Two-pion interferometry for the granular sources in the heavy ion collisions at RHIC and LHC energies

Wei-Ning Zhang[*]

School of Physics and Optoelectronic Technology, Dalian University of Technology, Dalian, Liaoning 116024, China
Department of Physics, Harbin Institute of Technology, Harbin, Heilongjiang 150006, China
E-mail: wnzhang@dlut.edu.cn

We investigate the two-pion interferometry in ultrarelativistic heavy ion collisions in the granular source model of quark-gluon plasma droplets. The pion transverse momentum spectra and HBT radii of the granular sources agree well with the experimental data of the most central Au-Au collisions at $\sqrt{s_{NN}} = 200$ GeV at RHIC and Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV at LHC. In the granular source model the larger initial system breakup time for the LHC collisions as compared to the RHIC collisions may lead to the larger HBT radii R_{out}, R_{side}, and R_{long}. However, the large droplet transverse expansion and limited average relative emitting time of particles in the granular source lead to the ratio of the transverse HBT radii $R_{\text{out}}/R_{\text{side}} \sim 1$.

---

[*]Speaker.

1. Introduction

Hanbury-Brown-Twiss (HBT) interferometry is a useful tool to probe the space-time geometry of the particle-emitting sources in high energy heavy ion collisions [1, 2, 3, 4]. The experimental results of the HBT measurements for the Au-Au collisions at the high energies of the Relativistic Heavy Ion Collider (RHIC) indicate that it is hard to describe the source space-time dynamics by a simple evolution model [5, 6, 7, 8]. HBT interferometry data provide strong constraints for the models of source space-time dynamics. Recently, the HBT measurement for the $\sqrt{s_{NN}} = 2.76$ TeV Pb-Pb most central collisions at the Large Hadron Collider (LHC) has been performed [9]. A consistent explanation to the HBT data of the LHC and RHIC experiments is required naturally for the source models, which will be helpful to understand the initial condition, source evolution, and particle freeze-out in ultrarelativistic heavy ion collisions.

In Refs. [10, 11], the granular source model of quark-gluon plasma (QGP) droplets [12] is developed to explain the RHIC HBT data [7, 8]. In this work we investigate the two-pion HBT interferometry in ultrarelativistic heavy ion collisions in the granular source model of QGP droplets. Our results indicate that the granular source for the LHC Pb-Pb collisions may have a larger initial system breakup time as compared to the RHIC Au-Au collisions. The granular source model consistently reproduces the pion transverse momentum spectra and HBT radii in the most central collisions of the RHIC [13, 14, 8] and LHC [15, 9] experiments.

2. Granular source model in ultrarelativistic heavy ion collisions

In ultrarelativistic heavy ion collisions, the system at central rapidity may reach a local equilibrium at a very short time τ_0, and may then expand rapidly along the beam direction (z-axis). Because of the initial fluctuation, the initial local-equilibrium system is not spatially uniform [16]. It may form many tubes along the beam direction during the fast longitudinal expansion, and finally fragment into many droplets (see Fig.1 of Ref. [10]) due to the "sausage" instability and surface tension [10]. On the other hand, the rapidly increased bulk viscosity in the QGP near the phase transition may also leads to the breakup of the system [17].

We assume that the system fragments and forms a granular source of many QGP droplets at a time $t_0(> \tau_0)$. On the basis of the Bjorken hypothesis [18], the longitudinal velocity and rapidity of the droplets at t_0 are

$$v_{dz} = z_0/t_0, \quad \eta_0 = \frac{1}{2}\ln\frac{t_0 + z_0}{t_0 - z_0}, \tag{2.1}$$

and the transverse velocity of the droplets may be expressed as [19, 11]

$$v_{d\perp} = a_T\left(\frac{\rho_0}{\mathscr{R}_{\perp 0}}\right)^{b_T}\sqrt{1 - v_{dz}^2}, \tag{2.2}$$

where z_0 and ρ_0 are the longitudinal and transverse coordinates of the droplet centers at the breakup time t_0, $\mathscr{R}_{\perp 0}$ is the maximum transverse radius of the system at t_0. In Eq. (2.2), the quantities a_T and b_T are the magnitude and power parameters of the transverse velocity which will be determined by the data of particle transverse momentum spectra.

