Comparison of the space-time extent of the pion emission source in $d+$Au and Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV

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Two-pion interferometry measurements in $d+Au$ and $Au+Au$ collisions at $\sqrt{s_{NN}} = 200$ GeV are used to extract and compare the Gaussian source radii $R_{out}$, $R_{ide}$, and $R_{long}$, which characterize the space-time extent of the emission sources. The comparisons, which are performed as a function of collision centrality and the mean transverse momentum for pion pairs, indicate strikingly similar patterns for the $d+Au$ and $Au+Au$ systems. They also indicate a linear dependence of $R_{ide}$ on the initial transverse geometric size $R$, as well as a smaller freeze-out size for the $d+Au$ system. These patterns point to the important role of final-state rescattering effects in the reaction dynamics of $d+Au$ collisions.

PACS numbers: 25.75.Dw

Recent measurements for hadrons emitted in $d$-Au collisions ($\sqrt{s_{NN}} = 200$ GeV) at the Relativistic Heavy Ion Collider [1, 2], and in $p+$Pb collisions ($\sqrt{s_{NN}} = 5.02$ TeV) at the Large Hadron Collider [3, 8], have indicated a surprising ridge structure in two-dimensional correlations in relative pseudorapidity ($\Delta \eta$) and azimuthal angle ($\Delta \phi$). Elucidation of the origin of these long-range correlations should advance the current understanding of the very early-time dynamics of the matter produced in hadron nucleus ($p+A$ and $d+A$) and nucleus nucleus ($A+A$) collisions [9, 12].

Two successful approaches are currently being employed to study long-range correlations. The Color Glass Condensate (CGC) approach accounts for these correlations via an enhancement of interference diagrams in the saturation regime [10, 13]. The viscous hydrodynamical
approach \textsuperscript{3} \textsuperscript{14} \textsuperscript{18} accounts for the same correlations via collective harmonic flow. Thus, it is presently not clear whether the long-range ridge, observed in d+Au and p+Pb collisions, stems from (i) the final-state effects inherent in a hydrodynamical description, (ii) the initial-state effects driven by the correlations of gluons already present in the nucleon and nuclear wave functions or (iii) an interplay between these two mechanisms.

Interferometry measurements of the space-time extent of the emitting sources produced in A+A collisions indicate characteristic patterns (as a function of collision centrality and the mean transverse momentum $k_T$, of particle pairs) which serve as a “fingerprint” for collective expansion \textsuperscript{12} \textsuperscript{24}. Thus, it might be expected that similar measurements for d+A and p+A collisions could provide an important avenue to independently constrain the role of final-state interactions in the reaction dynamics for these systems \textsuperscript{15} \textsuperscript{24}. An observed similarity between the characteristic patterns for the space-time extent of A+A and d+A (or p+A) collisions would give a strong indication for the importance of final-state rescattering effects in d+A and p+A collisions.

In this Letter, we use the interferometry technique of Hanbury Brown and Twiss (HBT) \textsuperscript{22} to perform detailed differential measurements of two-pion correlation functions \textsuperscript{19} \textsuperscript{23} \textsuperscript{26} \textsuperscript{29} in d+Au and Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV. In turn, these correlation functions are used to extract and study the HBT radii which characterize the space-time extent of the emission sources for the two systems. We find striking similarities in the detailed dependence of the HBT radii for both systems on collision centrality, transverse system-size, and $k_T$, which point to the importance of final state rescattering effects in the reaction dynamics of d+Au collisions.

The present analysis uses the data recorded by the PHENIX experiment during 2007 and 2008. The collision vertex $z$ (along the beam axis) was constrained to $|z| < 30$ cm of the nominal crossing point. Collision centrality was determined from the charge distribution measured in the beam-beam counters, which span the pseudorapidity range $3.0 < |\eta| < 3.9$ \textsuperscript{30}. Track and momentum reconstruction for charged particles were performed by combining hits from the drift chambers (DC) and pad chambers in the PHENIX central spectrometers ($|\eta| < 0.35$). Charged pions were identified by combining time-of-flight from the time-of-flight detector and the electromagnetic calorimeters (EMCal) \textsuperscript{31} covering azimuthal angle $\Delta \phi < \pi/2$, with momentum reconstructed from the DC and pad-chamber hits in the magnetic field. Particles within 2 standard deviations of the peak for charged pions in the squared mass distribution were identified as pions for momenta up to $\sim 1$ GeV/$c$ as detailed in Ref. \textsuperscript{32}.

