
Simulations of momentum correlation functions of light (anti)nuclei in relativistic heavy-ion collisions at p s NN = 39 GeV postprint

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Abstract

Momentum correlation functions of light (anti)nuclei formed via the coalescence mechanism of (anti)nucleons are calculated for several relativistic heavy-ion collision systems—namely B + B, O + O, Ca + Ca, and Au + Au—at different centralities and a center-of-mass energy of 39 GeV within the framework of A Multi-Phase Transport (AMPT) model complemented by the Lednický and Lyuboshitz analytical method. Momentum correlation functions for both identical and non-identical light (anti)nuclei are constructed in the aforementioned collision systems at such high collision energies. The results suggest that emission of light (anti)nuclei originates from a source of smaller spacetime extent in more peripheral collisions. The effect of system-size on the momentum correlation functions of identical or non-identical light (anti)nuclei is also explored in several central collisions. The results indicate that the emission source-size of light (anti)nuclei pairs, as deduced from their momentum correlation functions and system-size, is self-consistent. Momentum correlation functions of non-identical light nuclei pairs, gated on velocity, are employed to infer their average emission sequence. The results indicate that protons are emitted, on average, on a similar time scale to neutrons but earlier than deuterons or tritons in the small relative momentum region. Additionally, a larger interval in the average emission order among them is observed in more central collisions and smaller collision systems.

Full Text

Preamble

Simulations of momentum correlation functions of light (anti)nuclei in relativistic heavy-ion collisions at $\sqrt{s_{NN}} = 39$ GeV

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Momentum correlation functions of light (anti)nuclei formed by the coalescence mechanism of (anti)nucleons are calculated in several relativistic heavy-ion collision systems at different centralities at center-of-mass energy $\sqrt{s_{NN}} = 39$ GeV within the framework of A Multi-Phase Transport (AMPT) model complemented by the Lednický and Lyuboshitz analytical method. Momentum correlation functions for identical or nonidentical light (anti)nuclei are constructed in the above collision systems at such high collision energy. The results suggest that emission of light (anti)nuclei occurs from a source of smaller space-time extent in more peripheral collisions. The effect of system size on the momentum correlation functions of identical or nonidentical light (anti)nuclei is also explored in several central collisions. The results indicate that the emission source size of light (anti)nuclei pairs deduced from their momentum correlation functions and system size is self-consistent. Momentum correlation functions of nonidentical light nuclei pairs gated on velocity are applied to infer the average emission sequence of them. The results indicate that protons are emitted on average on a similar time scale with neutrons but earlier than deuterons or tritons in the small relative momentum region. In addition, a larger interval of the average emission order among them is observed in large centrality and smaller system collisions.

INTRODUCTION

In heavy-ion collisions (HICs), the two-particle momentum correlation function, different from its original application in astronomy [1, 2], has been normally utilized to extract space-time information of the emission source and probe the dynamical evolution of nuclear collisions across an extensive energy range [3–12]. Many different studies on two-particle momentum correlation functions in intermediate-energy HICs can also be found in literature, e.g., Refs. [11, 13–25], which include the momentum correlation functions of neutron, proton, and light charged particle (LCP) pairs. Multi-variable dependences of the momentum correlation functions, such as impact parameters, total momentum of particle pairs, isospin of the emission source, nuclear symmetry energy, nuclear equation of state (EOS), and in-medium nucleon-nucleon cross section (NNCS), contain a wealth of information about the space-time characteristics of intermediate-energy HICs. In high-energy HICs, two-hadron momentum correlation functions, also called Hanbury Brown-Twiss (HBT) interferometry, were also well measured and some interesting properties of the emission source were extracted [26, 27]. Oscillations of the extracted HBT radii versus emission angle indicate sources elongated perpendicular to the reaction plane. The results indicate that the initial shape could be identified even though the pressure and expansion of the collision system. Furthermore, interaction between antiprotons has also been measured with momentum correlation functions and the equality of interactions between p-p and $\bar{p}$-$\bar{p}$ was approved by the STAR Collaboration [28]. The interaction property of particle pairs has been discussed for other particles, for instance Λ pairs [29], proton-Ω and proton-Ξ pairs [30, 31], with the same momentum correlation technique. Furthermore, measurements of momentum correlation functions for nonidentical nucleons and light clusters can be used to characterize the mean emission sequence of them, which was first proposed in Ref. [32]. Theoretical studies have been extended to different kinds of nonidentical particle pairs, for instance p-d, n-p [33–36], π-p [37], K^+-K^- [38], d-t [11, 22], as well as ^{3}He-α particles [39] in intermediate-energy HICs.

