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CORRELATIONS AT SMALL RELATIVE MOMENTA AMONG PROTONS PRODUCED IN COLLISIONS OF 1.8 GeV/nucleon ^{40}Ar WITH A KCl TARGET

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ABSTRACT

Correlations between two protons have been measured as a function of their relative momentum $\Delta P = |\vec{P}_1 - \vec{P}_2|/2$ for the inclusive reaction Ar + KCl → p + p + X at 1.8 GeV/nucleon. Measurements were made for proton rapidities near the beam rapidity Y_B and near $Y_B/2$. The correlation function, obtained from the ratio of the two-particle yield to the product of uncorrelated single-particle yields, exhibits a peak at $\Delta P \sim 20$ MeV/c which is larger for data at $Y_B/2$ than at Y_B. Comparison of our data to model calculations suggests that the size of the region of final scatterings is larger at Y_B than at $Y_B/2$. The sizes we obtain for the mid-rapidity data (with or without high multiplicity requirements) seem inconsistent with any thermalized source containing a large fraction of the available nucleons.

We report here the first experimental effort to use the correlation between two protons as a technique to measure the size of the interaction region in relativistic heavy-ion collisions. In an earlier streamer chamber experiment, Fung et al.[1] used the quantum interference between two particles (assumed to be non-interacting) to measure the size and lifetime of the pion-eimtting source for collisions of 1.8 GeV/nucleon Ar with various targets. S. Koonin[2] proposed a model in which the mutual interactions between two protons enhance the sensitivity of the correlation function R to the spatial (r_0) and temporal (τ) extent of the proton-emitting source. The choice of proton pairs is also experimentally attractive because of the larger number of protons than pions produced at Bevalac energies.

Correlations between two protons at small relative momenta were measured for the inclusive reaction Ar + KCl → p + p + X at 1.8 GeV/nucleon. The two protons were detected in a previously described[3] magnetic spectrometer to which we have added a 24-element scintillation counter hodoscope. Measurements were made at two different kinematic regions. The settings S_1 and S_2 (Figure 1) correspond to the rapidities of the protons being near the beam rapidity Y_B and near $Y_B/2$, respectively. Protons detected at S_1 are thought to come from an object we call the projectile remnant. Earlier work[3,4] suggests that this remnant has two components: projectile participants[5] that have undergone nucleon-nucleon collisions of small momentum-transfer, and the high energy tail of the spectator evaporation spectrum. The protons detected at S_2 are essentially stopped in the Ar-KCl center of mass (T_{cm} ~ 45 MeV at θ_{cm} ~ 90°) and are almost certainly participants that have received large momentum transfers from one or many scatterings.

These stopped protons may have come from a thermal source or fireball[6] if they are accompanied by a large number of high $P_\perp$ fragments. Nagamiya et al.[7] suggest that such a multiplicity requirement selects events with

small impact parameters and many nucleon-nucleon scatterings for Ar + KCl and Ar + Pb at 800 MeV/nucleon. We sampled the multiplicity of high $P_\perp$ fragments with an array (M) of 16 counters. Seven 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 Figure 1, the region labeled M 30° (M 50°) shows the significant part of the acceptance for a multiplicity detector at 30° (50°). By studying the correlation function in conjunction with a high multiplicity trigger, we attempt to determine the size of the source at the Ar-KCl center of mass.

Data were taken for four event trigger types: two-particle inclusive, single-particle inclusive, two-particle with high multiplicity, and single-particle with high-multiplicity. For data at Y_B, the average observed multiplicity increases from 1.66 to 1.86 as the trigger changes from one to two protons. For data at $Y_B/2$, the average observed multiplicity increases from 1.84 to 2.5. From earlier studies[7] of similar multiplicity counters we estimate that the true multiplicity averages for these different trigger conditions are 11, 12, 12, and 15, respectively. We also estimate that the average multiplicity is 25 when an observed multiplicity of five or more is required in the trigger.

