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TARGET FRAGMENTATION IN PROTON-NUCLEUS AND ^{16}O-NUCLEUS REACTIONS AT 60 AND 200 GeV/NUCLEON

WA80 COLLABORATION

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Target Fragmentation in Proton-Nucleus and ^{16}O-Nucleus reactions at 60 and 200 GeV/nucleon

WA80 Collaboration

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Schloss Nordkirchen, West Germany

Target remnants with Z<3 from proton-nucleus and ^{16}O-nucleus reactions at 60 and 200 GeV/nucleon were measured in the angular range from 30° to 160° ($-1.7 < \eta < 1.3$) employing the Plastic Ball detector. The excitation energy of the target spectator matter in central oxygen-induced collisions is found to be high enough to allow for complete disintegration of the target nucleus into fragments with Z<3. The average longitudinal momentum transfer per proton to the target in central collisions is considerably higher in the case of ^{16}O-induced reactions (≈300 MeV/c) than in proton-induced reactions (≈130 MeV/c). The baryon rapidity distributions are roughly in agreement with one-fluid hydrodynamical calculations at 60 GeV/nucleon ^{16}O+Au but are in disagreement at 200 GeV/nucleon, indicating the higher degree of transparency at the higher bombarding energy. Both, the transverse momenta of target spectators and the entropy produced in the target fragmentation region are compared to those attained in head-on collisions of two heavy nuclei at Bevalac energies. They are found to be comparable or do even exceed the values for the participant matter at beam energies of about 1-2 GeV/nucleon.

I. Introduction

The subject of relativistic and ultra-relativistic nuclear collisions is the study of the properties of highly excited and dense nuclear matter. The physical parameters of the fireball, formed in symmetric collisions of heavy nuclei at energies ranging from 0.1 to 2.1 GeV/nucleon have been extensively studied at the Berkeley Bevalac [DG86, DG87a, DG87b]. At these energies the measurement of the four-vector of most of the particles emitted from the participant fireball is experimentally possible. This goal is out of reach with present experimental techniques at ultrarelativistic energies. It is, however, possible to extend the detailed studies of participant matter at relativistic energies to "spectator" matter at ultrarelativistic energies, i.e. to investigate target fragmentation processes. Hereby it is of prime interest to investigate the mechanism and amount of momentum transfer to the target by a projectile passing through matter at practically the speed of light [BS75, AK80]. Observables are the parallel and transverse momenta of target fragments, whose distribution should reflect the degree of transparency of nuclear matter for an ultrarelativistic projectile.

In this paper we will present first results obtained by the WA80 collaboration with the newly available ^{16}O-ions of 60 and 200 GeV/nucleon at the CERN SPS. Uniquely, the WA80 experiment has the possibility to survey the target fragmentation region by its Plastic Ball [BG82], which covers the backward angles in the center of mass. In Sec. II we shall briefly describe the experimental setup and the data reduction. In Sec. III we shall discuss the rapidity and momentum distributions of target remnants from ^{16}O-induced reactions and compare them with those from proton-nucleus reactions. The experimental rapidity distribution will be compared with a prediction from the hydrodynamical model. In Sec. IV and V we shall extract the transverse energy and the entropy, respectively, produced in the target rapidity. The findings will be related to results from relativistic nucleus-nucleus collisions performed at the Berkeley Bevalac. Sec. VI will contain the investigation of collective flow effects and Sec. VII is a summary.

II. Setup and Data Reduction

The present data were measured employing the Plastic Ball detector [BG82]. It, formerly used at the Berkeley Bevalac as a 4π-device, is now incorporated into the WA80-experiment [SA87], where it serves to measure charged particles emitted in the angular range from 30° to 160° ($-1.7 < \eta < 1.3$). In its present configuration, it consists of 655 ΔE-E modules arranged in a sphere. The modules are capable to identify charged π's, protons, deuterons, tritons and ^{3,4}He. At energies above 400 MeV protons can not be separated from charged pions. This uncertainty is taken into account as systematic error. The data presented in this paper are characterized by the remaining energy of the projectile at small angles (± 0.3°), as measured in the zero degree calorimeter (ZDC) [AB87] of the WA80-experiment. "Minimum bias" events are defined by the condition that the ZDC measures less than 90% of the full beam energy [AA87]. The subclass of events with low energy at ± 0.3° (< 20% at 200 GeV/nucleon) are assumed to be "central collisions".

The data are corrected for multiple hits. For the most forward positioned modules and for central collisions (high multiplicity) of ^{16}O+Au this correction amounts up to 40%. The correction integrated over the whole Ball is about 18% for central collisions and about 10% for the average "minimum bias" event. The corrections are negligible in the case of ^{16}O+Cu and C.

III. Baryon Distributions

Throughout the paper we will refer to the "primary reaction zone", "participating baryons" and "spectators" having the simple picture of a clean cut geometry as a working hypothesis in mind. In this geometry the primary reaction zone is a cylinder with the length of the diameter of the target nucleus and with the base equal to the cross section of the projectile nucleus. The participating baryons are contained in this cylinder and the surrounding matter is called spectator matter. To estimate the distributions of baryons steming from the primary reaction zone, the participating baryons, we have performed LUND model calculations employing the code FRITIOF [NS87].

Fig. 1 shows the distribution of target and projectile baryons under minimum bias conditions for the reaction O+Au at 200 GeV/nucleon. The shaded area represents the baryon distribution measured with the Plastic Ball. The lower curve is the result of the model calculation. Two "bumps" at $\eta \approx 1.9$ and $\eta \approx 5.3$ are clearly seen, corresponding to the target and the projectile participants, respectively. The integrated yield of the participating baryons (from the LUND model) for an average central collision is 75, 55, 45 and 24 baryons for the reactions O + Au, Ag, Cu and C, respectively, at 200 GeV/nucleon. These numbers are very close to those calculated assuming a "clean cut" reaction geometry. The integral over the experimental η-distribution is shown in Fig. 2 for the reactions ^{16}O + Au, Ag, Cu and C as a function of the centrality of the collision. The error band accounts for the systematic uncertainty in proton identification at high energies. The most striking feature of this figure is the fact that for very central collisions the average number of baryons measured in the target rapidity region for all reactions amounts approximately to the total number of baryons of the colliding system if one subtracts the "participating" baryons from the primary reaction zone, as estimated by the LUND model. This means that for a central collision enough energy is transferred from the projectile to the target matter to allow for complete disintegration of the target into light particles with $Z<3$. With decreasing centrality of the collisions, more and more low energy heavy fragments are produced. These particles were not detected in the Plastic Ball, resulting in the observed decrease of the average number of baryons with ZDC energy. The presence of these low energy heavy fragments, however, was clearly seen by the NA41 experiment [BB87] and by Aleklett *et al.* [AS87].

