Production characteristics of light nuclei, hypertritons and Ω-hypernuclei in Pb+Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV

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Date: 2025-02-02T00:00:00+00:00

Abstract

We extend an analytical nucleon coalescence model with hyperons to study the productions of light nuclei, hypertritons and Ω-hypernuclei in Pb+Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV. We derive the formula of the momentum distribution of two bodies coalescing into dibaryon states and that of three bodies coalescing into tribaryon states. We explain the available data of coalescence factors B_2 and B_3, transverse momentum spectra, averaged transverse momenta, yield rapidity densities and yield ratios of the deuteron, antihelium-3, antitriton and hypertriton measured by the ALICE collaboration. We give predictions of different Ω-hypernuclei $H(p\Omega^-)$, $H(n\Omega^-)$ and $H(pn\Omega^-)$. We particularly study production correlations of different light (hyper-)nuclei and find two groups of interesting observables, the averaged transverse momentum ratios of light (hyper-)nuclei to protons (hyperons) and their corresponding yield ratios. The former group exhibits a reverse hierarchy of the nucleus size, and the latter is sensitive to the nucleus production mechanism as well as the nucleus's own size.

Full Text

Preamble

Production characteristics of light nuclei, hypertritons and Ω-hypernuclei in Pb+Pb collisions at √s_{NN} = 5.02 TeV

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We extend an analytical nucleon coalescence model with hyperons to study the production of light nuclei, hypertritons and Ω-hypernuclei in Pb+Pb collisions at √s_{NN} = 5.02 TeV. We derive the formula for the momentum distribution of two bodies coalescing into dibaryon states and that of three bodies coalescing into tribaryon states. We explain the available data of coalescence factors B_2 and B_3, transverse momentum spectra, averaged transverse momenta, yield rapidity densities and yield ratios of the deuteron, antihelium-3, antitriton and hypertriton measured by the ALICE collaboration. We give predictions for different Ω-hypernuclei $H(p\Omega^-)$, $H(n\Omega^-)$ and $H(pn\Omega^-)$. We particularly study production correlations of different light (hyper-)nuclei and find two groups of interesting observables: the averaged transverse momentum ratios of light (hyper-)nuclei to protons (hyperons) and their corresponding yield ratios. The former group exhibits a reverse hierarchy of the nucleus size, and the latter is sensitive to the nucleus production mechanism as well as the nucleus's own size.

Keywords: Light nucleus production, Hypernucleus production, The coalescence model, Relativistic heavy ion collision

INTRODUCTION

In ultra-relativistic heavy ion collisions, light nuclei and hypernuclei such as the deuteron (d), helium-3 (^{3}He), triton (t) and hypertriton (^{3}_ΛH) constitute a special group of observables [?]. These composite clusters have production mechanisms that remain under debate today. The production of such composite objects is closely related to many fundamental issues in the relativistic heavy ion community, including the hadronization mechanism [?], the hadronic rescattering effect [?], the structure of the quantum chromodynamics phase diagram [?], local baryon-strangeness correlation [?, ?], system freeze-out characteristics [?], hyperon-nucleon interaction [?], and the search for more hadronic molecular states [?, ?].

In recent decades, the production of light nuclei and hypernuclei in ultra-relativistic heavy ion collisions has attracted considerable attention both experimentally [?] and theoretically [?]. The STAR experiment at the BNL Relativistic Heavy Ion Collider (RHIC) and the ALICE experiment at the CERN Large Hadron Collider (LHC) have devoted significant effort to measuring light nuclei [?] and hypernuclei [?].

Two production mechanisms—the thermal production mechanism [?] and the coalescence mechanism [?, ?, ?]—have proven successful in describing the formation of such composite objects. The coalescence mechanism, which assumes that light nuclei and hypernuclei are produced by the coalescence of adjacent nucleons and hyperons in phase space, possesses some unique characteristics [?, ?, ?]. To examine whether, and to what extent, these characteristics depend on the particular coalescence models used, we developed an analytical method for describing the production of different species of light nuclei in our previous works [?]. We applied the analytical nucleon coalescence model to Au+Au collisions at RHIC to successfully explain the energy-dependent behaviors of d, t, ^{3}He and ^{4}He [?, ?]. We also applied it to pp, p+Pb, and Pb+Pb collisions at the LHC to understand different behaviors of coalescence factors B_2 and B_3 [?] from small to large collision systems, and gave a series of concise production correlations of d, ^{3}He and t [?].

Very recently, the ALICE collaboration published the most precise measurements to date of d, ^{3}He, t and especially ^{3}*ΛH in Pb+Pb collisions at* $\sqrt{s}${NN} = 5.02 TeV [?, ?, ?]. In this work, we extend the coalescence model considering the coordinate-momentum correlation [?] to include hyperon coalescence in addition to nucleon coalescence and apply it to simultaneously study the production of light nuclei, ^{3}_ΛH and Ω-hypernuclei. One main goal of this article is to provide a comprehensive understanding of the newest data in Pb+Pb collisions with the highest collision energy so far. The other goal is to bring production characteristics, especially production correlations, of light nuclei and hypernuclei originating from the coalescence mechanism itself to light. We propose two groups of interesting observables: the averaged transverse momentum ratios and centrality-dependent yield ratios of light nuclei to protons and hypernuclei to hyperons. These ratios happen to offset the differences of the primordial p, Λ and Ω^-. This makes them powerful tools for revealing whether a universal production mechanism exists for different species of nuclei in both light and strange sectors. We find these ratios exhibit certain relations in the coalescence picture that are very different from the thermal production mechanism.

The paper is organized as follows. In Sec. II, we introduce the coalescence model. We present the formulae for the momentum distributions of two baryons coalescing into dibaryon states and three baryons coalescing into tribaryon states, respectively. In Sec. III, we study behaviors of B_2 and B_3 as functions of collision centrality and transverse momentum per nucleon. We also examine the transverse momentum (p_T) spectra, averaged transverse momenta p_T , yield rapidity densities dN/dy and yield ratios of d, ^{3}He and $\bar{t}$. In Sec. IV, we present results for ^{3}*ΛH and Ω-hypernuclei. We specifically study the averaged transverse momentum ratios p_T* d/ p_T *p,* *p_T* {^{3}*ΛH*}/ *p_T* Λ, p_T {*H(nΩ⁻)*}/ *p_T* {Ω^-}, p_T {*H(pΩ⁻)*}/ *p_T* {Ω^-}, p_T *t*/ *p_T* p, p_T {^{3}*He*}/ *p_T* p, p_T {*H(pnΩ⁻)*}/ *p_T* {Ω^-} and centrality-dependent behaviors of yield ratios. In Sec. V, we give our summary.

II. THE COALESCENCE MODEL

In this section, we extend the analytical nucleon coalescence model from our previous work [?] to include hyperon coalescence. In the current model, the coalescence process is executed on an equivalent kinetic freeze-out surface formed from different times. To make analytical and intuitive insights possible, we abandon carrying out the time evolution step by step but absorb the finite emission duration in an effective volume. We first present the formalism of two baryons coalescing into d-like dibaryon states. We then give an analytical expression for three baryons coalescing into ^{3}He, t, and their partners in the strange sector.

