Strategy for Long Range Program in Theoretical Physics

Executive Summary:

Theoretical Physics

Throughout the JINR history, research in theoretical physics has always been one of the pillars of the JINR scientific program which has contributed to many major advances in Science. The Bogoliubov Laboratory of Theoretical Physics is one of the worldwide biggest research centres specialized in theoretical research at the frontiers of fundamental physics. BLTP has an expertise in a wide range of areas related to the theory of fundamental interactions, nuclear theory, condensed matter physics and modern mathematical physics. Studies at BLTP are carried out in close cooperation with scientists from many world leading research centres and in coordination with the JINR experimental program.

Scientific and organizational policy of the Laboratory relies on multidisciplinary theoretical physics on the basis of advanced mathematics, support of the JINR experimental program, strengthening of the scientific brainpower through the interplay of research and education. These principles as well as forming the international scientific task force groups dedicated to the enhanced study of the emergent hot topics will be in focus of a long-range development of theoretical physics at JINR.

BLTP and JINR will stay attractive to the international scientific community by organizing series of topical workshops, conferences, and schools for young scientists. A special emphasis will be placed on active participation of BLTP in educational programs of JINR as well as on its direct cooperation with universities of the JINR member states. The unique feature of “Dubna International School of Theoretical Physics (DIAS-TH)” is its coherent integration into the scientific life of BLTP and JINR ensuring regular and natural participation of the leading scientists in education and training activities.

Theory of fundamental interactions.

Theory of fundamental interactions of elementary particles based mostly on quantum field theory plays the central role in describing the properties of matter at the microscopic level. In particular, it is forming the solid background of quantitative analysis of both accelerator and non-accelerator experiments involving leptons, hadrons and heavy ions. The JINR long term research program in this field of theoretical physics will include a wide range of the most significant topics, running from the high-precision tests of the Standard Model and critical phenomena in Hadronic Matter to Dark Matter and Dark Energy problems.

Major attention will be paid to phenomenology of the Standard Model, searches for signatures of new physics beyond the Standard Model, neutrino physics, hadron structure and spin physics, heavy flavour physics and hadron spectroscopy, critical phenomena in hot and dense Hadronic Matter in the presence of strong electromagnetic fields, the Dark Matter problem, and astrophysical aspects of elementary particle physics. Theoretical research in the field of particle and relativistic heavy ion physics will be emphasized on the support of physics programs of major international collaborations with JINR participation (LHC, RHIC, FAIR, etc.), and those at the JINR basic facilities, primarily, of the NICA/MPD and NICA/SPD projects.

Nuclear theory.

The central questions of nuclear physics are: How does the forces between nucleons form bound nuclei, how is the nuclear chart emerging from the underlying interactions, how does the complexity of the bound and continuum nuclear structures arises from the interaction between nucleons? In order to get answers to these questions, it is necessary to develop a unified theoretical approach for treating few- and many-body systems and including a consistent description of nuclear reactions. This approach will play an important role in explanation of the experimental data and in guiding the experimental programs in nuclear structure of exotic nuclei, nuclear dynamics, and nuclear astrophysics. At the same time nuclear theory will be involved in a variety of interdisciplinary investigations in particle, atomic, and statistical physics.

Investigation of the properties of exotic and Super Heavy nuclei is the goal of the experimental project DRIBs III at JINR and projects in Europe, the United States, China, and Japan. Parallel to these experiments, microscopic self-consistent nuclear models will be elaborated which include non-harmonic and fragmentation effects beyond the mean field approximation. The models are to predict the rates of various nuclear reactions for astrophysical purposes and can be applied to production rates for isotopes far off-stability as measured in the future projects. Nuclear reactions in stellar environment will be studied with the rigorous methods of the few-body theory as well. In the context of multidisciplinary research, the methods of the few-body theory will be developed in application to ultra-cold atoms and molecules in confined geometry of laser traps.

Theory of condensed matter.

The research program will be based on both a systematic development of the general methods of statistical physics and studies in the condensed matter physics. It will be tightly correlated with practical problems in the field of nanotechnology for creation of new materials and electronic devises.

Theoretical models in condensed matter physics will be studied by using methods of equilibrium and non-equilibrium statistical mechanics with the aim of revealing general properties of many-particle systems based on the ideas of self-similarity and universality. Along with that, theoretical research will be focused on the analysis of systems with strong electromagnetic correlations such as transition metal compounds, high-temperature superconductors, colossal magneto-resistance compounds (manganites), heavy-fermion systems, low-dimensional quantum magnets with strong spin-orbit interaction, topological insulators, etc. A theory group will accompany the experimental studies of particular materials conducted at the Frank Laboratory of Neutron Physics. Investigations in the field of nanostructures and nano-scaled phenomena will be performed to find physical characteristics of nano-materials, which are promising for various applications in modern nanotechnologies. The problem of quantum transport in carbon-based and molecular devices as well as the resonance tunnelling phenomena in various hetero-structures and layered superconductors are of special interest and will be investigated.

Modern mathematical physics.

Superstring theory, the most serious and worldwide pursued candidate for the unification of all fundamental interactions including quantum gravity, will be the central topic in mathematical physics studies at BLTP. This requires a wide range of precise classical and quantum superstring solutions, application of modern mathematical methods to the fundamental problems of super-symmetric gauge theories, development of microscopic description of Black Hole physics, elaboration of cosmological models of the early Universe. In applying and developing new ideas generated with the string theory, it is crucial to use mathematical methods of the theory of integrated systems, quantum groups and non-commutative geometry, super-field methods, including the method of harmonic super-spaces.

