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The Role of Mean Field Dynamics and Two Body Collisions in Intermediate Energy Heavy Ion Collisions

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ABSTRACT

Medium energy collisions of Ar + Ca are studied in three different theoretical schemes: the intranuclear cascade model, in which the dynamics is governed by independent NN collisions; the Vlasov equation, where the nuclear mean field determines the collision dynamics; and the Vlasov-Uehling-Uhlenbeck approach which includes the nuclear mean field, two body collisions, and Pauli blocking. The Vlasov equation without collision term yields single particle distribution functions which - after the reaction - are only slightly modified in momentum space; even in central collsions, transparency is predicted. In contrast, large momentum transfer is obtained when the Uehling-Uhlenbeck collision term is incorporated; then the final momentum distribution is nearly spherically symmetric in the center of mass: The nuclei stop each other. The theory is supplemented with a phase space coalescence model of fragment formation. Calculated proton spectra compare well with recent data for Ar(42,92 and 137 MeV/N) + Ca. The mean field dynamics without two-body collisions exhibits forward peaked distributions in contrast to the data. The cascade approach underpredicts the yields of low energy protons by more than an order to magnitude.

The recent interest in medium energy (20-200 MeV/N) heavy ion collisions is motivated by the opportunity to study the transition from the Pauli principle dominated low energy region to a high energy region where two body collisions are important.[1] Time-dependent-Hartree-Fock and fluid-dynamical calculations have been applied in this energy region with drastically different results:[2] the mean field calculations exhibit transparency, while fluid dynamics predicts compound nucleus formation and rapid disintegration of the highly excited system. There is an obvious need to include the finite mean free path of nucleons, the interaction of nucleons with the nuclear mean field, and the two-particle viscosity due to NN collisions into a microscopic theory.[3] We present a microscopic approach based on the Boltzmann equation which incorporates both the nuclear mean field and NN collisions with an appropriate Pauli blocker. Recent data on inclusive light and heavy particle production from 40-140 MeV/N reactions[4] provide a testing ground for the theory.

Recently we have demonstrated that the mean field and the Pauli principle terms are important even at high bombarding energies, E > 300 MeV/N.[5] The microscopic intranuclear cascade model,[6] which may loosely be viewed as a solution of the Boltzmann equation without the mean field term and Pauli blocking factors, has difficulties in reproducing high multiplicity selected data at these high energies.[7] This is surprising in view of the success of this model in describing inclusive data. At intermediate energies, $E_{lab} \sim$ 100 MeV/N, both effects are even more important: the potential field keeps the nuclei from expanding before collisions can occur, and also provides the one-body dissipation effects which dominate the dynamics at lower energies. Furthermore, respecting the

Pauli principle is essential at these energies, where the incident nuclei are overlapping in momentum space.

In the present work medium energy collisions are studied via the Boltzmann equation, including the mean field and the Pauli blocking terms. The single particle distribution function f(r,p,t) is obtained by ensemble averaging over the phase space distribution of test particles.[5,8,9] The time evolution of f is given by[5,8,9]

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

The motion of the test particles under the influence of the mean field is governed by the Vlasov equation, which is the classical analogue to the TDHF equations[10].

The test particles are initially assigned random positions in a sphere of nuclear radius. Fermi momenta are also assigned. The nuclei are then Lorentz boosted to the center of mass frame. Trajectories in configuration and momentum space are computed by assuming that each particle moves on a curved trajectory under the influence of an acceleration term generated by the gradient of the mean field. For the density dependent potential field, $U(\rho)$, a local Skyrme interaction is used: $U(\rho) = -124\ \rho/\rho_0 + 70.5\ (\rho/\rho_0)^2$ MeV, with a compressibilty coefficient of K=380 MeV.

Fifteen collision simulations are followed in parallel and the ensemble averaged phase space density in a sphere around each particle is computed.[5] The ensemble averaging ensures a reasonably smooth (about 10% fluctuation at normal density) single particle distribution function, which is used to determine the mean field and the Pauli blocking probability.[5,8,9] Many such parallel ensembles are followed in order to simulate an actual reaction.

