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Abstract: The pseudo-rapidity density distributions of shower particles (n_s) are measured in central inelastic S + Au and S + Ag,Br interactions. The extracted maximum energy densities, while being higher for Au than for Ag,Br interactions, were found to be similar to those obtained for Oxygen emulsion interactions. The correlation between rapidity density and shower particle multiplicity shows a small deviation from the Lund Model Fritiof for the highest energy densities in S + Au interactions, whereas the bulk of the data yields satisfactory agreement.

Introduction: The prediction from both thermodynamics and lattice-QCD that nuclear matter under extreme conditions can evolve into a new state of matter, a Quark-Gluon-Plasma (QGP), motivates the investigation of unusual phenomena in the rapidity distribution of charged particles as compared with the outcome of good event simulators such as the Lund Model Fritiof [1], based on independently fragmenting colour strings. A key parameter for the transition is the energy density (ε) which must exceed a critical value ($\varepsilon > 2.5$ GeV/fm^3) to allow for such a transition. In a previous paper [2], on ^{16}O interactions with emulsion nuclei at 200 A GeV, we estimated the energy density to be about 3 GeV/fm^3 for a few high multiplicity events. The main aim of the present paper is to investigate the fluctuations in charged particle rapidity density, to compare them with the Lund model Fritiof, to determine the maximum energy densities for the tail events and to give and discuss the pseudo-rapidity distributions, subject to high multiplicity criteria.

Detector techniques: The emulsion technique with its superior spatial resolution is very well suited for obtaining precise multiplicity and angular measurements. In the EMU01 experiment at CERN two exposure techniques were used, horizontal and vertical. Both of these detection techniques have their own advantage and are complementary.

Vertical exposure: The vertical technique, utilizing emulsion chambers for the ^{16}O exposure, has been described elsewhere [2,3]. For the ^{32}S + Au vertical (V) exposure technique the emulsion chambers were additionally equipped upstream with a gold foil of 250 µm thickness immediately followed by two sheets of polysthyrene (780 µm thick) each coated with 220 µm thick emulsion layers on both sides. The chambers were exposed in october 1987 to the ^{32}S beam at CERN at 200 A GeV. The density of the beam was about $5*10^3$ nuclei/cm^2. The chambers were exposed on four spots with a beam approximately 20 mm across with about 20400 particles per spot. The S + Au reaction cross section can be estimated from the formula[4]:

$$\sigma_r = \pi r_o^2 \; ((A_1)^{1/3} + (A_2)^{1/3} - b)^2 \qquad (1)$$

Using $r_o = 1.5$ fm and $b = 1.3$ we get $\sigma_r = 4.18$ Barn. The mean free path corresponding to this reaction cross section is 4.05 cm. The expected number of S + Au interactions in a spot is approximately 20400 * 0.025 / 4.05 = 126. The number of interactions actually found is about 65, yielding an efficiency of about 52 %. Since the scanning is done up to 400 µm from the vertex the peripheral events are virtually impossible to detect. The central events are however easily found due to their high multiplicity. To select a "central" sample of high multiplicity events only such events were measured where the number of singly charged tracks observed inside the fragmentation cone was 0, 1 or 2 and no fragment with Z>2 was present. The fragmentation cone for projectile fragments were defined by $\Theta_{fp} \leq \Theta_c = 0.2/p_{beam}$ ($\Theta_c \simeq 1$ mrad at 200 A GeV). The value of Θ_c was chosen to minimize the probability of including produced particles among the fragments. All singly charged particles having $\Theta \leq \Theta_c$ ($\eta > 7.6$) were excluded from n_s. Due to difficulties in measuring large angle tracks $\Theta > 30°$ ($\eta < 1.32$) with the vertical technique these tracks were also removed from n_s. Our S + Au "central" sample consists of 133 events, where 125 events have $n_s \geq 200$ and 94 events have $n_s \geq 300$. The $<n_s>$ of our "central" sample was 342 ± 8. From the Lund model Fritiof 8000 minimum bias events were generated and after the same trigger condition the "central" sample consists of 1487 events which corresponds to 18.6% of the minimum bias cross section, whereas the additional cut $n_s \geq 200$ corresponds to 18.5% and $n_s \geq 300$ to 15.9%. The $<n_s>$ for the Lund model "central" sample was 371 ± 2 i.e. in fair agreement. The data were corrected for pair conversion (see below) in the Au target foil and the angular dependence of this process was determined from the Lund model.