In our model calculations, the initial droplet radius in droplet local frame satisfies a Gaussian distribution with standard deviation $\sigma_d = 2.5$ fm, and the initial droplet centers are assumed to distribute within a cylinder along the beam direction by [10, 11]

$$\frac{dN}{2\pi\rho_0 \, d\rho_0} \propto \left[1 - \exp\left(-\rho_0^2/\Delta\mathscr{R}_\perp^2\right)\right]\theta(\mathscr{R}_\perp - \rho_0), \tag{2.3}$$

where $\mathscr{R}_\perp$ and $\Delta\mathscr{R}_\perp$ are the initial transverse radius and shell parameter of the granular source [10, 11]. Because of the longitudinal boost-invariant in ultrarelativistic heavy ion collisions, we may obtain the initial coordinate z_0 of the droplet by the longitudinal distribution

$$\frac{dN}{dz_0} = \frac{dN}{d\eta_0}\frac{d\eta_0}{dz_0} \propto 1 \cdot \frac{t_0}{t_0^2 - z_0^2}, \quad |z_0| < \sqrt{t_0^2 - \tau_0^2}. \tag{2.4}$$

The evolution of the granular source after t_0 is the superposition of all the evolutions of the individual droplets, each of which is described by relativistic hydrodynamics. In our calculations, we use two kinds of equations of state. One is the entropy density with a cross over between the QGP and hadronic gas [20] (EOS1, the parameters are taken as the same as in Ref. [11]). Another is the S95p-PCE [21] (EOS2). In order to include the pions emitted directly at hadronization and decayed from resonances later, we let the pions freeze-out within a wide temperature region with the probability [11]

$$\frac{dP_f}{dT} \propto f_{\text{dir}}e^{-(T_c - T)/\Delta T_{\text{dir}}} + (1 - f_{\text{dir}})e^{-(T_c - T)/\Delta T_{\text{dec}}}, \quad (T_c > T > 80 \text{ MeV}), \tag{2.5}$$

where T_c is the transition temperature, f_{dir} is a fraction parameter for the direct emission, ΔT_{dir} and ΔT_{dec} describe the widths of temperature for the direct and decayed pion emissions. They are taken to be $T_c = 170$ MeV, $f_{\text{dir}} = 0.85$, $T_{\text{dir}} = 10$ MeV, and $T_{\text{dec}} = 90$ MeV [11].
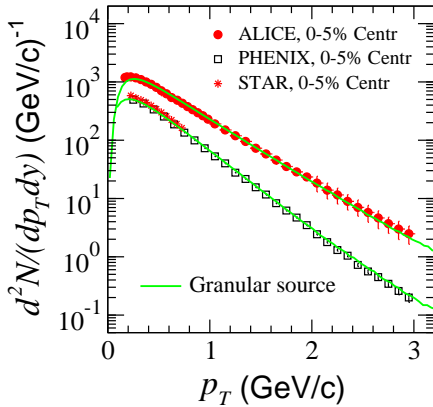

Fig. 1. (Color online) The pion transverse momentum distribution of the granular sources and the experimental data of $\sqrt{s_{NN}} = 200$ GeV Au-Au (PHENIX [13] and STAR [14]) and $\sqrt{s_{NN}} = 2.76$ TeV Pb-Pb (ALICE [15]) most central collisions.

In Fig. 1, we show the pion transverse momentum spectra calculated with the granular source model and the experimental data of the most central Au-Au collisions at $\sqrt{s_{NN}} = 200$ GeV [13, 14] and Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV [15]. Assuming that the systems fragment when the local energy density decreases at a certain value, we take the initial droplet temperature $T_0 = 200$ MeV [11] in the calculations. For the granular source in the RHIC collisions, τ_0 and the breakup time t_0 are taken to be 0.8 and 4.3 fm/c. The source parameters $\mathscr{R}_\perp$ are taken to be 6.5 fm for EOS1 and 6.8

