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Status of the mega-science project NICA

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Abstract. The Mega-Science project NICA (Nuclotron-based Ion Collider fAcility) is under construction at the Joint Institute for Nuclear Research (JINR) in Dubna (Russia). This is the first international mega-science project which will be build on the territory of the Russian Federation. The heavy ion programme at NICA includes two planned detector systems: the Baryonic Matter at Nuclotron (BM@N) and the Multi-Purpose Detector (MPD). The mission of future experiments at NICA is to explore the phase diagram of QCD matter at collision energies, where the highest net-baryon densities will be created. The perspectives for the experiments at NICA and the designed physics performance of the detector components will be presented and discussed.

1. Introduction

The mega-science NICA Complex project is being implemented at the Joint Institute for Nuclear Research (JINR), Dubna, Russia in accordance with the Agreement between the Government of the Russian Federation (RF) and the JINR on the construction and operation of a complex of superconducting rings on colliding beams of heavy ions NICA Complex [1]. This is the first international mega-science project which will be build on the territory of the Russian Federation. The design parameters of NICA in the collider mode are Au+Au collisions in the $\sqrt{S_{NN}}$ range of 4-11 GeV per nucleon pair [2]. The facility will also provide collisions of polarized protons and deuterons at the second stage of operation. The mission of future experiments with collisions of relativistic heavy-ions at NICA is to explore the phase diagram of QCD matter at collision energies, where the highest net-baryon densities will be created. The recent discoveries of neutron star mergers and supermassive neutron stars challenge our knowledge on high-density QCD matter, like its Equation-Of-State (EOS) and the microscopic degrees-of-freedom. The NICA physics program with heavy ions will address the following important topics of modern nuclear physics: the Equation-Of-State (EOS) of nuclear matter under extreme conditions, properties of the deconfinement phase transition, collective effects in strongly interacting matter, and search for signals of chiral symmetry restoration [2, 3].

2. Nuclotron-based Ion Colider facility NICA

The NICA Accelerator Complex, shown schematically in the left part of Fig.1, is located in the Veksler-Baldin Laboratory for High Energy Physics (VBLHEP) of JINR [2]. The NICA complex includes: a heavy-ion source and heavy-ion linear accelerator, the Nuclotron - superconducting synchrotron (in operation since 1993 and upgraded in 2010-2015 it provides beams of heavy ions up to 6A GeV for isospin-symmetric nuclei and 4.65A GeV for Au^{79+}), a booster accelerator, and two storage rings of the NICA collider. The beams from Nuclotron can be then extracted to the Fixed Target Area, where the Baryonic Matter at Nuclotron (BM@N) experiment is currently operating. For the NICA collider, the accelerated beams by design will consist of particles ranging from protons and light nuclei to fully stripped gold ions. Beam energies will span $\sqrt{s} = 1227$ GeV with luminosity $L_{pp} \geq 10^{30} cm^{-2}s^{-1}$, and $\sqrt{s_{NN}} =$ 4-11 GeV, and average luminosity $L_{AuAu} = 10^{27} cm^{-2}s^{-1}$. The second interaction point is planned to be occupied by a third experiment - Spin Physics Detector (SPD), which will focus on the investigation of nucleon spin structure and polarization phenomena through the use of polarized proton and deuteron beams. Civil construction of buildings of NICA Accelerator Complex and its transfer lines is significantly advanced, see right panel of Fig.1. First heavy-ion beam in NICA is expected in 2022.

Figure 1. Left: The general overview of the NICA Accelerator Complex. Right: Aerial view of the NICA constraction site (June 2020).

