Correlations at Small Relative Momenta among Protons Produced in Collisions of 1.8-GeV/nucleon ^{40}Ar with a KCl Target

F. Zarbakhsh, A. L. Sagle, F. Brochard,[a] T. A. Mulera, V. Perez-Mendez, R. Talaga,[b] and I. Tanihata
Lawrence Berkeley Laboratory, Berkeley, California 94720

and

J. B. Carroll, K. S. Ganezer, G. Igo, and J. Oostens
Physics Department, University of California, Los Angeles, California 90024

and

D. Woodard
California State University, Hayward, California 94542

and

R. Sutter
Brookhaven National Laboratory, Upton, New York 11973
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Correlations between two protons produced in the inclusive reaction Ar + KCl $\to p + p + X$ at 1.8 GeV/nucleon have been measured for proton rapidities near the beam rapidity Y_B and near $Y_B/2$. Comparison with model calculations suggests that the size of the region of final scattering is 3.5 fm at Y_B and corresponds to that expected for a projectile remnant. The sizes we obtain at $Y_B/2$ (with or without high multiplicity requirements) are smaller (2.4–2.8 fm) and seem inconsistent with a thermalized source containing a large fraction of the available nucleons.

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We report here the first measurement of the correlation between two protons produced in relativistic heavy-ion collisions, and its use as a technique to measure the size of the interaction region. It has been noted[1] that the final-state interactions between particles enhance the sensitivity of the correlation function R to the rms size of the particle-emitting source. We have studied the reaction Ar + KCl $\to p + p + X$ at 1.8 GeV/nucleon. This experiment was performed at the Lawrence Berkeley Laboratory Bevalac. The protons were detected in a previously described[2] magnetic spectrometer. A 24-element scintillation-counter hodoscope was added to detect two-proton coincidences. Measurements were made in two kinematic regions, S_1 and S_2. The corresponding $p_\perp$ rapidity regions are shown in Fig. 1. S_1 corresponds to the projectile remnant rapidity Y_B, and S_2 corresponds to the "fireball" rapidity $Y_B/2$. Earlier work[2,3] suggests that the former has two components: projectile participants[4] that have undergone nucleon-nucleon collisions of small momentum transfer, and the high-energy tail of the spectator evaporation spectrum. The protons in region S_2 have the rapidity of the Ar-KCl center of mass and may have come from a nuclear fireball.[4]

We have sampled the multiplicity of high-$p_\perp$ fragments with an array M of sixteen counters to select events with small impact parameters. Sev-

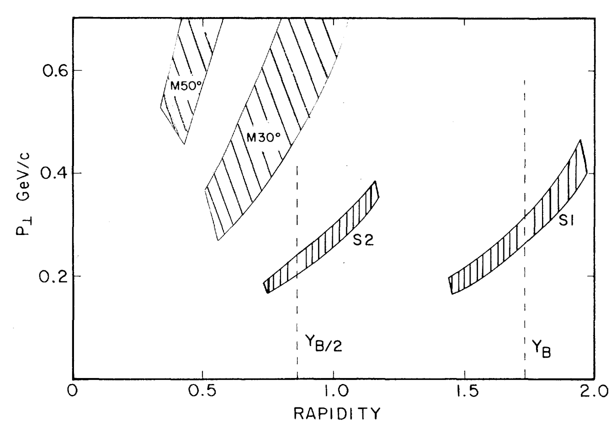

FIG. 1. The acceptance of the apparatus in $p_\perp$ rapidity space. The region S_1 shows the acceptance of the spectrometer for data near the beam rapidity Y_B, and the region S_2 shows the acceptance of the spectrometer for data near $Y_B/2$. The region $M30°$ ($M50°$) indicates the significant acceptance of the multiplicity detectors at 30° (50°).

en detectors were placed at polar angles of 30° and nine at 50°. Each detector is sensitive to protons whose kinetic energies are greater than 200 MeV. In Fig. 1, the regions labeled $M30°$ and $M50°$ show their acceptances.

