Rapidity Density Distributions in ^{16}O, ^{28}Si, ^{32}S, ^{197}Au, and ^{208}Pb Induced Heavy-Ion Interactions at 4A-200A GeV

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The mass, energy, and centrality dependence of rapidity density distributions of relativistic, charged particles, produced in heavy-ion interactions in the energy range 4A-200A GeV, are investigated. The results indicate that the rapidity density distributions show systematic variations, which are used to predict distributions for Au+Au and Pb+Pb interactions in a model-independent way.

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During the era of heavy ions at the CERN Super Proton Synchrotron (SPS) and the BNL Alternating Gradient Synchrotron (AGS) the EMU01 Collaboration has collected data from interactions at various energies and with different projectile nuclei. At the same time the EMU01 Collaboration has collected data with similar beams from the JINR Synchrophasotron in Dubna. We are thus in the rather unique position of being able to study aspects of the particle production in heavy-ion interactions at various energies and with various projectiles

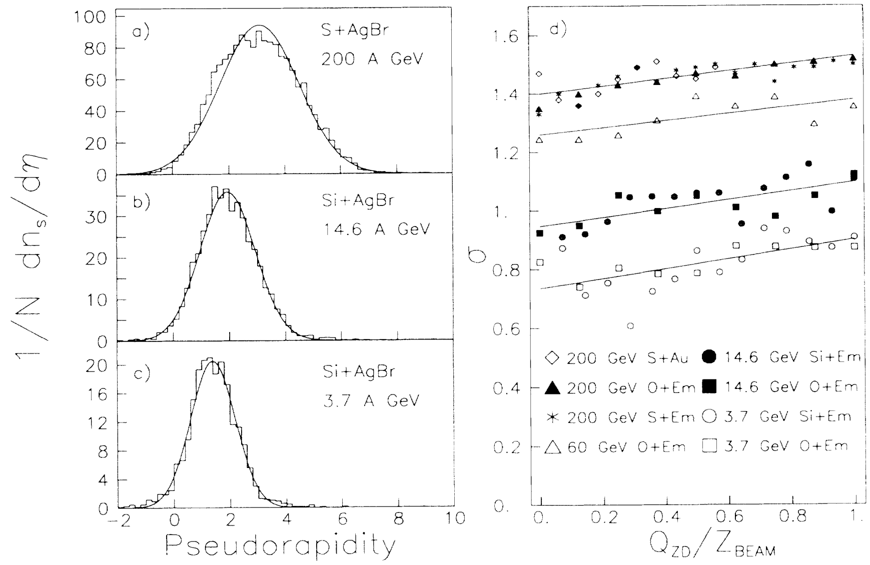

FIG. 1. (a)–(c) Examples of pseudorapidity distributions for central events and corresponding Gaussian fits. (d) Widths of pseudorapidity distributions and their centrality ($Q_{ZD}/Z_{\rm beam}$) dependence for various interacting systems at different energies [typical errors are (2–5)%]. The lines represent the fits in Table I.

using an identical detector and identical measuring techniques. Such studies are important and deviations from the general trends, as energies and ion masses increase, may suggest the existence of new phases of matter, e.g., the quark-gluon plasma.

In this Letter we will focus on pseudorapidity distributions of relativistic, charged particles and their dependence on projectile mass, incident energy, and the centrality of the interaction. The centrality is determined using the number of elementary charges, Q_{ZD}, that are found in a narow forward cone [1], thus corresponding to the spectator parts of the projectile. The particles considered here are shower particles, which are mainly charged pions with a small admixture of kaons, protons, and antiprotons all having a velocity larger than 70% of the light velocity. This velocity requirement ensures that essentially all fragments and knockout protons from the target are excluded. Those particles show energy-independent features [2] and should not be included among the produced particles. The characteristics of the data and the experimental technique have been given elsewhere [1]. Events due to electromagnetic dissociation are as far as possible excluded from the data.

