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Pion interferometry analysis for 1.2 GeV/nucleon Ar on KCl

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The technique of pion interferometry is used to study the pion source for central collisions of 1.2 GeV/nucleon Ar on KCl. The data are described by a Gaussian source of radius 3.8 ± 0.5 fm, a lifetime of 5.4 ± 1.8 fm/c, and a degree of coherence of 0.74 ± 0.17. The sensitivity of the analysis to the two-particle phase space is discussed. A comparison with previously reported results at 1.5 GeV/nucleon is presented.

[NUCLEAR REACTIONS ^{40}Ar(KCl)$E_{\rm lab} = 1.2$ GeV/nucleon, π^--π^- correlations, pion interferometry, pion source, Hanbury-Brown Twiss effect, multipion production, streamer chamber.]

The properties of the pion source produced in relativistic heavy ion collisions have been a major focus of interest of both theoretical and experimental investigations.[1–4] Measurement of the space-time structure and the degree of coherence of the pion source would provide important information on the pion emission process and the total reaction mechanism. Studying pion pair correlations through interferometry[5] has proven[6,7] to be a suitable tool for obtaining such information. In this Communication, we report the results of a pion interferometry analysis for 1.2 GeV/nucleon Ar on KCl central collisions.

The experimental data were obtained using the Lawrence Berkeley Laboratory streamer chamber. The 1.2 GeV/nucleon Ar beam was focused on a 0.44 g/cm^2 KCl target located inside the streamer chamber.[8] The chamber was triggered to preferentially select small impact parameter collisions, corresponding to 30% of the reaction cross section. Geometrically, this can be interpreted as selecting collisions with impact parameters of 5 fm or less. The observed average negative pion multiplicity is 2.3 per event. The detection efficiency, incorporating target absorption, scanning losses, and other inefficiencies is estimated to be $\approx 90\%$, giving a corrected value of the average negative pion multiplicity per event of 2.5. The observed negative pion multiplicity distribution is given in Fig. 1. The predictions of an effective one-pion fireball model,[2] including the trigger selection and detection efficiency, are shown in Fig. 1 for values of the critical freeze-out density ρ_c of $\frac{1}{3}$ (solid) and $\frac{1}{2}$ (dashed) the normal nuclear density ρ_0. For $N_\pi^- \geq 4$, the slope of the negative pion multiplicity distribution is sensitive to the value of ρ_c, and the data suggest a value between $\frac{1}{3}$ and $\frac{1}{2}$ ρ_0. Later we will show that the interferometry analysis suggests a similar value.

The interferometry analysis is performed by fitting the correlated two-π^- cross section with the product of a function C and the uncorrelated two-π^- cross section. The function C contains the effects of Bose-Einstein statistics, dynamical correlations, final state interactions, etc. For a Gaussian space-time pion emitting source with correlations induced only by the quantum statistics one obtains[9]

$$C(\vec{q}, q_0) = K[1 + \lambda \exp(-\vec{q}^2 R^2/2 - q_0^2 \tau^2/2)] \;, \qquad (1)$$

where $\vec{q}$ and q_0 are the center of mass relative momentum and energy of the pion pairs, R is the source radius, τ is the lifetime, λ is a measure of the degree of coherence, and K is a normalization factor.

The uncorrelated two-π^- cross section is generated by combining negative pions from different events with the same negative pion multiplicity. The generation of background events in this manner has the advantages of producing the single-particle phase space convoluted with the detection efficiency and being model independent. However, if the pion emission in an event has structure, such as pion jets, then this type of background generation will distort the interferometry analysis. An example is the possible absorption of pions by unexcited (cold) nuclear matter, causing a correlation between the direction of favored pion emission and the orientation of the event plane. In such a case, the background would be averaged over all orientations of the event plane and would distort the inter-