A. Formalism of two bodies coalescing into dibaryon states

We begin with a hadronic system produced at the final stage of high-energy collision evolution, and suppose the dibaryon state H_j is formed via the coalescence of two baryons h_1 and h_2. We use $f_{H_j}(p)$ to denote the three-dimensional momentum distribution of the produced H_j, given by

$$f_{H_j}(p) = \ dx_1 dx_2 dp_1 dp_2 \ f_{h_1 h_2}(x_1, x_2; p_1, p_2) \times R_{H_j}(x_1, x_2; p_1, p_2, p).$$

Here $f_{h_1 h_2}(x_1, x_2; p_1, p_2)$ is the two-baryon joint coordinate-momentum distribution, and $R_{H_j}(x_1, x_2; p_1, p_2, p)$ is the kernel function of H_j. Bold symbols denote three-dimensional coordinate or momentum vectors.

In terms of the normalized joint coordinate-momentum distribution denoted by the superscript '(n)', we have

$$f_{H_j}(p) = N_{h_1 h_2} \ dx_1 dx_2 dp_1 dp_2 \ f^{(n)}(x_1, x_2; p_1, p_2) \times R_{H_j}(x_1, x_2; p_1, p_2, p).$$

$N_{h_1 h_2} = N_{h_1} N_{h_2}$ is the number of all possible $h_1 h_2$ pairs in the considered hadronic system, and N_{h_i} ($i = 1, 2$) is the number of baryons h_i.

The kernel function $R_{H_j}(x_1, x_2; p_1, p_2, p)$ denotes the probability density for h_1, h_2 with momenta p_1 and p_2 at x_1 and x_2 to combine into an H_j of momentum p. It carries the kinetic and dynamical information of h_1 and h_2 combining into H_j, and its precise expression should be constrained by momentum conservation and constraints due to intrinsic quantum numbers such as spin [**?**]. To account for these constraints explicitly, we rewrite the kernel function in the following form:

$$R_{H_j}(x_1, x_2; p_1, p_2, p) = g_{H_j} \ R^{(x,p)}(x_1, x_2; p_1, p_2) \ \delta(p_i - p).$$

The spin degeneracy factor $g_{H_j} = (2J_{H_j} + 1)/[\,(2J_{h_i} + 1)]$, where J_{H_j} is the spin of the produced H_j and J_{h_i} is that of the primordial baryon h_i. The Dirac δ function guarantees momentum conservation in the coalescence process. The remaining $R^{(x,p)}(x_1, x_2; p_1, p_2)$ can be solved from the Wigner transformation when the H_j wave function is given. Considering that the wave function of a spherical harmonic oscillator is particularly tractable and useful for analytical insight, we adopt this profile as in Refs. [**?**] and obtain

$$R^{(x,p)}(x_1, x_2; p_1, p_2) = 8e^{-r'^2/\sigma^2} \ e^{-2\sigma^2 (m_2 p'_1 - m_1 p'_2)^2/(m_1+m_2)^2}.$$

The superscript '′' in the coordinate or momentum variables denotes the baryon coordinate or momentum in the rest frame of the $h_1 h_2$ pair. m_1 and m_2 are the masses of h_1 and h_2. The width parameter $\sigma = \surd(2(m_1+m_2)^2) R_{H_j}$, and R_{H_j} is the root-mean-square radius of H_j.

Substituting Eqs. (3) and (4) into Eq. (2), we have

$f_{H_j}(p) = N_{h_1h_2}g_{H_j} \quad dx_1dx_2dp_1dp_2 \; f^{(n)}(x_1, x_2; p_1, p_2) \times 8e^{-r'^2/\sigma^2} \; e^{-2\sigma^2(m_2p'_1 - m_1p'_2)^2/(m_1+m_2)^2} \; \delta(\, p_i - p)$.

This is the general formalism for H_j production via the coalescence of two baryons h_1 and h_2.

Noting that the root-mean-square radius R_{H_j} of the dibaryon state H_j is always about or larger than 2 fm, σ is even larger than R_{H_j}. Therefore, the Gaussian width in the momentum-dependent part of the kernel function in Eq. (5) has a small value, about or smaller than 0.1 GeV/c. We approximate the Gaussian form of the momentum-dependent kernel function to a δ function form as follows:

$e^{-2\sigma^2(m_2p'_1 - m_1p'_2)^2/(m_1+m_2)^2} \quad (\sqrt{\pi}/\sigma)^3 \; \delta(m_2p'_1 - m_1p'_2)$.

The robustness of this δ function approximation has been verified at the outset of the analytical coalescence model in our previous work [?]. Substituting Eq. (6) into Eq. (5) and integrating over p_1 and p_2, we obtain

$f_{H_j}(p) = N_{h_1h_2}g_{H_j}\gamma(\sqrt{\pi}/\sigma)^3 \quad dx_1dx_2 \; f^{(n)}(x_1, x_2; (m_1/(m_1+m_2))p, (m_2/(m_1+m_2))p) \; e^{-r'^2/\sigma^2}$.

γ is the Lorentz contraction factor corresponding to the three-dimensional velocity β of the center-of-mass frame of the h_1h_2 pair in the laboratory frame. The momentum transformation parallel to β is $p'_{1//} = \gamma(p_{1//} - m_1\beta)$, and that perpendicular to β is invariant.

Changing coordinate variables in Eq. (7) to $X = (m_1x_1 + m_2x_2)/(m_1 + m_2)$ and $r = (x_1 - x_2)/\sqrt{2}$, we have

$f_{H_j}(p) = 8\pi^{3/2}g_{H_j}\gamma \, (\sqrt{\pi}/\sigma)^3 \quad dXdr \; f^{(n)}(X, r; (m_1/(m_1+m_2))p, (m_2/(m_1+m_2))p) \; e^{-r'^2/\sigma^2}$.

Here $R_f(p)$ is the effective radius of the hadronic source system at the H_j freeze-out. C_0 is introduced to make r^2/C_0 the square of one-half of the relative position, and it is 2 [?]. In this way, $R_f(p)$ is just the Hanbury-Brown-Twiss (HBT) interferometry radius, which can also be extracted from two-particle femtoscopic correlations [?, ?].

With instantaneous coalescence in the rest frame of the h_1h_2 pair, i.e., $\Delta t' = 0$, we obtain the coordinate transformation $r = r' + (\gamma - 1)(r' \cdot \beta/\beta^2)\beta$. Instantaneous coalescence is a basic assumption in coalescence-like models where the overlap of the nucleus Wigner phase-space density with the constituent phase-space distributions is adopted [?]. Considering that the coalescence criterion judged in the rest frame is more general than in the laboratory frame, we choose instantaneous coalescence in the rest frame of the h_1h_2 pair, as in Refs. [?, ?]. Substituting Eq. (11) into Eq. (10) and using Eq. (12) to integrate over the relative coordinate variable, we obtain

$f_{H_j}(p) = 8\pi^{3/2}g_{H_j}\gamma \; (\sqrt{\pi}/\sigma)^3 \; [C_0(R_f(p)/\gamma)^2 + \sigma^2]^{-3/2} \times f_{h_1h_2}((m_1/(m_1+m_2))p, (m_2/(m_1+m_2))p)$.

