Effects of temperature and density on the two-nucleon momentum correlation function from excited single nuclei (Postprint)

Authors: Ting-Ting Wang, Yu-Gang Ma, De-Qing Fang, Huan-Lin Liu, Yu-Gang Ma

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

Abstract

Two-nucleon momentum correlation functions are investigated for different single thermal sourcesat given initial temperature (T) and density ( ). To this end, the evolutions of various singleexcited nuclei at T = 1 − 20 MeV and = 0.2 - 1.2 0 are simulated using the thermal isospindependent quantum molecular dynamics (T hIQMD) model. Momentum correlation functions ofidentical proton-pairs (Cpp(q)) or neutron-pairs (Cnn(q)) at small relative momenta are calculatedby Lednick ´ y and Lyuboshitz analytical method. The results illustrate that Cpp(q) and Cnn(q) keepsensitivities to the source size (A) at lower T or higher , but almost not at higher T or lower . Andthe sensitivities become stronger for smaller source. Moreover, the T , and A dependencies of the-Gaussian source radii are also extracted by fitting the two-proton momentum correlation functions,and the results are consistent with the above conclusions.

Full Text

Preamble

Effects of Temperature and Density on the Two-Nucleon Momentum Correlation Function from Excited Single Nuclei

Ting-Ting Wang (王婷婷),[1] Yu-Gang Ma (马余刚),*[1],[2] De-Qing Fang (方德清),[1],[2] and Huan-Lin Liu (刘焕玲)[3]

[1]Key Laboratory of Nuclear Physics and Ion-Beam Application (MOE), Institute of Modern Physics, Fudan University, Shanghai 200433, China
[2]Shanghai Research Center for Theoretical Nuclear Physics, NSFC and Fudan University, Shanghai 200438, China

[3]Shanghai Institute of Applied Physics, Chinese Academy of Sciences, Shanghai 201800, China

(Dated: December 28, 2021)

Two-nucleon momentum correlation functions are investigated for different single thermal sources at given initial temperature (T) and density (ρ). To this end, the evolutions of various single excited nuclei at $T = 1 - 20$ MeV and $\rho = 0.2 - 1.2\rho_0$ are simulated using the thermal isospin-dependent quantum molecular dynamics (ThIQMD) model. Momentum correlation functions of identical proton-pairs ($C_{pp}(q)$) or neutron-pairs ($C_{nn}(q)$) at small relative momenta are calculated by the Lednický and Lyuboshitz analytical method. The results illustrate that $C_{pp}(q)$ and $C_{nn}(q)$ maintain sensitivity to the source size (A) at lower T or higher ρ, but this sensitivity almost disappears at higher T or lower ρ. Moreover, the sensitivities become stronger for smaller sources. Additionally, the T, ρ, and A dependencies of the Gaussian source radii are extracted by fitting the two-proton momentum correlation functions, and these results are consistent with the above conclusions.

Introduction

Properties of nuclear matter constitute one of the most interesting topics in heavy-ion physics [1–5], with numerous works conducted around zero temperature, including studies of the nuclear equation of state (EOS). However, investigations into the properties of nuclear matter at finite temperatures remain relatively limited. Many previous works have primarily focused on the temperature dependence of hot nuclear matter and the nuclear liquid-gas phase transition (LGPT) [6–15], the ratio between shear viscosity to entropy density (η/s) [16–20], and nuclear giant dipole resonance [21–23], among others. Among these works, the relationship between the phase transition temperature and the source size has been investigated [6].

In Ref. [6], the finite-size scaling effects on nuclear liquid-gas phase transition probes were examined by studying de-excitation processes of thermal sources using the isospin-dependent quantum molecular dynamics model (IQMD). That study explored several probes including the total multiplicity derivative, second moment parameter, intermediate mass fragment multiplicity, Fisher's power-law exponent, as well as Ma's nuclear Zipf's law exponent, and obtained phase transition temperatures from them. Recently, deep neural networks have also been employed to determine the nuclear liquid-gas phase transition [24] and to estimate the temperature of de-excited nuclei through charge multiplicity distribution [25], with the latter work proposing that charge multiplicity distribution can serve as a thermometer for heavy-ion collisions.