III.1 Pseudorapidity Distributions of Baryons

Fig. 3a-c shows pseudorapidity distributions of baryons from central collisions of ^{16}O on Au,Ag,Cu and C at 60 and 200 GeV/nucleon and protons on Au,Ag,Cu and C at 200 GeV. Non-observed neutrons are taken into account by weighting the proton distribution by the A/Z-ratio of the target. Since the average parallel momentum per baryon is only of the order of several hundreds of MeV/c, the pseudo-rapidity distributions are merely the angular distribution of the particles and differs drastically from the corresponding rapidity distributions (see for example Figs. 5). The distributions exhibit the following features:

i) For the reactions ^{16}O+A at 60 and 200 GeV/nucleon the shape of the distribution is similar for all targets and both energies while its magnitude is proportional to the target mass. The shape itself reflects the "drag" of the target baryons into the forward direction: Since the baryon distribution exhibits no distinct maximum in the η-range of the Plastic Ball a sizable fraction of the target baryons, - the participating baryons, - must appear at $\eta > 1.3$, in accordance with the above observations.

ii) For the reactions p+A at 200 GeV the shape of the distribution is again similar for all targets and the magnitude is again proportional to the target mass. The shape, however, shows now a clear maximum within the Plastic Ball range at a pseudorapidity of about 0.5.

III.2 Momentum Distributions of Baryons

Another possibility to investigate the impact of the projectile on the target nucleus is to compare the average parallel and transverse momentum of particles for different target and projectiles. Fig. 4a,b shows $\langle p_{\parallel} \rangle$/proton and $\langle p_T \rangle$/proton distributions for central collisions of 200 GeV/nucleon ^{16}O and protons on various targets. The target and projectile dependence is qualitatively the same as for the η-distributions:

(i) The average momenta are fairly independent of the target nucleus.

(ii) Both the parallel and the transverse momenta of protons are significantly higher for heavy-ion induced reactions as compared to proton-nucleus reactions.

(iii) Experimentally we find no significant difference between oxygen induced reactions at 60 and 200 GeV/nucleon in the target rapidity.

The results in III.1 and III.2 demonstrate a clear difference between proton and heavy-ion induced reactions with regard to the collective acceleration of the target nucleus. They give a first clue to what happens when an ultrarelativistic heavy ion travels through target matter: A strong coupling of the projectile to the nuclear medium, which dissipates energy toward the target rapidity, seems to be of importance and modifies the simple picture of a clean cut geometry. The similarity of ^{16}O-induced reactions at 60 and 200 GeV/nucleon shows that the acceleration of the target matter does not depend on the energy of the projectile in this energy range. It seems, however, determined by velocity of the projectile, which is practically the speed of light in both cases.

III.3 Rapidity Distributions of Baryons

We compare now the data with a prediction of a one-fluid hydrodynamical model [RG87], which represents the extreme of high stopping of the projectile in the nuclear fluid. Experimental rapidity distributions of baryons, selected for central collisions, are compared with calculations performed for reactions of 200 and 60 GeV/nucleon ^{16}O + Pb at an impact parameter of 3 fm (Fig. 5a,b). The experimental distributions are plotted up to their apparent maximum; the distributions at larger values are strongly distorted due to the limited geometrical acceptance of the Plastic Ball. The theoretical distributions exhibit at both energies a two-component structure. The baryons at the higher rapidity might be identified as baryons coming from the primary reaction zone while particles at the lower rapidity are probably target spectators, hence those particles which are measured with the Plastic Ball detector. We find a qualitative agreement between data and theory at 60 GeV/nucleon, whereas data and the prediction disagree at 200 GeV/nucleon.

A recent analysis of the reaction ^{20}Ne+Au at 2.1 GeV/nucleon measured with the Plastic Ball detector at the Berkeley Bevalac [KS87] has shown, that for this reaction the projectile is almost fully stopped in the target nucleus. This seems to indicate, together with the above results, that the onset of nuclear transparency lies above 2.1 GeV/nucleon and close to 60 GeV/nucleon and that the degree of transparency increases from 60 GeV/nucleon to 200 GeV/nucleon.

IV Transverse Energy

Transverse energies of particles emitted from a common source are a measure of the temperature of this source. Fig. 6 shows the average transverse energy distribution of protons from central collisions of 200 GeV/nucleon ^{16}O on Au as a function of pseudorapidity. The width of the band represent the systematic uncertainty due to proton identification as discussed above. The transverse proton energies, taken at the maximum of the η-distribution, are plotted in Fig. 7 as a function of the centrality of the collision. Provided that this maximum can be associated with the target source, we could deduce a rapidity shift Δy of about 0.5 units for the target.

It is instructive to compare the transverse energies with those attained in collisions of equal mass heavy nuclei at Bevalac energies. In [DG87a] average transverse energies of protons at $y_{cm}=0$ for collisions of Au+Au at bombarding energies ranging from 150 MeV/nucleon to 800 Mev/nucleon were extracted. The results are shown in Fig. 8 as a function of the reduced multiplicity. Comparing Figs. 7 and 8 we learn the surprising fact that the transverse energies of protons from ultrarelativistic collisions, emitted in the target rapidity, are considerably higher then those produced in the fireball of symmetric systems at relativistic energies. This means that target matter in ultrarelativistic heavy-ion collisions is highly excited and is comparable with participant matter created in central collisions of very heavy nuclei in the energy range of at least 1-2 GeV/nucleon.

V Entropy

An observable which is assumed to carry the signature of the early stage of the collision, i.e. before the excited matter has exploded and has cooled down, is the specific entropy. If the above observation holds then the entropy of target matter should also reflect the similarity of "ultrarelativistic target matter" and "relativistic participant matter". The entropy is inferred from cluster ratio employing the Quantum Statistical Model [HS86] as described in Ref. Doss *et al.* [DG87b]. Fig. 9 shows as an example the ratio of deuteron-like to proton-like particles as a function of the centrality of the collision ^{16}O+Au at 200 GeV/nucleon. The ratios are, as described in [DG85], extracted only from well identified particles in a certain overlap area in phase space. As observed previously [HL83,DG85,DG87b] the ratio d-like/p-like varies strongly with the impact parameter, i.e. the entropy is smallest for the most central collisions. The entropies, extracted at the maximum value of the d-like/p-like ratio, are plotted in Fig. 10a as a function of the target mass. They show an increase of entropy as the mass of the target decreases. This decrease of entropy with target mass is similar to the decrease in entropy with the participant multiplicity [DG87b]: in both cases the "active" volume becomes larger and hence a decreased surface to volume ratio allows for less entropy production. Again, this observation suggests a strong coupling between the projectile and the target as a whole.

Part of the entropy produced during the collision process will be carried by pionic degrees of freedom. We have roughly estimated this fraction by assuming:

(i) The non-observed neutral pions amount to half the number of the observed charged pions.