Considering that the strong interaction and coalescence are local, we neglect the effect of collective motion on the center-of-mass coordinate and assume it is factorized, i.e.,

$f^{(n)}(X, r; (m_1/(m_1+m_2))p, (m_2/(m_1+m_2))p) = f^{(n)}(X) f^{(n)}(r; (m_1/(m_1+m_2))p, (m_2/(m_1+m_2))p)$.

Ignoring correlations between h_1 and h_2, we have the three-dimensional momentum distribution of H_j as

$f_{H_j}(p) = 8\pi^{3/2} g_{H_j} \gamma (\sqrt{\pi}/\sigma)^3 [C_0(R_f(p)/\gamma)^2 + \sigma^2]^{-3/2} \times f_{h_1}((m_1/(m_1+m_2))p) f_{h_2}((m_2/(m_1+m_2))p)$.

Denoting the Lorentz invariant momentum distribution with $f^{(inv)}(p_T, y) = (1/2\pi p_T)(d^2N/dp_{T}dy)$, we finally have

$f^{(inv)}_{H_j}(p_T, y) = 8\pi^{3/2} g_{H_j} \gamma (\sqrt{\pi}/\sigma)^3 [C_0(R_f(p_T, y)/\gamma)^2 + \sigma^2]^{-3/2} \times f^{(inv)}_{h_1}(p_T, y) f^{(inv)}_{h_2}(p_T, y)$,

where y is the longitudinal rapidity and m_{H_j} is the mass of H_j.

B. Formalism of three bodies coalescing into tribaryon states

For a tribaryon state H_j formed via the coalescence of three baryons h_1, h_2 and h_3, the momentum distribution $f_{H_j}(p)$ is

$f_{H_j}(p) = N_{h_1h_2h_3} \quad dx_1dx_2dx_3dp_1dp_2dp_3 \; f^{(n)}_{h_1h_2h_3}(x_1, x_2, x_3; p_1, p_2, p_3) \; R_{H_j}(x_1, x_2, x_3; p_1, p_2, p_3, p)$.

$N_{h_1h_2h_3}$ is the number of all possible $h_1h_2h_3$ clusters and equals $N_{h_1}N_{h_2}N_{h_3}$, $N_{h_1}(N_{h_1} - 1)N_{h_3}$ for $h_1 \neq h_2 \neq h_3$, $h_1 = h_2 \neq h_3$, respectively. $f^{(n)}(x_1, x_2, x_3; p_1, p_2, p_3)$ is the normalized three-baryon joint coordinate-momentum distribution, and $R_{H_j}(x_1, x_2, x_3; p_1, p_2, p_3, p)$ is the kernel function.

We rewrite the kernel function as

$R_{H_j}(x_1, x_2, x_3; p_1, p_2, p_3, p) = g_{H_j} \; R^{(x,p)}(x_1, x_2, x_3; p_1, p_2, p_3) \; \delta(p_i - p)$.

The spin degeneracy factor $g_{H_j} = (2J_{H_j} + 1)/[(2J_{h_i} + 1)]$. The Dirac δ function guarantees momentum conservation. $R^{(x,p)}(x_1, x_2, x_3; p_1, p_2, p_3)$ solved from the Wigner transformation [**?**] is

$R^{(x,p)}(x_1, x_2, x_3; p_1, p_2, p_3) = 8^2 \; e^{-r_1'^2/\sigma_1^2} \; e^{-[m_3p'_1 + m_3p'_2 - (m_1+m_2)p'_3]^2/[2(m_1+m_2+m_3)^2\sigma_2^2]}$.

The superscript '′' denotes the baryon coordinate or momentum in the $h_1h_2h_3$ cluster rest frame. The width parameters are $\sigma_1 = \sqrt{[3(m_1+m_2)[m_1m_2(m_1+m_2) + m_2m_3(m_2+m_3) + m_3m_1(m_3+m_1)]]/(4m_1m_2(m_1+m_2+m_3)^2)} \; R_{H_j}$ and $\sigma_2 = \sqrt{[3(m_1+m_2)[m_1m_2(m_1+m_2) + m_2m_3(m_2+m_3) + m_3m_1(m_3+m_1)]]/[m_3(m_1+m_2)(m_1+m_2+m_3)]} \; R_{H_j}$, where R_{H_j} is the root-mean-square radius of H_j.

Substituting Eqs. (17) and (18) into Eq. (16), we have

$f_{H_j}(p) = 8^2 N_{h_1h_2h_3} g_{H_j}$ $dx_1dx_2dx_3dp_1dp_2dp_3$ $e^{-r_1'^2/\sigma_1^2}$ $e^{-[m_3p'_1 + m_3p'_2 - (m_1+m_2)p'_3]^2/[2(m_1+m_2+m_3)^2\sigma_2^2]} \times f^{(n)}_{h_1h_2h_3}(x_1, x_2, x_3; p_1, p_2, p_3)\ \delta(p_i - p)$.

Approximating the Gaussian form of the momentum-dependent kernel function to δ function form and integrating p_1, p_2 and p_3 from Eq. (19), we obtain

$f_{H_j}(p) = 8^2 N_{h_1h_2h_3} g_{H_j} \gamma^2(\sqrt{\pi^3}/3\sigma_1\sigma_2)$ $dx_1dx_2dx_3\ f^{(n)}_{h_1h_2h_3}(x_1, x_2, x_3; (m_1/(m_1+m_2+m_3))p, (m_2/(m_1+m_2+m_3))p, (m_3/(m_1+m_2+m_3))p)$ $e^{-r_1'^2/\sigma_1^2}$.

Changing coordinate variables in Eq. (20) to $Y = (m_1x_1 + m_2x_2 + m_3x_3)/(m_1 + m_2 + m_3)$, $r_1 = (x_1 - x_2)/\sqrt{2}$ and $r_2 = \sqrt{3/2}$ as in Refs. [**?**], we have

$f_{H_j}(p) = 8^2 N_{h_1h_2h_3} g_{H_j} \gamma^2(\sqrt{\pi^3}/3\sigma_1\sigma_2)$ $3^{3/2}dY\ dr_1dr_2$ $f^{(n)}_{h_1h_2h_3}(Y, r_1, r_2; (m_1/(m_1+m_2+m_3))p, (m_2/(m_1+m_2+m_3))p, (m_3/(m_1+m_2+m_3))p)$ $e^{-r_1'^2/\sigma_1^2}$ $e^{-r_2'^2/\sigma_2^2}$.

