Prospects for the dense baryonic matter research at NICA

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Abstract. The project NICA (Nuclotron-based Ion Collider fAcility) is aimed to study hot and dense baryonic matter in heavy ion collisions in the energy range up to $\sqrt{s_{NN}}=11$ GeV at the Nuclotron extracted beams and at the NICA collider with average luminosity of $L=10^{27}$ cm$^{-2}$s$^{-1}$ (for $^{197}$Au$^{79}$). This study will be performed with two experiments, BM@N (Baryonic Matter at Nuclotron) and MPD (MultiPurpose Detector) at the NICA collider.

1. Introduction
The main goal of the NICA physics program is the study of hot and dense nuclear matter in the energy region of the maximum baryonic density [1–3]. NICA is a new accelerator complex being constructed in JINR (Dubna, Russia) to provide beams of ions over a wide range of atomic masses (from $p$ to Au) at the average luminosity of $L=10^{27}$ cm$^{-2}$s$^{-1}$ and $10^{32}$ cm$^{-2}$s$^{-1}$ for gold-gold and proton-proton collisions, respectively. The center-of-mass energy will be $\sqrt{s}_{NN} = 4–11$ GeV for Au+Au and up to 27 GeV for $p+p$. This energy range will be extended to cover the lower region providing the experiment with the beam extracted from the Nuclotron.

In this paper, we overview the main physics objectives of the NICA program and current status of the project realization.

2. Physics objectives of the NICA program
Lattice QCD calculations predict both the deconfinement phase transition and chiral symmetry restoration to occur at high enough energy densities, and there is strong experimental evidence that the deconfined phase of nuclear matter (Quark-Gluon Plasma - QGP) can be created in ultra-high-energy nuclear collisions [4, 5]. As the collision energy is decreased down to several GeV per nucleon-nucleon pair, there is a certain transition region of collision energy below which it is no longer possible to access the plasma phase in the course of the collision. Existing data on single-particle spectra and mean multiplicities [6] suggest that this transition occurs within the NICA energy range ($4 < \sqrt{s} < 11$ GeV). Moreover, the energy range of NICA is sufficiently large to encompass both collisions in which the plasma phase is well developed and collisions in which the matter remains purely hadronic throughout. However, the theoretical understanding of this transition, and how it manifests itself in nuclear collision observables, is still rather poor, and quantitative predictions cannot yet be made with confidence. In particular, lattice gauge calculations can presently not be employed at the finite baryon densities, which will be studied.
by NICA. Furthermore, in addition to determining the existence and location of the transition region, where the new plasma phase is first being created, it is of fundamental interest to establish the character of the associated phase transformation, whether it remains a smooth crossover or becomes a first-order transition, as many models predict. In the latter case, the phase diagram of strongly interacting matter must contain a critical point, and its experimental identification forms a focal point for this research field. Therefore, it has been suggested [7] that the first round of NICA experiments should concentrate on a variety of diagnostic observables that have already been employed in experimental programs at RHIC and the SPS. The experimental setup at the NICA collider has to be optimized for the study of fluctuations and correlations of bulk event properties with a primary goal to measure the excitation functions and the dependence of fluctuations and correlations on centrality and system size.

Theory predicts that the deconfinement phase transition can be accomplished by partial restoration of the chiral symmetry in heavy-ion collisions [8,9] leading to possible modifications of hadronic spectral functions in dense hadronic matter. The correlated \( e^+e^- \) pairs (dileptons) from decays of vector mesons (\( \rho, \omega, \phi \)) are the best candidates to study such in-medium modifications, since they escape the interaction region unaffected by subsequent strong interactions. Until now, no dilepton measurements have been performed at center-of-mass energies of several GeV and the dilepton program at NICA is aimed to close this gap. The range of collision energies from \( \sqrt{s}=4 \) to 11A GeV is very promising for dilepton studies, since the effect of modifications is expected to be sensitive to the baryon density, while the latter happens to reach the maximum in central Au+Au collisions at NICA [10].

Study of strangeness, in particular, hyperon production is of interest due to several reasons. First, theory predicts that the strangeness enhancement in heavy-ion induced interactions (relative to elementary p+p collisions) might be a signature for the deconfinement phase transition [11]. Secondly, since the hadronic cross-sections of multi-strange hyperons are small, additional re-scattering effects of hyperons in the dense nuclear matter are not as strong as for other hadrons. Thus, measured phase-space distributions of strange hyperons reveal important characteristics of the fireball at the early stages of the system evolution. Moreover, under such conditions nuclear objects with strangeness, hypernuclei [12], can be formed, and, since the energy range of the NICA covers the region of the maximal baryon density, the production rates of nuclear clusters with strangeness are predicted to be enhanced considerably [13]. The outcome of the NICA program, in particular, new experimental data on (anti)hyperon and hypernuclei production, which will be taken with the MPD detector, will provide valuable insight into the reaction dynamics and properties of the QCD matter.

