Effect of in-medium nucleon-nucleon cross section on proton-proton momentum correlation in intermediate-energy heavy-ion collisions post-print

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Date: 2023-06-20T00:00:00+00:00

Abstract

The proton-proton momentum correlation function (Cpp) from different rapidity regions is systematically investigated for Au + Au collisions at different impact parameters and energies from 400A MeV to 1500A MeV within the framework of the isospin-dependent quantum molecular dynamics model (IQMD) complemented by the Lednický and Lyuboshitz analytical method. In particular, the in-medium nucleon-nucleon cross section (NNCS) dependence of the correlation function is brought into focus, while the impact parameter and energy dependence of the momentum correlation function are also explored. The sizes of the emission source are extracted by fitting the momentum correlation functions using the Gaussian source method. We find that the in-medium nucleon-nucleon cross section obviously influences the proton-proton momentum correlation function from the whole rapidity or projectile/target rapidity region at smaller impact parameters, but there is no effect on the mid-rapidity proton-proton momentum correlation function, which indicates that the emission mechanism differs between projectile/target rapidity and mid-rapidity protons.

Full Text

Preamble

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(Dated: February 23, 2018)

The proton-proton momentum correlation function (C_{pp}) from different rapidity regions is systematically investigated for Au + Au collisions at various impact parameters and beam energies ranging from 400A MeV to 1500A MeV within the framework of the isospin-dependent quantum molecular dynamics model (IQMD) complemented by the Lednický and Lyuboshitz analytical method. In particular, the dependence of the correlation function on the in-medium nucleon-nucleon cross section (NNCS) is brought into focus, while the impact parameter and energy dependence of the momentum correlation function are also explored. The sizes of the emission source are extracted by fitting the momentum correlation functions using the Gaussian source method. We find that the in-medium nucleon-nucleon cross section significantly influences the proton-proton momentum correlation function from the whole rapidity or projectile/target rapidity region at smaller impact parameters, but has no effect on the mid-rapidity proton-proton momentum correlation function, which indicates that the emission mechanism differs between projectile/target rapidity and mid-rapidity protons.

PACS numbers: 25.70.Mn, 24.10.-i, 25.70.Pq, 27.80.+w

Introduction

The Hanbury Brown and Twiss (HBT) effect was first discussed in radio and stellar astronomy. The method was applied to measure the angular diameter and size of stars by Hanbury Brown and Twiss [1]. Later, the technique was introduced to particle physics research in the 1960s by Goldhaber et al., who studied the angular distribution of identical pion pairs in proton-antiproton annihilations and observed an enhancement of pairs at small relative momenta [2]. In the last decade, great strides have been made in experiments, accompanied by numerous theoretical studies ranging from low to high energy heavy-ion collisions (HICs) [3, 4].

Two-particle correlation is well known to be sensitive to characteristics of the particle emission source. Recently, two-particle correlation in subatomic physics has been employed as a probe for the space-time geometry of the particle emission source. Correlation between two protons has been measured by several experiments and explored by different models. In addition to protons, composite light fragments/particles (which will not be discussed in this paper) are also used to carry information about the emission source [5, 6]. Due to the rapid development of radioactive nuclear beams, the HBT method has also been used to study exotic nuclear structure. For instance, several measurements have revealed exotic structures of neutron-rich nuclei such as ^{6}He, ^{11}Li, ^{14}Be [7–9] and proton-rich nuclei such as ^{23}Al [10] as well as ^{22}Mg [11, 12]. Furthermore, the dependence of proton-neutron correlation on binding energy has been theoretically explored [13]. Besides applications to investigating exotic structure, the HBT method has become an important tool in heavy-ion collisions across a wide energy range [3, 4, 14–16].

