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Author
Ritter, H.G.

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Lawrence Berkeley Laboratory
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H.G. Ritter

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H.G. Ritter

Gesellschaft für Schwerionenforschung
Darmstadt, West Germany

and

Nuclear Science Division, Lawrence Berkeley Laboratory
University of California, Berkeley, CA 94720

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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 the new 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 and the streamer chamber experiments, the first complete event detectors in use at the Bevalac, are presented in this report.

Experiments

The Plastic Ball and streamer chamber are two complementary detectors. As a visual detector the streamer chamber is ideally suited for the observation of overall features and to study processes that result in a clear pattern, e.g., the characteristic decay in "Vee" form of strange particles. The cross sections that can be seen with a reasonable amount of beam time are limited to about 10 mb because experiments have to be performed with low beam intensities, only three events per second can be accepted, and the photographs of the events have to be scanned. Light cluster identification is possible within limits. The Plastic Ball can identify composite particles up to ≈250 MeV/u with much better quality and is well suited for experiments with high statistics because high beam intensities can be used and all the measured information is immediately available in digital form.

The streamer chamber at the Bevalac has been in use for a long time and has been well described in ref. 7. Considerable qualitative and quantitative progress in automatizing the scanning has made complete event analysis possible.

The first experiments with the Plastic Ball[8] were performed in 1981. The general layout of the experiment 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 inner counters serve together with the beam counter as a trigger.

The Plastic Ball covers the region between 10 and 160 degrees, 96% of the total solid angle. It consists of 815 detectors, where each module is a ΔE-E telescope capable of identifying the hydrogen and helium isotopes and positive pions. The ΔE measurement is performed with a 4-mm thick 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, ΔE 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.

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. The streamer chamber measures the momentum of the charged particles above 15 MeV/u with the exception of two blind spots at 90° where the particles travel parallel to the magnetic field.

With both detector systems 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, 800 MeV/u Ne on Pb, 800 MeV/u Ar on Pb, and 1.8 GeV/u Ar on KCl measurements will be presented.

Thermalization and Entropy

Thermalization in the reaction is characterized by the effect that the originally longitudinal energy is randomized over longitudinal and transversal degrees of freedom. The degree of thermalization reached can be expressed by the ratio[9]

$$2\sum|p_\perp|_i \Big/ \pi\sum|p_\parallel|_i \,.$$

This ratio is shown in fig. 4 as a function of the charged particle multiplicity for the reaction 400 MeV/u Ca on Ca. The peripheral events show, as expected, a high degree of transparency, whereas in central collisions thermalization or randomization is nearly reached. In the mass 40 system the surface effects are too large to expect complete thermalization, as there are always enough nucleons that escape after one collision. It will be interesting to study the mass and energy dependence of that ratio for central collisions.

Due to the ability of identifying the particles, the Plastic Ball is well suited for investigating the emission of protons and light clusters in high energy heavy ion reactions. Such studies should yield information about the reaction mechanism and answer the question whether composite particles come from a thermalized source, or whether a coalescence process that only requires closeness in phase space of the constituents, is reponsible for cluster production. The ratio of the production cross sections of deuterons to protons has been related to the entropy in the reaction zone in ref. 10. This proposition to determine the entropy from directly accessible experimental results has stimulated a vivid discussion[11,12]. Corrections to the Siemens and Kapusta formula have been proposed[13], where the deuteron-to-proton ratio is replaced by the ratio of deuteron-like to proton-like particles[14], thus taking into account heavier composites.

The inclusive deuteron-to-proton ratio was measured for many reactions[15]; now it can be plotted as a function of the charged particle multiplicity as shown in fig. 5a for the case 400 MeV/u Ca on Ca and in fig. 5b for 800 MeV/u Ne on Pb. Both curves rise with increasing multiplicity and show saturation at high multiplicity. A similar trend can be observed with cascade calculations[16]. In relation to the entropy discussion, that would indicate that the entropy per baryon decreases slightly with increasing violence of the collision. The event-by-event fluctuation of the ratio is smaller, when the deuteron-like to proton-like particle ratio is used, which might be more related to the entropy than the d/p ratio.

Global analysis

The global analysis methods (sphericity, thrust) were developed as a tool to detect and distinguish predicted two jet events at high energy e^+-e^- storage rings from events with spherically symmetric emission patterns[6]. Both methods define a jet axis, the sphericity by minimizing $\sum_i p_{i\perp}^2$ and the thrust by maximizing $\sum |p_{i\parallel}|$ relative to this axis. The sphericity is calculated analytically by diagonalizing the sphericity tensor. One obtains the orientation of the sphericity axis, e.g. relative to the beam direction and three eigenvalues which define an ellipsoid that describes the shape of the event. The thrust analysis yields in addition to the orientation only the magnitude of the thrust, a quantitative measure distinguishing between isotropic and back-to-back emission.

