A NEW SOLUTION TO THE HBT TIME-RELATED PUZZLE* **

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The UrQMD results of the HBT correlation of two-identical particles (pions, kaons, and Lambdas) at freeze-out in heavy ion collisions (HICs) from AGS to RHIC energies are shown. When the cascade mode is considered, the "lifetime" of the emission source is larger than the experimentally observed values at all investigated energies. After the mean-field potentials for both confined and "pre-formed" hadrons are considered, it is found that the inclusion of potential interactions pushes down the HBT $R_{\rm O}$ and pulls up the $R_{\rm S}$ so that the HBT time-related puzzle disappears and the HBT radii of pions and kaons and even those of Λs with large transverse momenta follow the $m_{\rm T}$-scaling fairly well. Furthermore, it is seen to reproduce the proper stopping power for net protons and to improve the elliptic flow at large transverse momenta.

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It is well-known that one can extract information on the space-time dimensions of the particle emission source (the region of homogeneity) in heavy-ion collisions (HICs) by using the Hanbury-Brown–Twiss interferometry (HBT) [1–3] techniques. Although the AGS, SPS and RHIC experiments

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(with nucleon–nucleon center-of-mass energies $\sqrt{s_{\rm NN}}$ from about 2.5 GeV up to 200 GeV for heavy ion collisions) have been stimulating the HBT related investigations further into another golden era, several unexpected but interesting phenomena occurred, namely, the "E-puzzle", the "t-puzzle", and the "non-Gaussian" effect [4–7].

In a recent work on the HBT correlation, adopting the Ultra-relativistic Quantum Molecular Dynamics (UrQMD, v2.2) transport model and the "correlation after-burner" (CRAB, v3.0β) analyzing program, the transverse momentum, system-size, centrality, and rapidity dependence of the HBT parameters of the sources of different identical particle pairs (two πs, two Ks, and two Λs) at AGS, SPS and RHIC energies [6,12–16] were investigated. It was found that although the calculations are generally in line with the experimental data, discrepancies are not negligible. One of the most puzzling phenomena is that the calculated ratio of HBT radii in the outward direction ($R_{\rm O}$) and the sideward direction ($R_{\rm S}$) from central HICs is always larger than that extracted from the data at all investigated energies, if the cascade mode is employed, which was named as the HBT time-related puzzle ("HBT t-puzzle") [6].

In this paper, we firstly introduce very briefly the UrQMD model and the treatments in the mean field, and the three dimensional Gaussian fitting on the HBT correlator. Then, the HBT results are shown and the origin of the HBT time-related puzzle is discussed.

In UrQMD [8, 9], the hadrons are represented by Gaussian wave packets in phase space. The phase space of hadrons is propagated according to Hamilton's equation of motion [8]. The Hamiltonian H consists of the kinetic energy T and the effective interaction potential energy U, $H = T + U$. Recently, a soft equation of state with momentum dependence (SM-EoS) for formed hadrons and a density dependent Skyrme-like term for "pre-formed" hadrons from string fragmentation have been supplied into the UrQMD transport model, please see details in [14, 16].

To calculate the HBT two-particle correlation, firstly, central HICs at AGS (E_b = 2 A, 4 A, 6 A, and 8 A GeV), SPS (E_b = 20 A, 30 A, 40 A, 80 A, and 158 A GeV), and RHIC ($\sqrt{s_{\rm NN}} = 130$ and 200 GeV) energies are calculated with UrQMD. The physical cuts used are same as those listed in [6]. Secondly, for each case about 20–40 thousand events are calculated. All particles with their phase space coordinates at their freeze-out times are put into the "correlation after-burner" (CRAB) analyzing program [10, 11] with quantum statistics and final state modifications so that one can construct the HBT correlator to be compared with experimental data. In this work, the strong interaction of pions and kaons is not considered in the final state interactions (FSI) because of its negligible effect. For Λs, the nuclear modification is not considered in this work for simplicity. We do not consider the Coulomb effect in FSI for the pion–pion correlation due to its small effect but do consider it for the kaon–kaon case (using Bowler–Sinyukov method).

