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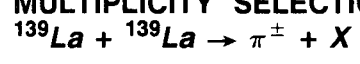
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## SUBTHRESHOLD PION PRODUCTION WITH ASSOCIATED MULTIPLICITY SELECTION IN THE REACTION

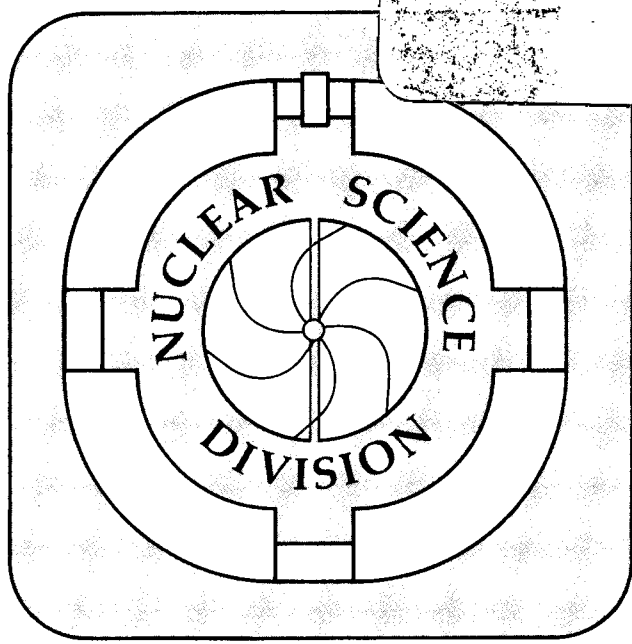


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Subthreshold Pion Production with Associated Multiplicity Selection in the  
Reaction  $^{139}\text{La} + ^{139}\text{La} \rightarrow \pi^{\pm} + X$

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Abstract: 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 behaviour 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. We find evidence for Coulomb distortion of the pion spectra.

PACS numbers: 25.70.Np

In recent years a great deal of experimental<sup>1-9</sup> and theoretical<sup>10</sup> 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,<sup>11</sup> both experiment and theory<sup>12</sup> 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.<sup>4,8</sup> In addition, significant pion production has recently been reported<sup>9</sup> 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.<sup>1-9,13</sup> 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,<sup>8</sup> 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  $T_{CM}^{\pi} \simeq 30 - 275$  MeV

and  $30^\circ \leq \theta_{CM} \leq 90^\circ$  were obtained at beam energies of 138, 183 and 246 MeV/nucleon (MeV/N) for  $^{139}\text{La} + ^{139}\text{La}$  and 244 MeV/N for  $^{20}\text{Ne} + \text{NaF}$ . 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,<sup>3</sup> with the idea that the seven-fold 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 using the Beam 30-2 single-armed magnetic spectrometer, which has been described elsewhere.<sup>13</sup> For this experiment, several modifications and additions were made, including an additional multi-wire 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 when measuring positive pions to suppress triggers due to light nuclear fragments, which would otherwise have dominated the pion signal to an unacceptable degree. Its effect on pions was studied by comparing 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%.

Fig. 1 shows the cross section,  $d^3\sigma/dp^3$ , for inclusive production of negative pions in La+La collisions at  $\theta_{CM} = 90^\circ$  for three beam energies. Included for comparison is a fit to  $\pi^-$  data for the same system at 800 MeV/N.<sup>14</sup> The cross sections fall approximately exponentially over several orders of magnitude. The shape of the spectra, and the dependence of slope and yield upon beam energy are consistent with trends observed at both higher and lower energies for lighter

systems.<sup>1-9,13</sup> The results of an intranuclear cascade calculation<sup>15</sup> for the 246 MeV/N  $\pi^-$  spectra are also shown. This cascade code, in which pions are produced only in binary nucleon-nucleon collisions through the  $\Delta$  isobar, reproduces the slope but consistently overestimates the yield, as is also the case at higher beam energies.<sup>16</sup>

