**­** Форма № 24

КВАНТОВЫЕ СИСТЕМЫ НЕСКОЛЬКИХ ЧАСТИЦ

ТЕМА: «ТЕОРИЯ ЯДЕРНЫХ СИСТЕМ»

ЛТФ ОИЯИ

ФАМИЛИИ РУКОВОДИТЕЛЕЙ ПРОЕКТА: Мотовилов А.К., Мележик В.С.

ДАТА ПРЕДСТАВЛЕНИЯ ПРОЕКТА В ДНОД \_\_\_06.04.2023\_\_

ДАТА НТС ЛАБОРАТОРИИ \_\_22.12.2022\_\_\_ НОМЕР ДОКУМЕНТА \_\_9\_\_\_\_\_\_\_

ДАТА НАЧАЛА ПРОЕКТА \_\_\_\_\_2024\_\_\_\_\_\_\_

(ДЛЯ ПРОДЛЕНИЙ –– ДАТА ПЕРВОГО УТВЕРЖДЕНИЯ ПРОЕКТА)\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_

**APPROVED**

**JINR DIRECTOR**

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**Block Theoretical Physics  
Title of a project within the theme «Theory of Nuclear Systems»**

Quantum Few-Body Systems **Duration of the project: 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. Title of the project**

Quantum Few-Body Systems

**1.5. Project leaders:** Motovilov A.K., Melezhik V.S.

**2. Scientific rationale and organisational structure**

**2.1. Annotation**

The project is aimed at the study of properties of the systems formed by a small set of constituents of nuclear, subnuclear or atomic-molecular origin. The smallness of the number of constituents in a system allows one to develop and use mathematically rigorous, precise and consistent approaches to its investigation, the approaches that do not require further simplifying physical assumptions and approximations. Goal of the project consists in developing and improving the methods of numerical solving of few-body problems in nuclear, atomic and molecular physics, and in astrophysics. One of the central problems of the project is the study of universal laws in the behavior of few-body systems at ultra-low energies and numerical calculations of characteristics of three-atom systems in Efimov and pre-Efimov states. Universal features in the behavior of ultracold few-body systems will be also studied for the space dimensions smaller than three.

**2.2. Scientific justification**

Few-body systems theory is dedicated to various quantum systems that might be considered consisting of several (say two, three, or four) elementary constituents [1,2]. Depending on a particular situation and the energy range under consideration, the role of such constituents may be played by quarks, mesons, individual nucleons, nuclei or even by atoms and molecules [2,3]. Smallness of the number of constituents in a system allows one to develop mathematically rigorous, exact and faithful approaches to its treatment, that do not require further simplifying physical assumptions or approximations. Due to their universality, the theory of few-body systems has an interdisciplinary character. Approaches based on this theory pave the way to successful solving various problems in nuclear physics, in physics of atoms and molecules, in quantum chemistry etc.

By now, the theory of few-body systems has achieved a significant success. This refers, first of all, to the quantum problem of several particles with rapidly decreasing interactions. For a numerical solving of the three- and four-body problems one may efficiently employ the formalism of Faddeev-Yakubovsky equations in their either form, integral or differential [4]. However, in the theory of *N*-particle systems with Coulomb interactions for *N* > 2, there still remain significant unresolved theoretical issues. This concerns, in particular, asymptotic boundary conditions for scattering wave functions at infinity in coordinate space, definitions and analytical properties of three-particle scattering matrices, *S*-matrix interpretation of resonances, etc.

An important place in the theory of few-body systems belongs to the study of their behavior in external fields, in particular, in the fields depending on time [5]. An example of such a few-body system is represented by few atoms placed in an optical trap created by the interference of counter-propagating laser beams. Even in the case of two particles, a practical study of such systems requires a development of adequate mathematical models and new approaches to numerical solving of arising non-stationary problems.

One of the most interesting directions of research is the study of universal features in the behavior of few-body systems at ultra-low energies. Examples of such universal phenomena determined by the radii of two-body interactions or pair scattering lengths are given by the celebrated Thomas and Efimov effects for three-body systems [6-8]. Experimental evidence for the Efimov effect was obtained for the first time in 2005 [9], that is, 35 years after the theortical prediction of the effect [6]. Universal features (such as the Efimov effect) in the behavior of the ultracold few-body systems are theoretically predicted also for the spatial dimensions smaller than three [10] as well as in the case of few-particle problems on a lattice [11]. There is already a new discipline that brings together all the universal phenomena in few-body systems. It has got the title of «Efimov physics» [7,8]. Many problems of this new discipline still remain open. Of considerable interest is the identification of new universal laws in the behavior of few-particle systems. In this context, it is also important to perform numerical calculations of ultracold tri-atom systems in Efimov or pre-Efimov states [6].

All said above implies that the research in the field of few-body systems is still relevant. It is important not only to develop purely theoretical approaches but also to invent new methods of practical numerical study of various concrete nuclear and atomic-nuclear few-particle systems.

Our theoretical efforts are aimed at obtaining answers, in particular, to the following questions:

- In which nuclear and molecular few-body systems could one expect a manifestation of the Efimov states, suitable for an experimental identification? Is it possible to influence the forming and decay of such systems?