(ii) The entropy per pion is about four units of entropy, which is the value obtained for a massless pion gas [HS86].

The entropy carried by pions, normalized to the number of baryons, is shown in Fig. 10b, where we see again the decrease in entropy with increasing target mass. Differently from the case of the cluster ratios we account here for all baryons and pions falling into the acceptance window of the Plastic Ball. The error bars represent the systematic error due the lack of particle identification for very energetic protons and pions.

Like for the transverse energies it is instructive to compare the extracted entropies of "ultrarelativistic spectator matter" with the entropy of "relativistic participant matter". Fig. 11 shows a calculation of the dependence of S/A on the bombarding energy for symmetric systems taken from [HS86]. We have included the experimental entropy per baryon for the reaction ^{16}O+Au at 200 GeV/nucleon as the open and closed squares. Hereby the open and closed squares stand for S/A with and without the inclusion of the fraction of entropy carried by pions, respectively. The corresponding bombarding energy was determined by requiring the same ratio of the nucleonic and the full S/A for the experiment and for the calculation. As a result we obtain that the entropy of "ultrarelativistic spectator matter" is as high as the entropy of "relativistic participant matter" created in head-on collisions of heavy symmetric systems at about 2±0.5 GeV/nucleon.

VI Collective Flow

The Danielewicz-Odyniec transverse momentum analysis [DO85] has proven to be a sensitive tool to measure collective, azimuthally asymmetric, sidewards emission of nuclear matter [DG86]. In order to determine the "reaction plane" of the collision from the transverse momenta the knowledge of the center of mass is essential. In our case we assume that the effective center of mass is at angles smaller than 30°, hence the reaction plane, calculated from the transverse momenta of protons in the Plastic Ball's acceptance, is determined in the backward hemisphere of the center of mass only. This assumption has been cross checked by determining the reaction plane from particles emitted at laboratory angles larger than 90° only, which yielded the same results. Fig. 12 shows the result of the above discussed transverse momentum analysis for protons emitted in the reaction ^{16}O+Au at 200 GeV/nucleon. Here the data are selected for semi-central collisions. Differently from symmetric collisions at Bevalac energies we observe no azimuthal asymmetry of the transverse momenta distribution, indicating the absence of asymmetric sidewards flow of nuclear matter. It should be noted, however, that the method is not sensitive to an emission pattern where collective effects are azimuthally symmetric.

VII Summary and Conclusion

Summarizing, we have shown that the simple picture of a clean cut geometry, involving a clear separation into "hot" participant and "cold" spectator matter has to be modified considerably: The target "spectator" matter in oxygen induced reactions at 60 and 200 GeV/nucleon is highly excited (with temperature and entropy comparable to those attained in central collisions of heavy nuclei at an energy of about 2 GeV/nucleon) and due to this high excitation energy practically no fragments heavier than A=4 are produced in central collisions. The rapidity of the target is probably shifted by about 0.5 units, in rough agreement with one-fluid hydrodynamical calculations [RG87] at 60 GeV/nucleon, but in disagreement at 200 GeV/nucleon, where the calculation predicts a too high rapidity shift of the target. From this observation we might conclude a different degree of transparency for the projectile at the two energies.

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Figure Captions

Fig. 1 Pseudorapidity distributions of target and projectile baryons. The shaded area represents the baryon distribution measured with the Plastic Ball. The solid curve is the result of a LUND model calculation yielding the participating target and projectile baryons.

Fig. 2 Average number of baryons per event for the reaction ^{16}O+Au at 200 GeV/nucleon as a function of the energy measured at ±0.3° in the zero degree calorimeter. The number of baryons is corrected for multiple hits and the non-observed neutrons. The error band accounts for the systematic uncertainty in proton identification at high energies.

Fig. 3 (a) Average number of baryons per event as a function of pseudorapidity for the reaction ^{16}O+Au, Ag,Cu and C at 60 GeV/nucleon bombarding energy.
(b) Same as (a) for 200 GeV/nucleon.
(c) Same as (b) for proton induced reactions.

Fig. 4 (a) Average over the parallel momentum of protons in the pseudorapidity interval $-1.7 < \eta < 1.3$ as a function of the target mass. The curves through the data points are to guide the eye. The upper curve is for ^{16}O+Au,Ag,Cu and C at 200 GeV/nucleon, the lower curve is for p+Au,Ag,Cu and C at 200 GeV. The error bars account for the systematic uncertainty in proton identification at high energies.
(b) Same as (a) for the transverse momentum.

Fig. 5 (a) Comparison of the experimental rapidity distribution of target baryons for 60 GeV/nucleon ^{16}O+Au with a prediction from a one-fluid hydrodynamical model [RG87].
(b) Same as (a) for 200 GeV/nucleon.

Fig. 6 Mean transverse proton energy as a function of pseudorapidity for 200 Gev/nucleon ^{16}O+Au.

Fig. 7 Mean transverse proton energy in the pseudorapidity range $0.8 < \eta < 1.2$ as a function of centrality for 200 Gev/nucleon ^{16}O+Au.

Fig. 8 Mean transverse proton energy at $y_{cm}=0$ as a function of the reduced participant proton multiplicity (N_p/N_p^{max}) for Au+Au at different beam energies between 150 and 800 MeV/nucleon.

Fig. 9 Ratio of deuteron-like to proton-like particles of the reaction ^{16}O+Au at 200 GeV/nucleon as a function of the centrality of the reaction.

Fig .10 Dependence of the entropy per baryon for the fraction carried by baryons (a) and by pions (b) on the target mass.

Fig. 11 Comparison of the experimental entropy per baryon produced in 200 GeV/nucleon O+Au carried by baryons only (closed squares) and by baryons and pions (open squared) with calculations. The calculations [HS86] are done for symmetric collisions as a function of the bombarding energy. The lower and upper curve is for the nucleonic and full (nucleonic and pionic) entropy per baryon, respectively.

Fig. 12 Mean transverse momentum of protons projected into the reaction plane as a function of rapidity.

