Prospects for the study of the strangeness and hypernuclei production at NICA/MPD

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Abstract. The prospects for the study of the strangeness and hypernuclei production with the MultiPurpose Detector (MPD) at NICA are presented and the detector performance for such physics analyses, evaluated from the Monte Carlo simulation, are demonstrated.

1. Introduction
Relativistic heavy-ion collisions provide a unique opportunity to study nuclear matter under extreme density and temperature. The Nuclotron-based Ion Collider fAcility (NICA) is a new flagship project aimed in the construction at JINR (Dubna) a modern machine providing beams of heavy ions with the highest intensity ever achieved in the energy range from 4 to 11 GeV per nucleon [1]. The main scientific goal of the NICA project is the experimental exploration of a yet poorly known region of the QCD phase diagram of the highest net-baryon density with an emphasis on the nature of the deconfinement phase transition, study of hadron properties in dense baryon matter, and search for the critical end point (CEP).

The study of the strangeness production is of particular interest. Since strange hadrons are initially not present but created during the heavy-ion collision, the strangeness is one among the most sensitive probes for the deconfinement phase transition as well as for the in-medium effects in dense nuclear matter.

Relativistic heavy-ion collisions, where lots of strange particles (kaons and hyperons) are produced, offer a unique possibility to create exotic nuclear objects with strangeness - hypernuclei. The mechanism and dynamics of hypernuclei formation is not well understood - several approaches are suggested to explain their production rates: coalescence of lambdas with nucleons at midrapidity, thermal models, or absorption of some of the produced hyperons by the residual spectator nuclei. To distinguish between different models, new experimental data on the energy and centrality dependence of the hypernuclei production over a large phase-space are needed. The NICA energy range covers the region of the maximal net-baryon density where the production rates of nuclear clusters with strangeness are predicted to be enhanced considerably [2] allowing a detailed study of the hypernuclei production mechanism.

2. The Multi-Purpose Detector (MPD) at the NICA collider
In order to fulfill the project physics goals the MPD detector at NICA is designed as a close to 4π acceptance apparatus comprising precise trajectory measurements, advanced secondary vertex...
reconstruction, sophisticated event characterization, as well as excellent particle identification (PID) capability [3]. The experimental setup shown in figure ?? has a full azimuthal coverage and consists of several subsystems operated in a homogeneous magnetic field:

- tracking system based on the Time-Projection Chamber (TPC), straw tube endcap trackers (ECT) and silicon vertex system (IT);
- PID system with a Resistive Plate Chambers time-of-flight detector (TOF) and electromagnetic calorimeter for electron and gamma measurements (ECAL);
- forward hadronic calorimeter (FHCAL) for centrality determination and event plane reconstruction;
- arrays of fast quartz Cherenkov counters (FD) which will be used for timing and triggering of the experiment.

In the first stage of the project realization starting from 2021 the main focus will be on the extended midrapidity region ($|\eta| < 1.4$) with the TPC, barrel TOF, and ECAL detectors. Later on (after 2023), the phase-space region up to $|\eta| = 3$ will be covered with the tracking and PID systems.

3. Event generators

As an input for the present study we used the Parton-Hadron-String Dynamics (PHSD) and Quark-Gluon String Model (DCM-QGSM) event generators. The PSHD model is based on a microscopic off-shell dynamical transport approach incorporating the partonic degrees-of-freedom in terms of strongly interacting quasi-particles, their hadronization and further off-shell dynamics for the hadronic stage [4]. The deconfinement phase is realized to reproduce the lattice QCD Equation-of-State with a crossover phase transition at high temperature and small chemical potential. The PHSD has been successfully applied to describe many observables measured from low to very high energies [5].

The DCM-QGSM generator was used for hypernuclei studies. It is based on the Monte Carlo solution of a set of the Boltzmann-Uehling-Uhlenbeck relativistic kinetic equations with the collision terms, including cascade-cascade interactions. The model includes a proper description of pion and baryon dynamics for particle production and absorption processes. In addition, using the information about the phase space for the particles, produced in a heavy ion collision, the model realizes cluster formation based on a coalescence prescription. The model is capable to reproduce experimental data for clusters over a wide range of beam energies [6].
4. Event simulation and reconstruction

Particles produced by the event generators were transported through the detector using the GEANT3 transport package. Track and vertex reconstruction methods [7] were based on the Kalman filtering technique.

(Multi)strange hyperons were reconstructed by combining charged tracks found in the TPC, first to select a V0-candidate (a characteristic topology of two oppositely charged daughter tracks) and then to match it with one of the secondary pion candidate.

In figure 4 is drawn a pictorial representation of the decay topology for Λ hyperons in the bending plane of the magnetic field. In order to reject wrong track combinations several selection criteria were applied. To ensure that the charged tracks are secondary ones, special cuts were applied on the minimum value of the impact parameters to the primary vertex (dca_p, p). Next, the track combination was rejected if the distance of the closest approach (dca_V0) in space between the two oppositely charged tracks was larger than a given value. To further suppress mostly primary track combinations, it was also required from the secondary vertex position to be at a certain distance from the primary one (path). Finally, the invariant mass was calculated under the proper particle hypothesis, i.e. a proton and a pion for the case of V0 or Ξ^− hyperon.

The exact values of selection cuts were found by performing a multidimensional scan over the whole set of selection criteria with a requirement to maximize the invariant mass peak significance, defined as \( \frac{S}{\sqrt{S + B}} \), where S and B are total numbers of signal (described by the Gaussian) and background (polynomial function) combinations inside ±2σ interval around the peak position.