The studies in the collider mode will be complemented by a fixed target experiment at the Nuclotron at energies up to 6 GeV per nucleon. The Baryonic Matter at Nuclotron (BM@N) research program on heavy-ion collisions includes [20] the following topics: investigation of the reaction dynamics and nuclear EOS, study of the in-medium properties of hadrons, production of (multi)-strange hyperons at the threshold and search for hypernuclei. Particle yields, ratios, transverse momentum spectra, rapidity and angular distributions, as well as fluctuations and correlations, will be studied at BM@N as a function of the collision energy and centrality.

3. MPD detector at NICA

The Multi Purpose Detector (MPD) is designed as a 4\( \pi \) spectrometer capable of detecting charged hadrons, electrons and photons in heavy-ion collisions at high luminosity in the energy range of the NICA collider [14]. The experimental setup (see Fig. [1]) will comprise a precise 3D tracking system and a high-performance particle identification (PID) system based on the time-of-flight measurements and calorimetry. At the design NICA luminosity, the event rate of minimum bias interactions is 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. The whole detector setup includes Central Detector (CD) covering pseudorapidity interval $|\eta|<2$ and two forward spectrometers (FS-A,B) for $2<|\eta|<3$ (optional). The cross-sectional view of the MPD Central Detector (CD) is shown in Fig. 2. The MPD CD is 9 meters long and 6.6 meters in diameter and will be constructed in two stages. At the first stage (at the end of 2019), MPD will consist of the superconducting solenoid with a flux return yoke, Time-Projection Chamber (TPC), barrel Time-Of-Flight system (TOF), Electromagnetic Calorimeter (ECal), Zero-Degree Calorimeter (ZDC) and Fast Forward Detector (FFD). A detailed description of the detector components can be found in Ref. [15].

The Time-Projection Chamber is the main tracking detector of the MPD and will provide tracking and particle ID (dE/dx measurements with a resolution better than 8%) in the pseudorapidity range $|\eta|<1.2$, momentum resolution for charge particles better than 3% in the transverse momentum range $0.1 < p_t < 1$ GeV/c and two-track resolution of about 1 cm. The TPC has an inner diameter of 54 cm, an outer diameter of 280 cm, and an overall length along the beam direction of 340 cm. The uniform electric field in the active volume is created by a thin central HV electrode together with a voltage dividing network at the surface of the outer and inner cylinders and at the readout end-caps. Since the amount of material traversed by particles in the MPD has to be kept as low as possible, the TPC field cage will be made of composite materials (kevlar and tedlar), thus we estimate the TPC overall thickness to be less than 5$X_0$. It has been shown that for precise tracking the relative radial magnetic and electric field components in MPD have not to exceed $\approx 5\cdot10^{-4}$. Hence, the mechanical structure and electric field defining network have to be designed in a way to keep radial field non-uniformity below $10^{-4}$. The TPC readout system is based on the Multi-Wire Proportional Chambers (MWPC) with cathode pad readout. The gas mixture of 90% argon and 10% methane (P10), or 90% Ar and 10% CO2, is supposed to be used. In Fig. 3 a relative momentum resolution $(\Delta P/P)$ for charged tracks in the MPD TPC from Monte-Carlo simulations is shown.

Identification of charged hadrons in MPD in the range of momentum from 0.1 to 2 GeV/c will be achieved by the time-of-flight (TOF) measurements, which are complemented by the energy loss (dE/dx) information from the TPC (see Fig. 4). The cylindrical part of the TOF MPD has a full azimuthal and $|\eta|<1.2$ coverage. The TOF outer diameter is 3.4 m, and the total surface is of about 53 m$^2$. The basic element of the TOF system will be a Multigap Resistive Plate Chamber (MRPC). This technology, which provides the intrinsic time resolution in the range 60-80 pc, is widely used in heavy-ion experiments at RHIC and LHC. MRPCs are easily

