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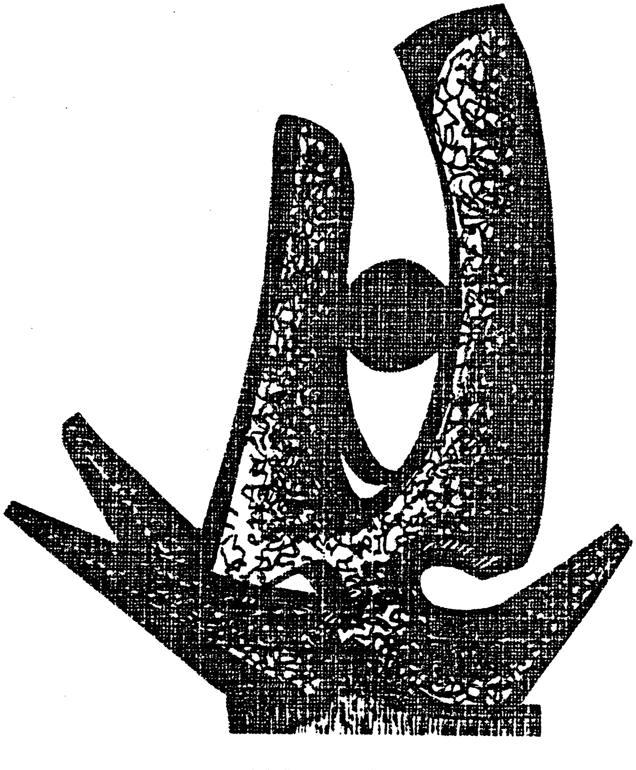

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Evidence for a Stiff Nuclear Equation of State from a Novel Transverse Momentum Analysis

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Abstract

The novel momentum analysis technique introduced by Danielewicz and Odyniec can be used to detect and exhibit collective flow in the light system Ar (1.8 GeV/A) + KCl where the usual kinetic energy flow analysis fails. The microscopic Vlasov-Uehling-Uhlenbeck approach which includes the nuclear mean field, two body collisions, and Pauli blocking is used to study this phenomenon. The resulting transverse momentum transfers turn out to be quite sensitive to the nuclear equation of state. From a comparison to the experimental data of the GSI-LBL streamer chamber group evidence is presented for a rather stiff nuclear equation of state. The cascade model is unable to describe the data.

Early indications for the occurrence of a collective sidewards flow in relativistic nucleus-nucleus collisions have been reported for asymmetric reactions (C + Ag and Ne + U) in particle track and solid state detector experiments,[1] but only recently has this phenomenon been unambiguously observed in the 4π exclusive event by event analysis[2] of near central collisions of heavy nuclei, i.e. Nb(400 MeV/A)+ Nb[3] and Ar(770 MeV/A)+ Pb.[4] Experimental data for systems as heavy as Au + Au and U + U continue to accumulate and support these results[5]. The collective sidewards flow has first been predicted on the basis of nuclear fluid dynamics.[6] In contrast, microscopic intranuclear cascade models, which have been successful in describing inclusive data,[7] only predict flow when unbound nuclei expand due to Fermi motion.[8,9] On the other hand, the microscopic Vlasov-Uehling-Uhlenbeck (VUU) theory used in the present work and the classical equations of motion approach, both of which incorporate a repulsive nuclear equation of state at high densities, have successfully reproduced the sidewards peaking observed experimentally.[9,10,11] Light systems have not exhibited any signatures of collective sidewards flow when the kinetic energy flow analysis is applied.[12]

