Bose-Einstein Correlations in Si + Al and Si + Au Collisions at 14.6*A* GeV/*c*

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The E802 Spectrometer at the Brookhaven Alternating Gradient Synchrotron has been used to measure the correlations in relative momentum between like-sign pions emitted in central Si+Al and Si+Au collisions at 14.6*A* GeV/*c*. Data are presented in terms of the correlation function for both identified π^- and π^+ pairs near the nucleon-nucleon center-of-mass rapidity. All parametrizations of the correlation function are consistent with a spherically symmetric source of rms radius $R_{\rm rms} \approx 3.5 \pm 0.4$ fm and lifetime $\tau \sim 2$ fm/*c*.

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The primary motivation for colliding heavy ions at relativistic energies is the study of high-density nuclear matter, since sufficiently high energy or baryon densities are expected to produce a phase transition leading to a quark-gluon plasma [1]. The extent to which the initial longitudinal momentum of the projectile is transformed to transverse motion is one important factor in determining the energy density. The E802 collaboration has previously reported measurements of transverse neutral energy distributions [2] and of charged single-particle inclusive momentum spectra [3], both of which indicate the amount of energy present in transverse degrees of freedom. We report here the first measurement, at energies of the Brookhaven Alternating Gradient Synchrotron (AGS), of the spatial and temporal extent of the pion source, as obtained from the Bose-Einstein correlations between identified pion pairs emitted in central collisions of 14.6*A* GeV/*c* ^{28}Si ions with Au and Al targets. These data provide a direct constraint on geometrical aspects of the collision process, and are obviously relevant to dynamical models for source expansion and freeze-out, which, when combined with the transverse energy measurements, may be used to determine the average energy density.

Intensity interferometry [4] exploits the fact that identical bosons emitted by a chaotic source of spatial extent R exhibit a correlation in relative momentum q over a range $q \lesssim \hbar/R$. This correlation is conveniently expressed in terms of the correlation function, defined as the ratio of the actual measured distribution in relative momentum $A(q)$ to a background distribution $B(q)$ which contains the two-body phase space in the absence of Bose statistics. For simple models of the source distribution, this ratio, defined as $C_2(q)$, is given by

$$C_2(q) \equiv A(q)/B(q) = 1 + \lambda|\tilde{\rho}(q)|^2 , \tag{1}$$

where $\tilde{\rho}(q)$ is the Fourier transform of the pion source density $\rho(r)$ and λ is a phenomenological parameter introduced to account for final-state interactions and possible coherence of the pion source, as well as more mundane factors such as experimental biases.

This experiment was performed using the E802 magnetic spectrometer, which has been described previously [5]; only features relevant to this measurement are presented here [6]. A collimated beam of 14.6*A* GeV/*c* ^{28}Si ions from the BNL Tandem-AGS complex is normally incident upon either an Al or Au target, corresponding to approximately 3% or 1% of an interaction length, respectively. High-multiplicity ("central") events are selected by triggering on the uppermost 12% of the charged particle multiplicity spectrum as detected by the target multiplicity array (TMA). The acceptance for pions, shown in Fig. 1(a), is optimized for π^-'s emitted near 90° in the nucleon-nucleon center of mass ($y_{NN}^{\rm c.m.}=1.72$), while accepted π^+'s tend to have slightly higher transverse momenta and lower rapidities. Information for each event from the tracking chambers and the time-of-flight wall permitted momentum determination and essentially unambiguous identification of charged pions. The contamination from electrons and kaons is estimated to be $<0.5\%$ for π^-'s and $\leq 1\%$ for π^+'s.

For each data set, a correlation function is formed according to the prescription of Eq. (1). Three different projections of the relative four-momentum $q \equiv p_1 - p_2$ were studied: the Lorentz-invariant relative momentum $Q \equiv \sqrt{-q\cdot q}$, the momentum and energy differences ($|\mathbf{q}| \equiv |\mathbf{p}_1 - \mathbf{p}_2|$, $q_0 \equiv |E_1 - E_2|$), and the longitudinal and transverse components of $\mathbf{q}$ relative to the beam axis q_L and q_T. All three-vectors are evaluated in the nucleon-nucleon center-of-mass system for the ^{28}Si+Al data set and in the "participant c.m." ($y_{\rm part}^{\rm c.m.}=1.25$) for the ^{28}Si+Au data set [3]. The background $B(q)$ is formed from artificial pairs created by selecting pions from different events in the data sample. The effect of the residual correlation of the actual pairs in the background [7] is corrected by an iterative procedure [8]. The background distribution is also weighted pair by pair with a standard Gamow factor $G(Q)$ [8,9] to account for the effect of the dipion mutual Coulomb interaction. Finally, the raw number of counts $A_{\rm raw}(q)$ in a given relative momentum bin q is corrected by a multiplicative factor $M(q)$, which is determined by a Monte Carlo simulation of the detector incorporating multiple scattering, energy loss, hadronic interactions, and detector resolution. The effect of these successive corrections on a narrow slice $5 < q_L < 15$ MeV of the two-dimensional correlation function $C_2(q_L, q_T)$ is illustrated in Figs. 2(a)–2(c).

