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Mass dependence of pion production in heavy ion collisions near, but below threshold

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We have measured the inclusive cross section for production of negative pions near mid-rapidity in ^{20}Ne + NaF, ^{139}La + ^{139}La and ^{197}Au + ^{197}Au collisions at E = 183 and 236 MeV/u. Au + Au is the heaviest system from which subthreshold pion production has been measured to date. The dependence of the pion cross section on pion energy, beam energy and associated charged particle multiplicity is consistent with previous results both above and below threshold. The dependence of the cross section on the mass of the colliding system varies only slightly as the beam energy is reduced below threshold, in contrast to some previous measurements. Comparison with theory suggests that at these energies the pion production process is still dominated by nucleon-nucleon collisions.

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Subthreshold pion production in heavy ion collisions has been studied extensively, with the idea that observables associated with pion production below threshold might be sensitive to a change in the dominant reaction mechanism from nucleon–nucleon to collective at sufficiently low collision energies. The general approach has been to look for changes in the systematics of pion production as the beam energy was lowered and the number of colliding nucleons increased. The experiments done thus far are for the most part grouped into two classes: those employing light projectiles at low energies ($T_{\text{beam}} \lesssim 100$ MeV/u, $A_{\text{beam}} \lesssim 20$) [1,2] and those using heavier projectiles at higher energies ($T_{\text{beam}} \gtrsim 150$ MeV/u, $A_{\text{beam}} \gtrsim 20$) [3–7].

Data for beam energies as low as 60 MeV/u are adequately explained by nucleon–nucleon or statistical models [2]. Bertsch [8] has calculated an approximate threshold of 54 MeV/u for nucleon–nucleon pion production, due to phase space constraints, and results for the lowest beam energies are consistent with a collective production mechanism (see, e.g., ref. [9]). For pions produced near but below the 290 MeV/u nucleon–nucleon threshold, spectra have for the most part been found to behave in much the same way as spectra taken above threshold. This is not unexpected, since in nucleus–nucleus collisions Fermi-boosted nucleon–nucleon interactions contribute strongly to pion production at collision energies well below 290 MeV/u. Under these circumstances, for collective production mechanisms to have a measurable effect probably requires specific conditions, such as a heavy colliding system or small impact parameter, or both. With this in mind, in a previous publication [7] data from several different experiments were combined in an attempt to extract the dependence of mid-rapidity pion production on system mass.

The ratio of the cross sections of mid-rapidity negative pions from La + La and Ne + NaF collisions was determined by combining independently normalized measurements taken several years apart, albeit under similar conditions [5,7,10,11]. The combined data consist of the differential pion cross section, $d\sigma/d\Omega$, for pions produced at $\theta_{\text{cm}} \simeq 90°$ in La + La and Ne + NaF collisions at three beam energies, $E = 800, 246$ and 183 MeV/u. When the ratio of cross sections from the heavy and light systems was calculated, the ratio at $E = 246$ MeV/u was found to be approximately the same as that at 800 MeV/u, but the ratio at $E = 183$ MeV/u was found to be greater by a factor of almost four.

However, since the data at $E = 183$ MeV/u were obtained in different experiments, we undertook to measure, in a single experiment, subthreshold pion production in several symmetric projectile–target combinations, extending to the heaviest feasible symmetric system, where the large number of colliding nucleons should enhance the probability of collective effects. The main goal was to establish the mass scaling behavior of the subthreshold pion yield as a function of beam energy down to 183 MeV/u – which is more than 100 MeV/u below threshold – and over an order of magnitude variation in the mass of the colliding systems. All data were taken during the same running period, to reduce the likelihood of systematic errors in the relative normalization.