The use of global methods to analyze the more complex events from heavy ion collisions was proposed by several authors[17,18]. Sphericity (p^2) overweights leading particles and gives two nucleons a different weight from a deuteron with the same energy per nucleon. Corrections for these shortcomings have been proposed[18], e.g. the flow analysis presented at this conference[19]. Since a global analysis has to be performed for each event, statistical fluctuations due to finite number effects and to limited experimental acceptance and efficiency are expected. Experimental data have to be compared with results from an analysis of theoretically calculated events, which have been filtered for experimental acceptance and efficiency. Most theoretical models have not yet reached the sophistication of the experimental equipment in the sense that they are not able to calculate all the measured quantities. Cascade codes do not include composite particles and hydrodynamical codes do not produce event-to-event fluctuations. This makes the comparison between experiment and theory difficult. Complete events generated with a statistical model calculation by Randrup and Fai[20] will be extremely useful to study the effect of finite number fluctuations and experimental biases.

Figure 6a shows the comparison between a flow analysis of 170 streamer chamber events from the reaction 1.8 GeV/u Ar on KCl and the results from a calculation with the Cugnon cascade code[3] filtered with the experimental acceptance and selected according to impact parameters. Mean values and variances of the ratio of the largest to the smallest axes of the flow ellipsoid are plotted against the angle of the main axis with respect to the beam direction. The experimental point falls between cascade and hydrodynamical predictions[1] and is compatible with both. Figure 6b shows the same comparison for the asymmetric system 800 Mev/u Ar on Pb. The data again are compatible with cascade calculations. For an asymmetric collision the c.m. system depends on the impact parameter and is not known experimentally. The flow analysis is therefore performed in the center of mass system of all measured particles (not identical with the participant c.m. system). This introduces additional fluctuations. For asymmetric systems a cluster analysis[21] that can be performed in the laboratory system may be more appropriate and is presently being tested.

Conclusions

Data from complete event analyses with 4π detectors have just become available. The use of more complex observables taking more of the correlations measured in one event into account can shed new light on problems first studied with inclusive experiments. From observables such as the ratio of transverse to longitudinal momentum, the degree of thermalization can be measured. If equilibrium is found, the concept of temperature can be applied and compared to predictions of various models. That and the prospect to measure the entropy from the ratio of proton to composite particle production promise a big step forward towards the establishment of the equation of state.

Global analysis methods can be used to test possible hydrodynamical behaviour of nuclear matter. It is not yet clear which specific exclusive variable is best suited to differentiate between existing dynamical models. A variable that limits the influence of fast particles like the velocity β should be tried since calculations and experimental evidence for a forward suppression[5] exist only for low energy protons and composites. The application of the global analysis to asymmetric sytems is studied. If both experiments are equipped with forward detectors now in development that can identify heavy projectile residues, the bounce-off effect[22] can be investigated by bombarding light targets with heavy projectiles. Finite particle effects and the large surface-to-volume ratio make one treat with care conclusions from the symmetric mass 40 system alone. With the upgraded Bevalac heavier systems become available and mass dependent effects can be studied. The Plastic Ball group has just finished an experiment with niobium beam on a Nb target.

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Figure Captions

1) General layout of the Plastic Ball experiment.