Correction for pair conversion: For the S + Au interactions a correction due to the pair production mechanism must be applied. Since a produced Π^0 (with velocity β) decays to a $\gamma\gamma$ pair at extremely short distance ($0.024\gamma\beta$ μm) from the primary interaction the probability (P) for a γ to convert to a e^+e^- pair will be given by $P = s/\lambda$ where s is the distance traversed by the γ from the primary interaction in the Au foil to the exit point in the foil, and λ is the conversion length for the photon. The conversion length is related to the radiation length L_{rad} by $\lambda = 9/7*L_{rad}$ valid at high energy[5]. We use the value L_{rad} = 0.34 cm for Au. In average we will have $100*2*P/(1+2*P)\%$ admixture of e^+ and e^- tracks in our data sample. We calculate p from half the target thickness (125 μm) as $P = 0.029$ leading to an average admixture of ~ 5%.

The opening angle of the e^+e^- pair is generally speaking very small and can be estimated from Bethe's expression[6] $\omega^0 = 4*m_e c^2/E_\gamma$, where ω^0 is the most probable angle (rad) of divergence between the pair, $m_e c^2$ is the rest mass of the electron (positron) = 0.511 MeV and E_γ is the energy of the γ in MeV. As a typical case a 1 GeV γ will give a typical angle of divergence of about 2 mrad. This simple formula is correct when the electron and positron share the incident energy equally. A general formula valid also for different energy sharing has been given by Borsellino[7]. The correction that we will apply might thus be slightly overestimated since it will not always be possible to resolve the two e^+e^- tracks.

Another possible correction is due to the single Dalitz pair decay mode

$\Pi^0 \to \gamma + e^+ + e^-$. The branching ratio is 1.15 ± 0.05 %, leading to an admixture of ~ 1%. The opening angle ω (deg) of the e^+e^- single Dalitz pair has a probability distribution $e^{(-a/\omega)}/\omega$, where $a \sim 1.7*\exp(-0.17*p_{\pi^0}/m_{\pi^0})$ [8]. Due to the smallness of the correction we have not corrected the spectra for this mechanism and they are also present in the Lund model Fritiof simulations.

Horizontal exposure: Utilizing the horisontal technique, ^{16}O induced emulsion interactions at 14.6, 60 and 200 A GeV, have shown scaling properties of the shower multiplicity distributions[9] and limiting fragmentation in the projectile and target pseudo-rapidity regions[10].

In order to be able to investigate ^{32}S + Em interactions we have also used horizontally (H) exposed emulsion stacks. These 12 stacks contain emulsion of BR-2 type and consist of 30 pellicles, each of size 20 x 10 x 0.06 cm^3 (8 stacks) or 10 x 10 x 0.06 cm^3 (4 stacks). The emulsion has a sensitivity of 32±2 grains per 100 microns for a minimum ionizing particle. The stacks were exposed to the same beam as described above.

