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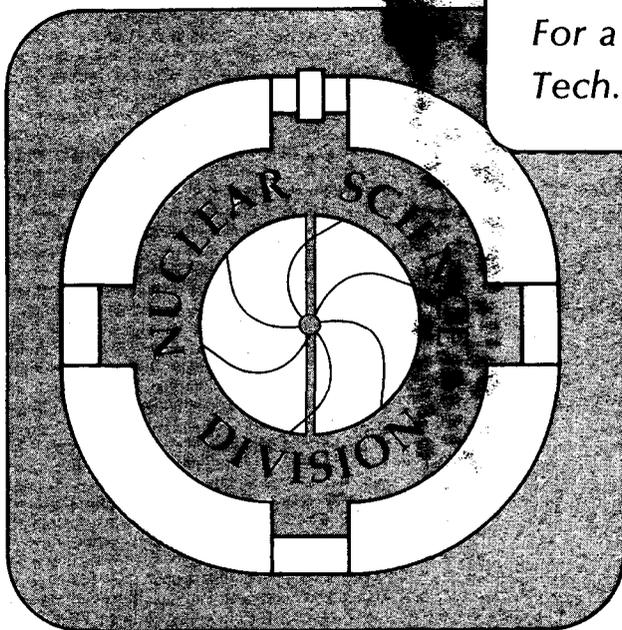
## RESULTS OBTAINED USING THE PLASTIC BALL

H.G. Ritter, H.A. Gustafsson, H.H. Gutbrod, B. Kolb,  
H. Löhner, B. Ludewigt, A.M. Poskanzer, T.R. Renner,  
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## Results Obtained Using the Plastic Ball

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### Introduction

Single particle inclusive experiments, and experiments that additionally measure a few correlations like the associated multiplicity, have provided the main contribution to our present understanding of high energy heavy ion collisions. The results from those experiments are in overall agreement [1] with calculations of the cascade [2,3] and hydrodynamical [4] models. In the cascade model the collision of two nuclei is simulated as a cascade of nucleon-nucleon collisions using measured N-N cross sections. The hydrodynamical model, on the other hand, describes the nuclear collision as that of two fluids and makes use of a nuclear equation of state relating thermal and compressional energy densities to pressure. The pressure field dominates the expansion phase and leads to collective flow of the reaction products in a preferred direction. The observation of such effects in inclusive experiments is not well established [5,6]. Collective effects that manifest themselves in the shape of the event in phase space are expected to be seen best in complete event detectors that measure the final state as exclusively as presently possible by measuring most of the charged particles emitted in the reaction. In addition, those detectors are well suited to test macroscopic concepts such as equilibrium and temperature. Global methods like the sphericity or thrust analysis [6] take into account all the correlations measured in the event and are specially designed to determine the shape of an event in phase space and thus to define a reaction plane.

Recent data from the Plastic Ball experiment about the study of nuclear stopping and thermalization and on global analysis are presented in this report. Of course, data from  $4\pi$  detectors like the Plastic Ball can be analyzed under many different aspects. Especially, the characterization of events according to charged particle multiplicity, presently still the best experimental approximation to impact parameter selection, has yielded new and unexpected results, e.g., about the production of composite particles [7] and two particle correlations [8].

### Experiment

The Plastic Ball [9] is a segmented multielement detector that covers 96 of the total solid angle. The general layout of the spectrometer is shown in fig. 1. The Plastic Wall, placed 6 m downstream from the target, covers the angular range from 0 to 10 degrees and measures time of flight, energy loss, and position of the reaction products. In addition, the information from the inner counters (0 to 2 degrees) is used to produce a trigger signal.

The Plastic Ball covers the region between 10 and 160 degrees. It consists of 815 detectors, where each module is a  $\Delta E$ -E telescope capable of identifying the hydrogen and helium isotopes and positive pions. The  $\Delta E$  measurement is performed with a 4-mm thick  $\text{CaF}_2$  crystal and the E counter is a 36-cm long plastic scintillator. Both signals are read out by a single photomultiplier tube. Due to the different decay times of the two scintillators,  $\Delta E$  and E information can be separated by gating two different ADCs at different times. The positive pions are additionally identified by measuring the delayed  $\pi^+ \rightarrow \mu^+ \rightarrow e^+$  decay. The quality of the particle identification is shown in fig. 2 for the hydrogen and helium isotopes.

Figure 3 shows the acceptance of the Plastic Ball experiment for protons in the plane of rapidity versus transverse momentum. In the different areas charged particles can be identified with different quality. Different projectile-target combinations have been measured with a minimum bias trigger and with a trigger configuration that selects central reactions. Results from 400 MeV/u Ca on Ca, 400 MeV/u Nb on Nb, and 800 MeV/u Ne on Pb are presented.