For example, in the relativistic energy region, collaborations at RHIC and LHC have carried out extensive experimental measurements of two-pion correlation functions as functions of energy and system size [17, 18]. Moreover, the same method has been applied to make the first measurement of two-antiproton interaction by analyzing momentum correlation functions between antiprotons, namely the quantitative extraction of the scattering length and effective range—two key parameters characterizing the strong interaction for antiproton interactions—by the STAR Collaboration [19–22]. Theoretically, correlation functions between two identical pions or kaons have also been investigated in simulation work using hydrodynamic models and the AMPT model, among others [4, 23–27].

In the intermediate energy region, two-proton correlation functions have primarily been applied to extract space-time properties such as source size and emission time in nuclear reactions [28]. Additionally, many investigations have examined dependences of correlation functions in experiments and theories, including dependences on impact parameter [29, 30], total momentum of nucleon pairs [31], isospin of the emission source [32], nuclear symmetry energy [33], nuclear equation of state (EOS) [30], density distribution of valence neutrons in neutron-rich nuclei [6], and so on.

Investigation of in-medium nucleon-nucleon scattering is of particular interest in intermediate energy heavy-ion reactions. In this energy domain, nucleus-nucleus collisions provide a unique opportunity to form compressed nuclear matter with densities up to 2-3 times normal nuclear matter density (ρ_0). The in-medium nucleon-nucleon cross section (NNCS) has a close relation with nuclear matter density and is therefore an important component in model simulations. Recently, medium effects on nucleon-nucleon cross sections have been widely investigated by replacing the vacuum NNCS with an in-medium one, and various effects have been discussed [35–38].

The dependence of the two-proton correlation function on in-medium NNCS has been briefly studied through the CRAB code in an IQMD framework [30]. Since two-particle correlation functions, through final-state interactions and quantum statistical effects, have been shown to be sensitive probes of the space-time distributions of emitted particles in heavy-ion collisions [16], it is of great interest to investigate in-medium NN cross section effects on source evolution. In the present paper, we use another theoretical approach proposed by Lednický and Lyuboshitz [39] to explore in greater detail the relationship between these factors and the proton-proton correlation function. Two-particle correlation at small relative velocities is sensitive to space-time characteristics of the production process due to effects of quantum statistics and final-state interaction [40, 41].

In most proton-proton correlation functions, the HBT strength at 20 MeV/c of the p-p relative momentum is taken as a unique quantity to determine the source size or emission time of two-proton emission [30]. The proton phase spaces of Au+Au collisions at freeze-out time generated by the IQMD model are used as input for the Lednický and Lyuboshitz code, from which the effective source size is extracted.

The rest of the paper is organized as follows. In Sec. II we briefly describe the models and formalism used in the present study: the Lednický and Lyuboshitz analytical formalism and the isospin-dependent quantum molecular dynamics (IQMD) model. Detailed analysis and discussion of systematic proton-proton momentum correlation functions and extracted source size results for different rapidity regions are presented in Sec. III for Au + Au collisions at various in-medium nucleon-nucleon cross sections, impact parameters, and beam energies. Additionally, we fit the proton p_T spectra with the distribution function from the Blast-Wave model. Finally, Sec. IV summarizes the results.

II. Formalism and Models

A. Lednický and Lyuboshitz Analytical Formalism

We first present a brief review of the theoretical approach proposed by Lednický and Lyuboshitz [39] for HBT analysis. The method is based on the principle that correlation functions of identical particles at small relative momenta are determined by effects of quantum-statistical symmetry (QS) of particles and final-state interaction (FSI) [42].

In this technique, we assume particles are emitted by independent one-particle point sources and that spin is independent in the production process as well as in two-particle interaction. We can then investigate particle pairs (1, 2) emitted at small relative momenta. Following the conditions in references [43], we neglect the effect of FSI in all pairs (1, i) and (2, i) except (1, 2). This process is illustrated in Fig. 1.

[Figure 1: see original paper]

The correlation function for identical particles takes the expression:

$$B(p,q) = B_0(p,q) + B_1(p,q),$$

where $p = p_1 + p_2$ and $q = |p_2 - p_1|$ are the total momentum and relative momentum of the particle pair, respectively.