Interactions were found by along-the-track scanning which, because of its high detection efficiency, produces a reliable minimum bias sample. Each track was followed from the entry point up to a distance of 6-7 cm. For events found at a distance of 2-5 cm from the edge of the plate the angles of all particles were measured. Measurements at distances more than 5 cm from the front edge are difficult due to the background of secondary particles. All measurements of angles $\Theta \leq 10\text{-}15^\circ$ were done relative to non-interacting beam tracks selected in the vicinity of the interaction point. This procedure results in an accuracy of about $\Delta\Theta \simeq 0.1$ mrad for angles $\Theta \leq 1$ mrad. In the measured events the angles of all particles were recorded as well as the multiplicities of n_s (shower particles), N_g (grey particles), N_b (black particles) and N_f (fragments with $Z \geq 2$ inside the fragmentation cone). For the definition of these quantities and how the particles are categorized see, for instance, ref [11]. For the projectile fragments the charge Z was determined by δ-rays or gap density counting. To select central Ag,Br interactions only those events satisfying the trigger condition $\Sigma Q_i = 0,1$ were used, where ΣQ_i is the summed charge inside the fragmentation cone. In total we have 48 such events out of which 47 have $n_s \geq 200$ and 30 with $n_s \geq 300$. As for the vertical case we count n_s inside the region $1.32 < \eta < 7.6$. From the Lund model Fritiof 4500 S + Em minimum bias events were generated out of which 149 fulfilled similar trigger conditions. The "central" sample corresponds to 3.3% of the S+Em minimum bias cross section, whereas the additional cut $n_s \geq 200$ corresponds to 3.3% and $n_s \geq 300$ to 2.8%. As expressed in terms of the S+Ag,Br minimum bias cross section the corresponding figures are 6.3%, 6.2% and 5.3%. This relatively hard trigger warrants that only S + Ag,Br interactions will be observed.

Pseudo-rapidity distributions: In Fig. 1a and 1b we show the pseudo-rapidity distribution of S + Ag,Br and S + Au interactions for events with $n_s \geq 300$. The peak position in the spectra are close to the pseudo-rapidity for NN interaction ($\eta_{NN} \sim 3$). The charged particle density, $\rho = 1/N_{int}\, dn/d\eta$, at the peak position is about 110 for S + Ag,Br and 120 for S + Au interactions. The quotient 120/110 ~ 1.1 could be related to the number of participating nucleons, which for a central collision becomes (32+81)/(32+60) ~ 1.2, where the slight difference in quotient could be attributed to the less stringent trigger condition for ^{32}S+Au interactions. The outcome of the Lund model Fritiof shows excellent agreement with the data both in shape and magnitude. The latter, while being sensitive to the applied n_s cut, is also affected by the exact shape of the multiplicity distribution and the similarities are thus not a simple consequence of the cut. Note, in Fig. 1a, that for the range $-1 < \eta < +1$ the cascading inside the target nucleus does not seem to affect the pionproduction [10], which can be seen from the nice agreement with the Lund model Fritiof which ignores cascading.

Fluctuations in rapidity density: In Fig. 2 and 3 we show the fluctuations in the charged particle density in four different rapidity regions ($1.5 < \eta < 2.5$, $2.5 < \eta < 3.5$, $3.5 < \eta < 4.5$ and $4.5 < \eta < 5.5$) for S + Ag,Br and S + Au events having $n_s \geq 200$. Each region is divided into five bins with $\Delta\eta = 0.2$, and the distribution of densities for all bins and all events are shown. We see that the general shape of the distributions in Fig. 3 are well described by the Lund model, indicating that these fluctuations are due to fluctuations in the number of participating nucleons, breakup of excited strings, decay of resonances etc. The smaller fluctuations at the highest pseudo-rapidity region $4.5 < \eta < 5.5$ and the similarity in shape of Fig. 2d and Fig. 3d can be related to the fact that in this region we mainly find projectile associated particles and due to the multiplicity requirement nearly all projectile nucleons participate and hence their number does not fluctuate as much as the number of participants from the target. An estimate of the energy density ε (GeV/fm^3) utilizing the Bjorken formula [12]:

$$\varepsilon = (3/2)*\rho*m_T(\tau_0 \pi R^2)^{-1} \qquad (2)$$

with τ_0 = 1 fm/c, m_T = 0.38 GeV, and R = 3.8 fm gives for S + Ag,Br (ρ = 190) ε = 2.4 and for S + Au (ρ = 240) ε = 3.0 GeV/fm^3. In case of S + Ag,Br, the observed maximum energy density is close to the values obtained for a few tail events in ^{16}O + Ag,Br interactions[2]. However, the percentage of such high density events is higher in the case of S + Ag,Br than for O + Ag,Br interactions and the spatial region with this high energy density is likely to be much larger in S + Ag,Br and S + Au interactions than in ^{16}O + Em.