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**Figure 1.** MPD setup.  
**Figure 2.** MPD detector cross-sectional view.
manufactured and are relatively inexpensive. The TOF electronics will be based on the NINO specific integrated circuit [16], and TDC based on a multihit High Performance ASIC (HPTDC) chip developed at CERN [17]. The detector is segmented in azimuth into 12 sectors of 5.7 m length. Each sector consists of 4 modules, and each module comprises 6 MRPCs detectors arranged in 2 layers. The overall TOF geometrical efficiency is above 95%, and time resolution is better than 100 pc. It allows us to separate pions from kaons up to $p_t < 1.5 \text{ GeV/c}$ and identify (anti)protons up to $p_t \approx 3 \text{ GeV/c}$, thus more than 95% of the transverse momentum spectra of hadrons will be measured. As can be seen from Fig. 4, the basic detector parameters, namely, dE/dx resolution of $\sigma_{dE/dx} \approx 8\%$ and TOF resolution of $\sigma_{TOF} \approx 100 \text{ ps}$, will provide a high degree of selectivity for hadrons at momenta below 2 GeV/c.

The primary role of the electromagnetic calorimeter is to measure the spatial position and energy of electrons and photons produced in heavy ion collisions. The MPD electromagnetic calorimeter is proposed to be built of towers as basic building elements of about 3 cm$^2$ cross section. Each lead-scintillator sampling tower contains 250 alternating tiles of Pb (0.275 mm) and plastic scintillator (1.5 mm). A module of 18 radiation length thickness will be $\approx 40 \text{ cm}$ long. The cells of each tower are optically combined by 9 longitudinally penetrating wavelength shifting fibers for light collection. The light collected by these fibers will be read out by avalanche photodiodes (MAPD) units of 33 mm$^2$ sensitive area. The towers, mechanically grouped together, make 139 trapezium-shape modules which are combined into 48 detector sectors. The heat-producing electronics will be thus separated from the modules and mounted on the upper parts of sectors.

The goal of the FFD detector, located at $\approx 75 \text{ cm}$ on both sides of the interaction point, is to provide a fast interaction trigger and timing signal for TOF. A FFD module is made of 1.5 cm thick quartz Cherenkov radiator, optically coupled to a multianode MCP-PMT Planacon capable of registering high energy photons and relativistic charged particles of velocity $\beta > 0.69$ with a timing resolution better than 50 ps.

The MPD Zero Degree Calorimeter (ZDC) located in both sides of MPD at a distance of 3.2 m from the MPD center will be used for classification events by centrality by measuring the energy of spectators. Each ZDC semi-part consists of identical modules in parallelepiped-shaped with a transverse dimension of 10x10 cm$^2$ and a longitudinal size of 90 cm. A distinctive feature of the proposed design is the existence of square hole in the center of the calorimeter for the passage of the primary beam. Each ZDC module of consists of 60 lead-scintillator tile sandwiches with thickness of 16 and 4 mm for Pb and scintillator, respectively. The sampling
ratio of $4 \div 1$ will provide the compensation condition. Light readouts will be provided by WLS-fibers embedded in the round grooves in the scintillator plates, which will ensure a high efficiency and uniformity of light collection over the scintillator tiles within a few percent. WLS-fibers from each 6 consecutive scintillator tiles are collected together and viewed by an avalanche photodiode at the end of each module.

4. MPD feasibility study

All the Monte-Carlo simulation and feasibility study tasks for MPD were performed in the framework of a dedicated program tool - MPDRoot comprising interfaces to many event generators and Geant as well as detector response simulation and reconstruction algorithms.

4.0.1. Study of hyperon production at MPD: feasibility

The performance of the MPD detector for hyperon measurements was studied for a combination of Time Projection Chamber (TPC) and Time-Of-Flight system (TOF) covering the mid-rapidity region ($|\eta| < 1.3$). A small material budget (not exceeding 10% of the radiation length in the region of interest) and powerful particle ID based on ionization loss (dE/dx) measurements in the TPC and time-of-flight information from the TOF allow precise trajectory reconstruction and reliable separation of particle species.

Hyperons and cascades were reconstructed using the secondary vertex finding technique with an optimized set of topological and track quality cuts as described in [19]. In Fig. 5, invariant mass distributions of ($p, \pi^-$), ($\Lambda, \pi^-$) and ($\Lambda, K^-$) pairs from central Au+Au collisions at center-of-mass energy $\sqrt{s} = 9$ GeV are shown. The estimated efficiencies, Signal-to-Background (S/B) ratio and significance are also printed. Based on the results of this study, we have estimated the expected yields of particle species under interest for 10 weeks of data taking at the nominal NICA collider luminosity of $\approx 10^7$ and $\approx 10^6$ for $\Xi^-$ and $\Omega^-$, respectively. The accumulated statistics will allow us to get unique experimental information on cascade production over a broad region of the QCD phase diagram and a large phase-space of the reaction.