A constant time-step integration routine is used to insure synchronization of the ensembles.[5,8,9] The acceleration of the test particles due to the field gradient is calculated prior to each transport step, and is assumed to be constant within a synchronization time-step. The local gradient of the field is computed via a finite difference method between two hemispheres centered around the test particle. This method[5] is analogous to Lagrange's method in fluid dynamics, in contrast to the space-fixed Eulerian mesh.[8,9]

Protons, neutrons, deltas and pions of different isospin are included separately with their experimental scattering cross sections.[5] Two particles may undergo s-wave scattering if they approach each other with a minimum distance of less than $(\sigma/\pi)^{1/2}$ and if the final states are not Pauli blocked. The Pauli blocking factor for each nucleon is given by $(1-f)$, and the scattering cross section is then reduced by the Uehling-Uhlenbeck factor $(1-f_1)(1-f_2)$. The Pauli blocker has been tested on ground state nuclei and has an efficiency of about 96%.

The Pauli blocking is very important at these bombarding energies: even at 137 MeV/N 80% of the attempted collisions are blocked due to lack of available final state configurations. Many of these attempted collisions are between nucleons of the same nucleus. The spectra of low energy ($E < 80$ MeV) nucleons are also influenced by the improved Pauli blocker, which prevents collisions that would yield one very low and one high energy nucleon. The cascade calculation, on the other hand, suppresses the cross sections of low energy nucleons, in contrast to the measured spectra.

We have also studied the system Ar + Ca in the mean field approximation by excluding two body collisions in the present theory, thus mimicking TDHF by solving the Vlasov equation[10]: the lack of two body collisions results in strongly forward peaked angular distributions, in qualitative agreement with TDHF calculations[2] in this energy regime. Fig. 1a shows the initial state in momentum space for Ar (137 MeV/N) + Ca; note that at this higher energy the Fermi spheres of target and nuclei are well separated. The Ar projectile moves in the positive z-direction, while the Ca target moves in the negative z-direction in this center of mass frame. Fig. 1b,c show the evolution of an Ar(137 MeV/N)+Ca collision without and with the Uehling-Uhlenbeck collision term. Note the increased isotropy in Fig. 1c, indicative of substantial thermalization. A convenient way to compare the results is by using

$$R = 2/\pi \; \Sigma p_{per} / \Sigma p_{par} \qquad (2)$$

where p_{per} and p_{par} are the momenta perpendicular to and parallel to the beam. Comparing the ratio of final to initial R values, we find 1.08 for the mean field only case and 2.05 for the mean field + collisions approach. At lower energies, the comparison is not as dramatic; the initial R values are already high since the nuclei overlap more in momentum space. Furthermore, most of the collisions are Pauli blocked. But the collision term always leads to increased isotropy. In fig. 2 we show the reaction Ar(42 MeV/N)+ Ca as it develops in configuration space. Note that without the collision term (fig. 2b), the nuclei tend to pass through one other, whereas when the collision term (fig. 2a) is present there is stopping and a more isotropic final state.

A generalized 6-dimensional coalescence model is used to find the nucleons bound in clusters, and prevent them from contributing to the proton cross sections. This is important at medium energies, where a large fraction of the emitted protons are found to be bound in fragments.[4] In this scheme, a nucleon is part of a cluster if it is within a configuration space distance r_0 from any other member of the cluster, and within a momentum space distance p_0 from the center-of-momentum of the cluster. The decay of excited clusters is not included; evaporation protons are absent in the calculated spectra.

The present program has been tested at higher energies[5] by comparison to experimental data and to cascade model results. We have calculated inclusive proton spectra for Ar (40 - 140 MeV/N) + Ca. The generalized coalescence prescription has been applied to the primordial nucleon distribution after NN collisions ceased; this also corresponds to the time at which the flow angle saturates. We use r_0=2.2 fm and p_0=200 MeV/c, having adjusted these parameters to yield correct total cross sections for observed nucleons, and to correspond to reasonable fragment sizes. Variation of the coalescence parameters changes the magnitude of the cross sections, but has a negligible effect on the shape of the spectra. The calculated neutron and proton distributions are practically identical, and have been combined to decrease the statistical uncertainty.