High-performance computing.

Implementation of the outlined research program in theoretical physics, first of all related to Lattice QCD and, in general, theory of dense and hot Hadronic Matter, multi-loop calculations in the Standard Model, astrophysical and cosmological modelling, will necessarily boost development of high-performance computing infrastructure of JINR to the highest level.

Long Range Program in Theoretical Physics

Theory of fundamental interactions

The main research directions will be

- the quantum field theoretical (QFT) description of the strong, electromagnetic and weak interactions of elementary particles within the Standard Model (SM) and beyond,
- the detailed description of the hadron structure in QCD with special attention paid to hadron spin physics in a broad sense, the critical phenomena undergoing in hadronic matter under the influence of high energy and baryonic charge densities and strong electromagnetic fields .

In particular, the future studies will concern precision tests and extensions of the SM, hot topics in neutrino physics, QCD and hadron matter physics related to the running and future experiments at JINR and worldwide and based on development of new QFT methods, refinement of already existed techniques and advanced models.

The Standard Model and its extensions.

The focus point of the research program will be state of the art multi-loop calculations in the Standard Model, its supersymmetric extensions, in QCD as well as in the models of modern statistical physics complemented by the study of integrability in gauge theories with extended supersymmetry. QFT models with the AdS-CFT correspondence, and higher spin models will be a main stream in development of QFT methods. The new methods for calculation of the radiative corrections in non-perturbative approach for the sake of studying the problems like the false vacuum decay will be also in focus. Study of various possibilities for extension of the Standard Model will concern the Minimal Supersymmetric Standard Model (MSSM), the two-Higgs doublet model, the Next-to-Minimal SUSY model, supersymmetric Standard Model with R-parity violation and some other emergent scenarios.

The research will search for possibilities for experimental evidence for existence of new particles (super-particles, additional Higgs bosons, including charged ones); data from experiments based on the LHC, and search for the dark matter particles in non-accelerator experiments will be studied.

Precision tests of the Standard Model.

High-precision tests of the SM at LEP1, LEP2, Tevatron, and nowadays at the LHC confirmed the high predictive power of the model at the quantum level. However, the tests of the SM have to be continued, especially at high energy scales, where one might expect observations of new physical phenomena. In addition to the direct access to such energy scales at colliders, attention will be paid to the possibilities which are provided by the extremely accurate measurements of the muon anomalous magnetic moment, of rare decays, of the proton charge radius, etc. .

New high-precision predictions will be deduced for the cross sections of the electroweak particle interactions studied at modern and planned high-energy colliders, including the LHC, ILC, and FCC. A high accuracy of theoretical predictions will be achieved by taking into account radiative corrections within the SM framework. Emphasis will be placed on the processes involving electroweak vector bosons, the top quark, and the Higgs boson, the study of which are of ultimate importance for verification of the Standard Model.

Precision tests of the Standard Model require an improvement of the accuracy of its predictions by multi-loop calculations or/and development of a new better types of perturbation theory. The low energy predictions from pQCD can be treated by the analogous methods. In particular, Fractional Analytic Perturbation Theory (FAPT) combines the renormalization group method and dispersion relations and leads to non-standard, non-power series that have a wider range of applicability, improved convergence, and have no Landau singularity at finite transferred momentum. FAPT will be applied in calculations of various amplitudes in the regimes non-accessible within the standard perturbation expansions.

The active theoretical support for experiments on electron-positron colliders of intermediate energies (meson factories) will be continued, in particular to the physics program of the Super Charm-Tau Factory (INP SB RAS, Novosibirsk). A new Monte-Carlo event generator will be constructed for describing the processes of Bhabha scattering and electron-positron annihilation taking into account polarization of the initial particles.

In the field of **heavy flavour physics**, the program of calculating observables in exclusive processes with open charm hadrons will be realized. A quantitative estimates of the Wilson coefficients for four-quark operators, which are not presented in the Standard Model, will be obtained, and physical characteristics of semi-leptonic decays of open-charm hadrons (D-mesons, Λc-baryons) will be calculated in connection with experiments carried out by collaborations Belle (Japan), BESIII (China), as well as for future experiments on a new Super Charm-Tau-factory in Novosibirsk.

Low energy processes aimed to check the Standard Model and increase precision in parameters of fundamental interactions will complement the high energy tests. Calculation of hadronic contributions to the hyperfine splitting of the levels in muonic hydrogen atoms and to the anomalous magnetic moment of muon are the high-priority tasks. A spectrum of rotational and vibrational states in molecular ions of hydrogen isotopes with a relative precision 10−12 should be obtained within the nonrelativistic QED approximation. That would allow to increase precision values of the Rydberg constant, electron, proton and deuteron masses, and to give independent determination of the proton charge radius provided that corresponding experiments will be carried out.

Neutrino physics.

The neutrinos remain one of the most enigmatic of the fundamental fermions and the answers to several undeniably principal questions are still not known. The subject of the main interest are absolute neutrino mass scale, their hierarchy (spectrum) and mechanism of the mass generation, physical nature of the neutrino fields which may be described by Dirac, Majorana, or ELKO (eigen-spinors of charge conjugation operator) spinors, mechanism of the CP violation in the neutrino sector, fundamental nature of the neutrino flavour oscillations in vacuum and matter. Determining the answers (or even partial answers) to these hard questions would be an indispensable step towards completion and extension of the Standard Model (SM) of particle physics. Moreover, it may lead to hints of physics beyond the SM, since neutrinos may obtain their mass in a different way than other fundamental fermions.

