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# Nuclear Coulomb Field Effects in Two-Pion Bose-Einstein Correlations

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Differences are investigated in pion source sizes derived using $\pi^+\pi^+$ and $\pi^-\pi^-$ pairs in the large statistics data set collected with the E866 Forward Spectrometer for central Au+Au collisions at 11.6 A·GeV/$c$ in AGS Experiment E866. These differences in source radii are interpreted using a simple classical description for the Coulomb and the transverse-momentum ($p_T$) dependent source radius parameters. An estimated effective net charge responsible for the distortion is considerably smaller than the expected total projectile participant protons, which suggests that the system undergoes a rapid expansion in the longitudinal direction before freeze-out. This picture is consistent with the results derived from the $\pi^-/\pi^+$ singles yield ratios for the same reactions.

## 1 Introduction

It has been observed recently that the pion yield ratio $\pi^-/\pi^+$ rises faster as $m_T$ decreases at AGS energies [1]. This asymmetry is also observed at different energies [2,3,4] while the effect is strongest at lower beam energies. This phenomenon has been attributed to the nuclear Coulomb force induced by the large amount of positive charges from the protons in the colliding nuclei, which introduces distortions in the charged-particle distributions [1,5,6,7]. In particular pions are affected strongest by the Coulomb force since they are light particles compared to kaons and protons.

The nuclear Coulomb fields are also expected to be responsible for the distortions of the two-pion correlation parameters, such as measured radii in Bose-Einstein correlations. The investigation of such distortions from $\pi^+\pi^+$ and $\pi^-\pi^-$ correlations can provide information on the collision dynamics and the "effective" net charge of the system produced, in addition to the information observed in the single-particle spectral differences caused by the nuclear Coulomb field.

The large data set available allows for a detailed analysis on the differences in the pion source sizes measured from $\pi^+\pi^+$ and $\pi^-\pi^-$ correlations. The data used for the correlation analysis were taken using the E866 Forward Spectrometer [1] with the beam of 11.6 A·GeV/$c$ Au ions from the AGS. The

24% central events of the total interaction cross-section gated by the New Multiplicity Array[8] were selected for the analysis. The rapidity range of pairs was limited to $1.9 \leq y_{\pi\pi} \leq 2.3$ for this analysis. The description of the data and experimental details can be found elsewhere[1,9].

## 2 Nuclear Coulomb Interaction

To simplify the description of the nuclear Coulomb field created by the complicated many-body system in the heavy-ion collisions, we assume that charges are evenly distributed over a spherical source volume. Then the Coulomb potential $V_c$ created by the effective net charge $Z_{eff}$ at the surface of a source, i.e. at the freeze-out, can be described by

$$V_c = \frac{Z_{eff}e^2}{R}, \tag{1}$$

where $R$ is the radius of the source. Then the modified energy and momentum of the accelerated/decelerated $\pi^{\pm}$'s due to the Coulomb potential $V_c$ are

$$E' = E \pm V_c, \text{ and } p' = \sqrt{E'^2 - m_\pi^2}, \tag{2}$$

for $E' \geq m_\pi$, where $m_\pi$ is the mass of $\pi^{\pm}$. For a simplified picture, a further assumption is made that the two pions are parallel since the average angle between two pions in the E866 Forward Spectrometer for the region where the two pions are close to each other in phase-space ($Q_{inv} \lesssim 50$ MeV/$c$) is small, $\langle\theta\rangle \sim 6°$. Then the relative-momentum quantities for $\pi^+\pi^+$ and $\pi^-\pi^-$ pairs modified by the Coulomb field, if $V_c \ll E$, $Q'_{inv}$ and $q'_0$ can be written as

$$Q'_{inv} \simeq \sqrt{Q_{inv}^2 \pm 2V_c(p_1 - p_2)(\frac{E_1}{p_1} - \frac{E_2}{p_2})}\ , \tag{3}$$

and

$$q'_0 = q_0, \tag{4}$$

where $(q_0, \boldsymbol{q}) = (E_1 - E_2, \boldsymbol{p}_1 - \boldsymbol{p}_2)$, and the Lorentz-invariant variable $Q_{inv}$ in Eq. 3 is defined as $Q_{inv}^2 = q_0^2 - \boldsymbol{q}^2$. Thus the size of the collision volume fitted with $Q'_{inv}$ for $\pi^+\pi^+$ ($\pi^-\pi^-$) pairs is expected to be smaller (bigger) than the actual size. The energy difference $q_0$ is not affected by the external potential $V_c$.

