Two-Kaon Correlations in Central Pb + Pb Collisions at 158 A GeV/c

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Two-particle interferometry of positive kaons is studied in Pb + Pb collisions at mean transverse momenta \(\langle p_T \rangle = 0.25\) and 0.91 GeV/c. A three-dimensional analysis was applied to the lower \(p_T\) data, while a two-dimensional analysis was used for the higher \(p_T\) data. We find that the source-size parameters are consistent with the \(m_T\) scaling curve observed in pion-correlation measurements in the same collisions, and that the duration time of kaon emission is consistent with zero within the experimental sensitivity.

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Experimental studies of high-energy nuclear collisions at the BNL-AGS and CERN-SPS accelerators (beam energies from 10 to 200 GeV/nucleon) have revealed interesting features of hot and dense nuclear matter, and some characteristic signatures of a quark-gluon-plasma (QGP) phase have been reported [1]. If the hadronic source is formed in a first-order phase transition from a QGP phase in the course of collision, the hadronic expansion may slow down due to a softening of the equation of state. In such a case, a long duration time of particle emission is anticipated. Since a finite duration of particle emission increases the effective source size in the direction of particle velocity, and, since the shape of the two-particle correlation function is related to the effective source size, a difference between the widths of the peaks in the correlation functions in the direction of pair ("outward") and perpendicular to it ("sideward") might be a signature of QGP [2]. At SPS energies, systematic studies of particle correlations have been performed from \(p + A\) to Pb + Pb collisions [3–7]. From the pion correlation studies in the Pb + Pb collisions, NA44 [5] reported that the two transverse radius parameters in the outward and sideward directions in the longitudinal center of mass system (LCMS) frame (see below) are similar, implying no long duration time of emission. WA98 [6] measured the correlation function with the generalized Yano-Koonin parametrization and found the \(R_0\) parameter, which reflects the duration of emission, is compatible with zero. While NA49 [7] observed a finite \(R_0\) parameter in the Yano-Koonin-Podgoretskii parametrization to be approximately 3–4 fm/c, the value is small and not consistent with what would be expected from a strong first-order phase transition. All the experimental data support no long-lived intermediate hadron-parton mixed phase during the pion emission. There are discussions, however, that the pion-correlation functions might be distorted due to a large amount of decays from long-lived resonances, while kaon measurements can serve as a more sensitive probe of the space-time evolution [8–10]. The kaon duration time was measured in S + Pb collisions, but a long-lived mixed phase was also excluded by the data [4]. In this Letter, we present the first results of \(K^+K^-\) correlations in central Pb + Pb collisions at the SPS energy and extract the duration time of the kaon emission.

The data were taken at the CERN-SPS with a 158 GeV/c per nucleon lead-ion beam incident on a lead target, using the NA44 spectrometer at two laboratory
The acceptance in the horizontal (vertical) space

The horizontal (vertical) setting favors a wide momentum

The three-dimensional momentum acceptance of the spec-

1.5 and 3.3.

The secondary particles were transported to the track-
ing section through another dipole magnet and three
quadrupole magnets. The quadrupole magnets control
the three-dimensional momentum acceptance of the spec-

trometer. Two sets of quadrupole settings, referred to as
the “horizontal” and “vertical” focus settings, were used.
The horizontal (vertical) setting favors a wide momentum
acceptance in the horizontal (vertical) space p_{Tz}(p_{Ty}), and
reduces the acceptance p_{x}(p_{y}). In the discussion which
follows, the direction with wide acceptance for a given
mode (e.g., p_{x} for the horizontal mode) is referred to
as the “favored” direction and the direction with narrow
acceptance (e.g., p_{y} for the horizontal mode) is called
“unfavored”. For the small angle measurements, collin-
mators between the first dipole and the first quadrupole
magnets further reduced the acceptance in the unfavored
direction. These collimators reduced the number of par-
ticles in the acceptance without reducing the acceptance
in the favored direction. The momentum settings of the
spectrometer were 6 GeV/c for the small angle (low p_{T})
measurements and 7.5 GeV/c for the large angle (high
p_{T}) measurements.

After the magnets, there were three tracking chambers
(PC, SC1, SC2), three threshold-type gas Cherenkov
counters (C1, C2, TIC), and three scintillator hodoscopes
(H2, H3, H4). The pad chamber (PC) and the strip cham-
bers (SC) provided precise hit position for the tracking
algorithm. Although their position information was less
precise, the hodoscopes were also used in track finding.
C1 was the primary device for pion/kaon separation in
the small angle measurements, while C2 and TIC were
used for pion/kaon separation in the large angle measure-
ments. Tracks were reconstructed by requiring hits in the tracking
chambers and hodoscopes on straight lines. The three-
dimensional momenta were calculated from the track
information through a matrix, of which the elements were
determined by a Monte Carlo simulation combined with
the TURTLE code for the particle transportation through
the magnetic field. Particle identification used time-of-flight
information between the beam counter and the hodoscopes
along with pulse height information from the Cherenkov
counters. Figure 1 shows an example of such a plot

in the small angle measurements and also the particle-
identification (PID) selection adopted in this analysis.