In this work we extend, for the first time, the momentum correlation functions of light (anti)nuclei to ultra-relativistic heavy-ion collisions simulated by A Multi-Phase Transport (AMPT) model [40, 41] coupled with a dynamical coalescence model [42–44], specifically at $\sqrt{s_{NN}} = 39$ GeV. Different gating conditions such as centrality gates, system-size gates, and velocity gates are applied to the momentum correlation functions of light (anti)nuclei pairs. In particular, we report on the indication of the emission chronology of protons, deuterons, and tritons which can be deduced from their corresponding momentum correlation functions in ultra-relativistic HICs at $\sqrt{s_{NN}} = 39$ GeV. The emission sequence inferred from the correlation functions is expected to be measurable in future experiments to verify our deduction from the coalescence picture.

The rest of this article is organized as follows. In Section II A and II B, we briefly describe the A Multi-Phase Transport model [40, 41] and the coalescence model [42–44], then introduce how to calculate the momentum correlation functions of particle pairs using the Lednický and Lyuboshitz analytical formalism [3, 45–48] in Section II C. In Section III, we summarize the simulated results of the light (anti)nuclei momentum correlation functions gated on various parameters in relativistic heavy-ion collisions. Section III A compares the results of proton-proton and proton-antiproton momentum correlation functions with experimental data from the RHIC-STAR collaboration. From Section III B to III D, identical and nonidentical light (anti)nuclei momentum correlation functions gated on different conditions are systematically discussed, respectively. Finally, a summary and outlook are given in Section IV.

II. MODELS AND FORMALISM

A. AMPT model

To obtain phase-space distributions of (anti)particles, A Multi-Phase Transport model [40, 41] is used as the event generator, which has been applied successfully for studying heavy-ion collisions at relativistic energies, e.g., [43, 44, 49–57]. We briefly review the main components of the AMPT model used in the present work. In the version of AMPT, the initial phase-space information of partons is generated by the heavy-ion jet interaction generator (HIJING) model [58, 59]. The interaction between partons is then simulated by Zhang's parton cascade (ZPC) model [60]. During the hadronization process, a quark coalescence model is used to combine partons into hadrons [61–63]. Then, the hadronic rescattering evolution is described by a relativistic transport (ART) model [64].

In this paper, the collisions of ^{10}B+^{10}B, ^{20}Ca+^{40}Ca for the 0–10% central collisions at mid-rapidity ($|y| < 0.5$) as well as ^{197}Au+^{197}Au at the same mid-rapidity for five centralities of 0–10%, 10–20%, 20–40%, 40–60%, and 60–80% at $\sqrt{s_{NN}} = 39$ GeV are simulated. The phase-space distributions of (anti)particles are selected at the final stage in the hadronic rescattering process (ART model [64]) considering baryon-baryon, baryon-meson, and meson-meson elastic and inelastic scatterings, as well as resonance decay or weak decay. The transverse momentum spectra of light (anti)nuclei have been successfully reproduced by the AMPT model with the maximum hadronic rescattering time of 100 fm/c [44]. Therefore, the same maximum hadronic rescattering time is used for most calculations in this work except for a quantitative comparison with preliminary p-p and p-$\bar{p}$ data from the STAR collaboration in Sec. III A.

B. Coalescence model

In our model calculations, light (anti)clusters such as (anti)deuterons and tritons are constructed using the coalescence model as follows [65, 66]. The coalescence model has been widely used in describing the production of light clusters in intermediate [67–71] and high-energy [72, 73] heavy-ion collisions. In the model, the probability for producing an M-nucleon cluster is determined by its Wigner phase-space density and the nucleon phase-space distribution at the freeze-out stage [42]. The multiplicity of an M-nucleon cluster in transport model simulations for heavy-ion collisions is given by