The problem of neutrino interactions with matter is closely intertwined with studying the neutrino mass spectrum and mixing. In order to extract the neutrino mixing angles and squared-mass splitting from the data of the neutrino oscillation experiments with reactor, accelerator, atmospheric, solar, and astrophysical neutrinos, we need to know the cross sections of exclusive and inclusive neutrino interactions with nuclear targets within a rather wide energy region. The neutrino-matter interactions are related to a physics beyond SM as the possible non-standard weak currents which may violate the lepton number conservation and μ-τ reflection symmetry thus affecting the flavour transition probabilities in matter; the nonstandard second-class electroweak hadronic currents may affect the neutrino-nucleon cross sections and polarization of the final-state particles. Studying these effects and their astrophysical applications is an interesting item in the context of neutrino physics.

An essential part of the mentioned problems will be the subject of extensive joint theoretical and experimental studies by the physicists of BLTP and DLNP. The Baikal GVD (Giant Volume Detector) project is devoted to detecting the high-energy neutrinos from astrophysical point and diffuse sources, like active galactic nuclei (blazars, quasars, BL Lac objects, etc.), coalescing binaries (black holes, neutron stars), extragalactic jets, etc. . Detecting neutrino events and their joint analysis with observed electromagnetic and gravitational-wave signals will open the long-awaited era of "multi-messenger astronomy" and dramatical increase in our understating of natural high-energy particle accelerators. Theoretical problems related to these astrophysical studies include modelling the atmospheric muon and neutrino backgrounds, neutrino propagation through heterogenic media while taking into account neutrino flavour mixing (including possible mixing with hypothetical sterile neutrino fields), coherent scattering (MSW effect), absorption and regeneration due to charged and neutral current interactions of neutrinos with matter. Thus, the GVD project alone naturally connects theoretical and phenomenological studies of neutrino oscillations in matter and neutrino interactions with nuclei. Another experimental project NOvA, devoted to searching the CP violation and neutrino mass spectrum problem, relates to the same fields but at lower energies. The BLTP based theoretical group will proceed to participate actively in the international collaboration GENIE (Neutrino Event Generator & Global Analysis of Scattering Data) which builds a "Monte Carlo bridge" between theoretical and experimental neutrino physics. The group is also involved into several international projects on neutrino-less double beta decay and related items, such as NEMO-3, KamLAND-Zen, LEGEND, SuperNEMO. The main aim of these projects is the solution of the fundamental dilemma: Are the neutrinos Dirac or Majorana particles?

Hard scattering in QCD.

With the advent of new accelerators with very high luminosity in recent years, it became possible to study exclusive reactions also in hard scattering regime. For future accelerators like the EIC or the ILC, such studies are expected to constitute a large fraction of the research programs.

The great physics interest in hard exclusive reactions is due to the fact that one has learned how to relate the information obtained from such processes to well-defined QCD correlators involving the wave function of the hadron in question. This is possible within a formalism involving a new kind of parton distributions and distribution amplitudes, called Generalized Parton Distributions (GPDs) and Generalized Distribution Amplitudes (GDAs), introduced and developed with active participation of BLTP theorists.

Recently, understanding of three-dimensional (3D) structure functions of nucleons became one of hot topics in hadron/particle physics. The principle intention of these studies is, first, to apprehend the source of nucleon spin which should include the contributions emanating from partonic orbital-angular-momenta. At present, the different theoretical and experimental studies have mostly been focused on GPDs together with the transverse-momentum-dependent parton distributions (TMDs). The latter involves the nontrivial information on the non-perturbative primordial transverse momenta of partons inside hadrons.

It is natural to determine the unintegrated transverse-momentum-dependent parton densities and fragmentation functions if one omits the integration over transverse momentum. In this sense, the TMDs play a role of more fundamental objects which present detailed information on non-perturbative phenomena compared to the ordinary integrated functions. Therefore, it is very important to develop the approaches based on the different factorization procedures where the TMDs are the main ingredients. Both GPDs and TMDs can be considered as the main suppliers for mapping of the 3D hadron structure owing to the deeply virtual Compton scattering and semi-inclusive lepton and hadron scattering processes.

There is another type of 3D structure-functions called generalized distribution amplitudes (GDAs) which can be measured by time-like processes, typically by the two-photon process to produce a hadron pair in the final state. As mentioned above, it is the s-t crossed channel to the virtual Compton scattering.

The study of the single spin (left-right) asymmetries (SSA) measured in the Drell-Yan-type processes with the transversely polarized nucleon: (i) the first process corresponds to the standard Drell-Yan process in the inclusive mode, (ii) the second process is related to the first case but with the (almost) on-shell photon. In this case, we study the two hadron collisions, where one of the hadrons possesses the transverse polarization, which produce the direct photon in the final state.

The experimental investigations of 3D/spin hadron structure including various non-perturbative ingredients is performed and planned at various facilities, including COMPASS, JLab, J -PARC, NICA (mostly the SPD detector). A close collaboration with experimentalists will be enhanced, with the special emphasis on the development and support of NICA-SPD program.

Theory of hadronic matter.

