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CLUSTER APPROACH TO INTRANUCLEAR CASCADE FOR RELATIVISTIC HEAVY ION COLLISIONS

by

T. Kodama, S.B. Duarte, K.C. Chung
and R.A.M.S. Nazareth[1]

Centro Brasileiro de Pesquisas Físicas - CBPF/CNPq
Rua Xavier Sigaud, 150
22290 Rio de Janeiro, RJ - Brasil

[1]Instituto de Física, Universidade Federal do Rio de Janeiro
Ilha do Fundão - Cidade Universitária
21901 - Rio de Janeiro RJ - Brasil

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T. Kodama, S.B. Duarte and K.C. Chung
Centro Brasileiro de Pesquisas Físicas
Rio de Janeiro, Brasil

and

R.A.M.S. Nazareth
Instituto de Física, Universidade Federal do Rio de Janeiro
Rio de Janeiro, Brasil

A new approach to the intranuclear cascade model for relativistic heavy ion reaction is presented. The effect of nucleon concentration on the collision process is explicitly included. It is found that the contributions from the non-binary processes are far from being negligible. Such processes are shown to broaden the angular distribution of inclusive proton spectra for ^{20}Ne + ^{238}U head-on collisions.

In the last few years, a number of theoretical and experimental studies on relativistic heavy ion collisions (RHIC) has been done. The ultimate aim of such investigations is to learn about the properties of nuclear matter at extreme conditions of density and temperature. Up to present moment, our understanding on this subject is still far from being clear. Most of the available experimental data are inclusive ones, averaged over all impact parameters. Such data are shown to be not able, in general, to give detailed information about the collision dynamics. Thus they hardly detect any difference between the current models.

However, a new type of information is available from recent multiplicity-selected experiments[1]. Stöcker et al.[2] discussed the results of high multiplicity selected Ne (393MeV/A)+U reaction (head-on) with respect to the predictions of several theoretical models. They claimed that the model based on nuclear fluid dynamics has some advantage in reproducing the side-peaked angular distribution over the conventional intranuclear cascade calculation.

Nevertheless, the Monte-Carlo approach is useful to simulate the microscopic process, because it furnishes a direct way of calculating microscopic quantities without introduction of any phenomenological parameter. It remains still to discuss further to what extent the intranuclear cascade model is adequate in simulating the RHIC.

The basic point of the conventional cascade calculation is the assumption of sequential binary collisions[3]. However, this is not a trivial assumption. Rigorously speaking, such treatment is justified only in the limit of dilute gas approximation, where correlations, during the nucleon-nucleon collisions, are negligible. In RHIC, even when the incident energy is high enough so that the nucleon de Broglie wavelength is smaller than the mean nucleon interdistance at the normal nuclear density, we hardly expect that the system behaves as a dilute gas during the whole process. In fact for central collisions of heavy systems, a local density increase due to compression may cause correlations in nucleon-nucleon collisions. Such correlations manifest the non--binary character of RHIC. These non-binary correlations are fundamental for the possible appearance of novel collective phenomena, such as hydrodynamic shock wave, pion condensation and density isomeric states of nuclear matter. Thus it is essential to study the non-binary correlations in the context of intranuclear cascade model.

In this work, we propose a new approach to intranuclear cascade process which permits in a simple way, to incorporate correlation effects due to nucleon concentration. The procedure is the following:

At first, we simulate the projectile and target nuclei by randomly generated coordinates and momenta for A_P+A_T nucleons, where A_P and A_T are the mass number of projectile and target nucleus, respectively. The surface difuseness of density distribution is taken into account and the degenerate Fermi gas model is used. Then the incident nucleus with impact parameter b is boosted by a Lorentz transformation, according to laboratory incident energy E_{in}. Time evolution of the system is followed step by step with a time increment Δt appropriately chosen (see later discussion).

At each time t, we define clusters of nucleons according to the following prescription:

a) List up, for each nucleon, say i-th one, all nucleons j whose closest approximation r_{ij} to this i-th nucleon occur during the time interval Δt under the condition

$$\pi r_{ij}^2 \leq \sigma^{tot}(E_{ij})$$

where σ^{tot} is the total nucleon-nucleon cross section, and E_{ij} is the relative energy.