In Fig. 4 we show, as a scatterplot, the strong correlation between the rapidity density ρ and the number of shower particles n_s for ^{32}S + Au interactions. The curves indicate $\langle\rho(n_s)\rangle$ as estimated from the Lund model Fritiof. The scatterplot for ^{32}S + Ag,Br interactions has a similar appearance but in ^{32}S + Au interactions, there exist 6 events with high multiplicities and charged particle densities, which seem to be absent in the Ag,Br and the Lund model data. The correlation between n_s and ρ is otherwise well described by the model.

Conclusions: From the study above it seems natural to assume that the geometry of the nuclear collisions and the number of participating nucleons, play an important role in determining the pseudo-rapidity spectra and the fluctuations in charged particle density. Although the bulk of our central trigger data can be very well understood on the basis of the Lund model Fritiof a few high multiplicity events in ^{32}S + Au interactions remain unexplained. The maximum energy densities obtained are not larger than in ^{16}O + Ag,Br interactions, but the spatial region with this high energy density is likely to increase with the mass number of the projectile and target.

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Figure Captions

Figure 1

Pseudo-rapidity distributions for shower particles in events with $n_s \geq 300$, a) S + Ag,Br interactions and b) S + Au interactions. Filled circles gives the outcome of the Lund model Fritiof.

Figure 2

Rapidity density distributions of S + Ag,Br in bins of $\Delta\eta = 0.2$, in four different regions of η.

Figure 3

Rapidity density distributions of S + Au in bins of $\Delta\eta = 0.2$, in four different regions of η.

Figure 4

Rapidity densities versus multiplicity for S + Au (filled circles) interactions in individual events at four different η regions. The curves (solid line) indicate the average behaviour predicted by the Lund model Fritiof.