The nature of theoretical investigations in the field of hadronic matter under extreme conditions has a multidisciplinary and multilevel character. It requires the solution of a number of fundamental problems of strong interactions as well as implementation of the state-of- the-art phenomenological models directly related to experiments with relativistic heavy ion collisions and the physics of compact stars. Respectively, the JINR strategy for theoretical studies in this field will be based on a coherent implementation of a wide range of methods of quantum chromodynamics, relativistic nuclear physics, kinetic theory and hydrodynamics, and theory of critical phenomena in finite and short-lived statistical systems. As it can be seen from the already running project "Theory of hadronic matter under extreme conditions", BLTP has developed the level of its own expertise and broad international collaboration that is required for productive implementation of this highly challenging but only feasible approach to the problem. One of the strategic organizational aims is the enhancement of communication between different approaches, maximizing the actual use of their complementarity for systematic theoretical study of collective phenomena in hadronic matter typical for relativistic heavy ion collisions. The general scientific purpose of theoretical research at JINR is the detailed elaboration of the fundamental theoretical background of hadronic matter physics to such a degree that it permits the formulation of a robust experimental physics program with several clearly identified and formulated main problems in focus. The cooperation with experimental collaborations in the field if RHI, first of all the MPD and BM@N collaborations, will be strengthened.

For the current time, the rapid progress in computer performance along with algorithmic achievements has made it possible to perform lattice QCD calculations (LQCD) on a highly detailed lattices and also to work with light quarks at physical masses in order to describe the properties of hadronic matter in a much more optimal set-up than a decade ago. The functional renormalization group (FRG), a nonperturbative QFT method, has been developed to the level which became comparable with LQCD in accuracy and has allowed to directly compute real time correlation functions, in a way applicable not only at finite temperature but also at finite baryonic density, which makes it to be a highly valuable adjunction to LQCD. FRG has also been proven to be a particularly suitable framework for studying the properties of the QCD quantum effective potential. The effective potential is necessary for *ab initio* verification of self-consistency of mean field models of confinement, chiral symmetry realization and hadronization in QCD. The development of such models, the domain model of QCD vacuum in particular, has set up the frame for analytical studies of the properties of the effective meson actions with simultaneous incorporation of static and dynamical quark confinement and proper mechanisms of breakdown of the chiral symmetry. This has opened new perspectives for studying in detail the mechanisms of deconfinement and chiral symmetry restoration under extreme conditions.

State of the art hydrodynamic, kinetic and hybrid approaches to the task of modelling different stages of heavy ion collisions have seen a further development. In particular, the Parton-Hadron-String-Dynamics (PHSD) transport model has been recognized as a powerful method in application to highly complicated problems of relativistic heavy ion collisions. The statistical approaches capable to treat strongly interacting systems with finite size and short life time were developed. These methodological developments allow one to approach in practice the fundamental task of describing the collision of relativistic heavy ions, emphasizing its character as a rapidly evolving finite statistical system, which goes far beyond the exploration of equilibrium QCD.

The role of strong background electromagnetic and chromo-magnetic fields as well as vorticity generated in heavy ion collisions, was demonstrated via hydrodynamical and transport models to heavy ion collisions, in LQCD computations, as well as in FRG and analytical models of QCD vacuum. In particular, it has been realized that electromagnetic fields can lead to specific polarization effects in QCD vacuum which may trigger the phase transformations in hadronic matter and generate various asymmetries observable in heavy ion collisions.

Above mentioned developments as well as the start-up of the high-performance computing facility Govorun (LIT JINR) have created at JINR a solid background for high-profile theoretical studies of the hadron matter properties. Among others, the following specific tasks are particularly mapped out as short and mid-term priorities:

Lattice QCD.

Studies of dense baryonic matter based on numerical simulation of QCD will be vigorously continued. Even if the direct simulation of QCD at finite chemical potential is not possible due to sign problems, quest for collateral solutions to the problem will be continued, particularly through the lattice simulation at imaginary chemical potential and analytical continuation to real values. Combined use of LQCD and FRG techniques may provide an appropriate framework for investigation of QCD properties at large baryonic density. Another-already verified option, is the use of QCD-like theories free from the sign problem. Investigations of transport properties of QCD under extreme conditions (large baryonic density, strong magnetic field, high temperature) are on the agenda. The dependence of electric conductivity of hadronic matter on baryon density, temperature, masses of quarks, strength of magnetic field will be computed by means of improved methods for the extraction of the conductivity from Euclidean correlation functions.

Modelling the phase transformations in QCD.

Detailed mechanisms of deconfinement and chiral symmetry restoration during phase transformations in QCD under the influence of strong electromagnetic field, nonzero baryon and energy densities will be studied by means of analytical self-consistent mean field approach, motivated by the properties of QCD quantum effective action, supported by the FRG calculations of QCD effective action. Special attention will be paid to behaviour of gluon and quark condensates, topological charge density as functions of temperature, density and strength of electromagnetic fields.

In-medium effects.

Description of the particle freeze-out with account of in-medium changes of particle spectra will be studied within the effective QCD motivated hadron models by virtue of FRG techniques in particular. Two limits will be analysed - continuous freeze-out vs. sudden freeze out. In the strongly correlated system, particles participating in strong interaction acquire a non-trivial self-energy possessing both real and imaginary parts, interrelated by the dispersion relations. The latter one is a measure of a rate with which the particle participate in inelastic and elastic collisions. The in-medium polarization operator leads to the non-trivial spectral density or/and the spectrum of the in-medium excitations with the specific quantum numbers. The study of how these changes can be traced in observables measurable in HICs is of paramount importance. Production of strangeness (especially of multi-strange hadrons) or charm could be one of the promising windows to look after the effects. Particle fluctuations is another interesting observable.