Considering that the intermediate state at high temperature and density in the evolution process of nuclear reactions cannot be directly measured, one must explore properties of nuclear matter and the dynamical description of heavy-ion collisions through analysis of final-state products. As is well known, the two-particle momentum correlation function, also called the Hanbury-Brown Twiss (HBT) technique in the final state, has been used extensively as a probe of the space-time properties and characteristics of the emission source [26–28]. The two-proton momentum correlation function has been explored systematically by numerous experiments and different models, with several reviews available in Refs. [29–32]. In various HBT studies, effects of the impact parameter, the total momentum of nucleon pairs, the isospin of the emission source, the nuclear symmetry energy, the nuclear equation of state (EOS), as well as the in-medium nucleon-nucleon cross section have been discussed in the literature [33–39]. Furthermore, nuclear structure effects have also been carefully investigated, such as effects from binding energy and separation energy of the nucleus [40], density distribution of valence neutrons in neutron-rich nuclei [41], and the high momentum tail of the nucleon-momentum distribution [42]. Two-proton momentum correlation functions have also been constructed in few-body reactions as well as α-clustered nucleus induced collisions [43–47]. Additionally, two light charged particle momentum correlation functions offer a unique tool to investigate dynamical expansion of the reaction zone [39].

Here we extend the HBT method of final-state interaction to study the time-spatial information of finite-temperature nuclear systems. The purpose of the present paper is to systematically investigate the relationship between two-particle momentum correlation functions and system parameters, such as the source temperature, density, and system size within the framework of the thermal isospin-dependent quantum molecular dynamics (ThIQMD) model [6, 15, 18]. Additionally, Gaussian source radii are quantitatively extracted by assuming Gaussian source fits to the HBT distributions.

In this work, the evolution process of excited nuclear sources with initial temperatures varying from 1 MeV to 20 MeV are studied. The present work selects six different systems with similar neutron-to-proton ratios, i.e., $N/Z \sim 1.3$, which include $(A, Z) = (36, 15)$, $(52, 24)$, $(80, 33)$, $(100, 45)$, $(112, 50)$, and $(129, 54)$. The Lednický-Lyuboshitz theoretical approach [48] is then applied to calculate two-particle momentum correlation functions constructed based on phase-space information from the evolution process of single excited nuclear sources using the ThIQMD model.

The remainder of this article is organized as follows. In Section II, we first describe the thermal isospin-dependent quantum molecular dynamics model (ThIQMD) [15, 18], then briefly introduce the Hanbury-Brown and Twiss (HBT) technique using the Lednický and Lyuboshitz analytical formalism. In Section III, we present the results of the ThIQMD plus LL method for the source-temperature dependence of two-particle momentum correlation functions. The two-particle momentum correlation function and the influences of different temperatures and system sizes are systematically discussed. Detailed analysis of the extracted Gaussian source radii is presented under different source temperatures and densities. Furthermore, the momentum correlation function of two neutrons is also analyzed. Finally, Section IV provides a summary of the paper.

Models and Formalism

The ThIQMD Model

Since two-particle momentum correlation functions are calculated using the Lednický and Lyuboshitz theoretical simulation, the true single-particle phase-space distribution at the freeze-out stage is required. In this paper, the thermal isospin-dependent Quantum Molecular Dynamics transport model is used as the event generator, which has been applied successfully to study the LGPT [6, 25]. In the following discussion, we briefly introduce the modified model. As is well known, the isospin-dependent Quantum Molecular Dynamics (IQMD) model was used to describe the collision process between two nuclei. The Quantum Molecular Dynamics transport model is an n-body transport theory that describes heavy-ion reaction dynamics from intermediate to relativistic energies [49–53].

