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Interferometry analyses of pion and kaon for the granular sources for Au + Au collisions at $\sqrt{s_{NN}} = 200$ GeV

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Abstract We examine the interferometry results of identical pion and kaon for the granular sources of quark–gluon plasma droplets for the Au + Au collisions at $\sqrt{s_{NN}} = 200$ GeV. The effects of particle absorptions of pion and kaon on the results are investigated. We find that the absorptions lead to the decrease of the interferometry radii. After considering the absorptions, the interferometry radii of pion and kaon of the granular sources are in better agreement with the experimental data of the Au + Au collisions.

Keywords Pion interferometry · Kaon interferometry · Granular sources · Absorption effect

1 Introduction

Hanbury–Brown–Twiss (HBT) interferometry has been widely used in high-energy heavy ion collisions to explore the space–time structure of the particle-emitting sources [1–5]. In Refs. [6, 7], we systematically investigated the pion HBT interferometry, as well as the pion transverse-momentum spectrum and elliptic flow, in the granular source model of quark–gluon plasma (QGP) droplets [8–11]. The investigations [6, 7] indicate that the granular source model can reproduce the experimental data of pion HBT radii, transverse-momentum spectrum, and elliptic flow in the heavy ion collisions at the Relativistic Heavy Ion Collider (RHIC) and the Large Hadron Collider (LHC) concurrently and consistently. Recently, the PHENIX collaboration measured the kaon HBT correlations in the Au + Au collisions at $\sqrt{s_{NN}} = 200$ GeV in different centrality regions and provided the pion HBT radii in a larger transverse mass (transverse-momentum) region [12] compared to the previous measurements in the Au + Au collisions [13, 14]. Therefore, explaining the new interferometry data of pion and kaon in the granular source model will be of interest.

In this work, we perform the HBT interferometry analyses of pion and kaon for the granular sources for the central and approximately central Au + Au collisions at $\sqrt{s_{NN}} = 200$ GeV. With a simple treatment for the particle absorption in the granular sources, we investigate the absorption effects on the particle transverse-momentum spectra and HBT radii of pion and kaon. We find that the absorption effects on the transverse-momentum spectra of pion and kaon are small. However, the absorptions lead to the decreases of the HBT radii. The interferometry radii of pion and kaon of the granular sources are in better agreement with the experimental data of the Au + Au collisions at $\sqrt{s_{NN}} = 200$ GeV, after considering the particle absorptions in the granular sources.

2 Granular source model

The granular sources are assumed to be formed at a later time of the QGP expansion in relativistic heavy ion collisions. The lumps of the QGP after this time are considered

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to be spherical droplets for simplicity and evolve in hydrodynamics separately [6–11]. The strong interactions of the QGP matter before forming the granular source are assumed to lead to the anisotropic initial velocities of the QGP droplets in the granular source model [6–11].

In this work, we adopt all the ingredients of the granular source model used in Refs. [6] and [7]. The initial energy density distribution of single droplet is assumed with a Woods–Saxon distribution [7], and the QGP droplets distribute initially within a cylinder along the beam direction (z-axis) by [6, 7]

$$\frac{\mathrm{dN_d}}{\mathrm{d}x_0\mathrm{d}y_0\mathrm{d}z_0} \propto \left[1 - e^{-(x_0^2+y_0^2)/\Delta\mathcal{R}_\mathrm{T}^2}\right]\theta(\mathcal{R}_\mathrm{T} - \rho_0) \times \theta(\mathcal{R}_z - |z_0|), \tag{1}$$

where $\rho_0 = \sqrt{x_0^2 + y_0^2}$ and z_0 are the initial transverse and longitudinal coordinates of the droplet centers, $\mathcal{R}_\mathrm{T}$ and $\mathcal{R}_z$ describe the initial transverse and longitudinal sizes of the source, and $\Delta\mathcal{R}_\mathrm{T}$ is a transverse shell parameter. The initial radius of droplet, r_0, satisfies a Gaussian distribution with standard deviation, σ_d, in the droplet local frame. We take the initial velocities of the droplets in granular source as [6, 7]

$$v_{\mathrm{d}i} = \mathrm{sign}(r_{0i}) \cdot a_i \left(\frac{|r_{0i}|}{\mathcal{R}_i}\right)^{b_i}, \quad i = 1, 2, 3, \tag{2}$$

where r_{0i} is x_0, y_0, or z_0 for $i = 1$, 2, or 3, and $\mathrm{sign(r_{0i})}$ denotes the signal of r_{0i}, which ensures an outward droplet velocity. In Eq. (2), $\mathcal{R}_i = (\mathcal{R}_\mathrm{T}, \mathcal{R}_\mathrm{T}, \mathcal{R}_z)$, the quantities $a_i = (a_x, a_y, a_z)$, and $b_i = (b_x, b_y, b_z)$ are the magnitude and exponent parameters of droplet initial velocity in x, y, and z directions. In the model calculations in this paper, we take the values of the source parameters as the same in Ref. [7].