### Nuclear Stopping and Thermalization

Thermalization among the participant nucleons in high-energy nuclear collisions is predicted by thermal models and is a necessary condition for the determination of temperature. It is characterized by the fact that the originally longitudinal motion of the projectile is equally distributed over all available degrees of freedom (longitudinal and transversal). A necessary but not sufficient condition for thermalization is that [10]

$$\frac{1}{2} \sum_i p_{i\perp}^2 = \sum_i p_{i\parallel}^2$$

or

$$R = \frac{2 \sum_i |p_{i\perp}|}{\pi \sum_i |p_{i\parallel}|} = 1$$

(1)

A global stopping of the two nuclei at small impact parameters would show up in a ratio  $R = 1$  or even larger if hydrodynamical flow into transverse direction exists. In the presence of transparency this ratio would always be below 1. Data that fulfill the necessary condition of  $R = 1$  may indicate the existence of a nuclear fireball if, in addition, their energy spectra are of Maxwell Boltzmann shape in the center of mass.

In fig. 4 (top) contour lines of the yield of events in the plane  $2/\pi \sum_i |p_{i\perp}|/A$  vs  $\sum_i |p_{i\parallel}|/A$  are shown for the system Ca + Ca, the minimum

bias trigger applied. Most of the yield is far away from the  $R = 1$  (isotropy) region. The peak at small  $p_{\perp}$  but large  $p_{\parallel}$  corresponds to peripheral reactions and is dominated by projectile fragments. This contribution vanishes as the trigger is changed to a "central" one. Figure 4 (middle) shows central trigger events with a charge particle multiplicity larger than 30. The maximum of the yield is shifted toward the diagonal but only a few events reach  $R = 1$ , which, for large multiplicities and absence of any two jet structure, corresponds to a full stopping of the nuclei. In the lower part of fig. 4 for the reaction of 400 MeV/u Nb + Nb the central

trigger events with charge particle multiplicities beyond 55 are fulfilling the stopping condition ( $R = 1$ ) on the average.

The observed difference between the Ca + Ca and the heavier Nb + Nb system allows two different interpretations: The Ca nuclei are too small to stop one another, so a transparency remains in the longitudinal direction, or only a subvolume is fully stopped and eventually thermalized, but the surface zones show some transparency and therefore the differences are caused by the various surface-to-volume ratios of Ca and Nb. However, one has to keep in mind that the high multiplicity cuts correspond roughly to an impact parameter selection from 0 to 3 fm, where in these symmetric systems still large parts of the nuclei might pass one another rather undisturbed. Although spectator fragments are excluded within  $\theta_{lab} < 2^\circ$  with our central trigger condition, there are still some "leading particles" left outside of  $\theta_{lab} = 2^\circ$ . Any one of these particles strongly enhances the parallel momentum component, thus reducing the ratio R.

### Global Analysis

It has been pointed out that event shape analysis might be able to distinguish between predictions of cascade and hydrodynamical models. To do this the thrust [11-13] and sphericity [12,14] analyses used in high energy physics [6] have been proposed. Because the thrust vector cannot be calculated analytically, the sphericity method generally has been used.

The sphericity tensor

$$F_{ij} = \sum_{\nu} p_i(\nu) p_j(\nu) w(\nu)$$

is calculated from the momenta of all measured particles for each event. It is appropriate to choose the weight factor  $w(\nu)$  in a way that composite particles have the same weight as the individual nucleons of the composite particle at the same velocity. In this paper the weight  $w(\nu) = 1/(2m)$  as proposed in ref. 14 (kinetic energy flow) is used. Other coalescence invariant weights such as  $1/p$  [12] have been proposed and have been used in our analysis. The sphericity tensor approximates the event shape by an ellipsoid whose orientation in space and aspect ratios can be calculated by diagonalizing the tensor.

The shapes predicted by hydrodynamical and cascade calculations are quite different. The hydrodynamical model predicts prolate shapes along the beam axis for grazing collisions. With decreasing impact parameter the flow angle increases up to 90 degrees for zero impact parameter events and the shape becomes prolate [11,13,14]. This behavior is independent of projectile and target mass. Cascade calculations, on the other hand, predict finite nontrivial flow angles only for very heavy systems [14].

