Referee's report

on the proposal form for the renewal of
a project "STAR experiment (JINR participation)" (02-0-1066-2007/2029-1)
in 2025–2029 and report on the project for 2022–2024

This review considers the report of the authors of the project "STAR experiment (JINR participation)" for the period of work in 2022–2024 and the proposal to extend the project for 2025–2029. Over the past and upcoming periods, the project has solved and will continue to solve 2 major problems. This is the processing and analysis of data under the BES-II energy scanning program and the implementation of a new experimental program to upgrade the STAR facility and conduct measurements of nuclear and polarization effects in a new kinematic region (Hot QCD Physics, Cold QCD Physics).

The STAR facility was constructed at the Brookhaven National Laboratory with significant participation of the Joint Institute for Nuclear Research to perform experiments at the heavy-ion and spin-polarized proton collider RHIC. One of the tasks 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, ${}^{96}_{44}$Ru, ${}^{96}_{40}$Zr, U), in order to study its properties with various probes in a wide range of collision energies, from 3 to 200 GeV, and determine the properties of the phase diagram of nuclear matter. As a result of studies carried out at the STAR facility, the conclusion about the formation of strongly interacting nuclear matter, more reminiscent of a perfect liquid, at maximum RHIC energies was formulated. It has been established that the new state of nuclear matter at maximum RHIC energies is characterized by a strong suppression of particle yields in Au+Au collisions at large transverse momenta of produced hadrons, a large elliptical flow of hadron production with light and heavy strange quarks, and its difference for baryons and mesons at medium momenta p_T, the presence of strong $\Delta\eta$ and $\Delta\varphi$ correlations ("ridge" effect) and "Number Constituent Quark" scaling for light and heavy quarks. These properties more closely remind those of an ideal liquid than the long assumed properties of an ideal gas. In experiments with polarized proton beams at an energy of 510 GeV and with the production of W bosons, a difference in the spin-dependent distributions of sea u- and d-quarks in the proton was discovered. A positive integral contribution of gluons to the proton spin was established by measuring the two-spin longitudinal asymmetry of jet production in proton collisions at the energy of 510 GeV.

One of the main tasks of the JINR group in 2022–2024 in the STAR experiment was participation in the BES-II energy scan program. In 2021, the final run on the data taken under the BES-II program was completed. As a result of the BES-I and BES-II programs, the energy range $\sqrt{s_{NN}}$ = 7.7–200 GeV in the collider mode and the energy interval $\sqrt{s_{NN}}$ = 3.0–7.7 GeV in the experiments with a fixed target were scanned. For the first time in the world, within the same experiment, the energy range from 3.0 to 200 GeV was covered. This made it possible to study the phase diagram of nuclear matter over a wide temperature (T_{ch} = 60–160 MeV) and baryon chemical potential (μ_B = 25–720 MeV) range.

In 2022–2024 with the participation of the JINR group, new results were obtained under the energy scan program. These are studies of the femtoscopic characteristics of charged pions at the minimum energy of 3.0 GeV and in the energy range from 3.0 to 3.9 GeV, obtained in experiments with a fixed target; the nuclear modification factor at energies of 14.5, 19.6 and 27.0 GeV; the spectrum of neutral K_S^0 mesons at the energy of 19.6 GeV for seven centralities. I would like to note that for the first time after the integration of a new detector in the STAR facility – the internal time projection camera (iTPC) – it was possible to reconstruct spectra in the region of ultra-small transverse momenta of K_S^0 mesons. The authors also proposed a large research program for the reconstruction of hyperons.

It is important to note the results related to measurements at the minimum energy $\sqrt{s_{\mathrm{NN}}}$ = 3.0 GeV (*Phys. Rev. Lett. 128 (2022) 202303*). It has been established that the ratio of C_2/C_4 correlators is reproduced by the hadron-transport model (UrQMD). This indicates the dominance of hadronic interaction energies in this region. It was found that at the energy of 3.0 GeV there is no NCQ ("Number Constituent Quark") scaling, which is observed at higher energies. It is of interest to compare the STAR results and results from the HADES experiment obtained at similar energies, which also include femtoscopic characteristics (*Phys. Lett. B 827 (2022) 137003*). The STAR facility provides a unique opportunity to make comparisons of these characteristics at $\sqrt{s_{\mathrm{NN}}}$ = 7.7 GeV in both the collider mode and the fixed target experiment. Such studies are planned to be carried out within the framework of the project under consideration. Measurements at energies below 11.5 GeV are extremely important for comparison with future measurements at the NICA collider.

