Overview of Hypernuclei Reconstruction at NICA/MPD

M Ilieva\textsuperscript{1,2}, A Zinchenko\textsuperscript{1} and V Kolesnikov\textsuperscript{1}

\textsuperscript{1}VBLHEP, Joint Institute for Nuclear Research, Joliot-Curie str 6, 141980 Dubna, Moscow region, Russia
\textsuperscript{2}PFT, Plovdiv University "Paisii Hilendarski", Tzar Assen str. 24, 4000 Plovdiv, Bulgaria
E-mail: maiailieva@mail.bg

Abstract. The study of the formation of a dense and hot baryonic matter is the main goal of exploration for the NICA/MPD project. Strangeness production in nuclear collisions is a key part of the MPD project physics program and is an important tool for studying the QCD phase diagram. An overview of the relevant characteristics for hypernuclei reconstruction in the NICA energy range with the simulated MPD detector are presented. Focus is put on invariant mass distributions, reconstruction efficiency and expected yields.

1. Overview of the Nuclotron-based Ion Collider Facility (NICA)

In order to study the QCD phase diagram and the formation of dense and hot baryonic matter, a new facility is being constructed at the Joint Institute for Nuclear Research (JINR), Dubna, Russia - The Nuclotron-based Ion Collider facility\cite{1}. The main focus of the NICA project is to provide heavy-ion collisions to study hot and dense baryonic matter, as well as, to provide multiple beam configurations for a wide array of research program. It is expected that through a phase transition in the matter formed during heavy ion collisions, a restoration of chiral symmetry due to melting of the quark condensate, as well as, various confinement phenomena may be observed \cite{2, 3}. The NICA collider energy range ($4 < \sqrt{s} < 11$\text{A GeV}) will allow one to investigate fundamental QCD properties that are related to chiral symmetry and confinement phenomena \cite{4}.

2. The Multi-purpose Detector (MPD)

The multi-purpose detector is designed to have maximum acceptance at $4\pi$ with low material budget and capable of detecting charge hadrons, electrons and protons in heavy-ion collisions with good tracking and particle identification capabilities. The detailed description of the MPD geometry can be found in Ref. \cite{4} The NICA/MPD research program intends to perform a detailed energy scan with ion beams(protons,gold nuclei, etc.) in order to investigate: strangeness production, in-medium properties of vector mesons, correlations and event-by-event fluctuations. The present analysis is based on the MPD Stage I configuration (Fig. 1).

3. Event generator and data set

The data presented in this study has been generated with the DCM-QGSM model. Hypernuclei formation and yields at NICA energy range are well described by this model, with mechanisms for
Figure 1. MPD stage I includes the main tracker Time Projection Chamber (TPC) in addition to the Time-Of-Flight system (TOF) will provide precise momentum measurements and particle identification. The Forward Detector (FD) will play a role of a start trigger, Electromagnetic Calorimeter (ECAL) for measurements of electromagnetic showers, Forward Hadron Calorimeter (FHCal) will serve for determination of the collision centrality and the orientation of the reaction plane for collective flow studies. The detectors cover the mid-rapidity region $|\eta| < 1.3$.

Table 1. Hypernuclei decay modes and branching ratios under study

| Particle | Decay channel | Branching ratio % |
|----------|---------------|------------------|
| $^{3}_{\Lambda}H$ | $\pi^- + ^{3}_{\Lambda}He$ | 24.7 |
| $^{3}_{\Lambda}H$ | $\pi^- + p + d$ | 36.7 |
| $^{4}_{\Lambda}He$ | $\pi^- + ^{3}_{\Lambda}He + p$ | 32.0 |
| $^{4}_{\Lambda}H$ | $\pi^- + ^{4}_{\Lambda}He$ | 75.0 |

coalescence and cluster formation. DCM-QGSM has been used in the past with good agreement to experimental data for a wide set of beam energies[5, 6, 7]. For this study, the generator was used to produce a sample of central Au-Au collisions (0-3.8 fm) at $\sqrt{s} = 5A$ GeV. The number of events was $5 \times 10^5$ for $^{3}_{\Lambda}H$ and $6.1 \times 10^7$ for $^{4}_{\Lambda}H$ and $^{4}_{\Lambda}He$ corresponding to 30 min and 61 hour of NICA running time respectively. The GEANT3 transport package was used in order to transport particles produced by the event generator, through the simulated MPD detector. The decay modes and branching ratios of hypernuclei, have been introduced into GEANT from Ref. [8] (Tab. 1) and the hypernuclei lifetime has been taken to be the same as that of the $\Lambda$-hyperon.

4. Track Reconstruction and Particle identification

The track reconstruction used in MPD is based on the Kalman filter technique and a minimal requirement of 15 TPC hits ensures a low momentum error. On Fig. 2 one may see the track reconstruction efficiency for both primary and secondary TPC tracks as a function of transverse momentum. The secondary track sample includes only particles produced within 50 cm of the primary vertex both in transverse and longitudinal directions and did not include photon conversions ($e^- + e^+$). Fig. 3 shows the transverse momentum resolution as a function of $p_T$, where TPC coordinate resolutions of 0.5 mm in transverse and 1.0 mm in longitudinal directions were assumed.

Particle identification in the MPD experiment is obtained by using both the ionization loss ($dE/dx$) from TPC and time-of-flight measurements from TOF [9]. The so-called $\sigma$ method is used. Identified candidates (hadron and light nuclei) should be selected within predefined elliptical ranges around a nominal position fixed for each particle species. Furthermore, a probability of a particular particle can be calculated based on the widths of the distributions (along the $dE/dx$ and $M^2$ axes) and used as an additional criteria of identification selection.
Figure 2. Track reconstruction efficiency as a function of track $p_T$ for primary and secondary particles.

