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Pion source parameters in Ar on KCl collisions

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The space-time structure of the pion-emitting source for central collisions of Ar on KCl at 1.5 GeV/nucleon is studied. The fireball is found to be nearly spherical with a radius $R = 4.9 \pm 0.5$ fm. No significant dependence on pion multiplicity is present. A dependence on pion energy is observed.

[NUCLEAR REACTIONS ^{40}Ar(KCl) $E_{lab} = 1.5$ GeV/nucleon. Measured two-π^- correlations. Interferometry analysis deduced, size, shape, coherence of π^- emission source.]

Pion production is a topic of major interest in the study of relativistic heavy ion collisions (RHI). There has been a considerable range of theoretical speculation on the nature of the pion emission processes, from a straightforward superposition of nucleon-nucleon reactions,[1] to a chaotic pion source emanating from a thermalized pion fireball,[2] to exotic pion production through a coherent state of the pion field[3] that may exist under high temperature, high pressure, and high density conditions during the collision process. Measurement of the space-time evolution of the pion source would provide important information into the pion emission process and the total reaction mechanism. Studying pion pair correlations through interferometry has been suggested[4] as a method to investigate the space-time structure and the degree of coherence of the pion source. Its practical feasibility for nucleus-nucleus collisions was demonstrated in a previous streamer chamber experiment.[5]

In this paper, we report the results of an experiment on the pion emission source for the reaction 1.5 GeV/nucleon Ar + KCl $\rightarrow 2\pi^- + X$. The experiment was performed at the Bevalac using the 1.25 m streamer chamber. Details of the streamer chamber have been previously discussed.[6] The target was a 0.46 g/cm^2 KCl disk with a diameter of two inches. The chamber was triggered on central collision events, selecting 35% of the total inelastic reaction cross section. In a geometric interpretation, this corresponds to impact parameters of less then 5 fm. The negative pion multiplicity distribution is shown in Fig. 1. The average negative pion multiplicity is 3.3 per event. The solid curve in Fig. 1 is the prediction of an effective one pion fireball model[2,7] with a maximum impact parameter of 5 fm, a critical freeze-out density ρ_c equal to $\frac{1}{3}$ the nuclear density ρ_0, and convoluted with a 90% detection efficiency. A complete discussion of multiplicity, momentum, and angular distributions will be given in a future report. For the pion interferometry analysis, a subsample of 4500 events with $n_{\pi^-} \geq 2$ was selected. To ensure the quality of the data sample after scanning and measurement, events are selectively reexamined by a physicist.

The interferometry analysis is performed by comparing the correlated two-π^- cross section to the product of a function C and the uncorrelated two-π^- cross section. The uncorrelated two-π^- cross section is obtained by combining pions from two different

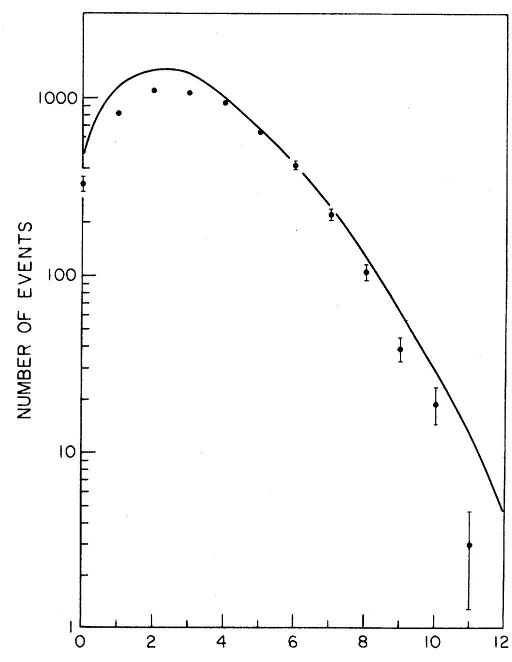

FIG. 1. Number of events as a function of negative pion multiplicity, n_{π^-}, for 1.5 GeV/nucleon Ar + KCl. The solid curve is the prediction of an effective one pion fireball model with a maximum impact parameter of 5 fm.

events with the same negative pion multiplicity. The function C contains the effects of Bose-Einstein statistics, dynamic correlations, space-time structure of the source, etc., and is usually expressed as a function of the pions' energy difference $q_0 = |E_1 - E_2|$ and their relative momentum $\vec{q} = |\vec{p}_1 - \vec{p}_2|$. The analysis and kinematic variables throughout this paper refer to the nucleon-nucleon center of mass frame. Our experimental resolution for q is 10 MeV/c.

Assuming a Gaussian space-time structure, Yano and Koonin[8] have derived the expression for the correlation function,

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

where R is the source radius parameter, τ is the lifetime parameter, λ is a measure of the degree of coherence (and other dynamic effects), and K is a normalization factor. The essential results of our study are summarized in Table I.