We also assume the center-of-mass coordinate in the joint distribution is factorized, i.e.,

$f^{(n)}{h_1h_2h_3}(Y, r_1, r_2; (m_1/(m_1+m_2+m_3))p, (m_2/(m_1+m_2+m_3))p, (m_3/(m_1+m_2+m_3))p) = f^{(n)}{h_1h_2h_3}(Y) f{(n)}_{h_1h$ $r_2; (m_1/(m_1+m_2+m_3))p, (m_2/(m_1+m_2+m_3))p, (m_3/(m_1+m_2+m_3))p)$.

Substituting Eq. (22) into Eq. (21), we have

$f_{H_j}(p) = 8^2 N_{h_1h_2h_3} g_{H_j} \gamma^2(\sqrt{\pi^3}/3\sigma_1\sigma_2)$ $dr_1dr_2\ f^{(n)}_{h_1h_2h_3}(r_1, r_2; (m_1/(m_1+m_2+m_3))p, (m_2/(m_1+m_2+m_3))p, (m_3/(m_1+m_2+m_3))p)$ $e^{-r_1'^2/\sigma_1^2}$ $e^{-r_2'^2/\sigma_2^2}$.

Adopting Gaussian forms for the relative coordinate distributions [**?**, **?**], we have

$f^{(n)}_{h_1h_2h_3}(r_1, r_2; (m_1/(m_1+m_2+m_3))p, (m_2/(m_1+m_2+m_3))p, (m_3/(m_1+m_2+m_3))p) = [\pi C_1 R_f^2(p)]^{-3/2}\ e^{-r_1^2/[C_1R_f^2(p)]}\ [\pi C_2 R_f^2(p)]^{-3/2}\ e^{-r_2^2/[C_2R_f^2(p)]}$.

Comparing relations of r_1, r_2 with x_1, x_2, x_3 to that of r with x_1, x_2 in Sec. II A, we see that C_1 equals C_0 and C_2 is $4C_0/3$ [**?**, **?**]. Substituting Eq. (24) into Eq. (23) and considering the coordinate Lorentz transformation, we integrate over the relative coordinate variables and obtain

$f_{H_j}(p) = 8^2\pi^3 g_{H_j}\gamma^2\ [C_1(R_f(p)/\gamma)^2 + \sigma_1^2]^{-3/2}\ [C_2(R_f(p)/\gamma)^2 + \sigma_2^2]^{-3/2} \times f_{h_1h_2h_3}((m_1/(m_1+m_2+m_3))p, (m_2/(m_1+m_2+m_3))p, (m_3/(m_1+m_2+m_3))p)$.

Ignoring correlations between h_1, h_2 and h_3, we have the three-dimensional momentum distribution of H_j as

$f_{H_j}(p) = 8^2\pi^3 g_{H_j}\gamma^2\ [C_1(R_f(p)/\gamma)^2 + \sigma_1^2]^{-3/2}\ [C_2(R_f(p)/\gamma)^2 + \sigma_2^2]^{-3/2} \times f_{h_1}((m_1/(m_1+m_2+m_3))p) f_{h_2}((m_2/(m_1+m_2+m_3))p) f_{h_3}((m_3/(m_1+m_2+m_3))p)$.

Finally, we have the Lorentz invariant momentum distribution as

$f^{(inv)}_{H_j}(p_T, y) = 8^2\pi^3 g_{H_j}\gamma^2 [C_1(R_f(p_T, y)/\gamma)^2 + \sigma_1{}^2]^{-3/2} [C_2(R_f(p_T, y)/\gamma)^2 + \sigma_2{}^2]^{-3/2} \times f^{(inv)}_{h_1}(p_T, y) f^{(inv)}_{h_2}(p_T, y) f^{(inv)}_{h_3}(p_T, y)$.

As a short summary of this section, we state that Eqs. (15) and (27) provide: (i) the relationships between dibaryon states and tribaryon states with primordial baryons in momentum space in the laboratory frame, and (ii) the effects of different factors on dibaryon or tribaryon production such as the whole hadronic system scale and the size of the formed composite object. They can be directly used to calculate the production of light nuclei, hypernuclei, and even other hadronic molecular states. Moreover, they can be conveniently used to investigate production correlations of different species of composite objects. Formulae for antiparticles are the same as these dibaryon and tribaryon states, and we omit the duplication. Their applications at midrapidity (i.e., y = 0) in heavy ion collisions at the LHC will be shown in the following sections.

III. RESULTS OF LIGHT NUCLEI

In this section, we use the coalescence model to study production of d, ^{3}He and $\bar{t}$ at midrapidity in Pb+Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV. We first calculate the coalescence factors B_2, B_3 and discuss their centrality and p_T-dependent behaviors. We then compute the p_T spectra of d, ^{3}He and $\bar{t}$. Finally, we calculate the averaged transverse momenta $\langle p_T \rangle$, the yield rapidity densities dN/dy and the yield ratios of different light nuclei.

A. The coalescence factor of light nuclei

The coalescence factor B_A is defined as

$$B_A(p_T) = (1/2\pi p_T)(d^2N/dp_T dy)_A \,/\, [(1/2\pi p_T)(d^2N/dp_T dy)_p]^{A-Z} [(1/2\pi p_T)(d^2N/dp_T dy)_n]^Z,$$

where A is the mass number and Z is the charge of the light nuclei. It is a unique link between the formed light nuclei and the primordial nucleons. Much effort has been devoted to B_A in different coalescence models [?, ?, ?, ?]. From Eqs. (15) and (27), we respectively have for d, ^{3}He and t:

$$B_2(p_T) = (8\pi^{3/2} g_d \gamma (\sqrt{\pi}/\sigma_d)^3 [C_0(R_f(p_T)/\gamma)^2 + \sigma_d{}^2]^{-3/2}) \,/\, (1/2\pi p_T)(d^2N/dp_T dy)_p,$$

$$B_3(p_T) = (8^2\pi^3 g_{^3He}\gamma^2 [C_1(R_f(p_T)/\gamma)^2 + \sigma_{^3He}{}^2]^{-3/2} [C_2(R_f(p_T)/\gamma)^2 + \sigma_{^3He}{}^2]^{-3/2}) \,/\, (1/2\pi p_T)(d^2N/dp_T dy)_p{}^3,$$

$$B_3(p_T) = (8^2\pi^3 g_t\gamma^2 [C_1(R_f(p_T)/\gamma)^2 + \sigma_t{}^2]^{-3/2} [C_2(R_f(p_T)/\gamma)^2 + \sigma_t{}^2]^{-3/2}) \,/\, (1/2\pi p_T)(d^2N/dp_T dy)_p{}^3.$$

Here $\sigma_d = \sqrt{2m_p{}^2} R_d$, and the root-mean-square radius of the deuteron $R_d = 2.1421$ fm [?]. $\sigma_{^3He} = \sqrt{2m_p{}^2} R_{^3He}$ with $R_{^3He} = 1.9661$ fm and $\sigma_t = \sqrt{2m_p{}^2} R_t$ with $R_t = 1.7591$ fm [?]. $m_{p,n}$ denotes the nucleon mass and $m_{d,^3He,t}$ the mass of d, ^{3}He or t.