Figure 3a shows the comparison between calculated and measured proton spectra for 137 MeV/N Ar + Ca. The calculated cross sections and the slopes of the spectra agree reasonably well with the data. Fig. 3b shows the same data compared to the proton spectra calculated with the cascade model of Cugnon et al.,[6] which serves as a reference model to demonstrate the importance of the mean field and phase space Pauli blocking. The cascade calculation includes a simple approximation to the Pauli blocking by excluding collisions with less than 24 MeV c.m. kinetic energy. The resulting nucleon distributions were analyzed via the same procedure as the Boltzmann equation results, including the coalescence step. The simple cascade simulation, though appropriate for high energies, cannot reproduce the medium energy data.

The measured proton cross sections are known to within 20% for the 137 and 92 MeV/nucleon data, but are uncertain by a factor of three for the 42 MeV/nucleon data due to beam monitoring difficulties.[4] At 92 MeV/nucleon (Fig. 3c), the calculations agree with the data. The calculation at 42 MeV/nucleon (Fig. 3d) agrees well with the data except for the 30° spectra, which are underpredicted at the lower proton energies. This is probably due to our neglect of evaporation protons, which dominate the projectile and target rapidity regions.

In summary, the Boltzmann equation, including the nuclear mean field and Pauli blocking corrections, provides a new approach to intermediate energy heavy ion collisions. Inclusive proton spectra from 42, 92 and 137 MeV/nucleon Ar + Ca collisions agree with the calculated cross sections. It may be useful to study the effect of the collision term on the mean field dynamics at even lower energies, where it may also be used to mimic TDHF. We are presently investigating the effect of the nuclear equation of state on intermediate energy collisions as well.

References:

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Figure Captions

Fig. 1 The momentum space evolution of an Ar(137 MeV/N)+ Ca collision at impact parameter b = 0 fm. The results from several parallel ensembles are superposed in order to represent the distribution function.

a) The initial state;

b) The final state without two body collisions;

c) The final state with two body collisions included.

Fig. 2 Time development of an Ar(42 MeV/N)+ Ca collision in configuration space at b = 0 fm. Again the results from several ensembles are superposed.

a) The reaction develops with two body collisions included;

b) The reaction without two body collisions.

Fig. 3 Inclusive proton spectra from Ar(42,92 and 137 MeV/N)+ Ca. The data[4] are indicated by points, and the theory by histograms. The largest statistical errors in the calculation are shown on the histograms. The breaks in the data from 30 to 40 MeV are the result of dead layers in the detectors.

a) Comparison of the present work with the 137 MeV/N data.

b) The same data compared to results obtained with the cascade model.[6]

c) The present theory compared to the 92 MeV/N data.

d) The present theory compared to the 42 MeV/N data.

