Effects of Ptot-gated and velocity-gated on light particle momentum correlations in intermediate-energy heavy-ion collisions Postprint

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Abstract

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Full Text

Preamble

Effects of Ptot-gated and velocity-gated on light particle momentum correlations in intermediate energy heavy-ion collision

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Momentum correlation functions at small relative momenta are calculated for light particles (n, p, d, t) emitted from ^{197}Au + ^{197}Au collisions at different impact parameters and beam energies within the framework of the isospin-dependent quantum molecular dynamics model complemented by the Lednický and Lyuboshitz analytical method. We first verify that our model reproduces the FOPI data of proton-proton momentum correlation across a wide energy range from 0.4A GeV to 1.5A GeV. We then explore additional physical insights through the emission times and momentum correlations among different light particles, with particular emphasis on the effects of total pair momentum among different light particles, impact parameters, and in-medium nucleon-nucleon cross section. Both two-deuteron and two-triton correlation functions exhibit anti-correlation due to final-state interaction, and they are affected by in-medium nucleon-nucleon cross section for higher total momentum particle pairs, but not for lower momentum ones. In addition, impact parameter and in-medium nucleon-nucleon cross section dependences of the emission source radii are extracted by fitting the momentum correlation functions. The results indicate that momentum correlation functions gated with total pair momentum are stronger for smaller in-medium nucleon-nucleon cross section factor ( ) or impact parameter (b). Non-identical particle correlations (np, pd, pt, and dt) are also investigated through velocity-gated correlation functions that provide information about particle emission sequences, with results indicating that heavier particles (deuteron/triton) are, on average, emitted earlier than protons in the small relative momentum region.

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Introduction

Two-particle momentum correlation functions at small relative momenta are sensitive to the space-time structure of particles at freeze-out and therefore to the characteristics of the particle emission source [1–13]. At relativistic energies, two-particle correlation functions provide a valuable tool for measuring freeze-out properties of partonic or hadronic systems [14–19] as well as interaction parameters between particle pairs [20–24]. In the intermediate-energy region, the two-proton correlation function has primarily served as a probe for space-time properties such as source size and emission time in nuclear reactions [25–27]. Numerous investigations of the two-proton correlation function have been conducted through experiments and explored with various models, including effects of impact parameter [28, 29], total momentum of nucleon pairs [29], isospin of the emission source [30], nuclear symmetry energy [31], nuclear equation of state (EOS) [29], and in-medium nucleon-nucleon cross section (NNCS) [29, 32]. Particularly, the dependence of the two-proton correlation function on the in-medium NNCS has been studied in detail via Pratt's CRAB code [29] or the Lednický and Lyuboshitz code [32, 33] within the framework of an isospin-dependent quantum molecular dynamics (IQMD) model. Since the magnitude of total pair momentum relates to nucleon emission time, the effect of total nucleon pair momentum on correlation function strength has also been discussed in heavy-ion collisions [29, 31, 34].

Correlation functions between two light charged particles other than protons carry additional information about light particle production mechanisms and reaction dynamics in heavy-ion collisions at intermediate energies [3, 6, 7, 28, 35–43]. Previous work [37, 41, 44, 45] has demonstrated that source sizes extracted from different particle species correlation functions differ, which may be attributed to dynamical expansion of the reaction zone and different time scales [46]. Simultaneous investigation of correlation functions involving composite light particles may offer a unique tool to study dynamical expansion of the reaction zone [7]. Furthermore, momentum correlations between two non-identical particles contain information about emission time differences between the particles. By comparing correlation functions between two non-identical particles with different velocity gates, one can infer emission sequences between these particles [47–49], such as p, d, t, ^{3}He, and so on [8, 49, 50].

In this paper, we discuss correlation functions of light particles at different centralities and in-medium nucleon-nucleon cross sections. We investigate correlation functions of light particles under different total momentum of particle pairs and examine whether the strength of correlation functions for light particle pairs with higher/lower total pair momenta is sensitive to the in-medium nucleon-nucleon cross section. For two non-identical light particle pairs, we extract information about emission time order from their velocity-gated correlation functions, applying this method to n—p/p—d/p—t/d—t correlation functions for particles emitted in the lower relative momentum region.