In the present work, we use a single excited source in the ThIQMD model, which differs from traditional IQMD. Usually, the ground state of the initial nucleus is considered to be $T = 0$ MeV in the traditional IQMD model. However, the ThIQMD model described by Fang, Ma, Zhou and Liu in Refs. [6, 15, 18] is used to simulate single nuclear sources at different temperatures $T > 0$ MeV.

The main components of the QMD transport model include the following: the initialization of the projectile and target, nucleon propagation under the effective potential, collisions between nucleons in the nuclear medium, and the Pauli blocking effect. In the ThIQMD model, instead of using the Fermi-Dirac distribution for $T = 0$ MeV, the initial momentum of the nucleons is sampled by the Fermi-Dirac distribution at finite temperature:

$$F(\vec{r}) = \hbar(3\pi^2\rho_i(\vec{r}))^{1/3} n(e_k) = \frac{g(e_k)}{e^{(e_k-\mu)/T} + 1}$$

where the kinetic energy $e_k = p^2/2m$, p and m are the momentum and mass of the nucleon, respectively. $g(e_k) = e_k$ represents the state density with the volume of the source $V = \frac{4}{3}\pi r^3$ where $r = r_0 A^{1/3}$. In addition, the chemical potential μ is determined by the following equation:

$$\int_0^\infty \frac{g(e_k)}{e^{(e_k-\mu)/T} + 1} de_k = \rho_i$$

In the ThIQMD model, the interaction potential is also represented in the following form:

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

where U_{Sky}, U_{Coul}, U_{Yuk}, U_{Sym}, and U_{MDI} are the density-dependent Skyrme potential, the Coulomb potential, the surface Yukawa potential, the isospin asymmetry potential, and the momentum-dependent interaction, respectively. Among these potentials, the Skyrme potential, the Coulomb potential, and the momentum-dependent interaction can be written as follows:

$$U_{Sky} = \alpha \left(\frac{\rho}{\rho_0}\right) + \beta \left(\frac{\rho}{\rho_0}\right)^{\gamma}$$

where ρ and ρ_0 are the total nucleon density and its normal value at the ground state, i.e., 0.16 fm^{-3}, respectively. The above parameters α, β, and γ with an incompressibility parameter K are related to the nuclear equation of state [54–60].

$$U_{Sym} = C_{sym}\frac{(\rho_n - \rho_p)^2}{\rho}$$

$$U_{Coul} = (1 - \tau_z)V_c$$

where ρ_n and ρ_p are neutron and proton densities, respectively, τ_z is the zth component of the isospin degree of freedom for the nucleon, which equals 1 or -1 for a neutron or proton, respectively. C_{sym} is the symmetry energy coefficient. U_{Coul} is the Coulomb potential where V_c is the Coulomb potential for protons.

$$U_{MDI} = \delta \cdot \ln^2\left[\epsilon \cdot (\Delta p)^2 + 1\right] \cdot \frac{\rho}{\rho_0}$$

where Δp is the relative momentum, and δ and ϵ can be found in Refs. [49, 50]. The values of the above potential parameters are all listed in Table I:

[TABLE I]

Lednický and Lyuboshitz Analytical Formalism

Next, we briefly review the method for the two-particle momentum correlation function proposed by Lednický and Lyuboshitz [48, 61, 62]. The main framework of the HBT technique is based on the principle that when particles are emitted at small relative momenta, the two-particle momentum correlation is determined by the space-time characteristics of the production processes due to effects of quantum statistics (QS) and final-state interactions (FSI) [63]. Therefore, the two-particle momentum correlation function can be expressed through the square of the symmetrized Bethe-Salpeter amplitude averaged over the four coordinates of the emission particles and the total spin of the two-particle system, which represents the continuous spectrum of the two-particle state.