In Eq. (1), $B_0(p,q)$ is the contribution from quantum statistics effects, described by:

$$B_0(p,q) = g_0 \cos(qx),$$

where g_0 is the spin factor.

The function $B_1(p,q)$ can be expressed through the symmetrized Bethe-Salpeter amplitude $\psi^{(S)}$, which can be approximated by the outer region solution of the scattering problem [19]:

$$B_1(p,q) = \int \rho_{S,p}(x_1,x_2,\bar{x}_1,\bar{x}_2) \times \psi_{S,p,q}(x_1,x_2)\psi^*_{S,p,q}(\bar{x}_1,\bar{x}_2)d^4x_1d^4x_2d^4\bar{x}_1d^4\bar{x}_2,$$

where $\rho_{S,p}$ is the two-particle density matrix.

Next, we introduce the detailed analytical calculation of the proton-proton correlation function [19]. The proton-proton correlation function $C_{pp}(k^*,r_0)$ can be described by the Lednický and Lyuboshitz analytical method [19, 39].

In this model, the space distribution of the Gaussian source is simulated according to:

$$S(r^*) \approx \exp\left(-\frac{r^{*2}}{4r_0^2}\right),$$

where r_0 is the source size parameter. The correlation function is obtained by assuming 1/4 singlet and 3/4 triplet states. The theoretical correlation function at a given k^* is calculated as the average FSI weight $\langle w(k^*,r^*)\rangle$ obtained from the separation r^*, simulated according to the Gaussian law, and the angle between vectors k^* and r^*, simulated according to a uniform cosine distribution. The average FSI weight is:

$$w(k^*,r^*) = |\psi_S^{(+),-k^*}(r^*) + (-1)^S\psi_S^{(+),k^*}(r^*)|^2,$$

where S is the total pair spin, r^* is the relative distance, and $\psi_S^{(+),-k^*}(r^*)$ is the equal-time ($t^*=0$) reduced Bethe-Salpeter amplitude approximated by the outer solution of the scattering problem [39]:

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

where $\delta_c = \arg\Gamma(1+i/k^*a_c)$ is the Coulomb phase corresponding to zero orbital angular momentum, $A_c(\lambda) = 2\pi\lambda[\exp(2\pi\lambda)-1]^{-1}$ determines the contribution of Coulomb interaction (positive value corresponding to repulsion), $\lambda = (k^*a_c)^{-1}$, $a_c = 57.5$ fm is the Bohr radius for two protons, $\rho = k^*r^*$, $\xi = k^*r^* + \rho$, F is the confluent hypergeometric function, $\tilde{G}(\rho,\lambda) = \sqrt{A_c(\lambda)}[G_0(\rho,\lambda) + iF_0(\rho,\lambda)]$ is a combination of regular (F_0) and singular (G_0) s-wave Coulomb functions, $f_c(k^*) = [1/d_0k^{*2}h(\lambda) - ik^*A_c(\lambda)]^{-1}$ is the s-wave scattering amplitude renormalized by Coulomb interaction, d_0 is the effective range of the interaction, and $h(\lambda) = \lambda^2 \sum_{n=1}^{\infty}(n^2+\lambda^2)^{-1} - C - \ln[\lambda]$ (with $C = 0.5772$ being the Euler constant). The dependence of scattering parameters on total pair spin S is omitted since only the singlet ($S = 0$) s-wave FSI contributes for identical nucleons.

B. The IQMD Model

To apply the above theoretical simulation, the single-particle phase-space distribution at freeze-out is required. In this work, the correlation function is established from the emission phase space given by the IQMD transport model [44].

The quantum molecular dynamics (QMD) model is a many-body transport theory that has been extensively applied to describe heavy-ion reactions from intermediate energies to 2A GeV [45]. Through QMD studies, valuable information about both collision dynamics and fragmentation processes has been obtained [46–55]. Excellent extensibility can be expected due to its microscopic treatment of collision processes. The model consists of several components: initialization of projectile and target nucleons, nucleon transport under effective potentials, nucleon-nucleon (NN) binary collisions in nuclear medium, Pauli blocking, and numerical testing. The isospin-dependent quantum molecular dynamics (IQMD) model is based on QMD and incorporates isospin factors [56] in the mean field, two-body NN collisions, and Pauli blocking.