To study these questions quantitatively, we apply the theoretical approach proposed by Lednický and Lyuboshitz [51] for momentum correlation function construction based on phase space data from an isospin-dependent quantum molecular dynamics (IQMD) model. We use the ^{197}Au + ^{197}Au system to investigate momentum correlation functions at different beam energies and impact parameters.

The remainder of this paper is organized as follows. In Section 2, we briefly describe the Hanbury-Brown Twiss (HBT) technique using the Lednický and Lyuboshitz analytical formalism and the isospin-dependent quantum molecular dynamics model. In Section 3, we present results from the IQMD plus Lednický and Lyuboshitz method for proton-proton correlation functions, comparing with FOPI experimental data. We then systematically discuss light particle momentum correlation functions and the influences of gates on total momentum of light particle pairs. Detailed analysis of light particle momentum correlation functions and extracted source size results are presented under different in-medium nucleon-nucleon cross sections and impact parameters for Au + Au collisions. Furthermore, correlation functions of non-identical light particles are analyzed to deduce the emission time order of two different particles in the lower relative momentum region. Finally, Section 4 provides a summary of the article.

II. Formalism and Models

A. Lednický and Lyuboshitz Analytical Formalism

We first present a brief review of the theoretical approach given by Lednický and Lyuboshitz [50–53] for the HBT technique and the underlying physics in this work. In this framework, the main formula is based on the principle that particle correlations at small relative momenta are determined by space-time characteristics of production processes due to effects of quantum statistics (QS) and final-state interactions (FSI) [3]. The correlation function can be expressed through the square of the symmetrized Bethe-Salpeter amplitude averaged over the four coordinates of emission particles and the total spin of the two-particle system, representing the continuous spectrum of the two-particle state. In this model, the FSI of particle pairs is assumed independent of the production process. Under the conditions in Refs. [48], the correlation function of two particles can be written as:

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

where $r^* = x_1 - x_2$ is the relative distance of the two particles at kinetic freeze-out, k^* is half of the relative momentum between the two particles, $S(r^*, k^*)$ is the probability to emit a particle pair with given r^* and k^* (the source emission function), and $\Psi_{k^*}(r^*)$ is the Bethe-Salpeter amplitude approximated by the outer solution of the scattering problem [20]. In the above limit, the asymptotic solution of the wave function for two charged particles approximately takes the form:

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

In this 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 (positive for repulsion, negative for attraction), and $\tilde{G}(\rho, \lambda) = \sqrt{A_c(\lambda)}[G_0(\rho, \lambda) + iF_0(\rho, \lambda)]$ is a combination of regular (F_0) and singular (G_0) s-wave Coulomb functions [52, 53]. $F(-i\lambda, 1, i\xi) = 1 + (-i\lambda)(i\xi)/1!^2 + (-i\lambda)(-i\lambda + 1)(i\xi)^2/2!^2 + \cdots$ is the confluent hypergeometric function with $\xi = k^*r^* + \rho$, $\rho = k^*r^*$. The s-wave scattering amplitude renormalized by long-range Coulomb interaction is:

$$f_c(k^*) = \left[K_c(k^*) - h(\lambda) - ik^* A_c(\lambda)\right]^{-1} + Pk^{*4} + 2d_0 k^{*2}$$

with $h(\lambda) = \left[n(n^2 + \lambda^2)\right]^{-1} \lambda^2 \sum_{n=1}^{\infty} -C - \ln[\lambda]$ where $C = 0.5772$ is the Euler constant. $K_c(k^*) = 1 + \cdots$ is the effective range function, where d_0 is the effective radius of strong interaction, f_0 is the scattering length, and P is the shape parameter. The parameters of the effective range function are important for characterizing essential properties of FSI and can be extracted from experimentally measured correlation functions [20, 41, 54]. Table I shows these parameters for different particle pairs in this work.