The correlation function R is formally defined from the relation

$$\frac{d^2\sigma}{d\vec{P}_1\, d\vec{P}_2} = \frac{1}{\sigma_T} \frac{\langle n\rangle^2}{\langle n(n-1)\rangle} \frac{d\sigma}{d\vec{P}_1} \frac{d\sigma}{d\vec{P}_2} (1 + R)$$

where $\frac{d^2\sigma}{d\vec{P}_1\, d\vec{P}_2}$ is the two-particle inclusive differential cross-section, $\frac{d\sigma}{d\vec{P}}$ is the single-particle inclusive differential cross-section, σ_T is the total inclusive cross-section for observing a proton, $\langle n\rangle$ is the first moment of the proton multiplicity distribution and $\langle n(n-1)\rangle$ is the second moment of the proton multiplicity distribution.

The quantity 1 + R is experimentally obtained from the ratio S_{2p}/S_{mix}, where S_{2p} is the relative momentum spectrum ($\Delta P = |\vec{P}_1 - \vec{P}_2|/2$) of two-particle events and S_{mix} is the relative momentum spectrum generated by mixing together the trajectories from two different single-particle events. The normalization is achieved by requiring that this ratio is unity for $95 < \Delta P < 215$ MeV/c where it is assumed that R = 0. It is also assumed that the quantity $\langle n \rangle^2/\langle n(n-1) \rangle$ does not vary with relative momentum. This quantity does not vary significantly with ΔP for the part of phase space subtended by our multiplicity array. We insure that S_{2p} and S_{mix} are associated with the same detection efficiency by discarding the mixed pair of events when the experimental resolution would prevent us from identifying two separate trajectories.

Results for the correlation function are shown in Figure 2. The symbols (O) represent data at $Y_B/2$ for which a multiplicity of five or more was required in the trigger for both the two-proton and single-proton data. The symbols (X) represent data at $Y_B/2$ with no multiplicity requirement. The symbols (•) represent data near Y_B with no multiplicity requirement. The error bars are statistical only. For data at $Y_B/2$, $|\Delta\vec{P}|$ is transformed to the fireball rest frame ($\beta_{Lab} = 0.7$). For the data at Y_B, $|\Delta\vec{P}|$ is transformed to the projectile rest frame ($\beta_{Lab} = 0.94$). The experimental resolution ($\sigma \sim 8$ MeV/c) and the inability to distinguish two overlapping trajectories are expected to significantly affect only the data in the 0-10 MeV/c interval. We estimate[8] that the systematic errors introduced into R, because single particle triggers are associated with different types of events than two particle triggers, are negligible for data at $Y_B/2$ with M>4 and largest for data at Y_B. Even at Y_B, these errors should not significantly affect the conclusions about sizes.

The curves shown in Figure 2 are S. Koonin's calculations of R for r_0 = 2, 3, and 4 fm. when τ = 0. In this model, the two protons are emitted independently from a source which, for the present data, is either the "fireball" or the projectile remnant. This emission is the final scattering of the protons with some other hadrons in the source. The quantity r_0 (τ) is the product of $\sqrt{2}$ times the standard deviation of the Gaussian distributed spatial (temporal) coordinates of the emitted protons. After the second proton is emitted, both protons travel at essentially the same velocity, $\vec{V}$, the p-p center of mass velocity in the source frame, and experience only mutual interactions (attractive hadronic and repulsive coulomb) which depend on the relative separation $\Delta\vec{r}$ and the relative momentum $\Delta\vec{P}$. These low energy proton-proton interactions cause the peak in R at $\Delta P \sim 20$ MeV/c.