The number of pions with and without Coulomb effects are assumed to be the same. The distribution of the inclusive cross-section $\sigma(\boldsymbol{p})$ of pions is modified via the Jacobian[5] given by

$$\sigma'(\boldsymbol{p}') = \sigma(\boldsymbol{p}(\boldsymbol{p}')) \left| \frac{\partial^3 p}{\partial^3 p'} \right| . \tag{5}$$

## DISCLAIMER

## 3 Source Size Differences and Nuclear Coulomb Fields

The two-pion correlation functions used for the source parameterizations are

$$C_2(Q_{inv}) = 1 + \lambda e^{-R_{inv}^2 Q_{inv}^2}, \qquad (6)$$

and

$$C_2(q_0) = 1 + \lambda e^{-R_0^2 q_0^2}, \qquad (7)$$

where $R_{inv}$ and $R_0$ are fitted radius parameters, and $\lambda$ is a chaoticity parameter. The details of the analysis including the corrections for the Coulomb interactions between pions can be found elsewhere [9].

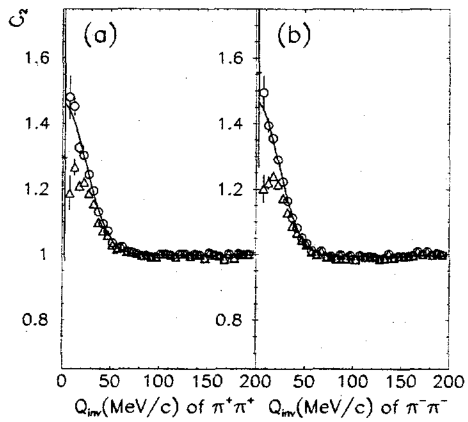


Figure 1: One-dimensional $\pi^+\pi^+$ (a) and $\pi^-\pi^-$ (b) correlation function $C_2(Q_{inv})$. The raw correlation function is shown with triangles (△) and the Coulomb function corrected one is shown with circles (○).

The correlation functions fitted to Eq. 6 for $\pi^+\pi^+$ and $\pi^-\pi^-$ are shown in Fig. 1. It should be noted that the Coulomb corrections applied to the correlation functions in the Fig. 1 are only for the mutual pionic Coulomb interactions [9], not for the nuclear Coulomb field. The fitted parameters are $R_{inv} = 5.76 \pm 0.09$, $\lambda = 0.47 \pm 0.01$ for $\pi^+\pi^+$ and $R_{inv} = 6.09 \pm 0.09$, $\lambda = 0.48 \pm 0.01$ for $\pi^-\pi^-$.

With the assumption that the Coulomb field of the rest of the system can be described by a central Coulomb potential as Eq. 1, the effective charge responsible for the difference in the source size is estimated as $Z_{eff} \approx 27$ by reversing Eq. 3. The radii used in the calculations are *r.m.s.* radii given by $R = R_{r.m.s.} = \sqrt{3}R_{geom}(k_T)$, where $R_{geom}(k_T)$ is the average of the two "geometrical" radius functions fitted to the transverse radii ($R_\perp$) for $\pi^+\pi^+$ and $\pi^-\pi^-$ as a function of the averaged transverse-momentum $k_T = \frac{p_{T1}+p_{T2}}{2}$, as shown in Fig. 2. The $R_\perp$ values used in the fits are derived in Ref. 9 using the three-dimensional Yano-Koonin-Potgoretskii parameterization [10]. With the estimated effective charge, the fitted parameters for the "actual" source volumes are derived as $R_{inv} = 5.92 \pm 0.09$, $\lambda = 0.49 \pm 0.01$ for $\pi^+\pi^+$ and $R_{inv} = 5.92 \pm 0.09$, $\lambda = 0.45 \pm 0.01$ for $\pi^-\pi^-$. To demonstrate the sensitivity of the calculations, $R_{inv}$'s calculated