Our analysis gives an overall result of $R = 4.9 \pm 0.5$ fm and $\lambda = 1.1 \pm 0.3$. The data sample is not sensitive to the lifetime parameter; therefore, we conduct the analysis with τ fixed at 5×10^{-24} sec $\simeq 1.5$ fm/c. The data and the fit have been integrated over q_0 and displayed in Fig. 2(a). The value of λ is consistent with a totally chaotic pion source.[3] A value of $R = 4.9$ fm is consistent with the expectations of a pion fireball model,[2] with $\rho_c \simeq 1/3\rho_0$. The negative pion multiplicity is sensitive to the value of ρ_c and is in agreement (see Fig. 1) with $\rho_c \simeq 1/3\rho_0$. We conclude that the values of R and λ are consistent with a thermalized pion fireball.

A nonspherical pion source could have implications for the reaction mechanism in RHI collisions. Therefore, we have investigated the spatial shape of the pion source. Since Eq. (1) is related to the Fourier transform of the pion source density, the factor $\exp(-q^2R^2/2)$ can be expanded into components parallel and perpendicular to the beam direction. The correlation function $C(q,q_0)$ then becomes

$$C(q,q_0) = K[1 + \lambda \exp(-q_\parallel^2 R_\parallel^2/2 - q_\perp^2 R_\perp^2/2 - q_0{}^2\tau^2/2)] \ , \qquad (2)$$

where $R_\parallel$ and $R_\perp$ are the longitudinal and transverse pion source dimensions. Using Eq. (2), we have obtained the values $R_\parallel = 5.0 \pm 1.5$ fm and $R_\perp = 5.0 \pm 0.5$ fm. Another method to investigate the shape of the

TABLE I. Result of the fits to the correlation function $C(q,q_0)$ given by Eqs. (1) and (2). Results for the data uncorrected and corrected by a Gamov factor are given. The radii are in fm. All kinematic variables are in the nucleon-nucleon center of mass frame.

Sample selection	Parameters	Fitted parameters: Data uncorrected	Data corrected with Gamov factor
Full sample	R	4.91 ±0.50	4.93 ±0.44
	λ	0.99 ±0.20	1.21 ±0.22
	χ^2/NDF	101/116	104/116
Full sample	$R_\parallel$	5.05 ±1.46	5.11 ±1.17
	R	5.02 ±0.52	5.03 ±0.47
	λ	1.03 ±0.24	1.26 ±0.25
	χ^2/NDF	194/206	198/206
$\lvert\cos(\theta_i)\rvert < 0.5, \ i = 1,2$	$R \simeq R$	5.04 ±0.88	5.16 ±0.78
	λ	1.50 ±0.47	1.81 ±0.51
	χ^2/NDF	97/115	100/115
$0.5 < \cos(\theta_i) < 1, \ i = 1,2$ or $-1.0 < \cos(\theta_i) < -0.5, \ i = 1,2$	$R \simeq R_\parallel$	4.76 ±0.60	4.80 ±0.54
	λ	0.90 ±0.24	1.11 ±0.26
	χ^2/NDF	110/116	112/116
$P_1,P_2 < 150$ MeV/c	R	5.99 ±1.08	6.20 ±1.05
	λ	1.56 ±0.50	1.96 ±0.59
	χ^2/NDF	30/39	32/39
$P_1,P_2 > 150$ MeV/c	R	4.11 ±0.51	4.14 ±0.46
	λ	0.88 ±0.23	1.06 ±0.24
	χ^2/NDF	129/116	131/116

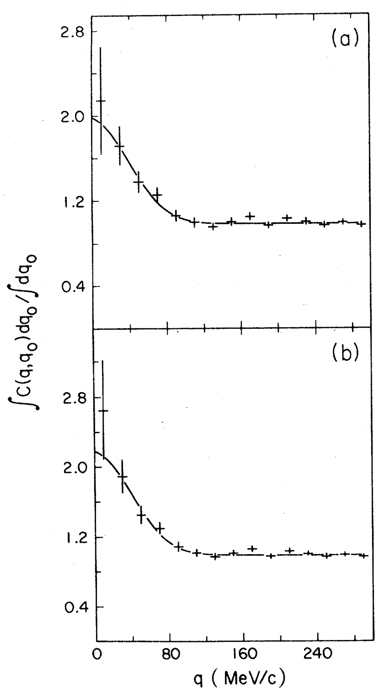

FIG. 2. Correlation function $C(q,q_0)$, for 1.5 GeV/ nucleon Ar +KCl collisions, integrated over q_0 as a function of q. The solid curves are the fits to the data. (a) Uncorrected; (b) corrected by a Gamov factor.

source is to restrict the pion pairs to particular angular regions. With the restriction that both π^- satisfy $|\cos\theta_{c.m.}| < 0.5$, we obtain $R \simeq R_\perp = 4.8 \pm 0.6$ fm. With both pions satisfying either $\cos\theta_{c.m.} > 0.5$ or $\cos\theta_{c.m.} < -0.5$, we obtain $R \simeq R_\parallel = 5.0 \pm 0.9$ fm. We thus find no significant deviation from a spherical pion source.