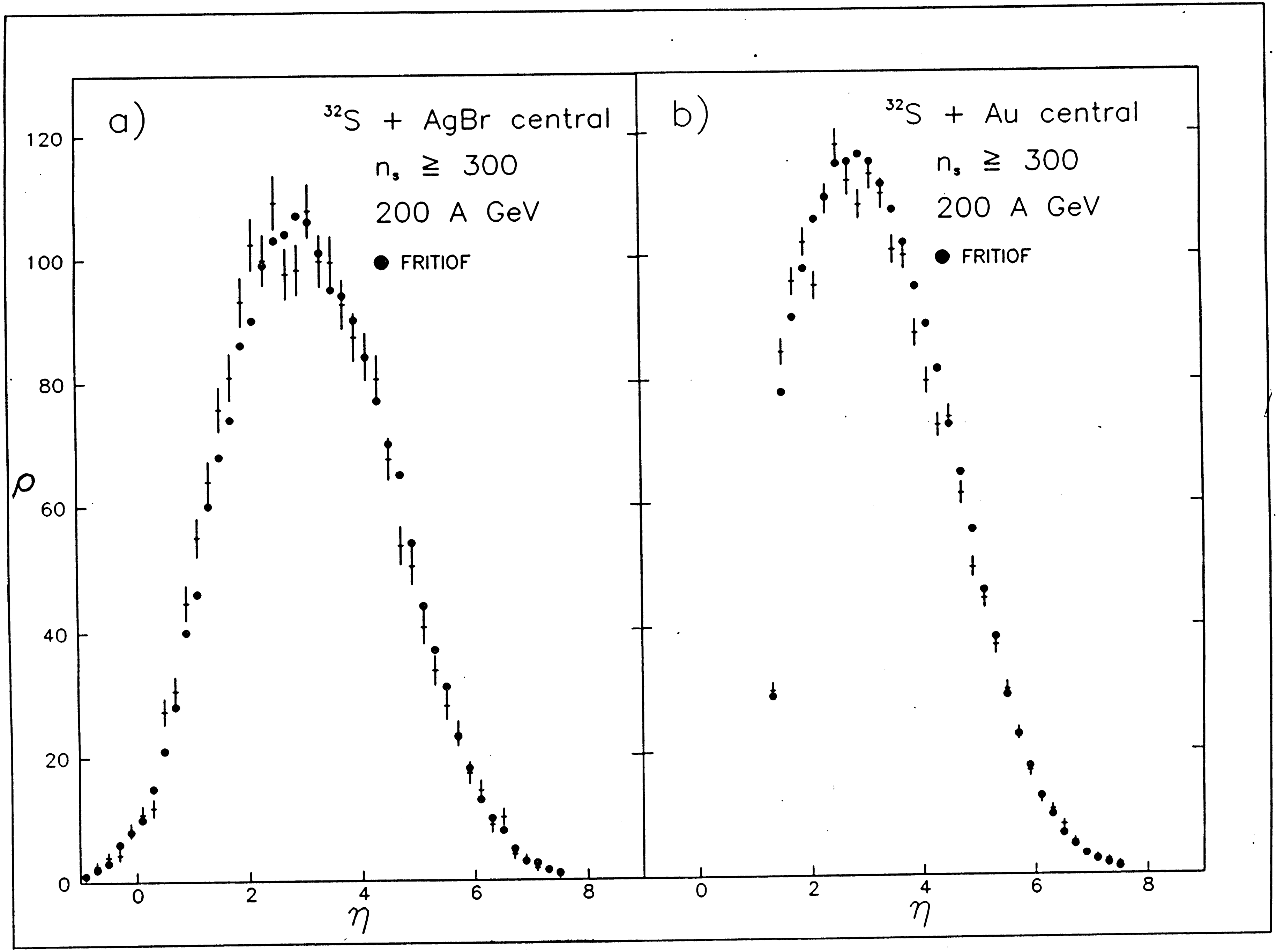
a)
^{32}S + AgBr central
$n_s \geq 300$
200 A GeV
● FRITIOF
b)
^{32}S + Au central
$n_s \geq 300$
200 A GeV
● FRITIOF
ρ
0
20
40
60
80
100
120
0
2
4
6
8
η
0
2
4
6
8
η