In the granular source model, the droplets evolve in relativistic hydrodynamics and with the equation of state (EOS) of the S95p-PCE-v0 [15]. The final identical pions and kaons are considered to be emitted from the surfaces of the droplets with the momenta obeying Bose–Einstein distribution in the local frame at freeze-out temperature, T_f. To include the resonance-decayed particles later as well as the directly produced pions at chemical freeze-out early, a wide region of T_f is considered with the probability [6, 7]

$$\frac{\mathrm{d}P}{\mathrm{d}T_\mathrm{f}} \propto f_\mathrm{dir}\, e^{-\frac{T_\mathrm{chem}-T_\mathrm{f}}{\Delta T_\mathrm{dir}}} + (1 - f_\mathrm{dir}) \times e^{-\frac{T_\mathrm{chem}-T_\mathrm{f}}{\Delta T_\mathrm{dec}}}, (T_\mathrm{chem} > T_\mathrm{f} > 80\mathrm{MeV}), \tag{3}$$

where f_dir is the fraction of the direct emission around the chemical freeze-out temperature T_chem, and ΔT_dir and ΔT_dec are the temperature widths for the direct and decay emissions, respectively. In the calculations, we take $\Delta T_\mathrm{dir} = 10$ MeV and $\Delta T_\mathrm{dec} = 90$ MeV as in Refs. [6, 7]. The value of T_chem is taken to be 165 MeV as in the EOS of S95p-PCE-v0 [15]. The parameter f_dir is taken to be 0.75 for pion as in Refs. [6, 7] and is taken to be 1 for kaon for its early freeze-out.

Unlike a continuous source which is emitting particles from source surface, the particles are freezed out on the droplet surfaces for the granular source, and the particle emitted from a droplet may also be absorbed by other droplets in the granular source. Because the particle emitted early (or at high T_f) from a droplet in the granular source is more possible to meet the other droplets with higher temperatures and be absorbed when propagating inward in the granular source, we apply simply the cut,

$$\not\subset [(T_\mathrm{f} > T'_\mathrm{f}).\mathrm{and}.((\boldsymbol{p} \cdot \boldsymbol{r}_\mathrm{T} < 0).\mathrm{or}.(\boldsymbol{p} \cdot \boldsymbol{r}_z < 0))],$$

to forbid the particle which freezes out at the higher temperatures $T_\mathrm{f} > T'_\mathrm{f}$ and has a momentum $\boldsymbol{p}$ with negative $(\boldsymbol{p} \cdot \boldsymbol{r}_\mathrm{T})$ or $(\boldsymbol{p} \cdot \boldsymbol{r}_z)$ value in our model calculations for the case with absorption, where $\boldsymbol{r}$ is the coordinate vector of the particle freeze-out point in the frame of the granular source. The particle absorption in high-density (temperature) medium is a complicated problem. The cross section of particle absorption is related not only to the medium environment, but also to the particle property. In the present consideration, the absorption effect is related to the values of T'_f parameter used in the calculations. We take T'_f =150 and 155 MeV in the calculations for pion and kaon, respectively, by the comprehensive comparisons of the model-calculated HBT radii with experimental data.

In Fig. 1, we show the transverse-momentum spectra of pion and kaon for the granular sources for the Au + Au collisions at $\sqrt{s_{NN}} = 200$ GeV and in 10–20 % centrality region. Here the dashed and solid lines are for the granular source results without and with the particle absorptions in the granular sources. In Fig. 1, the experimental data measured by the PHENIX collaboration [16] and the STAR collaboration [17] are also shown. One can see that the particle transverse-momentum spectra are in agreement with the experimental data. The particle absorption considered leads to the decreases of the spectra at small transverse momentum and the small increase of the spectra at large transverse momentum. This is because the absorption decreases the particles which propagate inward in the granular source, and the outward boost of the droplet velocities makes these particles have smaller average momentum than the particles propagating outward.

3 Pion and kaon interferometry analyses

Two-particle HBT correlation function is defined as the ratio of the two-identical-particle momentum spectrum $P(\boldsymbol{p}_1, \boldsymbol{p}_2)$ to the product of the two single-particle momentum spectra $P(\boldsymbol{p}_1)P(\boldsymbol{p}_2)$. In the interferometry analyses in high-energy heavy ion collisions, the two-