$$N_M = G \int d\vec{r}_{i1} d\vec{k}_{i1} \cdots d\vec{r}_{iM-1} d\vec{k}_{iM-1} \sum_{i1>i2>\cdots>iM} \langle \rho_W(\vec{r}_{i1}, \vec{k}_{i1}, \cdots, \vec{r}_{iM-1}, \vec{k}_{iM-1}) \rangle$$

where $\vec{r}_{i1}, \vec{r}_{iM-1}$ and $\vec{k}_{i1}, \vec{k}_{iM-1}$ are the relative coordinates and momentum in the M-nucleon rest frame, and the spin-isospin statistical factor G is 3/8 for (anti)deuteron and 1/3 for triton [42]. In addition, ρ_W is the Wigner density function, which is different for all kinds of particles. Therefore, we will calculate separately the Wigner phase-space density of (anti)deuteron and triton in detail.

The Wigner phase-space density of (anti)deuteron is constructed by

$$\rho_d(\vec{r}, \vec{k}) = 8 \sum_i c_i \exp\left(-2\omega_i r^2 - \frac{k^2}{2\omega_i}\right) \times \exp\left(\sum_{i>j} \frac{4\omega_i \omega_j}{(\omega_i + \omega_j)^2} \exp\left(-\frac{\omega_i + \omega_j}{2} \left(\frac{1}{2\omega_i} - \frac{1}{2\omega_j}\right)^2\right) \exp\left(\frac{4\omega_i \omega_j}{\omega_i + \omega_j} \vec{r} \right.\right.$$

where $\vec{k}=(\vec{k}_1-\vec{k}_2)/2$ is the relative momentum and $\vec{r}=(\vec{r}_1-\vec{r}_2)$ is the relative coordinate of (anti)proton and (anti)neutron.

The Wigner phase-space density of triton is constructed by a spherical harmonic oscillator [42, 43, 74],

$$\rho_t(\vec{\rho},\vec{\lambda},\vec{k}_\rho,\vec{k}_\lambda)=\int d\vec{R}_1 d\vec{R}_2 \left\langle \vec{R}_1,\vec{\lambda}+\frac{\vec{R}_2}{2}\middle|\psi_t\right\rangle \left\langle \psi_t\middle|\vec{R}_1,\vec{\lambda}-\frac{\vec{R}_2}{2}\right\rangle \times\exp(-i\vec{k}_\rho\cdot\vec{R}_1)\exp(-i\vec{k}_\lambda\cdot\vec{R}_2)=\frac{8^2}{\pi^4 b^{12}}\exp\Bigg($$

where $\vec{\rho}$ and $\vec{\lambda}$ are relative coordinates, $\vec{k}_\rho$ and $\vec{k}_\lambda$ are the relative momenta in the Jacobi coordinate.

The above parameters of the Gaussian fit coefficient c_i and ω_i for (anti)deuteron as well as b for triton are given in Ref. [42]. Based on the phase-space information of light (anti)cluster obtained by the above coalescence model, the momentum correlation functions of (non)identical light (anti)cluster pairs can be discussed in the following of this paper.

C. Lednický and Lyuboshitz technique

Finally, we briefly review the technique of the two-particle momentum correlation function proposed by Lednický and Lyuboshitz [45–47]. The method for calculating the two-particle momentum correlation function in heavy-ion collisions is based on the principle that when two particles are emitted at small relative momentum, their momentum correlation function is determined by the space-time characteristics of the production processes owing to the effects of quantum statistics and final-state interactions [3, 48]. Therefore, the two-particle momentum correlation function can be expressed through a square of the symmetrized Bethe-Salpeter amplitude averaged over the four coordinates of the emitted particles and the total spin of the two-particle system, which represents the continuous spectrum of the two-particle state. In this method, the final-state interaction of the particle pairs is assumed independent in the production process.

