# Referee's report
# on the project STAR (JINR participation)

The experimental results of the STAR collaboration on the study of nuclear matter under extreme conditions, the spin-dependent quark and gluon structure functions, the polarization of sea quarks in the W-boson production, the processes with heavy quark production are well known for scientific community and have made significant contributions to the formation of up-to-date knowledge in this field of physics. An important contribution to the creation of the STAR facility and realization of the experimental program was made by the JINR group which consists of physicists from JINR Member States including Slovakia.

The possibility to perform measurements at the RHIC collider with longitudinally and transversely polarized protons, various colliding nuclei (d, He, Cu, Au, U) over a wide energy range (from 7 to 200 GeV/nucleon) simultaneously with the development of detecting systems of the STAR facility allows us to study successfully the quark-gluon structure of matter for many years.

The main and significant contribution of JINR to the STAR experiment was the creation of End Cup Electromagnetic Calorimeter (EEMC). The creation of this detector and its stable operation during data taking has led to the successful realization of the physical program with longitudinally and transversely polarized protons (measurement of the asymmetries of the production of pions, jets, W-bosons) and obtaining new restrictions on spin-dependent gluon and quark (valence and sea) distributions of various flavors.

During the entire period of participation in the STAR project the JINR group has been developing new data processing algorithms to study nucleus-nucleus collisions and processes with jet production in experiments with polarized protons. The original method of data analysis ($z$-scaling) is proposed and developed. It is based on the fundamental physical principles – self-similarity, locality and fractality of hadron interactions at the constituent level. The existence of $z$-scaling finds its justification in the region that lies far from the boundary of the phase transition or out of the region where the critical point can be located. Nevertheless, the approach based on the $z$-scaling theory can also be adequate for searching for phase transitions and critical points in hadronic and nuclear matter.

During the period 2015–2018, the JINR team in the STAR experiment has made the significant contribution to obtaining new physical results at the world level:

1. The first statistically ensured results were obtained for measuring Λ-Λ correlations in Au + Au collisions at $\sqrt{s_{NN}} = 200$ GeV with the active participation of JINR physicists from the Czech Republic, Slovakia and Russia. These results became the basis for using the RHIC as a hyperon factory for studying hyperon-hyperon interactions by the method of correlation femtoscopy.

2. The interaction between antiprotons was measured by a correlation technique (Nature 527 (2015) 345) for the first time. It was found that attractive forces act between the antiprotons and define two key parameters characterizing the strong interaction – the scattering length and the effective radius. This experiment demonstrated once more the unique possibilities of the correlation technique for measuring the parameters of the strong interaction, determination of which is practically impossible with other methods.

3. The transverse momentum spectra of charged hadrons produced in Au+Au collisions over a wide energy range from 7.7 to 200 GeV were analyzed and the dependence on centrality was studied. Within the original method of data analysis ($z$-scaling) developed by the JINR group, the scaling regularities in the production of particles were verified. The parton energy losses, fractal dimensions of the colliding nuclei, the fragmentation process as a function of the energy and centrality of the collision and the transverse momentum of the produced particle were estimated.

4. A generally accepted hypothesis is that strange particles are good probes to study the properties of nuclear matter and determine the phase diagram. Therefore, I find quite interesting the analysis

of the experimental data performed by the authors of the project to study the scaling properties in the strange particle production (from K meson up Ω hyperon) in p+p collisions at the RHIC, as a reference frame for comparison with similar data obtained in Au+Au collisions.

5. The method of $z$-scaling proposed by the authors of the project was developed and applied to describe the double longitudinal asymmetries in the production of pions and jets, as well as the polarization transfer ($D_{TT}$) in the production of the Λ (anti-Λ) hyperon. The behavior of the spin-dependent scaling functions was verified, estimations for the spin-dependent fractal dimensions of the proton and Λ (anti-Λ) hyperon were obtained, the dependence of the parton loss and the similarity parameter on the transverse momentum of the produced particle was studied.

The results were published in referred journals and reported at various international conferences.

The new project proposes experiments at the STAR facility in 2019–2021. The high precision statistical measurements with various types of processes in collisions of relativistic nuclei will be performed in these experiments. It will give a possibility to discover new physical phenomena.

Among the tasks of the project, we note the following:

1. The fluctuations of the charge separation in a strong magnetic field (~ $10^{17}$ Gauss), arising in nucleus-nucleus collisions, which were called the chiral magnetic effect (CME), were observed by STAR. The measurements with the nuclei, the isobars of ruthenium-96 and zirconium-96, will be made for additional verification and clarification of the role of the magnetic field in the charge separation. It is expected that these measurements with an accuracy of ~ 6% will give an answer to the question: what fraction of the total charge is associated with CME and the restoration of chiral symmetry.