A rigorous comparison of experimental data with predictions is only possible if the theory calculates all observed quantities by generating a large number of complete events. Those events have to be filtered with the known experimental acceptance and efficiency of the detector. Most models, however, have not yet reached sufficient sophistication: cascade models do not include composite particles, and hydrodynamical codes do not yet produce

event-by-event fluctuations. This makes a useful comparison difficult, and it is not yet clear that the differences between the two models will show up after all distortions are taken into account.

Another big obstacle in extracting information from a flow analysis is fluctuations due to finite particle effects. Recently, Danielewicz and Gyulassy [15] have shown that those distortions strongly depend on multiplicity and that the flow angle,  $\theta$ , if properly weighted by the Jacobian ( $\sin\theta$ ), is much less severely shifted towards higher values than the aspect ratios. It now can be shown that the results of the flow analysis of the 400 MeV/u Ca + Ca data [16] (fig. 5), even though they differ from cascade predictions, can be explained with finite number distortions by assuming prolate shapes along the beam axis [17]. Deviations from cascade predictions seen in the analysis of asymmetric target projectile combinations measured with the streamer chamber [18,19] seem to be inconclusive as well because the data points in the flow plot do not fall in the region where, despite the distortions, nontrivial flow angles and aspect ratios can be detected.

It is hoped that heavier symmetric systems are less sensitive to distortions and that possible macroscopic effects can more easily be detected. As shown in fig. 6, the Nb + Nb data at 400 MeV/u reach flow angles up to 30 degrees (peak maximum) for the highest multiplicity bins, whereas predictions from the Yariv-Fraenkel cascade [2], filtered with the exact acceptance and efficiency of the Plastic Ball never deviate significantly from 0 degrees even for the highest multiplicity events. The fact that finite flow angles are seen in the data indicates that in those events there exists a plane defined by the flow axis and the beam axis, which will be called the reaction plane. All events can be rotated by the azimuthal angle  $\varphi$  determined by the flow analysis so that their individual reaction planes all fall into the x-z plane, with the z-axis being the beam axis. For those rotated events rapidity plots in the reaction plane [13,20] can be calculated. The use of  $p_{\perp}/m$  as proposed in ref. 13 is only of theoretical interest as the phase space vanishes. However, the invariant cross sections  $dp_x/mdy$  (in plane) and  $dp_y/mdy$  (out of plane) can be plotted, where  $p_x$  is the projection of the perpendicular momentum into the reaction plane and  $p_y$  the projection into the plane perpendicular to the reaction plane. Figure 7 shows these plots for 400 MeV/u Nb + Nb data and cascade calculations for events with charged particle multiplicities between 40 and 50, the second highest multiplicity bin considered here. The depletion near target rapidities is due to experimental acceptance. The two cascade plots and the out-of-plane data plots are symmetric around the beam axis, whereas the in-plane data plot is clearly asymmetric. Taking into account the multiplicity dependence of the rapidity plots (not shown here), two distinctly different trends can be observed. The outer low-intensity contour lines seem to follow the trend indicated by the  $dN/d \cos \theta$  distribution. At low multiplicity they can be described by ellipsoids elongated along the beam axis. With increasing multiplicity the ellipsoids are more and more turned relative to the beam axis. The peak in the rapidity distributions, resulting largely from the projectile remnants, on the other hand, is rather independent of multiplicity. It clearly shows a perpendicular and longitudinal momentum transfer to the spectator nuclei. The longitudinal degradation of about 0.05 units in rapidity is not dependent on multiplicity, and the perpendicular momentum transfer varies only slightly

from about 30 to 50 MeV/c per nucleon as a function of multiplicity. The deflection angle of the projectile remnants always stays below 10 degrees.

As can be seen from figs. 6 and 7 cascade calculations are not able to reproduce the data. An exact comparison with predictions from hydrodynamical model calculations is not possible as the impact parameter is not known experimentally. However, comparison with cascade events indicates that the highest multiplicity bin of the data contains events whose impact parameter can be as large as 3 to 4 fermis. Considering such large impact parameters the hydrodynamical predictions [13] seem to be in qualitative agreement with the  $dN/d \cos \theta$  distributions. The deflection of the spectator matter is a collective effect that might be due to the effect of a nuclear potential and should be explained, e.g., by classical equation of motion calculations [21].