According to the conditions in Ref. [33], the momentum correlation function of two particles can be written as the expression:

$$C(k^*)=\frac{\int S(r^*,k^*)|\Psi_{k^*}(r^*)|^2 d^{4r^*}}{\int S(r^*,k^*)d^{4r^*}}$$

where $r^*=x_1-x_2$ is the relative distance of the two particles in the pair rest frame at their kinetic freeze-out, k^* is half of the relative momentum between two particles in the pair rest frame, $S(r^*,k^*)$ is the probability to emit a particle pair with given r^* and k^*, i.e., the source emission function, and $\Psi_{k^*}(r^*)$ is the reduced Bethe-Salpeter amplitude which can be approximated by the outer solution of the scattering problem [28, 75]. This approximation is valid on condition $|t^*| \ll m(r^*)^2$, which is well fulfilled for sufficiently heavy particles like protons or kaons and reasonably fulfilled even for pions [46]. In the above limit, the asymptotic solution of the wave function of the two charged particles approximately takes the expression:

$$\Psi_{k^*}(r^*) = e^{i\delta_c}\sqrt{A_c(\lambda)} \times \left[e^{-ik^*r^*}F(-i\lambda, 1, i\xi) + f_c(k^*)\tilde{G}(\rho, \lambda)\right]$$

In the above equation, $\delta_c = \arg\Gamma(1+i\lambda)$ is the Coulomb s-wave phase shift with $\lambda = (k^*a_c)^{-1}$ where a_c is the two-particle Bohr radius, $A_c(\lambda) = 2\pi\lambda[\exp(2\pi\lambda) - 1]^{-1}$ is the Coulomb penetration factor, and its positive (negative) value corresponds to repulsion (attraction). $\tilde{G}(\rho, \lambda) = \sqrt{A_c(\lambda)}[G_0(\rho, \lambda) + iF_0(\rho, \lambda)]$ is a combination of regular (F_0) and singular (G_0) s-wave Coulomb functions [46, 47]. $F(-i\lambda, 1, i\xi) = 1 + (-i\lambda)(i\xi)/1!^2 + (-i\lambda)(-i\lambda + 1)(i\xi)^2/2!^2 + \cdots$ is the confluent hypergeometric function with $\xi = k^*r^* + \rho$, $\rho = k^*r^*$.

$f_c(k^*) = [K_c(k^*) - h(\lambda) - ik^*A_c(\lambda)]^{-1}$ is the s-wave scattering amplitude renormalized by the long-range Coulomb interaction, with $h(\lambda) = \lambda^2\sum_{n=0}^{\infty}(n^2 + \lambda^2)^{-1} - C - \ln[\lambda]$ where $C = 0.5772$ is the Euler constant. $K_c(k^*) = -\frac{1}{f_0} + \frac{1}{2}d_{0k}^{*2} + Pk^{*4} + \cdots$ is the effective range function, where d_0 is the effective radius of the strong interaction, f_0 is the scattering length, and P is the shape parameter. The parameters of the effective range function are important parameters characterizing the essential properties of the final-state interactions, and can be extracted from the correlation function measured experimentally [28, 34, 76, 77]. Table I shows the parameters of the effective range function for different particle pairs in the present work.

TABLE I. Experimental determination of the effective range function parameters for n-n ($\bar{n}$-$\bar{n}$), p-p ($\bar{p}$-$\bar{p}$), t-t, n-p ($\bar{n}$-$\bar{p}$), p-d ($\bar{p}$-$\bar{d}$), p-t and d-t systems [28, 76, 77].

System	Spin	f_0 (fm)	d_0 (fm)	P (fm^3)
n-n ($\bar{n}$-$\bar{n}$)		1×10^{-6}	1×10^{-6}	1×10^{-6}
p-p ($\bar{p}$-$\bar{p}$)				
n-p ($\bar{n}$-$\bar{p}$)				
p-d ($\bar{p}$-$\bar{d}$)				

In the above table, for n-n ($\bar{n}$-$\bar{n}$) and n-p ($\bar{n}$-$\bar{p}$) momentum correlation functions which include uncharged particles, the Coulomb penetration factor ($A_c(\lambda)$) is not considered and only the short-range particle interaction works. For the momentum correlation functions of charged particles such as p-$\bar{p}$, p-p ($\bar{p}$-$\bar{p}$), d-d ($\bar{d}$-$\bar{d}$), t-t, p-d ($\bar{p}$-$\bar{d}$), p-t and d-t, both the Coulomb interaction and the short-range interaction dominated by the s-wave interaction are taken into account. The momentum correlation function of p-p ($\bar{p}$-$\bar{p}$) particle pairs is dominantly contributed by only the singlet ($S = 0$) s-wave final-state interactions while both spins $1/2$ and $3/2$ contribute in the case of p-d ($\bar{p}$-$\bar{d}$) system. Moreover, for (anti)deuteron-(anti)deuteron momentum correlation function, a parametrization of the s-wave phase shifts δ has been used from the solution of $K_c(k^*) = \cot\delta$ for each total pair spin $S = 0, 1, 2$. Note that the effective range function for the total spin $S = 1$ is irrelevant, since it does not contribute due to the quantum statistics symmetrization.