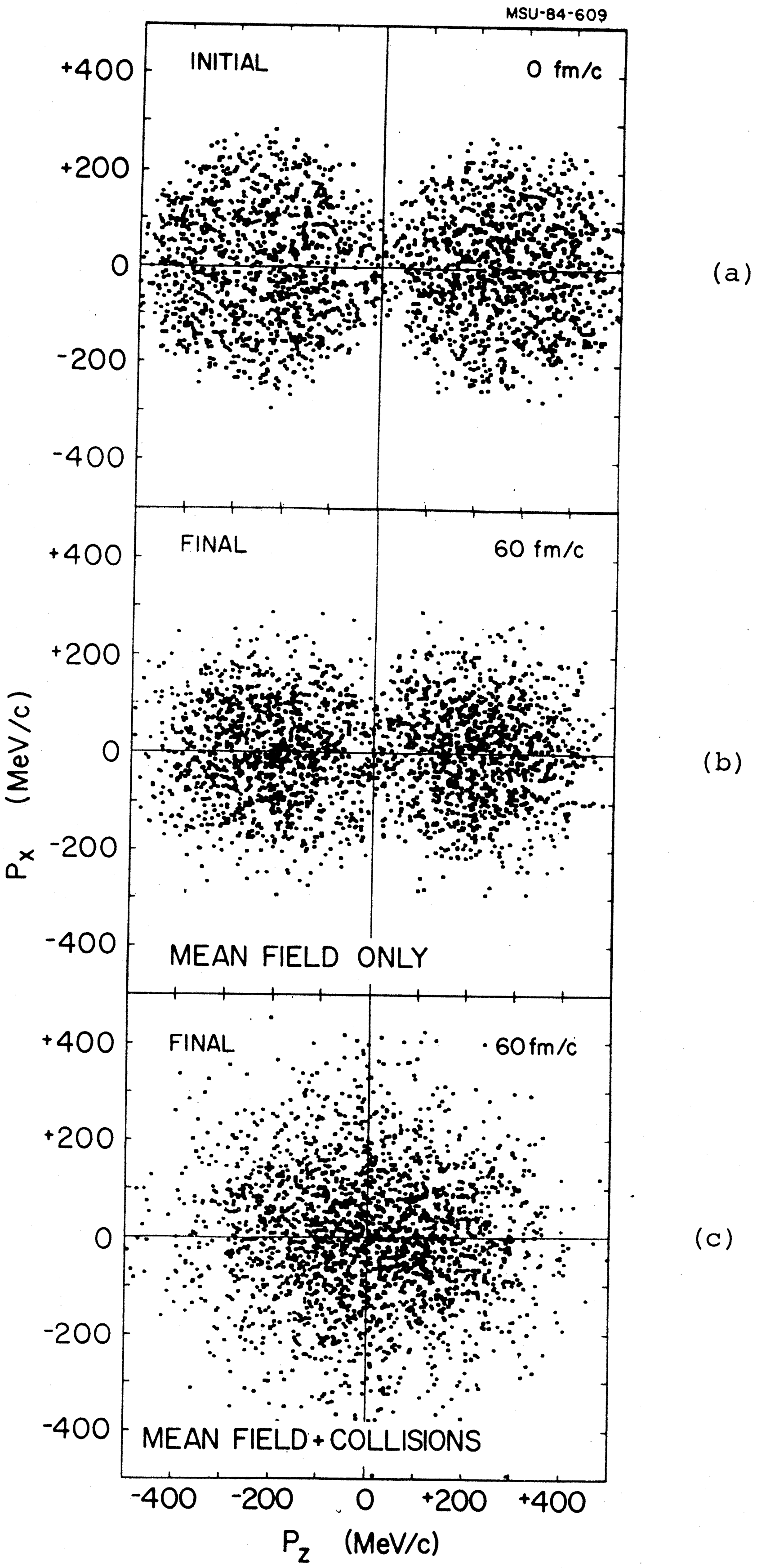
MSU-84-609
INITIAL
0 fm/c
(a)
FINAL
60 fm/c
(b)
MEAN FIELD ONLY
FINAL
60 fm/c
(c)
MEAN FIELD + COLLISIONS
+400
+200
0
-200
-400
P_x (MeV/c)
-400
-200
0
+200
+400
P_z (MeV/c)