The multiplicity distributions associated with negative pions produced at  $\theta_{\text{CM}} = 90^\circ$  and  $30^\circ$  and with protons produced at  $90^\circ$  and  $40^\circ$  in 246 MeV/N collisions are shown in Fig. 2. At  $\theta_{\text{CM}} = 90^\circ$  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  $\pi^+$  distributions are similar to those for  $\pi^-$ , and the distributions for both pions and protons are generally reproduced by the cascade code. Although the applicability of the cascade to energies below 250 MeV/N is uncertain,<sup>17</sup> 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  $\pi^-$  inclusive spectra from 246 MeV/N La+La collisions are summarized in Fig. 3a. The angular distribution is isotropic, with the exception of the  $\theta_{\text{CM}} = 30^\circ$  spectrum. Fig. 3b shows these spectra after multiplicity selection: spectra cut on  $M \leq 20$  show the enhancement at  $30^\circ$ , 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. The spectra in Fig. 3b 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.

Fig. 4 shows our  $\pi^+$  inclusive cross sections at 246 MeV/N, along with a fit to the  $\pi^-$  spectra, for comparison. The  $\pi^+$  angular distribution is isotropic, within statistics. Two striking features of the data are: (i) the turnover in the  $\pi^+$  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<sup>1,2,5,6</sup> in collisions of light nuclei ( $Z_{tgt} + Z_{proj} \leq 40$ ), and could be expected to be significant in La+La collisions ( $Z_{tgt} + Z_{proj} = 114$ ). Two possible, and perhaps complementary, explanations for such dependence are Coulomb distortion of the spectra and pion reabsorption. Kitazoe *et al.*<sup>18</sup> have calculated the effect of pion reabsorption in a cascade model, and find that it increases the  $\pi^-/\pi^+$  ratio in collisions of heavy nuclei at 800 MeV/N. Additional calculations will be needed to determine the influence of reabsorption on pions produced in lower energy collisions.

Coulomb distortion of charged particle spectra has been investigated theoretically by several authors,<sup>19,20</sup> and the spectra for forward angle pions from collisions of Ne+NaF have been explained as being due to distortion by the projectile fragments.<sup>2</sup> Charge dependence away from the influence of the projectile has been observed<sup>5,6</sup> at both  $0^\circ$  and  $\theta_{lab} = 90^\circ$  in collisions of  $^{12}\text{C} + ^{12}\text{C}$ . 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  $\theta_{lab} > 4^\circ$ . Furthermore, the associated multiplicity distributions (see Fig. 2) indicate a large number of participants. Applying the methods of



Ref. 20, we find that an expanding charge distribution, coincident with the pion source and containing 25% – 50% of the available charge, reproduces the ratio  $R(\pi^-/\pi^+)$  for  $T_{CM}^\pi > 75$  MeV. However, the value of  $R$  at lower pion energies is not reproduced by a single source of any reasonable charge.

Possible evidence of distortion due to projectile fragments is the enhancement in the  $\pi^-$  spectrum at  $\theta_{CM} = 30^\circ$  ( $\theta_{lab} \simeq 21^\circ$ ), as shown in Fig 3. Such a distortion would be most likely for pions emitted at forward angles in collisions with a substantial charge continuing at the beam velocity, hence low participant multiplicity, as observed in association with the enhancement at  $30^\circ$ .

It would appear that the spectra depend in a complicated way upon the Coulomb field of the reaction products. A detailed unfolding of this dependence 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.*<sup>4,13</sup> and Nagae *et al.*<sup>14</sup> we can study the mass and energy dependence of  $\pi^-$  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  $\pi^-$  yields for La+La vs. 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  $^{139}\text{La} + ^{139}\text{La}$  at several beam energies below pion threshold. We find that subthreshold pions emitted at  $30^\circ \leq \theta_{CM} \leq 90^\circ$  come predominantly from a single source, at rest in the center of mass 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 we interpret 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.

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- (c) Present address: ETH, CH-8093, Zürich, Switzerland.
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## Figure Captions:

Fig. 1—Inclusive cross section  $d^3\sigma/dp^3$  vs. pion kinetic energy in the center of mass for the reaction  $^{139}\text{La} + ^{139}\text{La} \rightarrow \pi^- + X$  at  $\theta_{CM} = 90^\circ$  and  $T_{beam} = 138, 183, 246$  and 800 MeV/N. The slope parameters,  $T_0$ , are extracted from a fit to  $Ae^{-T/T_0}$ . The 800 MeV/N data is presented in the form of a fit to the data of Ref. 14. The dashed line is a fit to 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.

