In total the completed form should not exceed 20 pages (together with tables).

Annex 3.

Form of opening (renewal) for Project /
Sub-project of LRIP

APPROVED

JINR DIRECTOR

____________/_________________

"_____" ______________________ 202 г.

PROJECT PROPOSAL FORM

Opening/renewal of a research project/subproject of the large research infrastructure project within the Topical plan of JINR

1. General information on the research project of the theme/subproject of the large research infrastructure project (hereinafter LRIP subproject)

1.1 Theme code / LRIP (for extended projects) **- 01-3-1137-2019/2023**

1.2 Project/LRIP subproject code (for extended projects)

1.3 Laboratory Bogoliubov Laboratory of Theoretical Physics

1.4 Scientific field Theoretical physics

1.5 Title of the project/LRIP subproject Mathematical models of statistical physics of complex systems

1.6 Project/LRIP subproject leader(s) A.M. Povolotsky

1.7 Project/LRIP subproject deputy leader(s) (scientific supervisor(s))

2 Scientific case and project organization

2.1 Annotation

Non-perturbative studies of large-scale systems with many interacting degrees of freedom constitute an important part of modern theoretical physics that has been experiencing a growing interest of researchers during the last decade. Recent advances in this direction are based on construction and investigation of exactly solvable models of equilibrium and non-equilibrium statistical physics, quantum mechanics and related quantum field theories. Then, with the use of the concepts of scaling and universality the results obtained from the exact solutions can be extended to vast classes of physical phenomena far beyond the realm of such systems. The exact solvability of models of physical systems is provided by their special mathematical structure coined by the term integrability. The models with such a structure is a major subject of studies within the current project.

The project is aimed at further exploration of the field of exactly solvable models of statistical physics, quantum mechanics and quantum field theories, which requires a development of new theoretical tools based on the theory of integrable systems and discovery of new mathematical structures standing behind the exact solvability. The main objectives of the project consist in obtaining exact results about the universal laws in interacting particle systems with stochastic dynamics and models of random interface growth, models of equilibrium statistical physics including percolation, polymers and other two-dimensional lattice models and quantum spin chains, studies of known and construction of new types of special functions playing the role of building blocks in the theory of integrable systems and computations of partition functions (superconformal indices), studies of known and construction of new algebraic structures standing behind the integrability concept.

2.2 **Scientific case** (aim, relevance and scientific novelty, methods and approaches, techniques, expected results, risks)

The main **aim** of the project is the construction and studies of mathematical models of statistical physics of complex systems and related models of quantum mechanics and quantum field theory with an emphasis on the concepts and structures of the theory of integrable systems as well as the development of mathematical tools lying at the core of this theory, including the theory of special functions and representation theory of quantum matrix algebras and braid groups.

Recently, a significant progress has been made in understanding the nature of limit shapes, universal fluctuations and correlations in models of equilibrium and non-equilibrium statistical physics. Among the equilibrium models the dimer packings and polymers on lattices, polymers in random media, vertex and spin models are studied, where the subject of study is, for example, the limiting macroscopic shape of the boundaries between different thermodynamic phases, as well as its random fluctuations and correlations between its parts. In the nonequilibrium context, similar issues are studied on the basis of particular stochastic models of nonequilibrium lattice gases or traffic flows like the asymmetric simple exclusion process, as well as various interfaces moving under the action of random forces, where the macroscopic description is given in terms of solutions of hydrodynamic type equations and random fluctuations characterized by the universal statistical laws specific for vast universality classes unifying a number of natural phenomena, like e.g. the prominent Kardar-Parisi-Zhang universality class.