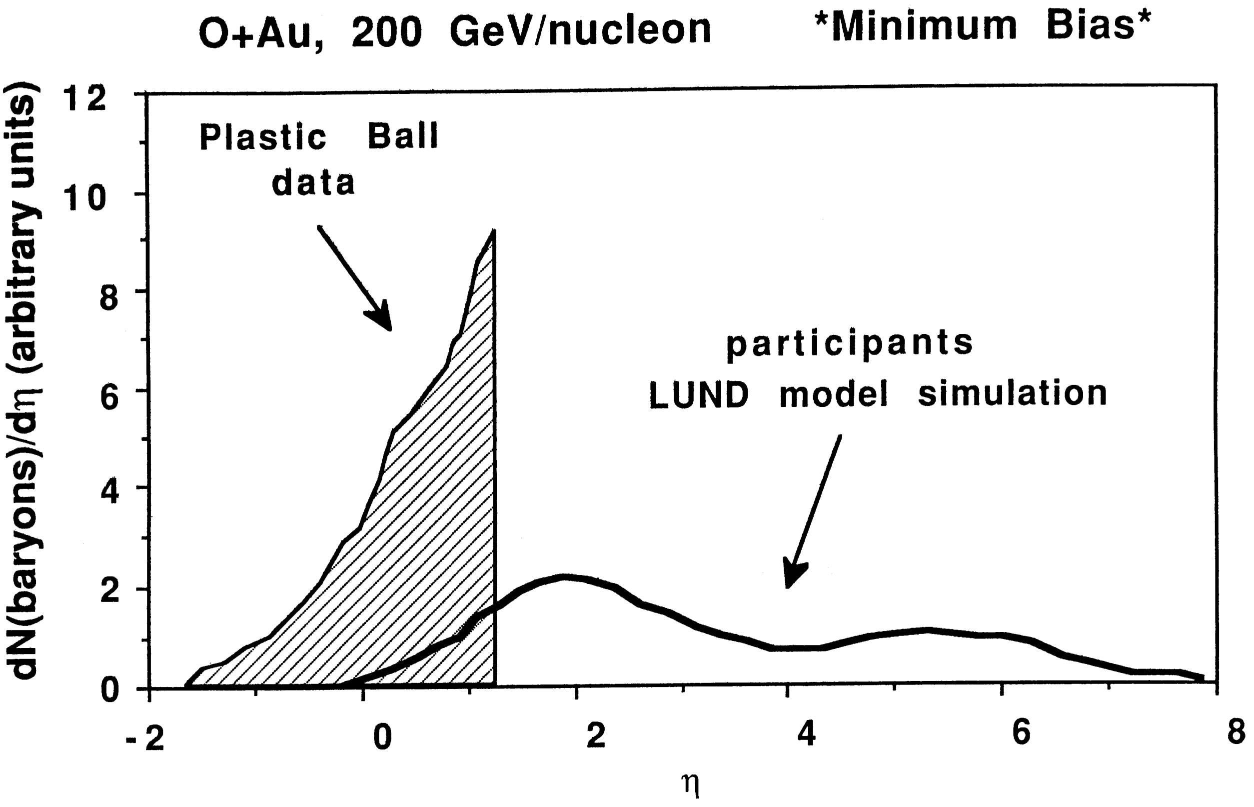
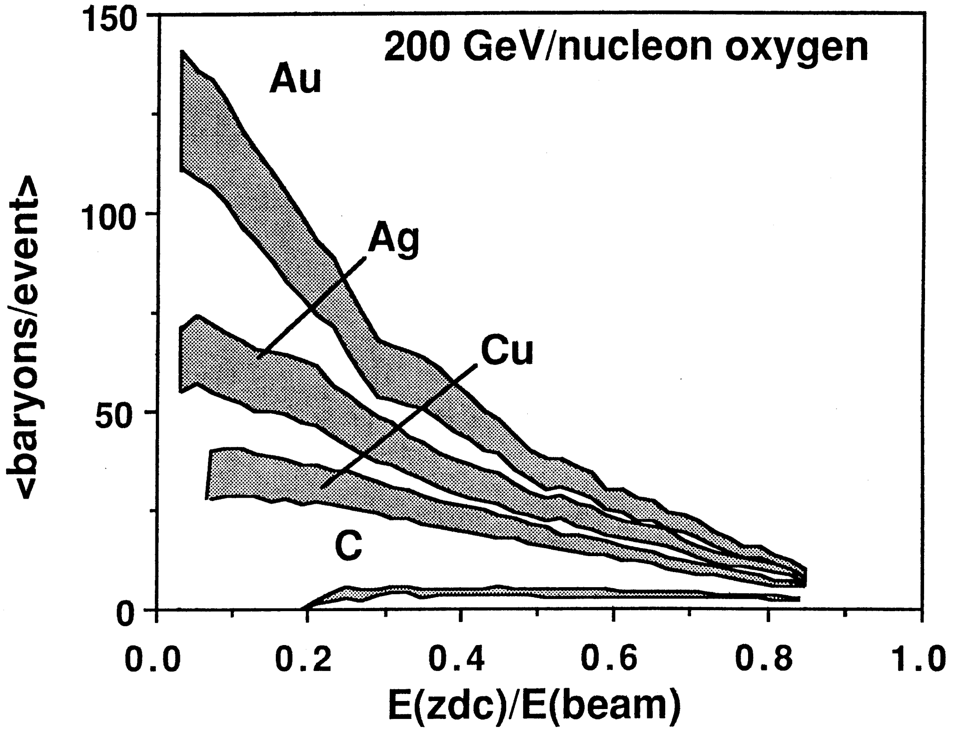

O+Au, 200 GeV/nucleon
Minimum Bias
dN(baryons)/dη (arbitrary units)
12
10
8
6
4
2
0
Plastic Ball
data
participants
LUND model simulation
-2
0
2
4
6
8
η

Fig. 1


150
100
50
0
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200 GeV/nucleon oxygen
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Ag
Cu
C
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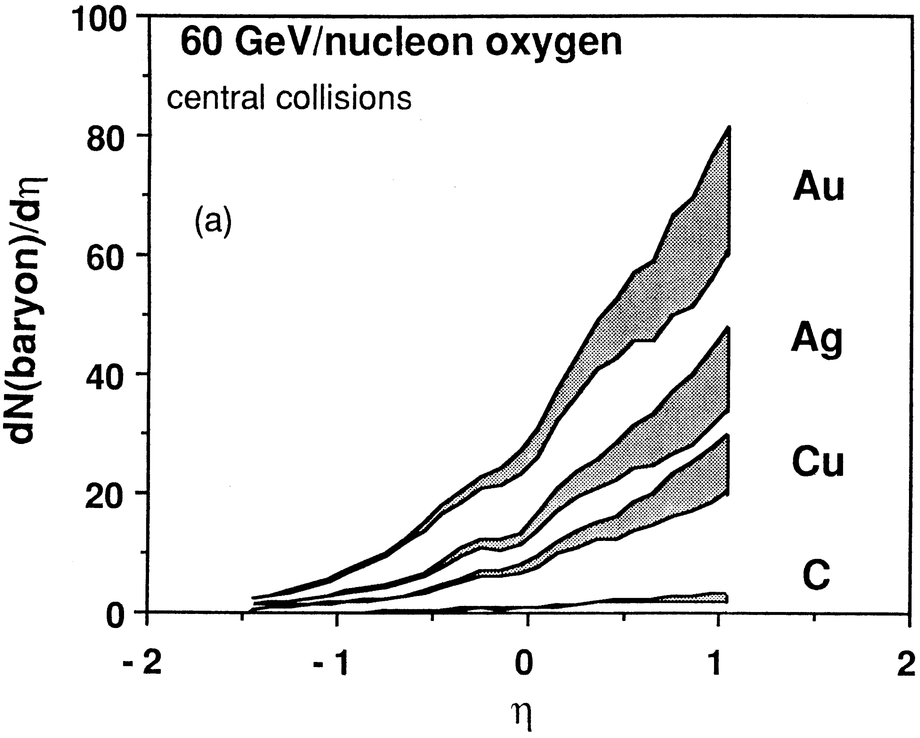
0.2
0.4
0.6
0.8
1.0
E(zdc)/E(beam)