The above procedure gives an estimate of nucleon concentration around each nucleon. According to this concentration we classify all nucleons into groups.

b) Then for each group, select the pair (i,j) which has the smallest relative de Broglie wavelength λ_{min} and associate to this pair all other nucleons in the group whose distance from i or j is smaller than λ_{min}. Such a subgroup is called a cluster. This procedure is continued until all nucleons are grouped into clusters. In this way m nucleons in a cluster are supposed to collide, during the time interval Δt, in a correlated manner, to which we refer as an m-body collision.

Once clusters are formed, nucleon collisions are simulated in each cluster. For m = 2 (binary collision), we adopt the same procedure as usual[3], distinguishing among neutron-neutron, proton-proton and neutron-proton collisions. Cross section data are taken from the Particle Data compilation[4].

For m-body collisions ($m \geq 3$), in principle, quantum correlations must be taken into account. Unfortunately we have neither theoretical nor experimental information for treating such correlations. Therefore, we tentatively simulate these m-body collisions regarding them as an isotropic decay of a compound state of m nucleons in the cluster, namely the final m momenta are generated randomly in the CM system of the cluster, according to the invariant phase space[5]. It should be noted that, by doing this, we are practically washing out the quantum correlations in m-body collision, since such a momentum distribution is equivalent to that obtained by taking an ensemble average of many binary collisions among m particles. However, we hope that this particular choice will be harmless to estimate the amount of non-binary processes in RHIC.

The intranuclear cascade described above is continued until all collisions cease. The ultimate momentum distribution is used to calculate the differential cross section of emitted particles.

In our approach, the time interval Δt has a crucial physical meaning. It should be identified with the timescale of nucleon-nucleon collisions τ_{nn} = 1-2 fm/c. Since the conventional classical binary cascade assumes $\tau_{nn} = 0$, our model falls back to the binary collision case in this limit. On the other hand, for very large Δt and large effective nucleon-nucleon interaction range, our model tends to a fireball-type one.

In this letter, we apply our model to the reactions $^{12}C + ^{12}C$ (E_{in}/A = 800 MeV) and $^{20}Ne + ^{238}U$ (E_{in}/A = 393MeV , head-on collision). We restricted ourselves here only to the nucleonic degree of freedom.

We encountered in both cases an unexpectedly large frequency of non-binary collisions. Even for a small system such as $^{12}C + ^{12}C$, the contributions from non-binary processes reach up to 60%. In Fig. 1, we showed the percentage of each m-body contribution to the invariant differential cross section of $^{12}C + ^{12}C \rightarrow p+X$ reaction ($E_{in}/A = 800$ MeV) at $\theta_{lab} = 15^o$ as a function of final energy of emitted protons. The peak of binary curve at around the energy of elastic scattering, indicates an existence of relatively large contribution from knock-out protons at this angle. It is worthwhile to note that this is consistent with the shoulder-arm structure of the proton spectra[6]. Fig. 2 shows the calculated proton spectra. The agreement with the experimental data is very good, as expected for such impact parameter averaged data.

In the case of $^{20}Ne + ^{238}U$ reaction ($E_{in}/A = 393$ MeV, head-on), we present the mean frequency of m-body collisions in Fig. 3. It is seen that the non-binary collisions are far from being negligible. The rapid increase and slow decrease of these curves, which attain maximum at the same time, suggest a mechanism of a somewhat abrupt compression followed by an adiabatic-type expansion. As a matter of fact, it is found that the calculated relative frequencies behave as a Poisson distribution, $P(m) = = \lambda^{m-1} e^{-\lambda}/(m-1)!$, where $\lambda = \lambda(t)$ is proportional to the average density at time t. This indicates that the nucleon concentration effect is correctly reflected on the formation of clusters.

In Fig. 4, angular distributions of protons emitted from the same reaction are compared with the high-multiplicity selected data[1]. The calculated curves exhibit a little bit broader angular distributions than those of the conventional binary cascade model[2], although the experimental side-peaked angular distributions are still far from our results. It should be remembered that our phase-space ansatz for the m-body momentum distribution, which is almost equivalent to a local thermalization, does not favour sideward maxima at large angles. The systematic lowerness of our results with respect to the experimental data is probably due to the maximum impact parameter chosen (b_{max}=1.5 fm[7]).