The advances made in these directions were due to novel applications of the theory of integrable systems to derivation of exact results in various models with many degrees of freedom. Using concepts of universality and scaling these results can often be extended to a whole universality class of natural phenomena. The progress became possible due to construction of new integrable models of non-equilibrium stochastic systems, systems of equilibrium statistical physics and quantum systems, development of new methods of exact solutions of these models and discovery of new mathematical structures standing behind the integrability, like new classes of special functions and new solutions of the Yang-Baxter equations and braid relations appearing in the representation theory of quantum matrix algebras and braid groups. Many cutting-edge results in these directions were obtained by the team involved in this project. The **relevance and scientific novelty** of the planned results follow the modern trends in exact solutions of systems with many degrees of freedom and are based on rich background of the team in the theory of integrable systems and its applications as well as in theory of special functions and theory of quantum groups.

The **methods, approaches and techniques** that will be used in the project will extend and generalize existing methods the theory of integrable systems like the coordinate algebraic and functional Bethe ansatz, quantum inverse scattering method, methods of functional relations and the theory of finite-difference equations, methods of integrable probability like the theory of determinantal and Pfaffian point processes, Markov dualities, etc. These methods are largely based on the mathematical core developed as a part of the project that stems from the representation theory and the theory of special functions.

Review of concrete research topics and expected results

Various reaction-diffusion models of interacting particles on one-dimensional lattice will be studied with the use of Markov dualities. A rich sets of Markov dualities are possessed by interacting particle systems whose stochastic generators are contained in the representations of infinite Hecke algebra. Examples are models of annihilating particles, models with annihilation and coalescence, voter model e.t.c. Existence of such dualities allow calculation of complete sets of correlation functions characterizing evolution of infinite particle configurations subject to the reaction-diffusion dynamics. Starting from representations of the Hecke algebra the classification of particle systems with one and many types of particles admitting various kinds of Markov dualities and full description of their dynamics is planned. In addition, new stochastic models of interacting lattice paths on two-dimensional lattices can be constructed on the basis of the same algebraic structures using the Baxterization procedure. These models describe statistics of lattice paths or particles with discrete time dynamics, which allows one to incorporate new types of interaction compared to the continuous time models studied earlier. Construction and full exact solution of such models with the help of Markov duality techniques is planned.

One of the main problems of the theory of phase transitions is the analysis of universal scaling behavior of the large systems at critical points. The criticality in an infinite system is known to reveal itself in the universal critical exponents and scaling functions governing correlations in the systems. At the same time in a confined system the hallmark of criticality is reflected in the universal finite size corrections to the infinite size limits of critical point observables, which are expected to be defined by conformal anomalies. Furthermore, the coefficients of asymptotic expansion of observables in the two-dimensional systems at criticality are expected to reflect the operator content of the corresponding conformal field theories, which conjecturally describe the critical points in two-dimensional systems. Therefore, the lattice calculations of boundary effects give a direct check of the conformal field theory predictions. Several related problems are planned to be solved within the project. These are the calculation of exact cluster densities and their asymptotic expansions in the bond percolation, as well as densities of loops in the related densely packed loop models on the lattices with different boundary conditions, which is possible due to a connection of these problems with the Bethe ansatz solvable six-vertex model, construction of asymptotic expansions of thermodynamic quantities characterizing finite-size behavior of the free fermionic lattice models, such as dimers, Ising and spanning trees with different geometries under different boundary conditions. Study of the boundary behavior of nonlocal correlations in dense polymer and spanning tree models and characterization of the limit shapes and universal fluctuations of polymer configurations.

Also, applications of the studied polymer models and quantum spin chains to problems from adjacent areas of quantum mechanics and biophysics are planned. Among them are the studies of «entangled states» and magnetic properties of complex quantum spin systems relevant for quantum computing problems. Also, applications of the rotor-router (Eulerian walk) model to studies of the dynamics of double-stranded DNA breaks will be developed.