In the IQMD model, the wave function of each nucleon is represented as a Gaussian wave packet with parameter L related to the size of the reaction system. For Au + Au systems, the width L is fixed at 2.16 fm^2. The Gaussian wave packet is written as:

$$\phi_i(r) = \frac{1}{(2\pi L)^{3/4}} \exp\left[-\frac{(r - r_i(t))^2}{4L}\right] \exp\left[\frac{ir \cdot p_i(t)}{\hbar}\right],$$

where $r_i(t)$ and $p_i(t)$ are time-dependent variables describing the center of the packet in coordinate and momentum space, respectively. All nucleons interact via the effective mean field and two-body NN collisions.

The nuclear mean field can be expressed as:

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

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. A general review of these potentials can be found in Ref. [45].

In the present work, the in-medium NN cross section is represented by:

$$\sigma_{NN}^{\text{in-medium}} = \left(1 + \eta \frac{\rho}{\rho_0}\right) \sigma_{NN}^{\text{free}},$$

where ρ_0 is normal nuclear matter density, ρ is local density, η is the in-medium factor, and $\sigma_{NN}^{\text{free}}$ is the available experimental NN cross section [57]. In this expression, increasing values of parameter η correspond to decreasing in-medium nucleon-nucleon cross sections.

In this model, fragments are identified using a modified minimum spanning tree algorithm. In this approach, two nucleons are assumed to belong to the same cluster if their centers are closer than 3.5 fm and their relative momentum is smaller than 0.3 GeV/c. If a nucleon is not bound to any cluster, it is treated as an emitted (free) nucleon.

C. The Blast-Wave Fit

In heavy-ion collisions, particles collide randomly, which can be described in terms of thermal motion [58]. We adopt the blast-wave model proposed by Siemens and Rasmussen [59] to describe mid-rapidity p_T spectra with two free parameters: collective transverse flow velocity β and kinetic freeze-out temperature T_f. The collective transverse flow velocity β is parametrized by the surface velocity β_s in the region $0 \le r \le R_{\max}$:

$$\beta_r(r) = \beta_s \left(\frac{r}{R_{\max}}\right)^{\alpha},$$

where $R_{\max}$ is the maximum radius of the expanding source at thermal freeze-out time, β_s is the particle radial velocity at the maximum surface ($r = R_{\max}$), and exponent α describes the evolution of flow velocity with radius. The p_T spectra are a superposition of individual thermal sources at different r, boosted with boost angle $\rho = \tanh^{-1} \beta_r(r)$ [60]:

$$\frac{d^2N}{p_T dp_T dY} \propto \int_0^{R_{\max}} r dr m_T I_0 \left(\frac{p_T \sinh\rho}{T_f}\right) K_1 \left(\frac{m_T \cosh\rho}{T_f}\right),$$

where K_1 and I_0 are modified Bessel functions. The spectral shapes are essentially determined by T_f, β_s, α, and the particle mass m_0. The average flow velocity is estimated by taking an average over the transverse geometry.

III. Analysis and Discussion

In this work, we use the soft equation of state with momentum-dependent interaction for all Au + Au collisions at beam energies from 0.4 to 1.5A GeV. Correlation functions are calculated using phase-space information from the freeze-out stage.