In the analysis, a lead ion was required at the entrance edge of the
beam counter. The signal amplitude from the beam

FIG. 1. The particle identification using the mass-squared and
the C1 pulse height. Kaon and proton peaks are seen near the
C1 pedestal (70 ch.), while a bump at around 600 ch. on C1
and mass^2 = 0 is of pion events accumulated with a hardware
calibrated trigger. On the top plane, a scatter plot is shown
with the PID selection adopted in this analysis.

The rapidity coverage in the large angle measurements overlap well. The trigger required a lead ion in the
beam counter, a large number of secondary particles in
the scintillator bars, and at least two hits in hodoscopes H2
and H3. Off-line we required at least two kaons in each
event and found the centrality of the lower p_{T} data set to
be around 10% of the most central events while that of the
high p_{T} sample was 18%.

The two-particle correlation function is defined by

\[ C_{\text{raw}}(\vec{p}_{1}, \vec{p}_{2}) = \frac{P_{2}(\vec{p}_{1}, \vec{p}_{2})}{P_{1}(\vec{p}_{1})P_{1}(\vec{p}_{2})} \approx \frac{\text{Real}(\vec{p}_{1}, \vec{p}_{2})}{\text{Back}(\vec{p}_{1}, \vec{p}_{2})}, \]

where the numerator is the joint probability of detecting
two particles with momenta \( \vec{p}_{1} \) and \( \vec{p}_{2} \), while the denomi-
nator is the product of the probabilities of detecting single
particles with momenta \( \vec{p}_{1} \) and \( \vec{p}_{2} \). The denominator was
obtained by mixing two tracks picked up from two ran-
domly selected different events. Ten mixed background
pairs were generated for each real pair to reduce statistical
uncertainties. There still remain several effects, which af-

\[ \frac{dN}{d\eta} \]

\[ \text{VOLUME 87, NUMBER 11 PHYSICAL REVIEW LETTERS 10 SEPTEMBER 2001} \]
the correlation function. The repulsive Coulomb force separates particles of a pair going out at \( p_1 = p_2 \) and strongly suppresses the yield at \( \vec{q} = \vec{p}_1 - \vec{p}_2 \sim 0 \). The background two-particle spectrum generated by the event mixing method still contains effects of two-particle correlations, since a particle in a real event is always accompanied by another particle nearby in phase space. Since the degree of these effects depends on the strength of particle correlations of interest in a source, these effects were corrected through a Monte Carlo (MC) based iteration method. A \( C_2 \) function (described in the next paragraph) was assumed for a given set of source-size parameters (\( R \)'s and \( \lambda \)), and MC events were generated taking the spectrometer resolution into account. The wave integration method [11] was employed to simulate Coulomb effects in the finite source volume. The MC events were analyzed using exactly the same procedure as was applied to the experimental data. The correction factors to the \( C_{\text{raw}} \) function were evaluated by comparing the resultant MC correlation function with the given input \( C_2 \) function. The source-size parameters were deduced from the experimental correlation function after applying the correction factors to the \( C_{\text{raw}} \) function. The iteration ends when the extracted source-size parameters agree with the given parameters within an acceptable accuracy. The detailed procedure is described in the first article in Ref. [4] and more discussion can be found in Ref. [12].

After the PID selection and quality cuts, we have around \( 20 \times 10^5 \) pairs in both the horizontal and vertical modes at the lower \( p_T \), while \( 17 \times 10^5 \) pairs in the horizontal mode at the higher \( p_T \). A three-dimensional fit is applied to the lower \( p_T \) data. The observed momenta of each kaon pair are transformed to the LCMS, in which the momentum sum of two particles along the beam axis is zero, \( \vec{p}_1 + \vec{p}_2 = 0 \). The momentum variables of interest are defined in this system. The average momentum of the pair in the frame is \( k_T = (\vec{p}_1 + \vec{p}_2)/2 \). \( Q_1 \) is a projection of the momentum difference onto the beam axis, and \( Q_T \) is the momentum difference perpendicular to the beam axis. \( Q_T \) is further divided into two components. \( Q_{TO} \) is the component of \( Q_T \) along \( k_T \), and \( Q_{TS} \) is the component of \( Q_T \) perpendicular to both \( k_T \) and the beam axis. The momentum resolution of \( Q_L \), \( Q_{TO} \), and \( Q_{TS} \), including effects of multiple scattering in the target, were around 10, 20, and 20 MeV/c, respectively. The correlation functions \( C_2 \) in both the horizontal and vertical modes are simultaneously fitted using the maximum likelihood method with

\[
C_2(Q_{TO}, Q_{TS}, Q_L) = D(1 + \lambda e^{-Q_{TO}^2 R_{TO}^2 - Q_{TS}^2 R_{TS}^2 - Q_L^2 R_L^2}),
\]

where \( \lambda \) is a factor introduced to express chaoticity of quantum states of the source and \( R \)'s are variables representing multidimensional radii of the system in question. \( D \) is a free parameter for normalization in each mode. A two-dimensional equation replacing

\[
Q_T = Q_{TO} - Q_{TS}
\]

\( -Q_{TO}^2 R_{TO}^2 - Q_{TS}^2 R_{TS}^2 \) in Eq. (2) with \( -Q_T^2 R_T^2 \) is employed to fit the correlation function in the horizontal mode at the higher \( p_T \). The fit results are given in Table I, where the systematic uncertainties reflect the effect of (i) cut parameters to define a track, (ii) cut parameters to select pairs, (iii) momentum resolution, (iv) two-track resolution, (v) momentum distribution of particle production in MC, and (vi) fitting to finite bins. Figure 2 shows projections of the correlation function onto each axis of the momentum difference where the projection is over the lowest 40 MeV/c of the other directions in the momentum difference. In these plots, the solid lines show the results of fit projected in the same way as the data.