fm for EOS2, and $\Delta\mathscr{R}_\perp$ is taken to be 3.5 fm. For the granular source in the LHC collisions, these parameters are taken to be $\tau_0 = 0.4$ fm/c, $t_0 = 8.0$ fm/c, $\mathscr{R}_\perp =$7.8(8.0) fm for EOS1(EOS2), and $\Delta\mathscr{R}_\perp = 5.4$ fm. By comparing the transverse momentum spectra of the granular sources with the data of $\sqrt{s_{NN}} = 200$ GeV Au-Au [13, 14] and $\sqrt{s_{NN}} = 2.76$ TeV Pb-Pb [15] most central collisions, we fix the parameters of the droplet transverse velocity $a_T =$0.65(0.68) for EOS1(EOS2) for the RHIC energy and $a_T = 0.65$ for the two EOSs for the LHC energy. The parameter b_T is fixed as 1.40 the same for the two EOSs and energies. In Eq. (2.2), $\mathscr{R}_{\perp 0}$ is taken to be 8.0 fm in the calculations. It can be seen that the transverse momentum spectra of the granular source agree well with the experimental data.

3. HBT interferomwtry results

In Fig. 2, we show the HBT radii R_{out}, R_{side} and R_{long} in the "out", "side", and "long" directions [22], and the chaotic parameter λ of the granular sources as functions of the transverse pion pair momentum, $k_T = |\mathbf{p}_{1T} + \mathbf{p}_{2T}|/2$. They are obtained by fitting the two-pion correlation functions in different k_T regions with the formula

$$C(q_{\text{out}}, q_{\text{side}}, q_{\text{long}}) = 1 + \lambda \, e^{-q_{\text{out}}^2 R_{\text{out}}^2 - q_{\text{side}}^2 R_{\text{side}}^2 - q_{\text{long}}^2 R_{\text{long}}^2},$$ (3.1)

in the longitudinal comoving system (LCMS) [4]. The HBT data of the most central collisions of $\sqrt{s_{NN}} = 200$ GeV Au-Au (STAR [8]) and $\sqrt{s_{NN}} = 2.76$ TeV Pb-Pb (ALICE [9]) are also shown. In our calculations, we use the same cuts as in the experimental analyses [8, 9]. That is the pion rapidity is limited with $|y| < 0.5$ for the granular source for the RHIC collisions and the pion pseudorapidity satisfies $|\eta| < 0.8$ for the granular source for the LHC collisions, respectively.

One can see the HBT radii of the granular sources agree well with the experimental data. Because of the higher collision energy, the granular source for the LHC collisions is formed (system energy density decreases to a certain value) at the larger t_0, and hence has a wider z_0 distribution (see Eq. (2.4)) and larger $\mathscr{R}_\perp$ value (wider ρ_0 distribution, see Eq. (2.3)). These lead to the wider distributions of the longitudinal and transverse source points for the LHC granular source than those for the RHIC granular source [23]. The wider distributions of the transverse and longitudinal source points for the LHC granular source lead to the larger transverse and longitudinal HBT radii than those for the RHIC granular source.

For a certain k_T bin, the transverse velocity of the pair, $(\mathbf{p}_{1T} + \mathbf{p}_{2T})/(E_1 + E_2)$, is fixed. The ratio of the transverse HBT radii $R_{\text{out}}(k_T)/R_{\text{side}}(k_T)$ is related to the source transverse expansion, which may change the source distribution of the correlated pions in the out and side directions [24, 25], and the average relative emitting time of the two pions, $\overline{\Delta t} = \langle |t_1 - t_2| \rangle \sim [\langle (t_1 - t_2)^2 \rangle]^{1/2} = [\langle t_1^2 \rangle - \langle t_1 \rangle^2 + \langle t_2^2 \rangle - \langle t_2 \rangle^2]^{1/2}$ [2, 4, 26]. Although the larger breakup time t_0 for the LHC source leads to a larger particle-emitting time, the limited value of $\overline{\Delta t}$ for the granular sources [12, 10, 11, 25] and the large droplet transverse velocity lead to the small $R_{\text{out}}/R_{\text{side}}$ results (see Fig. 2 (d) and (d')). In the upper panel of Fig. 3, we show the average pion-emitting time $\bar{t}$ and the average relative pion-emitting time $\overline{\Delta t}$ for the RHIC and LHC granular sources. It can be seen that the average pion-emitting time for the LHC source is much larger than that for the RHIC source. However, there is only small difference between the average relative pion-emitting times for the LHC and RHIC sources. In the lower panel of Fig. 3, we show the average source transverse