For asymmetric systems the flow analysis is usually performed in the center of mass of all the measured particles. The velocity  $\beta_{obs}$  of this system in the beam direction should depend on the impact parameter and thus on the multiplicity of charged particles  $m_c$ . Figure 8 shows a contour plot of  $m_c$  as a function of the observed velocity  $\beta_{obs}$  for the reaction 800 MeV/u Ne + Pb. This velocity varies from that of the nucleon-nucleon system  $\beta_{NN}$  for the most peripheral collisions up to the velocity of the compound system  $\beta_{comp}$ . It significantly overshoots the fireball system velocity  $\beta_{FB}$  even though only about one-third of all particles (and preferentially the faster ones) are detected. This strongly indicates not only that the projectile is stopped as, e.g., predicted by a clean-cut fireball model [22] but that the target nucleus as a whole stops the projectile. The emission pattern of this "compound" system can be studied by a flow analysis. The flow angle distributions  $dN/d \cos \theta$  for the different multiplicities all peak at 0 degrees, but for the highest multiplicities they become flat and angle independent, indicating isotropic emission. The same pattern is suggested by the rapidity plots.

## Conclusions

The ratio  $R$  of perpendicular to longitudinal momentum per nucleon shows that even for the most violent reactions in the Ca on Ca case at 400 MeV per nucleon there is always some transparency left, whereas in the Nb case the two nuclei are stopped in average and the participant nuclei seem to form an expanding fireball. The fact that for Nb finite flow angles are observed must not necessarily be in contradiction to this statement as the event-by-event variations of  $R$  are quite large, and only the rather crude classification of events according to the observed charged particle multiplicity has been studied so far.

The  $dN/d \cos \theta$  distributions show no finite flow angle for the Ca case but reach angles of up to 30 degrees for Nb. However, in both cases a clear collective deflection of the spectator nuclei that is nearly independent of multiplicity is observed. It will be necessary to study the energy and mass dependence of those effects and to compare with cascade and hydrodynamical calculations as well as with events generated with the Fai-Randrup code [23] where parameters like perpendicular and longitudinal momentum transfer can be adjusted before final conclusions about collective effects in relativistic nuclear collisions can be drawn.

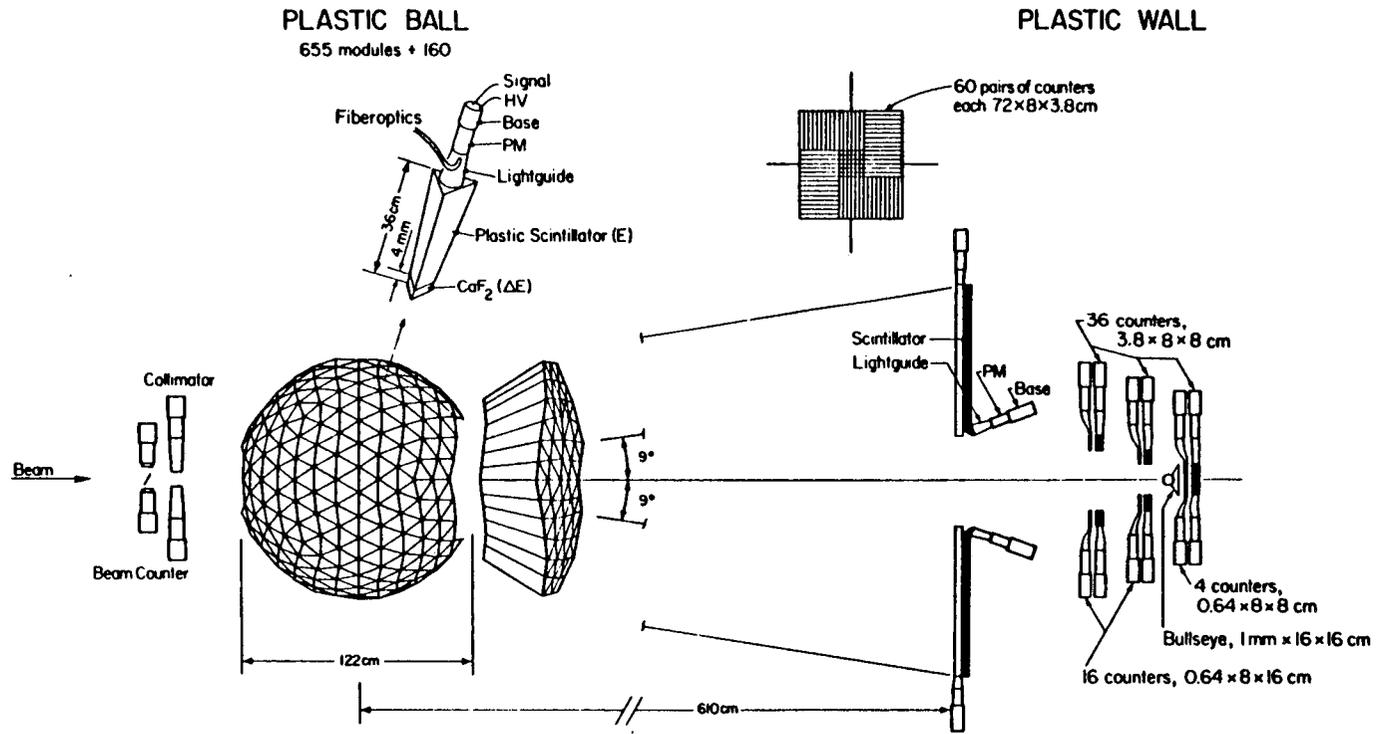
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Figure Captions