FIGURE 1

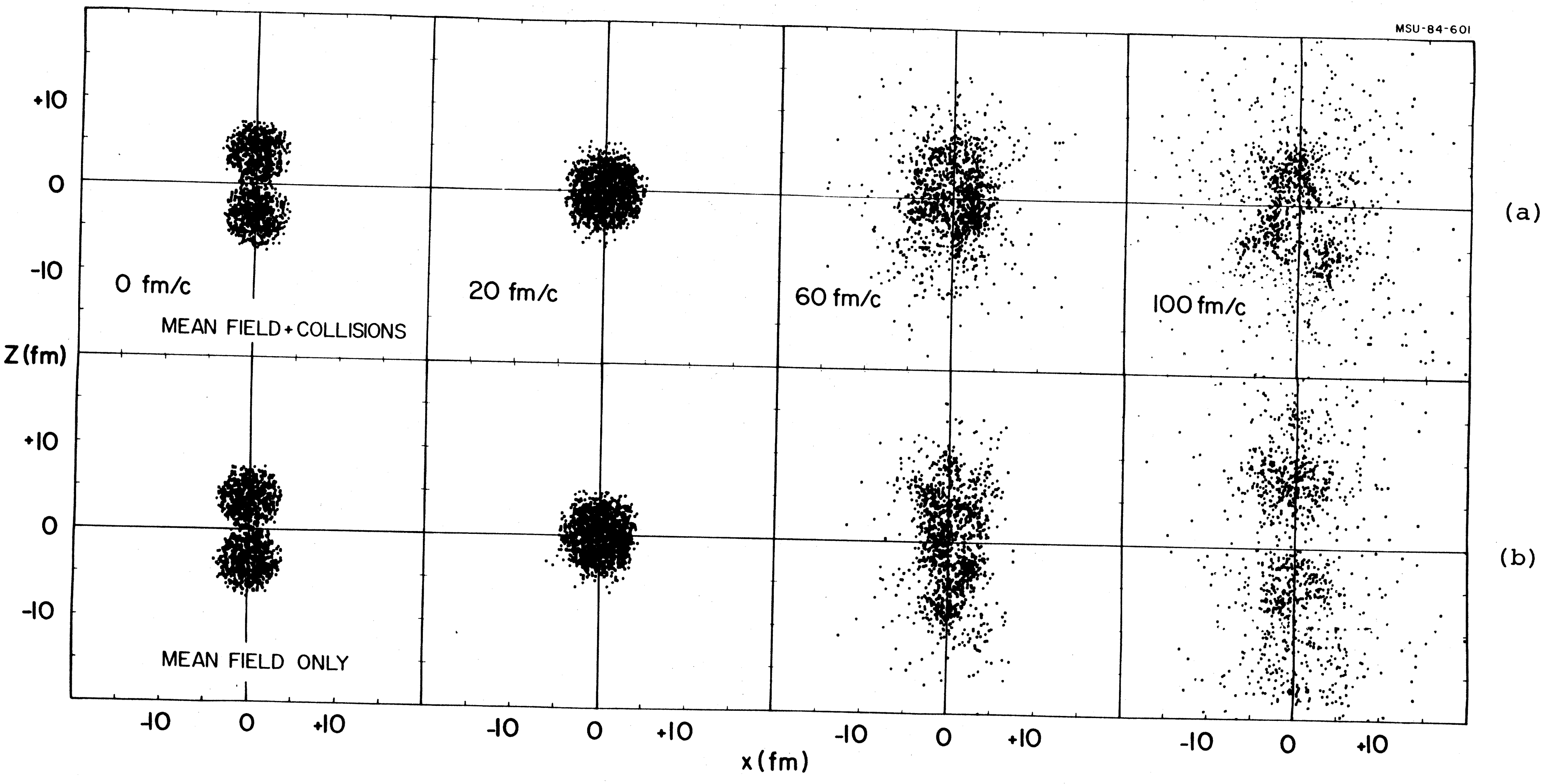MSU-84-601
+10
0
-10
Z (fm)
+10
0
-10
0 fm/c
MEAN FIELD + COLLISIONS
20 fm/c
60 fm/c
100 fm/c
(a)
MEAN FIELD ONLY
(b)
-10
0
+10
-10
0
+10
-10
0
+10
-10
0
+10
x (fm)