In the present work it is shown that transverse flow effects are predicted even in light systems in a microscopic theory based on the Vlasov and Boltzmann equations with an Uehling-Uhlenbeck collision integral.[9,11,13,14] This theory enables the investigation of the influence of the nuclear equation of state and the Pauli principle directly within the context of a microscopic model. Recall that the Vlasov equation with Uehling-Uhlenbeck's collision integral, which respects the Pauli principle, is:

$$\frac{\partial}{\partial t} f + \vec{v}\cdot \frac{\partial}{\partial \vec{r}} f - \nabla U \cdot \frac{\partial}{\partial \vec{p}} f = -\int \frac{d^3p_2 d^3p_1' d^3p_2'}{(2\pi)^6}\, \sigma v_{12} \times$$
$$[ff_2(1-f_1')(1-f_2') - f_1'f_2'(1-f)(1-f_2)]\delta^3(p+p_2-p_1'-p_2'). \qquad (1)$$

The classical equations of motion of a large number of marker particles, representing the single particle distribution function f, are integrated numerically to sölve the Vlasov equation (the l.h.s. of eq. 1) and the collision term is treated in a Monte Carlo framework that is reminiscent of the cascade model.[9,11,13,14] Protons, neutrons, deltas and pions of different isospin are included separately with their experimental scattering cross sections.[9]

To study the effects of the nuclear equation of state, or rather the nuclear compressional energy, $E_c(\rho)$, on the reaction dynamics, we use two distinct forms for the density dependent potential field, $U(\rho) = \frac{\partial(\rho E_c)}{\partial \rho}$:

stiff (K=375 MeV) $U(n) = -124\ n/n_0 + 70.5(n/n_0)^2$ MeV (2a)

medium (K=200 MeV) $U(n) = -356\ n/n_0 + 303(n/n_0)^{7/6}$ MeV (2b)

These are simplified local Skyrme interactions with compressibility coefficients K=200 MeV and K=380 MeV, respectively. In Figure 1, we plot $E_c(\rho)$, for the stiff (K = 380 MeV) and medium (K = 200 MeV) Skyrme parametrizations, and compare to the equation of state extracted recently from pion multiplicity data.[15] Note that the chemical and cascade model analysis,[15] which extract a nuclear matter equation of state from the differences of the calculated pion multiplicities to the observed pion yields, agree more closely with the stiff equation of state. In fact, it is this rather stiff equation of state which has been used to fit the observed pion yields with the present theory.[9] Medium energy collisions have also been successfully studied with this approach.[14]

In nuclear fluid dynamics, the classical equations of motion, and the Vlasov-Uehling-Uhlenbeck theory, the collective flow is caused by the nuclear compressional energy. For central impact parameters in symmetric systems, well defined peaks occur in the flow angular distribution.[2,3,9-11] In asymmetric systems the flow distribution is broad for small impact parameters so that finite flow angles are best observable for intermediate impact parameter collisions.[4,11] The flow angle is found to decrease with energy both experimentally[5] and theoretically.[11]

However, for light systems ($A_T \approx A_P \leq 40$) and high energies ($E_{Lab} > 1$GeV/N), flow effects are not observed when the standard kinetic energy flow tensor analysis is used.[12] In fact, the experimental flow angular distributions for the reaction Ar(1.8 GeV/A, b<2.4fm) + KCl[12,16] (Figure 2a) are peaked at zero degrees as the cascade model[7,8] (Figure 2b) predicts. But also the present Vlasov-Uehling-Uhlenbeck approach, which does predict finite flow angles for heavier systems at lower energies[9], does not yield any observable sidewards maxima in the flow angle distributions (see Figures 2c,2d); even less so can we distinguish between hard (Figure 2c) and medium (Figure 2d) equations of state when the standard kinetic energy flow tensor

$$K_{ij} = \Sigma_{\nu} p_i(\nu) p_j(\nu)/2m(\nu) \qquad (3)$$

analysis is used: All flow angle distributions are peaked at zero degrees. Therefore, one might be tempted to hastily conclude that flow effects do not occur for light systems.