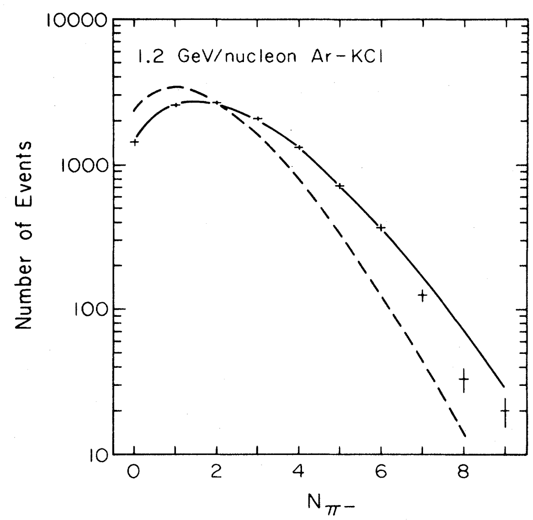

FIG. 1. The negative pion multiplicity distribution for central collisions of 1.2 GeV/nucleon Ar on KCl. Predictions of an effective one-pion fireball model (Ref. 2) for values of the critical freeze-out density of $\frac{1}{3}$ (solid) and $\frac{1}{2}$ (dashed) the normal nuclear density.

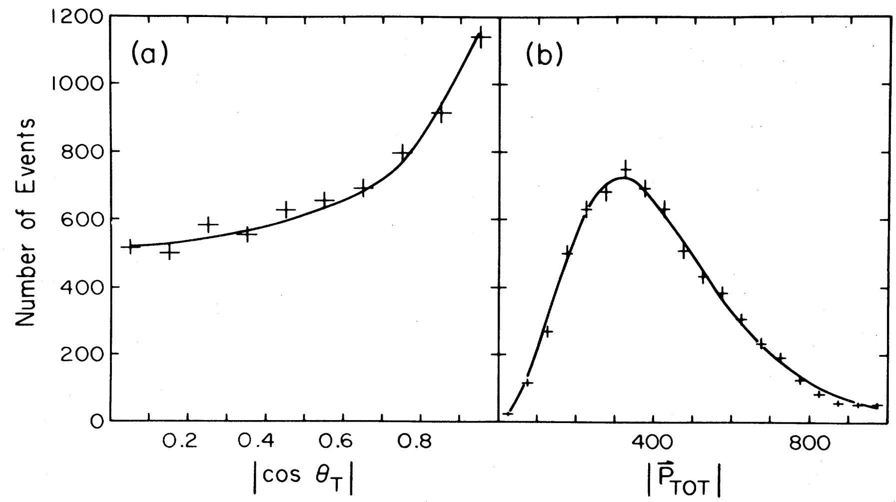

FIG. 2. The number of events vs (a) the cosine of the polar angle of the thrust axis, $|\cos(\theta_T)|$, and (b) the magnitude of the total center of mass momentum, $|\vec{P}_{tot}|$, for the negative pion in the data (error bars) and in the background events (solid curve).

ferometry analysis.[10] To address the question of structure in the pion events, we have performed a jet analysis, using thrust,[11] on the negative pions in the data and the background events. Thrust is defined as

$$T=\max[T(\hat{n})]=\max\left\{\sum_{i=1}^{N_{\pi^-}}|\vec{P}_i\cdot\hat{n}|\Big/\sum_{i=1}^{N_{\pi^-}}|\vec{P}_i|\right\} , \quad (2)$$

where $\hat{n}$ defines the jet axis, $\vec{P}_i$ are the negative pion momentum in the center of mass, and $N_{\pi^-}\geq 2$. In addition, we have examined the total vector momentum of the negative pions in the data and the background events. In both cases, no significant difference between the data and the background was observed. In Fig. 2(a) we display the results for the cosine of polar angle for the thrust axis, $|\cos(\theta_T)|$, and in Fig. 2(b) the magnitude of the total vector momentum of the negative pions in the center of mass, $|\vec{P}_{tot}|$. We conclude that there is no significant structure in the negative pion emission which will distort the interferometry analysis.

Final state Coulomb interactions can also distort the interferometry analysis. We have corrected for the π^--π^- Coulomb interaction by incorporating a Gamov factor[5]

$$G(\eta)=2\pi\eta/[\exp(2\pi\eta)-1] , \quad (3)$$

where $\eta=m_\pi\alpha/(q_0^2-\vec{q}^{\,2})^{1/2}$ in our data analysis. Only the degree of coherence λ is significantly affected by this correction.[7] The π^--proton Coulomb interaction is negligible for the interferometry analysis of this data sample.

