Form № 24

**Relativistic Nuclear Dynamics and Nonlinear Quantum Processes**

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

**BLTP JINR**

NAME OF THE PROJECT LEADER: Bondarenko S.G., Larionov A.B.

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 **APPROVED**

 **JINR DIRECTOR**

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

**“Relativistic Nuclear Dynamics and Nonlinear Quantum Processes”**

**Dates of the projects : 2024-2028**

**1. General information on the project**

**1.1.**  **Theme code** **01-3-1136-2019**

**1.2. Laboratory BLTP**

**1.3. Scientific field Theoretical Physics**

**1.4. Project name Relativistic Nuclear Dynamics and Nonlinear Quantum Processes**

**1.5. Project Leader(s): Bondarenko S.G., Larionov A.B.**

**2. Scientific rationale and organizational structure**

**2.1. Annotation**

 The aim of the project is to study the universal laws in relativistic collisions of heavy ions, accompanied by the various particles production; determining the most important observables to test the equation of state of the nucleus; theoretical support for experiments at the NICA complex. The large nuclear transparency compared to the predictions of Glauber-like models may indicate the presence of color transparency and should be carefully considered. Based on the generalized eikonal approximation, nuclear transparencies in dd collisions will be calculated, which are available at NICA SPD. It is planned to study three/four-nucleon bound (3He,T,4He) and scattering systems (elastic proton-deuteron) in the Bethe-Salpeter-Faddeev relativistic formalism. Study the properties of heated and compressed nuclear matter in the collision of heavy ions is based on the Nambu-Iona-Lasinio Polyakov loop model.

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

The task of nuclear theory is to unravel the mechanism of formation of nuclei from their building blocks, strongly interacting protons and neutrons, to study the dynamics of nucleus-nucleus collisions, leading to the various particles production and phase transitions. The NICA mega project requires theoretical support for the planned experiments. Large-scale installations around the world support the program of theoretical research in the field of relativistic nuclear dynamics and nonlinear quantum processes. Our theoretical efforts are aimed at answering the following questions:

- How can transport approaches be improved to describe the dynamics of relativistic collisions of heavy ions?

- What are the most important observables in relativistic heavy ion collisions for testing the equation of state of the nucleus?

- How does a rapidly colliding system evolve to a local isotropic state in momentum space?

- What are the features of the interaction of high-energy gamma rays with a strong laser field?

- What are the relativistic effects in the few-nucleon systems?

(a) In connection with the development of the European Research Center ELI, it is of interest to study nonlinear quantum processes in very strong polarized electromagnetic fields, which are achieved in short high-frequency laser pulses. In particular, the creation of particles as a result of the interaction of photons with such laser pulses will be studied.

The laser pulse is a coherent state in which the interaction of laser photons with charged matter is coherent. In high-intensity laser pulses the coupling between the charge and the field becomes large enough, which violates the perturbative representations and it is necessary to consider the interaction between the charge and the laser in all orders of perturbation theory simultaneously or non-perturbatively. The non-perturbative manifests itself by the fact that despite the small value of the fine structure constant α, the photon density ρ in the laser scales as ρ ∼ ξ2/α, in which the dimensionless intensity parameter ξ2 is proportional to the laser power and can currently easily be much greater than unity. So the effective charge-field interaction constant is (αρ)1/2 ∼ ξ>> 1.

Besides the well-known Schwinger mechanism of spontaneous e+e- pair production in constant strong electromagnetic fields, which is of rather purely academic interest, recently nonlinear, non-perturbative 1→2 processes, kinematically forbidden in vacuum but allowed in the presence of a background (laser) field, have been intensively studied. These are, for example, nonlinear formation of photons (nonlinear Compton effect) and nonlinear birth of e+e- pairs (nonlinear Breit-Willer effect). These processes can be studied experimentally, so these effects are currently being studied in many theoretical centers and large experimental facilities are devoted to them. Relevant references can be found in a recent review [1].

In the near future, we plan to further develop theoretical models and methods in the theory of nonlinear quantum processes of interaction of charged particles with intense electromagnetic fields. In this case, in addition to the dependence of the observed on the field intensity, it is planned to study the polarization effects, the role of the shape and the carrier phase of the pulse.