Fig. 2


60 GeV/nucleon oxygen
central collisions
(a)
dN(baryon)/dη
η
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20
40
60
80
100
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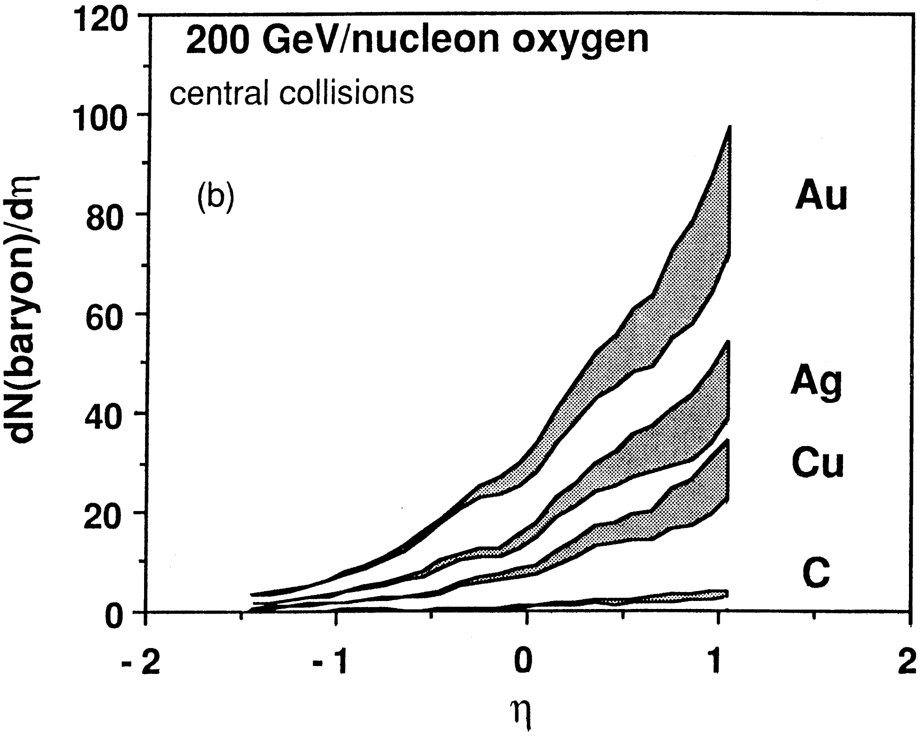
-1
0
1
2
Au
Ag
Cu
C

Fig. 3a


200 GeV/nucleon oxygen
central collisions
(b)
dN(baryon)/dη
η
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20
40
60
80
100
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0
1
2
Au
Ag
Cu
C

Fig. 3b

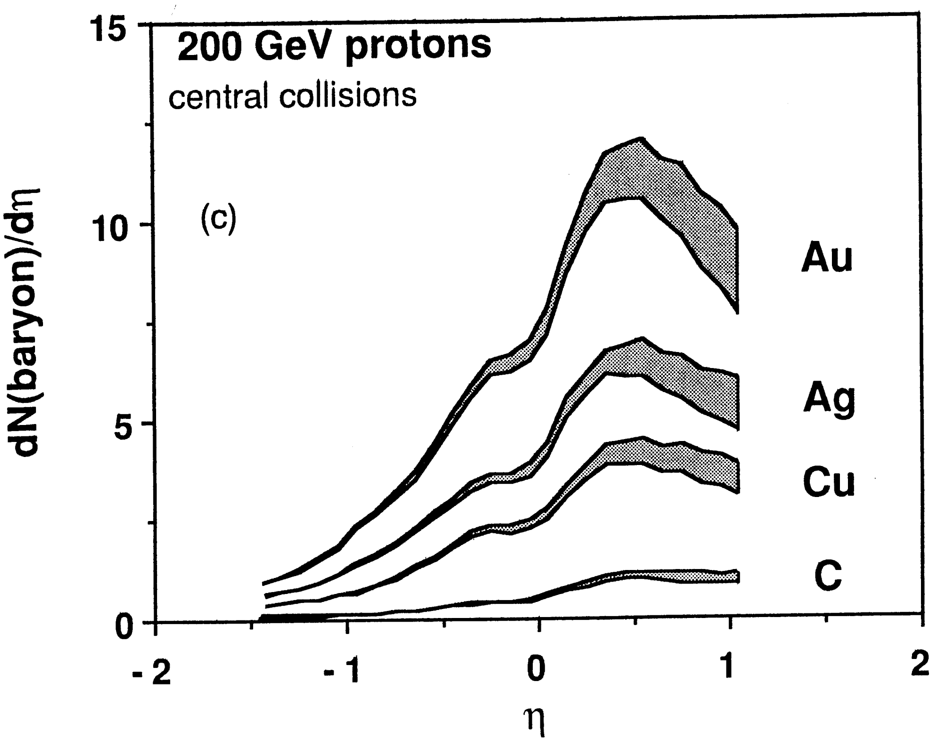
200 GeV protons
central collisions
(c)
dN(baryon)/dη
15
10
5
0
-2
-1
0
1
2
η
Au
Ag
Cu
C

Fig. 3c

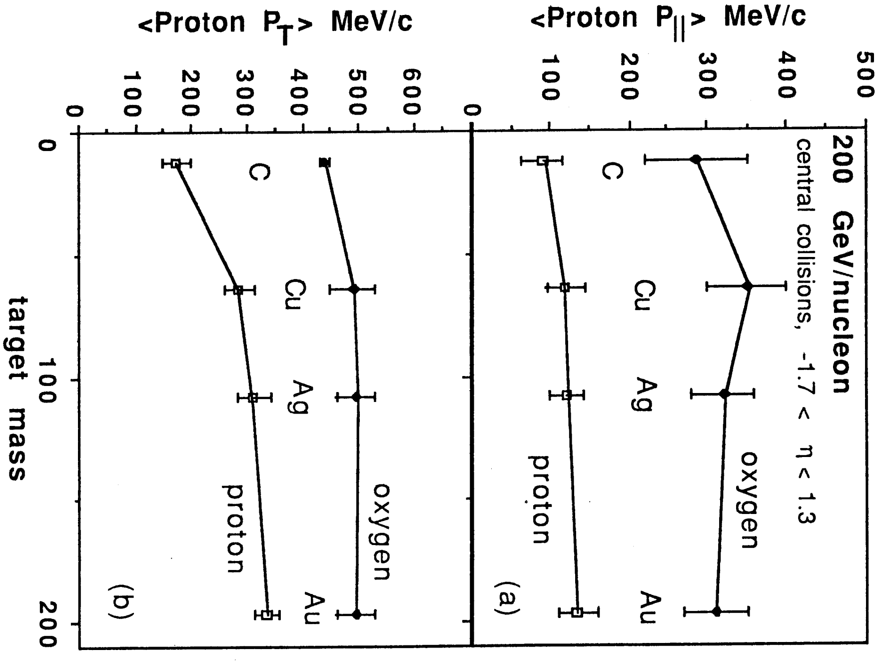
200 GeV/nucleon
central collisions, -1.7 < η < 1.3
<Proton $P_{||}$> MeV/c
0
100
200
300
400
500
C
Cu
Ag
Au
oxygen
proton
(a)
<Proton P_T> MeV/c
0
100
200
300
400
500
600
C
Cu
Ag
Au
oxygen
proton
(b)
0
100
200
target mass