Table 1: The "actual" Radii $R_{inv}$ (fm) and $\lambda$ parameters calculated by assuming the nuclear Coulomb fields with different effective charges $Z_{eff}$. The errors are statistical only.

| | | $Z_{eff} = 10$ | $Z_{eff} = 20$ | $Z_{eff} = 30$ | $Z_{eff} = 40$ |
|---|---|---|---|---|---|
| $\pi^+\pi^+$ | $R_{inv}$ | 5.83 ± 0.09 | 5.88 ± 0.09 | 5.94 ± 0.09 | 6.00 ± 0.11 |
| | $\lambda$ | 0.47 ± 0.01 | 0.48 ± 0.01 | 0.49 ± 0.01 | 0.49 ± 0.02 |
| $\pi^-\pi^-$ | $R_{inv}$ | 6.03 ± 0.08 | 5.96 ± 0.09 | 5.90 ± 0.09 | 5.85 ± 0.08 |
| | $\lambda$ | 0.47 ± 0.01 | 0.46 ± 0.01 | 0.45 ± 0.01 | 0.45 ± 0.01 |

with various effective charges are shown in Table 1. The $q_0$ values are fitted with Eq. 7 to $R_0 = 4.75 \pm 0.11$, $\lambda = 0.22 \pm 0.004$ for $\pi^+\pi^+$ and $R_0 = 4.65 \pm 0.10$, $\lambda = 0.22 \pm 0.004$ for $\pi^-\pi^-$, which shows no significant differences compared to $R_{inv}$'s as expected in Eq. 4.

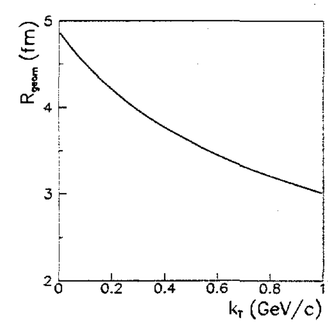


Figure 2: Average geometrical source radii of $\pi^+\pi^+$ and $\pi^-\pi^-$ as a function of $k_T$.

The estimated effective net charge is significantly smaller than the number of total participant protons [11], $N_p \sim 120$. This small $Z_{eff}$ suggests that the system expands more rapidly than the pion velocity, especially in the longitudinal direction along the beam axis, so that the net charge is reduced with increasing time resulting in decreased Coulomb effects. This analysis, approximated with a spherical source geometry, supports the rapid longitudinal expansion consistently indicated in $p_T$-dependent three-dimensional pion source measurements [9].

## 4 $\pi^-/\pi^+$ Ratio

The Fig. 3 shows the $\pi^-/\pi^+$ ratio as a function of $m_T - m_\pi$. The symbols represent data measured in AGS Experiment E866 [1] for a rapidity interval $\delta y = |y - y_{NN}| < 0.4$ for the 6% most central total cross-section events in the reaction Au+Au at 11.6 A·GeV/$c$. The $\pi^-/\pi^+$ ratio rises to about 1.5 at low $m_T$ ($m_T - m_\pi \sim 50$ MeV/$c^2$), while the average $\pi^-/\pi^+$ ratio is about 1.25, which indicates that there is abundant pion production not connected with $\Delta$ resonances [a] at this energy. The baryonic $N$ resonances, such as $N(1440)$ and $N(1520)$ as well as the production of pions via multiple collisions tend to lower

[a] If the pions are produced through the $\Delta$ resonances, the averaged ratio is $\langle\pi^-/\pi^+\rangle \simeq 1.94$ for the Au+Au collisions.

the global $\pi^-/\pi^+$ ratio.

