Subthreshold Pion Production with Associated Multiplicity Selection in the Reaction $^{139}La + ^{139}La \rightarrow \pi^{\pm} + X$

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(Received 16 March 1987)

We have measured the energy and angular dependence of charged-pion production, with associated multiplicity selection, in La+La collisions at 138, 183, and 246 MeV/nucleon. The pions are produced mainly in collisions with a large number of participants. The general behavior of the spectra is consistent with results at higher energies, but the yield of subthreshold pions depends much more strongly upon the target and projectile mass. The pion spectra at 246 MeV/nucleon exhibit a strong charge dependence.

PACS numbers: 25.70.Np

In recent years a great deal of experimental[1-10] and theoretical[11] attention has been devoted to the study of pion production in collisions of heavy ions with beam energies per nucleon below the free nucleon-nucleon (*NN*) threshold of about 290 MeV. One goal of these studies has been to identify and study ways in which nucleons might act collectively in the hot, dense matter formed in the interaction region of two colliding nuclei. While Fermi motion allows pion production via binary *NN* collisions to proceed at beam energies per nucleon well below the free-nucleon threshold,[12] both experiment and theory[13] indicate a role for more collective effects. For example, production (in binary processes) of pions of the highest observed momenta requires either very large Fermi momenta or a large number of *NN* scatterings.[4,9] In addition, significant pion production has recently been reported[10] at beam energies near the absolute threshold, where the kinetic energy of almost all the incident nucleons must be pooled to produce a single pion.

Interestingly, while it is quite possible that different processes dominate pion production at low and high beam energies, the differences have not been directly reflected in the pion spectra, which exhibit consistent behavior over a range of beam energies above and below threshold[1-10,14]: Cross sections fall roughly exponentially with pion energy and inclusive yields monotonically decrease with beam energy and with target and projectile mass. However, the conclusions of previous experiments have been limited by the fact that generally only light projectiles have been used and only inclusive, impact-parameter–averaged data have been taken.

In an earlier experiment,[9] we made the first measurements of subthreshold pion production in a heavy system. Here we report on a more comprehensive study of such production; in particular, we have for the first time made use of multiplicity selection to gain insight into the reaction dynamics of subthreshold pion production. Spectra for positive and negative pions at $T^{\pi}_{\mathrm{c.m.}} \simeq 30$–$275$ MeV and $30° \leq \theta_{\mathrm{c.m.}} \leq 90°$ were obtained at beam energies of 138, 183, and 246 MeV/nucleon (MeV/N) for ^{139}La + ^{139}La and 244 MeV/N for ^{20}Ne+NaF. These energies were chosen to cover the region where a transition from primarily nucleon-nucleon to more collective effects might be expected to occur, and to complement previous Ne+NaF data,[3] with the idea that the sevenfold increase in mass of the target and projectile might increase the probability for such effects.

The experiment was carried out at the Lawrence Berkeley Laboratory Bevalac with the Beam 30-2 single-armed magnetic spectrometer, which has been described elsewhere.[14] For this experiment, several modifications and additions were made, including an additional multiwire proportional chamber and increased segmentation of the downstream scintillation hodoscope for improved track reconstruction. The most significant additions were a 110-element scintillator multiplicity array of roughly cylindrical geometry centered around the beam axis, and an adjustable copper absorber located before the last scintillator hodoscope. The absorber was used in the measurement of positive pions to suppress triggers