3. BM@N experiment at NICA Accelerator Complex

BM@N (Baryonic Matter at Nuclotron) is the first experiment operational at the NICA Accelerator Complex. The purpose of the BM@N experiment is to study relativistic heavy-ion beam interactions with fixed targets [4, 5]. The Nuclotron will provide the experiment with beams of a variety of particles, from protons to gold ions, with a kinetic energy ranging from 1 to 6 GeV/nucleon. The maximum kinetic energy of ions with the charge to atomic weight ratio of 0.5 is 6 GeV/nucleon. The maximum kinetic energy of gold ions with Z/A of 0.4 is 4.5 GeV/nucleon, while the maximum kinetic energy for protons is 13 GeV. The planned intensity of the gold ion beam at BM@N is 10^6 ions/s. The acceleration of the gold ion beam is planned in 2021, after the Nuclotron upgrade. The view of the BM@N detector setup in a first experimental run in 2018 is presented in the left panel of Fig.2. The charged track momentum and multiplicity will be measured by the inner tracking system, which consists of set of forward silicon detectors (FwdSi), large apperture silicon tracking system (STS) and 7 planes of two-coordinate GEM (Gaseous Electron Multiplier) detectors mounted downstream of the target inside of the analyzing magnet. The GEM detectors are operational at high particle densities and in strong magnetic fields. The outer tracking system consists of cathode chambers that will be supplemented with cathode strip chambers to increase the effectiveness of track measurement in Au+Au collisions. The time-of-flight detectors (ToF) based on the multi-gap Resistive Plate Cham- ber (mRPC) technologies with strip readout provide an opportunity to separate hadrons (π, K, p) and light nuclei with momentum up to few GeV/c. The Zero Degree Calorimeter (ZDC) detector is foreseen for the extraction of the collision impact parameter (centrality) by measuring the energy of the fragments of colliding particles. In 2022, at the second stage of the BM@N experiment, at least four planes of two-coordinate silicon strip detectors will be installed in front of the GEM detectors to improve track reconstruction in Au+Au collisions.

The International BM@N Collaboration formed to study Baryonic Matter at the Nuclotron includes 20 Institutions from 10 countries and consists of 246 participants. NRNU MEPhI group joined the BM@N experiment in 2017 and participates in the projects related to GEM detectors and new tracking system with two-coordinate silicon strip detectors.

4. MPD experiment at NICA Accelerator Complex

The Multi Purpose Detector (MPD) is designed as a 4π spectrometer capable of detecting charged hadrons, electrons and photons in relativistic heavy-ion collisions at high luminosity in the energy range of the NICA collider [6, 7]. The estimated event rate for AuAu collisions at minimum bias is at a maximum of about 7 kHz, and the total charge particle multiplicity exceeds 1000 in the most central Au+Au collisions at $\sqrt{s_{NN}} = 11$ GeV. As the average transverse momentum of the particles produced in a collision at NICA energies is below 500 MeV/c, the detector design requires a very low material budget. Two stages of realization are planned for the MPD. A barrel setup is constructed at the present first stage. A cut-away schematic view of the MPD detector is shown in Fig. 2 (right panel). All the MPD sub-detectors are placed inside a large superconducting solenoid, which generates a magnetic field B up to 0.5 T. In order to ensure precise track reconstruction, high magnetic field homogeneity within the solenoids working volume will be provided by means of dedicated trim coils in the magnet poles (field inhomogeneity less than $|\Delta B|/|B_0| \simeq 3 \cdot 10^{-3}$).

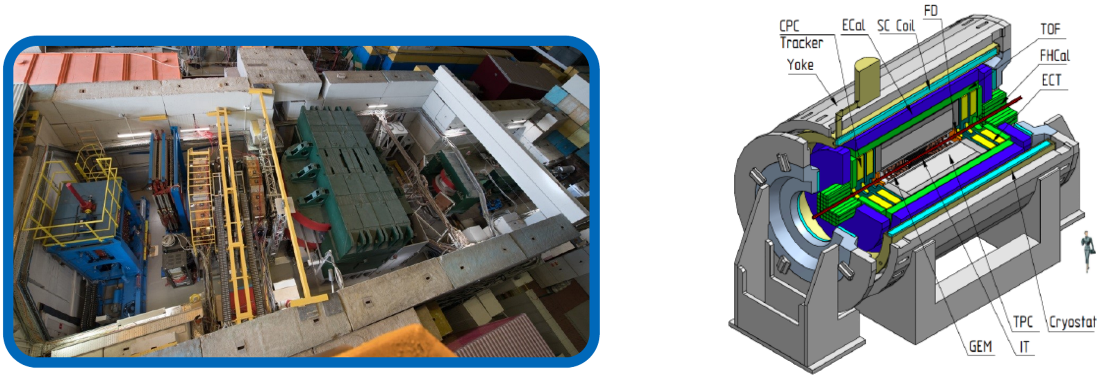

Figure 2. Left: View of the BM@N detector setup in a first experimental run in 2017. Right: Schematic layout of the Multi-Purpose Detector (MPD) for the first stage of the experiment expected in 2022.