The three source-size parameters (\( R_L, R_{TO}, R_{TS} \)) in the three-dimensional fit are quite similar to each other—as was observed in pion correlation measurements in the same colliding system [5]. Since \( R_{TS} \) and \( R_L \) represent the geometric information of the source most directly, they are compared in Fig. 3 with those of pions. The present data at \( m_T \approx 0.55 \text{ GeV}/c^2 \) seems to stay on the \( m_T \) scaling

<table>
<thead>
<tr>
<th>( p_T ) [GeV/c]</th>
<th>0.25</th>
<th>0.91</th>
</tr>
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<tr>
<td>( \lambda )</td>
<td>0.84 ± 0.06 ± 0.07</td>
<td>0.61 ± 0.20 ± 0.16</td>
</tr>
<tr>
<td>( R_L ) [fm]</td>
<td>4.36 ± 0.33 ± 0.32</td>
<td>3.20 ± 0.54 ± 0.45</td>
</tr>
<tr>
<td>( R_{TO} ) [fm]</td>
<td>n/a</td>
<td>3.59 ± 0.67 ± 0.97</td>
</tr>
<tr>
<td>( R_{TS} ) [fm]</td>
<td>4.04 ± 0.28 ± 0.32</td>
<td>n/a</td>
</tr>
<tr>
<td>( p_T ) [GeV/c]</td>
<td>4.12 ± 0.26 ± 0.31</td>
<td>n/a</td>
</tr>
<tr>
<td>( \chi^2/\text{d.o.f.} )</td>
<td>5139/2978</td>
<td>117/107</td>
</tr>
</tbody>
</table>

FIG. 2. Projections of the \( K^+ K^+ \) correlation functions at \( p_T \approx 0.25 \text{ GeV}/c \) (top) and \( p_T \approx 0.91 \text{ GeV}/c \) (bottom). The solid lines show the projections of the fit with the Gaussian parametrization.
curve (dashed line) which came from the pion correlation measurements. To confirm this tendency, we put $R_T$ and $R_L$ from the two-dimensional fit at the higher $p_T$ ($m_T = 1.0 \text{ GeV/c}^2$) on the same plot. They also seem consistent with the scaling curve. A fit to the four data points in each plot with a single scaling curve, $R = A/\sqrt{m_T}$, gives $A = 3.0 \pm 0.2 \text{ fm GeV}^{1/2} \text{ c}^{-1}$ in both cases as shown with solid curves.

The dependences on $m_T$ are predicted with models including hydrodynamical expansion in a source [13–15]. The experimental radius parameters are interpreted as a length of homogeneity which is in turn dependent on a geometrical source-size $R_{\text{geom}}$ and a thermal length $R_{\text{therm}}$. The “boost invariant expansion” along the longitudinal direction leads to an expression $R_L = \tau \sqrt{T_0/m_T}$, ignoring the contribution from $R_{\text{geom}}$. Assuming a freeze-out temperature $T_0$ of 100–140 MeV, we could extract the freeze-out time $\tau$ from the present $A$ parameter to be 7–10 fm/c, which is in good agreement with the WA98 [6] and NA49 [7] results. In a hydrodynamic model under certain conditions [15], one can derive an analytic expression for the radii $R_T = R_L = \tau \sqrt{T_0/m_T}$. Our data are consistent with such a scenario. The common $m_T$ scaling for pions and kaons may imply that thermal freeze-out occurs simultaneously for both pion and kaons and that therefore they receive a common Lorentz boost. This is consistent with the hydrodynamic hypothesis. A similar conclusion can be drawn from the linear increase of the single particle inverse slopes with mass [16].

We derived the duration time $\Delta \tau$ of kaon emission from the quadratic difference of $R_{T0}$ and $R_{TS}$ in Eq. (2) as $\Delta \tau = \sqrt{R_{T0}^2 - R_{TS}^2}/\beta$, where $\beta$ is the transverse velocity of the kaon pair in the LCMS frame. We find $\Delta \tau = 2.2 \pm 0.2(\text{stat}) \pm 0.1(\text{syst}) \text{ fm/c}$. The kaon duration time is short and similar to those observed for pions in the same colliding system and for kaons in the S + Pb collisions. The present result excludes simple scenarios of a prolonged mixed phase anticipated in a first-order phase transition from a QGP phase.

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†On an unpaid leave from P.N. Lebedev Physical Institute, Russian Academy of Sciences.