An important part of the research planned is the development of mathematical structures standing behind the integrability. In particular, the elliptic beta-integrals and elliptic hypergeometric functions, which were discovered at BLTP and form the top-level special functions of mathematical physics comprising most of known special functions as particular limiting cases, provide the most profound mathematical framework for the theory of integrable systems. The research planned under the project includes further investigation of the properties of these functions and of their various limiting forms. In particular, this is the search for applications of these functions in quantum field theory, quantum and statistical mechanics, and in the theory of solitons, building complex hypergeometric functions on root systems in the Mellin-Barnes representation and study of their connection with two-dimensional conformal field theories, finding generalized modular transformations for elliptic hypergeometric integrals and description of their consequences for superconformal indices (partition functions) of four-dimensional supersymmetric field theories. Also, there are plans to generalize obtained results to the cases of rarefied hypergeometric functions of various types and to describe the relevant physical systems, as well as to investigate connections between soliton solutions of integrable equations, lattice Coulomb gases, non-local Ising chains and ensembles of random matrices.

The last block of the research planned is devoted to studies of algebraic structures behind the integrability and their use for constructing new integrable systems which could be useful in various applications. In particular, investigations of a family of quantum matrix algebras will be continued. These algebras were discovered in the context of the quantum inverse scattering method in the late 1980s. They have found various applications in the theory of integrable systems, quantum mechanics and field theory, statistical physics and the theory of stochastic processes. The study of the mathematical structures and representation theory of these algebras led to the development of new branches of modern mathematics: the theory of quantum groups (quasi-triangular Hopf algebras), the theory of link/knot invariants and related invariants of 3-dimensional manifolds.

It is planned to generalize the Hamilton-Cayley theorem to the case of quantum matrix algebras of orthogonal type and to study subalgebras of spectral values of orthogonal quantum matrices. The structural theory of a special family of quantum matrix algebras - reflection equation algebras - will be used to construct an analogue of the Gauss expansion in these algebras, which, in turn, will allow one to develop the theory of representations of these algebras. Investigations of the R-matrix representations of the braid group will be continued.

It is also planned to study a series of R-matrix solutions of the braid relation, which make it possible to model stochastic reaction-diffusion processes and study the possibility of constructing new link/knot invariants using new series of R-matrices.

2.3 Estimated completion date 2028

2.4 Participating JINR laboratories

2.4.1 MICC resource requirements

Computing resources	Distribution by year				
	1st year	2nd year	3rd year	4th year	5th year
Data storage (TB) - EOS - Tapes					
Tier 1 (CPU core hours)					
Tier 2 (CPU core hours)					
SC Govorun (CPU core hours) - CPU - GPU					
Clouds (CPU cores)					

2.5. Participating countries, scientific and educational organizations

Организация	Страна	Город	Участники	Тип соглашения
NRU HSE	Russia	Moscow	Gritsenko V.A.	Exchange of visits
NRU HSE	Russia	Moscow	Krotkov D.I.	Joint works
NRU HSE	Russia	Moscow	Uvarov F.V.	Exchange of visits
NRU HSE	Russia	Moscow	Gorbunov V.G.	Exchange of visits
NRU HSE	Russia	Moscow	Khoroshkin S.M.	Exchange of visits
SPDMI RAS	Russia	St. Petersburg	Derkachev S.E.	Joint works
SPDMI RAS	Russia	St. Petersburg	Mudrov A.I.	Exchange of visits
SPDMI RAS	Russia	St. Petersburg	Bytsko A.G.	Exchange of visits
IHEP	Russia	Protvino	Sapronov P.A.	Joint works
IHEP	Russia	Protvino	Razumov A.V.	Exchange of visits
YerPhI	Armenia	Yerevan	Apresyan E.	Joint works
YerPhI	Armenia	Yerevan	Izmailyan N.S.	Joint works
YerPhI	Armenia	Yerevan	Ananikyan N.S.	Joint works
YSU	Armenia	Yerevan	Morozov V.F.	Joint works
YSU	Armenia	Yerevan	Mamasakhlisov E.S.	Joint works