Fig. 4

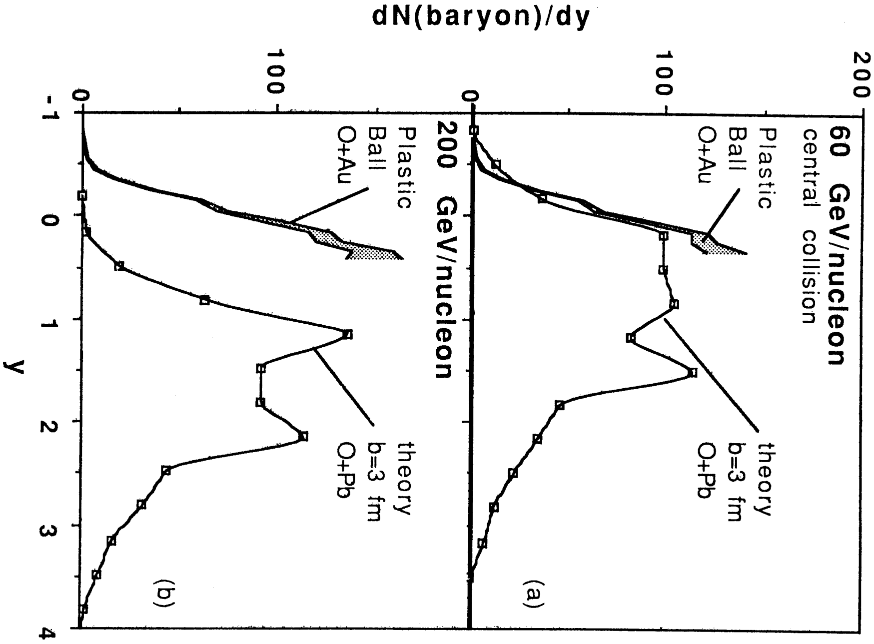
dN(baryon)/dy
200
100
0
60 GeV/nucleon
central collision
Plastic
Ball
O+Au
theory
b=3 fm
O+Pb
(a)
100
0
200 GeV/nucleon
Plastic
Ball
O+Au
theory
b=3 fm
O+Pb
(b)
-1
0
1
2
3
4
y

Fig. 5

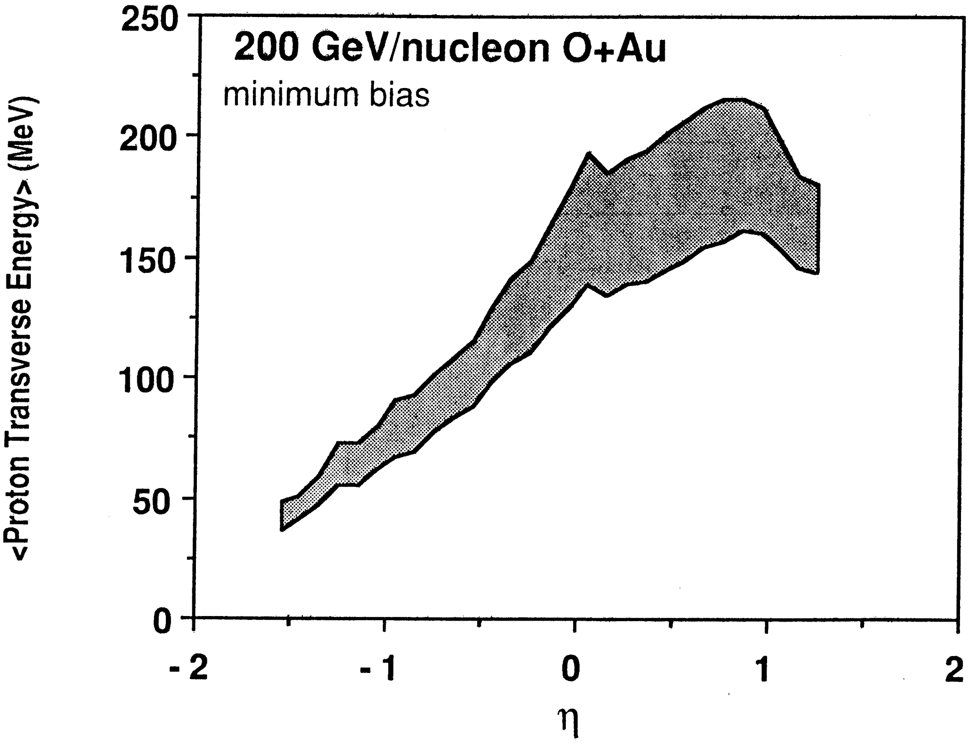
200 GeV/nucleon O+Au
minimum bias
<Proton Transverse Energy> (MeV)
250
200
150
100
50
0
- 2
- 1
0
1
2
η