The two-pion correlation function is defined as the ratio $C_2(q) = A(q)/B(q)$, where $A(q)$ is the measured distribution of the relative momentum difference $q = p_2 - p_1$ between particle pairs with momenta $p_1$ and $p_2$: $B(q)$ is the so-called background distribution, obtained from particle pairs in which each particle is selected from a different event but with similar event centralities, vertex positions, and charge sign. The relative momentum $q$ is calculated in the longitudinally comoving system, where the longitudinal pair momentum is zero. It is also decomposed into its three components, $q_{\text{out}}$, $q_{\text{side}}$, and $q_{\text{long}}$, following the Bertsch–Pratt convention \textsuperscript{33} \textsuperscript{34}. That is, the “out” axis points along the pair transverse momentum, the “side” axis is perpendicular to the out axis in the transverse plane, and the “long” axis points along the beam.

Track merging and track splitting \textsuperscript{21} were suppressed via pair selection cuts in the DC and the EMCal. Correlation functions were studied as a function of collision centrality, as well as for different pion-pair transverse momenta $k_T = |p_{T,1} + p_{T,2}|/2$ or transverse mass $m_T = \sqrt{(k_T^2 + m_\pi^2)}$, where $m_\pi$ is the pion mass.

![FIG. 1. (Color online) Slices of the three-dimensional two-pion ($\pi^+\pi^-$ and $\pi^-\pi^-$) correlation functions for central d+Au collisions (left panels) and peripheral Au+Au collisions for $0.2 < k_T < 0.7$ GeV/$c$ ($k_T^2 = 0.39$ GeV/$c^2$). These centrality selections give similar $N_{\text{part}}$ values for the two systems. The curves represent fits to the correlation function (see text).](image)
central (0%–10%) d+Au and peripheral (60%–88%) Au+Au collisions for 0.2 < k_T < 0.7 GeV/c (⟨k_T⟩ = 0.39 GeV/c). They all show the familiar Bose–Einstein enhancement peak at low q, as well as the expected difference in the peak widths for d+Au and Au+Au. The latter reflects the difference in the emission source sizes for the d+Au and Au+Au systems. Note that these centrality selections give similar values for the number of participants (N_part = 16.7 ± 1.1 and 15.7 ± 1.6), but different values for the transverse geometric size (R = 0.44 ± 0.02 fm and 0.71 ± 0.06 fm) for d+Au and Au+Au, respectively.

A similar set of correlation functions was extracted for several centralities to facilitate detailed comparisons of the d+Au and Au+Au emission sources as a function of N_part, R and k_T. Monte Carlo Glauber (MC-Glauber) calculations [30, 35, 36] were used to compute N_part and R as a function of collision centrality, from the two-dimensional profile of the density of point-like sources in the transverse plane ρ_s(R_x), where

\[ 1/R = \frac{1}{\sqrt{1/\sigma_x^2 + 1/\sigma_y^2}}, \]

with \( \sigma_x \) and \( \sigma_y \) the respective root-mean-square widths of the density distributions [37]. The systematic uncertainties for these geometric quantities, obtained via variation of the MC-Glauber model parameters, are less than 10% [31].

To aid the comparisons, the measured correlation functions were fitted with the following expression (in which cross-terms are assumed to be negligible) which accounts for the Bose–Einstein enhancement and the Coulomb interaction between pion pairs [38, 39]:

\[ C_2(q) = N[(1 + G(q))F_c + (1 - \lambda)], \]

\[ G(q) \equiv \exp(-R_{side}^2k^2 - R_{out}^2q^2 - R_{long}^2q^2), \]

where N is a normalization factor, \( \lambda \) is the correlation strength, \( F_c \) is the Coulomb correction factor [39] evaluated with the Coulomb wave function, and \( R_{out}, R_{side}, \) and \( R_{long} \) are the Gaussian HBT radii which characterize the emission source. \( R_{side} \) and \( R_{long} \) are related to the transverse and longitudinal size of the source; \( R_{out} \) includes additional effects from the emission duration.

Excellent fits to the correlation functions for the d+Au and Au+Au systems were obtained and cross-checked to confirm agreement with our earlier measurements for Au+Au and d+Au collisions [20, 21, 40]. The fit parameters for \( \pi^+\pi^+ \) and \( \pi^-\pi^- \) pairs were also found to agree within statistical errors; the data for \( \pi^+\pi^- \) and \( \pi^-\pi^- \) were therefore combined. The systematic uncertainties for the fits were estimated via variations of the cuts used to generate the correlation functions (single track cuts, pair selection cuts and particle identification cuts). Typical values of the systematic uncertainties are 5.0% (7.5%) for the extracted values of \( R_{out}, R_{side}, \) and \( R_{long} \) for Au+Au and d+Au collisions and do not exceed 7.5% (10.0%).