The quantity x, the value of r_0 for τ = 0, is the parameter most easily extracted from the results shown in Figure 2. Since for our data $\vec{V}$ is non-relativistic ($V \approx 0.3$ C), x is also $\Delta r/\sqrt{3}$, where Δr is the RMS separation between the two protons in the p-p center of mass at the time the second proton is emitted. From the dependence of R on r_0 (τ = 0) reported in Reference (2), we estimate that x = 1.5, 1.75, and 2.2 fm. for the data at $Y_B/2$ (M > 4), $Y_B/2$ (M > 0), and Y_B (M > 0), respectively.

Since Gaussian distributions are used, x should be multiplied by 1.58 to obtain r_s, the radius of the corresponding sharp sphere. For the data at Y_B, r_s = 3.5 fm., which is slightly less than 4.1 fm., the size of an Ar nucleus. This suggests that these protons come from a projectile remnant. The r_s for this remnant is larger than those for possible sources at the Ar-KCl center of mass.

By describing our data with the single parameter x, we assume that the vector separation between the two emitted protons is distributed isotropically. To look for anisotropy, we show R (Figure 3) with the components of $\Delta\vec{P}$

parallel and perpendicular to $\vec{V}$. The symbols (0) represent data for $\Delta P \cdot V < 10$ MeV/c. The symbols (•) represent data for $\Delta P \times V < 10$ MeV/c. While the data are not extensive and the statistical uncertainties are large, the peaks in R are not very different for either direction.

In Koonin's model, the separation along $\vec{V}$ is increased by a length characterized by $\vec{V}\tau$. Unfortunately, this lifetime effect could be obscured if the average separation along $\vec{V}$ is limited to λ, the mean free path for final scatterings. We are not able to quote values for r_{11}, $r_{\perp}$, and τ because we have not yet made a three-parameter fit to our entire data set in ΔP_{11}, $\Delta P_{\perp}$, and $|\vec{V}|$ space.

Our data, by themselves, do not rule out the existence of a high density source that contains a large number of nucleons which are emitted isotropically from a small spatial region. It seems, however, that such a system could be formed only by processes that populate phase space in very special (non-thermal) ways. For now it seems more reasonable to assume that these stopped protons have undergone their final scatterings in a low density source that contains only a small fraction of the total participants. To obtain a quantitative estimate of the number of stopped participants, it seems necessary to modify Koonin's model because he assumes that the center of the source is the most probable emission point.

The multiplicity requirement $M > 4$ might prevent the observation of a large source at the Ar-KCl center of mass. The value of x is smaller for data at $Y_B/2$ with $M > 4$ than with $M \geq 0$. The sensitivity of the multiplicity counters to protons with rapidities $< Y_B/2$ may bias the data against collisions with high stopping powers.

The experiment warrants further consideration of the many crude approximations in the model which are discussed here and in Reference (2). The apparent success of the model in describing our data, however, suggests

that future measurements of R with improved multiplicity counters should show how the size of the final scattering region and possibly the number of stopped participants scale with energy and projectile-target mass.

We are deeply indepted to S. Nagamia and H. Steiner for the use of their multiplicity counters, to H. Palevsky and R. Sutter for the loan of their chamber electronics, and to R. Fuzesy for the KCl target. We wish to also thank Y. Miake for help in part of the data aquisition and we greatfully acknowledge J. B. McClelland and E. T. B. Whipple for their help with software used in this experiment.

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[1]S. Y. Fung, W. Gorn, G. P. Kiernan, J. J. Lu, Y. T. Oh, and R. T. Poe, Phys. Rev. Lett. 41, (1978) 1597.

[2]S. Koonin, Phys. Lett. 70B (1977) 43.

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[5]Participants are those nucleons in the geometrically overlapping parts of the colliding nuclei. Spectators are non-participant target or projectile nucleons.

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[8]F. Zarbakhsh, Ph.D thesis (in preparation).

FIGURES

Figure 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 M 30° (M 50°) indicates the significant acceptance of the multiplicity detectors at 30° (50°).

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

Figure 3. The correlation function for the components of $\Delta\vec{P}$ parallel and perpendicular to $\vec{V}$ for the M > 4 data at $Y_B/2$.