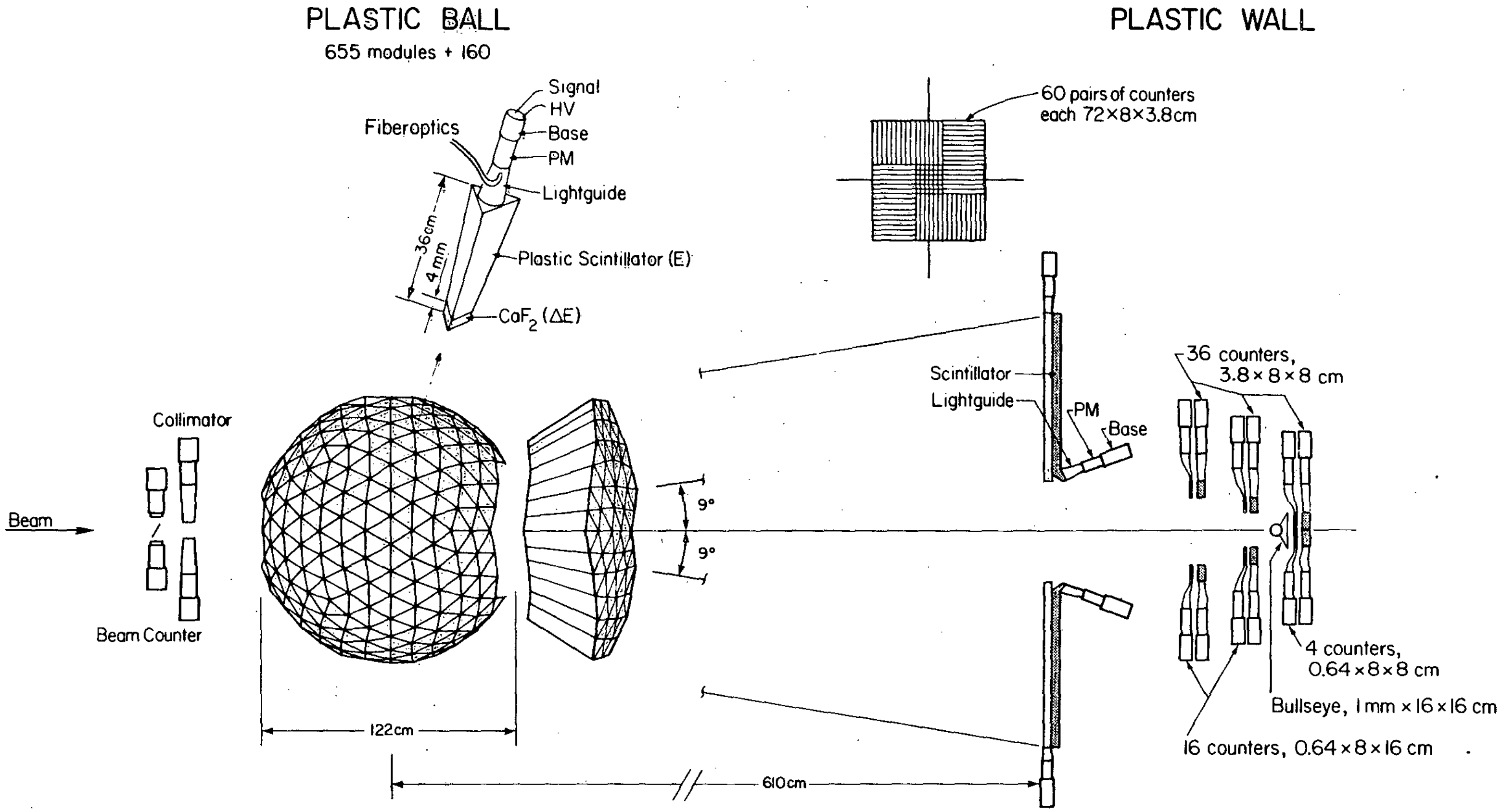
2) Particle identification spectrum for 655 modules after gain-matching with (dashed line) and without (solid line) scattering out reconstruction.

3) Plastic Ball acceptance in the plane rapidity versus transverse momentum.

4) Ratio of transverse to longitudinal temperature as a function of charged particle multiplicity.