The experimental apparatus at the Lawrence Berkeley Laboratory Bevalac is described in detail in ref. [12]. It consisted of a single arm magnetic spectrometer with an azimuthally-symmetric scintillator multiplicity array surrounding the beam pipe and subtending laboratory angles between 10 and 90 degrees. Essentially the same apparatus was used to obtain the data in refs. [5,7,10,11]. Data were taken for negative pions produced in collisions involving the following symmetric systems: ^{20}Ne + NaF, ^{139}La + ^{139}La and ^{197}Au + ^{197}Au. Target thicknesses were 0.251 gm/cm^2 Au, 0.391 gm/cm^2 La and 0.377 gm/cm^2 NaF. The energies of the extracted beams were chosen such that the beam energy per nucleon at one half the target depth was approximately the same for each beam–target combination. The beam intensity was monitored by means of an in-beam ionization chamber. The ionization chamber was calibrated by ^{12}C activation [13] for the neon beam at $E = 800$ MeV/u; for the other beams this value was scaled according to the stopping power for each beam. Based on calibration data for an ionization chamber of similar design for D, He, C, Ca and Nb beams at 1 GeV/nucleon [14], we estimate the uncertainty in the beam normalization to be ±25%.

For this experiment, data were taken at a fixed laboratory angle of 60°; with angular and energy acceptance taken into account, this corresponds to center of mass angles of 80° ± 5° at $E = 183$ MeV/u and

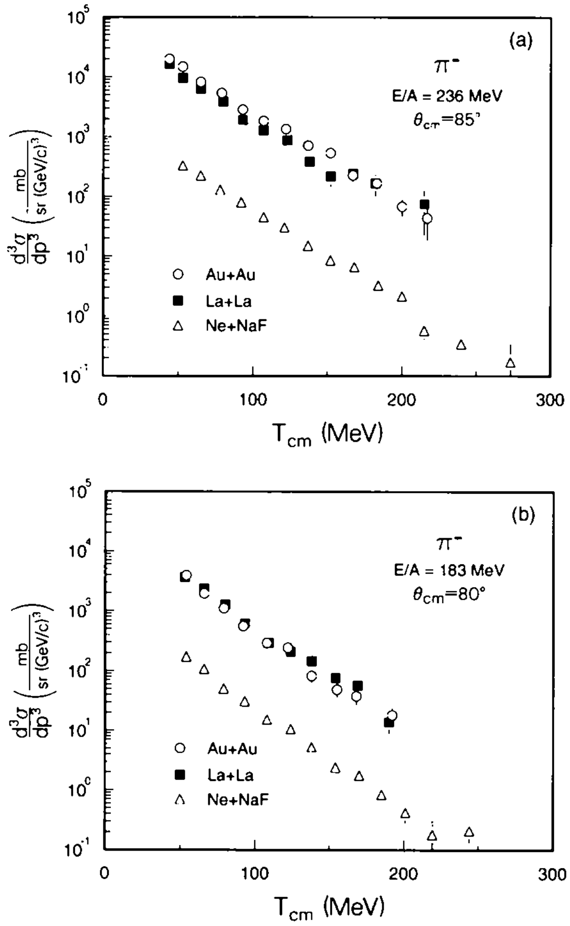

Fig. 1. Inclusive cross section $d^3\sigma/dp^3$ versus pion kinetic energy in the center of mass for the reactions ^{20}Ne + NaF $\to \pi^-$ + X, ^{139}La+^{139}La$\to$ π^- + X and ^{197}Au+^{197}Au$\to$ π^- + X at $\theta_{cm} \simeq 80° - 90°$. (a) E = 236 MeV/u. (b) E = 183 MeV/u.

85° ± 5° at E = 236 MeV/u. In an earlier measurement [7] it was shown that subthreshold pion production at these energies is approximately isotropic between 45° and 90° in the c.m.