Figure 3. Relative transverse momentum resolution for primary tracks with $|\eta| < 1.3$ reconstructed in TPC.

5. Analysis procedure

Hypernuclei with two and three charged track decay modes were reconstructed. Fig. 4 shows the particle decay topology along with the cut selection criteria: distance of the closest approach to the primary vertex of decay products, distance between tracks in the decay vertex, flight distance of the reconstructed mother particle. Both the DCA and two-track separation cuts are more efficient when values are normalized to their respective errors ($\chi^2$-space). Multiple selections were performed in loops for all selection criteria over all candidates with the requirement of maximizing both significance (defined as $S/\sqrt{S+B}$) and signal-to-background ratio ($S/B$) within the invariant mass peak. Here $S$ and $B$ are the yields in a range of $2\sigma$ interval around the gaussian peak’s mean value. The background was modeled with a second order polynomial function.

Figure 4. Charged particle event topology of two-prong decays. Here $dca_1$ and $dca_2$ are the distances of the closest approach to the primary vertex $PV$ of the decay tracks, $dca_{12}$ is the distance between daughter tracks in the decay vertex $V_M$, $dca_M$ is the distance of the closest approach of the mother particle to the primary vertex, $path$ is the decay length, $p_1$ and $p_2$ are the momenta of daughter particles.

6. Results and discussions

The hypernuclei reconstruction efficiency for the studied decay channels are presented in Figs. 5 - 8. Figures 5 and 6 demonstrate the obtained invariant mass distributions for $\Lambda H \rightarrow ^4\!\!He + \pi^-$ and $\Lambda He \rightarrow p + \pi^- + ^3\!\!He$ decay modes. $6.1 \cdot 10^7$ central events were used, corresponding to about 61 hours of NICA running time. Figures 7 and 8 show invariant mass distributions for $\Lambda H$ 2-prong and 3-prong decay modes. The sample used here $5 \cdot 10^5$ central events, corresponding to about 30 min of NICA running time. In Table 3 the influence of detector acceptance (for both pseudo-rapidity and low momentum cuts) on hypernuclei efficiency (with respect to the total number of hypernuclei in model) is shown. The effect of the transverse momentum cut on the efficiency can be seen in lines from 2 to 5. Line 6 shows the reconstruction efficiency,
i.e. considering the reconstructed in the detector decay particles without any explicit $p_T$-cut (and without PID efficiency). Finally, the last line includes all relevant to efficiency factors, i.e. reconstruction and PID efficiencies as well as selection efficiency and acceptance. One can see that the detector provides rather efficient reconstruction of hypernuclei with $p_T$ of decay tracks above 0.1 GeV/$c$ in good agreement with Fig. 2. It is also clear that a higher $p_T$-threshold (e.g. 0.2 GeV/$c$) significantly reduces the detector efficiency. Therefore a delicate balance between cuts is required in order to both suppress the combinatorial background for a clean invariant mass peak and to maintain a good level of efficiency. Tab. 2 shows estimated expected yield for particle under study, based on model predictions and the results presented in this paper, for 10 weeks of data taking.

Figure 5. Invariant mass distribution of $^4\Lambda$He 3-prong decay mode.

Figure 6. Invariant mass distribution of $^4\Lambda$H 2-prong decay mode.

Figure 7. Invariant mass distribution of $^3\Lambda$H 3-prong decay mode.

Figure 8. Invariant mass distribution of $^3\Lambda$H 2-prong decay mode.

7. Conclusion
NICA energy range will cover the region of the maximal baryon density, where the production rates of nuclear clusters with strangeness are predicted to be enhanced considerably: as many as $3 \cdot 10^2$ of $^3\Lambda$H and $1 \cdot 10^{-5}$ of $^5\Lambda$He per unit of rapidity are expected in a central Au+Au collision at $\sqrt{s} = 5A$ GeV \cite{10}. With an event rate of 6 kHz, luminosity of $10^{27}$ cm$^{-2}$ c$^{-1}$ and a total
Table 2. Expected particle yield for 10 weeks of NICA running time.

| Particle | Expected yield |
|----------|----------------|
| \(^3\)H | \(8.1 \cdot 10^5\) |
| \(^4\)He | \(1.4 \cdot 10^5\) |
| \(^7\)H | \(1.9 \cdot 10^5\) |

Table 3. Efficiency vs detector acceptance cut

| Factor | Efficiency, % | \(^3\)H 2-prong | \(^3\)H 3-prong | \(^4\)H | \(^4\)He |
|--------|---------------|-----------------|----------------|--------|--------|
| Branching ratio | 24.6 | 36.4 | 75.0 | 32.0 |
| \(|\eta| < 1.3\) | 14.9 | 19.8 | 48.9 | 28.1 |
| \(|\eta| < 1.3 \text{ and } p_T > 0.05 \text{ GeV/}c\) | 14.2 | 15.7 | 48.3 | 25.3 |
| \(|\eta| < 1.3 \text{ and } p_T > 0.1 \text{ GeV/}c\) | 8.9 | 6.2 | 35.0 | 16.4 |
| \(|\eta| < 1.3 \text{ and } p_T > 0.2 \text{ GeV/}c\) | 0.7 | 0.1 | 4.0 | 0.18 |
| Reconstructed \(|\eta| < 1.3\) | 7.9 | 8.3 | 27.7 | 9.4 |
| Maximum significance | 0.8 | 1.2 | 2.3 | 0.3 |

charged particle multiplicity above 1000, in-depth study of the production mechanism of single hypernuclei as well as an observation of double hypernuclei at NICA look feasible.

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