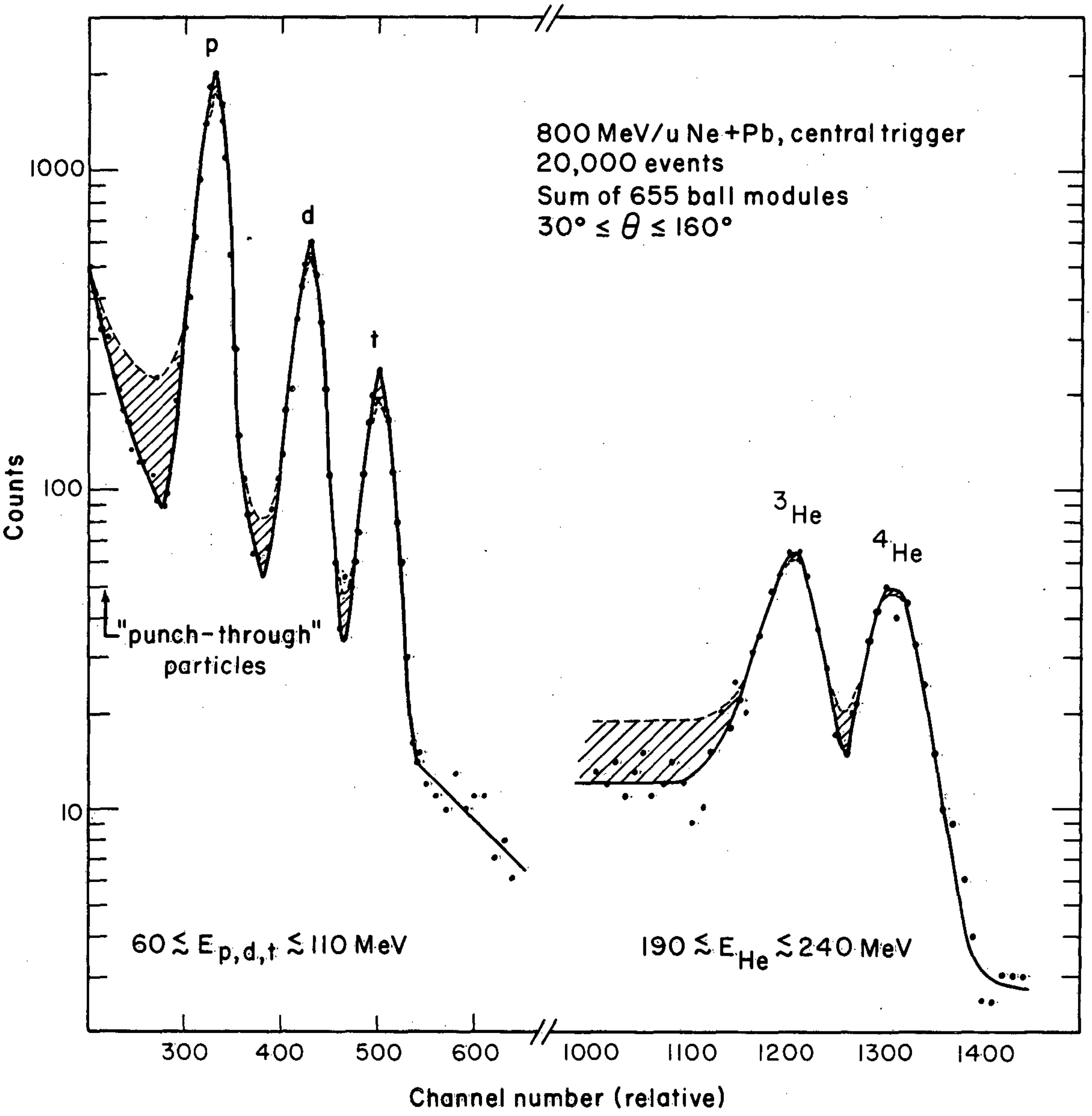
5) Ratio of number of deuteron-like to proton-like particles as a function of multiplicity (deuteron like = d + 3/2 t + 3/2 ^{3}He + 3 ^{4}He; proton like = Z = p + d + t + 2 ^{3}He + 2 ^{4}He).

6) Comparison between a flow analysis of streamer chamber data and impact parameter selected cascade calculations.