However, Danielewicz and Odyniec[16] have recently proposed a novel transverse momentum analysis technique that provides a much more sensitive test for collective flow. They analyze the transverse momentum spectrum $p_x(y)$ where

$$y=1/2 \ln (E+p_{par})/(E-p_{par}) \quad (4)$$

is the rapidity, E is the total energy of the fragment, p_{par} is the momentum in the beam z-direction, and p_x is the projection of the transverse momenta into the scattering plane. Danielewicz and Odyniec have detected collective flow effects in the streamer chamber data[12] for Ar(1.8 GeV/A)+ KCl using this technique (see Figure 3a). There is a transverse momentum accumulation at both the projectile and target rapidities $y = \pm 0.86$ in the center of momentum frame. They report[16] that the collective flow effects are weaker than in the hydrodynamic model, but much stronger than in the cascade[7] (see Figure 3b). It is important to point out that the intranuclear cascade model fails to reproduce the data, even though it appeared to be consistent when the kinetic energy flow analysis had been applied. The highly increased sensitivity of this new technique has more recently been used to predict the presence of collective flow for O (600 MeV/A) + O within the context of the time dependent Dirac equation with relativistic mean field dynamics.[17]

We have applied this novel transverse momentum analysis technique to the Vlasov-Uehling-Uhlenbeck results for the reaction Ar(1.8 GeV/A, $b < 2.4$ fm) + KCl studied experimentally. We find that the peak in the transverse momentum spectrum $p_x(y)$ depends linearly on the nuclear equation of state: The cascade model predicts $p_x^{max} \approx 25$ MeV/c (Figure 3b), the medium equation of state in the Vlasov-Uehling-Uhlenbeck approach predicts $p_x^{max} \approx 50$

MeV/c (Figure 3d), and the stiff equation of state yields $p_x^{max} \approx 100$ MeV/c (Figure 3c). Only the latter is in agreement with the data. This result is supported by the previous finding[9] that the stiff equation of state reproduces best the pion yields observed in the streamer chamber at this energy (1.8 GeV/N) and also at lower energies, down to 0.36 GeV/N. It is interesting to remark that this equation of state agrees rather well with the one extracted phenomenologically from the pion data.[15]

In summary, a novel transverse momentum analysis has been applied to collisions of Ar (1.8 GeV/A) + KCl. The intranuclear cascade model, lacking compressional energy, is unable to produce the transverse momenta of ~100 MeV/c at the beam and target rapidities; there is only a small effect of the order of 25 MeV/c. With the Vlasov-Uehling-Uhlenbeck theory, a soft nuclear equation of state produces about 50 MeV/c of transverse momentum at y_P and y_T: this is greater than with the cascade model, but still clearly inconsistent with the data. The theory reproduces the measured transverse momentum spectrum only with the stiffer nuclear equation of state; this is in qualitative agreement with the equation of state derived from the pion yields of the GSI-LBL streamer chamber group.

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Figure Captions

Fig. 1 The nuclear equation of state with K=200 MeV and K=380 MeV as used in the Vlasov-Uehling-Uhlenbeck theory compared with values extracted from pion yields.[15]

Fig. 2 Kinetic energy flow angular distributions for Ar(1.8 GeV/A)+ KCl for

a) the experimental data[12];

b) the intranuclear cascade model[7];

c) the VUU approach with the stiffer equation of state;

d) the VUU approach with the softer equation of state.

Fig. 3 In plane transverse momentum vs. rapidity for Ar(1.8 GeV/A)+KCl for

a) the experimental data[12,16];

b) the intranuclear cascade model[7];

c) the VUU approach with the stiffer equation of state;

d) the VUU approach with the softer equation of state.

