Identical Meson Interferometry in STAR Experiment

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The influence of Bose-Einstein statistics on multi-particle production characterized for various systems and energies by the STAR collaboration provides interesting information about the space-time dynamics of relativistic heavy-ion collisions at RHIC. We present the centrality and transverse mass dependence measurements of the two-pion interferometry in Au+Au collisions at $\sqrt{s_{NN}} = 62.4$ GeV and Cu+Cu collisions at $\sqrt{s_{NN}} = 62.4$ GeV and 200 GeV. We compare the new data with previous STAR measurements from p+p, d+Au and Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV. In all systems and centralities, HBT radii decrease with transverse mass in a similar manner, which is qualitatively consistent with collective flow. The scaling of the apparent freeze-out volume with the number of participants and charged particle multiplicity is studied. Measurements of Au+Au collisions at same centralities and different energies yield different freeze-out volumes, which mean that $N_{part}$ is not a suitable scaling variable. The multiplicity scaling of the measured HBT radii is found to be independent of colliding system and collision energy.

1. Introduction

The information about the space-time structure of the emitting source created in elementary particle and heavy ion collisions from the measured particle momenta can be extracted by the method of two-particle intensity interferometry techniques also called the Hanbury – Broom – Twiss (HBT) effect\textsuperscript{12}, which was initially developed to measure the angular size of distant stars\textsuperscript{3}. HBT is a useful method to understand the crucial reaction mechanisms of the particle emitting source in relativistic heavy ion collisions, where the Quark-Gluon Plasma (QGP) is expected to be formed. Experimental search for evidence of QGP is the most fundamental and challenging task in modern nuclear physics.

In this paper, we present the comparative pion intensity interferometry measurements from large collision systems of Au+Au and Cu+Cu at $\sqrt{s_{NN}} = 62.4$ and 200 GeV with small systems like p+p and d+Au at $\sqrt{s_{NN}} = 200$ GeV using *http://www.star.bnl.gov
the Solenoidal Tracker At RHIC (STAR) detector at Relativistic Heavy Ion Collider (RHIC). The wealth of new data from STAR detector with its large acceptance and full azimuth capabilities have provided a new systematic study of the hot and dense medium created in ultra-relativistic heavy-ion collisions. The measured HBT radii are studied as a function of average transverse momentum ($k_T = (\sqrt{p_{\text{T}}^1 + p_{\text{T}}^2})/2$) in 4 bins that correspond to [150,250] MeV/c, [250,350] MeV/c, [350,450] MeV/c and [450,600] MeV/c. The results are presented and discussed as a function of average $k_T$ (or $m_T = \sqrt{k_T^2 + m^2}$) in each of those bins. The $m_T$ dependence of HBT radii for all RHIC energies in Au+Au and Cu+Cu collisions are compared for the first time.

2. $m_T$ and energy dependence of HBT parameters in Au+Au and Cu+Cu collisions

The first measured centrality dependence of HBT radius parameters for Cu+Cu collisions at \( \sqrt{s_{\text{NN}}} = 62.4 \) GeV is shown in Fig. 1. The three HBT radii $R_{\text{out}}$, $R_{\text{side}}$ and $R_{\text{long}}$ increase with increasing centrality. The $R_{\text{out}}/R_{\text{side}}$ ratio $\sim 1$ and exhibits no clear centrality dependence.

![Graph of HBT parameters vs $m_T$ for 6 different centralities for Cu+Cu collisions at $\sqrt{s_{\text{NN}}} = 62.4$ GeV. Only statistical errors are shown.](image)

As shown in Fig. 1, the decrease of HBT radii with $m_T$ at all observed centralities is qualitatively consistent with collective flow. The presence of collective flow...
in the expanding system causes a decrease in “HBT radii” with $m_T$ where the fall-off of “out” and “side” components is caused by transverse flow and for the “long” component due to the longitudinal flow. The $\lambda$ parameter increases with $m_T$ as observed in previous STAR measurements in Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV. Such increase is due to the decreasing contribution of pions produced from long-lived resonance decays at higher transverse momenta.

![Fig. 2. The HBT radii ratio at top centralities for Au+Au and Cu+Cu collisions.](image)

The ratios of transverse and longitudinal HBT radii at top centralities in Au+Au and Cu+Cu collisions at $\sqrt{s_{NN}} = 200$ GeV and 62.4 GeV is presented in Fig. 2, from which we infer that the corresponding HBT radii vary similarly with $m_T$.

3. Volume estimates and multiplicity scaling

The pion freeze-out volume estimates using the HBT radii will provide an understanding of the freeze-out properties. The freeze-out volume can be estimated using the expressions like:

$$V_f \propto R_{side}^2 R_{long}$$  \hspace{1cm} (1a)

$$\propto R_{out} R_{side} R_{long}$$  \hspace{1cm} (1b)

where $V_f$ is the freeze-out volume.

We have discussed in the previous section that the effects of collective expansion of the system lead to the $m_T$-dependence fall-off on HBT radius parameters.
compared to the measured dimensions of source. The femtoscopic radii of such an expanding source correspond to the \( m_T \) (or \( k_T \)) dependent region of homogeneity which is smaller than the entire collision region. Henceforth the best volume estimates in Eq. (1a) and (1b) are measured for lowest \( k_T \) bin which in our case corresponds to \([150,250]\) MeV/c as described previously.

![Graph showing pion freeze-out volume estimates](image)

Fig. 3. Pion freeze-out volume estimates as a function of number of participants and charged particle multiplicities for Au+Au collisions at \( \sqrt{s_{NN}} = 200 \) and 62.4 GeV. The lines are plotted to guide the eye and represent linear fits to data.

Fig. 3 shows the comparative study of freeze-out volume estimates (using Eq. (1a) and Eq. (1b)) as a function of the number of participants and charge particle multiplicity for Au+Au collisions, where the earlier measurements at \( \sqrt{s_{NN}} = 200 \) GeV are presented with the preliminary STAR results from 62.4 GeV. Measurements of Au+Au collisions at same centralities and different energies show different freeze-out volume, which means that \( N_{\text{part}} \) (initial overlap geometry) is not a suitable scaling variable in this case. On the other hand charge particle multiplicity (final freeze-out geometry) seems to be a better scaling variable.
The study of freeze-out volume estimates are presented in Fig. 4 for p+p, d+Au, Cu+Cu and Au+Au collisions as a function of charge particle multiplicity. The freeze-out volume estimates for measured systems show a linear dependence as a function of charge particle multiplicity. The linear dependence of HBT radii with $(dN_{ch}/d\eta)^{1/3}$ for all STAR data-sets is exhibited in Fig. 5. Such dependences are naturally expected within a framework of universal mean-free-path of pions at freeze-out.

![Fig. 4. Pion freeze-out volume estimates as a function of charged particle multiplicity. The lines are plotted to guide the eye and represent linear fits to data.](image)

### 4. Conclusions

The systematic study of HBT radii for varied initial energy and system are presented. For the systems studied, the multiplicity and $m_T$ (or $k_T$) dependence of the radii are strongly consistent with the previously measured colliding systems at RHIC. Measurements of Au+Au collisions at same centralities and different energies yield different freeze-out volumes, which infer that $N_{part}$ is not a suitable scaling variable. The radii scale with the collision multiplicity; in a static model, this is consistent with a universal mean-free-path at freeze-out. As in measurements at all other energies, the $m_T$ (or $k_T$) dependence remains independent of $\sqrt{s_{NN}}$, collision system, and multiplicity.
Fig. 5. Pion source radii dependence on charged particle multiplicity. The lines are plotted to guide the eye and represent linear fits to data.

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