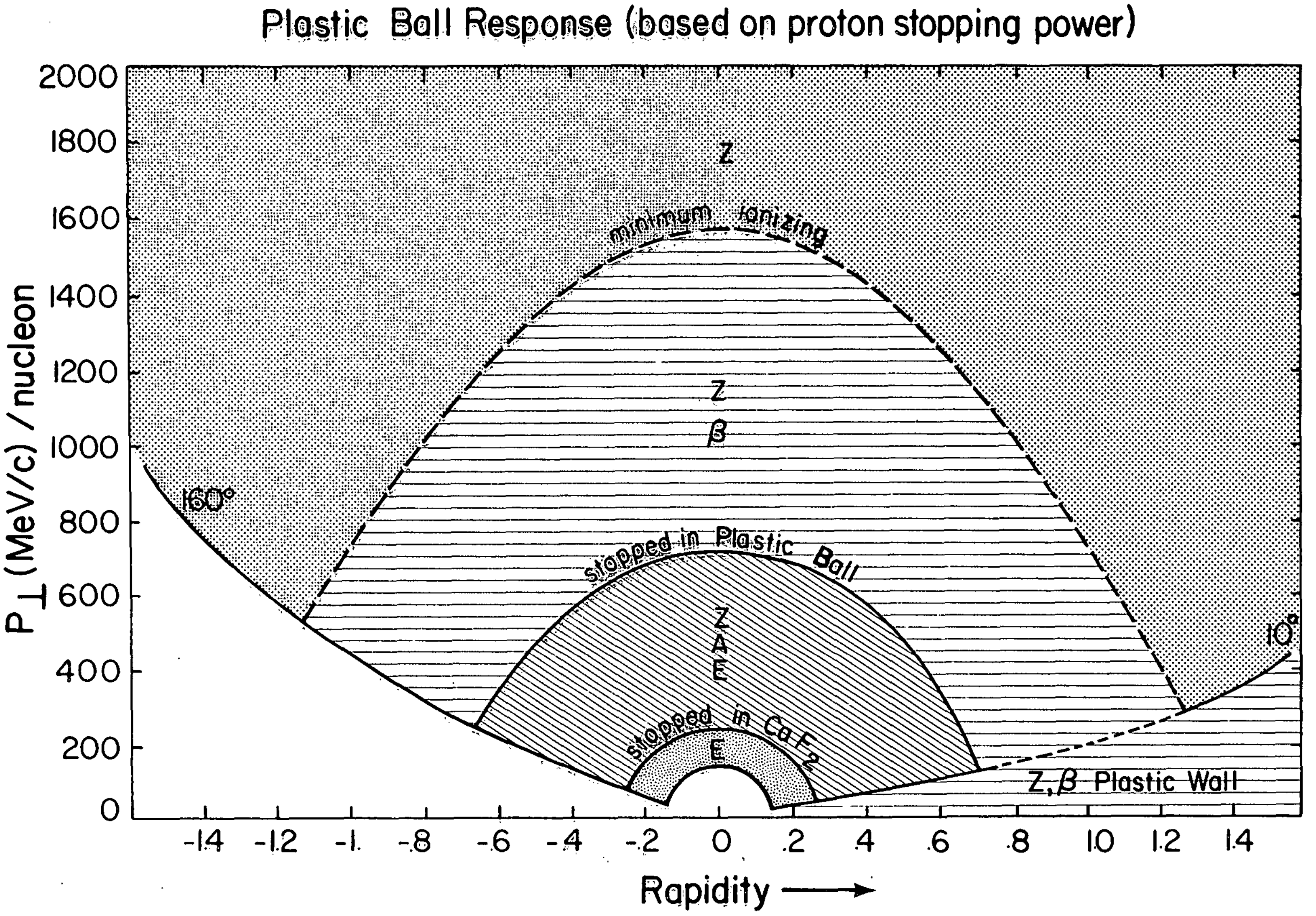
XBL 792-329A

Fig. 1



XBL 823-278

Fig. 2