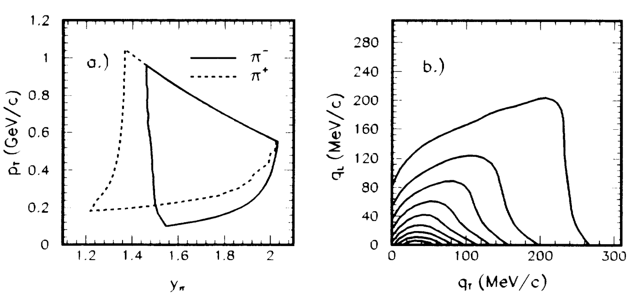

FIG. 1. (a) Spectrometer acceptance vs rapidity and transverse momentum for charged pions used in this analysis. (b) Contours vs q_L and q_T of the distribution of accepted pairs from $^{28}\mathrm{Si}+{}^{197}\mathrm{Au}\to 2\pi^- + X$ collisions. Each contour represents 30 counts per 10 MeV/c by 10 MeV/c bin.

Fully corrected correlation functions are fit to several functional forms. The two-dimensional projections are fit to ($\hbar = c = 1$)

$$C_2(|\mathbf{q}|, q_0) = \mathcal{N}[1 + \lambda e^{-|\mathbf{q}|^2 R^2 - q_0^2 \tau^2}] , \tag{2}$$

$$C_2(q_L, q_T) = \mathcal{N}[1 + \lambda e^{-q_L^2 R_L^2 - q_T^2 R_T^2}] , \tag{3}$$

while distributions in Q are fit to the two forms

$$C_2(Q) = \mathcal{N}[1 + \lambda e^{-Q^2 R_{\rm inv}^2}] , \tag{4}$$

$$C_2(Q) = \mathcal{N}[1 + \lambda e^{-2QR_{\rm inv}}] . \tag{5}$$

The parameter $\mathcal{N}$ is simply a normalization constant; its value is established by the number of events chosen for the $B(q)$ distribution. The parameters $R_{\rm inv}$, R, R_L, and R_T will be referred to collectively as "radii." The correlation functions are fitted using a principal of maximum likelihood technique extended to allow for fluctuations in the (unknown) true background distribution [6,10]. The results of these fits are given in Table I; a typical fit to the form of Eq. (3) is shown in Fig. 2(c). The uncertainties in estimating the combined effects of the Gamow and acceptance corrections for the lowest bin in relative momentum lead us to exclude the corresponding data point from all fits.

A number of tests were performed to determine the

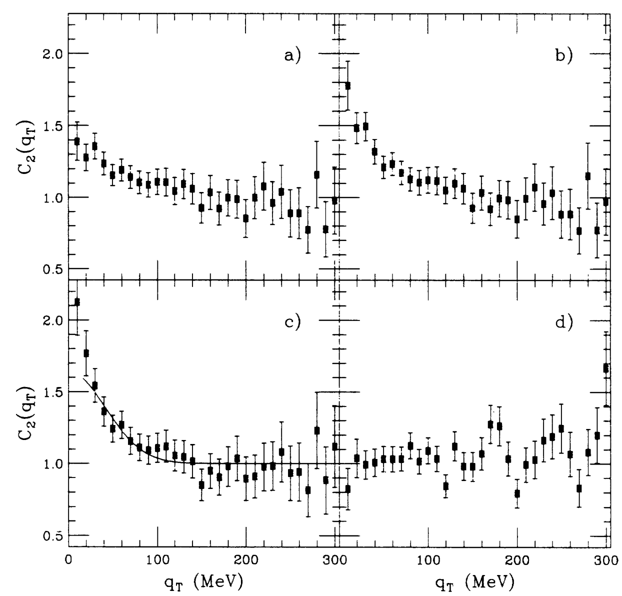

FIG. 2. The effect of successive corrections on $C_2(q_L, q_T)$ in the region $5 < q_L < 15$ MeV for the $^{28}\mathrm{Si}+{}^{197}\mathrm{Au}\to 2\pi^- + X$ data set: (a) Raw ratio. (b) Corrected with the Gamow factor. (c) Corrected for the Gamow factor plus acceptance corrections. The result of the two-dimensional fit is also shown projected into the same q_L slice as the data. (d) Fully corrected data for the $^{28}\mathrm{Si}+{}^{197}\mathrm{Au}\to \pi^-\pi^+ + X$ data set.

