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Energy Dependence of Multi-Pion Production in High-Energy Nucleus-Nucleus Collisions

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Exclusive π^- and charged-particle production in collisions of Ar+KCl is studied at incident energies from 0.4 to 1.8 GeV/u. Complete disintegration of both nuclei is observed. The correlation between π^- and total charge multiplicity shows no islands of anomalous pion production. For constant numbers of proton participants the π^- multiplicity distributions are Poissons. For central collisions $\langle n_{\pi^-}\rangle$ increases smoothly and to first order linearly with the c.m. energy. Disagreement with the firestreak model is found.

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There is considerable interest in studying pion production and its energy dependence in heavy-ion central collisions.[1-7] Pion multiplicity distributions at various energies are needed to test and constrain thermal- and cascade-model calculations as well as the hydrodynamical-model prediction of an increase in the pion yield at the onset of a phase transition.[4] Although exclusive π^- and charged-particle production data have been reported for projectiles from p to Ar incident on various targets,[8-10] no comprehensive study of their energy dependence in central collisions has been undertaken.

In this Letter we present the results of a systematic study of π^- production and accompanying nuclear disintegration in the interaction of ^{40}Ar +KCl for bombarding energies from 0.4 to 1.8 GeV/u. The experiment was performed at the Bevalac using the streamer-chamber facility. A 3-mm-thick KCl target was placed inside the sensitive volume of the chamber permiting 4π exclusive charged-particle detection and charge sign and rigidity determination in a 1.32-T magnetic field.

The streamer-chamber trigger technique as developed by Fung *et al.*[8] consists of an upstream beam-defining counter, a target, and a downstream scintillator which, covering 74 msr, detected the projectile spectator fragments. Data were taken at each energy in two trigger modes: an inelastic mode which rejected the noninteracting beam particles, and a central mode which selected events with small total charge in leading fragments compared to that of the beam. For each trigger mode 2000 to 5000 events were accumulated at bombarding energies at the target center of 360, 566, 772, 977, 1180, 1385, 1609, and 1808 MeV/u. Each event was classified according to its negative-pion multiplicity, total charged-particle multiplicity, and number of leading tracks.

Total charged-particle (n_{tot}) and negative-pion (n_{π^-}) multiplicity distributions are shown in Fig. 1 for both trigger configurations at 1.8 GeV/u. For the inelastic trigger, $\sigma(n_{tot})$ decreases exponentially for low multiplicities, and reaches a plateau for $25 < n_{tot} < 40$ which is followed by a sharp cutoff at higher multiplicities. The observed shoulder at high multiplicities, which appears at all bombarding energies, is not reproduced by the fireball[7] or cascade[5,6] models. In the fireball model this may be ascribed to the clean-cut geometry which neglects dissipation of momentum and energy along the transverse direction, underestimating the number of participants. The total cross section observed for the

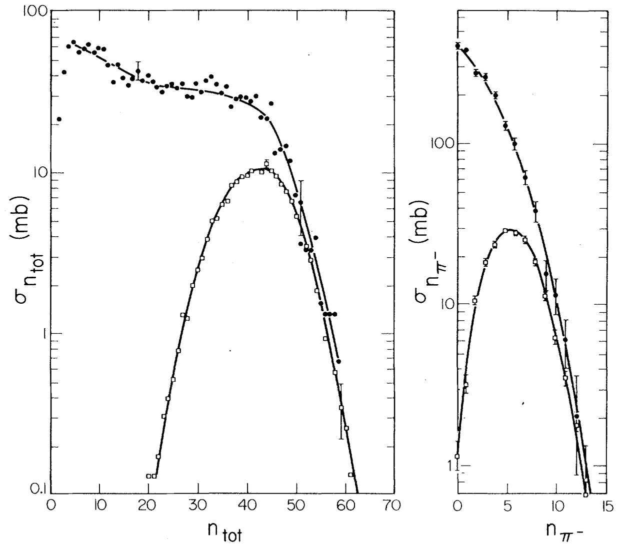

FIG. 1. Total charged-particle (n_{tot}) and negative-pion (n_{π^-}) multiplicity distributions for the interaction of Ar + KCl at 1.8 GeV/u for the inelastic (circles) and central (squares) trigger modes. For the inelastic trigger, representative error bars are shown and the curve is drawn to guide the eye. At this energy the total cross section for π^- production is $\sigma = 4.4$ b.