5. Results and discussion

A PHSD data set of \( 2 \cdot 10^6 \) Au+Au minimum bias events at \( \sqrt{s_{NN}} = 11 \) GeV was partitioned into four centrality bins. In Table 1 the specification for each bin is tabulated in terms of the impact parameter interval, percentage of the total cross-section, and charged track multiplicity.
Figure 3. Invariant mass spectra of charged pions and protons in $p_T$ bins.

In each centrality bin the analysis was performed in several transverse momentum intervals of 0.5 GeV/$c$ width. In figure 3 are shown invariant mass spectra of charged pion and proton candidates in several $p_T$ bins. Each distribution was fitted with a sum of a Gaussian and a polynomial, the resulting fitted functions are plotted in figures with solid lines. The raw yield was then obtained by subtracting the background from the integral over the peak region. The latter was calculated by counting the bin content in the $\pm 3\sigma$ interval around the peak position, while the former was determined by integrating the background fit function in the peak region. In figure 4 are shown invariant mass spectra of $\Lambda$, $\bar{\Lambda}$, and $\Xi^-$ candidates in the most central (top row) and the most peripheral (bottom row) bins.

The raw yields of (anti)hyperons were then corrected for the detector acceptance and the reconstruction efficiency; the latter includes the losses in the detector material, those due to the applied cuts and PID selection criteria, as well as the branching ratio of the corresponding decay channel. The corrections were determined in each centrality and $p_T$ bin from the Monte Carlo data itself. In figure 5 the correction factors for all hyperon species are plotted as a function of transverse momentum for the most central (solid symbols) and the most peripheral (open symbols) centrality bins.

In figure 6 is plotted the MPD detector phase-space for $\Lambda$, $\bar{\Lambda}$, and $\Xi^-$ in terms of rapidity and transverse momentum. As one can see, the proposed detector setup has a sufficient coverage to study both the longitudinal and transverse distributions of (anti)hyperons. As an example, in figure 7 are shown the invariant transverse momentum spectra for $\Lambda$ in the most central and the most peripheral centrality bin. The distributions were obtained after correcting the raw particle yields in $p_T$ bins by acceptance and efficiency factors determined as described above. The reconstructed yields are plotted with symbols and initial spectra from the model are drawn as histograms. As one can see, the difference between the initial spectra (from the model) and the reconstructed ones is small, the averaged point-by-point difference does not exceed 2%.

The rapidity density $dN/dy$ was obtained by summing up the measured data points and adding the integral over the unmeasured interval. The latter was estimated from the fit function to the $p_T$-spectra. We used a thermal function fit in the form

$$\frac{1}{p_T} \frac{d^2N}{dp_Tdy} = Const \cdot \exp \left( -\frac{\sqrt{p_T^2 + m^2} - m}{T} \right),$$

where the slope parameter $T$ is the so-called “effective temperature” and $m$ is the hyperon rest mass.

The fit results are shown in figure 7 as solid lines. The extrapolation to low and high $p_T$ contributes between 10% and 25% to the rapidity density value depending on the particle sort and centrality.
Figure 4. Invariant mass spectra of $\Lambda$, $\bar{\Lambda}$, and $\Xi^-$ candidates in the most central (top row) and the most peripheral (bottom row) bin.

Figure 5. The correction factor (acceptance, efficiency, and branching) for $\Lambda$, $\bar{\Lambda}$, $\Xi^-$ as a function of transverse momentum for the 0-5% most central (solid symbols) and 30-80% central (open symbols) collisions.

The results on hypernuclei reconstruction using an event sample of $9 \cdot 10^5$ central (0 - 3.8 fm) Au+Au events at $\sqrt{s_{NN}}=5$ GeV from the DCM-QGSM event generator are presented in figure 8 and tabulated in Table 2. Here it was necessary to suppress a larger combinatorial background as compared to the cases of hyperons, and the requirement to have a sufficient significance of the signal resulted in stronger cuts and much lower efficiencies. Based on these results rough estimates of the expected signal statistics for hypertrions was done for several collision energies (see the second column of Table 2).
Figure 6. MPD detector $y-p_T$ phase-space for $\Lambda$ (left panel), $\bar{\Lambda}$ (center panel), and $\Xi^-$ (right panel).

Figure 7. The transverse momentum spectra of $\Lambda$ within the rapidity range ($|y| < 0.5$) for 0-5% and 30-80% central Au+Au collisions at $\sqrt{s_{NN}}=11$ GeV. The reconstructed data are indicated by symbols, while histograms represent the spectra from the model. The solid lines are the thermal fits used for the extrapolation (see text for details).

Figure 8. Reconstructed invariant mass of $^3$He and $\pi^-$ (left panel) and proton, deuteron and $\pi^-$ (right panel).
Table 2. $^3\Lambda$H yields for 10 weeks of NICA running time.

| $\sqrt{s_{NN}}$ (GeV) | Yield     |
|-----------------------|-----------|
| 5                     | $8.1 \times 10^5$ |
| 8                     | $4.5 \times 10^3$  |
| 11                    | $1.6 \times 10^3$  |

6. Outlook
As a continuation of this work it is foreseen to do the analysis for more rear hyperons ($\Xi^+$, $\Omega^-$, $\Omega^+$) and hypernuclei ($^3\Lambda$H, $^4\Lambda$He, $^4\Lambda\Lambda$H).

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