III. ANALYSIS AND DISCUSSION

A. Comparison between our simulations and preliminary data

Fig. 1 [Figure 1: see original paper] presents results of p-p and p-$\bar{p}$ correlation functions for three different centrality classes of 0–10%, 10–30%, and 30–70% calculated by the AMPT model in Au + Au collisions at $\sqrt{s_{NN}} = 39$ GeV. Within the cut of transverse momentum p_t and rapidity y, we confront the experimental data with the predictions of the AMPT model combined with Lednický and Lyuboshitz code. When the phase-space information of nucleons at the maximum hadronic rescattering time of 700 fm/c is selected from the AMPT model, it is found that the results can well describe the experimental data for the momentum correlation functions of p-p and p-$\bar{p}$ from the RHIC-STAR collaboration [78, 79], especially in more central collisions. Considering that the preliminary experimental results were not corrected by feed-down effect corrections [78, 79], the real correlation functions for primary p-p and p-$\bar{p}$ could be much stronger. In this case, using a much longer hadronic rescattering time of 700 fm/c in the AMPT model might be a reasonable choice for making quantitative comparison with feed-down uncorrected data since the system will become more expanded and weakly correlated among particles after longer hadronic rescattering time in AMPT. However, the quantitative reproduction is not our main concern in the present work. In the following calculations, we fixed the maximum hadronic rescattering time at 100 fm/c and presented systematic results among different light (anti)nuclei.

B. Centrality and system-size dependence of identical light (anti)nuclei momentum correlation functions

The centrality dependence of the two-particle momentum correlation function can systematically investigate the contributions from the system size and particle interactions on the correlations. Fig. 2 [Figure 2: see original paper] (a) and (c) presents the momentum correlation functions of identical (anti)particle pairs (n-n ($\bar{n}$-$\bar{n}$) and p-p ($\bar{p}$-$\bar{p}$)) for ^{197}Au + ^{197}Au collisions at different centralities of 0–10%, 10–20%, 20–40%, 40–60%, and 60–80% at $\sqrt{s_{NN}} = 39$ GeV. The momentum correlation functions of (anti)neutron pairs exhibit more than unity in Fig. 2 (a), which is caused by the attractive s-wave interaction between the two (anti)neutrons. In Fig. 2 (c), the shape of the (anti)proton-(anti)proton momentum correlation functions looks as expected from the interplay between quantum statistical (QS) and final state interactions (FSI) and is consistent with previous results [13, 28, 34]. The (anti)proton-(anti)proton momentum correlation functions exhibit less than unity at low relative momentum q in Fig. 2 (c), which is mainly caused by the Coulomb repulsion between the (anti)proton pairs. With increasing relative momentum, the attractive s-wave interaction between the two (anti)protons gives rise to a maximum of the (anti)proton-(anti)proton momentum correlation functions at q around 0.020 GeV in Fig. 2 (c). The antiproton-antiproton momentum correlation functions show a similar structure with proton pairs, resulting from the same attractive interaction between two antiprotons [28]. Fig. 2 (a) and (c) compare five centralities of 0–10%, 10–20%, 20–40%, 40–60%, and 60–80% for the two-(anti)particle momentum correlation functions. The enhancement strength of the n-n ($\bar{n}$-$\bar{n}$) and p-p ($\bar{p}$-$\bar{p}$) momentum correlation functions is observed in peripheral selection. These results indicate that (anti)particle emission occurs from a source of smaller space-time extent in peripheral collisions.

In addition, the effect of system size on the momentum correlation functions of (anti)particles is also investigated by four different systems, namely ^{10}B+^{10}B, ^{20}Ca+^{40}Ca, and ^{197}Au+^{197}Au, in central collisions. In Fig. 2 (b) and (d), the n-n ($\bar{n}$-$\bar{n}$) and p-p ($\bar{p}$-$\bar{p}$) momentum correlation functions appear very sensitive to system size and an enhancement strength is observed when particle pairs are emitted from smaller system collisions. This enhancement strength of the momentum correlation functions for particle pairs is a physical effect stemming from the smaller space-time extent of the emission source [8]. Therefore, the emission source size of particle pairs obtained from their momentum correlation functions and system size is self-consistent.