In summary, we present a new approach to intranuclear cascade calculation, which include the degree of freedom of non-binary processes. It is shown that the simple phase-space ansatz does not give the experimental side-peaked angular distributions. However, it is expected that a more elaborated m-body momentum distribution may enhance the non-binary collision effects, leading to possible collective phenomena. Hence, it is crucial to investigate further the quantum m-body correlations in RHIC.

On the other hand, it should be remembered that our approach deals only with local correlation effects. Long range correlations can still be analysed in our approach in terms of interaction between clusters. We are studying this question, as well as the problem of the action of the mean field on low energy outgoing nucleons.

References

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Figure Captions

Fig. 1: Relative frequency of m-body collisions in ${}^{12}C + {}^{12}C$ reaction ($E_{in}/A = 0.8$ GeV) at $\theta_{lab} = 15^{o}$. Note that the maximum contribution of binary collisions occurs at the quasi-elastic region[6].

Fig. 2: Proton spectra for ${}^{12}C + {}^{12}C$ ($E_{in}/A = 0.8$ GeV) reaction. Experimental data (dots) are compared with calculated spectra (solid line). The bars denote statistical uncertainties (total event number = 7000). The data are not corrected for the emission of light composite nuclei.

Fig. 3: Mean frequencies of m-body collisions as function of time for the ${}^{20}Ne + {}^{238}U$ reaction ($E_{in}/A = 393$ MeV, head-on). The whole process has a relatively long duration, around five times the time T_0 necessary for Ne to pass through U without interaction.

Fig. 4: Angular distribution for protons emitted from central collisions of ${}^{20}Ne + {}^{238}U$ ($E_{in}/A = 393$ MeV). Dashed curve: our calculation; solid curve: experimental. Numbers indicated are final proton energy in MeV.

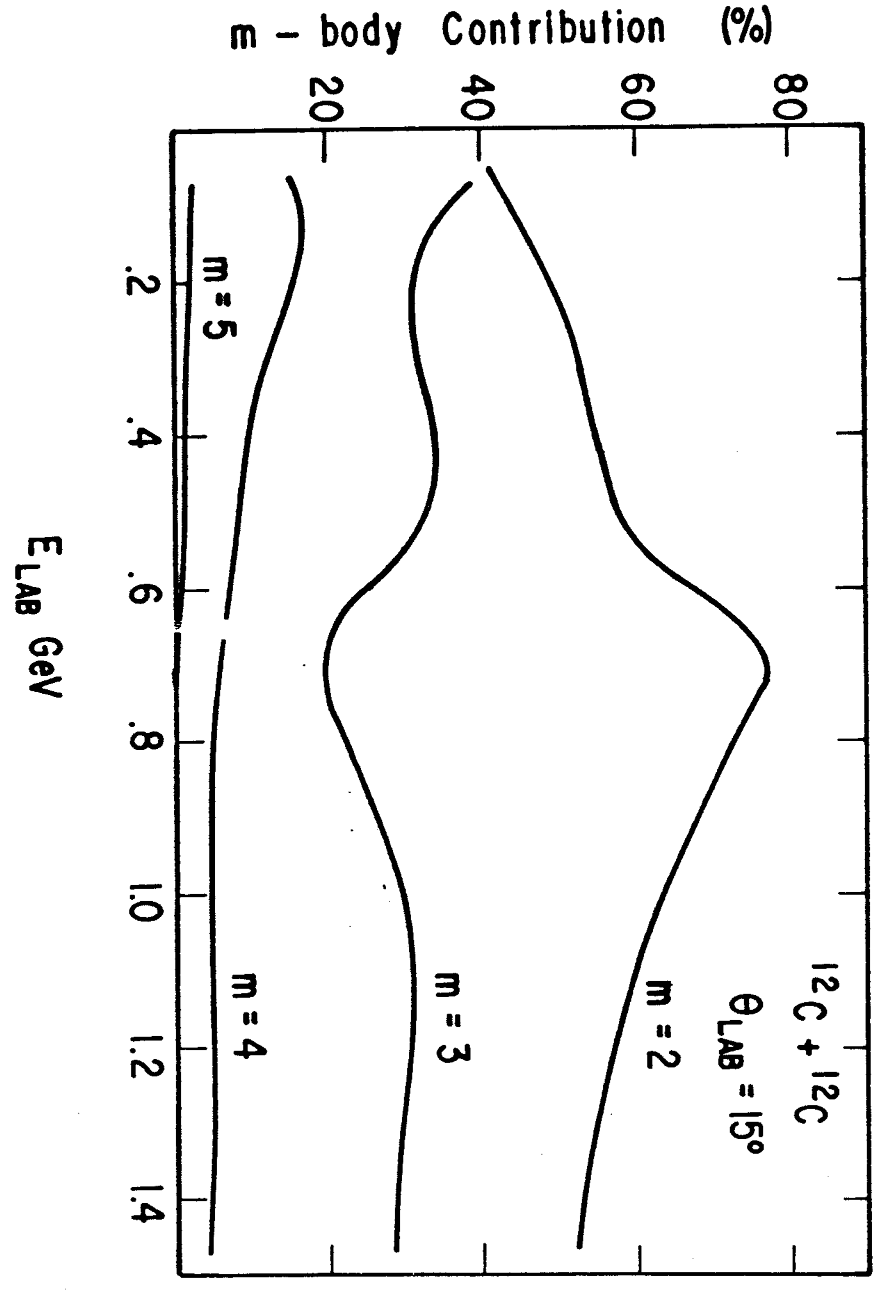
m - body Contribution (%)
20
40
60
80
.2
.4
.6
.8
1.0
1.2
1.4
E_LAB GeV
m = 5
m = 4
m = 3
m = 2
12C + 12C
θLAB = 15°

