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Abstract: Proton cross sections with associated multiplicities have been measured in ^{139}La $+^{139}$La collisions at E/A = 138 and 246 MeV. Data were taken at center of mass angles between 40 and 90 degrees. At both energies the inclusive proton cross section is approximately isotropic over the range of c.m. angles covered. At E/A = 246 MeV the angular distribution of protons depends strongly on the associated multiplicity. We discuss the possibility that hydrodynamic flow of nuclear matter is manifested in the semi-inclusive cross section.

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Recently, the first extensive data on inclusive measurements of light particle emission from a heavy symmetric system were published [1]. Proton production from the La+La system at $E/A = 800$ MeV was measured and found to be generally consistent with the results of measurements made for lighter systems at the same beam energy. In this paper we present data for the La+La system at $E/A = 138$ and 246 MeV.

The experiment was carried out at the Lawrence Berkeley Laboratory Bevalac. The detector has been described elsewhere [1]–[3]. A magnetic spectrometer was augmented with a 110-element plastic scintillator multiplicity array, consisting of three concentric rings of detectors covering 10–90 degrees in the laboratory.

The associated multiplicity was not used as a trigger but rather was used in the analysis to identify central and peripheral collisions. For the purposes of this analysis, events with high associated multiplicity are assumed to be predominantly small impact parameter "central" events; those with low associated multiplicity, large impact parameter "peripheral" events. The relation between centrality and associated multiplicity is not absolute, but there is a strong correlation as has been established in previous work [2, 4].

Figure 1 shows the inclusive proton cross section, $d^3\sigma/dp^3$, as a function of kinetic energy in the center of mass at angles of 65 and 90 degrees for $E/A = 138$ and 40, 65 and 90 degrees for $E/A = 246$ MeV. The shapes and beam energy dependence of these cross sections are generally consistent with the characteristics of spectra taken at higher energies [1, 5]. However, over this range in c.m. angle the present data are closer to isotropy.

In Fig. 2a, the inclusive data at $E/A = 246$ MeV are compared with the results of calculations for c.m. angles of 40 and 90 degrees and proton c.m. kinetic energy between 10 and 200 MeV made with an intranuclear cascade (INC) simulation [6], and with the quantum molecular dynamics (QMD) model [7, 8]. The data have been truncated to coincide with the range in proton energy covered by the calculations. Both calculations overpredict the proton yield, although QMD does somewhat better for proton energies above about 100 MeV. The tendency of the INC to overpredict the proton yield has been observed in earlier work [9]; it reproduces the slope of the exponential fall-off quite well, however. Perhaps more significant is the isotropy of the data relative to the model calculations, in contrast to the good agreement between the INC and data for protons from ^{40}Ar+KCl collisions at E/A = 800 MeV [6]. The angular dependence of the data might be attributed to the approximate isotropy of protons emitted in binary pp collisions near the pion production threshold. However as shown in Fig. 2a, the fact that the INC, which takes the nucleon-nucleon (NN) cross section as input in a simple multiple binary collision picture, does not yield isotropy suggests that the isotropy in the data may be due to an increase in stopping in the heavier La+La system.

In Figs. 2b and 2c we compare the proton cross section at 40 and 90 degrees with the INC and QMD results for two different cuts on associated multiplicity for E/A =246 MeV. The calculations have been filtered through our detector acceptance, and the high multiplicity cuts select approximately the 15% of the events with the highest multiplicity. The low multiplicity cuts select the lowest 15% for the data and the INC, and the lowest 50% for QMD, the latter selection dictated by limited statistics. In collisions with low associated multiplicity (Fig. 2b), the measured cross section at 40 degrees is substantially higher than that at 90 degrees in all cases. However, when events with high associated multiplicity are selected from the data (Fig. 2c) the 90 degree cross section is enhanced by a factor of 1.5 – 2 over the cross section at the smaller angle. By contrast, in the INC the 40 degree cross section is still somewhat in excess of the 90 degree cross section, and in the QMD results the two cross sections are approximately equal. Similar, albeit less strong effects are observed in the cross section at 65 and 90 degrees for E/A = 246 and 138 MeV (not shown). It is clear that thermal models, which predict isotropic angular distributions for central collisions, cannot describe the data selected on high multiplicity. Furthermore, there is no evidence of such an enhancement in the multiplicity-selected proton data at $E/A = 800$ MeV [10].