In this theoretical approach, the final-state interactions of particle pairs are assumed independent in the production process. According to the conditions in Ref. [64], the correlation function of two particles can be written as:

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

where $r^* = x_1 - x_2$ is the relative distance of the two particles at their 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^*, i.e., the source emission function, and $\Psi_{k^*}(r^*)$ is the Bethe-Salpeter amplitude which can be approximated by the outer solution of the scattering problem [65]. 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 [61, 62]. $F(-i\lambda, 1, i\xi) = 1 + (-i\lambda)(i\xi)/1!^2 + (-i\lambda)(-i\lambda + 1)(i\xi)^2/2!^2 + \cdots$ 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 $h(\lambda) = \lambda^2 \sum_{n=1}^{\infty} \frac{1}{n(n^2+\lambda^2)} - C - \ln[\lambda]$ 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 FSI and can be extracted from experimentally measured correlation functions [39, 65–67].

For n-n correlation functions which involve uncharged particles, only the short-range particle interaction contributes. For p-p correlation functions, both the Coulomb interaction and the short-range particle interaction dominated by s-wave interaction are considered.

Analysis and Discussion

Within the framework of the isospin-dependent quantum molecular dynamics model [15, 18], two-particle momentum correlation functions are calculated using phase-space information from the freeze-out stage of excited nuclear sources with initial temperatures varying from 1 MeV to 20 MeV and/or densities varying from $\rho = 0.2\rho_0$ to $1.2\rho_0$. This work performs calculations for thermal source systems with different masses including $(A, Z) = (36, 15)$, $(52, 24)$, $(80, 33)$, $(100, 45)$, $(112, 50)$, and $(129, 54)$.

We first calculated the proton-proton momentum correlation function $C_{pp}(q)$ for finite-size systems at temperatures ranging from 1 to 20 MeV. In [Figure 1: see original paper], the results of $C_{pp}(q)$ for temperatures of 2, 4, 6, 8, 10, and 12 MeV at different density values ($0.2\rho_0$–$1.2\rho_0$) are presented. The proton-proton momentum correlation function exhibits a peak at relative momentum $q = 20$ MeV/c, which arises from strong final-state s-wave attraction together with suppression at lower relative momentum due to Coulomb repulsion and the antisymmetrization wave function between two protons. The shape of the two-proton momentum correlation functions is consistent with previous experimental data in heavy-ion collisions [68]. For protons emitted from lower temperature sources ($T < 8$ MeV) in Figure 1: see original paper-(c), the general trend is very similar. The figure shows that $C_{pp}(q)$ increases as ρ increases for fixed T ($T < 8$ MeV). The increase in density indicates that the geometrical size becomes smaller for a source with fixed numbers of neutrons and protons, which makes the strength of the momentum correlation function larger. Finally, the p-p momentum correlation function becomes almost unity at $q > 60$ MeV/c. For larger T ($T > 8$ MeV) in Figure 1: see original paper-(f), the difference in $C_{pp}(q)$ between different densities becomes smaller. From [Figure 1: see original paper], it is found that $C_{pp}(q)$ is almost the same after $T = 8$ MeV for different densities, and the p-p momentum correlation function becomes almost unity above approximately $q = 30$ MeV/c. This indicates that the emitted proton is not affected by changes in density when the source temperature exceeds a certain value ($T \approx 8$ MeV in the present work).