In Table I, for n—n and n—p correlation functions involving uncharged particles, the Coulomb penetration factor ($A_c(\lambda)$) is not considered and only short-range particle interaction operates. For charged particle correlation functions, Coulomb interaction dominates the correlation functions of t—t, p—t, and d—t systems. However, in addition to Coulomb interaction, short-range particle interaction dominated by s-wave interaction is considered for p—p, d—d, and p—d pairs at small relative momenta. The p—p correlation function is dominated by only singlet (S = 0) s-wave FSI contribution, while both spin-1/2 (doublet) and spin-3/2 (quartet) contributions occur for p—d systems. For deuteron-deuteron correlation functions, a parametrization of s-wave phase shifts δ is 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 total spin $S = 1$ is irrelevant since it does not contribute due to QS symmetrization.

B. The IQMD Model

The isospin-dependent Quantum Molecular Dynamics transport model is based on the QMD transport model with isospin factors. The main components of dynamics in HICs at intermediate energies include the mean field, two-body collisions, and Pauli blocking. Therefore, it is important to include isospin degrees of freedom for these three components in the IQMD transport model. Moreover, due to large differences between neutron and proton density distributions for nuclei far from the β-stability line, neutron and proton samples in phase space should be treated separately in projectile and target nuclei initialization.

In the IQMD model, the interaction potential takes the form:

$$U = U_{Sky} + U_{Coul} + U_{Yuk} + U_{Sym} + U_{MDI} + U_{Pauli}$$

where U_{Sky}, U_{Coul}, U_{Yuk}, U_{Sym}, U_{MDI}, and U_{Pauli} are the density-dependent Skyrme potential, Coulomb potential, surface Yukawa potential, isospin asymmetry potential, momentum-dependent interaction, and Pauli potential, respectively.

The density-dependent Skyrme potential U_{Sky} reads:

$$U_{Sky} = \alpha\left(\frac{\rho}{\rho_0}\right) + \beta\left(\frac{\rho}{\rho_0}\right)^{\gamma} + t_4 \ln^2\left[\epsilon\left(\frac{\rho}{\rho_0}\right)^{2/3} + 1\right]$$

when the momentum-dependent potential is included, where ρ and ρ_0 are total nucleon density and its normal value, respectively. Parameters α, β, γ, t_4, and ϵ relate to the nuclear equation of state [67–70] and are listed in Table II, where $K = 200$ or 380 MeV indicates soft or stiff momentum-dependent potential, respectively.

A general review of these potentials appears in Ref. [60]. In this work, the in-medium nucleon-nucleon cross section with isospin dependence is represented by:

$$\sigma_{NN} = \left(1 - \eta \frac{\rho}{\rho_0}\right) \sigma_{NN}^{free}$$

where ρ_0 is normal nuclear matter density, ρ is local density, η is the in-medium NNCS factor, and σ_{NN}^{free} is the available experimental NNCS [71]. This reduction factor for in-medium NNCS was introduced through studies of collective flow in HICs at intermediate energies [72–74], with $\eta \approx 0.2$ found to better reproduce flow data.

In this model, particles are identified using a modified isospin-independent coalescence description—the Minimum Spanning Tree approach. In this approach, nucleons are assumed to share the same cluster if their centers are closer than 3.5 fm and their relative momentum is smaller than 0.3 GeV/c. In the present calculations, protons and neutrons are considered emitted when their surrounding density falls below 0.02/fm^3 and they are unbound with no other nucleon within a coalescence distance of 3.5 fm and relative momentum smaller than 0.3 GeV/c before freeze-out time. If a nucleon is not bound by any clusters, it is treated as an emitted (free) nucleon. Our calculations simulate ^{197}Au + ^{197}Au reactions using the soft EOS with momentum-dependent interaction for different impact parameters at various beam energies. For each run and particle species, the momentum correlation function is constructed when the system reaches the corresponding freeze-out time and then processed within the Lednický and Lyuboshitz model.

III. Analysis and Discussion

A. Comparison of Model Predictions with Experimental Results

Collision centrality is an important variable for controlling reaction dynamics. Experimentally, it can be estimated by the total multiplicity distribution of charged particles [8]. In previous FOPI experiments, total multiplicity distribution was measured in the outer Plastic Wall [8]. For specific selection of central collisions, the corresponding integrated cross-sections for the Au + Au system represent about 10% of the total cross-section [25]. To make quantitative comparison with experimental data at 10% centrality [25], we use an impact parameter of about $b = 3$ fm. Protons are selected in the polar-angle range ($8.5^\circ \leq \theta_{lab} \leq 26.5^\circ$) at mid-rapidity as in Ref. [25].