FIG. 1

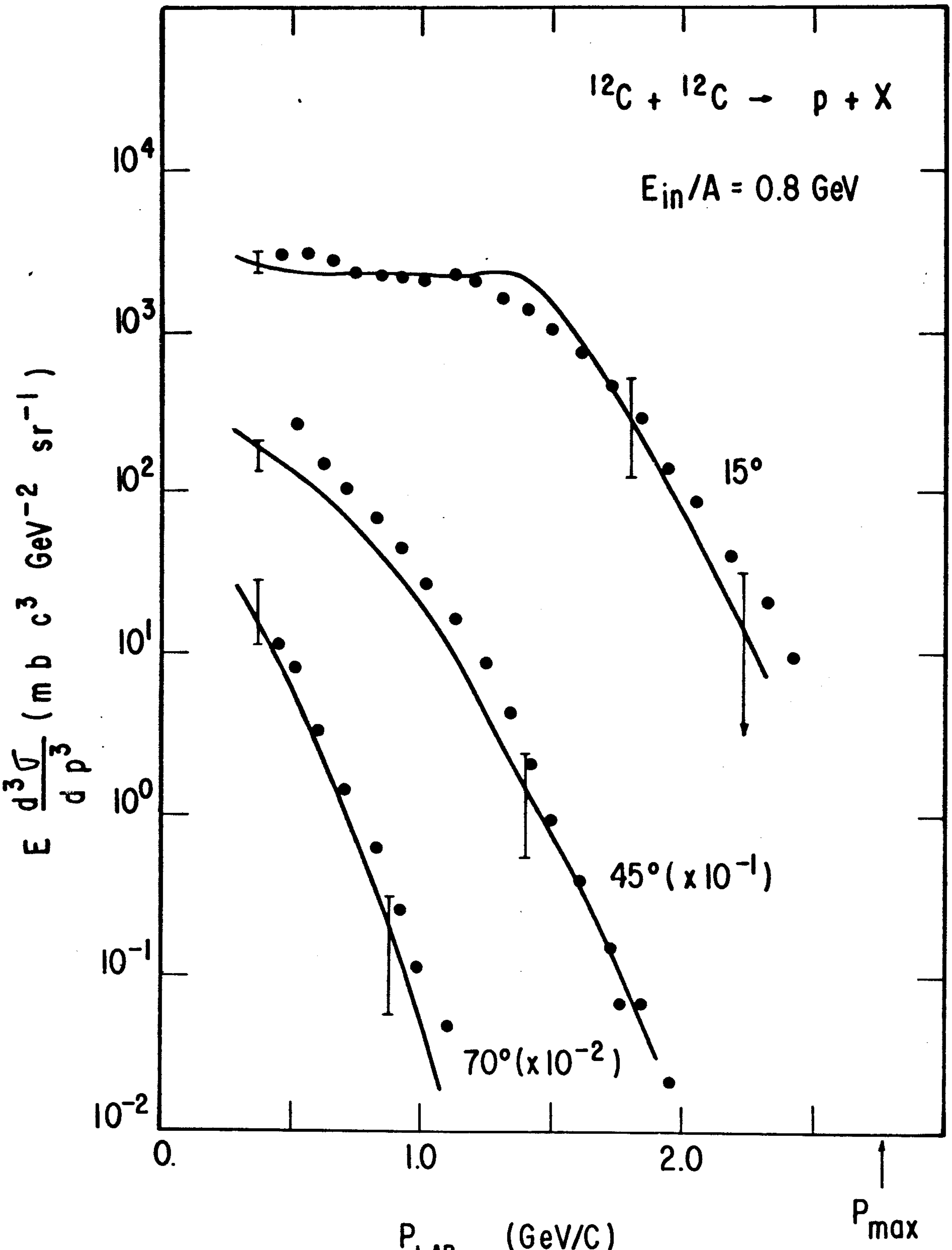
$^{12}C + ^{12}C \rightarrow p + X$
$E_{in}/A = 0.8$ GeV
$E \frac{d^3\sigma}{dp^3}$ (m b c^3 GeV^{-2} sr^{-1})
10^4
10^3
10^2
10^1
10^0
10^{-1}
10^{-2}
15°
45° (x 10^{-1})
70° (x 10^{-2})
0.
1.0
2.0
P_{max}
P_{LAB} (GeV/C)

