Negative-Pion Production in Relativistic Heavy-Ion Collisions

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(Received 8 August 1977)

Negative-pion production in relativistic heavy-ion collisions has been studied in a triggered streamer-chamber experiment with projectile nuclei ^{12}C and ^{40}Ar in the energy range 0.4–2.1 GeV/nucleon incident on targets LiH, NaF, BaI_2, and Pb_3O_4. Negative-pion yields, multiplicity distributions, and angular and momentum distributions are reported.

In the study of relativistic heavy-ion collisions, much interest has been focused on the production of pions. There are theoretical speculations[1-5] about the occurrence of exotic phenomena such as nuclear collective effects, shock waves, pion condensates, or quark-matter production which may involve pion production significantly greater than what is expected from an aggregate of individual nucleon-nucleon collisions. The study of pion production in heavy-ion collisions may also shed light on less exotic but equally important questions such as the multiple scattering and thermaization processes in nuclear matter.

We report the results of an experimental study of negative pion production using the Lawrence Berkeley Laboratory streamer chamber. The streamer chamber is particularly well suited for this kind of experiment because it can be selectively triggered, it has high efficiency for multitrack events over a 4π solid angle, and it can yield accurate angle and momentum information on all charged tracks. The chamber, which has a volume of 127 cm$\times$61 cm$\times$40.6 cm, was operated in a magnetic field of ~14 kG. The targets were located inside the chamber. They were typically quite thin (0.32 cm) in order to minimize effects due to multiple scattering and secondary interactions.

We present here results from twenty sets of runs with ^{40}Ar beams at 0.4, 0.9, and 1.8 GeV/nucleon, and ^{12}C beams at 0.4 and 2.1 GeV/nucleon, incident on targets of LiH, NaF, BaI_2, and Pb_3O_4. These targets, rather than pure elements, were chosen because they were compatible with the electrical operation of the chamber. Each run consists of ~2000 pictures where the chamber was trigered in the "inelastic mode," a trigger setting which rejects most noninteracting events but is relatively unbiased for inelastic events. This triggering mode, which will be described in more detail elsewhere, is based on pulse height in a counter inside the streamer chamber immediately downstream of the production target. It subtended an angle of 73.8 msr at the target. Whenever it had a pulse height smaller than that produced by a beam particle, we triggered the chamber. We estimate that this trigger condition causes us to lose no more than (10–15)% of the inelastic interactions. These lost events tend to leave the projectile almost intact and are most likely due to peripheral processes which involve small pion multiplicities. Consequently, our partial cross sections for the production of zero, one, and two pions are probably just slightly low.

Scanning for negative tracks yields predominantly negative pions. Contamination consists of electrons mainly from pair production. Most of these electrons are detected during scanning and the final overall electron contamination is estimated to be less than 1%. Measurement of the negative-pion tracks is carried out on standard Micrometric scanner-digitizer tables and the subsequent geometric reconstruction is performed using a modified version of TVGP. The use of thin targets enables us to extend the low-momentum cutoff of the observed pion spectrum to around 50 MeV/c.

We present, in Table I, the average negative-pion production $\langle N_{\pi^-}\rangle$ per (inelastic) interaction for the twenty runs. Also shown is the ratio of average negative-pion production $\langle N_{\pi^-}\rangle$ to average number of charged fragments $\langle N\rangle$. We observe that this ratio rises sharply as the incident energy increases, but that the ratio is roughly independent of the projectile or the target. A re-

TABLE I. Average number of negative pions produced per (inelastic) interaction, $\langle N_{\pi^-}\rangle$, and the ratio of average number of negative pions produced to the average number of charged fragments, $\langle N\rangle$, for twenty beam-target combinations.

