaporation channels and, as a consequence, to the neutron-deficient isotopes.

In complete fusion-evaporation reactions induced by the 48Ca on the actinide targets, the larger part of SHN have been obtained in the 3- and 4n evaporation channels. The evaporation residue in the 2n channels have been found only in 48Ca + 242Pu, 48Ca + 243Am и 48Ca + 245Cm reactions. Nuclei 285,287Fl and 292Ts have been found also in the evaporation channel 5n. At present time the extension of the SHN region to the one with the magic neutron number N = 184 is urgent. For that it is necessary to explore the different reaction channels. New isotopes of the most heavy nuclei with Z – 112 – 117 can be produced in the complete fusion-evaporation reactions with 48Ca and charge-particle (proton ‘p’ or ‘*α’* particle) or neutron(s) emission from the excited compound nucleus (CN). Note that the possibility to produce the new most heavy isotopes of SHN with Z = 113, 115 and 117 in the proton evaporation channels with reasonably high efficiency have for the first time been checked in works [17] and [18].Also it is possible to expect the appearance of new isotopes in the evaporation channels 1n and 2n. It should identified how fast the evaporation residue cross sections is decreasing with increasing of the beam energy at subbarrier region.

The fusion dynamics are strongly different when it is described by the adiabatic or diabatic potentials. The adiabatic potentials preferably lead to the fusion dynamics described by the coordinate R between nuclei while adiabatic potentials describe fusion as a motion along the mass asymmetry coordinate η. The question arise what reaction mechanism is realized in the nature? The possible answer can be obtained, for example, from the detailed studies of the quasi-fission processes that go with fusion ones.

It is known that adiabatic descriptions with many collective variables is reduced to diabatic one since the kinetic energy of the relative motion between clusters, that are initially in the system, is transformed to other degrees of freedom and the nuclear system will be stopped near the touching point. But it is a starting point for conception of the double nuclear system (DNS) applied for description of the nuclear fusion.

Besides of the CN creation probability the decisive importance for residual cross section is its survivability. Indeed the excited compound nucleus must survive in a competition between a cooling evaporation and fission. To estimate the survival probability we have to get information about nuclear properties such as separation energy of the evaporated particles, the fission barrier and binding energy. These values for SHN can be taken only from calculations based on the nuclear structure models. Usually these models are divided on the microscopic-macroscopic (MM) and self-consistent ones. The MM models are based on parametrizations of the nuclear shape and single-particle potential. The self-consistent models or the mean-field ones are based on the energy density functional that is built or partially built on the base of the *ab initio* calculations. Different models give different predictions. The aim of the theory is to establish the relationship between all these models, what allows to understand the differences and choose the best model for further calculations in the SHN region.

Stability of the SHN is due to the shell effects that are defined by the mean-field and spin-orbital interaction. In complete fusion reactions induced by 48Ca the experimental cross sections σ*xn* for the evaporation residuals depend weakly from the atomic number Z of the SHN and have values about picobarn. Since the CN formation cross sections are strongly decreasing with increasing *Z*1 × *Z*2 and the absolute value of the evaporation residual cross sections is defined by the product of the complete fusion cross section and survival probability, the obtained experimental data give an evidence that the closed neutron shell exists at *Z* ≥ 120 [19, 20].

The experimental dependencies of the nuclear properties (*Qα* and half-life periods) and production cross sections of SHN evidence about increasing nuclear stability at approaching to the spherical closed neutron shell N = 184, and also indicate to relatively small influence of the proton shell at Z = 114. The MM models [21–24] predict the “island of stability” of SHN at the charge number Z = 114 and the neutron number N = 184. But the *Qα* jump is not observed at crossing the proton number 114 with the neutron numbers from 172 till 176. This experimental observation is agreed with predictions of the relativistic and nonrelativistic mean-field models [25–28], where the larger stability is expected near a nucleus with Z = 120 – 126 and N = 184. If the shell effect at Z = 120 – 126 is thus much as at Z = 114, than there is a hope that the synthesis of the new SHN with *Z* ≥ 120 is possible on the present experimental installations. Therefore the structure of SHN influences significantly the evaporation residual cross sections in the complete fusion reactions and must be thoroughly studied.

At present time the nuclear excitations above different thresholds, when a few nuclear fragments are in the continuum spectra of the atomic nuclei, attract the wide interest of the nuclear community and are actively investigated in many laboratories including FLNR JINR. Examples are studies of the properties of the heavy hydrogen 5-7H [29-30], 10He [31], searches for the 2- and 4- neutron radioactivities [32], and so on. These investigations are in the field of the few body continuum spectroscopy and demand the executions of the coincidence experiments and developing the theoretical methods for their analysis.

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Nuclear reactions that are taken part in the nuclear synthesis in the different astrophysical objects will be studied. Observations show that the initial abundance of the 7Li is only one third of the value that the Big Bang model predicts. It is necessary to study in details the influence of the environment on the rate of the astrophysical reactions. It demands the further development of the theory of the open quantum systems. It is essential to investigate the low-energy dipole excitations that assumingly play a noticeable role in the stellar nucleosynthesys. These studies will be related with experiments at ELI-NP.

The study of the nuclear properties as they depend on the excitation energy has a crucial importance for the exposition of the effects beyond the mean field description. The potential energy surface with the energy increasing is changed such a way that the fission barrier height is decreasing for the superheavy nuclei. Therefore the investigations of the shell effects damping with the energy increasing are important for estimation of the stability of the excited heavy nuclei.

