Prospects for the study hyperons and hypernuclei at the NICA collider

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For the MPD Collaboration

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Outline

- NICA complex at JINR
- NICA/MPD physics cases: hyperons and (hyper)nuclei
- MPD performance studies results
- Summary
Energy: $\sqrt{s_{NN}}=4\text{--}11$ GeV (Au, collider), up to 26 GeV (p+p), E/A=2\text{--}6$ GeV (fixed target)

Beams: from p to Au, $L \sim 10^{27}$ cm$^{-2}$ c$^{-1}$ (Au), $\sim 10^{32}$ cm$^{-2}$ c$^{-1}$ (p)

Commissioning with beams - 2021
NICA niche for A+A collisions

**QCD matter under extreme conditions (NICA niche – high $\mu_B$)**

<table>
<thead>
<tr>
<th>$\mu_B$ (MeV)</th>
<th>560-230</th>
<th>850-670</th>
<th>790</th>
<th>720-210</th>
<th>750-330</th>
<th>780-400</th>
<th>850-490</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\sqrt{s_{NN}}$ (GeV)</td>
<td>4.9-17.3</td>
<td>2-3.5</td>
<td>2.4</td>
<td>3-19.6</td>
<td>2.7-11</td>
<td>2.7-8.2</td>
<td>2-6.2</td>
</tr>
<tr>
<td>Facility</td>
<td>SPS</td>
<td>NICA</td>
<td>SIS-18</td>
<td>RHIC</td>
<td>NICA</td>
<td>SIS-100</td>
<td>J-PARC HI</td>
</tr>
<tr>
<td>Experiment</td>
<td>NA61</td>
<td>BM@N</td>
<td>HADES</td>
<td>HADES</td>
<td>STAR</td>
<td>MPD</td>
<td>CBM</td>
</tr>
<tr>
<td>Start Year</td>
<td>2009</td>
<td>2017</td>
<td>2018</td>
<td>2019</td>
<td>2020</td>
<td>2025</td>
<td>2025 (earliest)</td>
</tr>
</tbody>
</table>

- **NICA ($\mu_B = [320-850]$ MeV):** highest net baryon density – essential to probe deconfinement and CSR
- Maximum of the strangeness/entropy ratio and density favor hypernuclei production
- High luminosity guarantees sufficient event rate
Experimental strategy: energy and system size scan to measure a variety of signals systematically changing collision parameters (energy, centrality, system size). Reference data (i.e. p+p) will be taken in the same experimental conditions.

Bulk properties, EOS
particle yields & spectra, ratios, femtoscopy, flow
measure: $\gamma$, $\pi$, $K$, $p$, $\Lambda$, $\Omega$, (anti)particles, light nuclei

In-Medium modification of hadron properties
onset of low-mass dilepton enhancement
measure: $\rho$, $\omega$, $\phi \rightarrow e^+e^-$

Deconfinement (chiral) phase transition at high $\rho_B$
enhanced strangeness production
Chiral Magnetic (Votical) effect, $\Lambda$ polarization

QCD Critical Point
event-by-event fluctuations and correlations

Strangeness in nuclear matter
hypernuclei, exotica
MPD physics cases: hyperon production at NICA

EOS and phase transition from hadronic matter to QGP

- Excitation function of hadrons, including strangeness
- Systematic study of particle yields, spectra, and ratios
- Excitation function of strangeness → chemical equilibration at the phase boundary

<table>
<thead>
<tr>
<th>Particle</th>
<th>Multiplicity</th>
<th>Decay mode</th>
<th>BR</th>
<th>*Effic. %</th>
<th>Yield / 1 week</th>
</tr>
</thead>
<tbody>
<tr>
<td>π⁺</td>
<td>293</td>
<td>----</td>
<td>---</td>
<td>61</td>
<td>7.7 · 10⁸</td>
</tr>
<tr>
<td>K⁺</td>
<td>59</td>
<td>----</td>
<td>---</td>
<td>50</td>
<td>1.5 · 10⁸</td>
</tr>
<tr>
<td>p</td>
<td>140</td>
<td>----</td>
<td>---</td>
<td>60</td>
<td>4.2 · 10⁸</td>
</tr>
<tr>
<td>Λ</td>
<td>~35</td>
<td>p+π⁻</td>
<td>64%</td>
<td>10%</td>
<td>2 · 10⁷</td>
</tr>
<tr>
<td>Ξ⁻</td>
<td>~2</td>
<td>Λ+π⁻</td>
<td>~100%</td>
<td>2.5%</td>
<td>1.5 · 10⁵</td>
</tr>
<tr>
<td>ρ</td>
<td>31</td>
<td>e+e⁻</td>
<td>4.7 · 10⁻⁵</td>
<td>35</td>
<td>2.5 · 10³</td>
</tr>
<tr>
<td>ω</td>
<td>20</td>
<td>e+e⁻</td>
<td>7.1 · 10⁻⁵</td>
<td>35</td>
<td>2.5 · 10³</td>
</tr>
<tr>
<td>φ</td>
<td>2.6</td>
<td>e+e⁻</td>
<td>3 · 10⁻⁴</td>
<td>5</td>
<td>2.0 · 10²</td>
</tr>
<tr>
<td>Ω</td>
<td>0.14</td>
<td>Λ+K</td>
<td>0.68</td>
<td>1</td>
<td>7.0 · 10³</td>
</tr>
</tbody>
</table>

*Efficiency includes the MPD acceptance, realistic tracking and particle ID.