We first investigate the influence of in-medium NN cross section on the momentum correlation function for Au + Au collisions at 1.0A GeV. Fig. 2 [Figure 2: see original paper] shows the proton-proton momentum correlation function for Au + Au collisions at 1A GeV with different in-medium reduction factors η, impact parameters, and proton rapidity regions. In each panel, in-medium reduction factors of 0.0, 0.2, 0.5, 0.7, and 0.9 are compared. From top to bottom, panels correspond to impact parameters $b = 3$, 6, 9, and 12 fm, respectively. From left to right, columns represent correlation functions for proton pairs within whole rapidity, mid-rapidity, and projectile/target rapidity regions, respectively. The mid-rapidity cut means both protons are emitted in the rapidity window $-0.5 \leq y/y_{\text{proj}} \leq 0.5$, while projectile or target rapidity region means both protons come from $y/y_{\text{proj}} \geq 0.5$ or $y/y_{\text{proj}} \leq -0.5$, where y is proton rapidity and y_{proj} is initial projectile rapidity.

Overall, the proton-proton momentum correlation function exhibits a peak at relative momentum $q = 20$ MeV/c, due to strong final-state s-wave attraction together with suppression at lower relative momentum from Coulomb repulsion and antisymmetrization of the wave function between two protons. For protons emitted in whole rapidity or projectile/target rapidity, the general trend is very similar. With increasing in-medium NN cross section (i.e., decreasing in-medium reduction factor η), the collision rate between nucleons increases, causing more nucleons to be emitted early and making the momentum correlation function strength larger. This difference is further revealed in central and semi-peripheral collisions, but the difference in momentum correlation function among various η factors almost disappears in peripheral collisions. This indicates that the NN cross section in peripheral collisions does not change significantly even when η varies substantially. Overall, with smaller nucleon-nucleon cross section (i.e., larger η factor), the correlation peak decreases, indicating that proton-proton correlation has a positive correlation with nucleon-nucleon cross section. The sensitivity of correlation strength to η values becomes less important as the reaction becomes more peripheral.

For mid-rapidity protons, correlation functions are much stronger than in whole-rapidity or projectile/target rapidity cases and show almost no dependence on in-medium nucleon-nucleon cross section, indicating a very different space-time structure for mid-rapidity protons. Essentially, mid-rapidity protons are emitted very early and non-equilibrated, making them insensitive to in-medium NN cross section. Additionally, they possess radial flow, which will be discussed later. Another difference is that the strength of the correlation peak as a function of impact parameter shows opposite behavior compared to whole-rapidity or projectile/target rapidity protons, displaying a stronger correlation peak in peripheral than in central collisions, indicating a slightly more compact mid-rapidity source in peripheral collisions.

The influence of three variables—incident energy, impact parameter, and in-medium nucleon-nucleon cross section—on C_{pp} strength is presented in Fig. 3 [Figure 3: see original paper] for proton-proton correlation functions with whole rapidity window (blue squares) or mid-rapidity (solid circles) applied to emitted protons in Au + Au collisions. For incident energy dependence, panel (a) of Fig. 3 clearly shows the increase of momentum correlation peak from low to high energy, with mid-rapidity cut displaying a stronger peak. This can be generally understood as resulting from a more rapid collision process, smaller emission source space, and shorter time intervals among emitting nucleons at higher energy, as does the mid-rapidity source [30]. Panel (b) of Fig. 3 shows that correlation strength increases with impact parameter for mid-rapidity cut but decreases for whole rapidity cut, demonstrating that geometrical cuts for the two rapidity regions are complementary. For example, stronger correlation for mid-rapidity protons at peripheral collision indicates smaller source size, while weaker correlation for whole-rapidity protons indicates larger source size. Panel (c) of Fig. 3 shows that with increasing in-medium cross section modification factor (i.e., decreasing in-medium NN cross section), the peak strength becomes smaller. In other words, proton-proton correlation depends positively on nucleon-nucleon collisions. In contrast to whole-rapidity protons, mid-rapidity protons show weaker sensitivity to NNCS. Since correlation function strength depends mainly on source size, the above behavior of HBT strength essentially reflects the changing size of the emission source versus beam energy, impact parameter, and nucleon-nucleon cross section.