In order to understand which of the two factors (temperature or density) has a larger influence, the two-particle momentum correlation in [Figure 2: see original paper] is plotted by exchanging the two input parameters. From [Figure 2: see original paper], we can intuitively observe the dependence of the two-particle momentum correlation on the source temperature. The dependence of $C_{pp}(q)$ on source temperature is stronger than on density. In other words, $C_{pp}(q)$ is more sensitive to T than to density ρ. Additionally, for larger ρ from Figure 2: see original paper to (f), the difference in $C_{pp}(q)$ between different densities becomes bigger. Next, we explore whether this phenomenon exists in the momentum correlation of uncharged particle pairs. [Figure 3: see original paper] presents the neutron-neutron momentum correlation functions ($C_{nn}(q)$) for temperatures of 2, 4, 6, 8, 10, and 12 MeV at different density values, respectively. For the neutron-neutron momentum correlation function, it peaks at $q \approx 0$ MeV/c caused by s-wave attraction. Although $C_{nn}(q)$ has a different shape compared with the p-p momentum correlation, it shows similar dependence on source temperature and density. The similar trend in $C_{pp}(q)$ and $C_{nn}(q)$ indicates a close emission mechanism in the evolution process.

[Figure 4: see original paper] shows the results for a larger system at different source temperatures and densities, demonstrating similar behavior of $C_{pp}(q)$. We also observe that the proton-proton momentum correlation in the larger-size system ($(A,Z) = (129,54)$) in [Figure 4: see original paper] becomes weaker compared to the smaller-size source ($(A,Z) = (36,15)$) in [Figure 1: see original paper].

In view of the above phenomenon, [Figure 5: see original paper] describes the relationship between system size and momentum correlation function in more detail. The decrease of $C_{pp}(q)$ as the system size increases for a fixed value of T or ρ can be clearly seen in Figure 5: see original paper, which is consistent with previous results for Gaussian sources [38, 39, 69]. In Figure 5: see original paper-(i), with larger temperature or lower density, the difference in $C_{pp}(q)$ between different T or ρ becomes smaller, respectively. The Gaussian source radii are extracted for further discussion later in this article.

From the above plots, we can extract $C_{max}(q)$, i.e., the maximum value of $C_{pp}(q)$, as well as the full width at half maximum (FWHM) of the $C_{pp}(q)$ distribution, i.e., at $C_{pp}(q) = [C_{max}(q) - 1]/2$. The source-temperature T dependence of $C_{max}(q)$ and FWHM for the proton-proton momentum correlation function with different densities is given in [Figure 6: see original paper]. As shown in Figure 6: see original paper and (b), both $C_{max}(q)$ and FWHM decrease gradually with increasing T. Additionally, both increase gradually with increasing density. At high temperature, the change in $C_{max}(q)$ and FWHM is very small and not plotted in the figure. Of course, the behavior of $C_{max}(q)$ and FWHM with T and ρ can also be clearly seen in [Figure 2: see original paper], and the increase of $C_{max}(q)$ and FWHM are generally inversely proportional to the Gaussian radius r_0 as shown later. Similarly, the system-size A dependence of $C_{max}(q)$ and FWHM for the proton-proton momentum correlation function at $T = 2$ MeV and $\rho = 0.6\rho_0$ is shown in [Figure 7: see original paper]. The dependence of $C_{max}(q)$ and FWHM on system size A is quite similar to the temperature dependence in [Figure 6: see original paper]. The $C_{max}(q)$ and FWHM values become smaller for systems with larger size.

[Figure 8: see original paper] shows the source-temperature, density, and system-size dependence of Gaussian radii extracted from two-particle momentum correlation functions, where panels (a) and (b) are results for the smaller source size and the larger source size, respectively. The radii are extracted under a Gaussian source assumption, i.e., $S(r) \approx \exp[-r^2/(4r_0^2)]$, where r_0 is the Gaussian source radius from the proton-proton momentum correlation functions. The theoretical calculations for $C_{pp}(q)$ were performed using the Lednický and Lyuboshitz analytical method. The best-fitting radius is determined by finding the minimum of the reduced chi-square between the ThIQMD calculations and the

Gaussian source assumption. It can be observed that the Gaussian radius initially increases and then decreases slightly after reaching a maximum value at a certain temperature in [Figure 8: see original paper]. As the density decreases, the decreasing speed of the Gaussian radius for the small system is larger than that for the larger system. [Figure 9: see original paper] shows how the Gaussian radius of different system sizes varies with temperature in panels (a)-(c) or density in panels (d)-(f). The Gaussian source radius is consistent with the system size, i.e., at higher temperature or larger density, the differences in Gaussian source radii between different system sizes are larger in the low-density and low-temperature region, but these differences almost disappear under opposite conditions.

