The Nuclotron-based Ion Collider Facility Project.  
The Physics Programme for the Multi-Purpose Detector

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Abstract. The Nuclotron-based Ion Collider fAcility (NICA) is a new accelerator complex being constructed at the Joint Institute for Nuclear Research (JINR). The general objective of the project is to provide beams for the experimental study of hot and dense strongly interacting QCD matter. The heavy ion programme includes two planned detectors: BM@N (Baryonic Matter at Nuclotron) a fixed target experiment with extracted Nuclotron beams; and MPD (MultiPurpose Detector) a collider mode experiment at NICA. The accelerated particles can range from protons and light nuclei to gold ions. Beam energies will span $\sqrt{s} = 12 - 27$ GeV with luminosity $L \geq 1 \times 10^{30}$ cm$^{-2}$s$^{-1}$ and $\sqrt{s_{NN}} = 4 - 11$ GeV and average luminosity $L = 1 \times 10^{27}$ cm$^{-2}$s$^{-1}$ (for $^{197}$Au$^{31+}$), respectively. A third experiment for spin physics is planned with the SPD (Spin Physics Detector) at the NICA collider in polarized beams mode. A brief overview of the MPD is presented along with several observables in the MPD physics programme.

1. Introduction  
The Nuclotron-based Ion Collider fAcility (NICA)(Fig.1) is a new accelerator complex being constructed at the Joint Institute for Nuclear Research (JINR), Dubna [1]. The main goal of this facility is to provide heavy-ion collisions in order to investigate the hot and dense barionic matter produced in heavy ion collisions at relatively low energies compared to previous experiments at RHIC and SPS (Fig.2), [2]. Thus formulated the experimental programme at NICA includes simultaneous measurements of observables that are sensitive to high-density effects and phase transitions.

The proposed research programme contains a wide range of collision configurations in both fixed target and collider modes.

2. Nuclotron-based Ion Collider facility NICA  
The NICA project in its entirety is going to incorporate several already existing facilities, as well as such still being developed. The injection complex comprises of four sources (for light and heavy ions) and two linacs. The light ion sources are: laser, duoplasmatron sources, source of polarized protons and deuterons, a modernized LU-20 accelerates for beam injection into the synchrotron Nuclotron. The electron string source KRION-6 provides heavy ions of Au$^{31+}$ and delivers them into HILac, which accelerates them to 3.24 MeV/u and injects them to the Booster. The main purpose of the booster is accumulation of $2 \times 10^{9}$ Au$^{31+}$ ions and acceleration of heavy
ion bunches to energy required for effective stripping. The Booster is equipped with an electron cooling system for the ion beam cooling in the energy range from injection energy up to 100 MeV/u. The maximum energy of Au\(^{79+}\) ions accelerated in the Booster is 600 MeV/u. After acceleration in the Booster ions will be fully stripped and injected into the Nuclotron providing acceleration of \(^{197}\)Au\(^{79+}\) ions up to the energy of 4.5 GeV/u. The required bunch intensity is about \(1 - 1.5 \times 10^9\) ions. Two collider rings are constructed one above the other. To provide the beam storage and bunch formation in the collider, three independent RF systems are used. Twenty-two bunches per ring will be stored. For luminosity preservation, an electron and/or a stochastic cooling system will be used [3]. Beam energies will span \(\sqrt{s} = 12 - 27\) GeV with luminosity \(L \geq 1 \cdot 10^{30}\) cm\(^{-2}\)s\(^{-1}\) and \(\sqrt{s_{\text{AuAu}}} = 4 - 11\) GeV and average luminosity \(L = 1 \cdot 10^{27}\) cm\(^{-2}\)s\(^{-1}\) (for \(^{197}\)Au\(^{79+}\)), respectively.

Two NICA experiments are dedicated to the exploration of the QCD phase diagram: Baryonic Matter at Nuclotron (BM@N)[4] - a fixed target experiment in the beam extracted from the Nuclotron, which will cover the lower energy region, and the Multi-Purpose Detector (MPD)[5] at one of the collider interaction points (IP).

These two experiments will be focused on measurements of particle yields and spectra, ratios, femtoscopy and collective flow; observation of in-medium modification of hadron properties like low-mass dilepton enhancement; study of deconfinement (chiral) phase transition at high baryon density through observation of onset of enhanced strangeness production; search for QCD Critical Point via studies of event-by-event fluctuations and correlations; investigation of the Chiral Magnetic (Vortical) effect through a measurement of Λ-polarization; investigation of hyperon-nucleon interactions in dense nuclear matter via studies of hypernucleus production and their properties.