Projectile	Projectile energy (GeV/nucleon)	LiH $\langle N_{\pi^-}\rangle$/int.	LiH $\langle N_{\pi^-}\rangle/\langle N\rangle$	NaF $\langle N_{\pi^-}\rangle$/int.	NaF $\langle N_{\pi^-}\rangle/\langle N\rangle$	BaI_2 $\langle N_{\pi^-}\rangle$/int.	BaI_2 $\langle N_{\pi^-}\rangle/\langle N\rangle$	Pb_3O_4 $\langle N_{\pi^-}\rangle$/int.	Pb_3O_4 $\langle N_{\pi^-}\rangle/\langle N\rangle$
^{40}Ar	0.4	0.043 ± 0.022	0.006 ± 0.003	0.034 ± 0.015	0.003 ± 0.001	0.107 ± 0.019	0.007 ± 0.001	0.099 ± 0.020	0.007 ± 0.001
	0.9	0.31 ± 0.04	0.033 ± 0.004	0.60 ± 0.09	0.044 ± 0.005	0.87 ± 0.09	0.045 ± 0.003	0.92 ± 0.88	0.045 ± 0.003
	1.8	0.97 ± 0.05	0.08 ± 0.003	1.91 ± 0.12	0.104 ± 0.004	3.27 ± 0.18	0.106 ± 0.003	3.27 ± 0.15	0.104 ± 0.002
^{12}C	0.4	0.02 ± 0.01	0.004 ± 0.002	0.038 ± 0.013	0.006 ± 0.002	0.078 ± 0.014	0.010 ± 0.002	0.066 ± 0.014	0.009 ± 0.002
	2.1	0.68 ± 0.07	0.095 ± 0.008	1.03 ± 0.08	0.108 ± 0.006	1.91 ± 0.17	0.110 ± 0.006	1.79 ± 0.16	0.101 ± 0.006

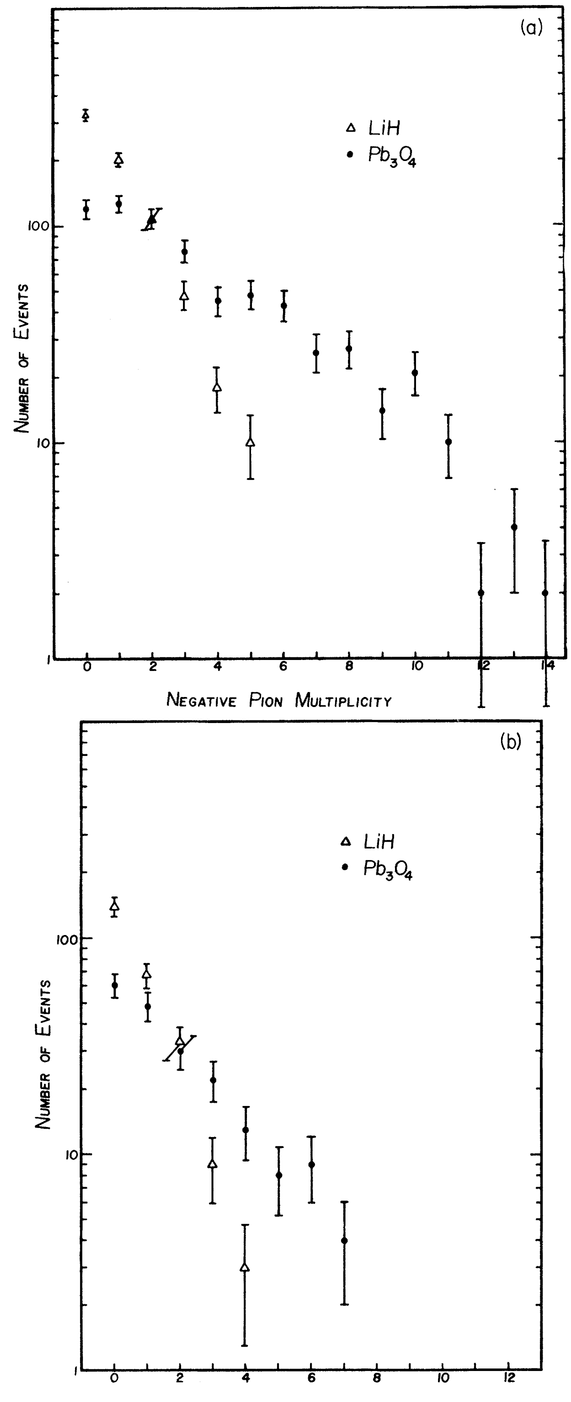

FIG. 1. Negative-pion multiplicity for (a) 1.8-GeV/nucleon ^{40}Ar and (b) 2.1-GeV/nucleon ^{12}C beams incident on LiH and Pb_3O_4.

