Measurement of Triton Production and Yield Ratio ($N_t \times N_p/N_d^2$) in Au+Au Collisions at RHIC Beam Energy Scan

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Introduction

Au+Au Collisions at RHIC STAR \[1\]

\[
\sqrt{s_{\text{NN}}} : 3 - 200 \text{ GeV} \\
\mu_B : 750 - 25 \text{ MeV}
\]

QCD Phase Diagram and Critical Point

Introduction

Production of Light Nuclei in HIC

Our understanding of the production mechanisms of light nuclei in relativistic heavy-ion collisions are currently incomplete

- Thermal emission
  \[ N_A \approx g_A V (2\pi m_A T)^{3/2} e^{(A \mu_B - m_A)/T} \]

- Nucleon coalescence
  \[ N_A = g_c \int d\Gamma \rho_s(\{x_i, p_i\}) \times W_A(\{x_i, p_i\}) \]

- Hadronic re-scattering
  \[ \pi NN \leftrightarrow \pi d, \text{NNN} \leftrightarrow N d, \text{NN} \leftrightarrow \pi d \ldots \ldots \]
Introduction

Formation Mechanisms of Light Nuclei

If one assumes that the potential energy of a proton and neutron has the shape of a simple $g$ hole, it is possible from the experimental value mass defect of the HP, to derive a connection between mean width and the depth of this curve. This can be proven to be, to a large amount, independent of details of the potential curve. By assuming a probable value, obtained from scattering experiments

$$\frac{dN_d(K)}{dN_p(K)} \propto \frac{4m^3}{3}$$

$$N_d(K) \propto [N_p \ (K/2)]^2$$

...
Introduction

Searching for QCD Critical Point with LN

Nucleon Coalescence picture:

\[ N_d = \frac{3}{2^{1/2}} \left( \frac{2\pi}{m_0 T_{eff}} \right)^{3/2} N_p(n)(1 + C_{np}) \]

\[ N_t = \frac{3\pi}{4} \left( \frac{2\pi}{m_0 T_{eff}} \right)^3 N_p(n)^2(1 + \Delta n + 2C_{np}) \]

\[ N_t \times N_p / N_d^2 = g(1 + \Delta n) \]

- In the vicinity of the critical point or the first order phase transition, density fluctuations become larger

- In the coalescence picture, nuclear compound yield ratio is sensitive to the baryon density fluctuations and can be used to probe 1st order phase transition and/or critical point in heavy-ion collisions

Analysis Details

Event Selection:

<table>
<thead>
<tr>
<th>Energy(GeV)</th>
<th>Year</th>
<th>Vr(cm)</th>
<th>Vz(cm)</th>
<th>Event(M)</th>
</tr>
</thead>
<tbody>
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<td>7.7</td>
<td>2010</td>
<td>2</td>
<td>40</td>
<td>2.37</td>
</tr>
<tr>
<td>11.5</td>
<td>2010</td>
<td>2</td>
<td>40</td>
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</tr>
<tr>
<td>14.5</td>
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<td>1</td>
<td>40</td>
<td>16.69</td>
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<tr>
<td>27</td>
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<tr>
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<td>2010</td>
<td>2</td>
<td>40</td>
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<tr>
<td>54.4</td>
<td>2018</td>
<td>2</td>
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<td>566.15</td>
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<td>62.4</td>
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<td>2</td>
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<tr>
<td>200</td>
<td>2011</td>
<td>2</td>
<td>30</td>
<td>465.07</td>
</tr>
</tbody>
</table>

[1] Hui Liu (For the STAR Collaboration), QM2019, Poster ID: 389
Track Selection:

<table>
<thead>
<tr>
<th>nHits</th>
<th>nHits/nHitspos</th>
<th>ndEdxHits</th>
<th>DCA</th>
<th>η</th>
<th>y</th>
<th>p_T</th>
</tr>
</thead>
<tbody>
<tr>
<td>&gt; 20</td>
<td>&gt; 0.52</td>
<td>&gt; 10</td>
<td>&lt; 1 cm</td>
<td>&lt; 1</td>
<td>&lt; 0.5</td>
<td>&gt; 0.2 GeV</td>
</tr>
</tbody>
</table>

Figure 3.1.2: The example of tracks selection criteria for √s_{NN} = 39 GeV Au+Au collisions.

3.2 Centrality Determination

In high energy heavy-ion collisions, the centrality of nucleus-nucleus collisions is an essential parameter. It can be defined using various parameters, with the most common being the collisional parameter b, which is the distance between the geometric center of the colliding nuclei in the cross-section.
Analysis Details

Centrality Determination

Analysis Details

Particle Identification & Signal Extraction

- Energy loss corrections
- Absorption corrections
- TPC tracking efficiency
- TOF matching efficiency

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Results

Triton $p_T$ Spectra

-$\star$ Mid-rapidity (|y| < 0.5) transverse momentum distributions for tritons

-$\star$ Dashed lines: Blast-wave function fits

\[
\frac{d^2N}{p_T dp_T dy} \propto \int_0^R r dr m_T I_0 \left( \frac{p_T \sinh \rho}{T} \right) K_1 \left( \frac{m_T \cosh \rho}{T} \right)
\]