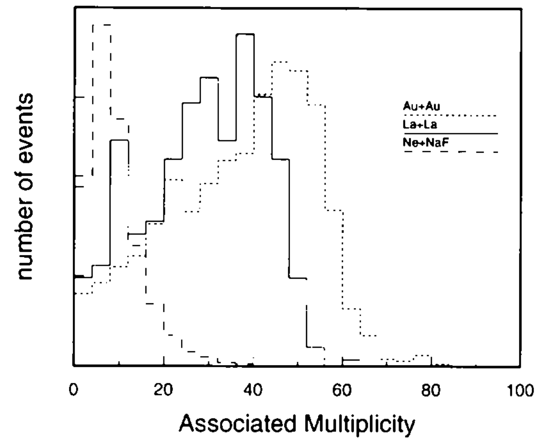

Fig. 2. Associated charged particle multiplicity per event for π^- produced at mid-rapidity in Ne + NaF (dots), La + La (dashes) and Au + Au (solid line) collisions at E = 236 MeV/u. The units in the ordinate are arbitrary.

Figs. 1a and 1b show the cross section, $d^3\sigma/dp^3$, for inclusive production of negative pions produced near mid-rapidity for all three systems at the two beam energies. The cross section has an exponential dependence on pion energy which is typical of pion production both above and below threshold. In the framework of thermal models [15], the inverse slope of the exponential distribution can be identified with the temperature of a thermalized pion source. Experimentally, the inverse slope increases with increasing beam energy, but at a fixed beam energy is independent of system mass over about an order of magnitude change in the mass. The pion cross section falls with both decreasing beam energy and decreasing system mass. The approximate equality of the cross section from La + La and Au + Au collisions at E = 183 MeV/u is somewhat surprising, since from a simple mass scaling one would expect the Au + Au cross section to be about 50% greater, as it is at E = 236 MeV/u, but this is within the systematic uncertainty. The dependence of the pion cross section on system mass will be discussed in more detail, below.

The associated multiplicity distributions for the three systems at E = 236 MeV/u are shown in fig. 2. These distributions are consistent with the previous observation [7] that at these beam energies, mid-rapidity pions are produced predominantly in high-multiplicity collisions. As discussed in refs. [7,12], the associated multiplicities are reproduced rather well by an intranuclear cascade calculation: high associated multiplicities are strongly correlated with small impact parameter collisions, and low multiplicities with large impact parameter collisions. The multiplicity scales with the number of colliding protons, in each case peaking at about 32% of the total system charge for E = 236 MeV/u and 27% of the total charge for E = 183 MeV/u. (The high multi-

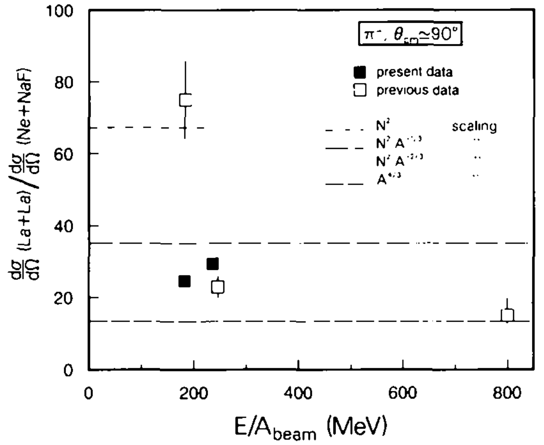

Fig. 3. Ratio of the cross section, $d\sigma/d\Omega$, of π^- produced near mid-rapidity from La + La and Ne + NaF collisions, as a function of beam energy. Open squares: old data. Filled squares: new data. The horizontal lines show the values of the ratio expected from several different mass and neutron number scaling rules: Long dashes: pure surface production ($A^{4/3}$). Dots: geometric, with one nucleus weighted by neutron number ($N^2 \cdot A^{-2/3}$). Dot-dashes: geometric, with both nuclei weighted by neutron number ($N^2 \cdot A^{-1/3}$). Short dashes: neutron number-weighted volume dependence (N^2).

plicity tail in the multiplicity from Ne + NaF collisions is due to a small pile-up effect at the higher beam intensities used for neon.)