- How does a strong laser field influence atoms and nuclei? How does a qubit behave when it is placed in thermostats with different statistics?

- What features are should be visible in the behavior of ultracold atoms placed in traps?

One of the main goals of the project consists in the development of methods and approaches of the theory of few-body systems, clarification of the still-remaining mathematical questions such as, e.g. structure of long-range asymptotics of the Coulombic scattering wave functions, proofs of the equivalence between complex-scaling resonances and *S*-matrix resonances etc. In order to develop formal theoretical tools, we will also study related operator-theoretical issues. For example, we will study the change in invariant subspaces of quantum mechanical Hamiltonians under the influence of various perturbations, which are not necessarily small. We will look for optimal bounds on the speed of evolution of subspaces, described by time-independent and some time-dependent Hamiltonians.

A contribution will also be made to the development of Efimov physics. On the basis of Faddeev differential equations, numerical calculations of the characteristics of ultracold three-atom systems in Efimov or pre-Efimov states will be carried out. It is expected that on the basis of a theoretical study of possible variants of the regularization of the three-particle problem with point interactions, some still unknown new universal features in the behavior of three-particle systems at ultralow energies will be established. Furthermore, it is expected that in the problem of three particles on a two-dimensional lattice, the existence of an effect similar to the Efimov supereffect for three particles on a plane will be proved.

The study of small-dimension few-particle systems is also necessary to describe resonance processes and to model critical phenomena in nuclear and high-energy physics. For establishing connections between atomic and nuclear physics, we will use the analysis of Compton ionization by a high-power laser field as a method of dynamical spectroscopy of atoms and molecules. Dynamical adiabatic theory and theory of hidden crossings of the potential-energy levels will be applied for the study of inelastic transitions at atom-atom collisions. Numerical methods will be developed on the basis of the finite-element approach, adiabatic hyperspherical representation and parametric basis functions. The developed methods will be applied for analysis of bound states, scattering processes and resonances in various few-particle systems. An further improvement of the calculation procedure within the coupled-channel method will be performed.

Employees of Sector No. 3 of the Research Department of Theory of Nuclear Systems have many years of successful work in the field of few-body physics, they annually publish about 15 articles in high-ranking international journals. It follows from the list of their publications for the last 4 years, that the project participants have successfully solved a wide range of quantum few-body problems arising in nuclear, atomic and molecular physics etc. and, thus, they have a great research potential in this area for the future.

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**of employees of Sector No. 3 of BLTP RD TNS (2019-2022)**

**MONOGRAPHS**

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

**2.4. Participating JINR laboratories**

BLTP in cooperation with LIT, LNP, and LNR

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

All of these are mentioned in the proposal on the theme extension.

**3. Staffing**

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

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| **№№**  **п/a** | |  | | --- | | **Category**  **employee** | | |  | | --- | | **Core staff,**  **Amount of FTE** | | |  | | --- | | **Associated**  **Personnel**  **Amount of FTE** | |
| 1. | Scientific staff | 14 | 1 |
| 2. | engineers | 0 | 0 |
| 3. | professionals | 2 | 0 |
| 4. | employees | 0 | 0 |
| 5. | workers | 0 | 0 |
|  |  | **Total: 16** | **1** |

**3.2. Human resources available**

**3.2.1. JINR, BLTP core staff**

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **№№**  **п/a** | **Category of employees** | **NAME** | **Position** | **FTE** |
| 1. | scientific staff | Valiolda Dinara | Junior researcher | 100% |
| 2. |  | Janseitov Daiyar | Researcher | 50% |
| 3. |  | Koval Evgenii Aleksandrovich | Researcher | 100% |
| 4. |  | Malykh Anastasia Vladimirovna | Researcher | 100% |
| 5. |  | Vladimir Nikolaevich Kondaratyev | Senior Researcher | 100% |
| 6. |  | Popov Yurii Vladimirovich | Senior Researcher | 50% |
| 7. |  | Shadmehri Sara Abbas | Senior Researcher | 100% |
| 8. |  | Vinitsky Sergei Il’ich | Leading researcher | 100% |
| 9. |  | Kolganova Elena Aleksandrovna | Leading researcher | 50% |
| 10. |  | Melezhik Vladimir Stepanovich | Leading researcher | 100% |
| 11. |  | Pupyshev Vasilii Veniaminovich | Leading researcher | 100% |
| 12. |  | Rakityansky Sergei Anatolievich | Leading researcher | 100% |
| 13. |  | Solov’ev Evgenii Aleksandrovich | Leading researcher | 100% |
| 14. |  | Motovilov Aleksandr Konstantinovich | Head of sector | 100% |
| 15. | professionals | Torekhan Dimash | Senior laboratory assistant | 50% |
| 16. |  | Khamitova Dinara Raikhatovna | Senior laboratory assistant | 50% |
|  | **Total:** | **11 people – main work place**  **5 people — part-time workers** |  |  |

**4.  Financial support**

The project will be supported within the theme «Theory of nuclear systems».



**Head of the project \_\_\_\_\_\_\_\_\_/\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_/**

Form № 25

**APPROVAL SHEET FOR PROJECT**

**QUANTUM FEW-BODY SYSTEMS**

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

NAME OF THE PROJECT LEADER: Motovilov A.K., Melezhik V.S.

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