(b) It is planned to extend the relativistic consideration of three-nucleon (3He,T) systems in the formalism of the Bethe-Salpeter-Faddeev equation with separable interaction kernels [2] to four-nucleon systems in the Yakubovsky formalism. The resulting equation will be solved to calculate the binding energy of 4He in various approximations to study them. It is also planned to calculate the electromagnetic form factor of this system.

One of the most common approaches to the study of pD scattering in the relativistic case is the analysis of the Feynman interaction diagram based on one-nucleon exchange, as well as the correction of higher-order diagrams taking into account the π-meson exchange [3], Δ isobar [4], etc. The scattering amplitude includes the deuteron wave function, which can be found, for example, by solving the Bethe-Salpeter (BS) equation. The elastic scattering cross section is proportional to the fourth power of the deuteron wave function, so the result is very sensitive to the choice of this function. We can confine ourselves to the partial states of the deuteron S and D and take into account the P-states [3], as well as take into account exchange mesons and Δ isobars.

To study the elastic backward proton-deuteron scattering, it is assumed to use the relativistic three-nucleon Bethe-Salpeter-Faddeev equation with separable kernel of interaction. It makes possible to take into account nucleon rescattering diagrams and lay the foundation for taking into account other reaction mechanisms. At the first stage, the solution of the equation for low-energy parameters (scattering length) and then the full scattering amplitude will be considered. Comparisons will be made with calculations using Feynman diagrams of scattering subprocesses.

We will also consider the elastic electromagnetic form factors of the pion, taking into account the anomalous magnetic moment of the quark in the framework of the covariant separable quark-quark interaction.

(c) The Nambu-Iona-Lasinio (NJL) Polyakov loop model is one of the most developed models that allows one to describe the state of matter at finite temperature and density, in contrast to lattice calculations or other functional methods, in which it was not possible to advance to high values of the chemical potential. However, the NJL model with the Polyakov loop [4, 5] phase diagram is characterized by an overestimated value of the phase transition temperature at zero chemical potential compared to that obtained in lattice QCD. This is explained, for example, by the fact that the connection between gluons and quarks, described in such a model through the covariant derivative and the effective potential, is not strong enough. In [6,7], it was proposed to introduce a phenomenological dependence of the four-quark interaction constants (scalar and vector) on the field of the Polyakov loop. The inclusion of an additional vector interaction in the NJL model with a Polyakov loop and its influence on the structure of the phase diagram was considered in [8–10], where it was shown that taking into account the vector interaction leads to a significant change in the structure of the phase diagram: with an increase in the Gv/Gs ratio, the first-order phase transition region decreases, and at certain values, it disappears altogether. However, the non-local version of the NJL model [11] does not demonstrate the disappearance of the first-order phase transition and the critical point. Thus, the NJL model is a flexible tool that makes it possible to qualitatively describe the properties of matter under critical conditions of high temperatures and densities. The equations of state obtained within the framework of the NJL model are often used as initial conditions for calculations in hydrodynamic models, as well as in studying the characteristics of neutron stars.

The main goal of our investigations is to study the properties of heated and compressed

nuclear matter in the collision of heavy ions. Of particular interest is the study of possible phase transitions that occur during the cooling of the system, as well as the problem of violation of CP invariance in strong interactions, which may be a consequence of the influence of the chiral anomaly on the topological structure of QCD vacuum in strong magnetic fields arising during the collision of heavy ions.

Source of information about the state of the environment in critical collision conditions

heavy ions can be processes of scattering of quarks and hadrons at the various stages of cooling of nuclear matter. One of the objectives of our study is to study the production of dilepton pairs. The production spectrum of dilepton pairs is directly related to various intermediate states of quark-hadron matter. Its study can provide information about phase transitions.