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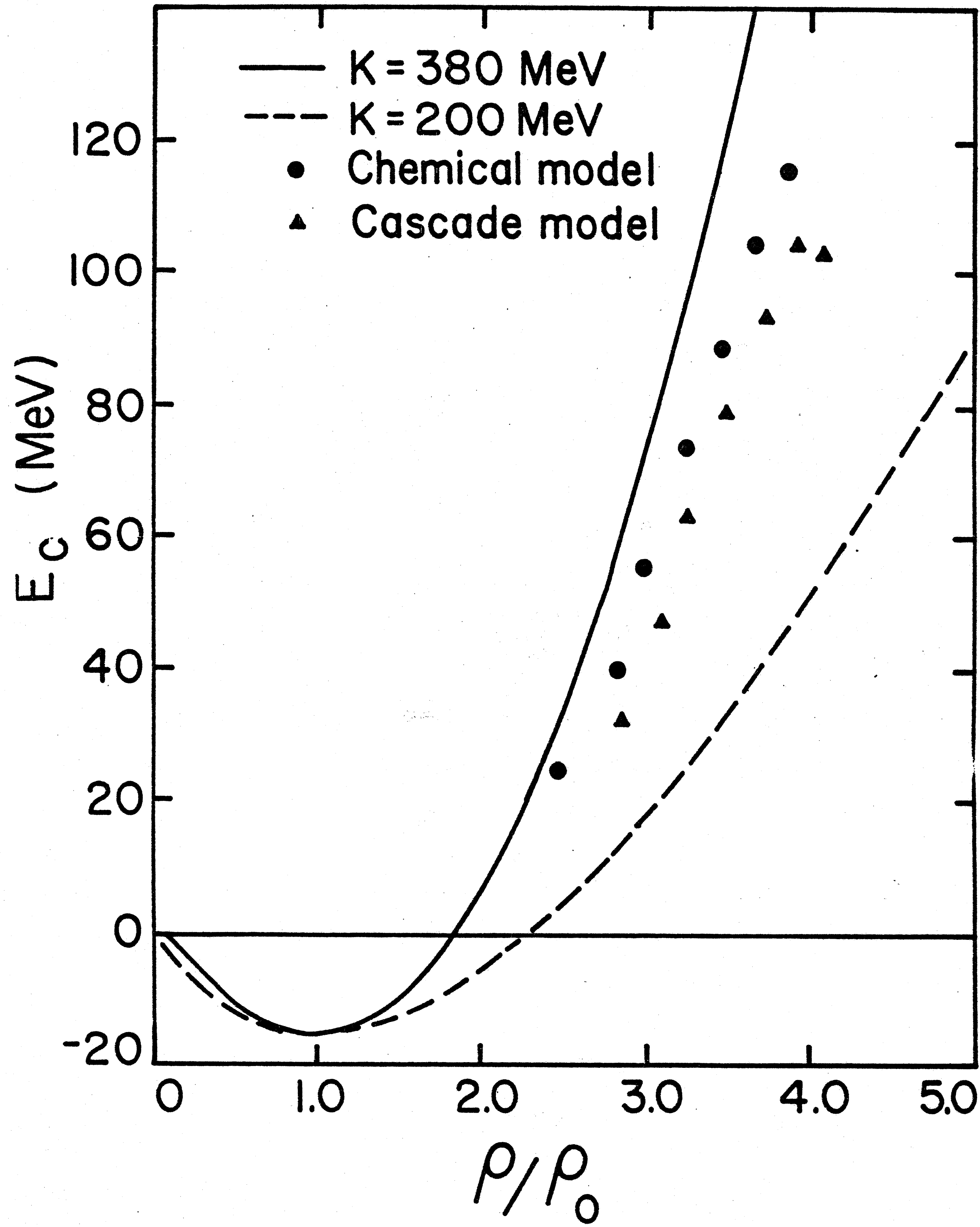