TABLE I. Fit parameters for the four data sets. For each data set, the results (in order) of fitting to Eqs. (2), (3), (4), and (5) are shown. All errors are statistical only; see text for a discussion of systematic errors.

System	λ	R_{inv}	R or R_T	τ or R_L	χ^2/NDF
$^{28}Si+^{197}Au \to 2\pi^- + X$	0.58 ± 0.06	...	2.50 ± 0.28	1.61 ± 0.68	366/384
58583 pairs, 49528 events	0.65 ± 0.07	...	3.42 ± 0.26	2.33 ± 0.35	715/807
	0.60 ± 0.08	4.45 ± 0.44	...	...	20.4/25
	1.25 ± 0.22	3.75 ± 0.68	...	...	20.6/25
$^{28}Si+^{197}Au \to 2\pi^+ + X$	0.51 ± 0.06	...	1.82 ± 0.23	1.56 ± 0.43	405/409
29791 pairs, 25667 events	0.55 ± 0.07	...	2.32 ± 0.25	2.36 ± 0.28	873/846
	0.44 ± 0.10	4.19 ± 0.71	...	...	17.8/25
	0.95 ± 0.26	3.46 ± 1.05	...	...	16.7/25
$^{28}Si+^{27}Al \to 2\pi^- + X$	0.59 ± 0.05	...	1.72 ± 0.19	2.27 ± 0.47	287/309
23376 pairs, 21418 events	0.67 ± 0.06	...	2.41 ± 0.20	2.08 ± 0.27	517/523
	0.59 ± 0.08	3.44 ± 0.36	...	...	20.5/25
	1.29 ± 0.21	2.63 ± 0.55	...	...	20.5/25
$^{28}Si+^{27}Al \to 2\pi^+ + X$	0.72 ± 0.13	...	2.60 ± 0.30	0.00 ± 1.98	299/320
7953 pairs, 7286 events	0.62 ± 0.15	...	3.10 ± 0.42	2.33 ± 0.92	525/480
	0.53 ± 0.15	4.03 ± 0.71	...	...	33.2/25
	1.35 ± 0.56	4.19 ± 1.45	...	...	32.9/25

sensitivity of the results to the analysis procedure. First, doubling the bin size in relative momentum (from 10 to 20 MeV) systematically decreases the fitted radii by roughly 10%, as expected from the corresponding artificial loss of momentum resolution. The values for λ upon rebinning show a variation of 10% or less, but exhibit no systematic trend. Second, the role of residual correlations in the background pair phase space is tested by comparing the results of fits with and without this correction; in all cases this amounts to a change of 5% or less. A related background test [11] involves fitting the experimental correlation functions with an additional linearly varying term $\mathcal{N} \to \mathcal{N}[1+\alpha Q]$. All such fits find values for α consistent with zero. Third, the effect of both the Gamow and the acceptance correction can be examined by successively fitting to raw data, raw data with Gamow correction only, and fully corrected data. The extracted radii are remarkably insensitive to the corrections, typically varying by 10% or less. The intercepts (λ), on the other hand, roughly double in value in going from raw to fully corrected data.

An important test of the entire correction method can be made by applying the same procedure to the opposite-sign pairs: The resulting correlation functions should be flat. A typical result for the (q_L, q_T) projection is shown in Fig. 2(d). Similar results are obtained for the Q and $(|\mathbf{q}|, q_0)$ projections. The fluctuations of these distributions suggest a conservative systematic error of 5% and 15% in λ values for the one- and two-dimensional fits, respectively. The dominant uncertainty in λ results from the dependence on the assumed functional form of the correlation function, as seen by comparing the exponential and Gaussian parametrizations in Q. The reduction of λ due to pions produced in the decay of long-lived resonances is estimated to be 15% or less [12], based on the measured yield of ω's, η's, and K^*'s in pp collisions at 12 GeV/c [13].

The various values presented in Table I may best be understood in terms of the results from fits to Eq. (2). Confidence contours for the extracted values of R and τ are presented in Fig. 3 for the four systems studied. At