Kinetics of particles with non-trivial spectral densities is a further object of intensive studies. Several approximations are usually to be done to write a kinetic equation in a closed-form. Since several forms of the kinetic equations exist, one has to study which form is more applicable. As a minimal inclusion of in-medium effects, mean-field potentials acting on hadrons and partons have to be consistently included in the transport model (e.g., PHSD). On the most violent stage of nucleus collisions, the kinetic approach is more efficient to be replaced by the hydrodynamic description. Viscous effects are known to be important and have to be included in an agreement with the underlying kinetic equation.

Theoretical analysis of data from NICA and FAIR.

This work implies refinement of the 3FD model and THESEUS event generator based on it. The refinement will proceed in several directions:

- Refinement of the EoS used in the 3FD model based on new results in the lattice QCD combination with FRG, and in astrophysics (neutron star merger);
- extension of ability of the 3FD model and THESEUS generator to predict and analyse new classes of observables (light (hyper)nuclei, fluctuations, etc.);
- refinement of the dynamics incorporated in 3FD model, microscopic evaluation of the friction force in the quark-gluon phase.

Spin observables (polarization) deserves special attention. This is a comparatively new topic. Though presently many open questions concerning this topic remain, both of conceptual and technical nature, it is expected that the spin-physics in heavy-ion collisions will become one of the major topics at NICA.

Theoretical Nuclear Physics

The central questions of nuclear physics are:

- How does the forces between nucleons form bound nuclei?
- How does the nuclear chart emerge from the underlying interactions?
- How does the complexity of the bound and continuum nuclear structures arise from the interaction between nucleons?

In order to get answers to these questions, it is necessary to develop a unified theoretical approach to treat few- and many-body systems including a consistent description of nuclear reactions. These approaches play an important role in explanation of the experimental data and in guiding the experimental programs in nuclear structure of exotic nuclei, nuclear dynamics, and nuclear astrophysics. At the same time nuclear theory is involved in a variety of investigations in particle, atomic, and statistical physics.

Much of our understanding of nuclei comes from nuclear reaction experiments. A proper description of nuclear reactions requires a combination of nuclear structure models, and development of the methods describing nuclear reaction mechanisms. It will include an application of the Faddeev formalism to reactions with light weakly bound projectiles and a development of the theory of the multinucleon transfer, fusion, and quasi-fission reactions. At the same time many of nuclear structure characteristics can be understood by concepts similar to those used to describe simple Fermi systems. For instance, the important characteristics of nuclear structure require an investigation of the shape phase transitions and shape coexistence phenomena, especially important for understanding the properties of exotic nuclei. Thus, a particular challenge in nuclear theory is to bridge the gap between different scales in nuclear physics for achieving a unified description.

Faddeev equations will be applied to investigate the properties of lightest nuclei and some other few-body systems, ab-initio shell model methods will be developed for investigation of the properties of light and medium mass nuclei, while the approaches based on the Energy Density Functionals (EDF) with realistic nucleon interaction will be used for studying of the structure of heavy and super-heavy nuclei. The important area of the research will be related to the investigations of nuclear properties and mechanisms of low-energy nuclear reactions important for understanding of the star evolution.

Our future theoretical studies will be closely coordinated with programs at facilities in operating or under construction, which exploit various high-intensity beams of stable and/or radioactive ions in JINR (SHE-factory, ACCULINA-2) and the world (FAIR, ISOL facilities HIE-ISOLDE, SPES, SPIRAL2, FRIB or DERICA at JINR).

The fully quantum model for a halo-nucleus breakup will be developed. In investigating collisions with weakly bound nuclei, one can apply the Faddeev formalism, the continuum coupled-channels methods, few-body reaction formalisms. Few-body systems provide us with important observables for testing and constraining nuclear forces. The understanding of the properties of few-body systems is important for extending microscopic methods for description of heavier nuclei. Studies of universal laws in three-particle systems at ultralow energies and numerical calculations of characteristics of ultra-cold three-atom systems in Efimov or pre-Efimov situations are of great interest. One should study the low-dimensional few-body systems with the aim to describe the resonant processes and to model the critical phenomena in nuclear and high energy physics.

To establish the interplay between the atomic and nuclear physics, the ionization/excitation of atoms and nuclei in a strong laser field will be studied by applying the Faddeev reduction of wave function in the non-stationary Schrödinger equation. The dynamic-adiabatic theory and theory of hidden intersections of potential energy curves will be applied to calculate inelastic transitions in atomic collisions. The numerical approaches will be developed based on finite-element method and parametric basis functions. The approaches will be applied to the analysis of bound and metastable states, and to scattering processes in few-particle systems.

The magic numbers are well-known for the nuclei near the line of stability. However, it is not fully clear how magic numbers evolve as a function of the neutron-to-proton ratio. Comparison of the theoretical results with available experimental energies of first excited states would be a good test of the nuclear-shell-model inputs. The role of neutron-proton $T=0$ pairing in the region of $N=Z$ nuclei has to be understood.

Microscopic calculations based on the state-of-the-art nuclear models that start from the realistic effective interactions between nucleons (i.e., EDF theory) provide us with valuable tool to connect with experiments at existing and future rare isotope beam facilities-like e.g. at JINR DERICA. To provide reliable predictions, the form and parameters of the density functional will be extrapolated far beyond the stability valley. Special attention will be paid to iso-vector properties of EDF that plays crucial role in nuclei with large neutron-proton asymmetry. The developed self-consistent EDF methods will be applied to the area of beta-decay (especially in the context of astrophysical r-process) and others weak-interaction responses of nuclei and nuclear matter in various astrophysical scenarios.