Figure 1 [Figure 1: see original paper] shows the phase space coverage corresponding to experimental distributions in the c.m. system for central collisions. Here, $P_0^t = (p_t/A_{clus})/(p_{proj}/A_{proj})_{cm}$ and $y_0 = (y/y_{proj})_{cm}$ are normalized transverse momentum and rapidity, respectively. Within these cuts on P_0^t and y_0, we confront the experimental beam-energy dependence of two-proton correlations with predictions from the IQMD + Lednický and Lyuboshitz hybrid model. Figure 2 [Figure 2: see original paper] shows our calculated proton-proton correlation functions for central Au + Au collisions compared to experimental results. In the figure, q on the X-axis represents half of the relative momentum between particle pairs (i.e., k^* in the equations). In all following figures, q denotes the same quantity. Under these conditions in the transport approach, the correlation functions nicely agree with data. We note that our IQMD-predicted correlation functions fit the experimental data much better than previous BUU calculations [25]. With increasing beam energy, the proton-proton correlation function peak increases, and the apparent source radius decreases, similar to trends found in Refs. [29, 32].

B. Emission Times of Neutrons, Protons, Deuterons, and Tritons

Based on the good agreement between data and our calculations for proton-proton momentum correlations, we proceed with more detailed calculations and discussion of momentum correlation functions among neutrons, protons, deuterons, and tritons, particularly investigating effects of pair momentum cuts, in-medium nucleon-nucleon cross section, and emission time sequences among these particles.

We begin by discussing emission time distributions of different light particles since they are relevant for understanding both collision dynamics and particle production mechanisms. In heavy-ion collisions at intermediate energies, nucleon emissions are mainly governed by pressure from excited nuclear matter during the initial collision stage [34]. We performed calculations for different choices of density-dependent in-medium nucleon-nucleon cross section with factors of 0.2 and 0.5, and impact parameters of $b = 0.0$ and 6.0 fm. Previous studies show that $= 0.2$ provides the best agreement with balance energy in collective flow data. To examine and impact parameter effects on light particle emissions, Figure 3 [Figure 3: see original paper] (a–d) shows emission time distributions for neutrons, protons, deuterons, and tritons, respectively, for Au + Au collisions at 0.4A GeV. Neutron emission time distributions are similar to those of protons. However, light particle emission time distributions differ from those of protons and neutrons. While proton and neutron emission times peak earlier at about 50 fm/c, light particle emission times peak later at about 60 fm/c. Regarding and impact parameter effects on particle emission, we find that particle emission rates are larger for smaller or b because larger in-medium nucleon-nucleon cross sections or central collisions produce greater initial pressure that drives more particle emission. Emission times show only slight differences.

Particles emitted in earlier stages of heavy-ion collisions typically have higher energy than those emitted later. It is therefore interesting to study the relationship between average emission times and kinetic energy. Figure 4 [Figure 4: see original paper] shows average emission times of neutrons, protons, deuterons, and tritons as functions of their c.m. kinetic energy under the same conditions as Figure 3. Particles with higher kinetic energies are emitted earlier than those with lower kinetic energies in central collisions (i.e., $b = 0$ fm). However, at $b = 6$ fm, average emission times are not monotonic functions of kinetic energy, especially for deuterons and tritons. This difference indicates different emission mechanisms in central versus semi-peripheral collisions. In central collisions, most light particle emissions are driven by a high-pressure dynamical source, while in semi-peripheral collisions, light particle emissions compete between overlapping dynamical and thermal sources.

In relatively high kinetic energy regions (e.g., above ~0.32 GeV for neutrons and protons, and 0.30 GeV for deuterons and tritons), average emission times become later when increases (i.e., for smaller in-medium nucleon-nucleon cross section). However, in relatively low kinetic energy regions, the effect of in-medium nucleon-nucleon cross section on average emission time reverses.