Fig. 3—(a) Inclusive cross sections for negative pions produced at  $30^\circ \leq \theta_{CM} \leq 90^\circ$  in 246 MeV/N La+La collisions. (b) Same as Fig. 3a, 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.

Fig. 4—Inclusive cross sections for positive pions at  $30^\circ \leq \theta_{CM} \leq 90^\circ$  in 246 MeV/N La+La collisions. The solid line is an overall fit to the  $\pi^-$  cross sections in Fig. 3a. The inset shows the ratio of  $\pi^-$  to  $\pi^+$  cross sections for  $\theta_{CM} = 30^\circ, 60^\circ$  and  $90^\circ$ , vs. pion kinetic energy in the center of mass frame.

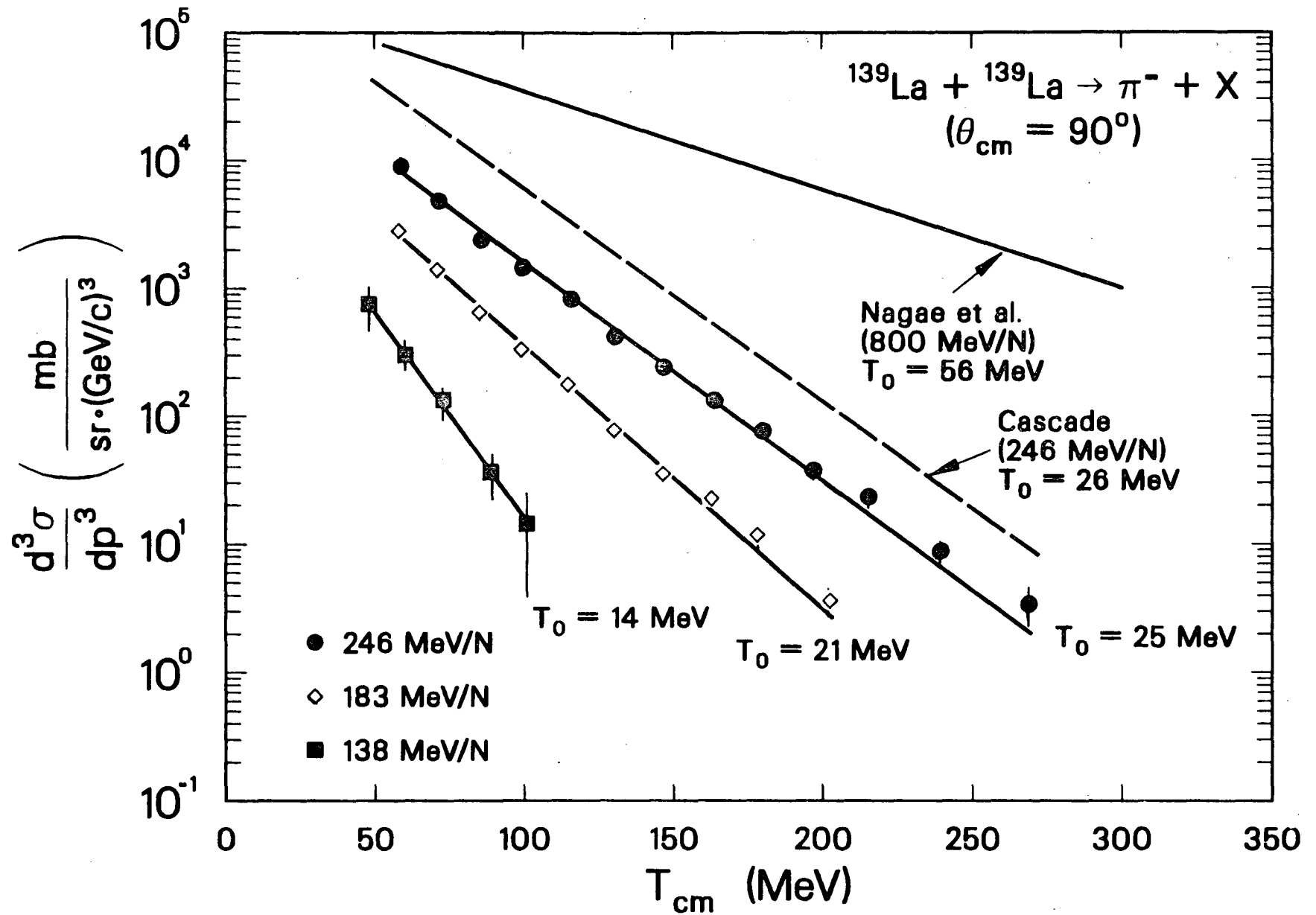


Fig. 1

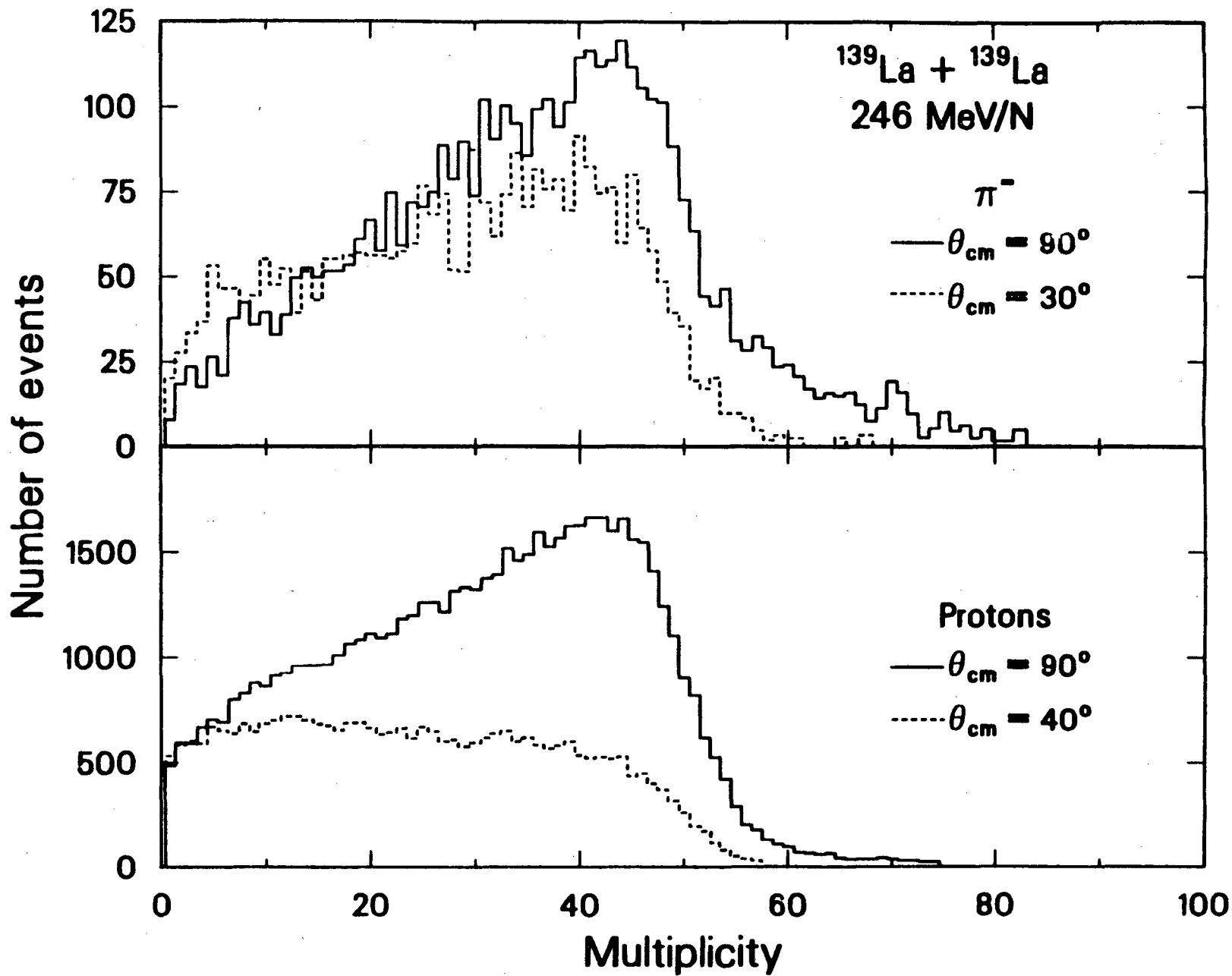


Fig. 2

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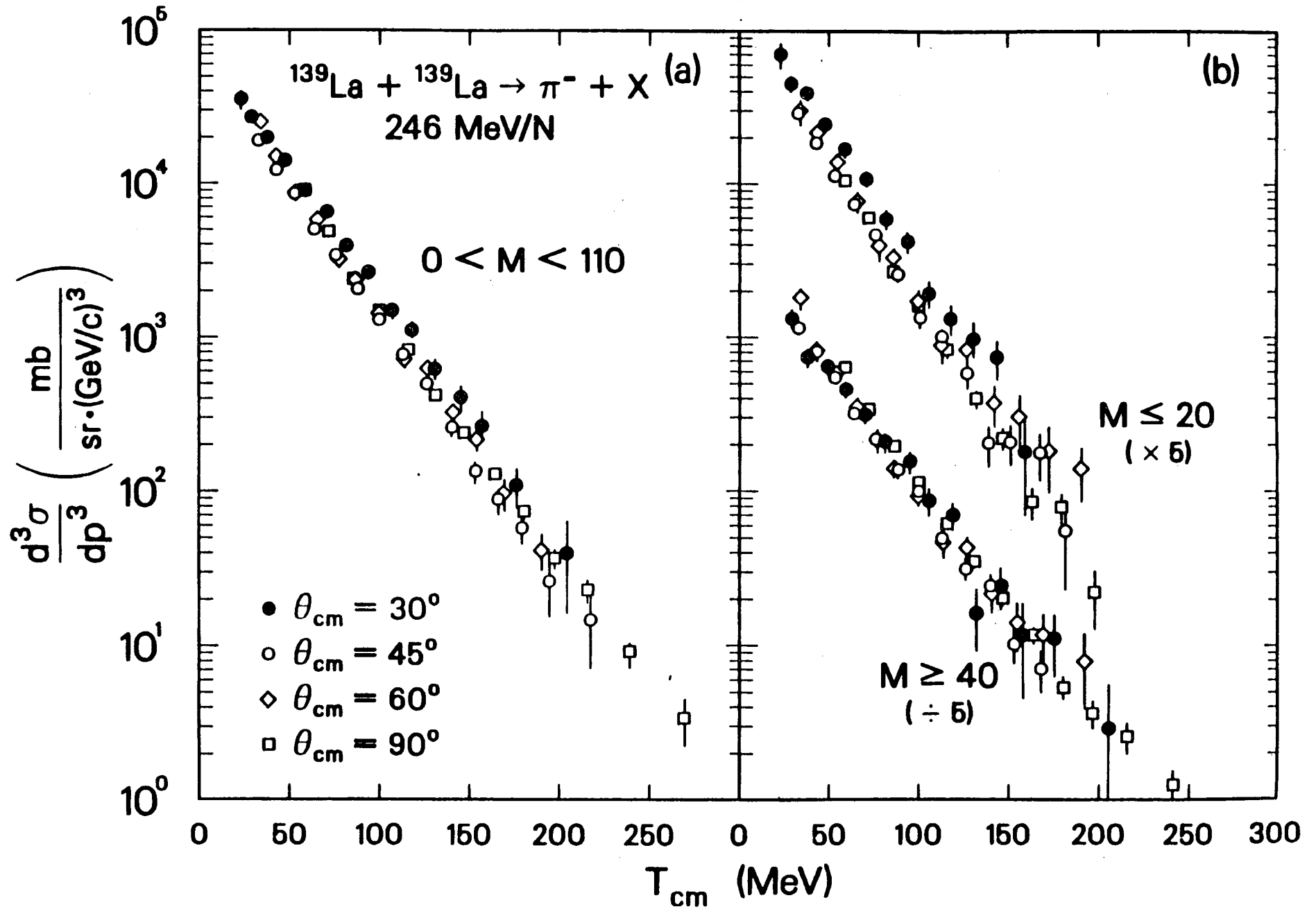