FIGURE 2

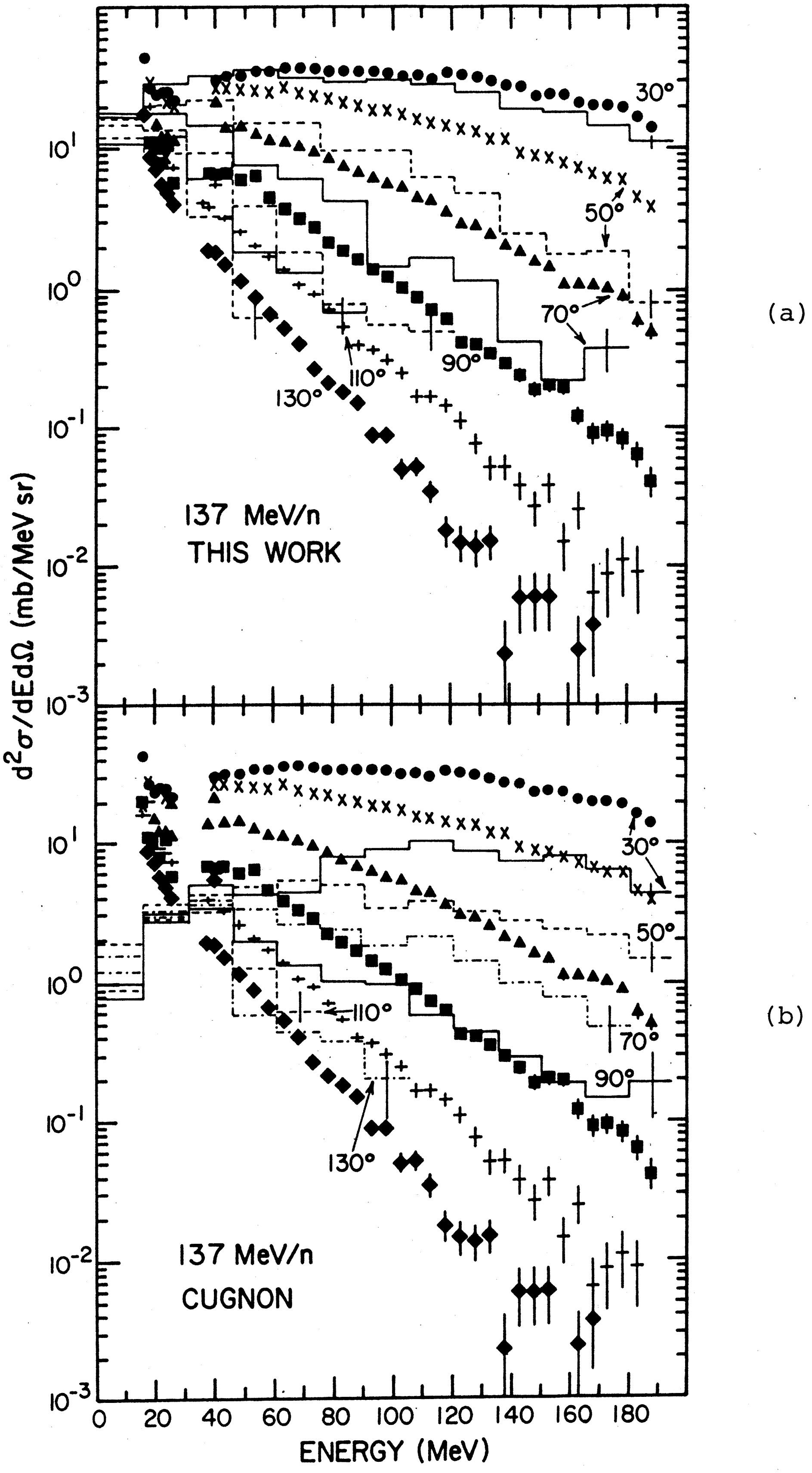
30°
50°
70°
90°
110°
130°
137 MeV/n
THIS WORK
(a)
30°
50°
70°
90°
110°
130°
137 MeV/n
CUGNON
(b)
$d^2\sigma/dEd\Omega$ (mb/MeV sr)
10^1
10^0
10^{-1}
10^{-2}
10^{-3}
0
20
40
60
80
100
120
140
160
180
ENERGY (MeV)