Institute of Mechanics BAS	Bulgaria	Sophia	Bnzarova N.	Joint works
Institute of Mechanics BAS	Bulgaria	Sophia	Pesheva N.	Joint works
UdeM Mathematical Research Center	Canada	Montreal	Loutsenko I.M.,	Joint works
Caltech	USA	Pasadena	Rains E.M.	Joint works
University of Wuppertal	Germany	Wuppertal	Boos G.	Exchange of visits
Aix-Marseille University	France	Marcel	Ogievetsky O.	Joint works
Angers University	France	Angers	Rubtsov V.	Exchange of visits
University of Warwick	Great Britain	Warwick	Zaboronsky O.	Joint works
University of Sydney	Australia	Sydney	Molev O.	Exchange of visits
Australian National University	Australia	Canberra	Mangazeev O.	Exchange of visits

2.6. Key partners *(those collaborators whose financial, infrastructural participation is substantial for the implementation of the research program. An example is JINR's participation in the LHC experiments at CERN).*

3. Manpower

3.1. Manpower needs in the first year of implementation

№№ n/a	**Category of personnel**	**JINR staff, amount of FTE**	**JINR Associated Personnel, amount of FTE**
1.	research scientists	6.5	
2.	engineers		
3.	specialists		
4.	office workers		
5.	technicians		
	Total:	6.5	

3.2. Available manpower

3.2.1. JINR staff

No.	Category of personnel	Full name	Division	Position	Amount of FTE
1.	Research scientists	V.I. Inozemtsev	BLTP	Leading research scientists	1.0
2.	Research scientists	V.V. Papoyan	BLTP	Senior research scientist	1.0
3.	Research scientists	A.M. Povolotsky	BLTP	Senior research scientist	1.0
4.	Research scientists	P.N. Pyatov	BLTP	Leading research scientists	0.5
5.	Research scientists	V.P. Spiridonov	BLTP	Head of sector	1.0
6.	Research scientists	G.Yu. Chitov	BLTP	Senior research scientist	1.0
	Total:				**5.5**

3.2.2. JINR associated personnel

No.	Category of personnel	Partner organization	Amount of FTE
1.	research scientists		
2.	engineers		
3.	specialists		
4.	technicians		
	Total:		

4. Financing

The project will be funded through the theme "Theory of complex systems and advanced materials"

Project (LRIP subproject) Leader __________/___________/

Date of submission of the project (LRIP subproject) to the Chief Scientific Secretary: _________

Date of decision of the laboratory's STC: 13.04.2023 document number: 14

Year of the project (LRIP subproject) start: 2024

(for extended projects) – Project start year: _______

APPROVAL SHEET FOR PROJECT / LRIP SUBPROJECT

TITLE OF THE PROJECT/LRIP SUBPROJECT

SHORT DESIGNATION OF THE PROJECT / SUBPROJECT OF THE LRIP

PROJECT/LRIP SUBPROJECT CODE

THEME / LRIP CODE

NAME OF THE PROJECT/ LRIP SUBPROJECT LEADER

AGREED

JINR VICE-DIRECTOR	____________ SIGNATURE	__________ NAME	__________ DATE
CHIEF SCIENTIFIC SECRETARY	____________ SIGNATURE	__________ NAME	__________ DATE
CHIEF ENGINEER	____________ SIGNATURE	__________ NAME	__________ DATE
LABORATORY DIRECTOR	____________ SIGNATURE	__________ NAME	__________ DATE
CHIEF LABORATORY ENGINEER	____________ SIGNATURE	__________ NAME	__________ DATE
LABORATORY SCIENTIFIC SECRETARY THEME / LRIP LEADER	____________ SIGNATURE	__________ NAME	________ DATE
PROJECT / LRIP SUBPROJECT LEADER	___________ SIGNATURE	__________ NAME	__________ DATE

APPROVED BY THE PAC	SIGNATURE	NAME	DATE