FIG I

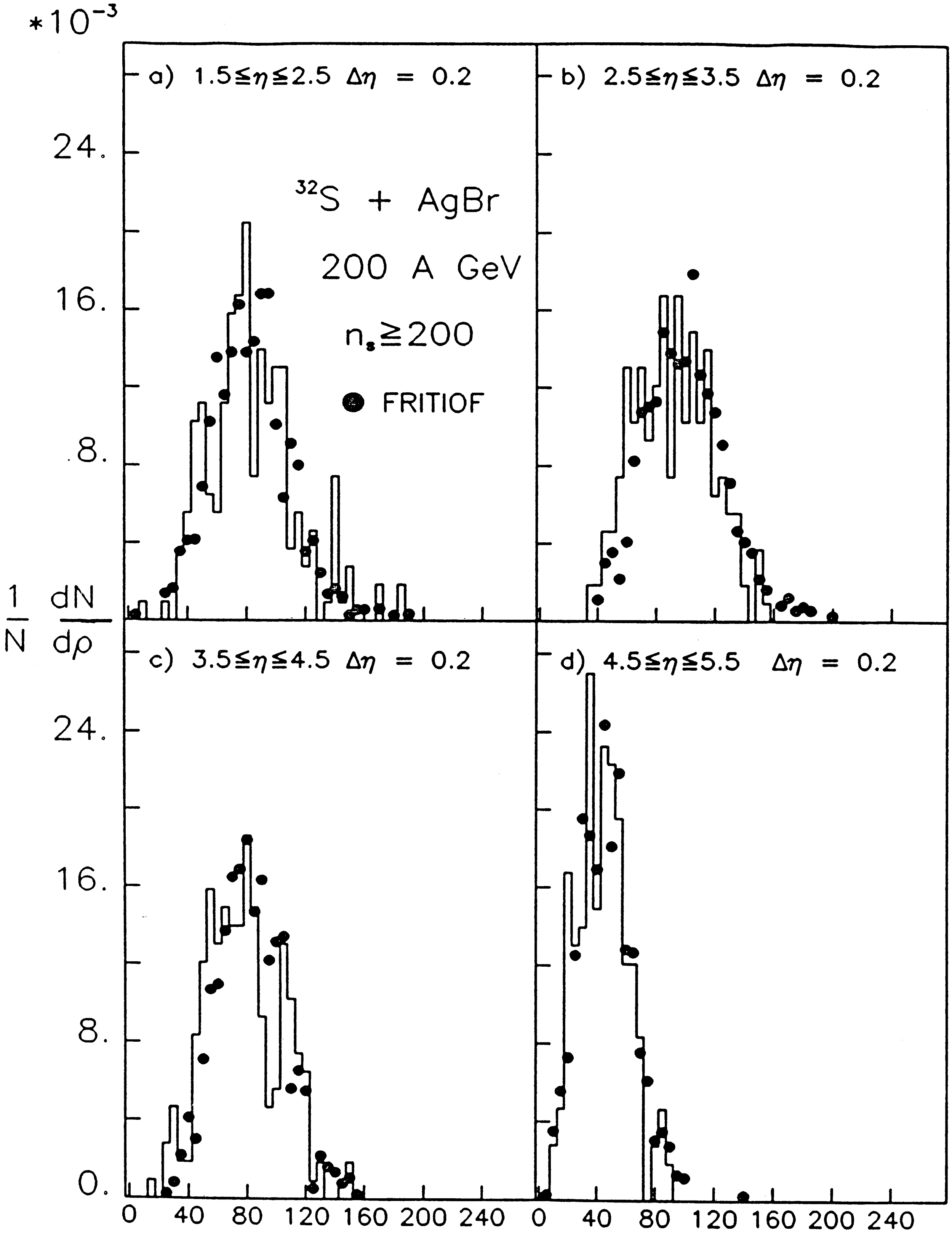
*10^-3
a) 1.5≦η≦2.5 Δη = 0.2
b) 2.5≦η≦3.5 Δη = 0.2
c) 3.5≦η≦4.5 Δη = 0.2
d) 4.5≦η≦5.5 Δη = 0.2
³²S + AgBr
200 A GeV
n_s≧200
● FRITIOF
24.
16.
8.
0.
1/N dN/dρ
0 40 80 120 160 200 240
RAPIDITY DENSITY ρ