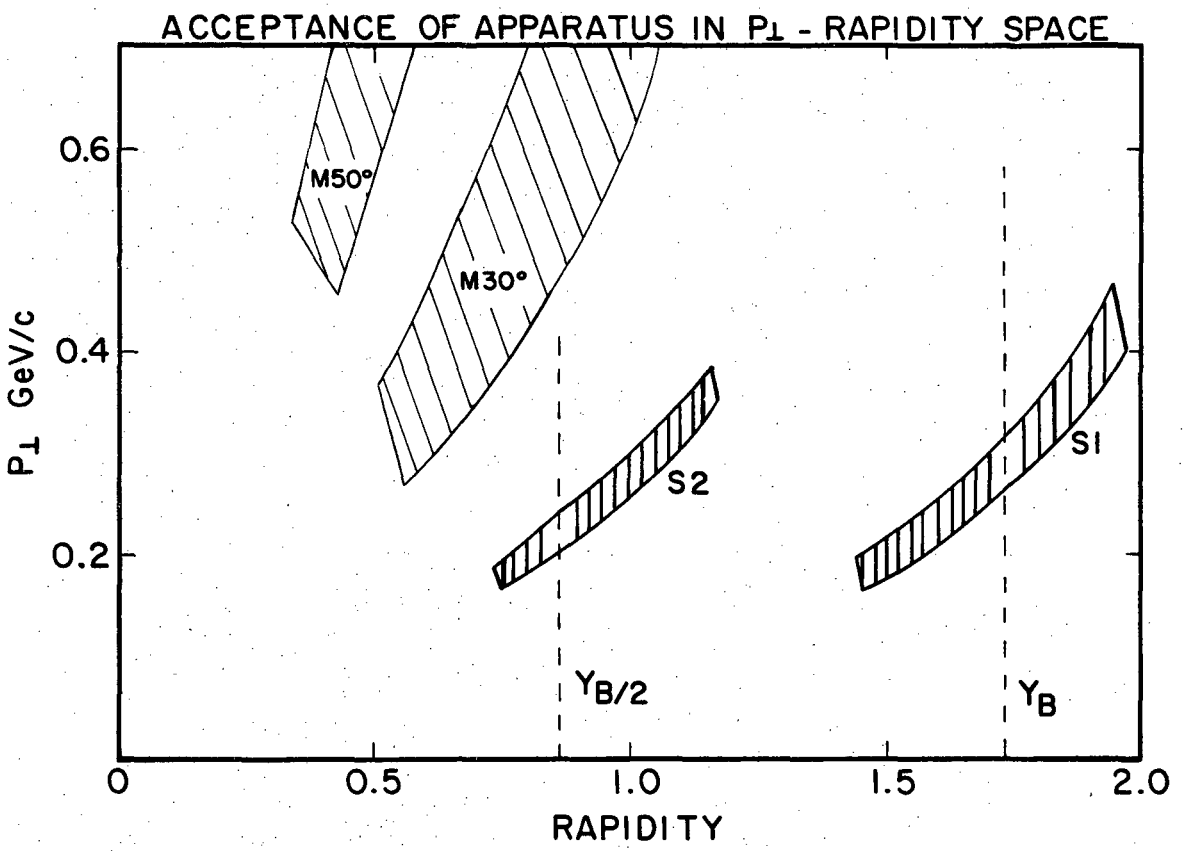


FIGURE 1

XBL 8010-12485

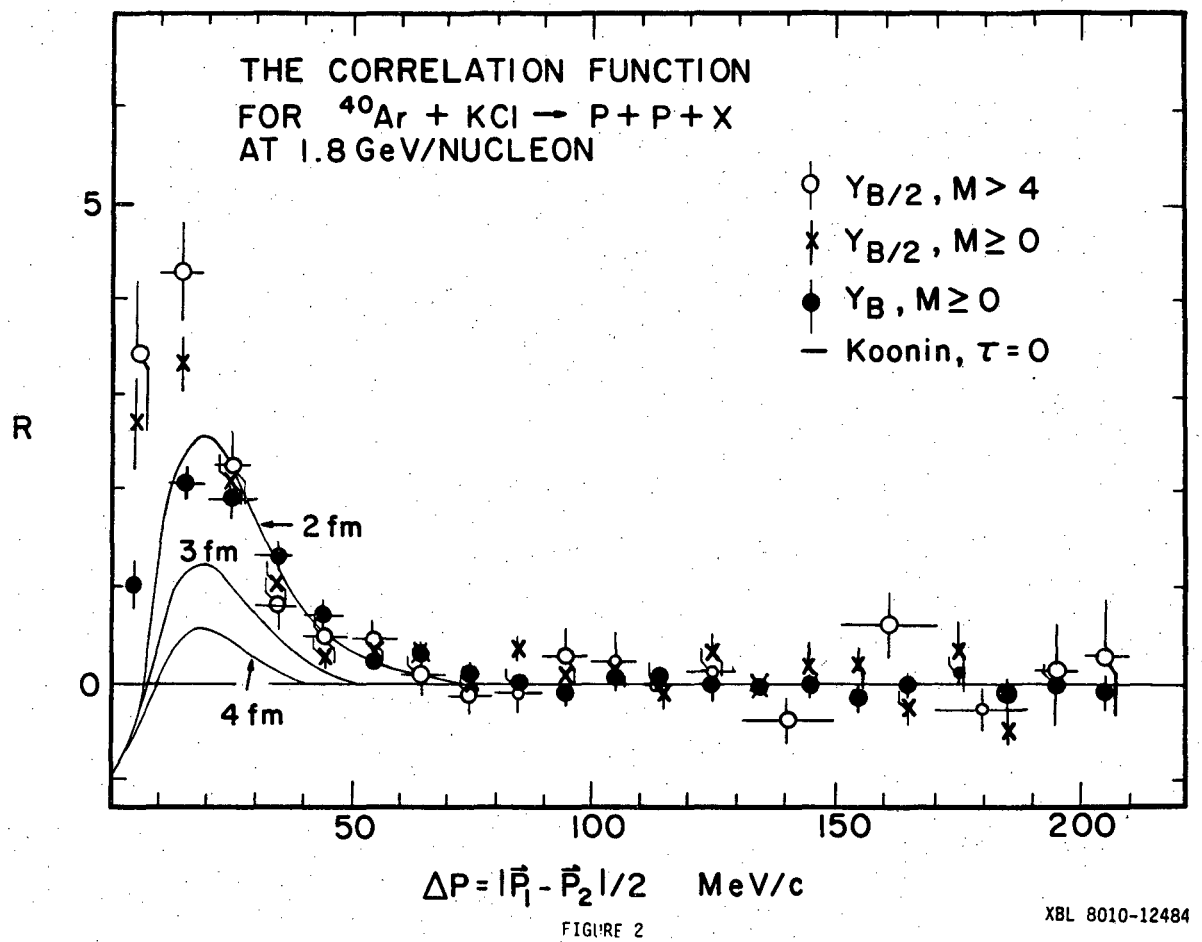

THE CORRELATION FUNCTION
FOR $^{40}Ar + KCl \rightarrow P + P + X$
AT 1.8 GeV/NUCLEON
$Y_{B/2}, M > 4$
$Y_{B/2}, M \geq 0$
$Y_B, M \geq 0$
Koonin, $\tau = 0$
R
5
0
2 fm
3 fm
4 fm
50
100
150
200
$\Delta P = |\vec{P}_1 - \vec{P}_2|/2$ MeV/c
XBL 8010-12484