To study absorption and production cross sections for Y mesons in BB collisions,

it is planned to use the covariant quark model with the SU(5) Lagrangian, taking into account anomalous interactions. The covariant quark model is a quantum field approach to the description of hadrons considered as bound states of quarks. The approach is based on the phenomenological, relativistic Lagrangian, which describes the relationship between the hadron field and its constituent quarks. For simplicity of calculations in the model, the form factor is chosen as the vertex function, the modeling of which allows one to change their interaction. The purpose of the study is to consider how the scattering cross section changes depending on the properties of the medium.

Study of two-photon and Dalitz decays of light mesons within the NJL model at finite temperature and density. The production spectrum of dilepton pairs is directly related to various intermediate states of quark-hadron matter, and its study can provide information on phase transitions. In this problem, the main difficulty is the choice of an approach that allows one to write down the Feynman integrals using the Matsubara technique to explicitly include the temperature in the case when one or two resulting photons are off-mass-shell.

(d) The goal of our investigations involves the study of the phenomenon of color transparency (CT), short-range nucleon-nucleon correlations (SRC) and the cumulative effect. The phenomenon CT is a reduced interaction of color-neutral quark configurations entering or leaving a hard interaction point with the surrounding nuclear medium. Reviews on the CT are given in [1,2,3]. Interest in the CT is due to the fact that this phenomenon is a direct consequence of the quark structure of hadrons. In addition, the presence of a CT is a necessary condition for the applicability of factorization (i.e., the separation of the process amplitude into a hard part, calculated by perturbative QCD methods, and a soft nonperturbative part, described by generalized parton distributions) in the calculation of this hard process. At high energies, the CT was observed at FERMILAB in the coherent dissociation of a pion beam with a momentum of 500 GeV/c into two jets on nuclei [4]. In the region of intermediate energies (Elab ~ 10-100 GeV), the CT is “smeared” due to the expansion of quark configurations compressed at the point of hard interaction with distance from it. However, it is in this energy region that experiments have already been performed [5, 6, 7] and are planned [8] at JLab, as well as experiments on the search for CTUs are planned at FAIR PANDA [9, 10] and NICA SPD [11, 12].

The CT-sensitive observable is nuclear transparency, i.e. the ratio of the measured cross section for production on the nucleus to the same cross section, but calculated in the momentum approximation. Thus, a larger nuclear transparency compared to the predictions of Glauber-like models may indicate the presence of a CT. Mixing of the quark counting and Landshoff mechanisms in the amplitude of elastic scattering pp → pp at large angles in the c.m. influences the CT signal, leading to characteristic oscillations of nuclear transparency as a function of the beam energy in the process d(p,2p)n [12]. The features of the NICA SPD detector suggest, however, that symmetric dd collisions will be more accessible initially than pd collisions. Therefore, based on the generalized eikonal approximation (GEA), taking into account the effects of the CT [12], we will calculate the nuclear transparency in hard processes d(d,2p)nn and A(p,2p) with heavier nuclear targets (A>2) , for which CT effects should be stronger.

(e) Nucleon-nucleon SRC manifest themselves in interactions of high-energy particles with nuclei with sufficiently large momentum transfers (Q > 1 GeV). The SRC is dominated by tensor nuclear forces, which single out the S=1, T=0 channel, which corresponds to the quasi-deuteron pn state (see, for example, the SRC review in [13]). This is confirmed experimentally by the fact that when a proton with an initial momentum higher than the Fermi momentum is knocked out of the nucleus, a neutron with a momentum equal in magnitude and opposite in direction to the initial proton momentum is also emitted with a high probability (>70%) [14]. In recent years, intensive studies of SRCs have been carried out at the JLab and have made it possible to obtain information on the fraction of nucleons bound in SRCs and their isospin composition in heavy nuclei [15, 16]. In addition, it turned out [17] that as the proton momentum in the nucleus increases from 0.4 GeV/c to 1 GeV/c, the probability that this proton belongs to pp SRC increases, i.e., the role of central nuclear forces increases. SRCs can provide information on nonnucleon degrees of freedom in nuclei [18].

Since the density of nuclear matter in the SRC is comparable to the density in the central region of neutron stars, the inclusion of the SRC in the equation of state for cold nuclear matter can help explain the existence of recently discovered neutron stars with a mass greater than two solar masses.