The main tracking detector in MPD barrel is the Time Projection Chamber (TPC). The TPC is a cylindrical gas detector 2.7 m in diameter and 3.4 m in length. The central high voltage electrode and the voltage dividing network create a uniform electric field for drift particles in the active volume. TPCs readout system is based on Multi-Wire Proportional Chambers (MWPC) with cathode readout pads. TPC will provide a sufficient transverse momentum resolution (with a resolution $<$ 1 cm) and energyloss measurements (dE/dx resolution better than 8%) for hadronic and leptonic tracks at pseudo-rapidities $|\eta| < 1.5$ and $p_T > 100$ MeV/c. Precise primary and secondary track reconstruction and also precise primary (Interaction point) and secondary (decay) vertex reconstruction are of top TPC priority.

The Time of Flight System (TOF) will provide time of flight measurements with geometrical efficiency above 95% and resolution in the range 60-80 ps. The basic element of the TOF system will be a Multigap Resistive Plate Chamber (MRPC). Combined, the measurements from TPC and TOF will provide an efficient pion/kaon PID separation up to 1.5 GeV/c, pion/proton separation up to 3 GeV/c, and a very good electron/hadron separation [8]. The Forward

Detector (FD) consists of two modular sets of Cherenkov detectors placed at a distance of 130 cm to the left and to the right from the interaction point. FD provides provides a trigger system for data taking and start time for TOF with resolution better than 50 ps. Two sets of Forward Hadron Calorimeter (FHCal) are allocated at 3.2 m at the forward and backward region pseudo-rapidity from 2.2 to 4.8. Each detector consists of 45 modules providing the necessary transverse granularity. The main goal of FHCal is to provide energy measurements of spectator energy for centrality determination and event-plane reconstruction. In 2015-2017 the NRNU MEPhI group participated in the preparation of the technical design report for FHCal detector. The civil construction for MPD Hall, where MPD detector system will be located is finished in 2020. The superconducting solenoid is manufactured and will be transported to JINR in late 2020 and assembled with the other parts of the system. Within the NICA timetable, MPD will be commissioned in the 2021 and will start physical data taking by 2022. In order to increase low momentum track and primary vertex resolution, the addition of an Inner Silicone Tracker (IT) and Gas Electron Multipliers (GEM) close to the interaction point are planned. Also, end-caps on both sides of the barrel are considered: ECT, ETOF, ECAL.
The International MPD Collaboration formed to study heavyion collisions at the Nuclotron based Heavy Ion Collider fAcility (NICA) at JINR includes 40 Institutions from 11 countries and consists of more than 500 participants. NRNU MEPhI group [8] joined the MPD experiment in 2015 and participates in the development of the techniques for the anisotropic flow measurements using different detector subsystems of the MPD experiment at NICA collider.

5. The physics program of the MPD experiment

Investigations of the quark-gluon matter (QGM) properties at high net-baryon densities is the main scientific mission of the MPD (Multi-Purpose Detector) at the accelerator facility Nuclotron-NICA, see left panel of Fig.3 [2, 3]. Collisions of relativistic heavy-ions at energies in the range of 4 to 11 GeV per nucleon in the center-of-mass system which are planned at the NICA collider allows for experimental investigation of the QGM in the region of high net-baryon densities exceeding that of the normal nuclear matter by 5-10 times.