- Fig. 1. General layout of the Plastic Ball experiment.
- Fig. 2. Particle identification spectrum for 655 modules after gain-matching with (dashed line) and without (solid line) scattering out reconstruction.
- Fig. 3. Plastic Ball acceptance in the plane rapidity versus transverse momentum.
- Fig. 4. Contour plots of the perpendicular momentum per nucleon as a function of the parallel momentum per nucleon for 400 MeV/u Ca on Ca for two different trigger selections (top) and for 400 MeV/u Nb on Nb.
- Fig. 5. Flow plot for 400 MeV/u Ca on Ca.
- Fig. 6. Frequency distributions of the flow angle  $\theta$  for different multiplicity bins (data and cascade calculations).
- Fig. 7. Contour plots (linear contours) of the projection of the transverse momentum in and out of plane as a function of cm rapidity.
- Fig. 8. Contour plot (linear contours) of the charged particle multiplicity as a function of the velocity of the cm system of the measured charged particles.



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Fig. 1

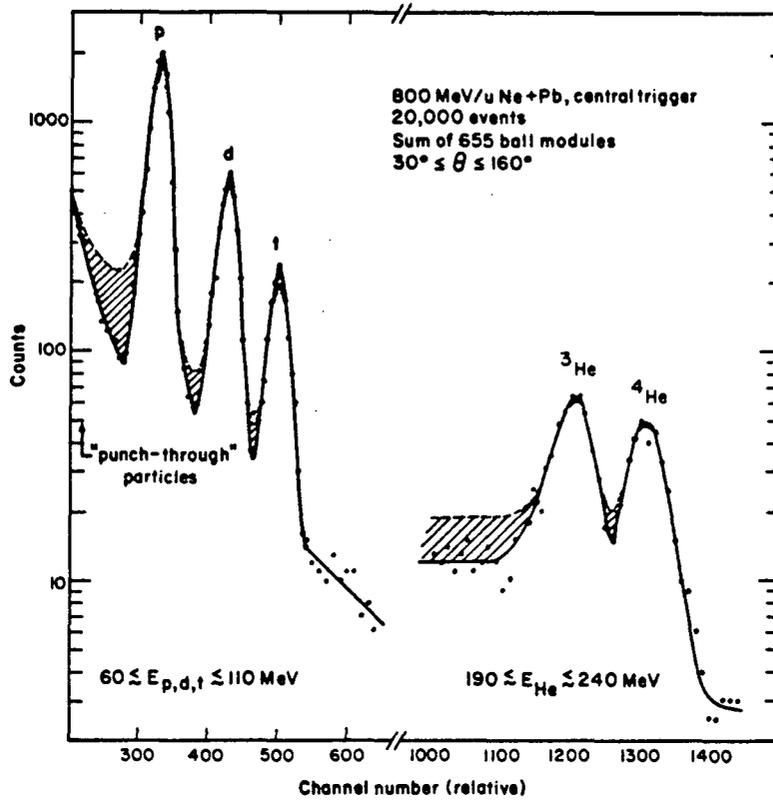


Fig. 2

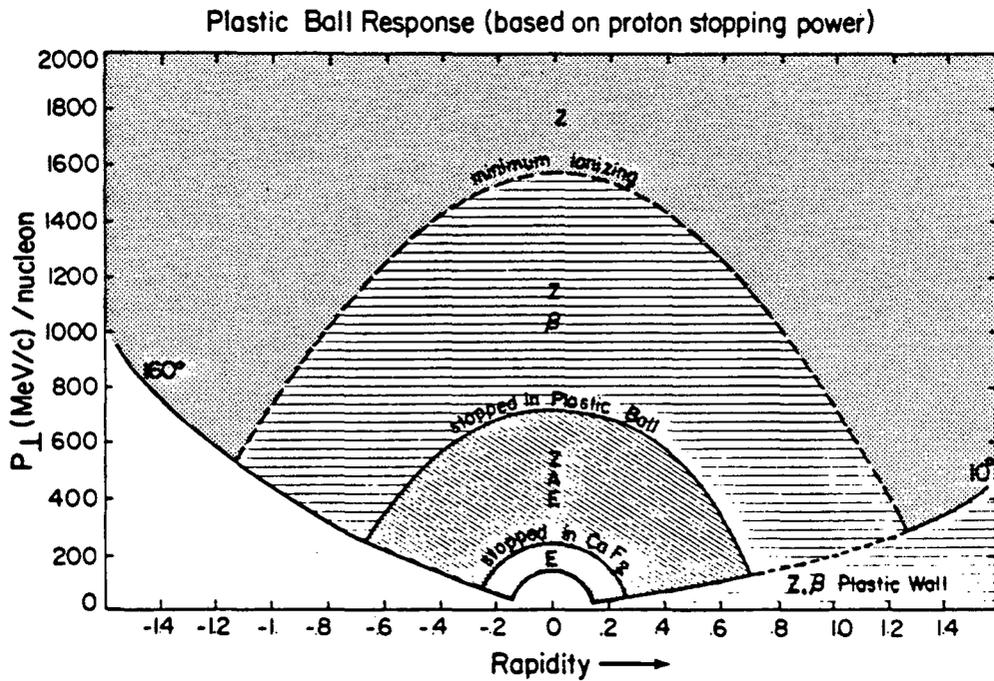


Fig. 3

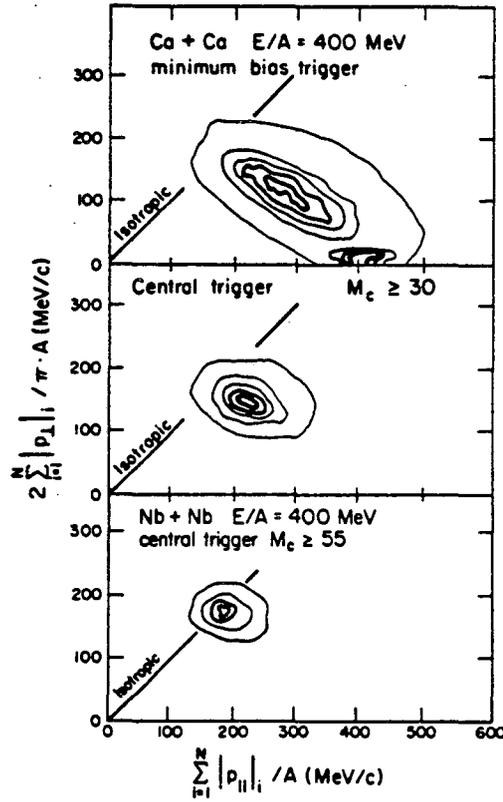
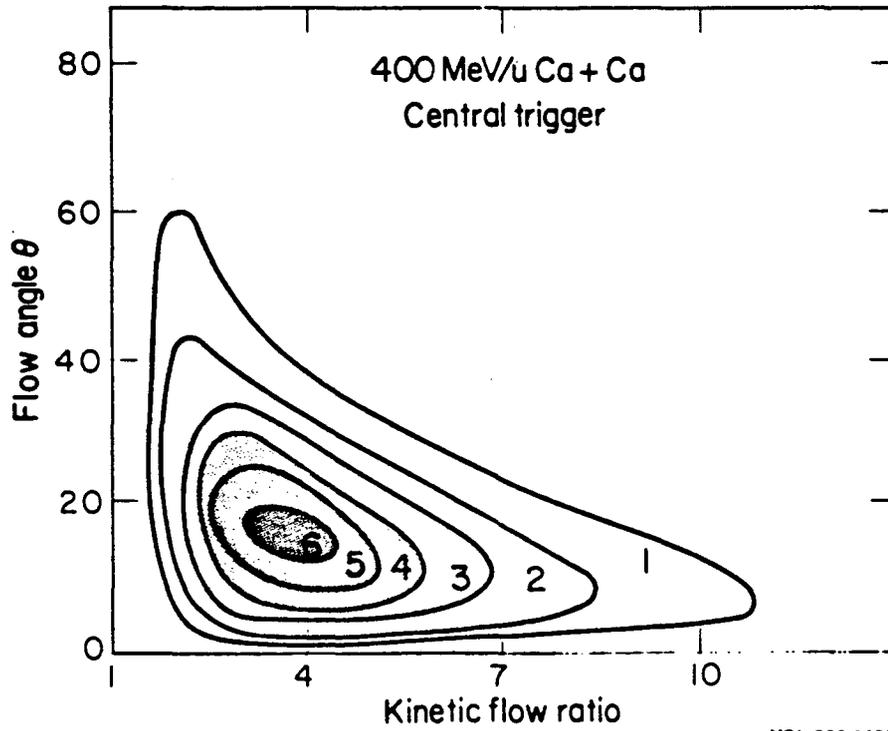
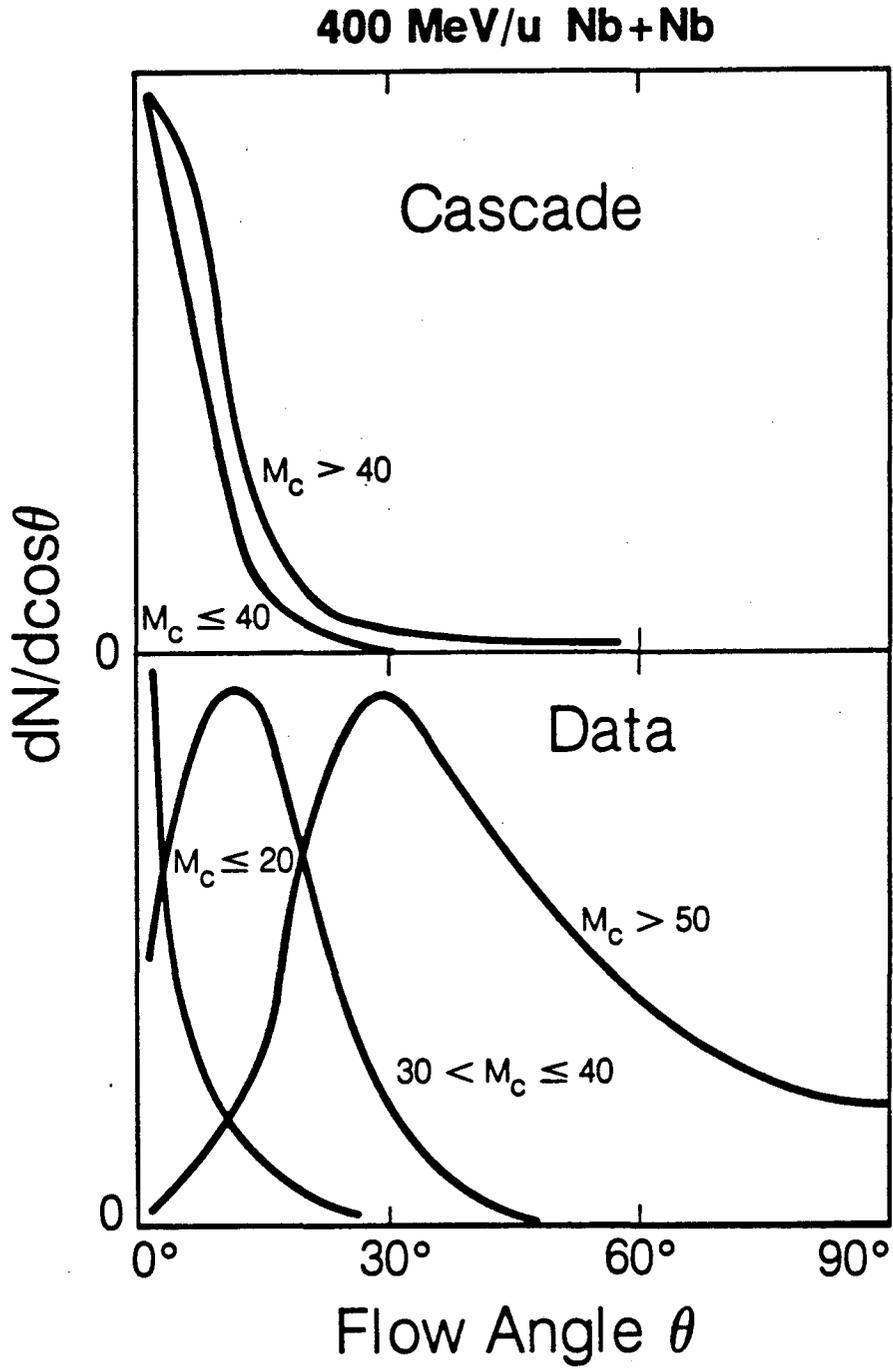