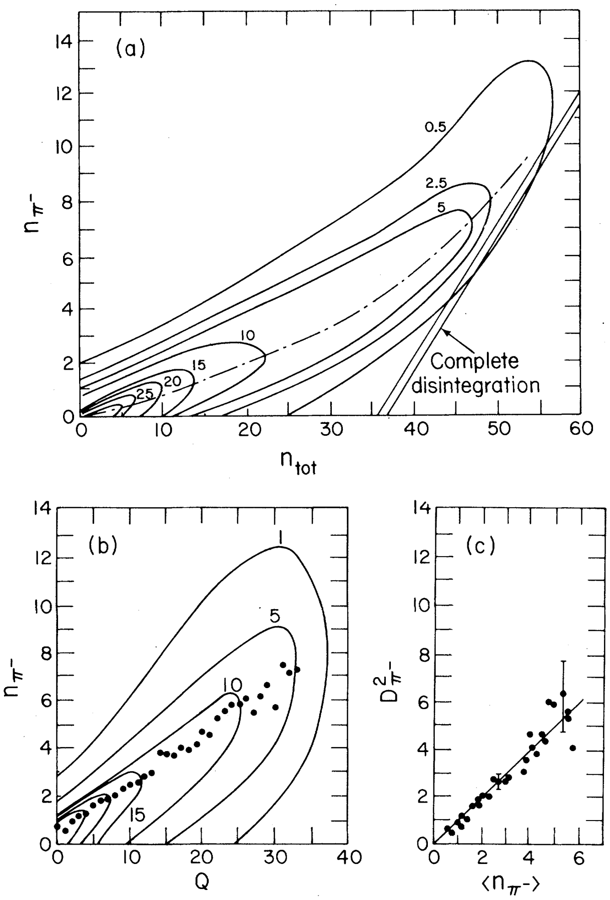

FIG. 2. (a) Topology of reaction products for Ar + KCl in the inelastic trigger mode at 1.8 GeV/u, drawn as contours of constant cross section (mb) in the n_{π^-} vs n_{tot} multiplicity plane. The dash-dotted curve corresponds to $\langle n_{\pi^-}\rangle$ as a function of the total multiplicity. The straight lines correspond to the total disintegration limit; see text. (b) Contour plot of the same reaction in the n_{π^-} vs Q (number of participant protons) plane. The dots correspond to $\langle n_{\pi^-}\rangle$ as a function of Q. For a given Q the n_{π^-} distribution is such that the square of dispersion, $D_{\pi^-}{}^2$, equals $\langle n_{\pi^-}\rangle$ as shown in (c). Representative error bars are drawn.