Fig. 4 [Figure 4: see original paper] presents the Gaussian source radius for emitted protons as a function of beam energy (left column), impact parameter (middle column), and in-medium cross section reduction factor (right column) for different rapidity windows: whole rapidity (upper row), mid-rapidity (middle row), and projectile/target rapidity (bottom row). Overall, for mid-rapidity proton-proton correlations, sensitivity to the in-medium cross section reduction factor is almost negligible. The source radius shows a slight drop with increasing beam energy or impact parameter. For whole rapidity or projectile/target rapidity windows, their beam energy dependences are very similar when the same η is applied, and source radius increases with increasing η (i.e., decreasing nucleon-nucleon cross section). When nucleon-nucleon cross section is larger (e.g., $\eta \leq 0.5$), source radius drops with incident energy, indicating fast emission and/or compact proton emission size at higher energies. However, the situation differs when nucleon-nucleon cross section is small (e.g., $\eta > 0.7$), where radius shows slight increase or plateau behavior. Overall, even though slight beam energy dependence of radius is seen, the trend is rather weak, as observed in ultra-relativistic energy heavy-ion collisions [63].

The middle and right columns demonstrate the Gaussian source radius as a function of impact parameter at different fixed η values or η at different impact parameters, respectively. As expected, for correlations between protons from whole rapidity or projectile/target regions, source size increases with impact parameter, and larger nucleon-nucleon cross section produces stronger dependence of source size on impact parameter. With increasing impact parameters, the effective source size grows because the (target or projectile) spectator region becomes larger, and this effect is more pronounced when the in-medium decrease of cross section is smaller. This indicates geometrical effects and protons coming from spectator fragmentation mechanism. Simultaneously, source size increases with decreasing in-medium NN cross section (i.e., larger η factor). The smaller the impact parameter, the stronger the dependence of source size on in-medium NN cross section, which can be understood as more frequent collision effects expected to affect dynamical evolution. However, for correlations between protons from mid-rapidity region, source size decreases with increasing impact parameter regardless of in-medium nucleon-nucleon cross section. This reverse dependence of source radius between mid-rapidity and projectile/target rapidity protons as a function of impact parameter indicates geometrical evolution of participant and spectator regions, also visible in Fig. 3(b).

We should mention that to extract the above source size, theoretical calculations for C_{pp} were performed using the Lednický and Lyuboshitz analytical method. The best-fitting source size was determined by finding the minimum reduced chi-square. Fig. 5 [Figure 5: see original paper] presents examples of χ^2 variance between IQMD calculations with Lednický-Lyuboshitz analytical formalism and Gaussian source correlation as a function of Gaussian source radius at different impact parameters with varying η factors (left panels) or at different η factors with varying impact parameters (right panels). Generally, the minimum is well defined, but errors on its location are apparently rather asymmetric.

Mid-rapidity protons may experience collective radial flow expansion compared to projectile/target rapidity protons. To demonstrate the magnitude of radial flow for mid-rapidity protons, we use Blast-wave (BW) fits to proton p_T spectra in the mid-rapidity region. We obtain the α value from p_T spectra of central collisions and fix this value when fitting other impact parameters [34]. The left column of Fig. 6 [Figure 6: see original paper] shows p_T spectra of mid-rapidity protons at different incident energies for $b = 3$ fm and $\eta = 0.2$ (top row), at different impact parameters for $E = 1$A GeV and $\eta = 0.2$ (middle row), and with different in-medium cross sections for $b = 3$ fm and 1A GeV (bottom row), where solid symbols represent IQMD calculations and solid lines are BW fits. Overall, all lines reproduce the spectra well, allowing systematic extraction of radial flow parameters. The right column of Fig. 6 displays extracted radial flow parameters (β) as functions of incident energy at $b = 3$ fm and $\eta = 0.2$ (top panel), impact parameter at $E = 1$A GeV and $\eta = 0.2$ (middle panel), and in-medium cross section factor at $E = 1$A GeV and $b = 3$ fm (bottom panel). Radial flow becomes stronger at higher incident energy and in more central collisions. Meanwhile, larger in-medium nucleon-nucleon cross section (i.e., smaller η values) leads to larger radial flow due to more frequent nucleon-nucleon collisions in the overlap zone. Radial flow has been extensively discussed in intermediate and high energy heavy-ion collisions, e.g., in Ref. [62] by J. Helgesson et al.