XBL 8110-1526

Fig. 3

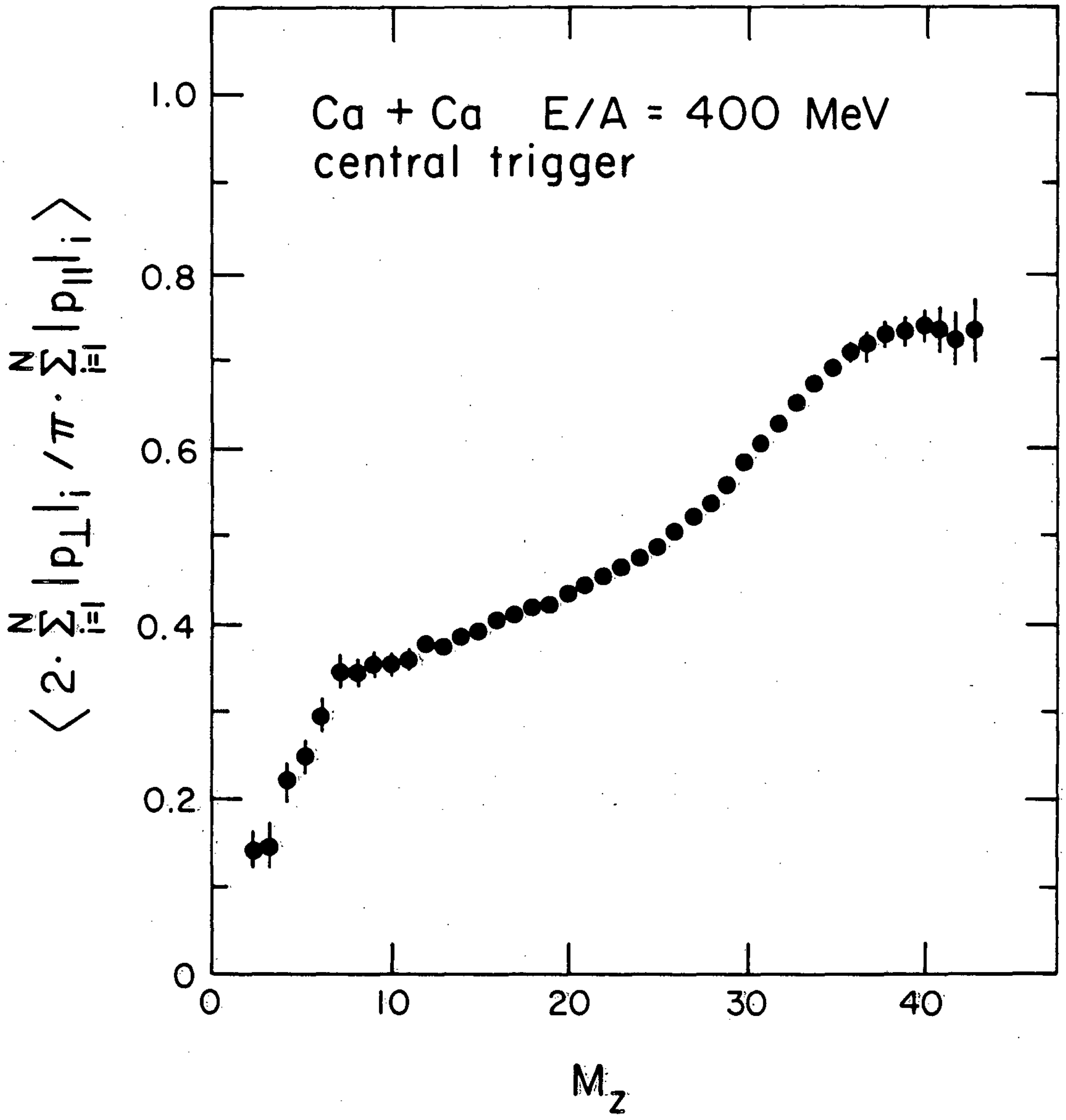


Fig. 4

XBL 8210 - 1209