To further compute B_2 and B_3, the specific form of R_f(p_T) is necessary. Similar to Ref. [?], the dependence of R_f(p_T) on centrality and p_T is considered to factorize into a linear dependence on the cube root of the pseudorapidity density of charged particles (dN_{ch}/d)^{1/3} and a power-law dependence on the transverse mass of the formed light nucleus [?]. Thus we have

R_f(p_T) = a × (dN_{ch}/d)^{1/3} (√(p_T^2 + m_{d,^{3}He,t}^{2}))^b,

where a and b are free parameters. Their values in Pb+Pb collisions at √s_{NN} = 5.02 TeV are (0.70, -0.31) for d and (0.66, -0.31) for ^{3}He and t, determined by reproducing the data of p_T spectra of d and ^{3}He in the most central 0-5% centrality. Here b is set to be centrality independent, consistent with hydrodynamics [?] and STAR measurements of two-pion interferometry in central and semi-central Au+Au collisions [?]. a is also set to be centrality independent, the same as in our previous work [?].

We use the data of dN_{ch}/d from Ref. [?] to evaluate R_f(p_T), and then compute coalescence factors B_2 and B_3.

[Figure 1: see original paper] shows B_2 of d as a function of the transverse momentum scaled by the mass number p_T/2 in different centralities in Pb+Pb collisions at √s_{NN} = 5.02 TeV. Symbols with error bars are experimental data [?] and solid lines are theoretical results of the coalescence model. From [Figure 1: see original paper], one can see that B_2 exhibits an increasing trend from central to peripheral collisions, due to the decreasing scale of the created hadronic system. For a given centrality, B_2 increases as a function of p_T/2. This increased behavior results on one hand from the Lorentz contraction factor γ, which has been studied in Ref. [?]. On the other hand, it results from the decreasing R_f with increasing p_T. The rising behavior of the experimental data as a function of p_T/2 from central to peripheral collisions can be quantitatively described by the coalescence model.

[Figure 2: see original paper] shows B_3 of ^{3}He and $\bar{t}$ as a function of p_T/3 in different centralities in Pb+Pb collisions at √s_{NN} = 5.02 TeV. Symbols with error bars are experimental data [?] and solid lines are theoretical results. Similarly to B_2, experimental data of B_3 also exhibit a rising trend as a function of p_T/3, which is well reproduced by the coalescence model from central to peripheral collisions. [Figure 1: see original paper] and [Figure 2: see original paper] show that the centrality and p_T-dependent behaviors of B_2 and B_3 are simultaneously explained by the coalescence model. Our extracted results for R_f(p_T) can provide quantitative references for future measurements of HBT interferometry radius from two-nucleon correlations. Through light nucleus production, we provide an alternative way to determine the HBT interferometry radius of the hadronic source system.

B. The p_T spectra of light nuclei

The p_T spectra of primordial nucleons are necessary inputs for computing p_T distributions of light nuclei in the coalescence model. We here use the blast-wave model to obtain p_T distribution functions of primordial protons by fitting the experimental data of prompt (anti)protons in Ref. [**?**]. The blast-wave function [**?**] is given by

$(1/2\pi$p_T)(d^2N/dp_{Tdy}) = $_0$ rdr m_T I_0(p_T sinh /T_{kin}) K_1(m_T cosh /T_{kin}),

where r is the radial distance in the transverse plane and R is the fireball radius. I_0 and K_1 are modified Bessel functions, and the velocity profile = $\tanh^{-1}\beta T$ *= tanh*$^{-1}$*[β_s(r/R)*^{n}*]. The kinetic freeze-out temperature* T{kin}, the averaged radial expansion velocity β_T and n are fit parameters. Their values can be found in Ref. [**?**].

[Figure 3: see original paper] shows the p_T spectra of prompt protons plus antiprotons in different centralities in Pb+Pb collisions at √s_{NN} = 5.02 TeV. Symbols with error bars are experimental data [**?**], and dashed lines are results of the blast-wave model. The p_T spectra in different centralities are scaled by different factors for clarity as shown in the figure. For the primordial neutron p_T spectra, we adopt the same as those of primordial protons as we focus on light nucleus production at midrapidity at such high LHC energy that isospin symmetry is well satisfied.

[Figure 4: see original paper] shows the p_T spectra of deuterons in different centralities in Pb+Pb collisions at √s_{NN} = 5.02 TeV. Symbols with error bars are experimental data [**?**] and solid lines are theoretical results. We first calculate the p_T spectra of deuterons in Pb+Pb collisions at √s_{NN} = 5.02 TeV in 0-5%, 5-10%, 10-20%, 20-30%, 30-40%, 40-50%, 50-60%, 60-70%, 70-80% and 80-90% centralities. Different solid lines scaled by different factors for clarity in [Figure 4: see original paper] are our theoretical results. We then compute the p_T spectra of ^{3}He and $\bar{t}$ in Pb+Pb collisions at √s_{NN} = 5.02 TeV in different centralities. Different solid lines in [Figure 5: see original paper] are our theoretical results, which agree with the available data denoted by filled symbols [**?**]. From [Figure 4: see original paper] and [Figure 5: see original paper], one can see that nucleon coalescence is the dominant mechanism for light nucleus production in Pb+Pb collisions at √s_{NN} = 5.02 TeV. More precise measurements for ^{3}He and $\bar{t}$ over a wide p_T range in the future can help further test the coalescence mechanism, especially in peripheral Pb+Pb collisions.

C. Averaged transverse momenta and yield rapidity densities of light nuclei

We here study the averaged transverse momenta p_T and yield rapidity densities dN/dy of d, ^{3}He and $\bar{t}$. Our theoretical results are in the fourth and sixth columns of . Experimental data in the third and fifth columns are from Refs. [**?**, **?**]. A decreasing trend for both p_T and dN/dy from central to peripheral collisions is observed. This is because in more central collisions more energy is deposited in the midrapidity region and collective evolution persists longer.

Theoretical results for d, ^{3}He and $\bar{t}$ are consistent with the corresponding data within experimental uncertainties except for a very slight underestimation for the dN/dy of $\bar{t}$ in peripheral 50-90% collisions. Such underestimation needs to be confirmed by future precise data.

D. Yield ratios of light nuclei

Yield ratios carry information on intrinsic production correlations of different light nuclei and are predicted to have nontrivial behaviors [**?**]. In this subsection, we study the centrality dependence of different yield ratios, such as d/p, ^{3}He/$\bar{p}$, d/p^2, ^{3}He/$\bar{p}^3$ and $\bar{t}$/^{3}He.