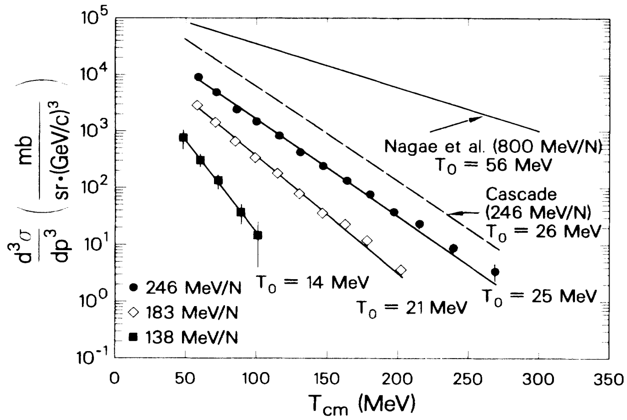

FIG. 1. Inclusive cross section $d^3\sigma/dp^3$ vs pion kinetic energy in the center-of-mass system for the reaction $^{139}La + ^{139}La \rightarrow \pi^- + X$ at $\theta_{c.m.} = 90°$ and $T_{beam} = 138$, 183, 246, and 800 MeV/N. The slope parameters T_0 are extracted from a fit by $A\exp(-T/T_0)$. The 800-MeV/N data are presented in the form of a fit to the data of Ref. 15. The dashed line is a fit by the results of a cascade calculation at 246 MeV/N, as described in the text.

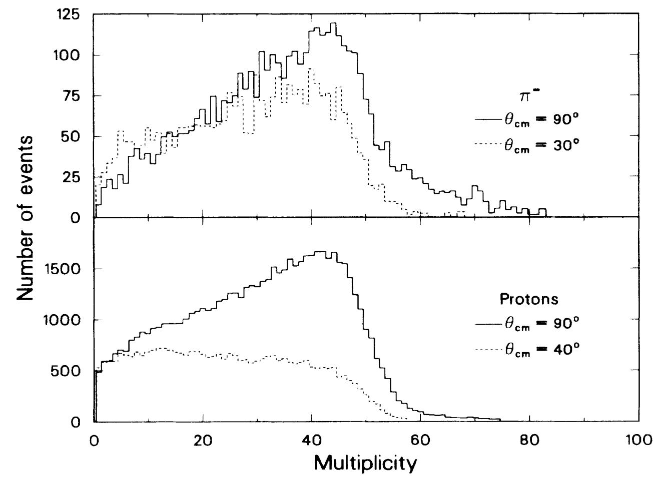

FIG. 2. Number of events vs associated charged-particle multiplicity for negative pions and protons produced at two different angles in 246-MeV/N La+La collisions.

due to light nuclear fragments, which would otherwise have dominated the pion signal to an unacceptable degree. Its effect on pions was studied by comparison of spectra for negative pions taken with and without the absorber, and was found to be negligible. The data have been corrected for electromagnetic and nuclear interactions in the target and the detector, and for pion decay in flight. The overall uncertainty in the cross sections is estimated to be about 25%.

Figure 1 shows the cross section $d^3\sigma/dp^3$ for inclusive production of negative pions in La+La collisions at $\theta_{c.m.} = 90°$ for three beam energies. Included for comparison is a fit to π^- data for the same system at 800 MeV/N.[15] The cross sections fall approximately exponentially over several orders of magnitude. The shape of the spectra and the dependence of the slope and yield upon beam energy are consistent with trends observed at both higher and lower energies for lighter systems.[1-10,14] The results of an intranuclear cascade calculation[16] for the 246-MeV/N π^- spectra are also shown. This cascade code, in which pions are produced only in binary nucleon-nucleon collisions through the Δ isobar, reproduces the slope but consistently overestimates the yield, as is also the case at higher beam energies.[17]

The multiplicity distributions associated with negative pions produced at $\theta_{c.m.} = 90°$ and 30° and with protons produced at 90° and 40° in 246-MeV/N collisions are shown in Fig. 2. At $\theta_{c.m.} = 90°$ the pion- and proton-associated multiplicity distributions are both seen to be strongly peaked at high multiplicity. This is indicative of a large number of participant nucleons, i.e., a relatively central collision. At more forward angles, however, the proton-associated multiplicities are shifted to much lower values, suggestive of a more peripheral collision, while those for pions still show a significant central component. The π^+-associated multiplicity distributions are similar to those for π^-, and the associated multiplicity distributions for both pions and protons are reproduced by the cascade code. Although the applicability of the cascade to energies below 250 MeV/N is uncertain,[18] its ability to replicate several features of the data below but near the pion threshold indicates that binary processes are still important in this region.