Data were taken with four event-selection requirements: single-particle and two-particle inclusive events, with and without a sample multiplicity requirement. At $Y \approx Y_B$ the average sample multiplicities are 1.66 and 1.86 for one- and two-particle inclusive events. At $Y \approx Y_B/2$, the average sample multiplicities are 1.84 and 2.5. From earlier studies[5] the true multiplicity averages are estimated to be 11, 12, 12, and 15, respectively. The requirement of a sample multiplicity of 5 or more selects 10–20% of the inclusive events and we estimate that the corresponding true average multiplicity is 25.

The correlation function R is formally defined in terms of the measured one- and two-particle differential cross sections, $d\sigma/d^3p$ and $d^2\sigma/d^3p_1 \times d^3p_2$, as

$$\frac{d^2\sigma}{d^3p_1 d^3p_2} = \frac{1}{\sigma_T}\frac{\langle n(n-1)\rangle}{\langle n\rangle^2}\frac{d\sigma}{d^3p_1}\frac{d\sigma}{d^3p_2}(1+R),$$

where σ_T is the total reaction cross section and $\langle n\rangle$ and $\langle n(n-1)\rangle$ are the first and second moments of the proton multiplicity distribution. The product $(d\sigma/d^3p_1)(d\sigma/d^3p_2)$ was generated by randomly mixing together the trajectories from two different single-particle events. The normalization was chosen so that the ratio of the relative momentum spectrum for two-particle events to that of mixed single-particle events was unity for $95 < \Delta p < 215$ MeV/c, where it is assumed that $R = 0$. [$\Delta p \equiv (\vec{p}_1 - \vec{p}_2)/2$.]

In Fig. 2 we show data accumulated in the rapidity region $Y \approx Y_B/2$ with a required sample multiplicity M of 5 or greater (open circles) and with no multiplicity requirement (crosses), and in the rapidity region $Y \approx Y_B$ with no multiplicity requirement (filled circles). The relative momentum Δp, plotted on the abscissa, has been transformed to the projectile rest frame ($\beta_{\rm lab} = 0.94$) for the Y_B data and to the fireball rest frame ($\beta_{\rm lab} = 0.7$) for the $Y_B/2$ data. The same results would be obtained in the center-of-mass frame of the two detected protons. The error bars shown are statistical only. The experimental resolution ($\sigma \approx 8$ MeV/c) and the inability to distinguish two overlapping trajectories affect only the data in the 0–10 MeV/c interval. We estimate[6] that other systematic errors are negligible (in comparison with the statistical uncertainties)

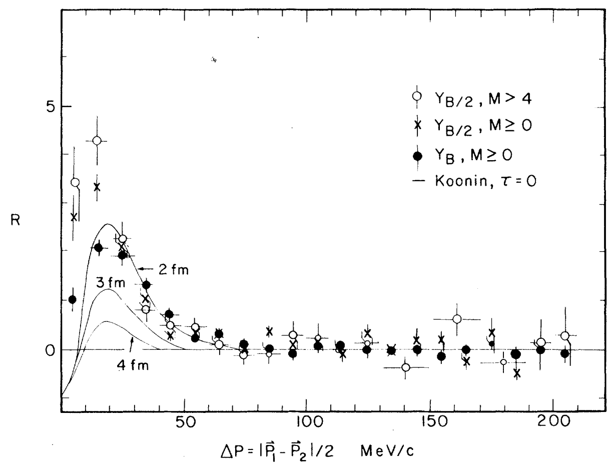

FIG. 2. The correlation function R as a function of $\Delta p = |\vec{p}_1 - \vec{p}_2|/2$. See discussion in text.

for the $Y_B/2$ spectrum. For Y_B, the systematic errors are larger but do not significantly affect the conclusions reached below concerning sizes.