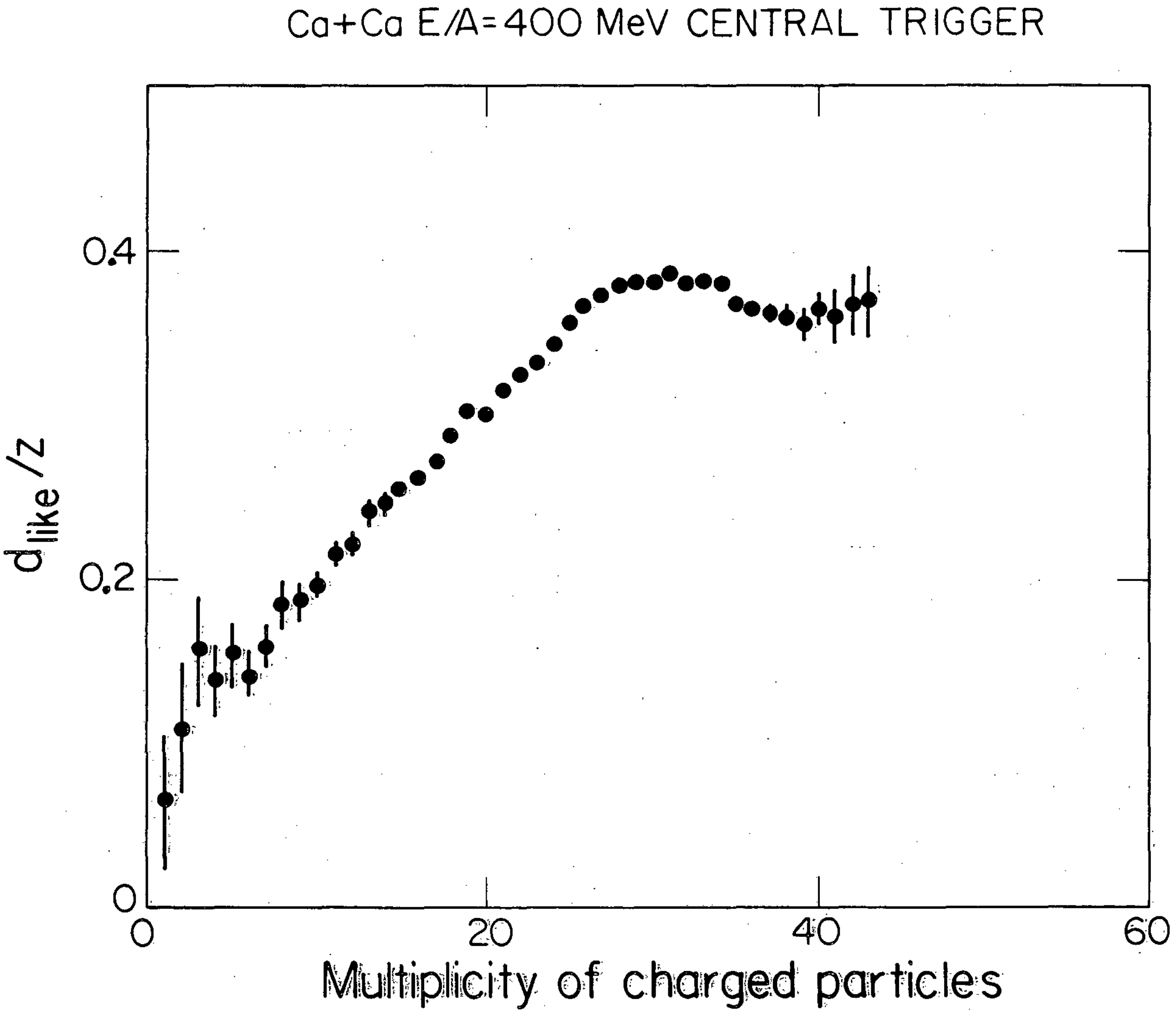
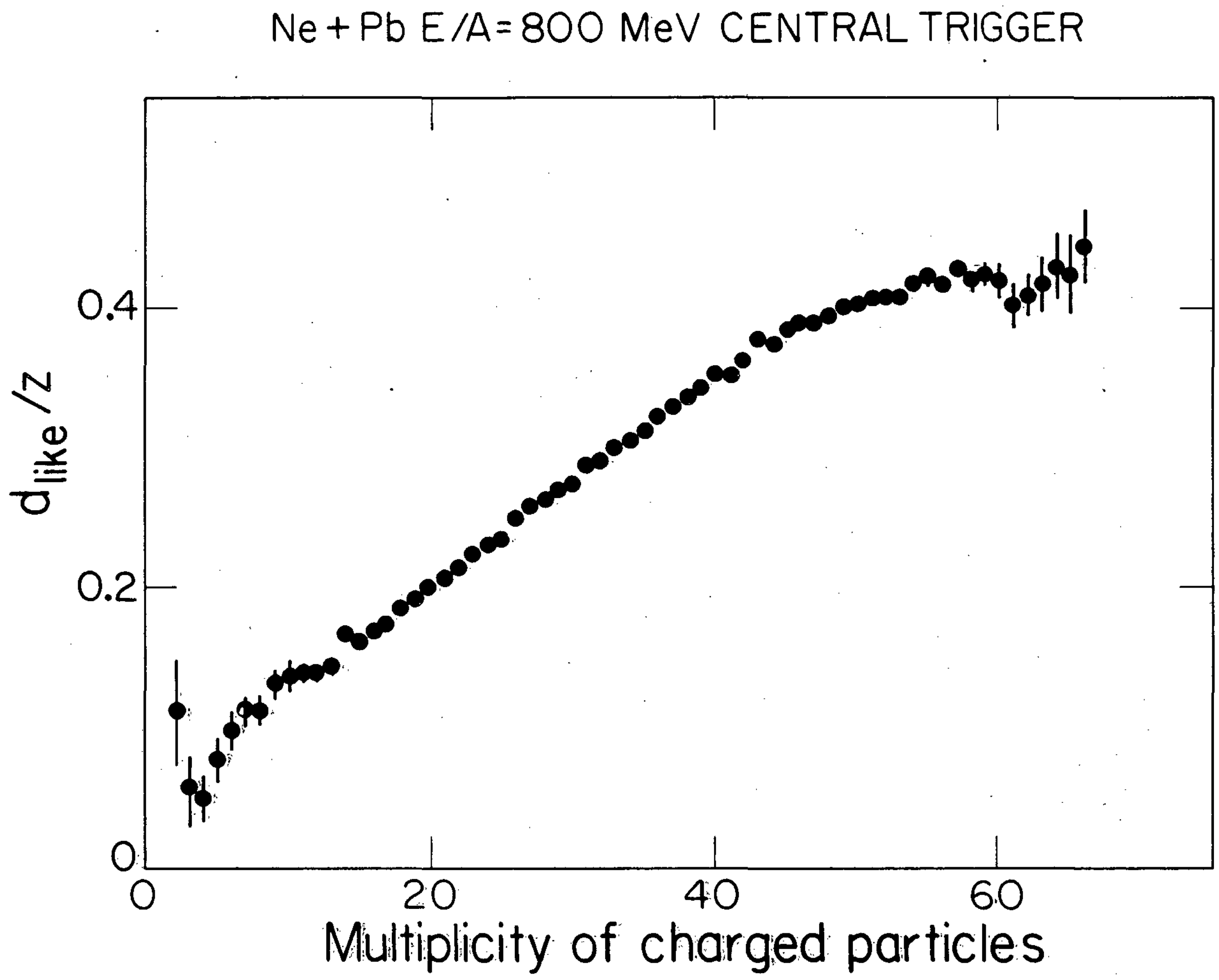