FIG 2

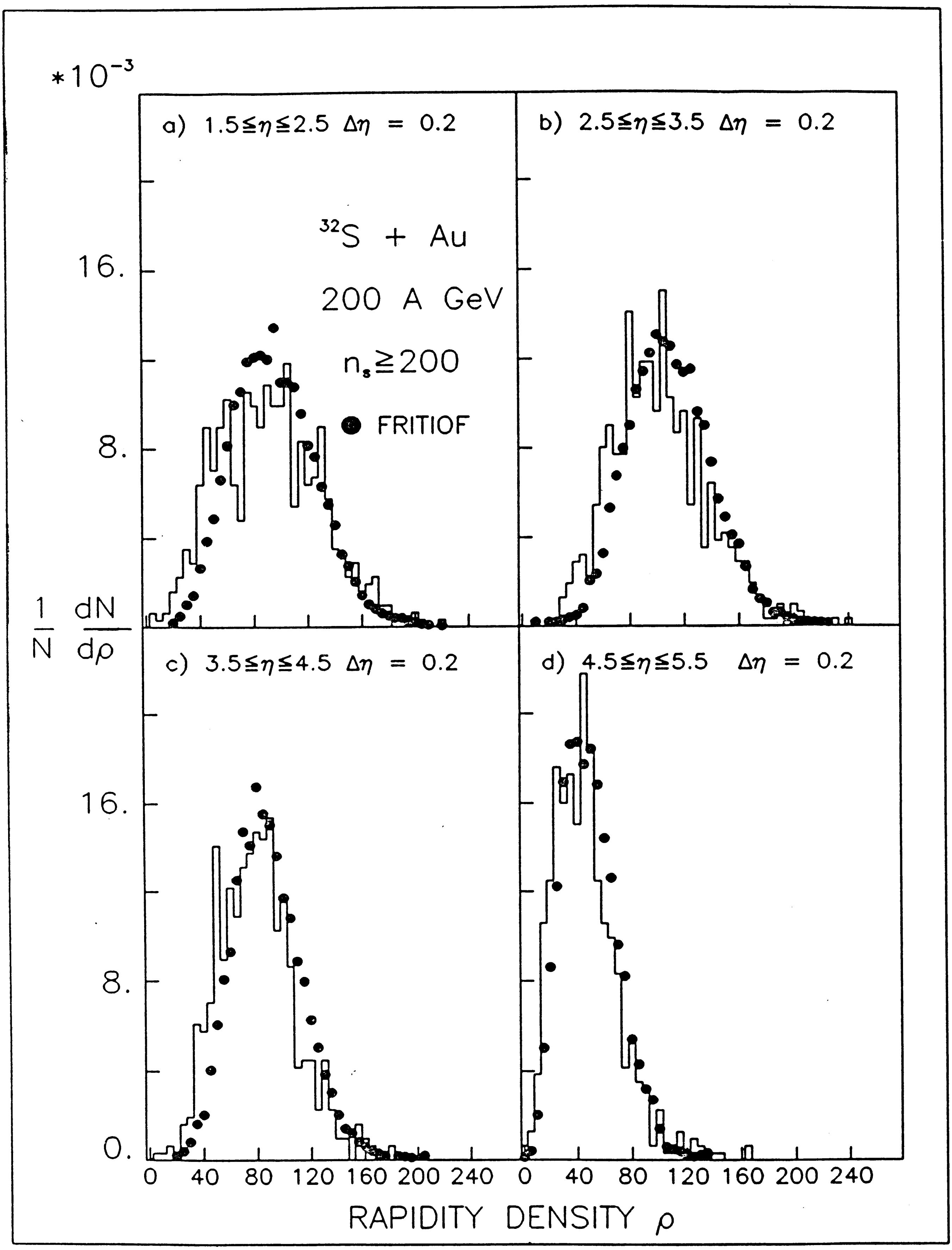
*10^{-3}
a) 1.5≦η≦2.5 Δη = 0.2
b) 2.5≦η≦3.5 Δη = 0.2
c) 3.5≦η≦4.5 Δη = 0.2
d) 4.5≦η≦5.5 Δη = 0.2
32S + Au
200 A GeV
ns≧200
● FRITIOF
16.
8.
0.
1/N dN/dρ
0 40 80 120 160 200 240
RAPIDITY DENSITY ρ