The general features of the data are readily understood. The proton pairs travel at almost the same velocity $\vec{V}$, at least for $\Delta p \leq 80$ MeV/c, and experience final-state interactions (attractive hadronic and repulsive Coulomb). These interactions are responsible for the peak at $\Delta p \approx 20$ MeV/c. The height of the peak is strongly dependent on source size; the smaller the source, the higher the peak. Note that the effects that dominate the nuclear correlation function are different from the analog in astronomy, the Hanbury-Brown–Twiss effect.[7] In the latter, since photons do not mutually interact, the shape of the correlation function is determined solely by Bose statistics. In the nuclear case, the interactions dominate and the quantum interference plays a secondary role.

The curves in Fig. 2 are theoretical calculations of the correlation functions obtained from Gaussian sources with rms radii $r_0 = 2$, 3, and 4 fm. The values of r_0 that describe our data are 1.5, 1.75, and 2.2 fm. The radii of the corresponding sharp sphere distributions, obtained by multiplying r_0 by 1.58, are 2.4, 2.8, and 3.5 fm. In obtaining these values we have assumed that the source lifetime $\tau = 0$. It should be noted that a nonzero lifetime would require even smaller sizes to describe our data.

To demonstrate possible anistropy in the source, we show, in Fig. 3, events having Δp approximately parallel to $\vec{V}$ ($|\Delta\vec{p} \times \hat{V}| < 10$ MeV/c) (filled circles) and approximately perpendicular to $\vec{V}$ ($\Delta\vec{p} \cdot \hat{V} < 10$ MeV/c) (open circles). The large statis-

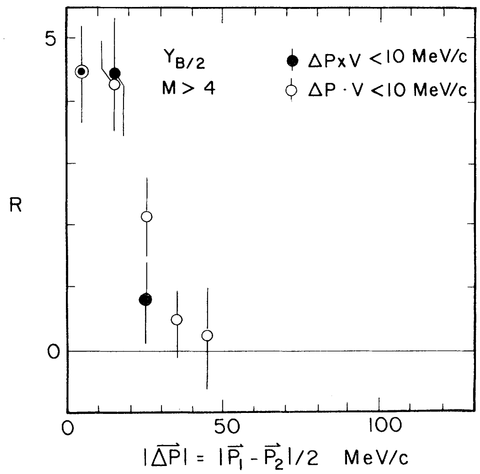

FIG. 3. The correlation function for the components of $\Delta\vec{p}$ parallel and perpendicular to $\vec{V}$ for the $M \geqslant 5$ data at $Y_B/2$.

tical errors which result from this selection process preclude any meaningful extraction of the two size parameters, $r_{\parallel}$ and $r_{\perp}$, but clearly there appear to be no qualitative differences in R for the two dimensions.

For $Y \approx Y_B$ we calculate from the data a sharp sphere radius of 3.5 fm, comparable to the radius of an Ar nucleus. This supports the hypothesis that these proton pairs come from a projectile remnant. At $Y_B/2$ the sharp sphere radius is considerably smaller (2.8 fm). This size may be consistent with the fireball model[4] if one assumes that large-impact-parameter events are included in the data. However, when the $M \geqslant 5$ restriction, which is expected to select events with small impact parameters, is imposed, an even smaller size (2.4 fm) is implied. This size is too small to be consistent with the fireball model, where one would expect a source size greater than that of the projectile since a fireball formed in a central collision should contain a large fraction of the projectile and target nucleons. This striking result is in disagreement with an earlier two-pion correlation measurement of source size for the same projectile and bombarding energies,[8] where it was concluded that the source size approximated that of the incident Ar projectile. In this earlier measurement, no attempt was made to separate events according to rapidity as was done in our measurement. This averaging over rapidity may be the origin of their larger source size.

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[a]Present address: Centre de Recherches Nucleaires, F-67200 Strasbourg, France.

[b]Present address: Los Alamos Scientific Laboratory, Los Alamos, N. Mex. 87544.

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