inelastic trigger is $\sigma = 1.78 \pm 0.03$ b. The effect of the trigger bias which suppressed events with charge multiplicities $n_{tot} < 5$ is estimated to be a 6% correction, yielding $\sigma_R = 1.9 \pm 0.1$ b. This value agrees well with a geometrical reaction cross section that fits the systematics of the available experimental data.[11,12] The central trigger mode was used to enrich the sample of high-multiplicity events. The resulting n_{tot} distributions are Gaussian as shown in Fig. 1. The total cross section observed for the central trigger is $\sigma_R = 180 \pm 5$ mb which in a geometrical model corresponds to $b \leq 2.4$ fm. Figure 2(a) shows a contour plot of the reaction cross section as a function of n_{π^-} and n_{tot} in the inelastic trigger mode. The reaction products are confined to a smooth distribution about a narrow ridge with no discernible signature of anomalous pion production. The dash-dotted curve, representing $\langle n_{\pi^-}\rangle$ as a function of n_{tot}, shows a monotonic increase with no discontinuities, a feature common to the other bombarding energies. For high multiplicities, the interaction approaches the total disintegration limit, which corresponds to the maximum number of observable charges; in this case, $n_{tot}{}^{max} = Z(\mathrm{Ar}) + Z(\mathrm{K\ or\ Cl}) + 2n_{\pi^-}$, which is given by the straight lines in Fig. 2(a). For theoretical analysis a multiplicity correlation in terms of the number of participant nucleons instead of n_{tot} is more appropriate. From the streamer-chamber data, a good estimate of the number of projectile and target participant protons (Q) can be obtained. The participants may be defined as all nucleons outside the projectile- and target-fragmentation Fermi spheres.[13] To estimate the number of participant charged nuclei in each collision, the charges created ($2n_{\pi^-}$) and the number of observed projectile ($n_{proj}{}^s$) and target ($n_{tgt}{}^s$) spectator fragments were subtracted from n_{tot}:

$Q = n_{tot} - 2n_{\pi^-} - (n_{proj}^s + n_{tgt}^s)$, where n_{proj}^s is the number of leading fragments traveling with the projectile velocity in a 4° forward cone and n_{tgt}^s is the number of positive tracks observed with $p_{lab} \lesssim 200$ MeV/c. The resultant Q is identified as the number of participant protons, assuming that all these participant nuclei are singly charged.[14] In Fig. 2(b) the data of Fig. 2(a) are transformed into the n_{π^-} vs Q space. As shown by the dots in Fig. 2(b) $\langle n_{\pi^-}(Q)\rangle$ increases linearly with Q. The resulting π^- distributions are such that, for a given Q, the square of the dispersion is equal to the mean, $D_{\pi^-}^2(Q) = \langle n_{\pi^-}(Q)\rangle$, as shown in Fig. 2(c). This extends the results of Bartke[15] for central collisions to all impact parameters, if the distributions are classified according to the number of participants. There are two main contributions to these dispersions: (a) the dispersion in the number of negative pions produced in a N-N collision at the relevant energy, and (b) the fluctuations of the number of pion-producing and -absorbing interactions, a statistical process. Since (a) has a narrower distribution at these energies[10] ($D_{\pi^-}^2 - \langle n_{\pi^-}\rangle > 0$), the observed Poisson distributions suggest that the second distribution is dominant.

In order to maintain the same range of impact parameters for the study of the energy dependence of central collisions, the trigger bias was adjusted to maintain a constant cross section of $\sigma_R = 180$ mb at all bombarding energies. The results for the mean multiplicities and their dispersions are summarized in Table I. $\langle Q\rangle$ is relatively constant above 800 MeV/u, below which a decrease in $\langle Q\rangle$ is observed, most likely due to an increase in cluster formation. The $\langle n_{\pi^-}\rangle$ are shown in Fig. 3 as a function of the c.m. energy per nucleon. A linear dependence of $\langle n_{\pi^-}\rangle$ with the c.m. energy is observed above 150 MeV/nucleon, which is a faster increase than observed in p-p collisions. A deviation from the linear behavior may be expected for the lowest energy point since effects of Fermi motion become important as the threshold energy is approached.

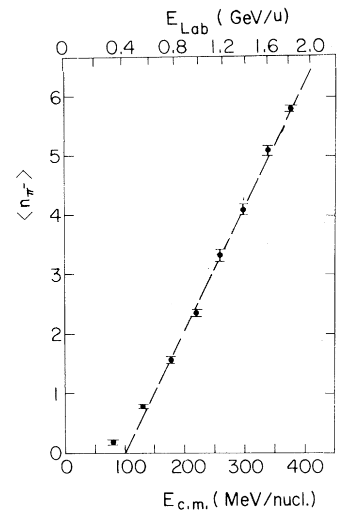

FIG. 3. Center-of-mass energy dependence of the mean negative-pion multiplicity $\langle n_{\pi^-}\rangle$ for central collisions of ^{40}Ar + KCl corresponding to a constant $\sigma_R = 180$ mb. Above 100 MeV/nucleon the data are fitted by a linear dependence on the c.m. energy as represented by the dashed line.