At the second interaction point of the collider facility, a Spin Physics Detector is proposed to investigate problems related to the origin of spin and a number of scattering problems. The NICA accelerator will be capable of running in polarized beam modes for protons and deuterons. The high intensity and high polarization (> 50%) of the colliding beams present a unique possibility for spin physics research, which is of crucial importance for the solution of the nucleon spin problem (spin puzzle) - one of the main tasks of the modern hadron physics.

3. Multi-Purpose Detector MPD

The Multi Purpose Detector (MPD) (Fig.3) 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. 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. Two stages of realization are planned for the MPD. For the first stage a barrel setup is being constructed.

Figure 3. Schematic view of MPD sub-detector allocation.

The main subdetector systems will be operating inside of a large solenoid with a superconducting NbTi winding and a flux return iron yoke. The solenoid should provide a homogeneous magnetic field of up to 0.5 T. The field inhomogeneity in the tracker area of the detector is about 0.1%. Homogeneity of the radial component of the magnetic induction in the volume of Charged Particle Tracker (TPC) has to be $< 0.775$ mm.

Figure 4. Relative transverse momentum resolution for primary tracks with $|\eta| < 1.3$ reconstructed in TPC.

Figure 5. Transverse momentum resolution as a function of pseudo-rapidity for primary tracks with $p_T = 1$ GeV/c.

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 uniform electric field in the active volume is created by a thin central high voltage electrode, together with a voltage dividing network at the surface of the outer and inner cylinders, and at the readout end-caps. The TPC readout system is based on Multi-Wire Proportional Chambers (MWPC) with cathode readout pads. The main requirements toward the TPC is to provide a sufficient transverse momentum resolution (with a resolution $< 1$ cm) and energyloss measurements.
(\textit{dE}/\textit{dx} resolution better than 8\%) for hadronic and leptonic tracks at pseudo-rapidities |\eta| < 1.5 and \( p_T > 100 \text{ MeV}/c \). Precise primary and secondary track reconstruction and also precise primary (Interaction point) and secondary (decay) vertex reconstruction are of top TPC priority [6].

The Time of Flight System (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 system will provide time of flight measurements with geometrical efficiency above 95\% and a resolution in the range of 60-80 ps [7], which are complemented by the energy loss (\textit{dE}/\textit{dx}) information from the TPC, in order to provide an accurate particle identification (PID). Combined, the measurements from TPC and TOF, should provide an efficient \( \pi/K \) PID separation up to 1.5 GeV/c, \( \pi/p \) separation up to 3 GeV/c, and a very good electron/hadron separation [8].

The Electromagnetic Calorimeter is constructed by shashlyk-type modules of lead+scintillator, each consisting of nine towers of 4x4 cm\(^2\) cross-section. ECal has 15 \( X_0 \) radiation lengths with readout wave length shifting fibers. The light collected by these fibers will be read out by avalanche photodiodes (MAPD). The primary role of the electromagnetic calorimeter is to measure the spatial position and energy of electrons and photons. For an increased energy resolution of electromagnetic showers a projective geometry targeting the IP is used. The ECal will provide energy resolution of 5\% at 300 MeV, and time resolution better than 0.5 ns [9].

Two sets of Forward Hadron Calorimeter (FHCaI) are allocated at 3.2 m to the right and to the left from the IP, each of which consists of 45 modules providing the necessary transverse granularity. The acceptance of FHCaI covers the pseudo-rapidity region from 2.2 to 4.8. The main goal of the FHCaI is to provide energy measurements of spectator nucleons for centrality determination and event-plane reconstruction with a resolution of 20-30 degrees [10].

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 [11].

Within the NICA timetable, MPD will be commissioned by the end of 2020 and will start physical data taking by 2021. 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 interaction point are planned. Also, end-caps on both sides of the barrel are considered: ECT, ETOF, ECAL.
4. Physics Programme for MPD

4.1. Anisotropic Flow Studies

The observation of a azimuthally anisotropic flow is one of the key observables for establishing that a QGP state of matter has formed in the collision. The initial spatial eccentricity in heavy-ion collision geometry leads to a non-uniformity in parton interaction which results in anisotropic particle emissions. The collective flow of hot and dense baryonic matter provides information on the transport properties of the medium and the equation of state. The anisotropic flow measurements of both identified charged particles and reconstructed hyperon decays will be a key measurement in the MPD research programme.

The magnitude of the anisotropic flow is defined using Fourier coefficients of the azimuthal distribution of particles with respect to the collision reaction plane. The reconstructed and generated(true) values of differential flow coefficients are in good agreement. Due to limits in TPC event-plane resolution, FHCal is used to determine the reaction plane.

These results present a good agreement between generated and reconstructed proton differential directed and elliptic flow (Fig.8) [12].