Figure 3 [Figure 3: see original paper] shows the centrality and system-size dependences of the momentum correlation functions for light (anti)clusters under similar conditions as in Fig. 2. Figure 3 (a) and (c) present the momentum correlation functions of d-d ($\bar{d}$-$\bar{d}$) and t-t for ^{197}Au + ^{197}Au collisions at different centralities of 0–10%, 10–20%, 20–40%, 40–60%, and 60–80% at $\sqrt{s_{NN}}$ = 39 GeV. The d-d ($\bar{d}$-$\bar{d}$) momentum correlation functions exhibit less than unity at lower relative momentum q in Fig. 3 (a) and (b), which is caused by the Coulomb repulsion. Then, with increasing relative momentum q, the anti-correlation between two-(anti)deuteron pairs becomes more complex. The two-triton momentum correlation functions are less than unity with increasing relative momentum q as shown in Fig. 3 (c) and (d), which is caused by only the Coulomb potential in the Lednický and Lyuboshitz code [45–47]. The antideuteron-antideuteron momentum correlation function also shows an exactly similar shape with deuteron pairs due to the similar phase-space distributions between deuteron and antideuteron. Due to significantly lower yields of tritons which induce too large errors, the antitriton-antitriton momentum correlation function is not shown in the present work, which should be observed as the same trend with triton pairs. Fig. 3 (a) and (c) also compare five centralities of 0–10%, 10–20%, 20–40%, 40–60%, and 60–80% for the momentum correlation functions of two light (anti)clusters. The more suppression of the d-d ($\bar{d}$-$\bar{d}$) and t-t correlation functions is clearly visible in peripheral selection.

These results also indicate that light (anti)cluster emission occurs from a source of smaller space-time extent for peripheral collisions, which is similar to Fig. 2 (a) and (c). In Fig. 3 (b) and (d), an enhancement strength of the momentum correlation function for d-d ($\bar{d}$-$\bar{d}$) and t-t is also observed when light (anti)cluster pairs are emitted from smaller systems. However, for small systems such as B and O, the sensitivity seems to disappear.

C. Nonidentical light (anti)nuclei momentum correlation functions gated on centrality and system size

Now we investigate centrality and system-size dependence of the nonidentical (anti)particle momentum correlation functions, such as n-p ($\bar{n}$-$\bar{p}$), p-$\bar{p}$, p-d ($\bar{p}$-$\bar{d}$), p-t and d-t. Fig. 4 (a) and (c) show results for the momentum correlation functions of n-p ($\bar{n}$-$\bar{p}$) and p-$\bar{p}$ for the same centrality classes as Fig. 2. The same centrality dependence is also clearly seen in Fig. 4 (a) and (c). Because of the strong attractive final state interaction between n and p, the n-p ($\bar{n}$-$\bar{p}$) momentum correlation functions show a strong positive correlation for small values of the relative momentum q in Fig. 4 (a) and (b). Fig. 4 (c) shows results for proton-antiproton momentum correlation functions, which are different from the results for proton pairs in Fig. 2 (c), however, qualitatively agree with the experimental results in Ref. [78, 79]. In addition, Fig. 4 (b) and (d) show system-size dependence of n-p ($\bar{n}$-$\bar{p}$) and p-$\bar{p}$ momentum correlation functions, which is almost unanimous with the identical (anti)particle ones in Fig. 2 (b) and (d). We can also observe an enhancement strength of particle pair momentum correlation functions in smaller systems.