Next, we fit the correlator as a three-dimensional Gaussian form under the longitudinally co-moving system (LCMS) system. When the nuclear and Coulomb modifications are not considered in the correlator, the fitting function can be expressed in the standard way,

$$C(q_{\rm L}, q_{\rm O}, q_{\rm S}) = K\left[1 + \lambda e^{-R_{\rm L}^2 q_{\rm L}^2 - R_{\rm O}^2 q_{\rm O}^2 - R_{\rm S}^2 q_{\rm S}^2 - 2R_{\rm OL}^2 q_{\rm O} q_{\rm L}}\right]. \tag{1}$$

Here the K is the overall normalization factor. The λ is the incoherence factor. $R_{\rm L}$, $R_{\rm O}$, and $R_{\rm S}$ are the HBT radii in longitudinal, outward, and sideward directions, while the cross-term $R_{\rm OL}$ plays a role at large rapidities. q_i is the pair relative momentum $\boldsymbol{q}$ ($\boldsymbol{q} = \boldsymbol{p}_1 - \boldsymbol{p}_2$) in the i direction.

Fig. 1 shows the transverse momentum $k_{\rm T}$ dependence ($\boldsymbol{k}_{\rm T} = (\boldsymbol{p}_{1\rm T} + \boldsymbol{p}_{2\rm T})/2$) of the HBT radii $R_{\rm L}$, $R_{\rm O}$, and $R_{\rm S}$ (at mid-rapidity) of charged pions for central HICs at AGS, SPS, and RHIC energies. At $E_b = 2\ A\,\text{GeV}$, we show a comparison of calculations between with and without Coulomb potentials for confined mesons. It is seen that the two-body mesonic

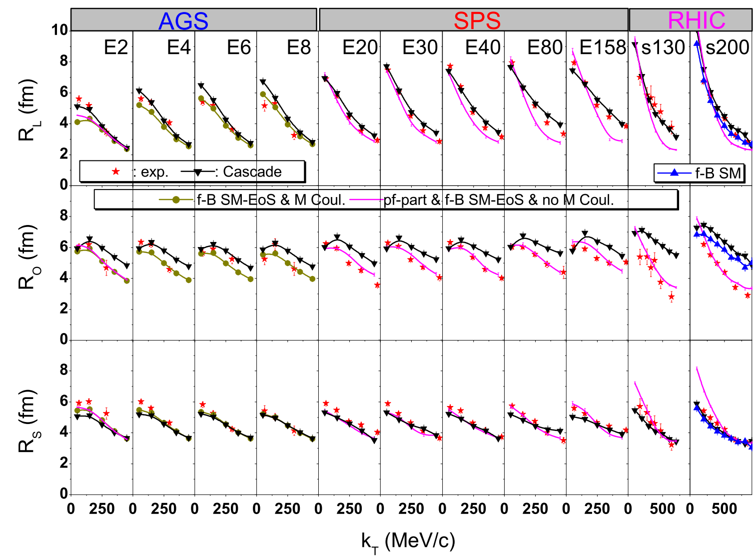

Fig. 1. $k_{\rm T}$ dependence of $R_{\rm L}$, $R_{\rm O}$, and $R_{\rm S}$ for central HICs at AGS, SPS, and RHIC energies. The data (solid stars) are from E895, NA49, STAR, and PHENIX collaborations [17–22]. The calculations with cascade mode and with potentials for confined baryons are shown by the lines with symbols. The results with potentials for both "pre-formed" particles and confined baryons but without Coulomb potential for mesons are shown by lines.

Coulomb potential before freeze-out affects the HBT radii only very weakly at about $k_{\rm T} < 100$ MeV$/c$. At SPS and RHIC energies, the Coulomb potential for confined mesons is switched off. At AGS energies hadrons are dominantly produced from the decay of resonances so that the considered potentials for "pre-formed" particles have no effect on the HBT radii. While at RHIC energies "pre-formed" particles play a dominant role for the early stage dynamics. The most exciting results show up in the transverse space: The nuclear potentials lead to a smaller $R_{\rm O}$ (especially at large $k_{\rm T}$) but a larger $R_{\rm S}$ (especially at small $k_{\rm T}$) generally allowing for a better description of the $k_{\rm T}$ dependent data.