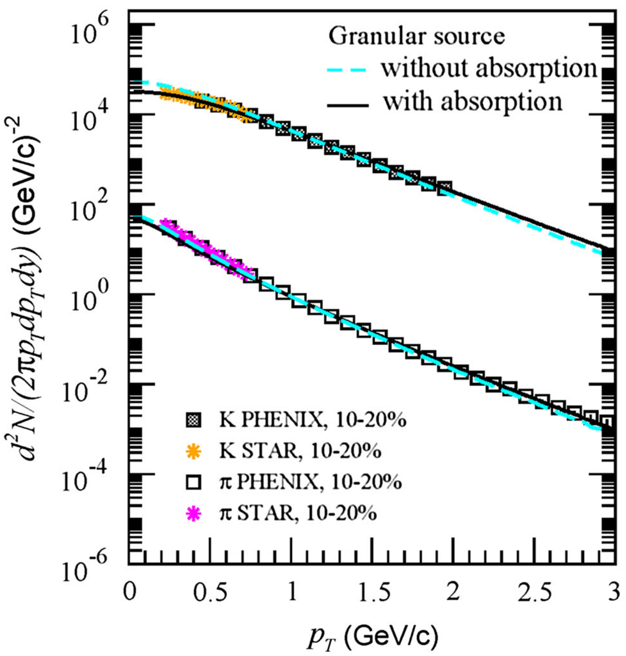

Fig. 1 (Color online) Transverse-momentum spectra of pion and kaon for the granular sources for the Au + Au collisions at $\sqrt{s_{NN}} = 200$ GeV and in 10–20 % centrality region. The *dashed* and *solid lines* are for the granular source results without and with the consideration of the particle absorptions in the granular sources. The experimental data are measured by the PHENIX collaboration [16] and the STAR collaboration [17]

particle correlation functions are usually fitted by the Gaussian-parameterized formula

$$C(q_{\rm out}, q_{\rm side}, q_{\rm long}) = 1 + \lambda\, e^{-R^2_{\rm out}q^2_{\rm out} - R^2_{\rm side}q^2_{\rm side} - R^2_{\rm long}q^2_{\rm long}}, \quad (4)$$

where $q_{\rm out}$, $q_{\rm side}$, and $q_{\rm long}$ are the Bertsch–Pratt variables [18–20], which denote the components of the relative momentum $\boldsymbol{q} = \boldsymbol{p}_1 - \boldsymbol{p}_2$ in transverse “out” (parallel to the transverse momentum of the pion pair $\boldsymbol{k}_{\rm T}$), transverse “side” (in transverse plane and perpendicular to $\boldsymbol{k}_{\rm T}$), and longitudinal (“long”) directions, respectively. In Eq.(4), λ is chaoticity parameter, and $R_{\rm out}$, $R_{\rm side}$, and $R_{\rm long}$ are the HBT radii in the out, side, and long directions.

In Fig. 2, we show the results of the two-pion interferometry for the granular sources for the central and approximately central Au + Au collisions at $\sqrt{s_{NN}} = 200$ GeV. The granular source parameters are taken as in Ref. [7] for the centralities of 0–5 and 10–20 %. The experimental data of the pion interferometry analyses performed by the PHENIX [12] and STAR [14] collaborations are also shown in Fig. 2, respectively. It can be seen that the particle absorption considered leads to little decreases of the HBT radii $R_{\rm out}$ and $R_{\rm side}$ and the decreases of the HBT radius $R_{\rm long}$ at larger transverse momenta. The effect of the particle absorption on chaoticity parameter λ is negligible. The HBT radii of the granular sources are in

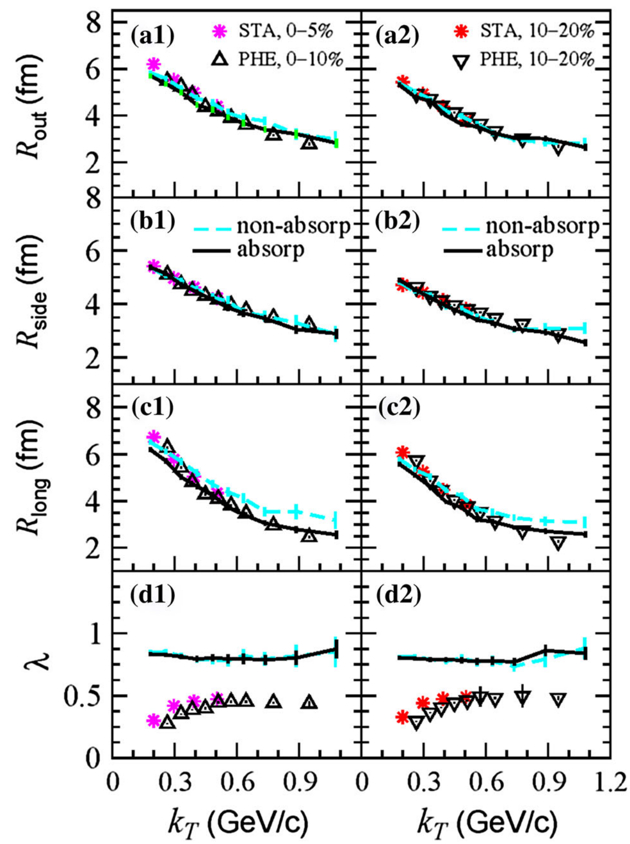

Fig. 2 (Color online) Two-pion interferometry results for the granular sources for the Au + Au collisions at $\sqrt{s_{NN}} = 200$ GeV. The *dashed* and *solid lines* are for the cases without and with the consideration of the particle absorption in the granular sources. The *symbols* are the experimental data in the Au + Au collisions measured by the PHENIX collaboration [12] and the STAR collaboration [14], respectively