Fig. 6

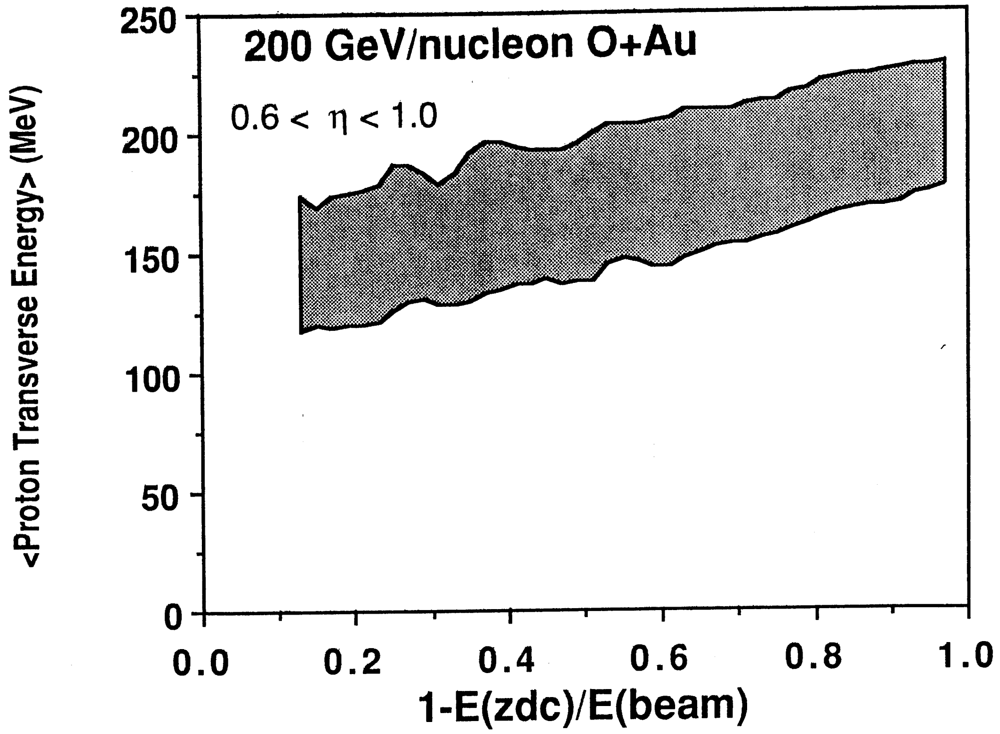
200 GeV/nucleon O+Au
0.6 < η < 1.0
<Proton Transverse Energy> (MeV)
250
200
150
100
50
0
0.0
0.2
0.4
0.6
0.8
1.0
1-E(zdc)/E(beam)

Fig. 7

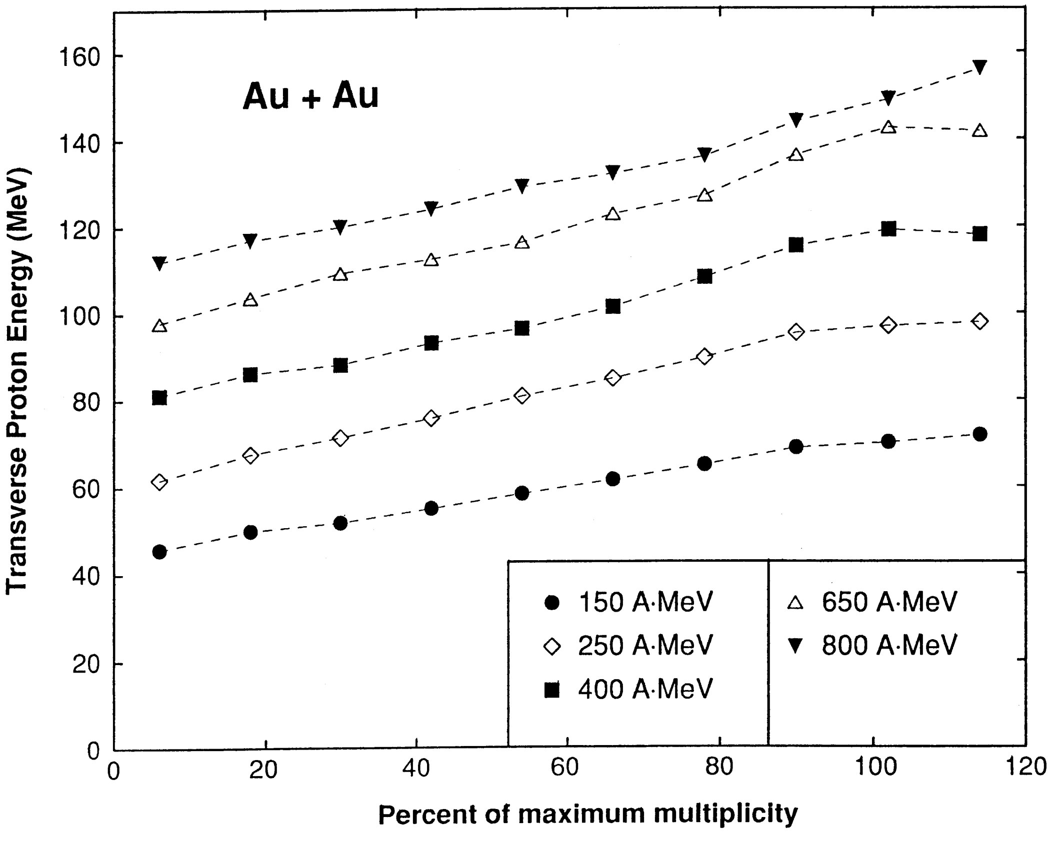
Au + Au
Transverse Proton Energy (MeV)
160
140
120
100
80
60
40
20
0
0
20
40
60
80
100
120
Percent of maximum multiplicity
● 150 A·MeV
◇ 250 A·MeV
■ 400 A·MeV
△ 650 A·MeV
▼ 800 A·MeV

Fig. 8

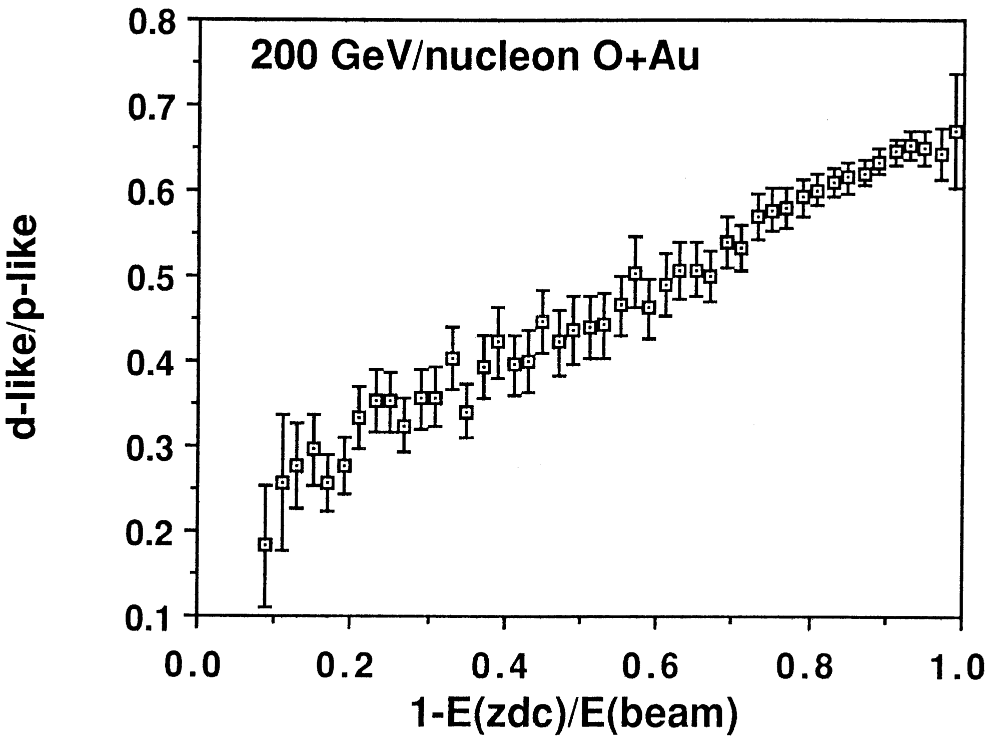
200 GeV/nucleon O+Au
d-like/p-like
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
0.2
0.4
0.6
0.8
1.0
1-E(zdc)/E(beam)