FIGURE 2

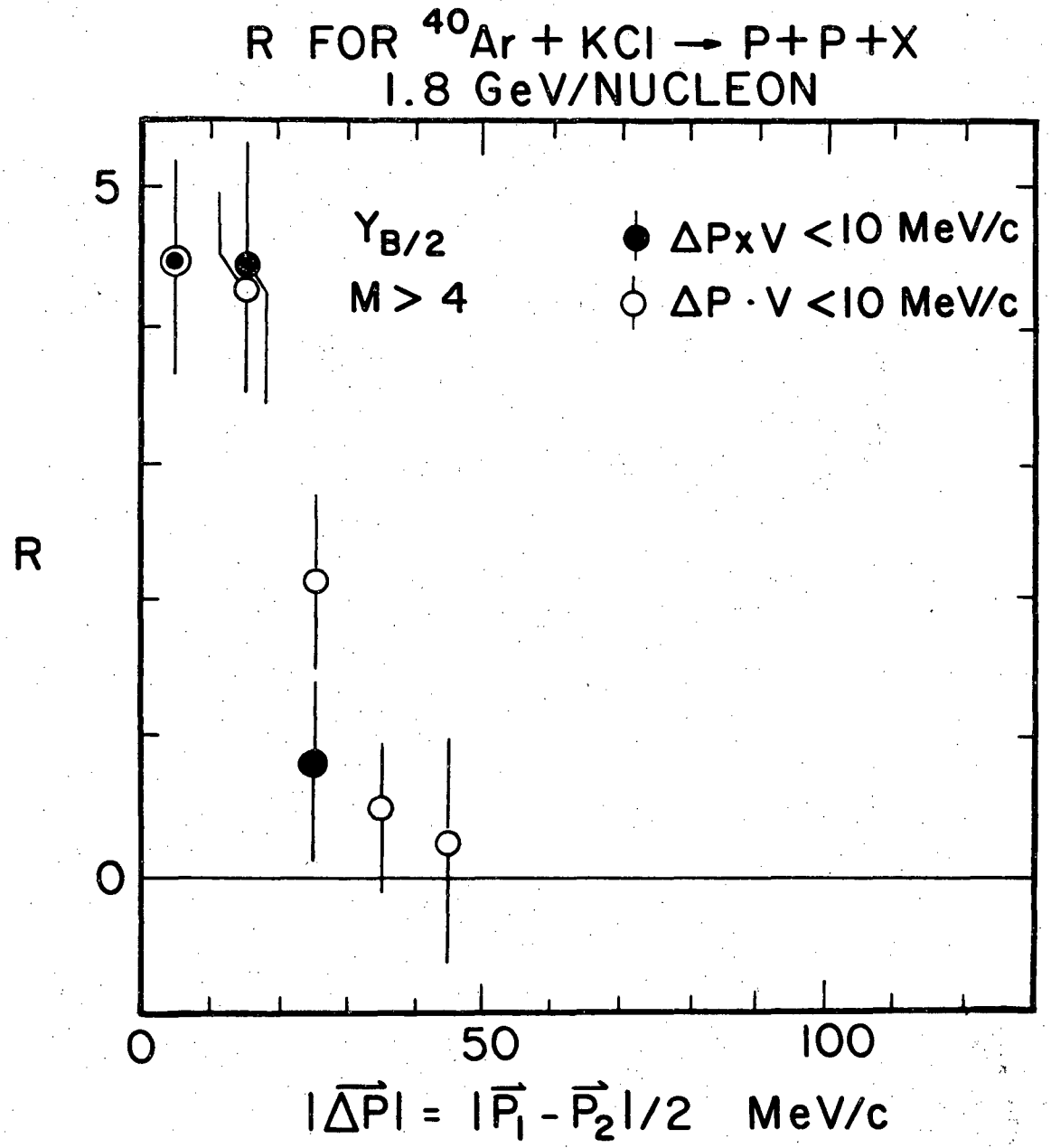


FIGURE 3

XBL 8010-12483

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