FIGURE 1

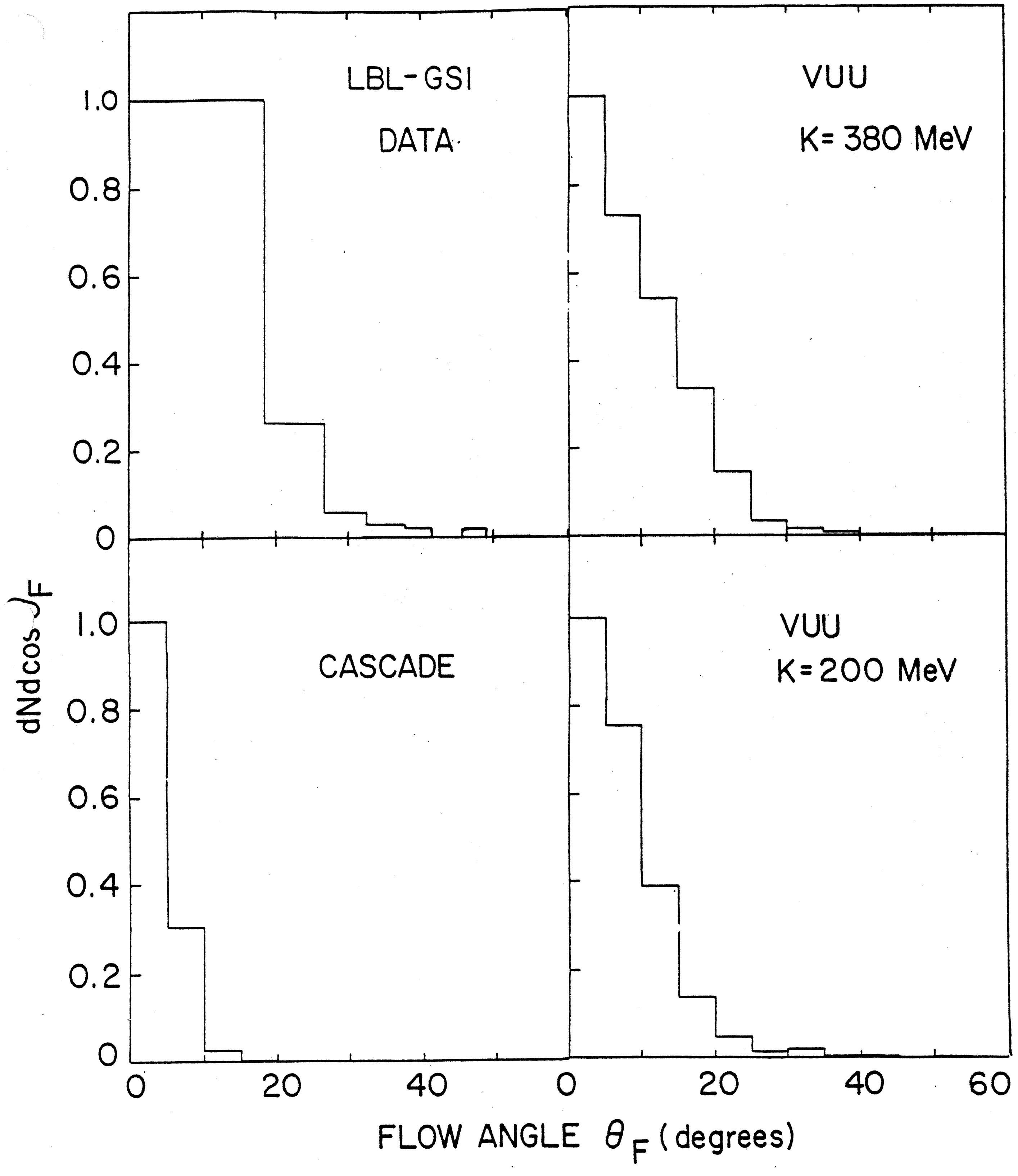
LBL-GSI
DATA
VUU
K= 380 MeV
CASCADE
VUU
K=200 MeV
dNdcos ϑ_F
1.0
0.8
0.6
0.4
0.2
0
0
20
40
60
FLOW ANGLE θ_F (degrees)