FIG. 2

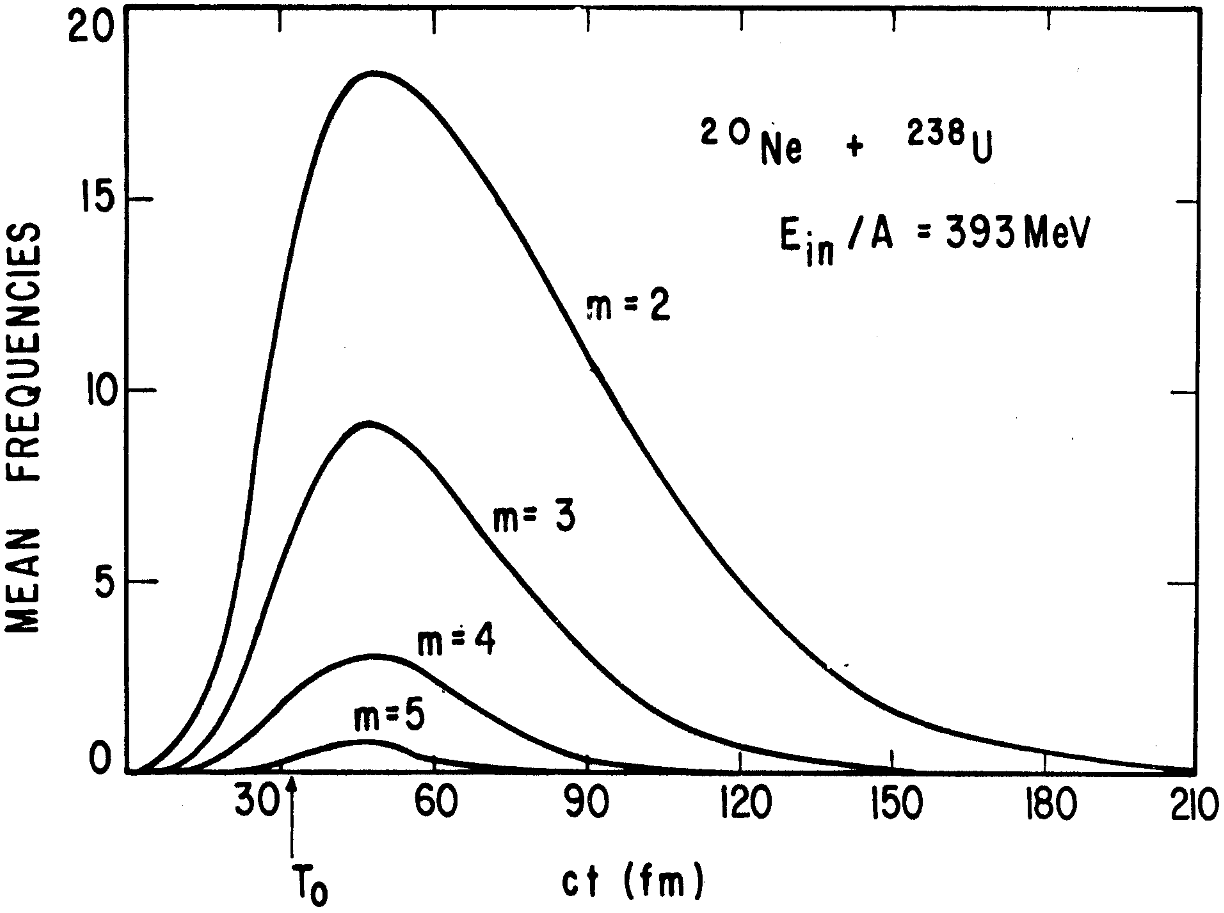
20
15
10
5
0
MEAN FREQUENCIES
30
60
90
120
150
180
210
ct (fm)
T_0
$^{20}Ne + ^{238}U$
$E_{in}/A = 393$ MeV
m = 2
m = 3
m = 4
m = 5