Fig. 2 depicts the excitation function of the $R_{\rm O}/R_{\rm S}$ ratio at small $k_{\rm T}$. The experimental data within the transverse momentum regions are compared with the calculations with and without potentials. In the cascade mode the $R_{\rm O}/R_{\rm S}$ is larger than the experimentally observed values at all investigated energies. When the SM-EoS is considered for confined baryons, the $R_{\rm O}/R_{\rm S}$ ratio decreases compared to the result in the cascade mode and reproduces the energy dependence of the data up to the lower SPS energies. At high SPS and RHIC energies, however, the $R_{\rm O}/R_{\rm S}$ increases further and deviates strongly from the data at top RHIC energies. The deviation from data can be interpreted by the absence of interactions of "pre-formed" particles: With the consideration of a density dependent EoS for "pre-formed" hadrons, the $R_{\rm O}/R_{\rm S}$ starts to decrease at SPS energies and even to be about unity (slightly below data) at high RHIC energies.

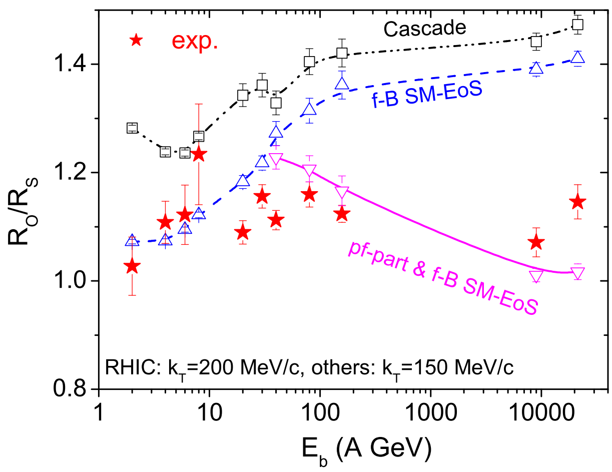

Fig. 2. Excitation function of the $R_{\rm O}/R_{\rm S}$ ratio at small $k_{\rm T}$. The data are indicated by solid stars. Results under cascade mode, with potentials for confined baryons, and with potentials for both "pre-formed" and confined particles are shown with lines with symbols.

The transverse mass $m_{\rm T}$ dependence of HBT radii of pions, kaons, and Λs at RHIC $\sqrt{s_{\rm NN}} = 200$ GeV is shown in Fig. 3. The left plots show the calculations with the SM-EoS for formed baryons, while the calculations with potentials for both "pre-formed" and formed particles are shown in the right plots. In each plot, the $m_{\rm T}$-scaling function $R_i = 3/\sqrt{m_{\rm T}}$ is also shown by solid line. In the left plots, one can not observe $m_{\rm T}$-scaling in all HBT directions. When considering potentials for "pre-formed" hadrons, the right plots show that the transverse radii $R_{\rm O}$ and $R_{\rm S}$ of the pion source nicely follow the scaling line. However, a steeper $m_{\rm T}$-dependence of $R_{\rm L}$ is seen which might be due to the absence of a proper collision term for the "pre-formed" hadrons. Secondly, it is exciting to see that the "pre-formed" hadron potential leads to a smaller $R_{\rm L}$ ($R_{\rm O}$) of kaon pairs as well so that the HBT radii of kaons also follow the scaling line quite well. Thirdly, the results for Λs also approach towards the scaling line especially at large $k_{\rm T}$.