Nuclear reactions and nucleosynthesis in different astrophysical sites based on the data obtained by space orbital and neutrino observatories will be explored and elucidated. Specifically, low-energy dipole excitations- presumably playing a prominent role in stellar nucleosynthesis, have to be investigated. This study can be related to the future experiments at ELI-NP. Investigating nuclear properties as a function of intrinsic excitation energy is crucial to reveal the effects beyond a mean-field description. With increasing excitation energy, the continuum domain takes over due to a decreasing nucleon threshold, and, for super-heavy nuclei, the lowering of the fission barrier.

To understand the stability of heaviest nuclei one should explore their shell structure. The vast majority of level assignments are derived from alpha-decay spectroscopy. So, the microscopic study of alpha-decays of heavy nuclei is required. The alpha-decays from the isomeric states have to be analysed, including the fission of nuclei from an isomeric state.

Our understanding of nuclear properties comes from the experiments involving nuclear reactions. A proper description of nuclear reactions requires to combine suitable models of nuclear structure and reactions. In nuclear reactions, one should reveal important dynamical features such as fusion, quasi-fission, capture, and breakup. The transfer reaction formalism can be improved by incorporating non-local interactions and pair or cluster transfers. Several developments would be desirable: Improvements in effective nucleus-nucleus potentials by using the microscopic inputs, accurate treatment of breakup reactions with calculation of spectroscopic factors for each decaying configuration, improvement of energy-density functional to make it suitable for description of the nucleus-nucleus interaction.

Extraction of valuable information from the reaction observables requires, in addition to an adequate modelling of the reaction dynamics, the realistic nuclear structure models and a proper understanding on how the structure information can be extracted from the reaction dynamics.

Fusion of nuclei leads to formation of a hot compound nuclear system following dissipation of their relative kinetic energy. The challenge of theory is to incorporate dissipation into the models and retain the essence of quantum many-body nature of the colliding nuclei. The methods of the theory of open quantum systems will be used for this aim.

Exploring formation of super-heavies in fusion and transfer reactions will be intensified. The di-nuclear system model suggested at BLTP will be improved by incorporating microscopically calculated transport coefficients and nucleus-nucleus potential. The features of quasi-fission will be further studied. The challenge is to find out firm criteria to discriminate fission from quasi-fission. New isotopes of heavy nuclei, which are not reachable in complete fusion reactions, can be produced in transfer reactions. These possibilities will be investigated and the available experimental yields have to be described. The study of production of new isotopes of super-heavies in charge particle evaporation channels will be continued to find out the most suitable reactions for future experiments. Progressing to yet heavier elements requires the use of heavier projectiles due to the present lack of targets beyond Cf.

The increased disparity between number of neutrons and protons in radioactive nuclei leads to enhancement of clustering phenomena in nuclear structure, weak binding energy and possibility of exotic decay modes. A development of few-body cluster models which allow us transparently understand peculiarities in nuclear structure at extremes of the neutron-proton map would be of priority. Structures of light nuclei in the valley of stability, nuclear systems at driplines and beyond will be the prime goal of our theoretical efforts.

In view of development of the European ELI research centre which involves two JINR–member countries, investigations of non-linear quantum processes in very strong polarized electromagnetic fields which are achieved in short high-frequency laser pulses are of interest. In particular, particle production as a result of interaction of photons with such laser pulses will be studied.

It is planned to explore three-nucleon systems within the relativistic extension of the Faddeev equations (the Bethe-Salpeter-Faddeev formalism). Their binding energies, electromagnetic form-factors and polarization observables will be calculated. Anomalous magnetic moment of quark will be studied as well.

Theory of Complex Systems and Advanced Materials

The scientific program of research in theory of complex systems and advanced materials will be focused on the development of analytical and numerical methods for studying complex many-body systems that are of current interest in modern condensed matter physics, the development of mathematical models of such systems and the identification of universal laws on an example of studied models. Particular attention will be paid to both lattice and field-theory models of equilibrium and non-equilibrium statistical systems and to modelling a wide class of new materials, including nanostructured materials, which are of great practical importance. The concepts of scaling and universality allow us to go beyond the model approach and to apply the results obtained to broad classes of phenomena studied in the physics of condensed matter. The results obtained will be used in carrying out experimental studies of condensed matter at JINR. It is important to note the markedly growing interdisciplinary nature of research, where Condensed Matter physics and Statistical physics closely intersect with Atomic and Nuclear physics, Particle physics, Mathematical physics, Astrophysics, and Biology. Below, in a structured form, the planned main topics of theoretical research are presented in the framework of the stated theme.

Complex systems.

Experimental studies directly point to an important relationship between the structural and physical properties of materials. In particular, correlations between magnetism and structural properties of heavy rare-earth metals at high pressures are observed. A combined theoretical and experimental study of effects of high pressure on the structural, electronic and magnetic properties of heavy rare-earth metals is planned. Changes of the lattice and magnetic structural properties under an applied pressure will be measured at the Laboratory of Neutron Physics, JINR. The measured data will be interpreted by using both the model analysis and the ab-initio band structure calculations, based on methods of density-functional theory at the Laboratory of Theoretical Physics, JINR.

Pronounced correlations between the physical properties of various fractal systems and their geometrical structure at nano- and micro scales have been observed. Theoretical and experimental investigations of the structure of complex hierarchical systems, including surface fractals and multifractals, will be performed for the purpose of explaining physical characteristics of nanomaterials with applications to modern nanotechnologies. Experimental methods are based on small-angle scattering of neutrons, which is relevant to the use of IBR-2 pulsed reactor at LNP JINR, as well as x-rays and/or light scattering.

