Referee Report on the project
"Investigation of the Properties of Nuclear Matter and Particle Structure at the Collider of Relativistic Nuclei and Polarized Protons"
(project STAR, JINR participation, theme 02-0-1066-2007/2023) in 2022-2024

The STAR facility was created at Brookhaven National Laboratory to carry out experiments at the Relativistic Heavy Ion Collider (RHIC). The main task of the physics program at the RHIC accelerator complex is to obtain a new state of nuclear matter formed in collisions of heavy ions (Cu, Au, $^{44}_{96}$Ru, $^{40}_{96}$Zr, U), and study its properties with various probes over a wide range of energies and centrality of collisions and determine the structure of the phase diagram of nuclear matter.

The results of the studies carried out at the RHIC confirm the conclusions about the formation of strongly interacting nuclear matter.

It was found that the new state of nuclear matter at maximum RHIC energies is characterized by strong suppression of particle yields in Au + Au collisions at large transverse momenta of produced hadrons, large elliptical flow of hadron production with light and heavy strange quarks, its difference for baryons and mesons at average momenta p_T, the presence of strong $\Delta\eta - \Delta\varphi$ correlations ("ridge effect") and "quark number scaling" for light and heavy quarks. These properties are more reminiscent of the properties of an ideal liquid than the properties of an ideal gas that have long been assumed.

The results obtained at the maximum energy of the RHIC collider still do not answer the question: What the structure of the phase diagram of nuclear matter is (the location of phase boundaries, types of phase transitions, and the presence of a critical point)?

To resolve this problem, the program for energy scanning of the nuclear matter was proposed, first BES-I, and then its successor – BES-II, at a new qualitative level (modernization of the STAR facility and creation of systems to increase the collider luminosity at low energies).

The participation of the JINR group from 2019 to 2022 in the energy scan program at the STAR facility is the main task of the project. The planned measurements have already been performed at five collider energies (7.7, 9.1, 11.5, 14.6, and 19.6 GeV). Measurements with a fixed target were also performed, which extend the range of energy scanning to lower energies (7.7, 6.2, 5.2, 4.5, 3.94, 3.5 GeV). Currently, statistics are being collected at the minimum energy of 7.7 GeV at the RHIC collider. Measurements at this point with high precision are extremely important for comparison with future measurements at the NICA collider. Additional measurements are offered at the sixth energy of 16.7 GeV, which will provide a more detailed scan in the range where there are indications that the energy dependence of net-baryon fluctuations is undergoing significant changes.

Among the most important physical results obtained in 2019–2021, I would like to note the following. The yields of hypertritons and anti-hypertritons in collisions of gold nuclei were measured, their masses and binding energies were determined, and no violations of CPT symmetry were found. This work continues the series of research of the JINR group on studying the properties of matter and antimatter, including antimatter with strange quarks. The experimental material obtained in the energy scan program in the collider mode and during experiments with a fixed target will allow the project authors to expand the scope of the search and study of multihypernuclei.

Within the framework of a previous project, important results in spin physics were obtained. The difference between the spin-dependent distributions of sea u- and d-quarks in the proton was found in experiments on measuring the longitudinal single-spin asymmetry of W-boson production at the energy of 510 GeV. The positive integral contribution of gluons to the proton spin was established when measuring the two-spin longitudinal asymmetry of jet production in proton collisions at the energy of 510 GeV.

In the proposed project in 2022, it is planned to continue the program of polarization research – Cold QCD Physics – with transversely polarized protons at the energy of 510 GeV and in 2024 with the energy of 200 GeV in the reactions of the interaction of polarized protons with nuclei.

The Hot QCD Physics program is also of great interest. It is planned to be carried out in 2023 and 2025 to study the microstructure of quark-gluon plasma (QGP) in gold-gold collisions at the energy of 200 GeV, aimed at solving the two most important problems – detailing the phase QCD diagrams and determination of QGP properties on small scales.

The STAR facility was modernized: with the help of the inner Time Projection Chamber (iTPC) and the endcap Time-Of-Flight Detector (eTOF), the identification of particles with high momentum in high-rapidity range was improved. The Event Plane Detector (EPD) has made it possible to determine the collision centrality and reaction plane in the region of high rapidity with low systematic errors. All these activities will allow in 2022–2025 to significantly expand the acceptance of the STAR facility (mid-rapidity from $-1.5 < \eta < 1.5$) in the area of front angles (forward-rapidity $2.8 < \eta < 4.2$) to measure nuclear and polarization effects in a new kinematic region.

Among the tasks of the project proposed by the JINR group, I would like to note the following:

1. Using the method of correlation femtoscopy for the systematic study of the space-time parameters of particle production during energy scanning, considering various fluctuations.
2. Investigation of event structure using the method of fractal analysis, cumulative production of particles depending on energy and multiplicity, modification of spectra in a nuclear environment.
3. Study of the energy and angular dependence of the global polarization and vorticity of nuclear matter for various hyperons.
4. Creation at JINR of infrastructure for data processing from the STAR facility using GRID technologies and the development of new methods for particle identification and obtaining the TPC response function with high accuracy.

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The physical results obtained by the JINR group in the STAR collaboration are constantly presented at international conferences and published in referred journals.

It should be noted that in the last 2–3 years it was possible to attract young specialists and university students to work in the STAR experiment. They show interest in the research carried out by the STAR collaboration.

The experience of the staff involved in this experiment is extremely important for the preparation of a physics project under the program of research with heavy ions at the NICA/MPD complex in the energy range $\sqrt{s_{NN}}$= 4–11 GeV and under the program of polarization research at the NICA/SPD in the energy range $\sqrt{s}$ = 12–27 GeV.

The resources requested by the authors for the STAR project (JINR participation) for 2022–2024 are reasonable. I recommend to prolong the work with the first priority and present the Project at the Program Advisory Committee (PAC) for Particle Physics.

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