New experimental observables to probe (anti)nucleosynthesis at the LHC with ALICE

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(for the ALICE collaboration)
Deuteron synthesis: Thermal vs. Coalescence

- Nuclei synthesis models

- Both models describe deuteron production
  - New observables to distinguish nuclei synthesis
Thermal model and baryon chemical potential ($\mu_B$)

- Nuclei synthesis models

- Both models describe deuteron production
  - New observables to distinguish nuclei synthesis

$\mu_B \rightarrow$ measure of antimatter-matter imbalance

$\mu_B = 0.7 \pm 3.8 \text{ MeV (0-5\% Pb-Pb, } \sqrt{s_{NN}} = 2.76 \text{ TeV)}$

New measurements of antiparticle-to-particle ratios with reduced systematic uncertainties

ALICE, JHEP 01 (2022) 106
**Fluctuation as a probe of deuteron synthesis**

**Event by event deuteron distribution:**
- Grand Canonical Ensemble (GCE) of Thermal model: Poisson
- Coalescence model: deviation from Poisson

- Average deuteron multiplicity: \( \lambda_d = B n_i n_j \)

- Multiplicity distribution for a given number of initial nucleons:
  \[
  P_d(n_d|n_i, n_j) = \frac{\lambda_d^{n_d} e^{-\lambda_d}}{n_d!} = \frac{(B n_i n_j)^{n_d} e^{-B n_i n_j}}{n_d!}
  \]

- Final deuteron multiplicity distribution:
  \[
  P_d(n_d) = \sum_{n_i, n_j \geq n_d} P_d(n_d|n_i, n_j) P_i(n_i) P_j(n_j)
  \]

**Model A:** nucleons are correlated  
**Model B:** nucleons fluctuate independently

**Model parameters:**
- Coalescence parameter B
- Average initial proton or neutron number 
  \( <n_i> = <n_p> + <n_d> \)

Observable:

\[ \kappa_1 = \langle n \rangle, \]

\[ \kappa_m = \langle (n - \langle n \rangle)^m \rangle, \quad m = 2, 3 \]

\[ \rho_{ab} = \frac{\langle (n_a - \langle n_a \rangle)(n_b - \langle n_b \rangle) \rangle}{\sqrt{\kappa_{2a} \kappa_{2b}}}, \]
Observable and analysis details

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Collision: \( \text{Pb-Pb}, \sqrt{s_{NN}} = 5.02 \text{ TeV} \)

Particle identification:

TPC: \( 0.8 < p_T < 1.0 \text{ GeV/c} \) (antideuteron)

\( 0.4 < p_T < 0.6 \text{ GeV/c} \) (antiproton)

TPC+TOF: \( 1.0 < p_T < 1.8 \text{ GeV/c} \) (antideuteron)

\( 0.6 < p_T < 0.9 \text{ GeV/c} \) (antiproton)

antideuteron purity > 90%, antiproton purity > 95%

TPC
Particle identification via specific energy loss

TOF
Particle identification via time-of-flight
Observable and analysis details

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Initial volume fluctuation:
Centrality Bin Width correction

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Binomial efficiency corrected cumulant:
\[ \kappa_1 = \langle q_1 \rangle \]
\[ \kappa_2 = \langle q_1^2 \rangle - \langle q_1 \rangle^2 + \langle q_1 \rangle - \langle q_2 \rangle \]
\[ \kappa_{11} = \langle q_1^d q_1^p \rangle - \langle q_1^d \rangle \langle q_1^p \rangle \]
\[ \rho = \kappa_{11} / \sqrt{\kappa_2^d \kappa_2^p} \]

\[ q_n = \sum_{i=1}^{M} \left( \frac{n_i}{\varepsilon_i^n} \right) \]
\[ M = \text{number of } p_T \text{ bins} \]
\[ \varepsilon = \text{efficiency} \]
\[ n_i = \text{raw counts in } i^{\text{th}} p_T \text{ bin} \]

Model expectation: coalescence vs. baryon conservation

Coalescence model
- By definition negative correlation between antiproton and antideuteron
- Sensitive to initial correlation between antiproton and antineutron

Canonical ensemble (CE) of Thermal model
- Negative correlation can also appear from baryon number conservation in CE SHM
- Correlation observables are more sensitive to conservation compared to cumulant ratios
First antideuteron fluctuation measurement

- Consistent with Poisson baseline and SHM
- Overpredicted by Coalescence model

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Correlation between antideuteron and antiproton

- Evidence of negative correlation
- Rules out Coalescence model with correlated production of nucleons
- Qualitatively explained by Coalescence model with independent fluctuation of nucleons
- Explained by CE SHM – smaller correlation volume compared to those describing $\kappa_2/\kappa_1$ of net-proton

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Data: strong acceptance dependence of correlation strength

SHM: describes data, strength depends on fraction of baryons in acceptance out of total produced baryons

Coalescence: ~flat with acceptance, strength depends on the nucleon phase space density or d/p ratio
Antiparticle over particle ratios and $\mu_B$

- Statistical Hadronization Model:
  $$\frac{\bar{h}}{h} \propto \exp \left[ -2 \cdot \frac{B_h \mu_B + S_h \mu_S + I_{3,h} \mu_{I_3}}{T} \right]$$