In order to test the sensitivity of our results to the array geometry, we looked at the proton spectra in two extreme cases, with multiplicity selection based on only the front ring of the array, covering 10 – 25 degrees in the laboratory, and on only the rear ring (44 – 90 degrees). The 90 vs. 40 degree enhancement was present at about the same strength in each case. In addition, calculations [11] based on a multiplicity array of similar geometry to the one in the current experiment [12] indicate that multiplicity detector bias is not nearly sufficient to account for the magnitude of the observed effect.

We have considered the question of whether the multiplicity-selected data may contain evidence for hydrodynamical effects as predicted by the nuclear fluid dynamics model [13]–[16]. While the existence of these effects has been well-established in exclusive 4π measurements [17]–[20], they have never been conclusively observed in semi-inclusive data. Multiplicity-selected data taken with light and medium projectiles were found to exhibit some sidewards peaking for low energy protons emitted in central collisions [12], but this has since been attributed to enhanced coalescence of forward-moving low energy protons, due to the compressed phase space at small angles [21].

The present data are qualitatively but not quantitatively consistent with predictions of two classes of theoretical models which predict hydrodynamic effects. A strong 90 degree enhancement in central La+La collisions has been found in calculations with both viscous hydrodynamics [22] and QMD, although in the latter case the effect is present only for proton kinetic energies in excess of 150 MeV. The QMD model is an extension of the Vlasov-Uehling-Uhlenbeck (VUU) formalism, further augmented in this case by the inclusion of isospin. It has been noted [16] that VUU and fluid dynamics can be expected to converge only for heavy systems, where there is sufficient material for nuclear stopping and consequent equilibration.

One scenario which might permit the observation of a fluid-dynamical effect in an inclusive measurement is the case of a near-head-on collision of two heavy, equal mass nuclei, in which there is almost complete stopping, with outward flow of material normal to the beam direction. This would lead to a strong signal at $\theta_{c.m.} = 90°$ for small impact parameters, and the QMD calculation for the La+La system does show an enhancement for proton kinetic energies above 100 MeV when the data are selected on impact parameter b < 1 fm. However, the effect disappears when selected on high multiplicity as filtered through our detector acceptance. We note that INC simulations show a dispersion in the relation between impact parameter and multiplicity, and therefore cutting on even the extreme tail of the multiplicity distribution still results in some impact parameter averaging. For example, in the present case the highest 15% in multiplicity corresponds to between approximately 0 and 3 fm, whereas in the calculation the 90 degree enhancement becomes evident only for b < 1 fm. Assuming that this dispersion is also present in the data, the implication is that the processes which act to produce a 90 degree enhancement are stronger than those assumed in the model calculations.

An enhancement at 90 degrees for small impact parameter is also predicted by a computational model [23, 24] which is sensitive to the value of the *NN* cross section as embodied in an assumed threshold radius for *NN* collisions [24]. The magnitude of the observed effect is reproduced by the model when the in-medium *NN* cross section is set to 60 mb [25]. This is generally consistent with the results [26] of calculations in which collisions of heavy nuclei (U+U and La+La) at E/A=250 MeV were simulated with a modified version of the INC. In this work the nuclear matter was found to exhibit collective flow when the *NN* cross section was increased by a factor of three, and the scattering was made repulsive rather than stochastic.