Fig. 5a

XBL 826-1422



XBL 826-1415

Fig. 5b

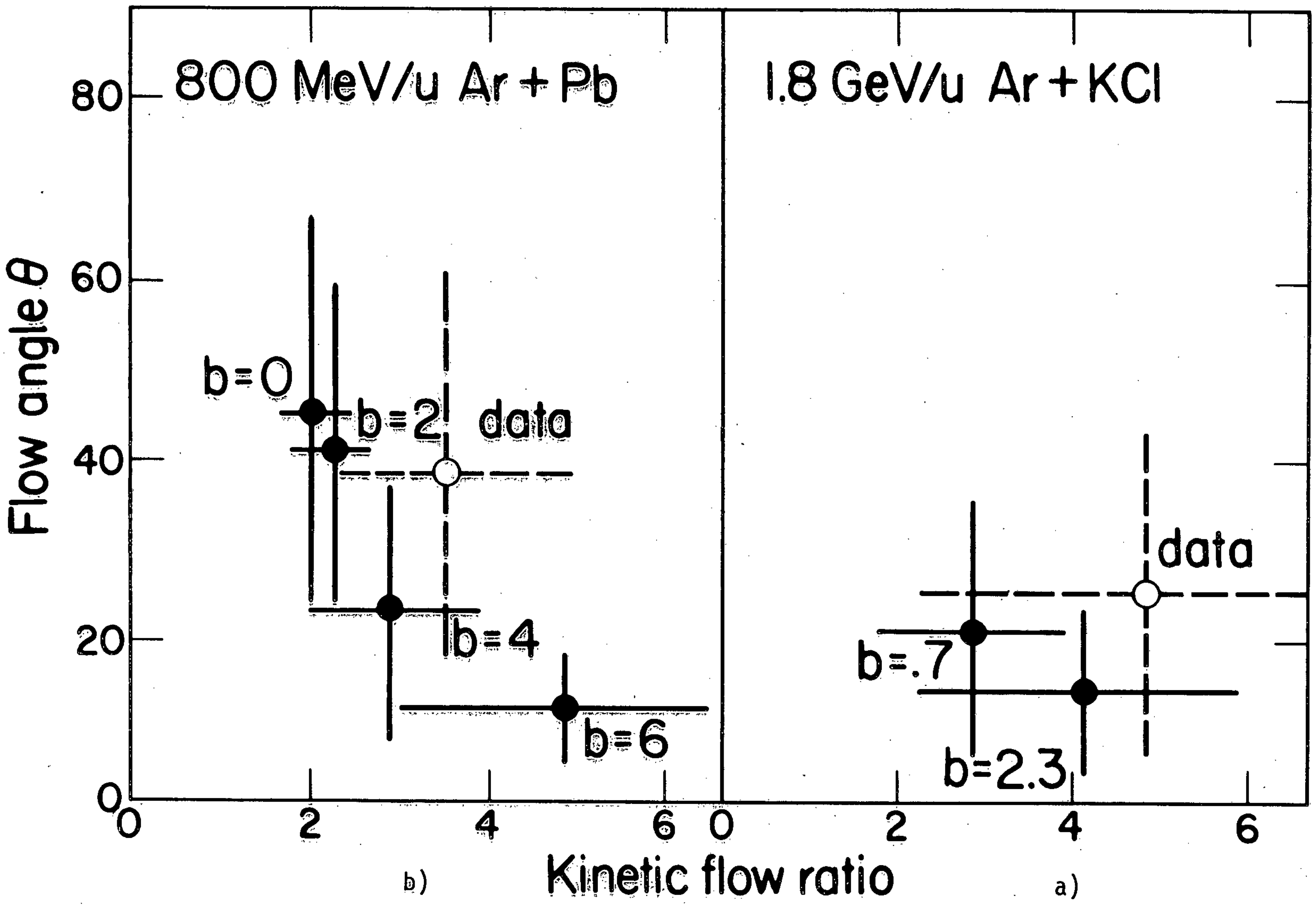

800 MeV/u Ar + Pb
1.8 GeV/u Ar + KCl
Flow angle θ
Kinetic flow ratio
b=0
b=2
b=4
b=6
data
b=.7
b=2.3
0
20
40
60
80
0
2
4
6
b)
a)
XBL 826-1418

Fig. 6

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LAWRENCE BERKELEY LABORATORY
UNIVERSITY OF CALIFORNIA
BERKELEY, CALIFORNIA 94720