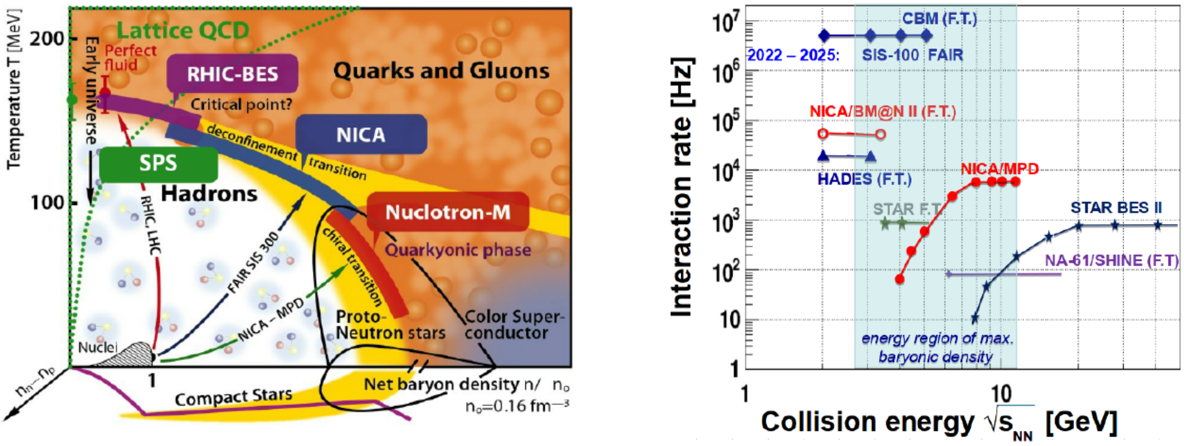

Figure 3. Left: The schematic view of the QCD Phase diagram. Right: Interaction rates (in Hz) for world wide high-energy nuclear collision facilities.

Situated between FAIR SIS100 and the low RHIC energies, NICA covers the energy range where the highest net-baryon densities can be created in laboratory experiments. This offers the opportunity to produce and to study QCD matter at neutron star core densities, and to address fundamental questions related to the high-density EOS, to the phase structure of strongly

interacting matter, to confinement and chiral symmetry. The NICA complex fills a gap in the energy landscape of existing and future accelerator facilities as illustrated in the right panel of Fig.3. The NICA collider is designed to run at a maximum luminosity of $L_{AuAu} = 10^{27} cm^{-2} s^{-1}$ at collision energies between $\sqrt{s_{NN}} = 8$ and 11 GeV corresponding to a reaction rate of 6 kHz for minimum bias Au+Au collisions, exceeding the available rates at STAR/RHIC and at NA61/CERN-SPS by about two orders of magnitude in this energy range.
Among the main experimentally observable effects which is sensitive to the properties of the QGM in relativistic heavy-ion collisions is the azimuthal collective flow of the produced hadrons relative to the collision symmetry plane. Detailed investigation of the azimuthal anisotropies at energies of the RHIC and LHC colliders and comparison with the model calculations demonstrated strong sensitivity of the azimuthal anisotropies to the QGM properties such as its equation of state, magnitude of the shear and bulk viscosity, as well as to the mechanism of the hadronization.
The goal of the project of NRNU MEPhI group [8] is to develop and deploy experimental measurement techniques for the azimuthal collective flow measurement with the MPD experiment at the NICA collider for different types of hadrons produced in nucleus-nucleus collisions. As a result of the project implementation a numerical modelling of the anisotropic collective flow based on the modern Monte-Carlo event generators of heavy-ion collisions with subsequent simulation of the realistic response of the MPD detector subsystems based on the GEANT platform and reconstruction algorithms build in the MPDROOT will be performed. A set of simulated heavy-ions collisions will be used for deploying of the existing and development of new algorithms for the measurement of the anisotropic collective flow which will utilize different combinations of the MPD detector subsystems. Figure.4 shows that MPD experiment will be able to provide a good event plane resolution for the measurements of directed and elliptic flow of the produced particles in the Au+Au and Bi+Bi collisions at NICA energies [9].