The implications of the present results are important for theories of the reaction dynamics. As pointed out by Aichelin, *et al.* [27], a good understanding of in-medium effects in heavy nuclear systems is an essential step in studies leading to the formulation of the nuclear equation of state. Furthermore, an analysis of the cross sections in the midrapidity region may reveal interesting information which may be lost in event shape analysis such as has been carried out in the past. This is due to the fact that the conventional flow analysis reduces the very detailed information contained in the full triple differential cross section to just one or two numbers. For example, the flow tensor analysis typically gives flow angles of about 30 degrees for central collisions [17]. However, the event shape might be strongly distorted by non-equilibrated high momentum particles which have undergone only a few collisions. Thus even an oblate momentum distribution, which would be consistent with the present experiment for the highest multiplicities, may appear prolate when analysed with the flow tensor method. Although the present data cannot easily be transformed into a rapidity distribution, we note that the Plastic Ball collaboration has observed for Au+Au at E/A=200 MeV that the high multiplicity events yield a baryon distribution which peaks at midrapidity [28]. The Plastic Ball results are not presented in the form of inclusive cross sections, however.

In conclusion, we have measured the cross section for protons emitted from La+La collisions at E/A = 138 and 246 MeV. The inclusive data are essentially isotropic over the range of c.m. angles covered, in disagreement with models that work well for lighter mass systems at higher beam energies. The observation of an enhancement in the 90 degree proton cross section for events with high associated multiplicity is evidence that under certain conditions collective flow can be manifested in simple observables. This fact and the disagreement with theoretical predictions indicate that hydrodynamic effects may be very strong at these intermediate energies, and that semi-inclusive measurements at these energies can carry significant information about the reaction dynamics.

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Figure Captions:

Fig. 1: $d^3\sigma/dp^3$ for ^{139}La $+^{139}$La $\rightarrow p + $ X as a function of c.m. kinetic energy for laboratory bombarding energies E/A = 138 MeV, $\theta_{c.m.}$ = 65 and 90 degrees and E/A = 246 MeV, $\theta_{c.m.}$ = 40, 65 and 90 degrees.

Fig. 2: $d^3\sigma/dp^3$ for ^{139}La $+^{139}$La $\rightarrow p + $ X, E/A = 246 MeV at 40 and 90 degrees in the c.m. and proton kinetic energy between 10 and 200 MeV. The curves represent the results of calculations with the intranuclear cascade (INC) simulation and the quantum molecular dynamics (QMD) model, as discussed in the text. a) Inclusive. b) Low associated multiplicity. c) High associated multiplicity. The bin width in energy is 20 MeV.