[Figure 6: see original paper] (a) and (b) show the dN_{ch}/d dependence of d/p and ^{3}He/$\bar{p}$ in Pb+Pb collisions at √s_{NN} = 5.02 TeV. Filled circles with error bars are experimental data [**?**], and open circles connected with dashed lines to guide the eye are theoretical results. From Eq. (15) we approximately have the p_T-integrated yield ratio

d/p (R_f ^{3}/ γ) (C$_0$ + σ_d^2/ R_f ^{2})^{3/2} / [C$_0$ R_f ^{3}/ γ (γ ^{2} + σ_d^2/ R_f ^{2})^{3/2} (C$_0$ + σ_d^2/ R_f ^{2})^{3/2}] = R_f ^{2}/ γ ^{2},

where angle brackets denote averaged values. Eq. (34) shows that the behavior of d/p is determined by two factors. One is the nucleon number density R_f ^{3}/ γ and the other is the suppression effect from the relative size of the d to the hadronic source system σ *d/ R_f . A similar case holds for ^{3}He/$\bar{p}$. The nucleon number density decreases especially from semi-central to central collisions [**?**], which makes d/p and ^{3}He/$\bar{p}$ decrease with increasing dN*{ch}/d . The relative size σ *d/ R_f decreases and its suppression effect becomes weak in large hadronic systems, which makes d/p and ^{3}He/$\bar{p}$ increase with increasing dN*{ch}/d [**?**]. For very high dN_{ch}/d regions, the difference in suppression extents across different centralities becomes insignificant and the decreasing nucleon number density dominates the behavior of d/p and ^{3}He/$\bar{p}$. For low dN_{ch}/d regions, different suppression extents of the relative size in different centralities make d/p and ^{3}He/$\bar{p}$ increase as a function of dN_{ch}/d . The combined result from the nucleon number density and the suppression effect makes d/p and ^{3}He/$\bar{p}$ first increase from peripheral to semi-central collisions and then decrease from semi-central to central collisions, as shown in [Figure 6: see original paper] (a) and (b).

[Figure 6: see original paper] (c) and (d) show d/p^2 and ^{3}He/$\bar{p}^3$ as a function of dN_{ch}/d in Pb+Pb collisions at √s_{NN} = 5.02 TeV. Filled circles with error bars are experimental data [**?**]. Open circles connected with dashed lines to guide the eye are theoretical results. Both show explicit decreasing trends with increasing dN_{ch}/d , which are very different from the previous d/p and ^{3}He/$\bar{p}$. Recalling that d/p^2 and ^{3}He/$\bar{p}^3$ represent the probability of any pn-pair coalescing into a deuteron and that of any $\bar{p}\bar{p}\bar{n}$ cluster coalescing into ^{3}He, this means it is more difficult for any pn-pair or $\bar{p}\bar{p}\bar{n}$ cluster to recombine into a deuteron or ^{3}He in larger hadronic systems produced in more central collisions.

The yield ratio $\bar{t}/^3$He is proposed as a valuable probe to distinguish thermal production from coalescence production for light nuclei [?]. In the coalescence picture, it is always larger than one and approaches one at large R_f where the suppression effect from the nucleus size can be ignored. The smaller R_f, the larger the deviation of $\bar{t}/^3$He from one. The same holds for $\bar{t}/^3$He. [Figure 7: see original paper] shows $\bar{t}/^3$He as a function of p_T in Pb+Pb collisions at √s_{NN} = 5.02 TeV in different centralities 0-10%, 10-30%, 30-50% and 50-90%. Filled circles with error bars are experimental data [?] and solid lines are theoretical results. The reference line of one is plotted with dotted lines. With increasing p_T, R_f decreases, so our theoretical results increase. This feature is very different from that in the thermal model, where the expectation for this ratio is one [?]. The trend of the data in 0-10%, 10-30%, and 30-50% centralities indicates an increasing hint but a final conclusion is hard to make due to the limited p_T range and large error bars. Data in the peripheral 50-90% centrality seem to decrease, but more precise measurements are needed to confirm. More precise data in the near future can be used to further distinguish production mechanisms of ^{3}He and $\bar{t}$.

The p_T-integrated yield ratio $\bar{t}/^3$He as a function of dN_{ch}/d is shown in [Figure 8: see original paper]. Filled circles with error bars are experimental data [?] and open circles connected with the dashed line to guide the eye are theoretical results. The reference line of one is also plotted with the dotted line. $\bar{t}/^3$He exhibits a decreasing trend. This is because larger dN_{ch}/d , i.e., larger R_f, makes $\bar{t}/^3$He decrease closer to one. Theoretical results of $\bar{t}/^3$He in the coalescence model give a non-flat behavior as a function of dN_{ch}/d . This is due to different relative production suppression between ^{3}He and $\bar{t}$ from their own sizes at different hadronic system scales.

IV. RESULTS OF HYPERTRITON AND Ω-HYPERNUCLEI

In this section, we use the coalescence model in Sec. II to study production of the hypertriton ^{3}_ΛH and Ω-hypernuclei. We give results for the p_T spectra, averaged p_T, and yield rapidity densities of ^{3}_ΛH. We present predictions for different Ω-hypernuclei: H(pΩ^-), H(nΩ^-) and H(pnΩ^-). We propose two groups of observables, both of which exhibit novel behaviors. One group refers to the averaged transverse momentum ratios of light nuclei to the proton and hypernuclei to hyperons. The other is the centrality-dependent yield ratios of light (hyper-)nuclei to the proton (hyperons).

A. The p_T spectra of Λ and Ω^- hyperons

The p_T spectra of Λ and Ω^- hyperons are necessary for computing p_T distributions of ^{3}*ΛH and Ω-hypernuclei. We use the blast-wave model to obtain p_T distribution functions by fitting the experimental data of Λ and* Ω^- *in Pb+Pb collisions at* √*s*{NN} = 5.02 TeV in 0-10%, 10-30%, and 30-50% centralities [?]. They are shown in [Figure 9: see original paper]. Filled symbols with error bars are experimental data [?], and dashed lines are results of the blast-wave model. Values of the blast-wave fit parameters for Λ and Ω^- are in . The p_T spectra in 0-10%, 10-30% and 30-50% centralities are scaled by 20, 2^{-1} and 2^{-2}, respectively, for clarity in the figure. We have also studied the p_T spectra of Λ and Ω^- hyperons with the Quark Combination Model developed by the Shandong group (SDQCM) in another work [?], where the results are consistent with the blast-wave model at low and intermediate p_T regions. We in the following use these Λ and Ω^- hyperons in [Figure 9: see original paper] to compute production of ^{3}_ΛH and Ω-hypernuclei.

B. The results of the ^{3}_ΛH

Based on Eq. (27), we compute the production of ^{3}*ΛH. Considering that experimental measurements of* ^{3}ΛH suggest a halo structure with a d core encircled by a Λ, we first use σ_1 = √(2(m_p+m_n)^2)R_d and σ_2 = √(2(m_d+m_Λ)^2)r*{Λd}. The Λ-d distance r*{Λd} is evaluated via r_{Λd} = √[^{2}/(4 B_Λ)] [?], where is the reduced mass and the binding energy B_Λ is adopted to be the latest and most precise measurement to date: 102 keV [?]. We also consider a spherical shape for ^{3}*ΛH to study the influence of shape on its production. In this case,* σ_1 *= √[4m_{pm}n(m_p+m_n+m_Λ)^2/(3(m_p+m_n)[m_{pm}n(m_p+m_n) + m_{nm}Λ(m_n+m_Λ) + m_Λm_p(m_Λ+m_p)])]R{*^{3}*ΛH} and* σ_2 *= √[4m_{pm}n(m_p+m_n+m_Λ)^2/(3(m_p+m_n)[m_{pm}n(m_p+m_n) + m_{nm}Λ(m_n+m_Λ) + m_Λm_p(m_Λ+m_p)])]R{*^{3}*ΛH}, where the root-mean-square radius R*{^{3}_ΛH} is adopted to be 4.9 fm [?].