Fig. 4



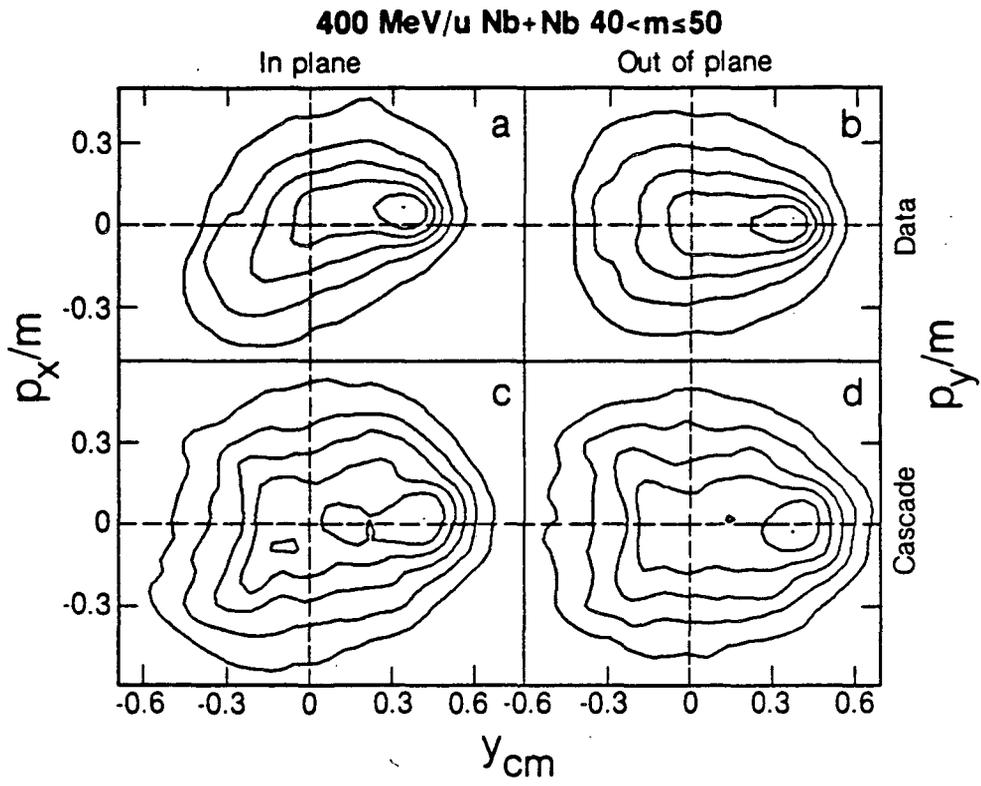
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Fig. 5



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Fig. 6



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Fig. 7

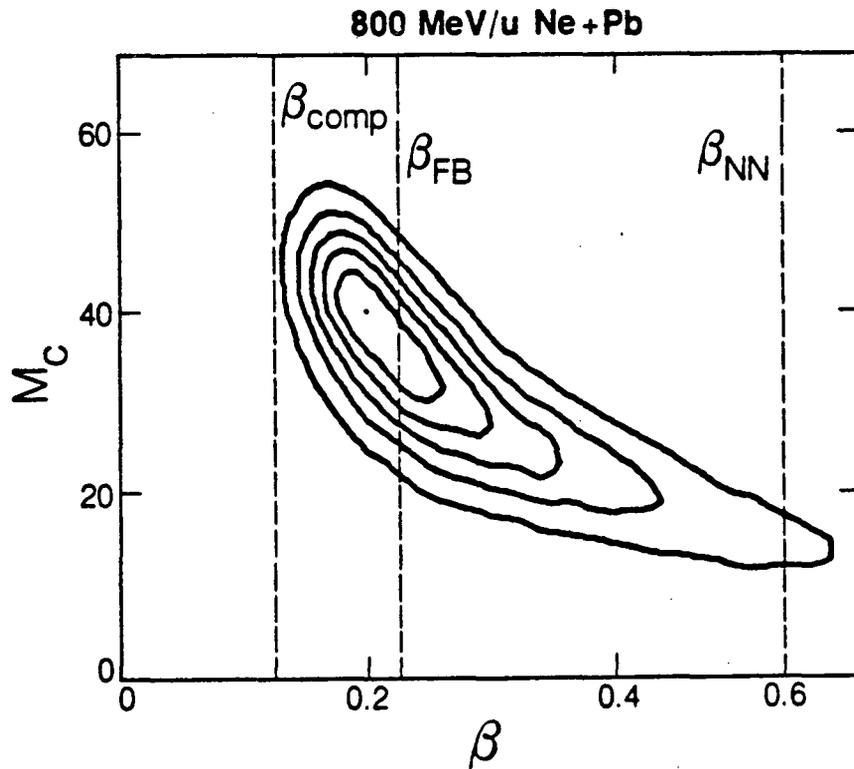


Fig. 8

XBL 835-245

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