cent emulsion study by McNulty *et al.*[6] reported the observation of copious pion production for heavy-ion collisions in the energy range of 275 MeV/nucleon and below. Our far lower π^- production observed at higher energy (400 MeV/nucleon) is difficult to reconcile with their result.

Negative-pion multiplicity distributions for four high-energy runs are presented in Fig. 1: ^{40}Ar incident on LiH and Pb_3O_4 targets at 1.8 GeV/nucleon in Fig. 1(a), and ^{12}C incident on the same targets at 2.1 GeV/nucleon in Fig. 1(b). In Figs. 2(a) and 2(b) we present two-dimensional scatter plots in the momentum-cosθ plane and their projections: histograms of the transverse and total momenta as well as angular distributions for the produced negative pions.

We note the following qualitative features in our data: (1) The $p_\perp$ distribution of the produced pions is independent of pion multiplicity. (2) The momentum (or energy) distribution is independent of pion multiplicity. (3) The pion multiplicity tends to be proportional to the total multiplicity of all charged particles with a proportionality constant which depends on bombarding energy. This constant is the same as that given in Table I for the ratio $\langle N_{\pi^-}\rangle/\langle N\rangle$. (4) When the data in Fig. 1 are replotted in terms of the variables $\langle N_{\pi^-}\rangle\sigma_{N_{\pi^-}}/\sigma_{\text{inel}}$ vs $N_{\pi^-}/\langle N_{\pi^-}\rangle$, the observed distributions are quite similar for all target/projectile combinations at all but the lowest bombarding energies (see Fig. 3). (5) The pion momentum distributions observed in this experiments of Nagamiya *et al.*[7] in those kinematical domains where comparisons are possible. (6) The recently reported pion multiplicity distributions of Jakobsson *et al.*[8] do not agree very well with the results reported here. (7) It is difficult to make meaningful comparisons between our data and those of the recent higher-energy experiments involving pion production by 18-GeV α particles on various nuclear targets reported by Baldin.[9] Our multiplicity distributions have more low-multiplicity events than are observed in those experiments when the average multiplicites are the same. However, in our experiment the energies are sufficiently low that kinematic threshold effects may be important. The dependence of our multiplicity distributions on the atomic numbers of projectile and target does not seem to have any of the simple forms suggested by Bialas, Bleszynski, and Czyz[10] using the concept of "wounded" nucleons. Here again kinematic and reabsorption effects may be important.

Theoretical attempts to explain pion production in nucleus-nucleus collisions have just started