A subsample of 7200 events with $N_{\pi^-}\geq 2$ is used for the interferometry analysis. In addition, a momentum requirement of $P_{\rm lab}\geq 100$ MeV/c is imposed to minimize multiple scattering effects in the target and electron contamination from photon conversion and Dalitz pairs. All negative pion pairs with $q\leq 60$ MeV/c (throughout $q=|\vec{q}|$) have been reexamined to remove any measurement errors. The final data sample contains 24 000 negative pion pairs. In Fig. 3 we plot contours of the pair density $dn/(dq_0dq)$. The distribution of $dn/(dq_0dq)$ controls the sensitivity to the fit parameters of Eq. (1). Our results are

$$R=3.8\pm0.5\ \text{fm} ,$$

$$\tau=5.4\pm1.8\ \text{fm}/c ,$$

and

$$\lambda=0.74\pm0.17 .$$

The data and the fit have been summed over the relative energy and displayed in Fig. 4. The large statistics in the region for $q\geq 150$ MeV/c gives an accurate determination of the normalization factor K and decouples the normalization from the source parameters. The determination of the normalization factor K is equivalent to requiring that the ratio of the correlated to uncorrelated two-π^- cross sections be unity at large relative momentum. A Gaussian source radius of 3.8 fm corresponds to a uniform distribution of ra-

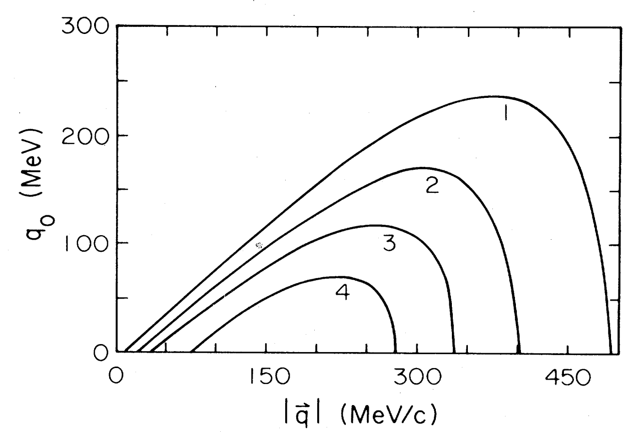

FIG. 3. Contours of negative pion pair density $dn/(dq_0dq)$. Contours labeled 1, 2, and 3 represent equal increasing increments of $dn/(dq_0dq)$.

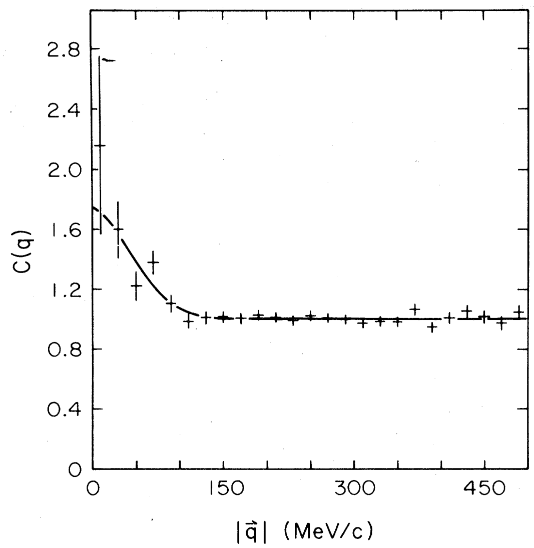

FIG. 4. The data and fit summed over the relative energy as a function of the relative momentum q.

dius 5.9 fm. Clearly, a radius of roughly 4–6 fm should be expected for the central collision of two nuclei each of radius 4 fm. Estimating the average number of participant nucleons to be 50, we obtain a critical freeze-out density, $\rho_c \simeq 0.45\rho_0$. This result agrees well with the expectation of the effective one-pion fireball model as determined from the multiplicity distribution in Fig. 1.

The lifetime of 5.4 fm/c is quite reasonable for a source radius of 3.8 fm. In addition, models such as the intranuclear cascade[3] suggest most of the pion production occurs during a period of 10 fm/c and therefore agrees well with our Gaussian width of 5.4 fm/c. Our data are much less sensitive to the lifetime (variations in q_0) than the radius (variations in q) which is a result of the distribution of $dn/(dq_0 dq)$. In the region of phase space where $q \simeq q_0$, Eq. (1) is no longer sensitive to R and τ separately but to $R^2+\tau^2$. This induces a coupling in the determination of these parameters. However, since the density $dn/(dq_0 dq)$ is distributed primarily where q_0 is substantially less than q (see Fig. 3), this coupling should be small. In Fig. 5(a), the likelihood contours for the parameter space of R and τ are shown. A weak correlation in the manner expected is evident.