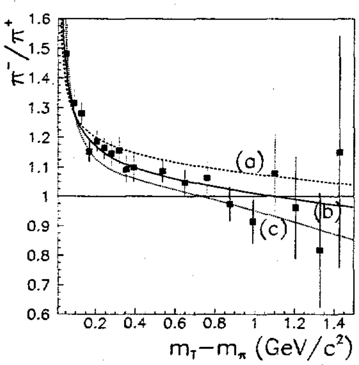


Figure 3: $\pi^-/\pi^+$ ratio as a function of $m_T - m_\pi$. The symbols with error bars are the data for a rapidity interval $0 < \delta y < 0.4$. The curves are from the simulations with $Z_{eff} = 45$ (a), $Z_{eff} = 65$ (b), and $Z_{eff} = 85$ (c).

The curves in Fig. 3 are $\pi^-/\pi^+$ ratios from simulations of exponential $\pi^\pm$ distributions modified by an external Coulomb field as Eqs. 2 and 5. The solid curve in Fig. 3, (b), represents the result assuming the overall ratio of $\pi^-/\pi^+ = 1.25$ and $Z_{eff} = 65$ with $p_T$-dependent radius function as shown in Fig. 2. The $\chi^2$ of the curve to the data is 0.71 for $Z_{eff} = 65$. The reason that the estimated effective charge from the single pion yields is bigger than the one from the source size differences can be due to the centrality difference for the data analyzed. To demonstrate the sensitivity of the calculations, two extra curves from the simulations with the different effective charges are also displayed in the figure for $Z_{eff} = 45$ ($\chi^2 = 1.61$), and for $Z_{eff} = 85$ ($\chi^2 = 1.24$). Although for a fixed $R_{inv}$ value at 6 fm with $Z_{eff} = 60$, the data seem to agree reasonably well with simulations at $\chi^2 = 1.13$, the $p_T$-dependent radius parameterization describes the data better. With the radius $R_{inv} = 6$ fm, fits with $Z_{eff} = 40$ and $Z_{eff} = 80$ result $\chi^2 = 2.21$, and $\chi^2 = 1.76$, respectively.

## 5 Summary

Nuclear Coulomb effects are sensitive to the space-time profile of source evolution in heavy-ion collisions, and can provide additional information on source dynamics measured by Bose-Einstein correlation analysis. The differences in size of the pion source in the Au+Au collisions at the AGS measured with the E866 Forward Spectrometer have been interpreted using a simple static description for the nuclear Coulomb field. The rise of the ratio $\pi^-/\pi^+$ at low $m_T$ also can be explained with the same assumption. The estimated effective net charges of the source from the correlation measurements and also from the ratio of the pion yields as a function of $m_T$ are significantly smaller than the expected total number of participant protons, which can be interpreted as if the system were expanding more rapidly than pions.

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## References


1. L. Ahle *et al.*, *Phys. Rev.* C **57**, R466 (1998).
2. C. Müntz *et al.*, *Z. Phys.* A **352**, 175 (1995).
3. D. Pelte *et al.*, *Z. Phys.* A **357**, 215 (1997).
4. H. Bøggild *et al.*, *Phys. Lett.* B **372**, 343 (1996).
5. M. Gyulassy and S.K. Kauffmann, *Nucl. Phys.* A **362**, 503 (1981).
6. B. Li, *Phys. Lett.* B **346**, 5 (1995).
7. H. Barz *et al.*, *Phys. Rev.* C **57**, 2536 (1998).
8. L. Ahle, Ph.D. Thesis, Massachusetts Institute of Technology (1997).
9. J.H. Lee, Proceedings of the *2nd* Catania Relativistic Ion Study: *Measuring the Size of Things in the Universe: HBT Interferometry and Heavy Ion Physics* (S. Costa *et al.*, eds.), World Scientific, Singapore, 1998.
10. F. Yano and S. Koonin, *Phys. Lett.* B **78**, 556 (1978).
11. F. Wang, Ph.D. Thesis, Columbia University (1996).