4.0.2. MPD prospects for dileptons

We investigated MPD performance for dileptons, in particular focusing on determination of the hadron suppression factor of the MPD particle ID system, and achieved signal-to-background ratio and invariant mass resolution in the region of masses of vector mesons. A detailed description of the analysis procedure and results can be found in Ref. [18]. The charged hadrons and dileptons from event generators (UrQMD+Pluto) were transported through the detector setup, which includes the Time Projection Chamber (TPC), Time-Of-Flight system (TOF) and Electromagnetic Calorimeter (EMC) covering $|\eta|<1.2$. A realistic detector response was simulated followed by track reconstruction, TPC-TOF matching and particle identification procedures, which were performed within the MPDRoot framework. Electron identification was achieved by using combined information about the

Figure 5. Invariant mass of $p$ and $\pi^-$ (left), $\Lambda$ and $\pi^-$ (center), $\Lambda$ and $K^-$ (right) candidates.
specific energy loss $dE/dx$ from TPC, time-of-flight from TOF and $E/p$ information from EMC.

After applying several quality and PID cuts, the achieved overall hadron rejection factor was of about 3200. The background from conversion pairs was eliminated by an extra set of topological and kinematical cuts. Fig. 6 shows the spectrum of reconstructed low-mass dielectrons after background rejection (dots) and true dielectrons from the event generator (line). $S/B$ ratio in mass region $0.2 < M_{e^+e^-} < 1.2$ GeV/$c^2$ was estimated to be of about 10%. This number is shown in Fig. 7 along with the published data from other experiments; the expected parameters of the MPD setup are among the best over the world.

### Figure 6. Invariant mass of dileptons after background subtraction.

### Figure 7. Overall Signal-to-Background $(S/B)$ ratio from heavy ion experiments ($0.2 < M_{e^+e^-} < 1.2$ GeV/$c^2$).

#### 4.0.3. Observation of hypernuclei at MPD: feasibility

In this section, we present the results of a study of MPD capability for reconstruction of hypertritons. The statistics of events from the DCM-QGSM event generator ($5 \cdot 10^5$ events were used in this study) corresponds to about 30 minutes of data taking time at NICA. The full event reconstruction, realistic particle ID and secondary vertex finding are described in [19]. The obtained invariant mass spectra of helium-3 and $\pi^-$ candidates is shown in Fig. 8. These results demonstrate good sensitivity of the MPD setup for hypernuclei; with a typical event rate of 7 kHz for the design NICA luminosity of $10^{27}$ cm$^{-2}$s$^{-1}$, we are able to register of about $10^5$ hypertritons in a week of data taking. Thus, a detailed study of the production mechanism of single hypernuclei, as well as an observation of double hypernuclei at NICA, look feasible.

### Figure 8. Invariant mass of $^3$He and $\pi^-$ candidates (MPD).
5. BM@N experiment

Baryonic Matter at Nuclotron (BM@N) is an experimental set-up at the Nuclotron extracted beam to accomplish the NICA physics program at low energy range. A sketch of the BM@N proposed experimental set-up is shown in Fig. 9. It combines high precision track measurements with time-of-flight information for particle identification and total energy measurements for the analysis of the collision centrality. The charged track momentum and multiplicity will be measured with the set of 12 two-coordinate planes of GEM (Gaseous Electron Multipliers) detectors located downstream of the target inside the analyzing magnet complemented by drift and straw tube chambers situated outside the magnetic field. The GEM detectors sustain high rates of particles and are operational in strong magnetic fields. At the second stage of the BM@N experiment, at least 4 planes of two-coordinate silicon strip detectors will be installed between the GEM tracker and the target. The design parameters of the time-of-flight detectors based on multi-gap Resistive Plate Chambers (mRPC-1,2) with a strip read-out allow us to discriminate between hadrons ($\pi, K, p$), as well as light nuclei with the momentum up to a few GeV/c. The Zero Degree Calorimeter (ZDC) is designed for the analysis of the collision centrality by measuring the energy of forward going particles. The T0 detector, partially covering the backward hemisphere around the target, is planned to trigger on central heavy ion collisions and provide a start signal for the mRPC-1,2 detectors. The Nuclotron will provide variety of beams from protons to gold ions with the kinetic energy from 1 to 6 GeV per nucleon, and the length of the beam line between the Nuclotron and the BM@N is around 160 meters. In order to provide beams of high quality, it comprises 26 elements of magnetic optics including 8 dipole magnets and 18 quadruple lenses. The planned intensity of the gold ion beam for the BM@N experiment (by the end of 2018) is expected to be of $10^7$ ions per second, and beams of xenon are expected by the end of 2017. The first technical run of the BM@N detectors was performed with deuteron and carbon beams already in spring 2015.