STAR: Phys. Rev. Lett. 130, 202301 (2023)
Analysis Details

**Proton Feed-down Corrections**

\[ \Lambda \rightarrow p + \pi^-, \text{ branching ratio } = 63.9\% \]
\[ \Sigma^+ \rightarrow p + \pi^0, \text{ branching ratio } = 51.57\% \]
\[ \Xi^- \rightarrow \Lambda + \pi^-, \text{ branching ratio } = 99.887\% \]
\[ \Xi^0 \rightarrow \Lambda + \pi^0, \text{ branching ratio } = 99.524\% \]
\[ \Omega^- \rightarrow \Lambda + K^-, \text{ branching ratio } = 67.8\% \]

- **Correction Procedure:**
  1. Parameterized the strange hadron and proton spectra by Blast-Wave function
  2. Weight the embedding input Monte Carlo strange particle to the corrected spectra
  3. Obtain the daughter proton coming from the embedding and scale by the weight factor from step 2.
Analysis Details

Proton Feed-down Corrections

STAR Au+Au Collisions

Data driven method: Use STAR published strange particle yields

From 7.7 – 200 GeV, proton feed-down fraction increases from 25% to 45%

Primordial proton $p_T$ Spectra

🌟Mid-rapidity transverse momentum spectra for primordial protons

Results

Centrality Dependence of $dN/dy$ & $<p_T>$

$\star dN/dy$ for tritons increases with decreasing collision energy: yields driven by baryon density

$\star <p_T>$ decreases from central to peripheral collisions and with decreasing collision energy
Results

Centrality Dependence of $dN/d\gamma$ & $<p_T>$

☆ Mass dependence of light nuclei yields (divided by the spin degeneracy factor) well described by exponential functions

☆ Average transverse momentum increase with increasing collisions energy and increasing particle mass: influence of radial flow

Results

Particle Yield Ratios

The triton results follow the trend of the world data, and thermal model overestimates the $N_t/N_p$ ratios

V. Vovchenko, B. Dönigus, B. Kardan, M. Lorenz, and H. Stoecker, Phys. Lett. B, 135746 (2020);

The effects of hadronic re-scatterings during hadronic expansion may play an important role in light nuclei production


STAR: Rev. Lett. Phys. 130, 202301 (2023)
W. Reisdorf et al. (FOPI), Nucl. Phys. A 781, 459 (2007);
T. A. Armstrong et al. (E864), Phys. Rev. C 61, 064908 (2000);
S. S. Adler et al. (PHENIX), Phys. Rev. Lett. 94, 122302 (2005);
S. S. Adler et al. (PHENIX), Phys. Rev. C 69, 034909 (2004);
J. Adam et al. (ALICE), Phys. Rev. C 93, 024917 (2016)
Results

$dN_{ch}/d\eta$ Dependence of LN Yield Ratio

The ratio monotonically decreases with increasing $dN_{ch}/d\eta$ and exhibits a scaling behavior: trend driven by interplay between the size of light nuclei and the size of fireball created in HIC.

The ratio can be described by the coalescence model, but thermal model overestimates the data.

The ratios at 19.6 and 27 GeV from 0%-10% centrality show enhancements to the coalescence baseline with a combined significance of 4.1 $\sigma$.

Phys. Rev. Lett. 130, 202301 (2023)

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**Results**

Energy Dependence of Light Nuclei Yield Ratio

- **Non-monotonic behavior observed in the energy dependence of the yield ratio from 0%-10% central Au+Au collisions around 19.6 and 27 GeV**
- **The yield ratio in peripheral (40%-80%) collisions exhibits a monotonic trend and the data can be well described by coalescence models within uncertainties**
- **The significance of the enhancements decreases with decreasing $p_T$ acceptance in the region of interest**

Phys. Rev. Lett. 130, 202301 (2023)
Mapping out the QCD phase structure at high baryon density with high precision:

1. RHIC BES-II: Collider ($\sqrt{s_{NN}} = 7.7 - 19.6$ GeV) and FXT ($\sqrt{s_{NN}} = 3 - 7.7$ GeV) mode

Stay tuned for the exciting physics from High Baryon Density!
Summary

★ We report triton and primordial proton production in Au+Au collisions from RHIC-STAR BES-I

★ The thermal model can describe the $N_d/N_p$ ratio but not $N_t/N_p$ ratio.

★ The light nuclei yield ratio $(N_t \times N_p / N_d^2)$ decreases monotonically with increasing $dN_{ch}/d\eta$ and exhibits a scaling behavior, which can be well described by the coalescence model. However, the thermal model over estimates the $N_t/N_p$ and $N_t \times N_p / N_d^2$ ratio at RHIC energies, possibly due to the effect of hadronic re-scatterings during the hadronic expansion stage.

★ Relative to the coalescence baseline, enhancements of the yield ratio $N_t \times N_p / N_d^2$ are observed in the 0%-10% most central collisions at 19.6 and 27 GeV with a combined significance of 4.1σ. The enhancements are not observed in peripheral collisions and in model calculations without critical fluctuations.
Thank you!