- Strangeness neutrality: $\mu_B \sim 3 \mu_S$

- Simplified expression:
  $$\frac{\bar{h}}{h} \propto \exp \left[ -2 \left( B + \frac{S}{3} \right) \frac{\mu_B}{T} - 2I_3 \frac{\mu_{I_3}}{T} \right]$$


- Ratios of hadrons with high $B+S/3$ → sensitive to $\mu_B/T$ → light (anti)baryons, (anti)nuclei, and (anti)hypernuclei
  - proton, $\Lambda$, $\Xi$, $\Omega$, $^3\text{He}$, $^3\Lambda\text{H}$

- Constraint on isospin chemical potential → $\pi^-/\pi^+$ ratio ($B = S = 0$)

- Ratios → reduce systematic uncertainties → precise $\mu_B$ measurement
Centrality-dependence of $\mu_B$ at Pb-Pb 5.02 TeV

- $T = 156.5 \pm 1.5$ MeV, fixed from SHM studies
- $\mu_B$ and $\mu_I$ as free fit parameters

- Most precise measurement in Pb-Pb at LHC
  - 6x improvement in precision with respect to Run 1 estimate
- Small but non-zero $\mu_B$ at LHC

See poster presentation by Mario Ciacco for more details
Summary and outlook

- EbyE fluctuation can be used as a probe of deuteron synthesis
  - ✔ SHM simultaneously describes fluctuation measurements but with a smaller correlation volume
  - ✔ Simple coalescence model does not simultaneously describe fluctuation measurements

- Most precise measurement of baryon chemical potential at LHC energy
  - ✔ Small but non-zero antibaryon-baryon imbalance at LHC

Outlook

- Experimental side: precise measurements with upcoming high statistics Run 3 and Run 4 data
- SHM: partial chemical equilibrium, interaction of hadrons could resolve the conundrum between p and d
- Coalescence: sensitive to the initial correlation between nucleons, and fluctuation measurements can be used to tune the model
Comparison with STAR

<table>
<thead>
<tr>
<th></th>
<th>STAR</th>
<th>ALICE</th>
</tr>
</thead>
<tbody>
<tr>
<td>choice of particle</td>
<td>baryon</td>
<td>antibaryon</td>
</tr>
<tr>
<td>d selection</td>
<td>larger $p_T$ acceptance</td>
<td>smaller $p_T$ acceptance</td>
</tr>
<tr>
<td>p and d selection</td>
<td>have large overlapping $p_T$ region</td>
<td>mostly separated</td>
</tr>
</tbody>
</table>

STAR results: by Debasish Mallick @ QM2022

$p_T$ and $d$ selection have large overlapping $p_T$ region mostly separated.
Comparison with STAR

$\sqrt{s_{NN}} = 5.02$ TeV
$|\eta| < 0.8$
$d$: $0.8 < p_T < 1.8$ GeV/c
$p$: $0.4 < p_T < 0.9$ GeV/c

STAR results: by Debasish Mallick @ QM2022
Hypertriton synthesis

- $\Lambda$, p, n bound state
- Lightest known hypernucleus
- $B_\Lambda$ is compatible with zero
- Loosely-bound nature confirmed
- Large radius of $^3\Lambda$He in Coalescence model leads to a larger suppression in small system → good discriminating power between SHM and coalescence in small system

<table>
<thead>
<tr>
<th>SHM</th>
<th>$dV/dy$</th>
<th>$3dV/dy$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Deviation ($\sigma$)</td>
<td>2.0</td>
<td>6.5</td>
</tr>
<tr>
<td>Coalescence</td>
<td>2-body</td>
<td>3-body</td>
</tr>
<tr>
<td>Deviation ($\sigma$)</td>
<td>1.2</td>
<td>1.5</td>
</tr>
</tbody>
</table>

ALICE, arXiv:2107.10627
Nuclei synthesis: Coalescence model

- Nuclear clusters are formed at kinetic freeze-out if nucleons are close in phase space.
- Coalescence into cluster A is determined by the momentum space density of n, p:

\[
E_A \frac{d^3 N_A}{dp_A^3} = B_A \left( \frac{d^3 N_{p,n}}{dp_{p,n}^3} \right)_A \bigg|_{\vec{p}_p = \vec{p}_n = \vec{p}_A}
\]

- State-of-the-art approaches include source size \( R \) and finite size \( r_d \) of the cluster, e.g. for deuterons:

\[
B_2 \approx \frac{3\pi^{3/2} \langle C_d \rangle}{2m_T R^3(m_T)} \quad \langle C_d \rangle \approx \left[ 1 + \left( \frac{r_d}{2R(m_T)} \right)^2 \right]^{-3/2}
\]


One, admittedly speculative, possibility is that such objects, at QGP hadronization, are produced as compact, colourless droplets of quark matter with quantum numbers of the final-state hadrons. The concept of possible excitations of nuclear matter into colourless quark droplets has already been considered. In the context of our work, these states should have a lifetime of 5 fm or longer, with excitation energies of 40 MeV or less, for evolution into the final-state hadrons that are measured in the detector. Since by construction they are initially compact, they would also survive a possible short-lived hadronic phase after hadronization. This would be a natural explanation for the striking observation of the thermal pattern for these nuclear bound states.