2. The journal Nature (Nature 548 (2017) 62) published a new unusual result of the STAR experiment – the detection of global polarization of nuclear matter in Au+Au collisions with production of Λ and anti-Λ hyperons. In the paper, the conclusion about the formation of the vortex structure in the "perfect fluid" in collisions of heavy ions was formulated. It is planned to perform additional measurements and collect large statistics on the production of Λ and anti-Λ hyperons in collisions of gold nuclei at the energy $\sqrt{s_{NN}}$ = 27 GeV, which is necessary for the global polarization measurement.

3. The main goal of the project is to carry out a new phase of the energy scan program – BES-II. Previously, the first phase of the energy scan program, BES-I, was performed at the energy $\sqrt{s_{NN}}$ = 7.7–200 GeV in order to study the phase diagram and search for the critical point of nuclear matter. Various characteristics of nucleus-nucleus interactions were measured, including direct and elliptical flows, rapidity correlations, fluctuations and the value of $\kappa\sigma^2$ for «net-protons», and the yield of dileptonic pairs at small transverse momenta. These results were published in more than 30 referred journals and reported at various international conferences. However, the statistical results obtained cannot draw final conclusions about both the existence and location of critical points and the character of the phase transition. That is why in 2019–2020 new programs of energy scan, BES-II, are planned.

4. The purpose of the new phase of the beam energy scan program BES-II is obtaining of data with high statistical precision for energies $\sqrt{s_{NN}}$ = 7.7–200 GeV. For high statistical precision measurements the new detectors (EPD, iTPC, eTOF) will be gained to the facility. At the RHIC collider the system of electron beam cooling will be created to increase the luminosity of the RHIC collider at low energies by 2–4 times. The key points for physical conclusions are: measuring the value of $\kappa\sigma^2$ for "net-protons", obtaining dilepton spectra in the region of small invariant masses, measuring elliptic flows for φ-mesons, and testing the number of constituent quark (NCQ) scaling.

5. During the energy scan program BES-II it is intended to measure the collisions of a beam of gold nuclei circulating in the collider ring with a fixed gold nucleus target in the energy range corresponding to the collider mode with $\sqrt{s_{NN}}$ = 3.5–7.7 GeV (6 points in energy). This will allow us to study the phase diagram in the range of the values of the baryon chemical potential ($\mu_B$) from 420 to 721 MeV. Measurements at the RHIC are important for JINR because they will allow one to obtain preliminary information about physical processes in the energy range of the NICA collider, which will have a higher luminosity during measurements.

The JINR team plans to participate in the following topics of the scientific program:

1. Participation in data analysis of global polarization on ruthenium and zirconium nuclei. A comparison of the polarization of Λ hyperons in collisions of the ruthenium and zirconium nuclei may allow us to distinguish the "vortex" model from the model associated with the magnetic field effects.

2. Participation in data taking and data analysis at BES-II energies for the study of hyperon global polarization and verification of predictions of theoretical models.

3. The analysis of experimental data on energy scan for studying the scaling properties and the fractal structure of nucleus-nucleus collisions to search for signatures of phase transitions and the critical point in nuclear matter.

In the new project, as in the previous stages of the research, it is expected that the JINR team will participate in the preparation and conduction of runs on data collection, in working groups for data processing and data analysis, analysis of experimental data from MuDST and PicoDST at JINR, in preparation of reports for international conferences and publications for referred journals also as principal authors.

As a reviewer, I recommend actively involving young scientists from JINR in the processing of experimental data, since the experience gained by them can be used directly for the forthcoming processing of experimental data that will be obtained in the near future at the NICA accelerator complex.

In general, the physical program proposed in the project is well grounded and its implementation is unquestionable.

One of the important achievements of the authors of the project is the possibility, realized together with the LIT staff, of using GRID for processing events from the STAR facility using the JINR computer cluster. This can allow the formation of MuDST and PicoDST files for priority research at JINR and the fulfillment of project tasks.

I would like to note that the participation of JINR in the STAR experiment at the RHIC is part of the JINR Seven-Year Plan for 2018–2024.

The funding requested by the authors of the project corresponds to the tasks that are planned to be performed. It should be also noted that this request corresponds to the level of funding that was provided to the authors at the previous stages of the project.

I suggest endorsing the project of JINR participation in the STAR experiment in 2019–2021 with first priority, provide the requested resources in full and present the Project at the PAC.

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