Investigations of electron properties, collective excitations (charge density waves, spin waves), phase transitions in complex systems such as strongly-correlated electromagnetic systems, low-dimensional quantum magnets with complicated lattice are some of the most important problems in condensed matter physics. These studies will be performed on the basis of the nonperturbative methods of Green functions developed in BLTP JINR. The results obtained will be used to explain the experimental results found in investigations of copper-oxide compounds and two-dimensional electron systems with the graphene-like structure. Cuprate high-temperature superconductors belong to one of the most intricate strongly correlated electron systems. Their theoretical analysis is challenging, because the traditional methods like the perturbation theory and the adiabatic continuation fail. It is planned to apply tools based on the quantum Monte Carlo method, which were developed in the BLTP, to study the properties of the superconducting phase in Cuprates. This will allow a description of the structure of the Fermi surface in doped Cuprates explaining possible mechanisms of high-temperature superconductivity.

It is planned to develop theoretical description of equilibrium and nonequilibrium properties of finite quantum systems, including trapped atoms and molecules, dipolar and spinor nanosystems, and complex quantum networks. The main purpose is to investigate the possibility for regulating the properties of such finite quantum systems for quantum information processing. The following theoretical methods, developed in BLTP JINR will be used: Scale separation approach, self-consistent theory of strongly correlated systems with spontaneous symmetry breaking, self-similar approximation theory. Also, numerical calculations will be employed.

Advanced materials.

One of the main topics of modern condensed matter physics is the study of nano-structures and nano-materials. This is not only due to the fundamental nature of their physical properties, but also owing to the practical importance for the creation of new electronic devices, storage devices, processing and transmission of information, sensors and biosensors, and others.

Two-dimensional materials play a special role: Graphene, phosphorene, silicene, and others. Theoretical investigations are planned of the influence of localized boundary states in various two-dimensional materials on electronic transport. In particular, effects such as electron-phonon interaction, the role of the substrate and external electromagnetic radiation will be taken into account. A theoretical study of thermal and electronic transport in polycrystalline two-dimensional structures is also planned. It will help to improve the quality of modern thermoelectric materials. In addition, the effect of structural defects on the kinetic properties of new materials will be investigated. The functionalization of new nanomaterials plays an important role. A detailed theoretical analysis of the physical properties of fluorinated and oxidized graphene is planned. Experimental studies are carried out in cooperation between the Institute of Semiconductor Physics of the SB RAS (synthesis, characterization) and the FLNR of JINR (ion irradiation for the creation of nanopores). There are also arrangements for close collaboration with experimental groups from Bulgaria (Institute of Solid State Physics, BAS, Sofia) and Russia (North-Eastern Federal University in Yakutsk and Kazan Federal University).

The two-dimensional materials are actively used as elements for developing highly sensitive sensors for various objects detection: From toxic metals and gases to complex biomolecules and even bacteria. Particular attention is paid to the sensors based on graphene because of their unique physical properties: attachment of biological molecules (proteins, DNA, RNA) to graphene increases the selectivity and sensitivity of the sensor, which opens up wide possibilities for using such devices as express analysers in medical research. It is planned to study the transport properties of systems formed by low-dimensional structures with detector biomolecules attached to them, in order to analyse the sensory characteristics of these devices. The quantum electrodynamic and correlation effects in atomic systems in nanostructured and biological materials will be studied for the description of the processes of transmission and processing of quantum information.

Investigation of resonance, chaotic and topological features of Josephson nanostructures and superconducting devices is planned. Dynamics and current-voltage characteristics of superconductor-ferromagnet-superconductor structures for superconducting spintronics will be studied.

The solution of many stated problems relies on computer modelling within the framework of packages for quantum chemical calculations, molecular dynamics and density functional. For this reason, it is planned to work closely with LIT JINR, first of all, by using the supercomputer "Govorun" and later by selecting specific computer architectures.

Models of statistical systems.

During last years, a significant advance in understanding of limit shapes, universal fluctuations and correlations in models of equilibrium and non-equilibrium statistical physics was achieved. Among the equilibrium models being studied are the dimer packings, lattice polymers, polymers in random media, vertex and spin lattice models, where the subject of studies is, for example, a limited macroscopic shape of interfaces between different thermodynamic phases as well as their random fluctuations and correlations between them. In the non-equilibrium context, similar questions are addressed to stochastic models of non-equilibrium lattice gases or traffic flows as well as to models of interfaces growth subject to a random force, where the macroscopic description is given in terms of hydrodynamic-like equations, while the random fluctuations reveal the universal properties.

The studies of statistics of particle flows on the lattices in stochastic models like exclusion processes with generalized interactions, zero-range processes and avalanche processes are planned. Their evolutions are also tightly connected with the evolution of interfaces subject to random forces. The universal fluctuations and correlations of particle flows in these models will be characterized. The formation of macroscopic jams will be described. The phase diagrams of the models on finite segments will be constructed. The statistics of avalanches in the interface growth “Raise and Peel model” will be studied. The probability of nonlocal configurations in the Branching Polymers or Spanning Trees models, their limit shapes and fluctuations in the scaling limit will be obtained. Statistics of the boundary of visited domain in the proposed in BLTP Eulerian Path model will be studied.