slightly better agreement with the experimental data after considering the particle absorptions in the sources. The results of λ of the granular sources are larger than the experimental data, because many other effects in experiments can decrease the measurement value of λ [1–5], which exceeds our considerations in the granular source model. By comparing the error bars of the HBT results for the cases without and with the absorption carefully, one can see that the error bars for the case without the absorption are greater than those with the absorption. The reason is that the absorption leads to the increase of the particle pairs with smaller relative momenta (two particles with approximate momentum direction and magnitude) and the HBT-fitted results are mainly dependent on the correlations at small relative momentum region, which have enhancements relative to 1.

We plot in Fig. 3 the two-kaon interferometry results for the granular sources for the Au + Au collisions at $\sqrt{s_{NN}} = 200$ GeV and in the same centrality regions as in

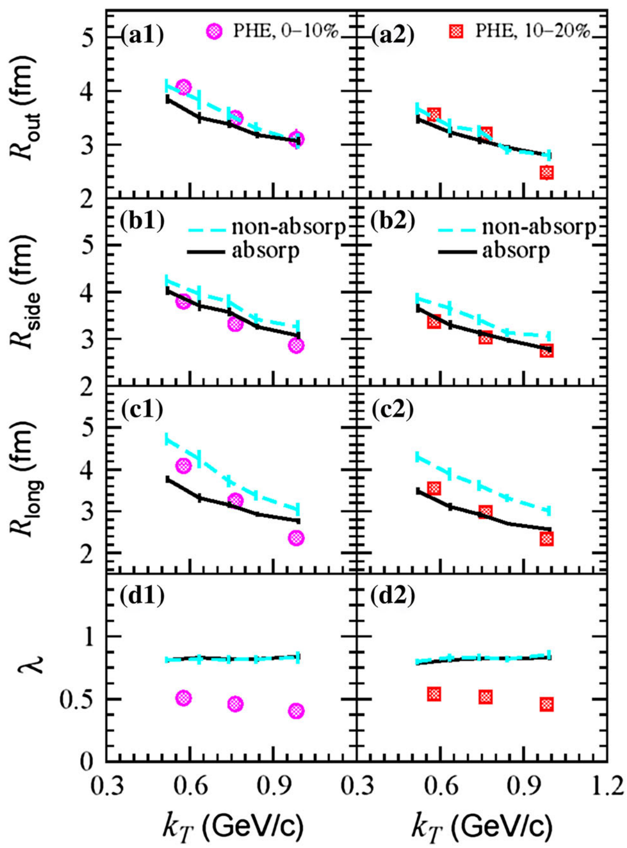

Fig. 3 (Color online) Two-kaon interferometry results for the granular sources for the Au + Au collisions at $\sqrt{s_{NN}} = 200$ GeV. The *dashed* and *solid lines* are for the cases without and with the consideration of the particle absorption in the granular sources. The *symbols* are the experimental data in the Au + Au collisions measured by the PHENIX collaboration [12]

Fig. 2. The experimental data of the kaon interferometry analyses performed by the PHENIX collaboration [12] are also shown in Fig. 3. For kaon, the distribution of freeze-out temperature is narrow near $T_{\rm chem}$, and the effect of the absorption is important. It is shown in Fig. 3 that the HBT radii for the absorption case are much smaller than those for the non-absorption case, because outward emission of particles can lead to the decrease of HBT radii [3, 6, 21].

4 Summary and conclusions

We have performed pion and kaon interferometry analyses in the granular source model of QGP droplets [6, 7]. The effect of particle absorption on the HBT radii of pion and kaon is investigated based on a consideration of forbidding inward emission for the particles freezed out earlier (or at higher temperature). This absorption effect is important in the kaon interferometry analyses. It leads to the decreases of the kaon HBT radii. In our analyses, the particle-emitting sources of pion and kaon have the same initial source parameters, but different freeze-out temperature regions. Although it is only a simple consideration for the particle absorption, the HBT radii of pion and kaon of the granular sources are in better agreement with the experimental data of the Au + Au collisions at $\sqrt{s_{NN}} = 200$ GeV at the RHIC after considering the particle absorption. Further investigations of the particle absorption in the granular source model and its influence on final-particle multiple observables will be of interest.

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