We subdivided the data sample in pion multiplicity bins. The resulting values of R do not show any n_{π^-} dependence. For impact parameters less than 5 fm, the pion multiplicity distribution is dominated by statistical fluctuations rather than by the change in the impact parameter. In addition, the combinatorics for the interferometry analysis compete against the impact parameter averaging to further dilute the dependence of n_{π^-} on the impact parameter.

To investigate the dependence of pion source parameters on the emitted pion energies, we performed pion interferometry analysis on two selected subsamples. For the subsample where both of the pions have $P_{c.m.} < 150$ MeV/c, we obtained $R = 6.0 \pm 1.1$ fm and $\lambda = 1.6 \pm 0.5$. For the subsample where both of the pions have $P_{c.m.} > 150$ MeV/c, we obtain $R = 4.1 \pm 0.5$ fm and $\lambda = 0.9 \pm 0.2$. While the present statistics preclude any definitive statement, these results are highly suggestive. The values of R are consistent with the picture of a pion fireball source whose temperature diminishes as its size expands. The trend is also consistent with the picture that the high energy pions are predominantly associated with directly produced pions, while the lower energy pions are emitted from a subsequent thermalized "fireball." The implications are further complicated by the suggestion that for $P < m_{\pi^-}$ the pion interferometry analysis may have substantial distortions caused by one-body optical potentials.[3] Further experimental and theoretical investigation into the possible dependence of the source parameters on energy seems warranted.

The effects of final state π^--π^- Coulomb interactions can be accounted for by the incorporation of a Gamov factor[3]

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

where $\eta = m_{\pi^-}\alpha/q$. Figure 2(b) shows the effect of such a correction on the data. The corresponding parameter values are included in Table I. Only the value of λ is significantly affected. We note that the χ^2/NDF increases slightly when the Gamov factor is incorporated (NDF means "number of degrees of freedom"). Finally, we remark that this correction for π^--π^- Coulomb interactions is a nonrelativistic approximation and also does not include the effects of the finite space-time structure of the pion source. The π^--proton Coulomb interaction is important only in a very small region of phase space, and it has a negligible effect on the π^--π^- momentum difference. Therefore, the π^--π^- interferometry analysis is unaffected by the π^--proton Coulomb interactions.

Recently, preliminary results from a fixed-angle counter experiment on the spatial structure of a pion-emitting source were reported.[9] Their value of R is considerably less than ours. This may be due to the difference in event selection, kinematic acceptance, and incident energy. More detailed comparisons should prove of interest when their final analysis becomes available.

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[1]J. P. Vary, Phys. Rev. Lett. 40, 295 (1978).

[2]M. Gyulassy and S. K. Kauffmann, Phys. Rev. Lett. 40, 298 (1978).

[3]M. Gyulassy, S. K. Kauffmann, and L. W. Wilson, Phys. Rev. C 20, 2267 (1979).

[4]G. Cocconi, Phys. Lett. 49B, 459 (1974); E. V. Shuryak, *ibid.* 54B, 387 (1975); G. I. Kopylov and M. J. Podgoretsky, Yad. Fiz. 18, 656 (1974) [Sov. J. Nucl. Phys. 18, 336 (1974)].

[5]S. Y. Fung, W. Gorn, G. P. Kiernan, J. J. Lu, Y. T. Oh, and R. T. Poe, Phys. Rev. Lett. 41, 1592 (1978).

[6]S. Y. Fung, W. Gorn, C. P. Kiernan, F. F. Liu, J. J. Lu, Y. T. Oh, J. Ozawa, R. T. Poe, L. Schroeder, and H. Steiner, Phys. Rev. Lett. 40, 292 (1978).

[7]While the effective one pion fireball model gives good agreement, it should be emphasized that internal consistency in energy also requires an implicit assumption of the model that about half of the available energy remains in unthermalized nuclear flow motion. We thank Dr. Gyulassy for this elucidation.

[8]F. B. Yano and S. E. Koonin, Phys. Lett. 78B, 556 (1978).

[9]W. A. Zajc *et al.*, in Proceedings of the Fifth Heavy Ion Conference, University of California at Berkeley, Berkeley, California, 1981, edited by G. S. Pappas (Report No. LBL-12652), p. 350.