The π^- inclusive spectra from 246-MeV/N La+La collisions are summarized in Fig. 3(a). The angular distribution is isotropic, with the exception of the $\theta_{c.m.} = 30°$ spectrum. Figure 3(b) shows these spectra after multi-

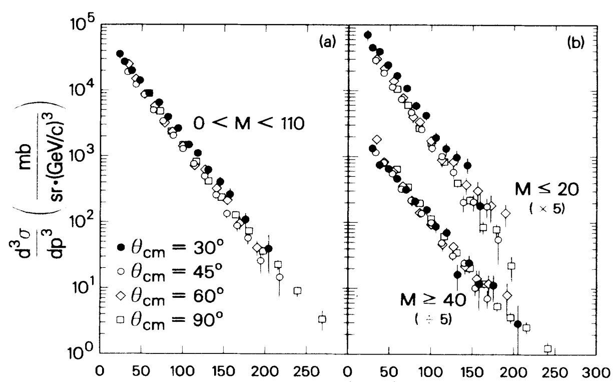

FIG. 3. (a) Inclusive cross sections for negative pions produced at $30° \leq \theta_{c.m.} \leq 90°$ in 246-MeV/N La+La collisions. (b) Same as (a), selected on associated multiplicities $M \leq 20$ and $M \geq 40$. For clarity, the cross sections for $M \leq 20$ have been multiplied by 5 before plotting, and those for $M \geq 40$ have been divided by 5.

plicity selection; spectra cut on $M \leq 20$ show the enhancement at 30°, while those cut on $M \geq 40$ are nearly isotropic. These results suggest that there are two contributions to the pion yield: a component emitted at forward angles in low-multiplicity (presumably peripheral) collisions, superimposed on a component, produced in high-multiplicity collisions, which is isotropically distributed and comprises the majority of the observed yield. The general isotropy implies pion emission from a single source, at rest in the center-of-mass system. The spectra in Fig. 3(b) also show a slight variation in slope parameter with multiplicity. In a simple thermal model, the higher slope parameter of the spectra cut on $M \geq 40$ corresponds to a higher temperature.

Figure 4 shows our π^+ inclusive cross sections at 246 MeV/N, along with a fit to the π^- spectra, for comparison. The π^+ angular distribution is isotropic, within statistics. Two striking features of the data are (i) the turnover in the π^+ spectra at low pion energies and (ii) the trend in the ratio $R(\pi^-/\pi^+)$ towards unity at higher pion energies, despite the large neutron excess in the target and projectile. Neither feature is sensitive to cuts on multiplicity.

Charge dependence of subthreshold pion spectra has previously been observed[1,2,5,6] in collisions of light nuclei ($Z_{tgt}+Z_{proj} \leq 40$), and could be expected to be significant in La+La collisions ($Z_{tgt}+Z_{proj}=14$). Two possible, and perhaps complementary, explanations for such dependence are Coulomb distortion of the spectra and pion reabsorption. Kitazoe *et al.*[19] have calculated the effect of pion reabsorption in a cascade model, and find that it increases the π^-/π^+ ratio in collisions of heavy nuclei at MeV/N. Additional calculations will be needed to determine the influence of reabsorption on pions produced in lower-energy collisions.

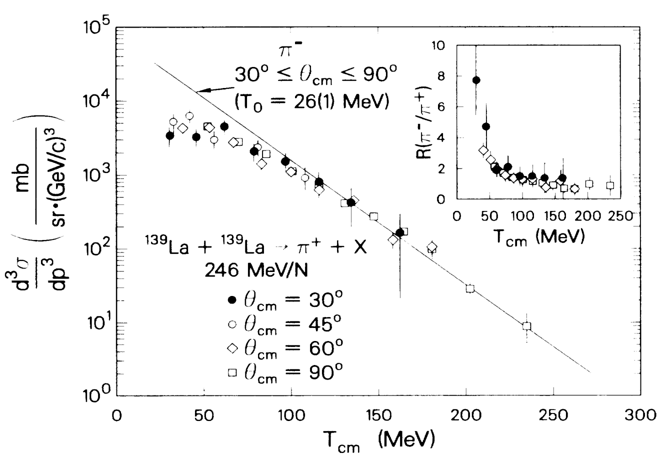

FIG. 4. Inclusive cross sections for positive pions at $30° \leq \theta_{c.m.} \leq 90°$ in 246-MeV/N La+La collisions. The solid line is an overall fit to the π^- cross sections in Fig. 3(a). Inset: Ratio of π^- to π^+ cross sections for $\theta_{c.m.} = 30°$, 60°, and 90° vs pion kinetic energy in the center-of-mass frame.

