Energy dependence of light nuclei ($d$, $t$) production at STAR

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Outline

- Introduction and Motivation
- The STAR Experiment
  - Data Sets and Particle Identification
- Results and Discussions
  - Transverse Momentum Spectra
  - Coalescence Parameters
  - Integral Yield $dN/dy$ and $\langle p_T \rangle$
  - Particle Ratio
  - Neutron Density Fluctuation
- Summary
Theory and Experiment: HIC

1) High temperature:
   QGP properties.

2) High baryon density:
   Critical Point and Phase boundary.

3) Search for the type of phase transition and critical point.
Coalescence picture: Production of light nuclei with small binding energy, such as triton (8.48 MeV), deuteron (2.2 MeV) etc, formed via final-state coalescence, are sensitive to the local nucleon density.

$$E_A \frac{d^3 N_A}{d^3 p_A} = B_A \left( E_p \frac{d^3 N_p}{d^3 p_p} \right)^Z \left( E_n \frac{d^3 N_n}{d^3 p_n} \right)^{A-Z} \approx B_A \left( E_p \frac{d^3 N_p}{d^3 p_p} \right)^A$$

$$B_A = \frac{4\pi}{3} p_0^{3(A-1)} \frac{1}{A!} \frac{M}{m^A}$$

$$B_A \propto V_f^{1-A}$$

The coalescence parameter $B_A$ reflects the local nucleon density.

In thermal model, $B_A \propto V_f^{1-A}$, $V_f$ is freeze-out volume.

In the vicinity of the critical point or the first-order phase transition, density fluctuation becomes larger.

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

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

\[ N_t \cdot N_p / N_d^2 = g (1 + \Delta n) \quad \Delta n = \langle (\delta n)^2 \rangle / \langle n \rangle^2 \]

The neutron density fluctuation can be derived from the yield ratio of light nuclei, hence it provides a tool to search for the QCD critical point.

Neutron density fluctuation can be expressed as: \( \Delta n = \langle (\delta n)^2 \rangle / \langle n \rangle^2 \)

In this case can be approximated as: \( N_t \cdot N_p / N_d^2 = g (1 + \Delta n) \), with \( g = 0.29 \).

RHIC Beam Energy Scan

- BES-I Au+Au collisions at $\sqrt{s_{NN}} = 7.7, 11.5, 14.5, 19.6, 27, 39, 62.4$ and $200$ GeV.

- Search for the Critical Point
- Search for the First-order Phase Transition
- Search for the Threshold of QGP Formation

<table>
<thead>
<tr>
<th>$\sqrt{s_{NN}}$ (GeV)</th>
<th>7.7</th>
<th>11.5</th>
<th>14.5</th>
<th>19.6</th>
<th>27</th>
<th>39</th>
<th>62.4</th>
<th>200</th>
</tr>
</thead>
<tbody>
<tr>
<td>$N_{eve}$(M)</td>
<td>4</td>
<td>11</td>
<td>27</td>
<td>40</td>
<td>71</td>
<td>133</td>
<td>67</td>
<td>480</td>
</tr>
<tr>
<td>$\mu_B$(MeV)</td>
<td>420</td>
<td>315</td>
<td>260</td>
<td>205</td>
<td>155</td>
<td>115</td>
<td>72</td>
<td>20</td>
</tr>
</tbody>
</table>

The Solenoidal Tracker At RHIC (STAR)

- Excellent Particle Identification.
- Large, Uniform Acceptance at Midrapidity.

Time Projection Chamber (TPC)
- Charged Particle Tracking
- Momentum reconstruction
- Particle identification from ionization energy loss ($dE/dx$)
- Pseudorapidity coverage $|\eta| < 1.0$

Time-of-Flight (TOF)
- Particle identification $m^2$
- Pseudorapidity coverage $|\eta| < 0.9$
Particle Identification

\[ z = \log \left( \frac{dE/dx}{dE/dx}^{BB} \right) \]

\[ m^2 = p^2 \left( \frac{c^2 t^2}{L^2 - 1} \right) \]

Transverse Momentum Spectra

\[ \frac{1}{2\pi^2 p_T^2} \frac{dN}{dp_T dy} \] transverse momentum distribution of \( d(\bar{d}) \) from Au+Au Collisions.

\[ \frac{1}{2\pi^2 p_T^2} \frac{dN}{dp_T dy} \] transverse momentum distribution of \( t \) from Au+Au Collisions.

Dash lines: blast-wave function fits.

\[ \int_0^R r dr m_T I_0 \left( \frac{p_T \sinh \rho}{T} \right) K_1 \left( \frac{m_T \cosh \rho}{T} \right) \]


Dingwei Zhang  
NN2018, Japan, Dec. 4-8, 2018
The values of $B_2$ increase as a function of $m_T$ and decrease with collision centrality: collective expansion.

$B_2(d)$ are smaller than that of $B_2(d)$, indicate anti-baryon freeze-out at a larger source.

$B_2$ decreases with collision energy. A minimum around $\sqrt{s_{NN}} = 20$ GeV: change of EOS?!
$B_3$ decreases from peripheral to central collisions and with increasing collision energy.

$B_2$ and $\sqrt{B_3}$ are consistent within uncertainties except 200 GeV.
For $d$ and $t$, the yield $dN/dy$ are smaller at higher energies:

- Baryon stopping.

For $\bar{d}$, the yield $dN/dy$ increase with increasing energy:

- Baryon pair production.
$<p_T>$

$Au + Au \Rightarrow d + X$

$Au + Au \Rightarrow \bar{d} + X$

$<p_T>$ decrease from central to peripheral collisions and with decreasing energy.

STAR Preliminary
\begin{equation}
T_{CF} = T_{CF}^{\text{lim}} / (1 + \exp(2.60 - \ln(\sqrt{S_{NN}})/0.45)) \quad \mu_B = a/(1 + 0.288\sqrt{S_{NN}})
\end{equation}

With $\sqrt{S_{NN}}$ in GeV and $T_{CF}^{\text{lim}} = 158.4$ MeV and $a = 1307.5$ MeV.

★Thermal model can describe the d/p ratios, but can not describe the t/p, t/d ratios.

Neutron density fluctuation, $\Delta n$, shows a non-monotonic behavior on collision energy. Peak around 20 GeV.

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

- We present STAR results of $d(\bar{d})$ and $t$ production ($dN/dy$, $<p_T>$) from Au + Au collisions at $\sqrt{s_{NN}} = 7.7, 11.5, 14.5, 19.6, 27, 39, 62.4$ and $200$ GeV.
- Coalescence parameter $B_2$ for $d$ and $\bar{d}$, $B_3$ for $t$ are extracted. $B_2$ and $\sqrt{B_3^t}$ are consistent within uncertainties except 200 GeV.
- Thermal model can not describe the triton production.
- The neutron density fluctuation, $\Delta n$, shows a non-monotonic behavior dependence on collision energy.
- Study the QCD phase structure with more statistics: BES-II at RHIC (2019-2021).
Thank you!