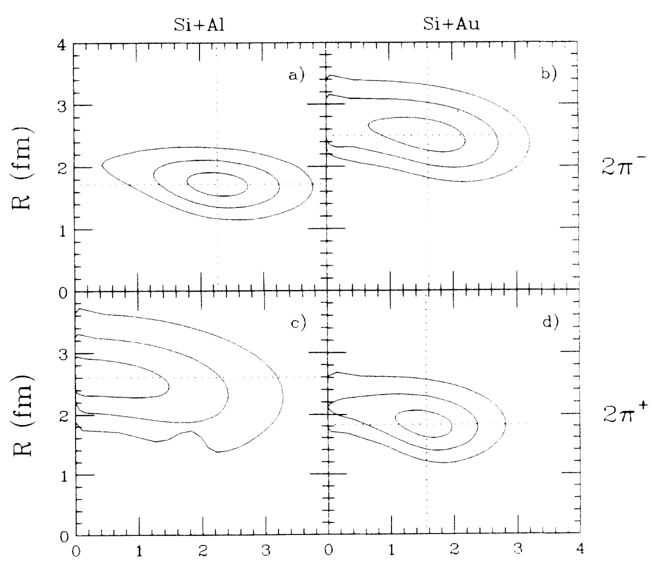

FIG. 3. Confidence contours for radii and lifetimes determined by fits to the form of Eq. (2) for (a) $^{28}Si+^{27}Al \to 2\pi^- + X$, (b) $^{28}Si+^{197}Au \to 2\pi^- + X$, (c) $^{28}Si+^{27}Al \to 2\pi^+ + X$, and (d) $^{28}Si+^{197}Au \to 2\pi^+ + X$.

the 2σ level, all results are consistent with $R=2.0\pm0.2$ fm and $\tau=2.0\pm0.35$ fm. Furthermore, Monte Carlo simulations of the phase-space acceptance of our spectrometer pairs indicate that all of the results in Table I (including the large values of λ for the exponential fits) are consistent with those expected from the correlations induced by Eq. (2) with $R\sim\tau\sim2$ fm. In particular, the systematic trends in the data ($R_T \gtrsim R_L$, $R_{\rm inv} > R_T$, $\lambda \sim 1.2$–1.3 for fits to the exponential in $Q_{\rm inv}$) are all well reproduced by this procedure.

These trends follow from single considerations: First note that $q_0 = \mathbf{q}\cdot\boldsymbol{\beta}_{\pi\pi}$, where the pair velocity $\boldsymbol{\beta}_{\pi\pi} \equiv (\mathbf{p}_1+\mathbf{p}_2)/(E_1+E_2)$. For our acceptance, $|\boldsymbol{\beta}_{\pi\pi}| \approx 0.9$ in the center-of-mass system, and is roughly perpendicular to the beam axis. Additionally, q_T is essentially one dimensional, lying in the plane determined by the collision axis and the pair velocity, and roughly parallel to $\boldsymbol{\beta}_{\pi\pi}$. Thus, the correlation function Eq. (2), *when binned* in q_L and q_T, becomes

$$C_2(q_L,q_T) = 1 + e^{-q_L^2 R^2 - q_T^2 (R^2 + \beta_{\pi\pi}^2 \tau^2)} . \qquad (6)$$

In this approximation, with $\tau = R$ and $|\boldsymbol{\beta}_{\pi\pi}| = 0.9$, one would expect to fit $R_T \approx 1.4R$ and $R_L = R$. The effects of averaging over the actual distribution of $\boldsymbol{\beta}_{\pi\pi}$ in our acceptance decrease the idealized relation for R_T somewhat, leading to $R_T \approx (1.2\text{–}1.4)R$, consistent with the observed trend. Thus, the tendency for R_T to be greater than R_L in our data set does not result from an intrinsic oblateness of the pion source, but is instead the consequence of observing a source with nonzero lifetime in our spectrometer acceptance.

Our simulations also show that when a correlation of the functional form given by Eq. (2) is projected into the invariant relative momentum Q the resulting correlation function is more sharply peaked than a Guassian. This conclusion depends sensitively on the relative magnitude of R vs τ. For instance, the results of a simulation performed with ($R=\tau=2$ fm) would favor a Gaussian, ($R=2, \tau=3$ fm) would allow either parametrization, while ($R=2, \tau=4$ fm) would favor the exponential form.

Since Eq. (2) describes the global features of our data, its corresponding source density, $\rho(\mathbf{r},t) \sim \exp[-|\mathbf{r}|^2/2R^2 - t^2/2\tau^2]$, can be used with the inferred value of $R=2\pm0.2$ fm to determine the rms radius of the pion source via $\langle r^2\rangle^{1/2} = \sqrt{3}R \approx 3.5\pm0.4$ fm. This is in good agreement with the projectile-mass scaling $\langle r^2\rangle^{1/2} = 1.2A_P^{1/3}$ fm established by Bartke [14]. Our results show no evidence for the large transverse radii observed in central $200A$ GeV collisions by the NA35 collaboration [15].

In conclusion, we have reported the first application of interferometry to heavy ion collisions in the AGS energy regime. The results verify the scaling in projectile radius observed at both lower and higher energies. Future measurements with this apparatus [16] will perform additional two-pion measurements to examine the multiplicity dependence of the source size, and will study correlations between both proton and K^+ pairs.

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