C. Correlation Functions of Neutrons, Protons, Deuterons, and Tritons

After discussing emission times of neutrons, protons, deuterons, and tritons from Au + Au collisions at 0.4A GeV, we proceed with systematic analysis of correlation functions for different particle pair combinations among these particles. Correlation functions are discussed with specific gates on impact parameter, in-medium NNCS factor, total particle pair momentum, and particle velocity. As mentioned in Sec. IIIA, our correlation functions use phase-space information from the freeze-out stage as input for the Lednický and Lyuboshitz code, with effective source size extracted assuming a Gaussian-type emission source.

Figure 5 [Figure 5: see original paper] shows four types of identical light-particle correlation functions—n—n, p—p, d—d, and t—t—for central ^{197}Au + ^{197}Au collisions at $E = 0.4A$ GeV. The dependence of correlation function strength on total particle pair momentum (P_{tot}) is examined through calculations with two P_{tot} gates. In Figure 5, curves with open and filled circles correspond to high and low P_{tot} cuts, respectively. Two-neutron and two-proton correlation functions are shown for two different total momentum ranges (low: 0–0.4 GeV/c, high: 0.8–1.2 GeV/c). Two-deuteron correlation functions are presented with gates on different total deuteron pair momenta (low: 0–0.8 GeV/c, high: 1.6–2.4 GeV/c). Two-triton correlation functions are gated on different total triton pair momenta (low: 0–1 GeV/c, high: 2–3 GeV/c). The correlation function shapes are consistent with experimental data from heavy-ion collisions [75]. The neutron-neutron correlation function peaks at $q \approx 0$ MeV/c. Two-proton, two-deuteron, and two-triton correlation functions are suppressed at low q due to Coulomb repulsion. Anti-symmetrization of the two-proton wave function may also suppress low-q proton pairs, possibly enhancing this anti-correlation signal. With increasing relative momentum, the two-proton correlation function shows a maximum at $q \approx 20$ MeV/c due to strong final-state singlet-wave attraction. However, the two-deuteron correlation function exhibits no peak since anti-correlation between deuteron pairs is induced by repulsive singlet-wave nuclear and Coulomb potentials. The two-triton correlation function also shows anti-correlation (Figure 5(d)) because only Coulomb potential is included in the final-state interaction as in Ref. [7].

In Figures 5(a) and 5(b), higher P_{tot} cuts clearly lead to larger strength in two-neutron and two-proton correlation functions. This trend implies that particles with higher momenta are emitted earlier or equivalently from a more compact source, consistent with results shown in Figure 4. These results are similar to those from a relatively simple approach in Refs. [80] that measured emission times for nucleons and light clusters in the coalescence model. The correlation between energy and emission time has been clearly demonstrated in experimental data and model results for momentum-gated nucleon pairs [28, 29, 31, 76]. Momentum correlation functions complement previous approaches for studying properties and space-time evolution of reaction systems. However, sensitivity to total pair momentum gradually weakens with increasing particle mass, e.g., for deuterons and tritons.

Next, we examine the effect of in-medium nucleon-nucleon cross section on momentum correlation functions under different total pair momenta. In Figure 6 [Figure 6: see original paper], curves with filled and open circles show results for = 0.2 and 0.5, respectively. Correlation functions of light particle pairs with high total momenta are more sensitive to in-medium NNCS factor dependence than those with low total momenta at the same impact parameter. Since pre-equilibrium light particles with higher momenta are emitted earlier or have smaller source sizes for smaller . The dependence on correlation functions with low total pair momenta shows the opposite trend, consistent with effects on particle emission times shown in Figure 4.

Figure 7 [Figure 7: see original paper] shows the dependence of radii extracted from light particle correlation functions on different in-medium NNCS factors and impact parameters for various total pair momentum gates, where squares and triangles represent results with low and high P_{tot} cuts, respectively. Radii are extracted using a Gaussian source assumption, $S(r^*) \approx \exp(-4r^2/r_0^2)$, where r_0 is the Gaussian source radius from correlation functions. Results for light particle pairs without momentum gating are shown by curves with circles, which fall between high and low P_{tot} cases. Extracted source radii from p—p and n—n are similar but quantitatively different, possibly due to Coulomb distortions between proton-proton pairs. Source radii from t—t and d—d correlation functions are generally smaller than those from p—p and n—n. For d—d and t—t correlations, lower (i.e., larger in-medium nucleon-nucleon cross section) leads to slightly smaller radii and stronger anti-correlation of deuteron or triton pairs than those obtained with larger , particularly for high P_{tot} pairs. For impact parameter dependence, radii generally increase with impact parameter except in the low P_{tot} case.