From the above discussion, it is demonstrated that the strength of the two-particle momentum correlation function is affected by source temperature, density, and system size. The two-particle momentum correlation function strength is larger for a single source with lower temperature, higher density, or smaller mass number, as shown in [Figure 1: see original paper]–[Figure 5: see original paper]. Otherwise, the strength becomes smaller. To some extent, the strong correlation between two particles is mainly caused by the proximity of each other in phase space in both coordinate and momentum. Varying only one of the three condition parameters (temperature, density, and system size), lower temperature means smaller momentum space, higher density means smaller coordinate space, and small system size also means smaller coordinate space to maintain fixed density compared with large system size. The dependencies of the two-particle momentum correlation function strength on source temperature, density, and system size can be explained by changes in phase space sizes. Two particles emitted from a small phase space will have strong correlation, while those from a large phase space will have weak correlation. For example, the increase in $C_{pp}(q)$ strength with increasing density for a fixed system size can be explained by the decrease in coordinate space as shown in Figure 1: see original paper. The small $C_{pp}(q)$ strength at temperatures higher than 8 MeV could be caused by the large momentum space compared with lower temperatures as shown in Figure 1: see original paper. The decrease in $C_{pp}(q)$ strength with increasing system size for a fixed density could also be explained by the increase in coordinate space as shown in Figure 5: see original paper. Thus it could be concluded that the phase space size for the emitted nucleons has a strong effect on the strength of the two-particle momentum correlation function, which can also be seen in the extracted Gaussian radii as shown in [Figure 8: see original paper]. However, the sensitivities to the source radii appear to differ in different regions of temperature and density. For example, the temperature sensitivity is better in the lower region at fixed density, and similarly for density sensitivity at lower temperatures.

Summary

In summary, two-particle momentum correlation functions for a single excited source are investigated using the Lednický and Lyuboshitz analytical formalism with phase-space points at the freeze-out stage for different initial temperatures and densities within the framework of the ThIQMD transport approach. We performed a series of studies focused on the varied effects of source temperature, density, and system size on two-particle momentum correlation functions. The results show that the shape of the two-proton momentum correlation function is in accordance with previous experimental data in heavy-ion collisions [68]. At the same time, the trend of the relationship between the two-proton momentum correlation and system size is consistent with previous simulations [38, 39, 69]. At low source temperature, larger density makes the two-particle momentum correlation stronger. However, at higher source temperature, this effect almost disappears. Both protons and neutrons exhibit similar behavior. This work also shows that emitted particles are not influenced by density above a given temperature in a single excited source. Similarly, emitted particles are only weakly influenced by temperature below a given density in a single excited source. In summary, the dependence of the two-particle momentum correlation function on source temperature, density, and system size can be explained by changes in coordinate and/or momentum phase space sizes. Finally, the Gaussian radius is extracted to explore the emission source size in single excited systems. The Gaussian radius becomes larger in larger systems. The dependence of the extracted Gaussian radius on source temperature and density is consistent with the behavior of the two-proton momentum correlation function as discussed in the text.

Acknowledgments

This work was supported in part by the National Natural Science Foundation of China under contract Nos. 11890710, 11890714, 11875066, 11925502, 11961141003, 11935001, 12147101 and 12047514, the Strategic Priority Research Program of CAS under Grant No. XDB34000000, National Key R&D Program of China under Grant No. 2016YFE0100900 and 2018YFE0104600, Guangdong Major Project of Basic and Applied Basic Research No. 2020B0301030008, and the China Postdoctoral Science Foundation under Grant No. 2020M681140.

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