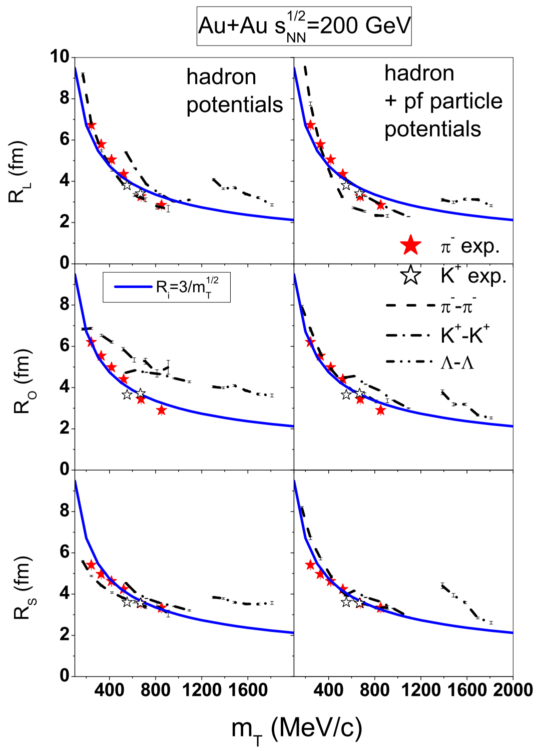

Fig. 3. $m_{\rm T}$ dependence of the HBT radii of π^-, K^+, and Λ sources in central Au + Au collisions at RHIC with potentials only for formed baryons (left plots) and for both formed baryons and "pre-formed" particles (right plots). The experimental data of pions and kaons are shown by stars [21–23]. The scaling function R_i is also shown.

Fig. 4 shows the time evolution of the ratio $R_{\rm O}/R_{\rm S}$ and the incoherence factor λ of pion pairs at $250 < k_{\rm T} < 350$ MeV/c for central Au + Au reactions at $\sqrt{s_{\rm NN}} = 200$ GeV. Without "pre-formed" particle interactions, the $R_{\rm O}/R_{\rm S}$ increases rapidly up to $t \sim 25$ fm/c from ~ 1.0 to ~ 1.5. In contrast, after considering the "pre-formed" hadron potential, the $R_{\rm O}/R_{\rm S}$ is nearly time independent. The effects of FSI continue to play visible roles (although relatively weakly after 25 fm/c) on the λ factor. It is known that for central collisions, the HBT radii can be approximately analytically expressed as [7] $R_{\rm O}^2 = \langle \widetilde{x}^2 \rangle + \langle \beta_{\rm T}^2 \widetilde{t}^2 \rangle - 2\langle \beta_{\rm T} \widetilde{x}\widetilde{t} \rangle$ and $R_{\rm S}^2 = \langle \widetilde{y}^2 \rangle$. In central collisions, $\langle \widetilde{x}^2 \rangle \simeq \langle \widetilde{y}^2 \rangle$. Therefore, the difference of $R_{\rm O}$ and $R_{\rm S}$ mainly comes from the relative strength of the time-related term $\langle \beta_{\rm T}^2 \widetilde{t}^2 \rangle$ and the $\widetilde{x}$–$\widetilde{t}$ correlation term $-2\langle \beta_{\rm T} \widetilde{x}\widetilde{t} \rangle$. Thus, one obtains a clear interpretation of the large reduction of the $R_{\rm O}/R_{\rm S}$ ratio, if "pre-formed" particle interactions are taken into account by relating it to the stronger phase-space correlation induced by the potentials.

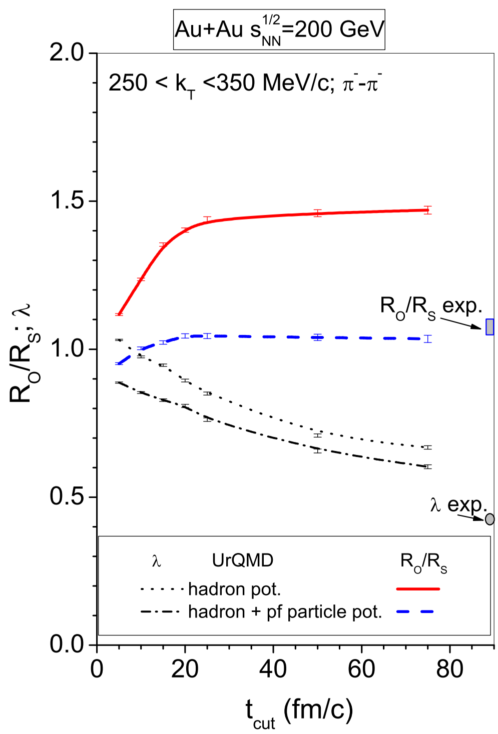

Fig. 4. Time evolution of the ratio $R_{\rm O}/R_{\rm S}$ and the λ factor of pion source at $250 < k_{\rm T} < 350$ MeV/c, which are calculated with potentials for formed baryons and with potentials for both formed and "pre-formed" particles. The $R_{\rm O}/R_{\rm S}$ and λ experimental data are represented by a square and a circle at the right end of the plot.

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