For mid-rapidity p-p correlation, let us examine correlation strength versus radial flow in detail. Since we have relationships between correlation strength at 20 MeV/c ($C_{pp}(q = 20\text{MeV/c})$) versus beam energy and between radial flow (β)

versus beam energy, we can obtain the relationship between $C_{pp}(q = 20\text{MeV/c})$ and β, displayed in Fig. 7 Figure 7: see original paper for $b = 3$ fm and $\eta = 0.2$. This shows that larger radial flow velocity produces stronger proton-proton correlation. Similarly, we obtained $C_{pp}(q = 20\text{MeV/c})$ versus β in Fig. 7(b) for $E = 1$A GeV and $\eta = 0.2$ with impact parameter as a variable, where anti-correlation is observed. Likewise, $C_{pp}(q = 20\text{MeV/c})$ versus β is shown in Fig. 7(c) for $E = 1$A GeV and $b = 3$ fm with in-medium nucleon-nucleon cross section reduction factor as a variable, demonstrating slight increasing behavior. From these three variables, we find no unique dependence of p-p correlation function on radial flow parameter.

IV. Summary

In the present work, we use the IQMD transport approach to calculate phase-space points at freeze-out for Au + Au collisions from 0.4 to 1.5A GeV. These phase-space points are then processed within the Lednický and Lyuboshitz analytical formalism to reconstruct the proton-proton correlation function. We systematically study how in-medium NN cross section affects the strength of proton-proton momentum correlation functions for Au + Au collisions from 0.4 to 1.5A GeV in different rapidity windows and impact parameters.

Results show that larger in-medium NN cross section produces stronger momentum correlation functions than smaller in-medium NN cross section, particularly at small impact parameters for whole-rapidity or projectile/target rapidity proton pairs. This behavior is interpreted as stronger correlation for equilibrium-like protons induced by higher nucleon-nucleon collision rate. However, for mid-rapidity proton emission, in-medium nucleon-nucleon cross section has less effect on momentum correlation function due to a very different emission mechanism.

Additionally, the impact parameter effect on HBT strength has been addressed. We show that HBT strength has very different dependence between whole-rapidity or projectile/target rapidity proton pairs and mid-rapidity proton pairs. For projectile/target rapidity proton pairs, HBT strength decreases with increasing impact parameter, but for mid-rapidity proton pairs, it increases with impact parameter.

By fitting momentum correlation functions with the Gaussian source method, effective proton emission source sizes are extracted. Results show that source radius generally increases with impact parameter for emitted protons within whole rapidity or projectile/target rapidity, but decreases with impact parameter for mid-rapidity protons and shows insensitivity to in-medium nucleon-nucleon cross section. This phenomenon reflects source size evolution with collision geometry: the mid-rapidity source becomes smaller while the projectile/target source becomes larger with increasing impact parameter.

Moreover, beam energy dependence of HBT strength is presented. Generally, HBT strength shows slight change with beam energy, especially for whole-rapidity or projectile/target rapidity proton pairs. Using Blast-wave fits to transverse momentum spectra of mid-rapidity protons, radial flow parameters are systematically extracted as functions of beam energy, impact parameter, and in-medium nucleon-nucleon reduction factor, and relationships between HBT strength and radial flow parameter are constructed under different conditions. However, no unique dependence is found, indicating that radial flow is not a decisive variable for p-p correlation.

This work was supported partly by the National Natural Science Foundation of China under Contract Nos. 11421505, 11220101005, the Major State Basic Research Development Program in China under Contract 2014CB845401, and the Key Research Program of Frontier Sciences of the CAS under Grant No. QYZDJ-SSW-SLH002.

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[Figure 2: see original paper]

[Figure 3: see original paper]

[Figure 4: see original paper]

[Figure 5: see original paper]

[Figure 6: see original paper]

[Figure 7: see original paper]

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