We turn now to the second motivation of this experiment, the determination of the mass scaling of the subthreshold pion yield as a function of beam energy. For each colliding system at each beam energy, the cross section was calculated directly from the number of detected pions, normalized to the detector acceptance, target thickness and number of incident ions. Fig. 3 summarizes the results. The filled squares represent the most recent data and the open squares the values obtained by folding together data for La + La and Ne + NaF from several previous, independently normalized measurements [5,7,11]. The dashed and dotted lines represent the values expected from several simple scaling rules; the neutron weighting reflects the strong isospin dependence of π^- production [12,16,17]. Any mass dependence of pion absorption is neglected. The yield ratios for Au + Au versus Ne + NaF (not plotted) are 23.2 ± 0.8 (E = 183 MeV/u) and 42.9 ± 1.3 (E = 236 MeV/u). For

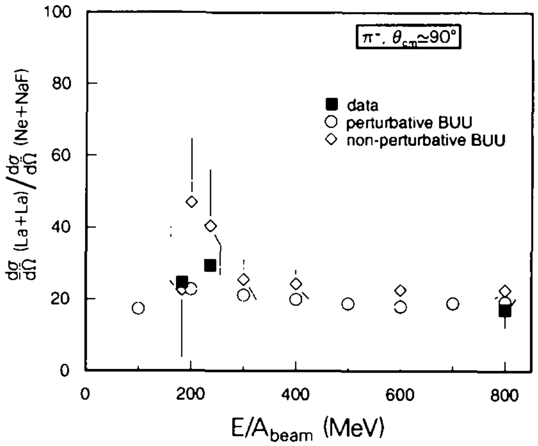

Fig. 4. Comparison between pion yield ratios from experiment (filled squares) and from two BUU calculations: perturbative (open circles) and non-perturbative (diamonds).

Au + Au versus La + La, the ratios are 0.95 ± 0.04 and 1.46 ± 0.08, respectively. In each case, as the beam energy is decreased from E = 236 to 183 MeV/u, the ratio of mid-rapidity pion cross sections from the heavy and light colliding systems falls rather than rises, as was found previously.

What is the source of the discrepancy between the two data sets? For Ne + NaF and La + La at E = 236 MeV/u and from La + La at E = 183 MeV/u the cross sections from the present experiment and from ref. [7] are equal within uncertainty; the difference in the ratios arises in a factor of 3.5 difference in the π^- yield from Ne + NaF collisions at E = 183 MeV/u between the most recent data and those reported in ref. [5], most probably due to an error in the normalization of the earlier data [18].

In fig. 4 we compare the data with the results of two calculations based on the nuclear Boltzmann–Uehling–Uhlenbeck (BUU) equation. In the non-perturbative BUU [19], delta resonances and pions are produced with their experimentally measured free cross sections, propagated in medium, possibly rescattered and absorbed. However, close to threshold the number of produced pions decreases rapidly, and thus the statistical errors in the calculations become very large. The perturbative approach to particle production [20,21] eliminates this problem. Here every nucleon–nucleon collision contributes probabilistically to the total production cross section. The

Table 1

System	E/A (beam)	$d\sigma/d\Omega$ (mb/sr)	
	(MeV)	Experiment	BUU (Pert.)
Ne + NaF	183	0.201 (0.004)	0.08 (0.06)
	236	0.480 (0.008)	0.23 (0.08)
La + La	183	4.5 (0.2)	1.8 (0.7)
	236	13.6 (0.8)	9.3 (2.8)
Au + Au	183	4.1 (0.2)	2.87 (0.20)
	236	19.6 (0.6)	17.2 (4.3)

contributions of all nucleon–nucleon collisions at a given impact parameter are summed, and the results integrated over impact parameter. The shortcoming of this approach is that one has to rely on a mean absorption length for pions, instead of being able to compute pion absorption directly from detailed balance as is done in the non-perturbative approach.