The exclusive 12C+p→10B+pp+n and 12C+p→10Be+pp+p reactions were measured by the BM@N collaboration at JINR in inverse kinematics with a 12C beam at 48 GeV/c interacting with a hydrogen target producing two protons under large angles [19]. In these two reactions, the proton interacts with the pn and pp SRCs, respectively, while the isolation of the 10A nucleus in the ground state is aimed at reducing the initial (ISI) and final (FSI) state interactions. Indeed, calculations [20] indicate that the ISI/FSI reduces the total cross section of the reaction without a significant change in the kinematic dependences of the differential cross section, except for the dependence on the total momentum of the residual nucleus. The calculations [20] are based on the Glauber theory of multiple scattering under the assumption that all particles move rapidly forward in the rest frame of the nucleus, which is not a completely justified assumption, especially for a slow spectator nucleon from a SRC pair.

The goal of our forthcoming work is to develop a solid theoretical basis for describing the interaction of a proton with a SRC pair in the nucleus, taking into account the ISI/FSI. The calculations will use the phenomenological relative wave function of the nucleus-SRC, and the spectroscopic factors for pn- and pp-pairs from the translationally invariant shell model [21]. The main attention will be placed on improving the formalism of the Glauber model and the GED for application to particles propagating at large angles in the laboratory frame of reference, for example, a spectator nucleon from a SRC pair.

Interest in the cumulative effect, i.e., the creation of particles in the kinematically forbidden region of the phase space, arose in the 1970s, when the first experiments with beams of light nuclei were carried out at the JINR synchrophasotron [22,23,24]. For the formation of nucleons, the cumulative region includes polar angles Θ≈180 grad in the laboratory frame of reference. The mechanism of the cumulative effect has not yet been established. Several possible mechanisms have been proposed. One possibility is that the incident proton collides in the nucleus with a massive compact object called "fluctuon" [25]. Another suggestion was that the exact inclusion of SRCs, together with the effects of Glauber's (anti)screening, explains the cumulative proton yield [26]. Finally, it is also possible that the key role is played by a chain of multiple rescatterings in the nucleus with the excitation and decay of baryon resonances [27, 28].

We plan to perform comparative calculations of pA reactions based on the SRC model (which will be developed at an earlier stage of the project) and on the basis of the GIBUU transport model [29] to study the cumulative production of protons and pions. The calculation results will be compared with the available experimental data for deuteron and heavier (A>2) nuclear targets, predictions for NICA energies will be provided, and the role of thermal equilibrium in cumulative yields will be established.

(f) Using the obtained early expression for the optical potential of nucleon-nucleus scattering, where it is expressed in terms of the parameters of the elementary amplitude of nucleon scattering on nucleons bound in a nuclear medium, we will analyze the corresponding experimental data on proton scattering on nuclei at energies from 100 MeV to 1 GeV. Thus, it becomes possible to reveal the influence of the nuclear medium on such fundamental characteristics of the elementary NN amplitude as the total cross section for the scattering of a nucleon on a bound nucleon of the nuclear medium, and two more characteristics of this amplitude, namely, the energy dependence of the ratio of its real part to the imaginary part, and also parameter of its slope depending on the momentum transferred to the nucleon bound in the nucleus.

(g) Calculation of the exact hadronic distributions in transverse momentum and rapidity by new methods within the framework of the Tsallis-1, Tsallis-3 and $q$-dual statistics and their application to describe the experimental data for hadrons produced in collisions of heavy ions and protons with protons at energies of the LHC, RHIC, NICA and FAIR. Introduction of a locally equilibrium relativistic statistical model of hadrons with a model geometry of an expanding fireball to describe the distributions in transverse momentum and rapidity for hadrons produced in collisions of heavy ions and protons with protons at high energies. Generalization of the quantum-statistical hadron model with exactly conserved strangeness of the system to the case of exact conservation of the baryon and electric charges of the system and finding recursive equations for the exact solution of the partition function and ensemble averages. Using this model to calculate the multiplicity of identified hadrons produced in heavy ion collisions at LHC, RHIC, NICA and FAIR energies. Introduction of a statistical quark-parton model for describing parton distribution functions in high-energy deeply inelastic lepton-hadron and proton-proton collisions.