In addition to the studies of models of equilibrium and non-equilibrium statistical physics a major attention will be paid to the development of mathematical methods related to the theory of integrable systems, theory of phase transitions and conformal field theories. The theory of elliptic hypergeometric functions and integrals proposed in BLTP will be further developed. This theory gives the most modern mathematical apparatus for studies both the lattice and field theory models of physics of complex systems. The properties of elliptic Fourier transform necessary for an analysis of these models will be studied. The structure properties of quantum matrix algebras will be investigated, the differential geometry of quantum matrix groups will be developed. Concrete realizations and the representation theory of these objects, which are important building blocks of new integrable models of statistical and quantum physics, will be constructed.

Modern mathematical physics: gravity, supersymmetry and strings

Modern mathematical physics plays an extraordinary role both in mathematics and in theoretical Physics. It is a bridge for the circulation of ideas. At the same time, the main purpose of research in modern mathematical physics is the development of mathematical methods for solving the most important problems of modern theoretical physics: clarifying the nature of fundamental interactions and their symmetries, construction and study of effective field models arising in the theory of strings and other extended objects, uncovering of the geometric description of quantum symmetries and their spontaneous breaking in the framework of search for a unified theory of all fundamental interactions, including quantum gravity.

Mathematical physics in recent years has been characterized by increasing interest in identifying and effective use of integrability in various areas, and in applying powerful mathematical methods of quantum groups, supersymmetry and non-commutative geometry to quantum theories of fundamental interactions as well as to classical models. The main goals and tasks of the research include: Development of new mathematical methods for investigation and description of a variety of classical and quantum integrable models and their exact solutions; analysis of a wide range of problems in supersymmetric theories including models of super-strings and super-branes, study of nonperturbative regimes in supersymmetric gauge theories; development of cosmological models of the early Universe, primordial gravitational waves and black holes. The main problems to be studied are as follows.

Study of the structure of super-field counter-terms and other invariants in N=(1,0), N=(1,1) and N=(2,0) supersymmetric gauge theories in 6 dimensions by the harmonic superspace methods will be undertaken. In particular, of high importance is the formalism of harmonic super-fields with the maximal number of manifestly realized supersymmetries.

Multiparticle systems with extended Poincaré d=1 and super-conformal super-symmetries and various SU(m|n) deformed super-symmetries will be investigated.

New models of multiparticle mechanics with extended super-symmetry on curved spaces as a continuation of studies related to the models of super-symmetric and super-conformal mechanics in flat space will be constructed.

The complex / quaternionic Euclidean and projective spaces of super-integrable analogues of known oscillator-like systems, allowing the interaction with constant magnetic / instanton field, and further super-symmetrisation of them, including analogues of the Smorodinsky-Winternitz and Rosokhatius systems and their "weak" N=4 supersymmetric extensions, study their symmetry algebra and classical and quantum-mechanical solutions, will be constructed. In carrying out this theme, research will be continued on twistor formulations of particles and super-particles of fixed spin (helicity), as well as higher spin particles.

The generalized (deformed) Calogero- Moser systems: in particular, the relations of the generalized KP hierarchies with the Calogero - Moser systems and their spin versions as well as the construction of classical integrable systems on quiver varieties and their quantization will be studied in detail.

A special Bohr - Sommerfeld geometry of algebraic varieties, in particular construction of finite dimensional moduli spaces of stable special Bohr - Sommerfeld cycles. Construction of the Landau - Ginzburg models on the moduli spaces of the special Bohr - Sommerfeld cycles over Fano varieties will be developed.

Investigations of the confinement-deconfinement transformation, using exact solutions of the holographic flow of renormalization group (RG) with SL(2,C)-symmetry and AdS-fixed point, including the construction of holographic RG flows with a couple of effective charges. Interpretation of the flows as a collection of branes in the corresponding super-gravity theory and studies of the transport coefficients of quark-gluon plasma using holographic approach in 5 dimensional Kerr - AdS solution.

Owing to the birth of gravitational-wave astronomy and the acquisition of new observational data (LIGO, VIRGO, etc.), it became possible to test both various theories of modified gravity and effective models of black holes and other compact highly gravitating objects. In this regard, the following research directions will be outlined:
- the study of the cosmological consequences of various theories of modified gravity;
- the development and study of new modified gravity theories, capable of explaining inflation and modern dark energy in a single approach;
- the construction of effective models such as rotating single and double black holes and other compact objects (such as NUT solutions) in various theories of gravity;
-the development of new approaches and methods of mathematical physics for the study of effective models of compact objects in various theories of modified gravity;
-the studying of various boundary effects in conformal theories, such as Casimir effect, and their possible holographic description in dual gravity theories in order to comprehend the behavior of these effects in the strong coupling regime;
- the calculation of the Casimir effect due to the interaction of the quantum field with another quantum field confined in the spatially non-connected regions (two half spaces, for instance) and elaboration of the methods explicitly taking this interaction into account without replacing it by effective boundary conditions;
- the elaboration of spectral geometry methods (zeta functions, heat kernel expansions) for differential operators on the singular background or with singular potential, along with the development of the spectral summation method with the goal to employ it in boundary problems with matching conditions on the interfaces between different material media.

In summary, the strategy of development of theoretical physics at JINR will be based on studies of the coherent set of fundamental problems at the frontiers of modern physics defined by the current and future experimental program of JINR as well as its own, purely theoretical, priorities. Respectively, the main objective of theoretical research will be not only a high-grade support of in-home and world-wide experimental program of JINR but also securing the predictive power of JINR scientific potential in whole, and high level of receptivity of JINR to new world-wide trends in fundamental physics.