Figure 1

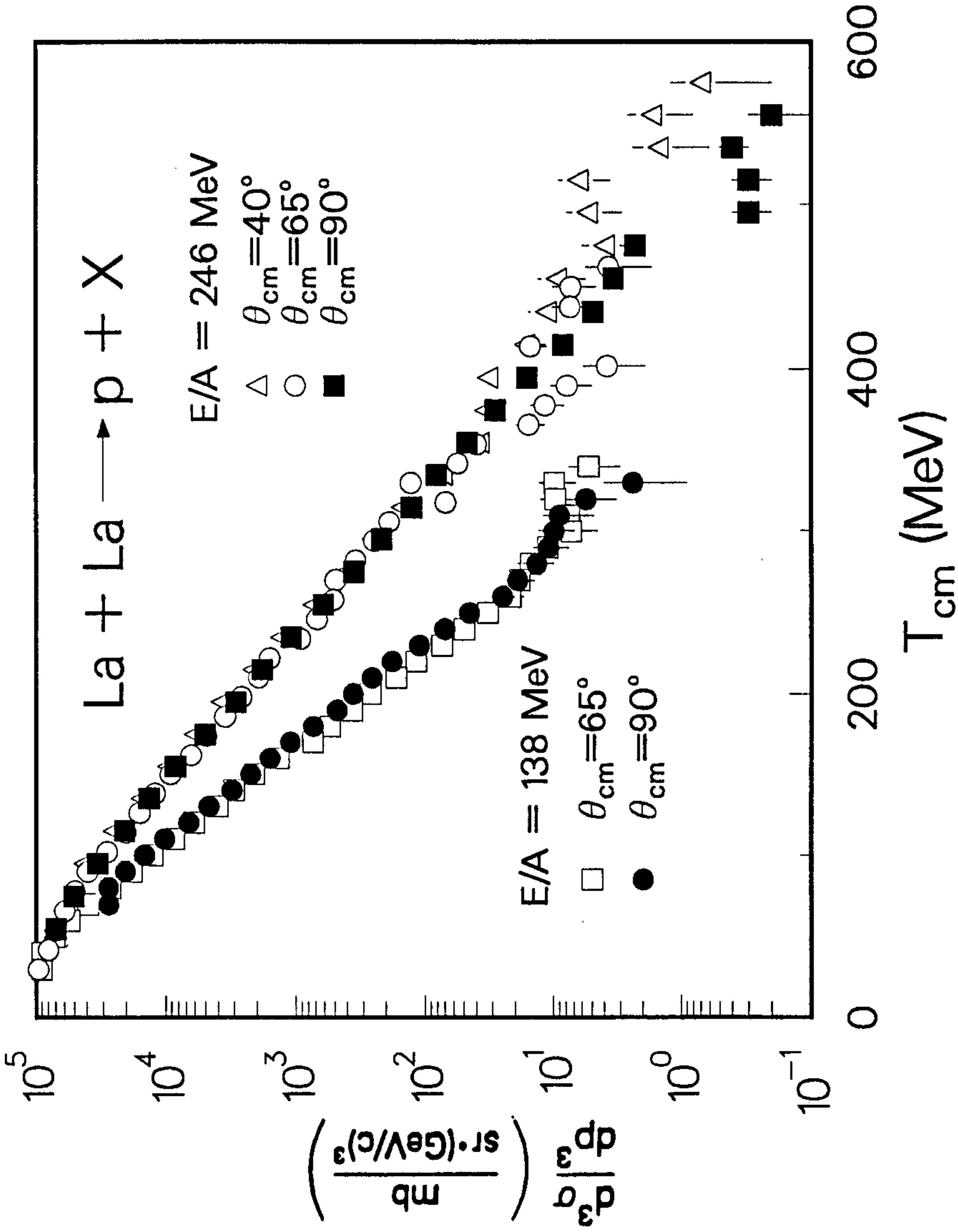

La + La → p + X
E/A = 246 MeV
θ_{cm}=40°
θ_{cm}=65°
θ_{cm}=90°
E/A = 138 MeV
θ_{cm}=65°
θ_{cm}=90°
T_{cm} (MeV)
$\frac{d^3\sigma}{dp^3}\left(\frac{mb}{sr\cdot(GeV/c)^3}\right)$
0
200
400
600
10^{-1}
10^{0}
10^{1}
10^{2}
10^{3}
10^{4}
10^{5}