Coulomb distortion of charged-particle spectra has been investigated theoretically by several authors,[20,21] and the spectra for forward-angle pions from collisions of Ne+NaF have been explained as being due to distortion by the projectile fragments.[2] Charge dependence of the pion spectra in kinematic regions away from that of the projectile has been observed[5,6] at both 0° and $\theta_{lab}=90°$ in collisions of $^{12}C+^{12}C$. In our data, the turnover in the positive-pion spectra persists at angles well removed from the projectile, in contrast to the data of Ref. 2, where the effect is strongly suppressed for $\theta_{lab} > 4°$. Furthermore, the associated multiplicity distributions (see Fig. 2) indicate a large number of participants. Applying the methods of Ref. 21, we find that the simple assumption of an expanding, spherically symmetric charge distribution, coincident with the pion source and containing 25%–50% of the available charge, reproduces the ratio $R(\pi^-/\pi^+)$ for $T^{\pi}_{c.m.} > 75$ MeV. At lower pion energies, the theory correctly predicts the sharp increase in R, but the calculated ratio is a factor of 2 to 5 lower than the data. In fact, the value of R for $T^{\pi}_{c.m.} < 75$ MeV is not reproduced by a single source of any reasonable charge. This suggests that, if the observed charge dependence of the pion spectra is due to the Coulomb field of the reaction products, then the dependence is relatively complicated, and a detailed unfolding of it could give insight into the space and time structure of the pion production process.

The charged-pion spectra which we measured at beam energies of 138 and 183 MeV/N follow the trends in shape, slope, yield, and associated multiplicity observed at higher energies, although information on the angular and multiplicity dependence is limited by low statistics. However, by combining our data with that of Nagamiya *et al.*[4,14] and Nagae *et al.*[15] we can study the mass and energy dependence of π^- production in the La+La and Ne+NaF systems at beam energies of 183, 246, and 800 MeV/N. At each beam energy, the slope parameters for the light- and heavy-mass systems are found to be equal within 10%. However, we find that the dependence of the pion yield upon the target and projectile mass increases greatly, below threshold. The ratio of π^- yields for La+La versus Ne+NaF increases by less than a factor of 2 as the beam energy is reduced by 554 MeV/N (from 800 to 246 MeV/N). When the beam energy is further reduced by only 63 MeV/N (from 246 to 183 MeV/N), the ratio of yields more than triples. This may signal the onset of collective effects, but more conclusive studies, over a wider range of energies and masses, are required.

To summarize, we have measured spectra of pions produced in collisions of $^{139}La+^{139}La$ at several beam energies below pion threshold. We find that subthreshold pions emitted at $30° \leq \theta_{c.m.} \leq 90°$ come predominantly from a single source, at rest in the center-of-mass system and involving a large number of participant nucleons. The spectra are qualitatively consistent with data for lighter systems at both higher and lower beam energies, but the mass dependence of the pion yield increases sharply, below threshold. We find evidence of distortion of the charged-pion spectra, which may be interpreted as arising from the strong Coulomb fields present during the collision. A detailed analysis of such distortions holds promise as a probe of the interaction region.

We would like to thank O. Hashimoto, T. Kobayashi, S. Nagamiya, I. Tanihata, and their co-workers for their collaboration in the construction of the multiplicity array and their assistance during the data taking, and for allowing us to use some of their results prior to publication. We also thank the Bevalac engineering and operations staff for their excellent support throughout the preparation and running of the experiment. This work was supported by the Director, Office of Energy Research, Division of Nuclear Physics of the Office of High Energy and Nuclear Physics of the U. S. Department of Energy under Contracts No. DE-AC03-76SF00098 and No. DE-AS05-76ER04699 and by the National Science Foundation under Grant No. PHY83-12245.

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