Continuation of the theme for 2025–2029 includes new areas of research. One of the main tasks of the topic is the processing of data obtained by the BES-II program. Analysis of the results from the energy scan program is important not only for further planning of the experimental program at the STAR facility, but also for determining the area of research in which it is necessary to carry out measurements with high statistical accuracy at the MPD facility at the NICA collider. I note that the analysis of data with a fixed target is an important for experiments on the extracted beams of the Nuclotron, for example, BM@N.

The planned completion date for the work on the theme in 2029 is due to the fact that for 2022–2026 the STAR collaboration presented a program of research into nucleus-nucleus interactions at maximum RHIC energies but in an extended pseudorapidity interval. It will allow to obtain fundamentally new information about the dynamics of nucleus-nucleus collisions and the manifestation of the spin structure of protons and nuclei. These programs are called "Cold QCD Physics" for experiments with polarized protons and "Hot QCD Physics" for experiments with heavy nuclei. To carry out these studies, new detectors were created, which made it possible to expand the acceptance of the setup into the wide region of pseudo-rapidity (mid-rapidity $-1.5 < \eta < 1.5$ and forward rapidity $2.8 < \eta < 4.2$).

In 2022, with the active participation of the JINR group (26 man-weeks), the first run under the Cold QCD Physics program with transversely polarized protons at the energy of 510 GeV was conducted. The statistics accumulated are twice as higher as those accumulated in all previous years. The second run on the collision of polarized protons with nuclei at the energy of 200 GeV is planned for 2024.

In 2023, also with the participation of the JINR group, the first run under the Hot QCD Physics program with beams of gold nuclei at the maximum energy of the RHIC collider was successfully carried out. The new capabilities of the STAR facility after its upgrade allowed in this session to carry out measurements in the pseudo-rapidity range of $-1.5 < \eta < 1.5$ (mid-rapidity) and $2.8 < \eta < 4.2$ (forward rapidity), corresponding to the range of the Bjorken variable $0.005 < x < 0.5$. This will make it possible to study the Sievers distribution, the transversity function, the Collins fragmentation function in previously inaccessible regions and to extend the possibilities of analyzing asymmetries in the production of $W^{\pm}$ and Z^0 bosons. The next run to study collisions of gold nuclei at maximum energy and maximum luminosity of the collider is planned for 2025.

A run planned for 2024 is aimed to study polarization effects at the energy of 200 GeV in p+p and p+Au interactions. It is quite possible that some of the measurements related to p+p interactions will be performed in 2024. The measurements related to p+Au interactions will be postponed to a later date (probably to 2026). Therefore, in 2024–2026, the authors of the project will continue to collect statistics. It seems reasonable to support the request of the project authors to extend the project until 2029 inclusive, so that they have at least three years for analysis of new experimental data.

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

1. Use of the correlation femtoscopy method for a systematic study of the space-time parameters of particle production during energy scan, together with a study of various fluctuations
2. Study of strange particle production (mesons and baryons) for sensitive probing the state of nuclear matter for searching and studying the signatures of phase transitions depending on the energy and centrality of the collision over a wide range of transverse momentum of produced hadrons.
3. Study of the structure of events using the method of fractal analysis, cumulative production of particles depending on energy and multiplicity, and study of the modification of spectra in the nuclear medium.
4. Study of the energy and angular dependence of global polarization, as well as the chiral magnetic effect.
5. Development and application of machine learning methods for data analysis in collider experiments.
6. Saving the necessary experimental data from the RHIC collider at JINR. Converting the collected data into pico- and femtoDST formats and placing them on the JINR LIT server (200 TB). These data can be used for additional analysis when planning and conducting experiments under the research program at the NICA accelerator complex, regardless of external circumstances.

The physical results obtained by the JINR group are regularly presented at international conferences. In 2022–2024, more than 15 reports were submitted. In 2022–2024, more than 10 publications were prepared with the participation of members of the JINR group.

It is important to note that university students and young researchers work in the group. In 2022–2024 15 bachelor's and master's theses were defended. Three young scientists are working on the preparation of Ph.D. dissertations on the subject of the BES-II program.

Young scientists of the JINR group in the STAR experiment received a grant from the Russian Science Foundation – "Measurement of the thermodynamic characteristics of a dense baryonic medium formed in heavy ion collisions at energies of 3–27 GeV" (RSF 22-72-10028).

The experience of the staff involved in the STAR experiment is extremely important for the preparation of a physics project under the heavy ion research program at the MPD/NICA complex in the energy range $\sqrt{s_{NN}}$ = 4–11 GeV and under the polarization research program at SPD/NICA in the energy range $\sqrt{s}$ =12–25 GeV.

I recommend accepting the report on the project "STAR experiment (JINR participation)" (02-0-1066-2007/2029-1) for 2022–2024. I also recommend to continue work on the project in 2025–2029. The resources requested by the authors in project proposal form for the renewal of the project for 2025–2029 are justified.

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