In the same way, we also investigate the effect of different centralities and system size on the momentum correlation functions of nonidentical light (anti)nuclei. The p-d ($\bar{p}$-$\bar{d}$), p-t and d-t momentum correlation functions in Fig. 5 (a), (c) and (e) are all characterized by an anti-correlation. For the p-d ($\bar{p}$-$\bar{d}$) momentum correlation functions in Fig. 5 (a), the anti-correlation shape is a little different from the proton-deuteron momentum correlation function in intermediate-energy heavy-ion collisions [34, 35], indicating a competition between the s-wave attraction and the Coulomb repulsion. The correlation functions of p-t and d-t in Fig. 5 (c) and (e) also display the trend of below unity due to the dominant Coulomb repulsion, which is similar to previous results in intermediate-energy heavy-ion collisions [34, 35]. In Fig. 5 (b), the system-size dependence of p-d ($\bar{p}$-$\bar{d}$) momentum correlation functions is shown, while we can observe an enhancement of p-d ($\bar{p}$-$\bar{d}$) momentum correlation function in smaller systems. In Fig. 5 (d) and (f), the p-t and d-t momentum correlation functions appear more sensitive to system size only in large systems such as Au and Ca.

D. Velocity selected nonidentical light nuclei momentum correlation functions

The momentum correlation functions of unlike particles can provide an independent constraint on their mean emission order by simply making velocity selections [22, 32, 33, 80, 81]. The principle of comparing the velocity-gated momentum correlation functions for the nonidentical particle pair to infer their average emission order is as follows. Here the two nonidentical particles are named "a" and "b", respectively. If the velocity of "a" particle is lower than "b" particle, the (anti)correlation will be stronger when the "a" particle is emitted on average earlier than the "b" particle, because the space-size between them is reduced during the flight and the final-state interaction (FSI) is enhanced, and vice versa. In addition, the velocity difference (Δv) spectrum between the two nonidentical particles is also sensitive to the mean emission order.

Fig. 6 [Figure 6: see original paper] presents the velocity-gated momentum correlation functions and velocity difference (Δv) spectra of unlike particle pairs *n*-*p* and p-$\bar{p}$ for ^{197}Au + ^{197}Au collisions at different centralities of 0–10%, 10–20%, 20–40%, 40–60%, and 60–80% at $\sqrt{s_{NN}} = 39$ GeV. In Fig. 6 (a) and (c), the centrality dependence on the velocity-gated momentum correlation functions of *n*-*p* and p-$\bar{p}$ are similar to Fig. 4. In Fig. 6 (a), the momentum correlation function for *n*-*p* pair with $v_n > v_p$ is similar to one with the reverse situation. The symmetry of velocity difference (Δv) spectra for *n*-*p* pairs is shown in Fig. 6 (b). The results demonstrate that the average emission sequence of neutrons and protons are almost the same and have no sensitivity to centrality. In Fig. 6 (c), the momentum correlation function for p-$\bar{p}$ pair with $v_p > v_{\bar{p}}$ is slightly higher than one with the reverse situation. The slight asymmetry of velocity difference (Δv) spectra for p-$\bar{p}$ pairs is shown in Fig. 6 (d). The corresponding relation indicates that the mean order of emission sequence between proton and antiproton may be a little different and also has no sensitivity to centrality.

In Fig. 7 (a), the momentum correlation functions for *n*-*p* pairs with $v_n > v_p$ are always similar to one with the reverse situation with increasing system size. The symmetry of velocity difference (Δv) spectra for *n*-*p* pairs in different systems is shown in Fig. 7 (b). The comparison of velocity-gated momentum correlation functions indicates that the average emission sequence between neutrons and protons can be always identical for different centrality and system size, which are also shown by their ratios in Fig. 8 (a) and (b). In Fig. 7 (c) and (d), the comparison of velocity-gated momentum correlation functions for p-$\bar{p}$ indicates that the mean order of emission sequence between protons and antiprotons may be a little different and has no dependence on system size, which are also shown by their ratios in Fig. 8 (c) and (d).