Finally, we investigate non-identical particle correlation functions such as p—d, p—t, d—t, and n—p. The p—d correlation function in Figure 8 Figure 8: see original paper displays a single broad peak due to both singlet-wave attraction and Coulomb repulsion, with shape similar to the proton-proton correlation function but peaking at $q \approx 55$ MeV/c. The p—t and d—t correlation functions in Figure

8(a) show anti-correlation due to final-state Coulomb repulsion. The neutron-proton correlation function peaks at $q \approx 0$ MeV/c due to s-wave attraction. Beyond non-identical particle correlation functions, analysis of velocity-gated correlation functions provides a powerful tool to probe detailed information about particle emission time sequences [43, 46–49, 77, 78]. Figure 8(b) shows ratios of proton-deuteron, proton-triton, deuteron-triton, and neutron-proton correlation functions calculated with different velocity gates. The ratio is defined by comparing two velocity-gated correlation functions: the first function, v^+, is constructed with pairs where the proton (deuteron) velocity is faster than the deuteron (triton) or triton, respectively; the second function, v^-, corresponds to the reverse situation. We obtain emission sequences through the following principle: if one of two particles is emitted earlier and has lower velocity, it will on average travel shorter distances before the other particle is emitted. In our work, when the first emitted particle is slower than the second, the average distance is reduced and Coulomb suppression is enhanced, and vice versa. Therefore, in Figure 8(b), ratios for p—d and p—t correlation functions below unity indicate that deuterons and tritons are on average emitted earlier than protons in the low relative momentum region. However, ratios for n—p or d—t correlation functions are only slightly above or below unity, respectively, indicating that emission time differences between neutron and proton or deuteron and triton are not significant, consistent with emission times shown in Figure 3. In contrast, these particles are emitted on similar time scales in larger relative momentum regions, as expected from analysis of velocity-gated correlation functions of non-identical particles.

IV. Summary

In summary, we present particle-particle momentum correlation functions reconstructed by the Lednický and Lyuboshitz analytical formalism using phase-space points at freeze-out for ^{197}Au + ^{197}Au collisions at different beam energies within the IQMD transport approach. As a necessary model verification, we performed quantitative comparison of proton-proton momentum correlation functions with FOPI data. Using the same transverse momentum and rapidity phase-space coverage as in experiments, we find that with increasing beam energy from 0.4A GeV to 1.5A GeV, the p—p correlation function becomes stronger and well reproduces FOPI experimental data. After this essential verification, we proceed with studies on emission times and momentum correlations of different light particles.

Emission time distributions of light particles and their dependence on c.m. kinetic energy are studied using two different in-medium NNCS and impact parameter sets. We find that emission times are earlier for particles with higher kinetic energies in central collisions. For semi-peripheral collisions, average emission times of deuterons and tritons first increase with kinetic energy then decrease. At low kinetic energies, larger in-medium nucleon-nucleon cross sections produce longer emission times, while at higher kinetic energies the effect reverses, indicating different emission origins: lower kinetic energy particles likely originate dominantly from statistical emission, while higher energy particles come from pre-equilibrium dynamical processes.

Momentum correlation functions with total momentum gating have been investigated for all particle pairs containing neutrons, protons, deuterons, and tritons. Two-particle correlation functions, especially for neutron-neutron and proton-proton pairs with higher total momentum, are stronger than those with lower momentum. Light particle pair correlation functions and emission source sizes gated on higher total momentum are sensitive to impact parameter and in-medium NN cross sections: source size increases from central to semi-peripheral collisions, and becomes larger for larger (i.e., smaller in-medium NN cross section).

Momentum correlations between non-identical light particles provide important information about emission sequences and source radii. Results indicate that heavier clusters (deuterons or tritons) are emitted earlier than lighter particles at the same momentum per nucleon, as expected from velocity-gated correlation function analysis of non-identical particles.

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