FIG. 3

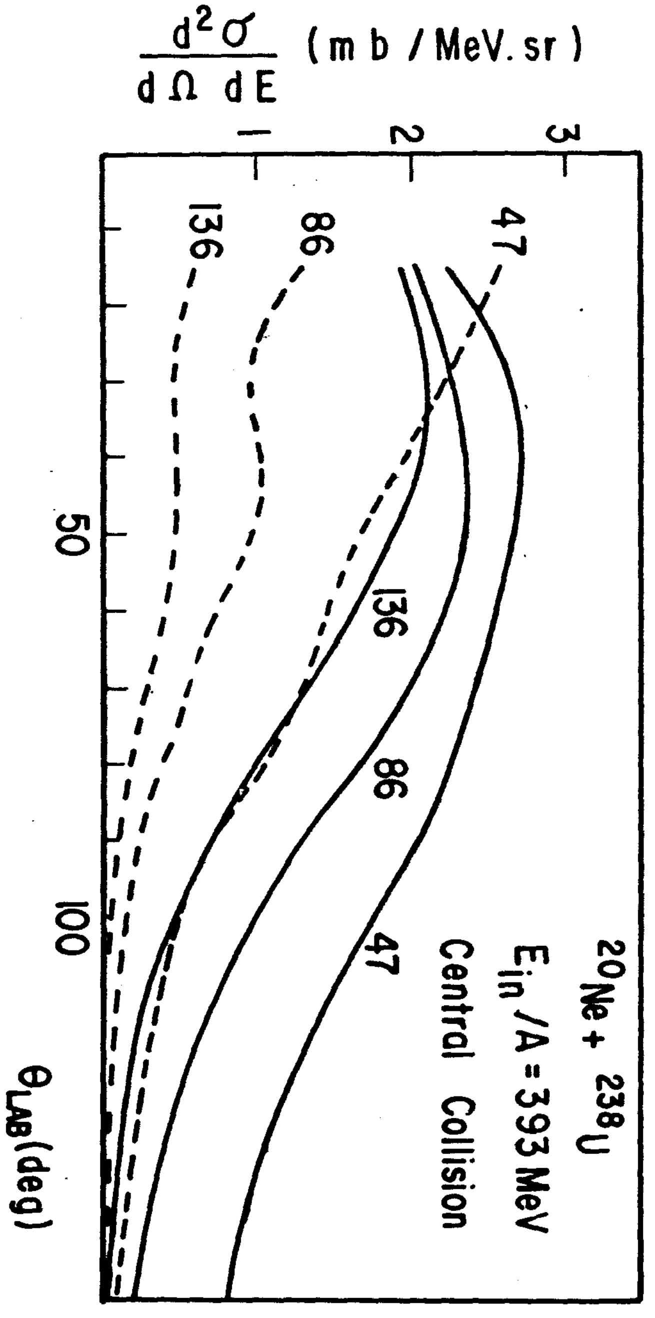
$\frac{d^2\sigma}{d\Omega\, dE}$ (m b / MeV. sr)
1
2
3
50
100
θ_{LAB}(deg)
136
86
47
136
86
47
^{20}Ne + ^{238}U
E_{in}/A = 393 MeV
Central Collision

FIG. 4