Figure 2 shows a comparison of the m_T dependence of \( R_{out}, R_{side}, \) and \( R_{long} \) for 0%–10% central d+Au and 60%–88% central Au+Au collisions, i.e. similar values of N_part. The radii for d+Au and Au+Au show a decreasing trend with increasing values of m_T. The \( R_{out} \) radius is also comparable to \( R_{side} \) (for both systems) and the m_T dependence of the ratio \( R_{out}/R_{side} \) is flat or gently decreasing, as shown in Fig. 3(a). The same trends have been observed in central Au+Au and Pb+Pb collisions [20, 21, 28] and are commonly identified as a characteristic signature for the expansion of an emitting source of short emission duration, driven by final-state rescattering effects [11]. Therefore, we interpret the similarity between the observed patterns for Au+Au and d+Au in Figs. 2 and 3 as an indication for final-state rescattering effects in the reaction dynamics for d+Au.

The curves in Fig. 2 show blast wave expansion model inspired fits to \( R_{side} \) and \( R_{long} \) with fit functions [42, 43]:

\[ R_{side} = R_{geom}/\sqrt{1 + \beta^2(m_T/T)}, \]

\[ R_{long} = \tau_0\sqrt{(T/m_T)[(K_2(m_T/T))/(K_1(m_T/T))]}, \]

where \( R_{geom} \) is the geometrical radius at freeze-out and

### TABLE I. Fit parameters

|         | d+Au       | Au+Au       |
|---------|------------|-------------|
| \( \tau_0 \) (fm/c) | 3.2 ± 0.04 ± 0.4 (syst) | 3.8 ± 0.04 ± 0.3 (syst) |
| \( \chi^2/ndf \) | 26/5       | 24/5        |
| \( R_{geom} \) (fm) | 2.2 ± 0.03 ± 0.2 (syst) | 2.8 ± 0.03 ± 0.2 (syst) |
| \( \chi^2/ndf \) | 6/5        | 4/5         |
FIG. 3. (Color online) Comparison of the $m_T$ dependence of; (a) the ratio $R_{out}/R_{side}$; (b) the freeze-out volume, and (c) the ratio of the freeze-out volumes, for 0%–10% central $d$+Au and 60%–88% central Au+Au collisions.

$\tau_0$ is the expansion time. The requisite freeze-out temperatures ($T = 0.118 \pm 0.02$ and $0.123 \pm 0.02$ GeV) and expansion velocities ($\langle \beta \rangle = 0.42 \pm 0.03$ and $0.38 \pm 0.08$ c) for $d$+Au and Au+Au (respectively), are interpolated values obtained from a blast wave fit to the $p_T$ spectra for identified charged hadrons [44]; $K_1$ and $K_2$ are modified Bessel functions. The fit results are summarized in Table I, they suggest a smaller transverse freeze-out size for the $d$+Au emitting source.

Figure 3(b) further illustrates the difference via the $m_T$ dependence of the freeze-out volume, evaluated as the product ($R_{out} \times R_{side} \times R_{long}$) for the same $\langle N_{part} \rangle$ values employed in Fig. 2. The magnitudes of the freeze-out volumes for Au+Au are larger. However, within uncertainties, the fall-off with increasing $m_T$ is comparable for $d$+Au and Au+Au as shown by the ratio in Fig. 3(c).

Detailed comparisons were also made as a function of collision centrality. Figs. 3(a–c) show one such comparison of $R_{out}$, $R_{side}$, and $R_{long}$ for $d$+Au and Au+Au, as a function of $N_{part}^{1/3}$ for $\langle k_T \rangle = 0.39$ GeV/c. The solid and dashed curves represent linear fits to the Au+Au and $d$+Au data, respectively. The data for $R_{out}$ and $R_{side}$ indicate a similar linear increase with $N_{part}^{1/3}$, albeit with larger magnitudes for Au+Au. An apparent slope difference between $d$+Au and Au+Au for $R_{long}$ (Fig. 3(c)), could be the result of a difference in the longitudinal dynamics for the two systems. The representative plot of $R_{side}$ vs. $(dN/d\eta)^{1/3}$ shown in Fig. 3(d), indicates that the HBT radii for $d$+Au do follow the linear dependence previously observed for $A$+$A$ and $p$+$p$ collisions [46], but with separate magnitudes for each system.

The dependencies shown in Figs. 3(a–c) suggest that the pattern of a strong correlation between the transverse freeze-out size and the initial geometric size, is similar for both $d$+Au and Au+Au. They also suggest that at $\sqrt{s_{NN}} = 200$ GeV, the change in the transverse expansion rates with centrality (defined by $N_{part}$) is similar for central $d$+Au and peripheral Au+Au collisions.