[Figure 10: see original paper] shows the p_T spectra of ^{3}*ΛH in 0-10%, 10-30% and 30-50% centralities in Pb+Pb collisions at √s*{NN} = 5.02 TeV. Filled symbols with error bars are experimental data [?]. Solid lines are theoretical results of the coalescence model with a halo structure and dashed lines are those for a spherical shape. The p_T spectra in different centralities are scaled by different factors for clarity as shown in the figure. From [Figure 10: see original paper], one can see that there exists a weak difference in the theoretical results of the p_T spectra between a halo structure and a spherical shape, with the latter giving slightly softer p_T spectra. The results with a halo structure approach the available data better, for both amplitude and shape. This point can also be seen in the averaged transverse momenta p_T and yield rapidity densities dN/dy of ^{3}_ΛH.

presents p_T and dN/dy of ^{3}*ΛH in different centralities in Pb+Pb collisions at √s*{NN} = 5.02 TeV. Experimental data in the seventh column are from Ref. [?]. Theory-4.9 in the third and eighth columns denotes theoretical results with a spherical shape at R_{^{3}_ΛH} = 4.9 fm. Theory-102 in the fourth and ninth columns are theoretical results with a halo structure at B_Λ = 102 keV. Theory-148 in the fifth and tenth columns are theoretical results at a world-averaged value of B_Λ = 148 keV [?]. We also give theoretical results at B_Λ = 410 keV measured by the STAR collaboration [?] in the sixth and eleventh columns.

Clear decreasing trends for p_T and dN/dy from central to semi-central collisions are observed, the same as for light nuclei, due to more energy deposition in the midrapidity region and longer collective evolution in more central collisions.

For the halo structure, with increasing B_Λ, the size of $^3_\Lambda$H decreases, and the suppression effect from the $^3_\Lambda$H size becomes relatively weak. This leads to an increase of dN/dy with increasing B_Λ. Besides dN/dy, such production suppression effect also affects the p_T distribution [?, ?]. This is because the suppression effect becomes stronger with a larger nucleus size in a smaller system. Recalling that $R_f(p_T)$ decreases with p_T, $^3_\Lambda$H production is more suppressed in larger p_T areas in the case of larger $^3_\Lambda$H size. Therefore, there exists a decreasing trend for p_T with decreasing B_Λ, as shown in . This is why the p_T of $^3_\Lambda$H is even smaller than that of the triton while the p_T of Λ is larger than the nucleon.

Due to its small binding energy compared to other light (hyper-)nuclei, $^3_\Lambda$H has a very loosely-bound structure and relatively large size. It would be easily destroyed after its formation from freeze-out nucleons and Λ's. As a result, $^3_\Lambda$H is more likely to be produced later than the kinetic freeze-out time for hadronic matter. In Ref. [?], the dependence of the yield of $^3_\Lambda$H on its freeze-out time was studied and found to be very weak. This suggests that $^3_\Lambda$H abundance is essentially determined when nucleons and Λ's freeze out from the system. Therefore, our coalescence calculations based on the same kinetic freeze-out as light nuclei can still reasonably describe the experimental data of $^3_\Lambda$H.

C. Predictions of Ω-hypernuclei

The nucleon-Ω dibaryon in the S-wave and spin-2 channel is an interesting candidate for a deuteron-like state [?, ?]. The HAL QCD collaboration has reported that the root-mean-square radius of H(pΩ^-) is about 3.24 fm and that of H(nΩ^-) is 3.77 fm [?]. According to Eq. (15), we study their production, where the spin degeneracy factor $g_{H(p\Omega^-)} = g_{H(n\Omega^-)} = 5/8$. [Figure 11: see original paper] shows predictions for their p_T spectra in 0-10%, 10-30% and 30-50% centralities with solid, dashed, and dash-dotted lines, respectively, in Pb+Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV. Different lines are scaled by different factors for clarity as shown in the figure.

presents predictions of the averaged transverse momenta p_T and yield rapidity densities dN/dy of H(pΩ^-) and H(nΩ^-). Both decrease from central to semi-central collisions, similar to light nuclei and $^3_\Lambda$H. The slightly lower results for H(nΩ^-) than H(pΩ^-) come from its slightly larger size.

The H(pnΩ^-) with maximal spin-5/2 is proposed to be one of the most promising partners of t and $^3\Lambda H$ *with multi-strangeness flavor quantum number [?]. With Eq. (27), we study its production and the spin degeneracy factor* $g\{H(pn\Omega^-)\} = 3/8$. As its root-mean-square radius $R_{H(pn\Omega^-)}$ is undetermined, we adopt 1.5, 2.0, and 2.5 fm to perform calculations. [Figure 12: see original paper] shows predictions of the p_T spectra in 0-10%, 10-30% and 30-50% centralities in Pb+Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV. Solid, dashed, and dash-dotted lines denote results with $R_{H(pn\Omega^-)} = 1.5$, 2.0, and 2.5 fm, respectively, which are scaled by different factors for clarity as shown in the figure.

presents predictions of the averaged transverse momenta p_T and yield rapidity densities dN/dy of $H(pn\Omega^-)$. Theory-1.5, Theory-2.0, and Theory-2.5 denote theoretical results at R_{$H(pn\Omega^-)$} = 1.5, 2.0, and 2.5 fm, respectively.

Our predictions in central collisions for $H(p\Omega^-)$ and $H(n\Omega^-)$ are of the same magnitude as BLWC and AMPTC models in Ref. [**?**], and those for $H(pn\Omega^-)$ are of the same magnitude as in Ref. [**?**]. Our predictions in other centralities provide more detailed references for centrality-dependent measurements of these Ω-hypernuclei in future LHC experiments.

D. Averaged transverse momentum ratios and yield ratios

Based on the results of light nuclei and hypernuclei above, we study two groups of interesting observables as powerful probes for the production correlations of different species of nuclei. One group refers to the p_T ratios of light nuclei to the proton and hypernuclei to hyperons. The other is their centrality-dependent yield ratios.