Fig. 9 [Figure 9: see original paper] and Fig. 10 [Figure 10: see original paper] also show centrality and system-size dependence of velocity-gated momentum correlation functions and velocity difference (Δv) spectra of *p*-*d*, *p*-*t* and *d*-*t* pairs, respectively. For *p*-*d* and *p*-*t* pairs, the momentum correlation functions with $v_p < v_d$ ($v_p < v_t$) are stronger than the one with the reverse situation $v_p > v_d$ ($v_p > v_t$) in Fig. 9. The comparison of the two anti-correlation strengths gives that the mean order of emission that protons are emitted on average earlier than deuterons and tritons according to the above criteria. The similar trend for *d*-*t* pairs is not obvious, where the momentum correlation function with $v_d < v_t$ is stronger and deuterons are emitted on average earlier than tritons especially in peripheral collisions. However, the average emission sequence of protons, deuterons, and tritons is opposite to the emission order in previous results for intermediate-energy heavy-ion collisions [11, 34, 35, 80]. At the same time, Fig. 9 presents velocity difference spectra for *p*-*d*, *p*-*t* and *d*-*t* pairs, respectively. The velocity difference spectra are all asymmetric due to the mean emission order. In addition, an enhancement difference between the momentum correlation functions for *p*-*d* (*p*-*t* or *d*-*t*) pairs with $v_p > v_d$ ($v_p > v_t$ or $v_d > v_t$) and ones in the reverse situation with larger centrality manifests the larger interval of the mean emission order for unlike light nuclei in peripheral collisions. Their ratios in Fig. 11 (a), (c) and (e) can also illustrate the above phenomenon. The system-size dependence for *p*-*d*, *p*-*t* and *d*-*t* pairs can be found that the momentum correlation function with $v_p < v_d$ ($v_p < v_t$ or $v_d < v_t$) is stronger than the one with the reverse situation $v_p > v_d$ ($v_p > v_t$ or $v_d > v_t$) in Fig. 10. Correspondingly, the velocity difference spectra for *p*-*d*, *p*-*t* and *d*-*t* pairs are all asymmetric about $\Delta v = 0$ caused by the average emission order in Fig. 10. Therefore, protons are emitted on average earliest and deuterons are emitted on average earlier than tritons in smaller system-size collisions. The system-size dependence of the velocity-gated momentum correlation functions is also clearly seen by their ratios in Fig. 11. With decreasing system size, we can also observe an enhancement difference between the momentum correlation functions for *p*-*d* (*p*-*t* or *d*-*t*) pair with $v_p > v_d$ ($v_p > v_t$ or $v_d > v_t$) and one with the reverse situation in Fig. 11 (b), (d) and (f).

IV. SUMMARY

In summary, with the AMPT model complemented by the Lednický and Lyuboshitz analytical method, we have constructed the momentum correlation functions of light (anti)nuclei formed by the coalescence mechanism of (anti)nucleons at different centrality and system size in $\sqrt{s_{NN}} = 39$ GeV heavy-ion collisions. We present a comparison of proton-proton and proton-antiproton momentum correlation functions with experimental data from the RHIC-STAR collaboration [78, 79]. Taking the same transverse momentum and rapidity phase space coverage corresponding to the experimental situation as well as the maximum hadronic rescattering time of 700 fm/c in AMPT, it is found that the *p*-*p* and p-$\bar{p}$ momentum correlation functions simulated by the present model can match the experimental data. We further study centrality and system-size dependence of momentum correlation functions for identical and nonidentical light (anti)nuclei pairs, respectively, under the condition of the maximum hadronic rescattering time of 100 fm/c in AMPT. The shape of momentum correlation functions for light (anti)nuclei pairs is consistent with previous works [13, 28, 34, 35, 78, 79], which is caused by both QS and FSI. The similar structure between light nuclei momentum correlation functions and anti-ones indicates that the interaction between them is the same, which has been confirmed in Ref. [28] only for proton and antiproton.

The centrality dependence of momentum correlation functions for light (anti)nuclei is investigated by ^{197}Au + ^{197}Au collisions at five different centralities of 0–10%, 10–20%, 20–40%, 40–60%, and 60–80% at $\sqrt{s_{NN}}$ = 39 GeV. It is found that with increasing centralities from central to peripheral, the momentum correlation functions for light (anti)nuclei become stronger, which are probably emitted from a smaller source. The momentum correlation functions of light (anti)nuclei are observed to be sensitive to system size through studying ^{10}B+^{10}B, ^{20}Ca+^{40}Ca, and ^{197}Au+^{197}Au in central collisions, and the indicated emission source size of light (anti)nuclei obtained is self-consistent with their system size.

Momentum correlation functions between nonidentical light nuclei can provide important information about the average emission sequence of them. The average emission time scale between neutrons and protons is almost identical. However, heavier light clusters (deuterons or tritons) are emitted later than protons in the small relative momentum region. In the future we can explore further the energy dependence on the average emission sequence of light nuclei and understand the physical interpretation.

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