Fig. 9

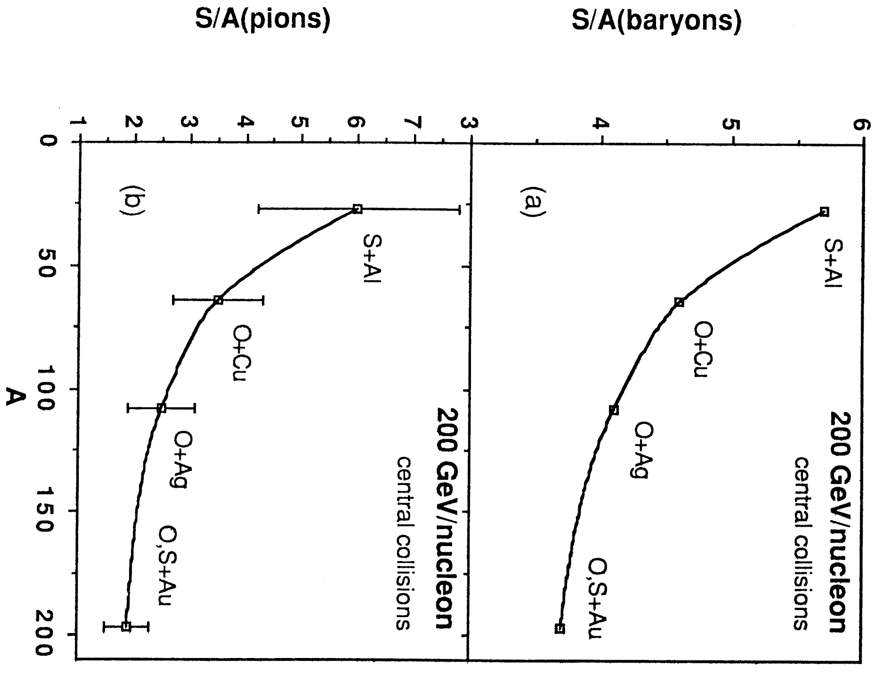
S/A(pions)
S/A(baryons)
(a)
(b)
200 GeV/nucleon
central collisions
S+Al
O+Cu
O+Ag
O,S+Au
6
5
4
3
7
2
1
0
50
100
150
200
A

Fig. 10

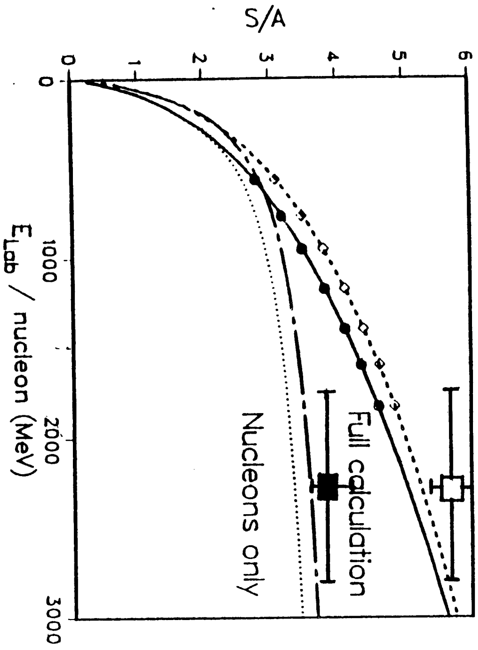
S/A
0
1
2
3
4
5
6
0
1000
2000
3000
E_{Lab} / nucleon (MeV)
Full calculation
Nucleons only

Fig. 11

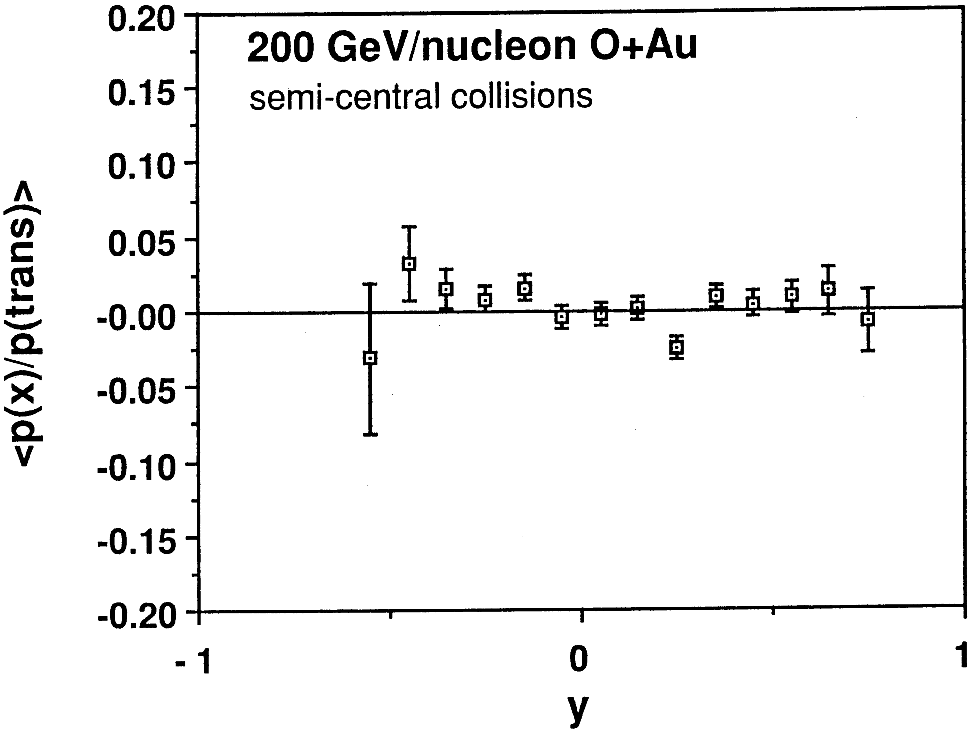
200 GeV/nucleon O+Au
semi-central collisions
<p(x)/p(trans)>
0.20
0.15
0.10
0.05
-0.00
-0.05
-0.10
-0.15
-0.20
- 1
0
1
y

Fig. 12