Fig. 3



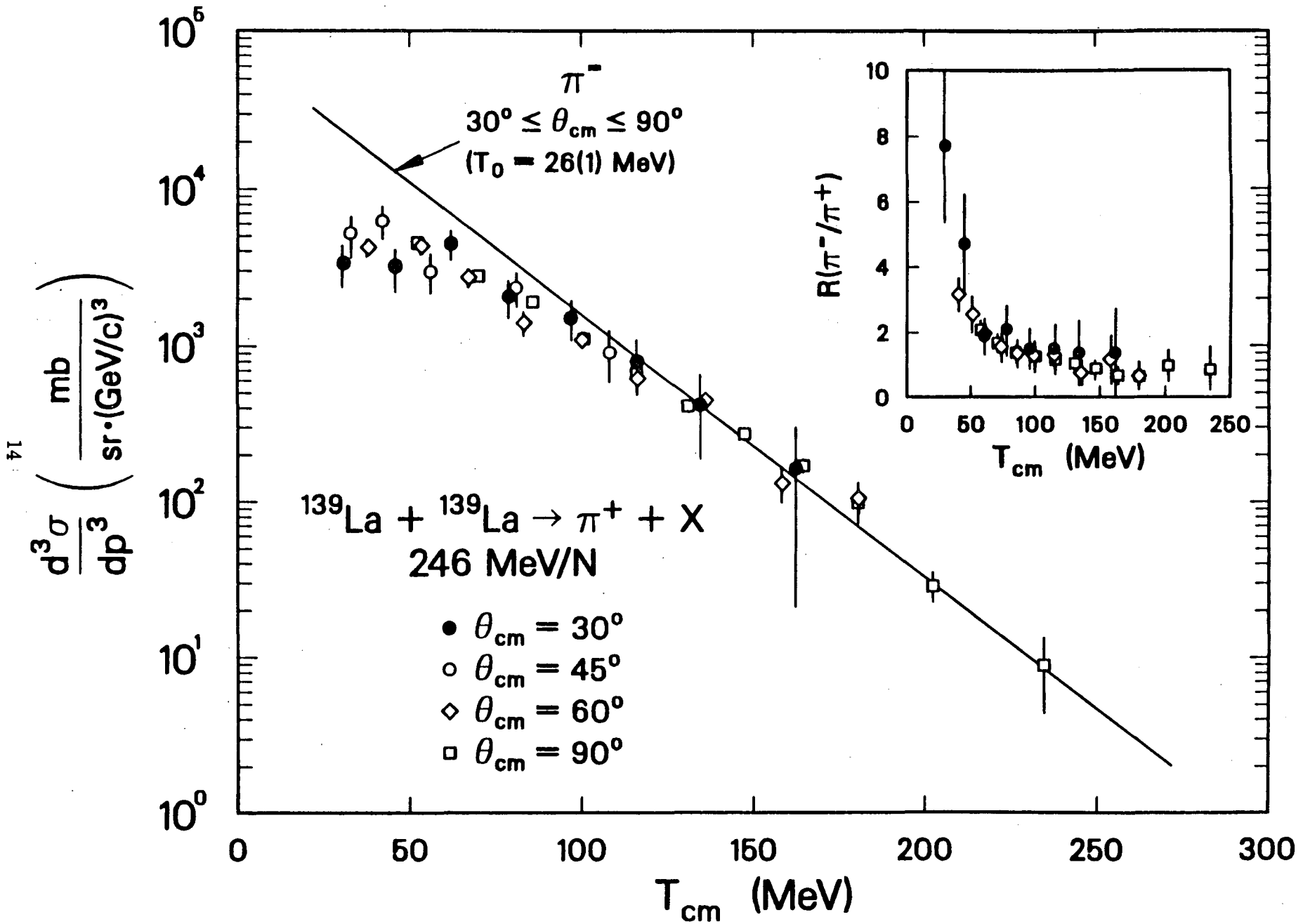


Fig. 4

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