At present, the activities on the detector and beam line construction are complemented with intensive Monte Carlo simulation studies to optimize the detector set-up. A focus is made on the efficiency of the measurement of strange hyperons and hyper-nuclei in central Au+Au collisions. In Figures 10 and 11 invariant mass of $(\Lambda, \pi^-)$ and $(^3He, \pi^-)$ candidates, respectively, reconstructed with the GEM tracker from central Au+Au collisions at the beam kinetic energy of 4.5A GeV are shown. The obtained results indicate that the proposed set-up has a reasonable reconstruction capability for strange hyperons produced in high multiplicity central Au+Au collisions. The reconstructed signals of $\Xi^-$ hyperon and hyper-triton correspond to 0.9M and 2M of central collisions, respectively. Taking into account the signal reconstruction efficiency, data acquisition capacity and the duty factor of the Nuclotron beam, the expected statistics of $\Xi^-$-hyperons and hypertritons for a month of the BM@N operation are expected to be of 2.7M.
Figure 10. Invariant mass of Λ and π− (BM@N)

Figure 11. Invariant mass of 3He and π− candidates (BM@N)

and 4M, respectively. These statistics are sufficient to perform studies of strange hyperon and hyper-nuclei production by measuring their transverse momentum spectra, rapidity and angular distributions.

6. Summary and Conclusions

The NICA project realization plan foresees a staged construction and commissioning with the goal to start the BM@N experiment with the Nuclotron extracted beams in 2017. The research program will be continued at higher energies after putting the startup configuration of the NICA collider into operation in 2019. The commissioning of the design configuration of the NICA accelerator complex is foreseen in 2023.

References

[1] G. Trubnikov, A. Kovalenko, V. Kekelidze, I. Meshkov, R. Lednicky, A. Sissakian, A. Sorin, PoS (ICHEP 2010) 523.
[2] G. Trubnikov, N. Agapov, V. Kekelidze, A. Kovalenko, V. Matveev, I. Meshkov, R. Lednicky, A. Sorin, PoS 36th International Conference of High Energy Physics (ICHEP2012), July 4-11, Melbourne, Australia.
[3] V. Kekelidze, A. Kovalenko, R. Lednicky, V. Matveev, I. Meshkov, A. Sorin, G. Trubnikov, 37th International Conference on High Energy Physics, ICHEP 2014, Valencia, Spain, 2 Jul 2014 - 9 Jul 2014 Nuclear physics B Proceedings supplements (2014).
[4] J. Adams et al, Nucl. Phys. A 757, 102-183 (2005).
[5] K. Adcox et al, Nucl. Phys. A 757, 184-283 (2005).
[6] C. Alt et al, Phys. Rev. C 77, 024903 (2008).
[7] NICA White Paper, http://nica.jinr.ru, free access
[8] R. Rapp and J. Wambach, Adv. Nucl. Phys. 25, 1 (2000).
[9] G. E. Brown and M. Rho, Phys. Rev. Lett. 66, 2720 (1991).
[10] J. Randrup and J. Cleymans, Phys. Rev. C 74, 047901 (2006).
[11] J. Rafelski and B. Müller, Phys. Rev. Lett. 48, 1066 (1982).
[12] A. K. Luev and M. S. Weiss, Phys. Rev. C 8, 408 (1973).
[13] J. Steiner and M., Phys. Lett. B 714, 85 (2012).
[14] K. U. Abraamyan et al., Nucl. Instrum. Meth. A 628, 99 (2011).
[15] MPD Conceptual Design Report. http://nica.jinr.ru/files/CDR_MPD/MPD_CDR_en.pdf.
[16] F. Anghinolfi et al., Nucl. Instr. Meth. A 533, 183-187 (2004).
[17] J. Christiansen, HPTDC V 1.3, March 2004, http://tdc.web.cern.ch/tdc/hptdc/docs/hptdc_manual_ver2.2.pdf.
[18] see paper of A. Zinchenko et al. from this Proceedings.
[19] see paper of M. Ilieva et al. from this Proceedings.
[20] BMN Conceptual Design Report. http://nica.jinr.ru/files/BN/BN_CDR.pdf.