New Theme "Theory of Nuclear Systems" BLTP

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The challenge of nuclear theory is to unravel the properties of nuclei from their building blocks, strongly interacting protons and neutrons, and to reveal the complex dynamics of nucleus-nucleus collisions. Nuclear theory is involved in a variety of investigations in particle, atomic, and statistical physics. It plays an important role to explain the experimental data and guide the experimental programs. Many large-scale nuclear physics facilities maintain a strong research program in nuclear structure of exotic nuclei, nuclear dynamics, and nuclear astrophysics. Our theoretical efforts are addressed the following questions:

- What are the limits of nuclear stability? Where are the positions of proton and neutron drip-lines? What are the properties of superheavies? Where is the proton shell closure beyond Pb?
- What is the best input of the self-consistent approaches?
- How do the fusion and fission dynamics occur? What is the best way to produce certain isotope?
- How to unify the descriptions of nuclear structure and reaction dynamics?
- How do the astrophysical processes occur?
- How does the nuclear structure change with temperature and angular momentum? What are the most important degrees of freedom in nuclear excitations?
- How do correlations appear in few-body systems? How does the atomic structure influence the nuclear decay? How does the strong laser field influence the atoms and nuclei?
- What are important observables in relativistic heavy-ion collisions to test the nuclear equation of state? How does the colliding system evolve quickly towards a local isotropic state in momentum space?

Nuclear theory team at BLTP has been making major advances that address these fundamental questions. The interesting world-level results have been obtained at the Lab. (see report). Our future theoretical studies will be closely coordinated with programs of operated and commissioning facilities 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). The studies of heavy-ion collisions at high energies will be related to the NICA project at JINR.

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 region of possible closed-(sub)shell nuclei ^{48}S, ^{60}Ca, and ^{100}Sn will be investigated. Specifically, the role of neutron-proton T=0 pairing in the region of ^{100}Sn 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., energy density functional theory) provide us with valuable tool to connect with experiments at existing and future rare isotope beam facilities. 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 isovector 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 (supernova explosions, associated nucleosynthesis and neutrino production). 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 of excitation energy the continuum domain takes over due to decreasing of nucleon threshold, and, for superheavy nuclei, fission barrier lowering.

To understand the stability of heaviest nuclei one should explore their shell structure. Different models predict various magic numbers beyond Z=82 for protons and N=126 for neutrons. As shown, the parameters of the model adjusted to describe the structure of heavy nuclei result in Z=120-126 as proton magic number. The systematic study of the properties of heavy nuclei within the Quasiparticle Phonon Model and Two-Center shell model would shed light on the positions of shell closures. 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 analyzed. The fission of nuclei from the isomeric states is going to be considered as well.

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. Investigating collisions with weakly bound nuclei, one can apply the Faddeev formalism, the continuum coupled-channels methods, few-body reaction formalisms. 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 the nucleus-nucleus interaction.

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

Fusion of nuclei involves the collision of two quantum many-body systems that form a hot compound nuclear system following dissipation of their relative kinetic energy. The challenge for theory is to incorporate dissipation into the models and retain the essence of quantum many-body nature of the colliding nuclei. Since many reaction channels are coupled and overlap with each other, the fusion model should consider the evolution from dinuclear system configuration to a compound nucleus and describe contributions of each reaction channel. The methods of the theory of open quantum systems will be used. As the first step, the quantum diffusion approach has been developed to consider the capture of colliding nuclei.

Exploring formation of superheavies in fusion and transfer reactions must be intensified. The dinuclear system model suggested at BLTP can be improved by incorporating microscopically calculated transport coefficients and nucleus-nucleus potential. The features of quasifission, which competes with complete fusion, will be further considered. The mass and TKE distributions of quasifission products will be studied and compared with those for fission products. The challenge is to find out the firm criteria to discriminate fission and quasifission.

New isotopes of heavy nuclei, which are not reachable in complete fusion reactions, can be produced in transfer reactions. These possibilities must be investigated and the available experimental yields have to be described. The study of production of new isotopes of superheavies in charge particle evaporation channels must 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. Studies of near-threshold effects demand a unified description of nuclear structure and reactions. 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 in a 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 the domain of light nuclei, to understand the structure and reaction mechanisms of weakly-bound nuclides the few-body theory seems to be the most productive. We are planning to develop the fully quantum model for a halo-nucleus breakup, investigate the Coulomb breakup of proton halo in light nuclei taking into account the effect of external field. Few-body systems provide us important observables for testing and constraining nuclear forces.

Study of universal laws in behavior of 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 current interest. One should study the low-dimensional few-body systems with the aim to describe resonant processes and to model the critical phenomena in nuclear and high energy physics. To develop theoretical tools, we will study the generalized invariant subspaces of a multi-channel Hamiltonian corresponding to the Feshbach resonances and establish the links between these resonances and complex scaling of the associated operator Riccati equations.

To establish the interplay between the atomic and nuclear physics, we will study the ionization/excitation of atoms and nuclei in a strong laser field 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, scattering processes in few-particle systems.

Since NICA project is the major experimental project of JINR in the forthcoming years, theoretical investigations in the field of high-energy nucleus-nucleus collisions and properties of nuclear matter under extreme conditions are of special importance. Exploring the heavy-ion collisions at NICA energies we plan to simulate a vorticity and investigate its properties. It is clear that gluon field drives the system towards isotropy much faster than initially thought and that viscous fluid dynamics can accommodate the residual anisotropy. The dense gluon fields in a nucleus may be related to forward particle production. Moreover, expansion of the developed approach to ultra-relativistic energies achievable at RHIC and LHC is desirable. A connection with the P-odd correlations of quarks and mesons, and possibly with a chiral magnetic effect will be elucidated.
Our aim is to develop a two-stage hybrid model joining an initial fast stage (described by Parton-Hadron-String-Dynamics (PHSD) model) with the subsequent evolution of the expanding system at a second stage (treated on the basis of hydrodynamics with viscosity). This will allow us to describe the production of hadrons and resonances more accurately and will essentially affect the treatment of multiplicity of created particles and the transverse momentum spectra. The event-by-event approach will be applied for our PHSD model. The transverse-momentum spectra for NICA collider energies will be calculated. It is supposed to investigate the influence of the equation of state on the observed characteristics and give predictions for future experiments at NICA.

In view of development of the European ELI research center 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.

Moreover, 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.

Close collaboration between theorist and experimentalists should be encouraged and nurtured to reach the progress in theoretical studies.