Figure 2a

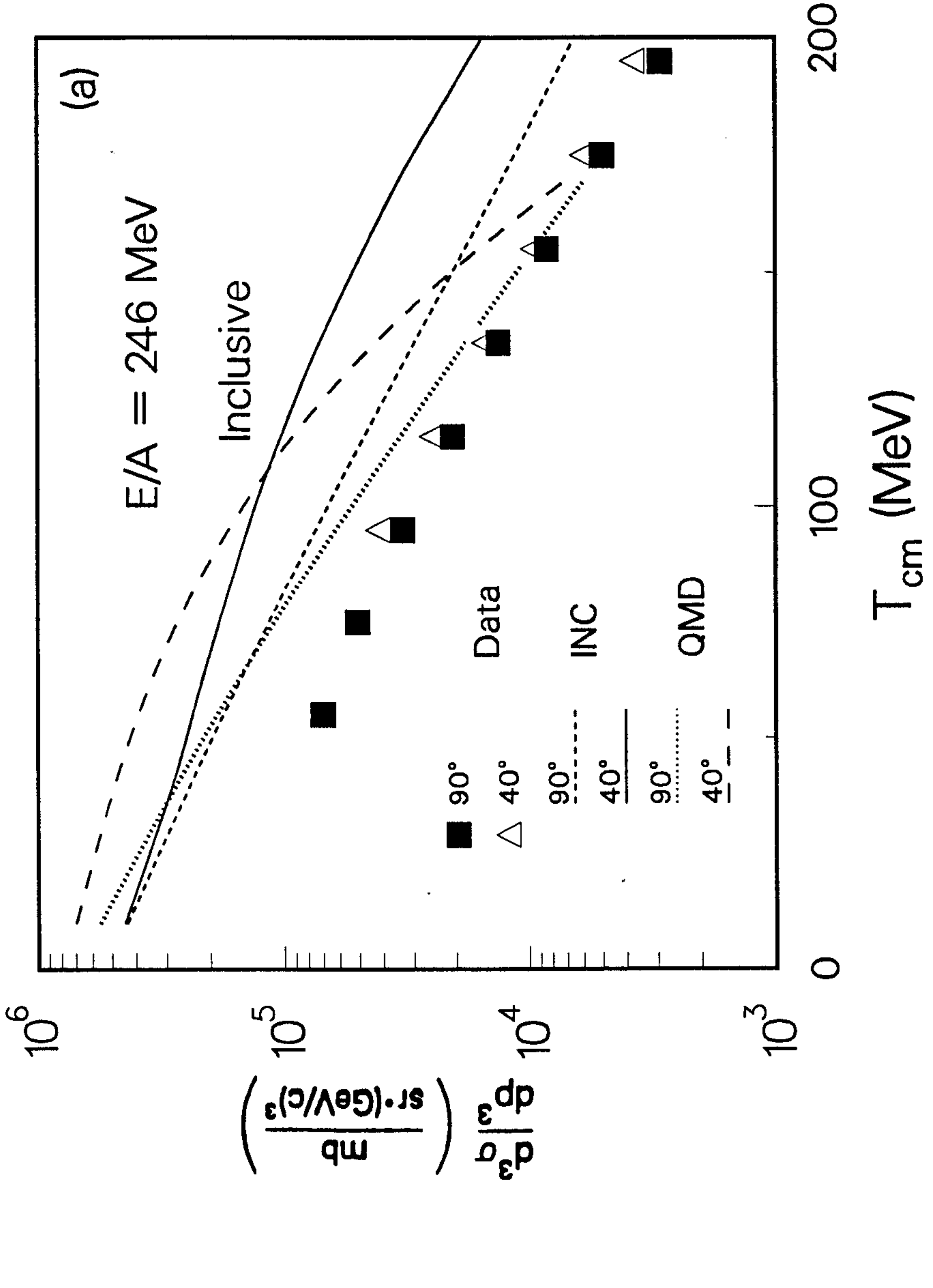
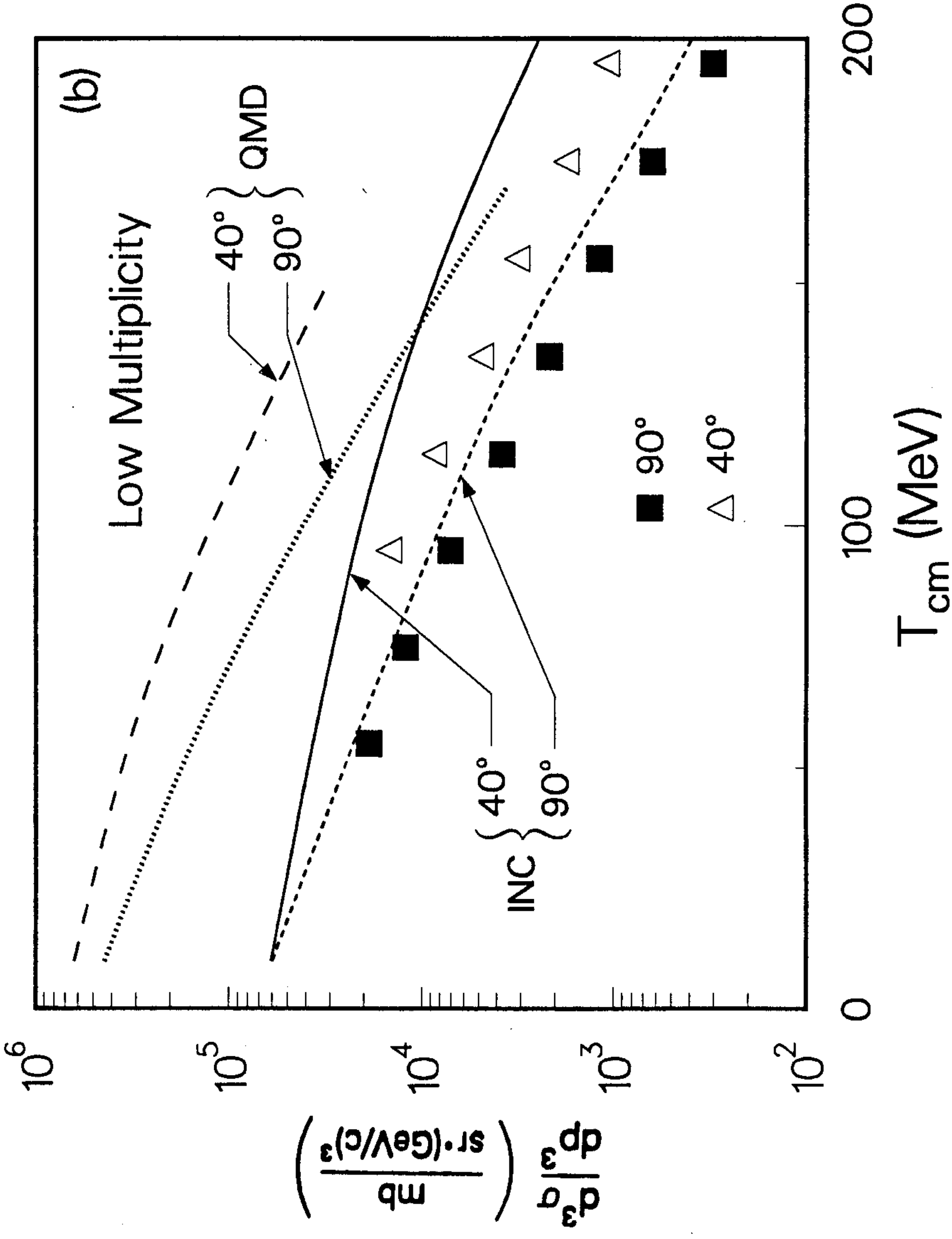
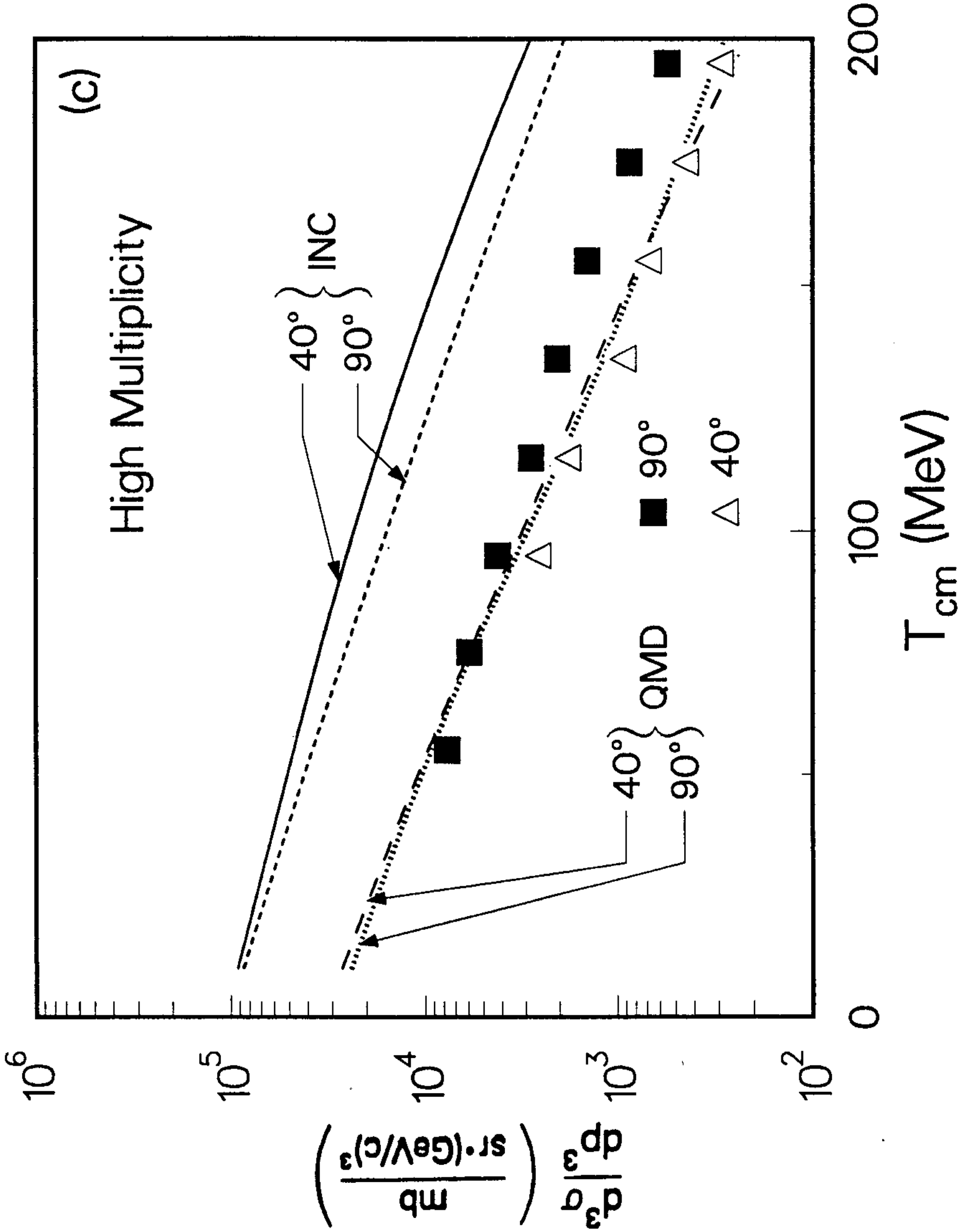

(a)
E/A = 246 MeV
Inclusive
90° Data
40°
90° INC
40°
90° QMD
40°
T_{cm} (MeV)
0
100
200
10^3
10^4
10^5
10^6
$\frac{d^3\sigma}{dp^3}$ $\left(\frac{mb}{sr\cdot(GeV/c)^3}\right)$

Figure 2b



(b)
Low Multiplicity
40°
90°
QMD
INC
■ 90°
△ 40°
T_{cm} (MeV)
0
100
200
10^2
10^3
10^4
10^5
10^6
$\frac{d^3\sigma}{dp^3}\left(\frac{mb}{sr\cdot(GeV/c)^3}\right)$

Figure 2c



(c)
High Multiplicity
40°
90°
INC
40°
90°
QMD
90°
40°
0
100
200
T_{cm} (MeV)
10^2
10^3
10^4
10^5
10^6
$\frac{d^3\sigma}{dp^3}\left(\frac{mb}{sr\cdot(GeV/c)^3}\right)$

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