FIGURE 2

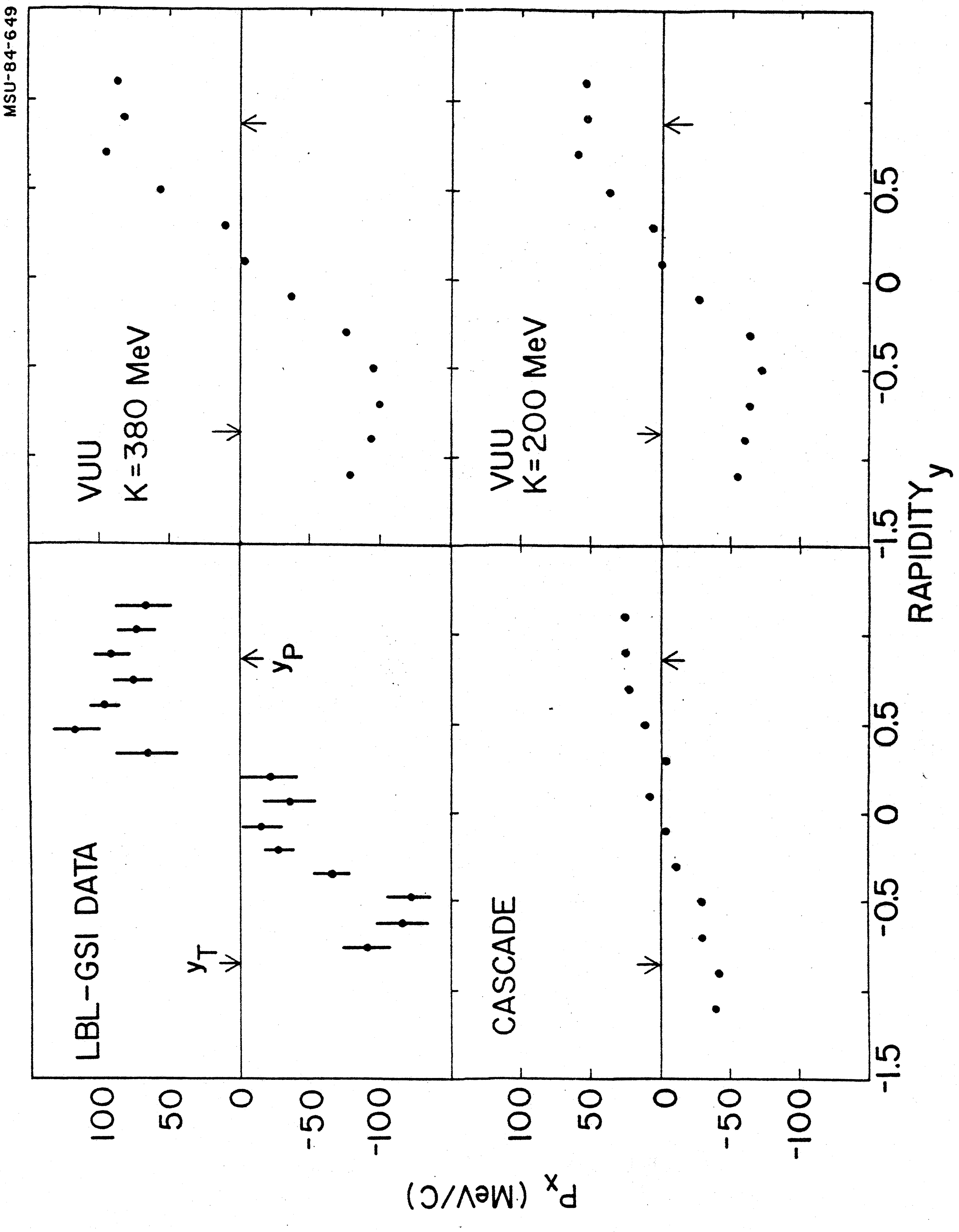
MSU-84-649
LBL-GSI DATA
y_T
y_P
CASCADE
VUU
K=380 MeV
VUU
K=200 MeV
P_x (MeV/C)
100
50
0
-50
-100
RAPIDITY y
-1.5
-0.5
0
0.5

FIGURE 3