At investigations of the collisions with weakly bound nuclei it is possible to apply models based on the description of the reaction mechanism within a few body approaches, Faddeev equations, the continuum coupled channel methods. Description of the transfer reactions can be improved by taken into account the nonlocal interactions and the pair or cluster transfers. The improvement of the energy density functional is demanded by a description of the nuclear properties including the calculation of the nucleus-nucleus interaction.

Nuclear fusion includes a collision of the two many-body quantum systems which produces a hot compound nucleus after the dissipation of their relative kinetic energy. The theory task is to include the dissipation and diffusion into the model and keep the essence of the quantum many-body nature of the colliding nuclei. Since the various reaction channels are interconnected and overlapped between yourself, the fusion model has to take into account the evolution from the double nuclear system configuration to a compound nucleus and describe contribution of the every channels. The theory methods of the open quantum systems are useful in this respect. The quantum diffusion approach developed for a consideration of the capture process for two colliding nuclei must be extended to take into account the degrees of freedom besides the distance between nuclei.

Exploring the formation of superheavies with *Z*=119 and 120 in fusion reactions must be continued within a microscopic approach. The transport coefficients and nucleus-nucleus potentials calculated microscopically would be used in the double-folding model for a description of the nuclear fusion. Also peculiarities of the quasi-fission competing with the complete fusion would be considered. There are plans to compare the calculated mass distributions and TKE of the quasi-fission products with distributions of the fission products. The task is to find the reliable criteria for a separation of

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An advantage of the cluster approach is the simultaneous description of the α-decay and spontaneous fission from the ground state of both even-even and even-odd nuclei with the same set of parameters. The main model assumption is that the charge asymmetry as a collective coordinate is responsible for these processes. In the same approach it is necessary to investigate the fission from isomeric states and induced fission. A success of the experimental data descriptions will lead to a new look at the fission process.

There are many examples that demonstrate the phase transitions in nuclei with increasing the excitation energy, angular momentum and with changing of the nucleon number. These phase transitions are associated with the change of symmetry. We are going to consider the peculiarities of symmetry breaking and symmetry transformation and also the related physical effects in finite quantum systems. The special type of the symmetry transformation, which is present only in the finite systems, is the change of the form symmetry. All above mentioned phenomena are in the mesoscopic systems such as atoms in the traps, quantum dots, atomic nuclei. Analysis of these systems combines both the classical and quantum ideas and methods. Really the symmetry role becomes evident in an interaction between the order and chaos in the classical limit, which assumes the most probable configurations of the quantum equilibrium in the finite systems. Thus one of directions for investigations can be the use of the random matrix theory developed in the nuclear physics for an analysis of the role of the statistical (random) constituents in properties of different manybody mesoscopic systems at different excitation energies. Application of the nuclear physics methods for a development of the nanotechnology is the one additional important aspect of our investigations.

The employees of the sector № 2 in the theme “Theory of Nuclear Systems” have the experience of many years successful work on the studies in the nuclear dynamics, the every year they publish about 20 articles in the high-raking international magazines. As follows from the selected list of publications for the last 4 years, the project participants successfully solve problems of the nuclear dynamics and nuclear structure description.

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

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

**2.4. Participating JINR laboratories**

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

**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**

|  |  |  |  |
| --- | --- | --- | --- |
| **№№**  **n/a** | **Category**  **employee** | **Core staff,**  **Amount of FTE** | **Associated**  **Personnel**  **Amount of FTE** |
| 1. | scientific staff | 16 | 1 |
| 2. | engineers | 0 | 0 |
| 3. | professionals | 5 | 0 |
| 4. | employees | 0 | 0 |
| 5. | workers | 0 | 0 |
|  | **Total:** | **16** | **1** |

**3.2. Human resources available**

**3.2.1. JINR core staff, BLTP**

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **№**№  п/**a** | **Category**  **of employees** | **NAME** | **Position** | **FTE** |
| 1. | Scientific employees | Mardyban E. V. | j.r. | 100% |
| 2. |  | Rogov I. S. | j.r.. | 100% |
| 3. |  | Bezbakh A. N. | r. | 100% |
| 4. |  | Urazbekov B.A. | r. | 100% |
| 5. |  | Kalandarov Sh. A. | s.r. | 100% |
| 6. |  | Kartavenko V. G. | s.r. | 100% |
| 7. |  | Pasca H. | s.r. | 100% |
| 8. |  | Rahmatinejad A. | s.r. | 100% |
| 9. |  | Sargsyan V. V. | s.r.. | 100% |
| 10. |  | Shneidman T.M. | s.r. | 100% |
| 11. |  | Shulgina N. B. | s.r. | 50% |
| 12. |  | Adamian G. G. | l.r. | 100% |
| 13. |  | Nazmitdinov R. G. | l.r. | 100% |
| 14. |  | Nasirov A. K. | l.r. | 100% |
| 15. |  | Jolos R. V. | c.r. | 100% |
| 16. |  | Ershov S. N. | h.s. | 100% |
|  | **Total:** | **15 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**

**LOW-ENERGY NUCLEAR DYNAMICS AND PROPERTIES OF NUCLEAR SYSTEMS**

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

NAME OF THE PROJECT LEADER: Ershov S. N., Antonenko N. V.

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| CHIEF SCIENTIFIC SECRETARY | SIGNATURE | DATE |
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| CHIEF ENGINEER | SIGNATURE | DATE |
|  |  |  |
| 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 |
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