Particle Yields from experimental data (NA49), statistical and HSD models.

Luck of systematic study of multi-strange hyperons at NICA energies!
MPD physics cases: hypernuclei in A+A collisions @ NICA

- Precise information on Y-N interaction: nuclear EOS, astrophysics
- Hypernuclei ground, excited states and life times: critical assessments or QCD calculations and model predictions
- Production mechanism of bound states with hyperons: coalescence versus spectators-participants interactions
- Hypertriton lifetime puzzle?

Hypernuclei production enhanced at high baryon densities (NICA)

Hypernuclei yields at NICA:
min. bias Au+Au collisions at 4 GeV reaction rate 7 kHz, efficiency ~ 1%

<table>
<thead>
<tr>
<th>Hypernucleus</th>
<th>Yield/week</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Lambda^3$H</td>
<td>$1 \cdot 10^5$</td>
</tr>
<tr>
<td>$\Lambda^5$H</td>
<td>20</td>
</tr>
</tbody>
</table>

To study hypernuclei, MPD detector must be able to detect and identify light nuclei in a wide rapidity range as well to have a good capability for precise secondary vertex reconstruction
MultiPurpose Detector for A+A collisions @ NICA

- 3D tracking (TPC,ECT), uniform acceptance, $2\pi$ in azimuth
- High resolution vertexing (IT)
- Powerful PID (TPC, TOF, ECAL)
  - $\pi/K$ up to 2 GeV/c, $K/p$ up to 3 GeV/c
  - $\gamma$, $e$ : $0.1<p<3$ GeV/c
- Precise event characterization (FHCAL)
- Fast timing and triggering (FFD)
- Low material budget
- High event rate (up to ~ 7 kHz)

Stage’1 setup

I stage (barrel)  – 2020
II stage (IT + endcaps)  – 2023
MPD tracking & PID performance

Based on realistic event simulation within the MPDRoot framework

- High tracking efficiency over the reaction phase-space
- Good vertexing
- Combined \((dE/dx+TOF)\) PID for hadrons provides \(\pi/K\) up to 2 GeV/c and \(K/p\) up 3 GeV/c

\[ \Delta p / p \text{ vs } \eta \]

\[ m^2 (\text{GeV/c})^2 \]

\[ p / Z \text{ (GeV/c)} \]

\[ \text{Primary vertex resolution, mm} \]

\[ TPC, TOF \]

\[ \sigma_X, \sigma_Z \]

\[ p_T \text{, GeV/c} \]

\[ \text{Efficiency} \]

Au+Au collision in MPD
MPD performance for (anti)hyperon reconstruction

Data set: 8M minbias Au+Au @ 11 GeV (PHSD model)

MPD setup: TPC & TOF, ideal centrality binning (no FHCAL)

Selection criteria: $|\eta| < 1.3$, $N_{\text{hits}} \geq 10 + \text{standard quality/analysis cuts}$

Realistic track reconstruction: clustering in TPC

Realistic PID: combined $dE/dx + \text{TOF}$

Analysis: secondary vertex finding technique

PV – primary vertex
V0 – hyperon decay vertex
\(dca\) – distance of closest approach
path – decay length

MPD provides a large phase-space coverage and high selectivity for hyperons
Reconstructed Lambda in pT-bins, invariant spectra

- Reconstructed spectrum is in a reasonable agreement with Monte Carlo
Reconstructed spectrum is in a reasonable agreement with Monte Carlo
Results for (anti)Ω⁻

Hyperon yields for 1 week of running (Stage’1, Au+Au at 11 GeV)

<table>
<thead>
<tr>
<th>Particle</th>
<th>Λ</th>
<th>anti-Λ</th>
<th>Ξ⁻</th>
<th>anti-Ξ⁺</th>
<th>Ω⁻</th>
<th>anti-Ω⁺</th>
</tr>
</thead>
<tbody>
<tr>
<td>Yield*</td>
<td>2 · 10⁷</td>
<td>3.5 · 10⁵</td>
<td>1.5 · 10⁵</td>
<td>8.0 · 10³</td>
<td>7 · 10³</td>
<td>1.5 · 10³</td>
</tr>
</tbody>
</table>

Encouraging results for multi-strangeness!
Hypertriton reconstruction at MPD/NICA

- **Generator:** 900k central Au+Au @ 5 GeV (DCM-QGSM\(^1\))
- **Detectors:** start version of MPD with up-to-date TPC & TOF
- **Track acceptance criterion:** \(|\eta| < 1.3, \ N_{\text{hits}} \geq 10\)
- Realistic track reconstruction (with clustering in TPC)
- Realistic particle identification in TPC & TOF


A signal of 400 \(^3\Lambda\text{H}\) is seen (~2 days of data taking)
Expected yield of $^{4}_{\Lambda}He$
10 weeks Stage’2 @ 5A GeV: $\sim5\times10^3$

Expected yield of $^{4}_{\Lambda}H$
10 weeks Stage’2 @ 5A GeV: $\sim4\times10^3$
Summary

- NICA complex has a potential for competitive research in the fields of dense baryonic matter

- The MPD detector at NICA is well suited for study production of multi-strange baryons and hypernuclei in high multiplicity environments of heavy-ion collisions.

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Thank you for your attention!