One of the primary objectives of the interferometry analysis is to determine whether the pion source is chaotic or coherent. The parameter λ is a measure of the degree of coherence with $\lambda=1$ for a totally chaotic source and $\lambda=0$ for a totally coherent source. We obtained a value of $\lambda=0.74 \pm 0.17$ for the degree of coherence suggesting that a component of the pion source may be nonchaotic. A value of $\lambda \simeq 0.55$ is obtained without the Gamov factor. A value of $\lambda=1$ lies within two standard deviations of the optimum and therefore cannot be excluded. Besides total statistics, the primary factor limiting the accuracy for the determination of λ is a strong coupling between the radius R and the degree of coherence λ. In Fig. 5(b) the likelihood contours for the parameter space of R and λ clearly show this coupling. The lower statistics in the region $q < 30$ MeV/c compared with $q > 30$ MeV/c results in both R and λ being primarily determined in the $q > 30$ MeV/c region. In this region, a change in R can be compensated for by a change in λ causing the coupling of these parameters and therefore limiting the accuracy of their determination.

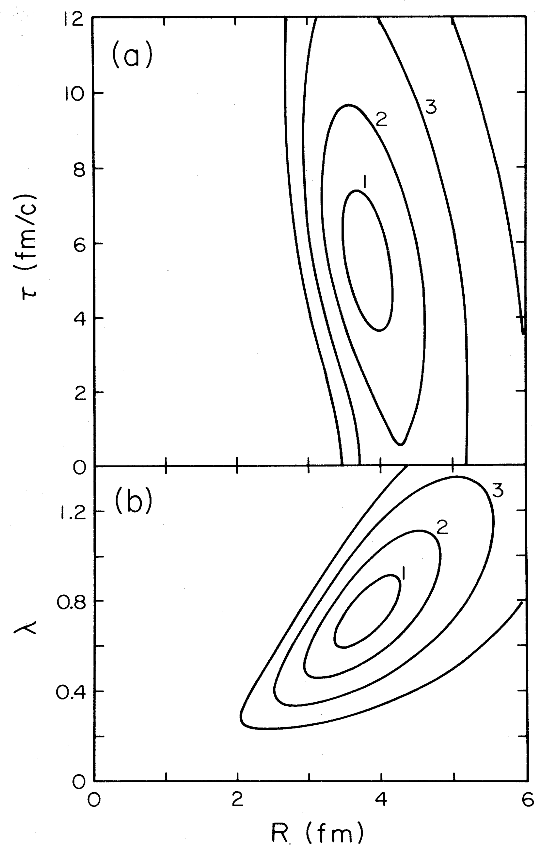

FIG. 5. Likelihood contours for 1, 2,... standard deviations for (a) the radius R and the lifetime τ, and (b) the radius R and the degree of coherence λ.

Recently, we reported[7] results for the pion source parameters for 1.5 GeV/nucleon Ar on KCl. The results reported there were for a fixed lifetime $\tau=1.5$ fm/c. For comparison we give here the 1.5 GeV/nucleon source parameters for the optimum fit:

$$R=4.7 \pm 0.5 \text{ fm} \quad ,$$

$$\tau=4.2^{+1.8}_{-4.2} \text{ fm}/c \quad ,$$

and

$$\lambda=1.2 \pm 0.2 \quad .$$

The lifetimes of both samples are similar; however, both the radius and the degree of coherence are larger for the 1.5 GeV/nucleon data. The two results differ by 1.7 standard deviations. Therefore the posssible differences in the source parameters for the two samples are not statistically significant at present. For the 1.5 GeV/nucleon data, we reported the results of the interferometry analysis with kinematic cuts. Because of the lower negative pion multiplicity per event, such kinematic cuts for the 1.2 GeV/nucleon data cause too large a reduction in the statistics to allow meaningful comparisons.

In summary, the pion source parameters for central collisions of 1.2 GeV/nucleon Ar on KCl have been measured using pion interferometry. The radius and lifetime of the source are in agreement with the expectations of simple geometrical considerations. The data suggest the pion source may have a coherent component, which can be confirmed with a moderate increase in statistics.

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