In some models [11, 47, 48], the expansion time is proportional to the initial geometric size $\tau \propto R$. Therefore, $R$ might be expected to be a more natural scaling variable for the HBT radii of expanding systems. The detailed dependencies of $R_{side}$ on $R$ are compared in Fig. 3(a) for $d$+Au and Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV, and $p+Pb$ collisions at $\sqrt{s_{NN}} = 2.76$ TeV for $\langle k_T \rangle \sim 0.4$ GeV/c. Fig. 3(b) shows a similar dependence for recent $R_{inv}$ measurements for $p$+Pb and Pb+Pb collisions [49]. The comparisons indicate that $R_{side}$ and $R_{inv}$ scale linearly with $R$ for all of these systems. This pattern is consistent with the observed $1/R$ scaling of collective anisotropic flow [12, 47]. The dashed curves in Figs. 3(a) and (b) are linear fits to the $d$+Au and Au+Au ($p$+Pb and Pb+Pb) data sets; they suggest similar slopes for $d$+Au and Au+Au ($p$+Pb and Pb+Pb). The fit to
FIG. 5. (Color online) (a) $R_{\text{side}}$ vs. $\bar{R}$ for $\langle k_T \rangle \approx 0.4$ GeV/c for $d$+$Au$, $Au$+$Au$ and $Pb$+$Pb$ collisions as indicated. (b) $R_{\text{inv}}$ vs. $\bar{R}$ for $p$+$Pb$ and $Pb$+$Pb$ collisions. The ALICE and STAR data are taken from Refs. [23, 49] and [22] respectively. Systematic uncertainties are 5.0%(7.5%) for $Au$+$Au$($d$+$Au$). The dashed curves in (a) (b) represents a linear fit to the $Au$+$Au$ and $d$+$Au$($p$+$Pb$ and $Pb$+$Pb$) data sets. The dotted curve is an extrapolation of the dashed-dot curve.

the $Pb$+$Pb$ data in Figs. [a] (dotted curve) indicates a larger slope for $Pb$+$Pb$ collisions at the much higher energy of $\sqrt{s_{NN}} = 2.76$ TeV, where the expansion rate is expected to be larger. The observed dependencies of $R_{\text{side}}$ and $R_{\text{inv}}$ on $\bar{R}$ reinforce our earlier inferences that the final-state rescattering effects, which are known to play a dominant role in $Au$+$Au$ and $Pb$+$Pb$ collisions, also play an important role in $d$+$Au$ and $p$+$Pb$ collisions.

In summary, we have presented detailed comparisons of HBT radii, which emphasize trends commonly associated with hydrodynamic-like expansion. Excellent agreement is found between the patterns for the $d$+$Au$ and $Au$+$Au$ systems. The radii extracted for the two systems at similar $\langle N_{\text{part}} \rangle$ show similar dependencies on $m_T$, which indicate a smaller geometric size (at freeze-out) for the emitting source in $d$+$Au$ collisions. The $R_{\text{side}}$ and $R_{\text{inv}}$ radii for different systems show scaling with the initial transverse size $\bar{R}$, across several collision energies, which is indicative of hydrodynamic-like collective expansion driven by final-state rescattering effects. An investigation of the interesting possibility of a similar pattern in high multiplicity $p$+$p$ events is deferred to a future study. Our present findings, which support the view that the expansion dynamics for $d$+$Au$ and $Au$+$Au$ ($p$+$Pb$ and $Pb$+$Pb$) are similar, constitute a significant contribution towards a more comprehensive understanding of the very early-time dynamics of the matter produced in hadronic collisions.

ACKNOWLEDGMENTS

We thank the staff of the Collider-Accelerator and Physics Departments at Brookhaven National Laboratory and the staff of the other PHENIX participating institutions for their vital contributions. We acknowledge support from the Office of Nuclear Physics in the Office of Science of the Department of Energy, the National Science Foundation, Abilene Christian University Research Council, Research Foundation of SUNY, and Dean of the College of Arts and Sciences, Vanderbilt University (U.S.A), Ministry of Education, Culture, Sports, Science, and Technology and the Japan Society for the Promotion of Science (Japan), Conselho Nacional de Desenvolvimento Científico e Tecnológico and Fundação de Amparo à Pesquisa do Estado de São Paulo (Brazil), National Science Foundation of China (P. R. China), Ministry of Education, Youth and Sports (Czech Republic), Centre National de la Recherche Scientifique, Commissariat à l’Énergie Atomique, and Institut National de Physique Nucléaire et de Physique des Particules (France), Bundesministerium für Bildung und Forschung, Deutscher Akademischer Austausch Dienst, and Alexander von Humboldt Stiftung (Germany), Hungarian National Science Fund, OTKA (Hungary), Department of Atomic Energy and Department of Science and Technology (India), Israel Science Foundation (Israel), National Research Foundation of Korea of the Ministry of Science, ICT, and Future Planning (Korea), Physics Department, Lahore University of Management Sciences (Pakistan), Ministry of Education and Science, Russian Academy of Sciences, Federal Agency of Atomic Energy
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