FIGURE 3

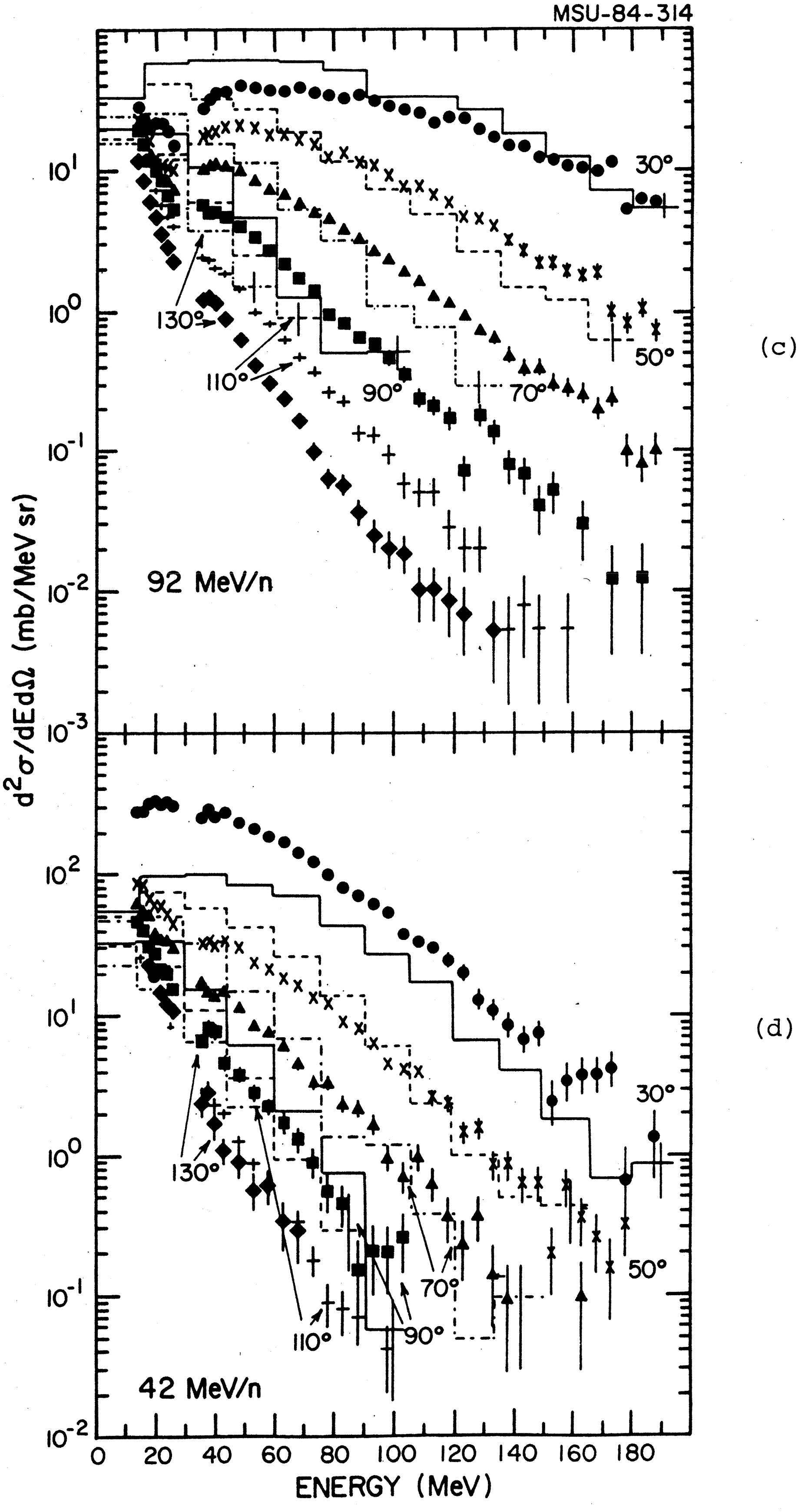

FIGURE 3 (cont.)