Figure 8. Generated and reconstructed differential anisotropic flow: (a Directed v1 and (b Elliptic v2.

4.2. Hyperon Studies

Production of strange particles is of particular interest because enhanced production of rare strange hadrons($\Xi^-$, $\Omega^-$) in A+Ag collisions (relative to the yields from elementary pp reactions) was predicted as a signal for the QGP formation. The enhancement of the strangeness was experimentally observed at SPS and RHIC, and it is more pronounced for hyperons with larger strangeness content. At present, a complete theoretical description of the (multi)strangeness production mechanism at collision energies of several GeV, has not yet been achieved.

The performance of the MPD detector for reconstruction of hyperons (Fig.9) in central collisions has been evaluated at $\sqrt{s_{AuAu}} = 9$ GeV, using the UrQMD generator and the full MPD reconstruction chain. The combination of particle yield and good signal-to-background ratio will be of key importance in lambda-polarization and hyperon elliptic flow studies [13].

Figure 9. Reconstructed invariant mass of $\Lambda$, $\Xi^-$, $\Omega^-$ hyperons.
4.3. Hypernuclei Studies

The NICA project has a good opportunity to investigate hypernuclei in heavy ion collisions as there is a predicted considerable enhancement of nuclear clusters with strangeness in the planned energy ranges. The better understanding of the dynamics of hypernuclei production will provide necessary information on hyperon-nucleon and hyperon-hyperon interactions which is important for the theoretical basis for neutron star models.

The feasibility of hypernuclei reconstruction with the MPD experiment was assessed. Presented are results of simulated $5 \times 10^5$ and $6 \times 10^7$ central events by the DCM-QGSM generator at $\sqrt{s} = 5$A GeV for the studies of $^3\Lambda$H and $^4\Lambda$He, respectively. The full reconstruction chain of MPD was used. In the presented invariant mass distribution results with a high signal-to-background ratio and significance are observed (Fig.10). As evident, MPD offers good opportunities for studies of heavy strange probes at the NICA collider [14].

Figure 10. Reconstructed invariant mass of $^4\Lambda$He and $^3\Lambda$H hypernuclei.

4.4. Dilepton Studies

The reconstruction of low-mass vector mesons $\rho$, $\omega$, $\phi$ by measuring their dileptonic decay channels is one of the top priorities for the MPD research programme (Fig.11). Dileptons are good probes to indicate medium modifications of spectral functions due to chiral symmetry restoration in A+A collisions; the effect is proportional to baryon density.

Figure 11. Reconstructed invariant mass of $\phi$ and $\omega$ vector mesons.

Figure 12. Signal-to-background ratio of dileptons for HIC experiments.

Due to the large combinatorial background, a strict particle selection is required and topological cuts are applied. For the low-mass dielectron study a strict dielectron selection with TPC, TOF, and ECal measurements were used. The signals can be separated from the background within the mass region 0.2-1.5 GeV/c$^2$. In comparison to other heavy-ion experiments a good signal-to-background ratio is achieved (Fig.12) [15].
4.5. Other Key Observables

The NICA/MPD physics programme entails a vast volume of research possibilities, such as the charge dependence of azimuthal correlations between produced hadrons, baryon stopping power and femtoscopy correlations.

Charged particle azimuthal correlations are an important probe of the QGP matter created in relativistic heavy-ion collisions, as they may be sensitive to a possible effect of local parity violation in the QCD. The azimuthal correlations and their projections are well reconstructed for central and mid-central collisions with MPD stage 1 setup, while stage 2 will afford the ability to study peripheral collisions.

Baryon stopping power is a requisite in describing the conversion of the initial particle collision energy into matter excitation and creation of hot and dense nuclear matter. It was argued that the baryon stopping in nuclear collisions can be a sensitive probe for the onset of deconfinement. At NICA energies, models indicate a peak-deep-peak behavior at mid-rapidity. MPD simulations confirm that this will be observable.

Femtoscopy correlations will provide information on the space-time evolution of a QGP. Such studies provide a constrain on model predictions for the early stage of collision and fireball evolution. The NICA large luminosity along with MPD’s precision measurements and large acceptance, will provide a much more detailed space-time information on the emitting system than in previous studies. A more detail overview of the studies above is available [16].

5. Conclusion

A brief description of the NICA project is given, as well as a short overview of the multi-purpose detector and planned physics programme. Models predict that at the NICA energy range a high net-barion density is reached in the interacting QCD matter. For a further understanding of QCD it is important to study the equation of state, to search for phase transitions, chiral symmetry restoration in multiple collision systems and experiments. The experiments on the NICA collider will present competitive and complementary results to those of BNL, CERN and FAIR, and will be able to shed light on multiple theoretical problems for which accurate experimental measurements are not present.

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