The firestreak model that assumes thermal and chemical equilibrium of mesons, nucleons, clusters, and isobars has been used to describe single-particle inclusive data[7] and π^- multiplicity distributions.[1] With use of the same parameters that best describe the inclusive p, d, and t data, this model overestimates the observed $\langle n_{\pi^-}\rangle$ for central collisions[16] by a factor of 2. When the results of a Fermi-gas model,[3] which assumes thermal but no chemical equilibrium for zero-

TABLE I. Energy dependence of the mean multiplicities and dispersions for participant protons (Q) and π^-'s in central collisions of Ar + KCl. The cross section corresponding to the central trigger mode is 180 mb.

E_{lab} (GeV/u)	$\langle Q\rangle$	D_Q	$\langle n_{\pi^-}\rangle$	D_{π^-}
0.360	23.16 ± 0.12	4.17 ± 0.07	0.20 ± 0.01	0.42 ± 0.09
0.556	25.97 ± 0.19	3.8 ± 0.12	0.79 ± 0.03	0.87 ± 0.09
0.772	26.94 ± 0.20	4.2 ± 0.10	1.58 ± 0.05	1.28 ± 0.07
0.977	29.30 ± 0.23	3.3 ± 0.10	2.35 ± 0.07	1.43 ± 0.06
1.180	29.13 ± 0.22	3.4 ± 0.14	3.34 ± 0.08	1.81 ± 0.06
1.385	28.2 ± 0.23	3.9 ± 0.13	4.10 ± 0.09	1.85 ± 0.05
1.609	28.2 ± 0.20	3.4 ± 0.08	5.09 ± 0.08	2.17 ± 0.05
1.808	28.0 ± 0.10	4.4 ± 0.05	5.79 ± 0.04	2.45 ± 0.03

impact-parameter Ar + Ar collisions, are scaled by the isobar-model $\pi^+:\pi^0:\pi^-$ ratios, the observed $\langle n_{\pi^-}\rangle$ and its energy dependence are fitted fairly well. However, this model does not take into account pion or isobar absorption. These are very important effects as shown by a recent relativistic Monte Carlo calculation,[6] in which the inclusion of the $\Delta + N \rightarrow N + N$ channel reduces the number of pions by 30–50%. When the results of this calculation for an isospin degenerate system are scaled to yield $\langle n_{\pi^-}\rangle$, the predictions are still 20% higher.

In summary, comprehensive information on exclusive π^- and charged-particle production now exists for inelastic and central collisions of a near-symmetric system, ^{40}Ar + KCl, in the incident energy range 0.4–1.8 GeV/u. The multiplicity distributions and the $\langle n_{\pi^-}\rangle$ exhibit a smooth and linear dependence on both the number of participants and the bombarding energy, with no discontinuities attributable to phase transitions. The dispersions of the n_{π^-} distributions are dominated by fluctuations in the number of pion-producing and -absorbing collisions rather than the elementary nucleon-nucleon process. Since $\langle n_{\pi^-}\rangle$ increases linearly with the number of participants and the bombarding energy, i.e., with the energy density, a thermal-model description seems appropriate. However, the firesteak model overpredicts the π^- multiplicities by a factor of 2. This leads one to question the validity of the assumed pion-production mechanism, namely chemical equilibrium. In a Monte Carlo calculation for relativistic heavy-ion interactions the inclusion of isobar absorption is needed to reproduce the pion multiplicities.

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