4

and longitudinal velocities as functions of the transverse pion pair momentum k_T. The transverse velocity $\overline{v}_{\mathrm{ST}}$ increases with k_T, and the longitudinal velocity $\overline{v}_{\mathrm{SL}}$ decreases with k_T. For the collisions at the LHC energy the granular source has larger transverse and longitudinal velocities.
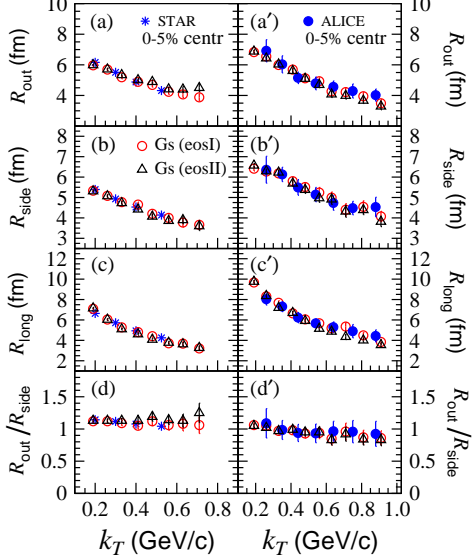

Fig. 2. (Color online) The HBT radii of the granular sources and the experimental data for the most central collisions of $\sqrt{s_{NN}} = 200$ GeV Au-Au [8] and $\sqrt{s_{NN}} = 2.76$ TeV Pb-Pb [9].
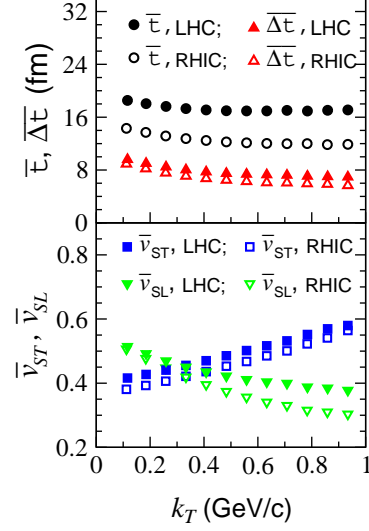

Fig. 3. (Color online) (a) The average pion-emitting time and relative pion-emitting time for the granular sources. (b) The average source transverse and longitudinal velocities for the granular sources.

4. Summary

In summary, we investigate the two-pion HBT interferometry in ultrarelativistic heavy ion collisions in the granular source model of QGP droplets. The pion transverse momentum spectra and HBT radii of the granular sources agree well with the data of RHIC $\sqrt{s_{NN}} = 200$ GeV Au-Au and LHC $\sqrt{s_{NN}} = 2.76$ TeV Pb-Pb most central collisions. Our results indicate that the granular source for the collisions at the LHC energy may have a larger initial system breakup time as compared to the collisions at RHIC energy. The larger breakup time leads to the broader longitudinal and transverse distributions of the source points, and hence leads to the larger longitudinal and transverse HBT radii. However, the average relative emitting time of the two pions is limited in the granular source model. The limited relative pion-emitting time and larger droplet transverse expansion lead to the ratio of the transverse HBT radii $R_{\mathrm{out}}/R_{\mathrm{side}} \sim 1$. In our granular source model, there is correlations between the space-time coordinates and source velocities. The data of the particle transverse momentum spectra and HBT radii for the collisions at the RHIC and LHC energies give strong constraints for the model parameters. The consistent explanation of the granular source model to these experimental data will be helpful to understand the formation and evolution of the pion-emitting sources in ultrarelativistic heavy ion collisions. Further studies on the relationship of the source radii and emission time and the comparison with other models, which can explain the source functions of $\sqrt{s_{NN}} = 200$ GeV Au-Au [27], will be interest.

