Multiplicity scaling of light nuclei productions in heavy-ion collisions

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Predictions for spectra and \( \nu_n (p_T) \) of light nuclei


- iEBE-VISHNU + Coalescence nicely predict spectra, \( \nu_2 (p_T) \) and \( \nu_3 (p_T) \) of light nuclei at different centrality bins for the ALICE measurements.
Light nuclei production at RHIC BES region

- iEBS-MUSIC + Coalescence well describe the spectra of light nuclei from 7.7 to 200 GeV.

- $B_2(d/\bar{d})$ and $\sqrt{B_3(t)}$ decrease monotonically with multiplicity. $dN/dy/(2J+1)$ decreases exponentially vs $m_A$.
Multiplicity scaling of $N_p \cdot N_t/N_d^2$

$N_d = g_d \int d^3x_1 d^3p_1 d^3x_2 d^3p_2 f_n(x_1, p_1) \times f_p(x_2, p_2) W_d(x, p),$ 
$N_t = g_t \int d^3x_1 d^3p_1 d^3x_2 d^3p_2 d^3x_3 d^3p_3 f_n(x_1, p_1) \times f_p(x_3, p_3) W_t(x, \lambda, p, p_\lambda),$

For Gaussian source:

$$f_{p,n}(x, k) = \frac{N_{p,n}}{(2\pi)^3 (mT_K R^2)^{3/2}} e^{-\frac{k^2}{2mT_K} - \frac{x^2}{2R^2}},$$

$$\frac{N_t N_p}{N_d^2} = \frac{4}{9} \left( 1 + \frac{2r_d^2}{3R^2} \right)^3 = \frac{4}{9} \left( 1 + \frac{4}{3} \frac{r_d^2 - r_t^2}{2R^2 + r_t^2} \right)^3.$$
Comparisons between different models

- **Thermal model:** 
  \[ N_A \approx g_A V (2\pi m_A T)^{3/2} e^{(A\mu_B - m_A)/T} \]
  1. It nicely describes the d/p from RHIC to LHC energies.
  2. It overestimates the t/p at RHIC, but fits at LHC.

- **Transport model:** 
  \( \pi NN \leftrightarrow \pi d, NNN \leftrightarrow Nd, NN \leftrightarrow \pi d \)
  1. It nicely describes the d/p at RHIC.
  2. No t/p calculations.

- **Coalescence model:**
  1. It reasonably describes the d/p from RHIC to LHC energies.
  2. It well describes the t/p at RHIC, but underestimates that at LHC.

- The t/p at LHC is much larger than that at top RHIC.

- Discrepancy of triton (helium-3) productions between top RHIC energy and LHC energy needs to be understood.

Back Up
Coalescence model

$$\frac{d^3 N_A}{d\mathbf{p}_A^3} = \frac{g_A}{Z! \cdot N!} \int \prod_{i=1}^{A} p_i^\mu d^3 \sigma_{i\mu} \frac{d^3 \mathbf{p}_i}{E_i} f(x_i, p_i, t) \times f_A(x'_1, \ldots, x'_A; p'_1, \ldots, p'_A; t') \delta^{(3)} \left( \mathbf{p}_A - \sum_{i=1}^{A} \mathbf{p}_i \right),$$


No free parameters. Here, $\sigma_\rho$ and $\sigma_\lambda$ are taken from [Atom. Data Nucl. Data Tabl. 99, 69 (2013)].  

1. The light nuclei productions encode the phase-space information of nucleons.
Coalescence Parameters \( (A - 1 / \sqrt{B_A}) \)

\( B_A \) (A=2,3) describe the coalescence probability

\[
E_A \frac{d^3 N_A}{dp_A^3} = B_A \left( \frac{d^3 N_p}{dp^3_p} \right)^Z \left( \frac{d^3 N_n}{dp^3_n} \right)^{A-Z} \\
\approx B_A \left( \frac{d^3 N_p}{dp^3_p} \right)^A \mid \bar{p}_p = \bar{p}_n = \bar{g}_A
\]

\( B_A \propto V_{\text{eff}}^{1-A} \). \( V_{\text{eff}} \): effective volume.

S. Leupold and U. Heinz, PRC50, 1110 (1994);
R. Scheibl and U. W. Heinz, PRC59. 1585(1999);

Triton productions:
Three body: \( p + n + n \to t \)

\( \cdot \) \( B_2(d/\bar{d}) \) and \( \sqrt{B_3(t)} \) decrease monotonically with multiplicity.

\( \cdot \) The slopes of \( B_2(d/\bar{d}) \) and \( \sqrt{B_3(t)} \) are different, attribute to the different sizes of deuteron and triton.

\( \cdot \) \( A^{-1} \sqrt{B_A} \) at \( p_T/A = 1.05 \text{ GeV} \) is slightly larger than \( p_T/A = 0.65 \text{ GeV} \), caused by the smaller \( V_{\text{eff}} \) at higher \( p_T \).
The STAR data observes the non-monotonic dependence of $N_p \cdot N_t/N_d^2$ on collision energy in central collisions at RHIC.

In central collisions at RHIC, $N_p \cdot N_t/N_d^2$ calculated by iEBE-MUSIC +Coalescence is flat.

$N_p \cdot N_t/N_d^2$ at Pb-Pb at LHC from coalescence much smaller than the ALICE data.
Collective flow of light nuclei

- Blast wave underpredicts $v_2(p_T)$ of d and 3He.
- Simple Coalescence overestimates $v_2(p_T)$ of d and 3He.
- In the framework of coalescence model, the collective flow of light nuclei is sensitive to the correlations between spatial and momentum distributions of nucleon.


$v_2(p_T)$ of light nuclei in Pb + Pb 2.76 TeV

- iEBE-VISHNU + Coalescence well reproduce the $v_2(p_T)$ of deuteron in all centrality bins in Pb+Pb at 2.76 TeV.
- iEBE-VISHNU naturally gives a good description of spatial-momentum correlations of nucleon at kinetic freeze-out.
- No free parameters in the model simulations.

Light nuclei production in Au + Au at 200 GeV

- \( \nu_2(p_T) \) and \( \nu_2(p_T) \) of \( d \) and 3He in Au+Au 200 GeV.