[Figure 13: see original paper] (a) and (b) show the p_T ratios of dibaryon states to baryons and those of tribaryon states to baryons, i.e., p_T $d/$ p_T p, p_T $\{H(p\Omega^-)\}/$ p_T $\{\Omega^-\}$, p_T $\{H(n\Omega^-)\}/$ p_T $\{\Omega^-\}$, and p_T $t/$ p_T p, p_T $\{^3He\}/$ p_T p, p_T $\{^3\Lambda H\}/$ p_T Λ, p_T $\{H(pn\Omega^-)\}/$ p_T $\{\Omega^-\}$. *Open symbols connected by dashed lines to guide the eye are theoretical results of the coalescence model. All these p_T ratios increase as a function of* $dN\{ch\}/d$ due to stronger collective flow in more central collisions. More interestingly, these p_T ratios of light nuclei to nucleons and hypernuclei to hyperons happen to offset the p_T differences of p, Λ and Ω^-. This makes them more powerful for bringing characteristics resulting from the production mechanism to light. Both dibaryon-to-baryon and tribaryon-to-baryon p_T ratios exhibit a reverse hierarchy of nucleus sizes at any centrality, i.e., p_T $\{H(p\Omega^-)\}/$ p_T $\{\Omega^-\}$ $>$ p_T $d/$ p_T p as R_d $<$ R$\{H(p\Omega^-)\}$ $<$ $R\{H(n\Omega^-)\}$, and p_T $t/$ p_T p $>$ p_T $\{^3He\}/$ p_T p $>$ p_T $\{H(pn\Omega^-)\}/$ p_T $\{\Omega^-\}$ $>$ p_T $\{^3\Lambda H\}/$ p_T Λ *as* R_t $<$ $R\{^3He\}$ $<$ R$\{H(pn\Omega^-)\}$ $<$ $R\{^3\Lambda H\}$. *Here we take results of* $H(pn\Omega^-)$ *at* $R\{H(pn\Omega^-)\}$ = 2 fm for exhibition, and those at R_{$H(pn\Omega^-)$} = 1.5, 2.5 fm give the same conclusion: a reverse hierarchy of nucleus size. Such reverse hierarchy comes from stronger production suppression for light (hyper-)nuclei with larger sizes in higher p_T regions. This production property is very different from the thermal model in which these ratios are approximately equal [**?**].

[Figure 13: see original paper] (c) and (d) show yield ratios of dibaryon states to baryons and those of tribaryon states to baryons. Open symbols connected with dashed lines to guide the eye are theoretical results of the coalescence model. Some ratios such as d/p, t/p, $^3He/p$ and $H(pn\Omega^-)/\Omega^-$ decrease while others $H(p\Omega^-)/\Omega^-$, $H(n\Omega^-)/\Omega^-$ and $^3\Lambda H/\Lambda$ *increase as a function of* $dN\{ch\}/d$. From Eqs. (15) and (27), similar to Eq. (34), we approximately have

$H(p\Omega^-)/\Omega^-$ (R_f $^3/$ γ) (C_0 + σ_{$H(p\Omega^-)$}$^2/$ R_f ^{2})^{3/2} / [C_0 R_f $^3/$ γ (γ^2 + $\sigma\{H(p\Omega^-)\}^2/$ R_f^2)^{3/2} (C_0 + $\sigma\{H(p\Omega^-)\}^2/$ R_f ^{2})^{3/2}] =

R_f ^{2}/ γ ^{2},

H(pnΩ^-)/Ω^- (R_f ^{6}/ γ ^{2}) (4C$_0$/3 + $\sigma_1{}^2$/ R_f ^{2})^{3/2} (4C$_0$/3 + $\sigma_2{}^2$/ R_f ^{2})^{3/2} / [C$_0$ R_f ^{3}/ γ (γ ^{2} + $\sigma_1{}^2$/ R_f ^{2})^{3/2} (4C$_0$/3 γ ^{2} + $\sigma_2{}^2$/ R_f ^{2})^{3/2}].

Eqs. (35) and (36) show that behaviors of these two-particle yield ratios closely relate to the nucleon number density R_f ^{3}/ γ and the production suppression effect terms of the relative size of nuclei to hadronic source systems σ_1/ R_f and σ_2/ R_f .

For the limiting case of nuclei with very small (negligible) sizes compared to the hadronic system scale, the dN_{ch}/d -dependent behaviors of their yield ratios to baryons are completely determined by the nucleon number density. For the general case, the term σi/ *R_f suppresses these ratios and such suppression becomes weaker in larger hadronic systems. This makes these yield ratios increase from peripheral to central collisions, i.e., with increasing dN*{ch}/d . The larger the nucleus size, the stronger the increase as a function of dN_{ch}/d . The nucleon density decreases with increasing dN_{ch}/d [**?**], which makes these ratios decrease. As the root-mean-square radii of d, t, ^{3}He and H(pnΩ^-) are about or smaller than 2 fm, the decreasing nucleon density dominates the behaviors of their yield ratios to baryons. But for H(pΩ^-), H(nΩ^-) and ^{3}*ΛH, their root-mean-square radii are larger than 3 fm, and the production suppression effect from their sizes becomes dominant, which leads their yield ratios to baryons to increase as a function of dN*{ch}/d . Such different centrality-dependent behaviors can help determine the sizes of more light nuclei and hypernuclei in future experiments.

V. SUMMARY

We extended the analytical coalescence model previously developed for light nuclei production to include hyperon coalescence to simultaneously study production characteristics of d, ^{3}He, $\bar{t}$, ^{3}_ΛH and Ω-hypernuclei. We derived the formulae for momentum distributions of two baryons coalescing into dibaryon states and three baryons coalescing into tribaryon states. The relationships between dibaryon states and tribaryon states with primordial baryons in momentum space in the laboratory frame were given. The effects of the hadronic system scale and the nucleus's own size on nucleus production were clearly presented.

We applied the extended coalescence model to Pb+Pb collisions at √s_{NN} = 5.02 TeV. We explained the available data of B$_2$ and B$_3$, p_T spectra, averaged transverse momenta and yield rapidity densities of d, ^{3}He, $\bar{t}$, and ^{3}_ΛH measured by the ALICE collaboration. We provided predictions of the p_T spectra, averaged transverse momenta and yield rapidity densities of different Ω-hypernuclei—H(pΩ^-), H(nΩ^-), and H(pnΩ^-)—for future experimental measurements.

More interestingly, we found two groups of novel observables. One refers to the averaged transverse momentum ratios p_T $d/$ p_T p, p_T $\{H(p\Omega^-)\}/$ p_T $\{\Omega^-\}$, p_T $\{H(n\Omega^-)\}/$ p_T $\{\Omega^-\}$, p_T _t/ p_T p, p_T $\{^3\mathrm{He}\}/$ p_T p, p_T $\{^3\Lambda H\}/$ p_T Λ, p_T $\{H(pn\Omega^-)\}/$ p_T $\{\Omega^-\}$. They exhibit a reverse hierarchy according to the sizes of the nuclei themselves at any collision centrality. The other involves the centrality-dependent yield ratios d/p, H(pΩ^-)/Ω^-, H(nΩ^-)/Ω^-, t/p, ^{3}He/p, $^3\Lambda H/\Lambda$, *and* $H(pn\Omega^-)/\Omega^-$. *Some of these yield ratios decrease while others increase as a function of* dN\{ch\}/d . Such different trends are caused by different production suppression degrees from the nucleus sizes. The behaviors of these two groups of ratios in the coalescence mechanism differ from the thermal model. They are powerful observables for probing the production mechanism of light (hyper-)nuclei. They reveal the production relations of different sorts of nuclei in the coalescence framework.

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