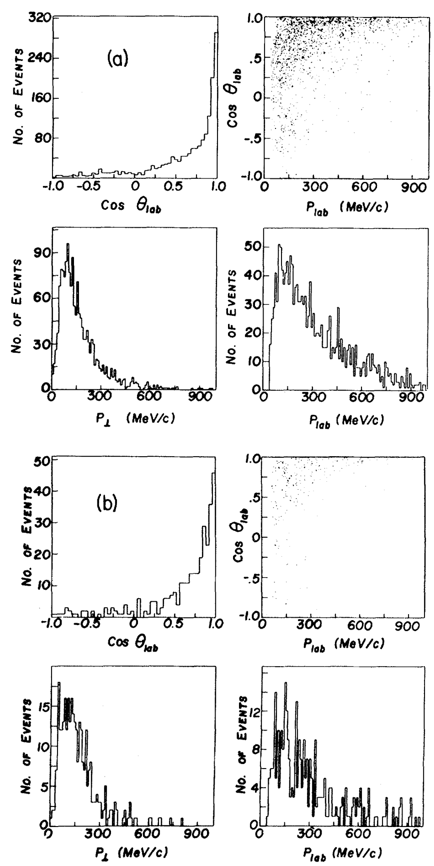

FIG. 2. Momentum and angular distributions of negative pions in the laboratory system for (a) 1.8-GeV/nucleon ^{40}Ar and (b) 2.1-GeV/nucleon ^{12}C inident on Pb_3O_4: cosθ vs total momentum with projections, together with transverse momentum.

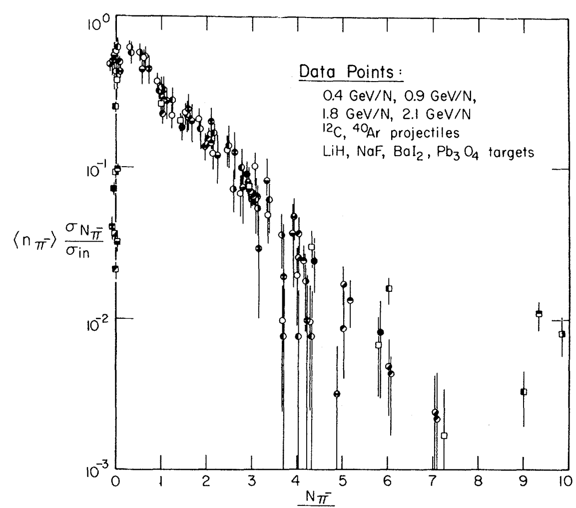

FIG. 3. Plot of $\langle n_{\pi^-}\rangle\sigma_{N_{\pi^-}}/\sigma_{\text{inel}}$ vs $N_{\pi^-}/\langle n_{\pi^-}\rangle$ on multiplicity distribution of negative pions in twenty beam-target combinations.

to be made; e.g., see the following papers by Vary,[11] and Kauffmann and Gyulassy.[12] It is our hope that the experimental data presented here will stimulate further theoretical activity and will provide useful new information for the development of meaningful theoretical models.

We wish to express our gratitude to the Bevalac staff, and in particular to James P. Brannigan for his untiring efforts to make the Lawrence Berkely Laboratory streamer chamber a reliable facility. We are grateful to the scanning staff at the University of California, Riverside. This work was supported by the U. S. Department of Energy.

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Multiple-Collision Model for Pion Production in Relativistic Nucleus-Nucleus Collisions

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A simple model for pion production in relativistic heavy-ion collisions is developed based on nucleon-nucleon data, nuclear density distribution, and the assumption of straight-line trajectories. Multiplicity distributions for total pion production and for negative-pion production are predicted for ^{40}Ar incident on a Pb_3O_4 target at 1.8 GeV/nucleon. Production through intermediate baryon resonances reduces the high-multiplicity region but insufficiently to yield agreement with data. This implies the need for a coherent production mechanism.

Considerable speculation has appeared suggesting that novel phenomena may be found in relativistic nucleus-nucleus collisions.[1] The possible detection of nuclear shock waves or new condensate states of hadronic matter are two notable examples. Such speculation is unfettered by any detailed knowledge of the nuclear equation of state at densities beyond saturation density. Critical experimental tests of these speculations have not been proposed and universally accepted but it should be clear that the results must deviate from a simple multiple-collision analysis in order to be conclusive.

Since a full treatment of internuclear cascades will involve substantial numerical work by computer, it is important to have approximate estimates which strive for an analytic framework. It should then be possible to focus the experimental and theoretical effort rapidly on specific types of measurements. Therefore, we present a simple multiple-collision model (MCM) and extract the pion production spectra which are then compared with experiment in order to look for "unusual," i.e., nonsimple features in the data. We also introduce a saturation mechanism, production through baryon resonances, which inhibits pion production, but find it, by itself, to be an inadequate explanation of the data. We then argue