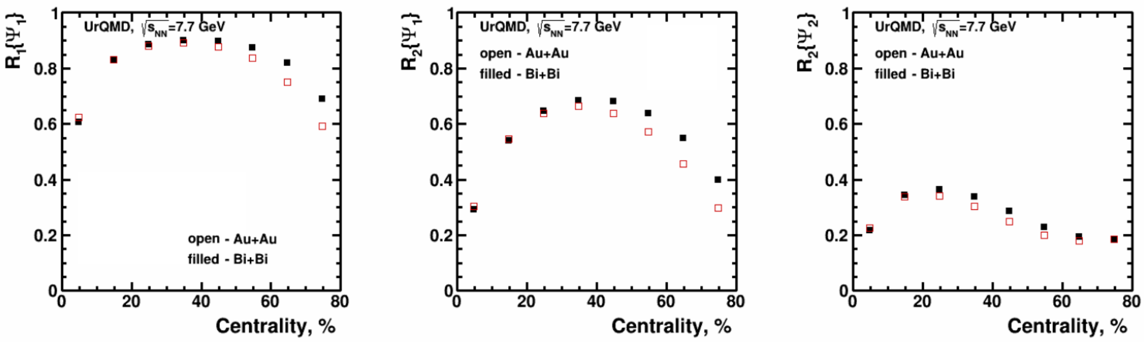

Figure 4. Centrality dependence of event plane resolution for directed and elliptic flow measurements in the MPD detector system for Au+Au and Bi+Bi collisions at $\sqrt{S_{NN}} = 7.7$ GeV.

The precise measurement of the excitation function of the yields of multi-strange antihyperons in the NICA energy range will provide information on the high-density EOS, and on the energy, where these particles reach thermal equilibrium, which is regarded as an indication for the onset of deconfinement. Furthermore, at NICA energies there are predictions of considerable enhancement of nuclear clusters with strangeness, thus allowing a better understanding of the dynamics of hypernuclei, hyperon-nucleon and hyperon-hyperon interactions, relevant for neutron star theoretical models. Figure 5. presents the results of the feasibility studies on strangeness at MPD with realistic simulations. The invariant mass distributions demonstrate good signal-to-background ratios for both hyperons and hypernuclei which is crucial for extracting parameters from the reconstructed decays, including momentum slope parameters, collective flow and polarization studies [2, 10].

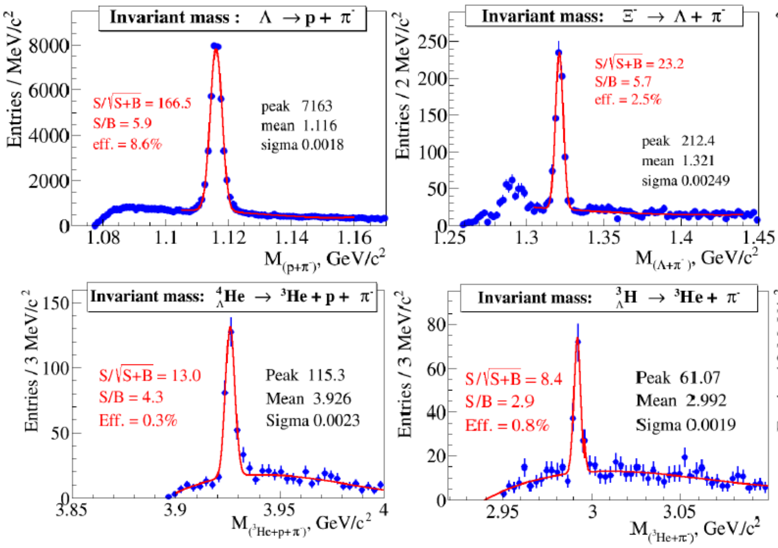

Figure 5. Reconstructed invariant mass distributions of hyperons (Λ, Ξ^-, Ω^-) (top) and hypernuclei (bottom) in the MPD detector system for Au+Au collisions at $\sqrt{S_{NN}} = 11$ GeV.

6. Summary

The status of the preparation of the Mega-Science project NICA has been briefly presented. NICA Accelerator Complex covers the energy range where the highest net-baryon densities can be created in laboratory experiments. This offers the unique opportunity to produce and to study QCD matter at neutron star core densities, and to address fundamental questions related to the phase structure of strongly interacting matter, to confinement and chiral symmetry. As a modern heavy-ion experiments, the Baryonic Matter at the Nuclotron (BM@N) and Multi-Purpose Detector (MPD) at NICA are designed to measure a variety of diagnostic probes: anisotropic collective flow of identified particles, event-by-event fluctuations, and the production of multi-strange hyperons and hypernuclei. The civil construction for NICA is progressing according to schedule and the first beams in NICA are expected in 2022.

7. Acknowledgments

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