FIG 3

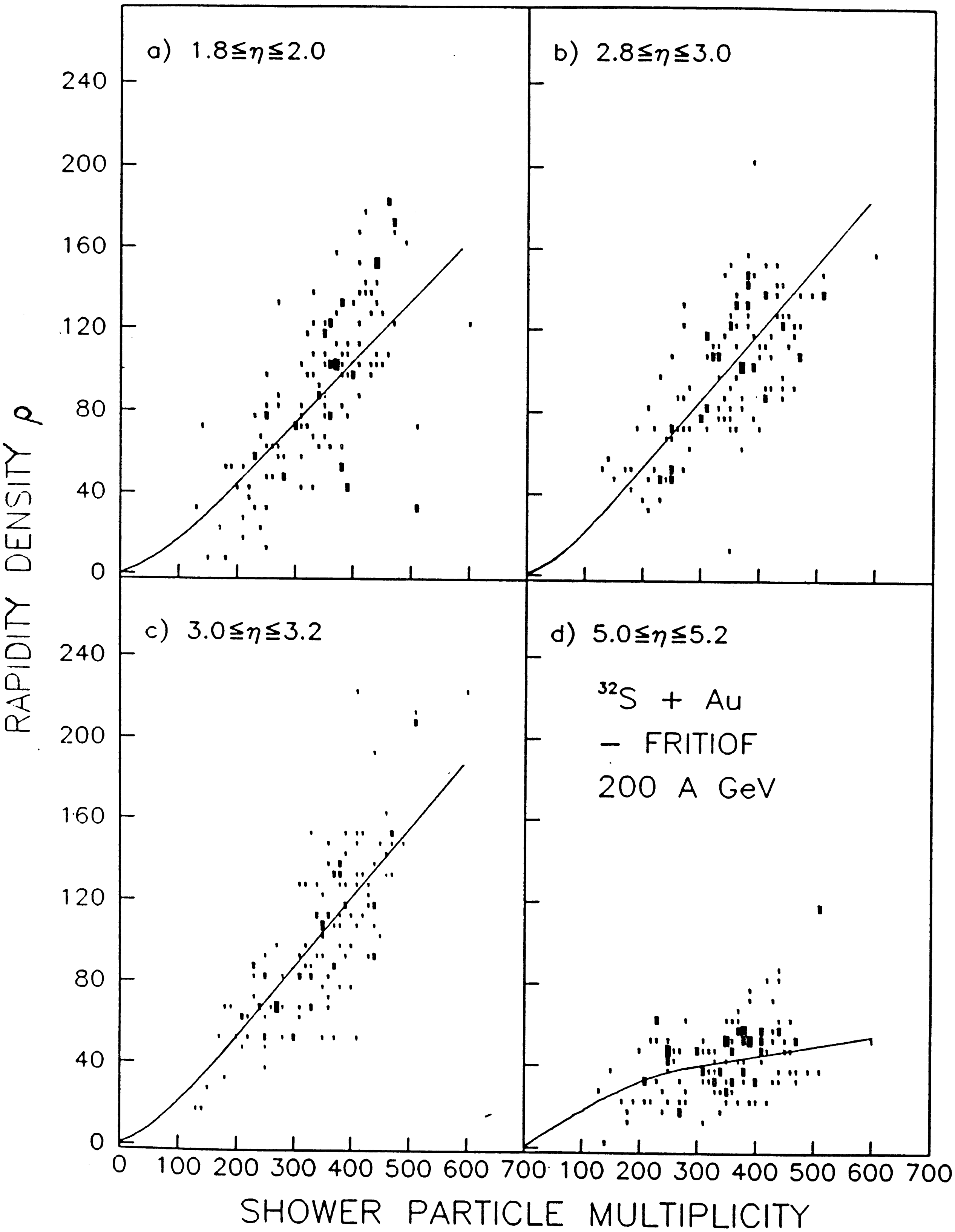
a) 1.8≤η≤2.0
b) 2.8≤η≤3.0
c) 3.0≤η≤3.2
d) 5.0≤η≤5.2
^{32}S + Au
– FRITIOF
200 A GeV
RAPIDITY DENSITY ρ
0
40
80
120
160
200
240
SHOWER PARTICLE MULTIPLICITY
0
100
200
300
400
500
600
700

FIG 4