Acknowledgments

References

[1] C. Y. Wong, *Introduction to High-Energy Heavy-Ion Collisions* (World Scientific, Singapore), 1994, Chap. 17.

[2] U. A. Wiedemann and U. Heinz, Phys. Rept. **319** (1999) 145.

[3] R. M. Weiner, Phys. Rept. **327** (2000) 249.

[4] M. A. Lisa, S. Pratt, R. Soltz, and U. Wiedemann, Ann. Rev. Nucl. Part. Sci. **55** (2005) 357.

[5] C. Adler *et al* (STAR Collaboration), Phys. Rev. Lett. **87** (2001) 082301.

[6] K. Adcox *et al* (PHENIX Collaboration), Phys. Rev. Lett. **88** (2002) 192302.

[7] S. S. Adler *et al* (PHENIX Collaboration), Phys. Rev. Lett. **93** (2004) 152302.

[8] J. Adams *et al* (STAR Collaboration), Phys. Rev. C **71** (2005) 044906.

[9] K. Aamodt *et al* (ALICE Collaboration), Phys. Lett. B **696** (2001) 328.

[10] W. N. Zhang, Y. Y. Ren, and C. Y. Wong, Phys. Rev. C **74** (2006) 024908.

[11] W. N. Zhang, Z. T. Yang, and Y. Y. Ren, Phys. Rev. C **80** (2009) 044908.

[12] W. N. Zhang, M. J. Efaaf, and C. Y. Wong, Phys. Rev. C **70** (2004) 024903.

[13] S. S. Adler *et al* (PHENIX Collaboration), Phys. Rev. C **69** (2004) 034909.

[14] J. Adams *et al* (STAR Collaboration), Phys. Rev. Lett. **92** (2004) 112301.

[15] M. Floris on behalf of ALICE Collaboration, plenary talk at Quark Matter 2011, May 26, 2011, Annecy, France, Quark Matter 2011 proceedings.

[16] H. J. Drescher, F. M. Liu, S. Ostapchenko, T. Pierog, and K. Werner, Phys. Rev. C **65** (2002) 054902; O. J. Socolowski, E. Grassi, Y. Hama, and T. Kodama, Phys. Rev. Lett. **93** (2004) 182301.

[17] G. Torrieri, B. Tomášik, and I. Mishustin, Phys. Rev. C **77** (2008) 034903.

[18] J. D. Bjorken, Phys. Rev. D **27** (1983) 140.

[19] G. Baym, B. L. Friman, J. P. Blazot, M. Soyeur, and W. Czyz, Nucl. Phys. A **407** (1983) 541.

[20] J. P. Blaizot and J. Y. Ollitrault, Phys. Rev. D **36** (1987) 916; D. H. Rischke and M. Gyulassy, Nucl. Phys. A **608** (1996) 479; E. Laermann, Nucl. Phys. A **610** (1996) 1.

[21] C. Shen, U. Heinz, P. Huovinen, H. C. Song, Phys. Rev. C **82** (2010) 054904.

[22] G. Bertsch, M. Gong, and M. Tohyama, Phys. Rev. C **37** (1988) 1896; G. Bertsch, Nucl. Phys. A **498** (1989) 173c; S. Pratt, T. Csörgő, and J. Zimányi, Phys. Rev. C **42** (1990) 2646.

[23] W. N. Zhang, H. J. Yin, and Y. Y. Ren, Chin. Phys. Lett. **28** (2011) 122501; arXiv:1107.3477[nucl-th].

[24] U. Heinz and P. Kolb, Nucl. Phys. A **702** (2002) 269.

[25] W. N. Zhang and C. Y. Wong, Int. J. Mod. Phys. E **16** (2007) 3262.

[26] S. Chapman, P. Scotto, and U. Heinz, Phys. Rev. Lett. **74** (1995) 4400.

[27] S. Afanasiev *et al* (PHENIX Collaboration), Phys. Rev. Lett. **100** (2008) 232301.

PoS(WPCF2011)051