(h) Continuation of the study of the behavior of ghost and gluon propagators at a finite temperature in an approach based on the Dyson-Schwinger equation in the Landau gauge in the truncated rainbow approximation. Solutions of the system of coupled equations for ghost and gluon propagators as a function of temperature $T$, Matsubara frequency $\Omega\_n$ and square of three-momenta ${\bf k}^2$ are planned to be solved numerically in a large $T$ range. The obtained solutions will serve as ingredients for introducing the temperature-dependent Bethe-Salpeter equation for glueballs into the calculations. It is planned to investigate possible phase transitions from a bound state of a glueball to a free gluon plasma. This study is directly related to the problems of phase transitions in a quark-gluon plasma in a hot nuclear medium (for example, in the processes planned for research in experiments at the NICA facility).

Analytical calculations of the $g-2$ lepton anomaly due to bubble Feynman diagrams up to the eighth order in QED will be performed in the framework of the combined Mellin-Barnes and dispersion relations to the $x-$parametrization of the corresponding diagrams. We plan to find a universal expression for the anomaly that is valid for any kind of leptons.

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Employees of Sector No. 4 NOTAYA BLTP have many years of successful work in the study of nuclear dynamics, annually publish about 15 articles in high-ranking international journals.

As follows from the above list of publications for the last 4 years (2019-2022), the project participants successfully solve the problems of describing quantum few-nucleon systems.

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

**2.4. Participating JINR laboratories**

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

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

**Given in the suggestion on the theme continuation**

**3. Staffing**

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

|  |  |  |  |
| --- | --- | --- | --- |
| **№№****n/a**  | **Category** **employee**  | **Core staff,** **Amount of FTE**  | **Associated** **Personnel** **Amount of FTE**  |
| 1. | scientific staff  | 11 | 1 |
| 2. | engineers  | 0 | 0 |
| 3. | professionals  | 0 | 0 |
| 4. | employees  | 0 | 0 |
| 5. | workers  | 0 | 0 |
|  | **Total:**  | **11** | **0** |

**3.2. Human resources available**

**3.2.1. JINR core staff, BLTP**

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **№**№п/**a**  | **Category****of employees** | **NAME** | **Position**  | **FTE** |
| 1. | Scientific employees  | Yurev S.A. | r. | 100% |
| 2. |  | Dorkin S.M. | s.r. | 25% |
| 3. |  | Parvan A. | s.r. | 100% |
| 4. |  | Friesen A.V. | s.r. | 100% |
| 5. |  | Baznat M. | l.r. | 100% |
| 6. |  | Kaptari L.P. | l.r. | 100% |
| 7. |  | Larionov A.B. | l.r. | 100% |
| 8. |  | Lukyanov V.K. | c.r. | 100% |
| 9. |  | Titov A.I. | c.r.. | 100% |
| 10. |  | Toneev V.D. | c.r. | 100% |
| 11. |  | Bondarenko S.G. | h.s. | 100% |
|  | **Total:**  | **10 p. – staff****1 p . – associated personal** |  |  |

**4. Financial support**

Project will be funded within the theme “Theory of nuclear systems”



**Project Leader \_\_\_\_\_\_\_\_\_/\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_/**

Form № 25

**APPROVAL SHEET FOR PROJECT**

**Relativistic Nuclear Dynamics and Nonlinear Quantum Processes**

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

NAME OF THE PROJECT LEADER: Bondarenko S.G., Larionov A.B.

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| CHIEF ENGINEER  | SIGNATURE | DATE |
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| LABORATORY DIRECTOR  | SIGNATURE | DATE |
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| CHIEF LABORATORY ENGINEER  | SIGNATURE | DATE |
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| PROJECT LEADER | SIGNATURE | DATE |
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| DEPUTY PROJECT LEADER | SIGNATURE | DATE |
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| APPROVED BY THE PAC  | SIGNATURE | DATE |
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