Agreement between calculated and experimental spectra is good both well below [21] and well above [19] threshold. In both calculations the theoretical yield ratios follow the trend in the data. The fall-off in the ratio below threshold is a reflection of the dependence of the phase space density on the beam energy and the number of colliding nucleons. The energy dependence of the yield ratios is consistent with a predominantly nucleon–nucleon production mechanism.

The calculated and measured pion cross sections integrated over pion kinetic energy between 50 and 250 MeV are tabulated in table 1. The non-perturbative BUU calculation consistently underpredicts the cross section by up to a factor of two, but the agreement is actually best for the two heavier systems, which argues against collective effects as the source of the discrepancy. The theoretical and experimental values of the cross section ratio for Au versus Ne and Au versus La have a beam energy dependence similar to that for La versus Ne.

To summarize, we have measured the cross section for production of mid-rapidity π^- as a function of beam energy and colliding system mass near but below threshold, and have found little difference in the systematics of pion production from what is observed above threshold. In particular, the system mass dependence was studied over an order of magnitude variation in atomic number, including the first measurements with the Au + Au system, and no evidence was found of a sharp change in the mass scaling of the pion yield, below threshold. The relative pion cross sections from different colliding systems are consistent with the predictions of a BUU calculation.

While it appears that nucleon–nucleon dynamics dominates pion production for beam energies down to at least 60 MeV/u, there are still no data in the region delimited by beam energies below 138 MeV/u and projectile $A > 20$. The lack of conclusive evidence of specific collective mechanisms in subthreshold pion production may be attributable to the fact that experiments with heavy beams, where collective effects might be favored, have thus far been limited to energies relatively close to the nucleon–nucleon threshold, where the signatures of collectivity may be lost in the incoherent background from binary collisions. Therefore, data for pion production from heavy projectile-target systems below 100 MeV/u should prove interesting: at very low energies, providing more insight into collective pion production mechanisms, and at higher energies, exploring the the transition from nucleon–nucleon to collective dynamics.

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References

[1] The numerous low energy subthreshold pion experiments done before 1987 are reviewed in: P. Braun-Munzinger and J. Stachel, Ann. Rev. Nucl. Part. Sci. 37 (1987) 97.
[2] A more recent review of subthreshold pion experiments at both low and high energies may be found in: T. Suzuki, Nucl. Phys. A538 (1992) 113c–120c.
[3] W. Benenson et al., Phys. Rev. Lett. 43 (1979) 683.
[4] J. Sullivan et al., Phys. Rev. C 25 (1982) 1499.
[5] S. Nagamiya et al., Phys. Rev. Lett. 48 (1982) 1780.
[6] G.F. Krebs et al., Phys. Lett. B 171 (1986) 37.

[7] J. Miller et al., Phys. Rev. Lett. 58 (1987) 2408; 59 (1987) 519 (E).
[8] G.F. Bertsch, Phys. Rev. C 15 (1977) 713.
[9] J. Stachel et al., Phys. Rev. C 33 (1986) 1420.
[10] S. Nagamiya et al., Phys. Rev. C 24 (1981) 971.
[11] S. Hayashi et al., Phys. Rev. C 38 (1988) 1229.
[12] J. Miller, Ph.D thesis, University of California, LBL Report 24275 (1988), unpublished.
[13] A.R. Smith et al., Phys. Rev. C 28 (1983) 1614; 38 (1988) 210.
[14] C.J. Naudet, private communication.
[15] G.D. Westfall et al., Phys. Rev. Lett. 37 (1976) 1202.
[16] M.M. Sternheim and R.R. Silbar, Phys. Rev. D 6 (1972) 3117.
[17] J. Sullivan, Ph.D thesis, University of California, LBL Report 12546 (1981), unpublished.
[18] S. Nagamiya, private communication.
[19] B.-A. Li and W. Bauer, Phys. Lett. B 254 (1991) 335; Phys. Rev. C 44 (1991) 450.
[20] W. Bauer, Phys. Rev. C 34 (1986) 2127.
[21] W. Bauer, Phys. Rev. C 40 (1989) 715.