When comparing pseudorapidity distributions of particles produced in different colliding systems and at different energies a suitable parametrization of their shapes is needed. Here we have chosen a Gaussian representation [3]. In our experience most pseudorapidity distributions are nicely represented by Gaussians, as long as shower particles are considered and the fragmentation regions are excluded in the fitting procedure. When Gaussians are fitted to the η distributions we use the interval $0 \leq \eta \leq y_p$, where y_p is the projectile rapidity. In Figs. 1(a)–1(c) three examples together with their Gaussian representations are given: central samples of ^{32}S and ^{28}Si induced interactions on Ag and Br targets at 200A, 14.6A, and 3.7A GeV, respectively. As can be seen the distributions are well described by the chosen form. The Gaussian distribution

$$\rho(\eta)d\eta = \rho_{\max}\exp\{-(\eta-\eta_{\rm peak})^2/2\sigma^2\}d\eta \qquad (1)$$

is given by three free parameters: $\eta_{\rm peak}$, representing the position of the peak, $\rho_{\max}$, representing the height of the distribution, and σ, representing the width of the distribution. Furthermore the integrated multiplicity n is given by

$$n = \sqrt{2\pi}\,\sigma\rho_{\max}\,. \qquad (2)$$

Let us first consider the widths of the distributions. In Fig. 1(d) the widths of the distributions for the different samples studied and different impact parameters are summarized. Each sample is subdivided into subsamples of different centralities as given by the parameter $Q_{ZD}/Z_{\rm beam}$, i.e., the fraction of noninteracting protons from the projectile. Thus $Q_{ZD}/Z_{\rm beam}$ close to 0 corresponds to the most central events. For fixed incident energy we see that σ is totally independent of the interacting system and furthermore show a (10–20)% variation when going from the most central to the most peripheral events. The obtained σ values are in good agreement with the results obtained by von Gersdorff *et al.* [3] and Åkesson *et al.* [4]. Widths obtained by Albrecht *et al.* [5], with a limited η coverage, are larger, but here target associated particles are included. In Table I the parameters s_1 and s_2 from fits with

$$\sigma = s_1 + s_2 Q_{ZD}/Z_{\rm beam} \qquad (3)$$

TABLE I. Coefficients s_1 and s_2 from Eq. (3) for the linear fits to data in Fig. 1(b).

Energy (GeV)	s_1	s_2
200*A*	1.40 ± 0.01	0.13 ± 0.02
60*A*	1.26 ± 0.03	0.12 ± 0.05
14.6*A*	0.95 ± 0.02	0.15 ± 0.04
3.7*A*	0.74 ± 0.03	0.17 ± 0.04

are given for the different samples. The small variation of the parameter s_2 between the different samples indicates that the nuclear stopping is similar at different energies [6]. The variation of σ (or s_1) with energy is simply connected to the available region of phase space and s_1 can be parametrized as

$$s_1 = \alpha + \beta \ln E , \tag{4}$$

with $\alpha = 0.51 \pm 0.05$ and $\beta = 0.17 \pm 0.01$. Similar results are obtained with simulated data from VENUS 3.11 [7] and from FRITIOF 1.7 [8] and typical values at 200*A* GeV are $s_1 = 1.31$ and $s_2 = 0.20$ for VENUS and $s_1 = 1.41$ and $s_2 = 0.10$ for FRITIOF. Thus for peripheral interactions (i.e., $\sigma = s_1 + s_2$) the two models agree with each other and with the data, whereas VENUS gives somewhat narrower distributions for the most central events, indicating a larger amount of stopping in that model. For the VENUS model the results are identical if only negative pions are considered instead of charged particles, and the same is true for the FRITIOF model.

Returning to Eq. (2) we see that, for fixed energy, σ can approximately be taken as a constant which immediately tells us that ρ_{max} is proportional to the globally observed total multiplicity of produced particles. We thus have the prediction that in a plot of ρ_{max} versus total multiplicity the results from all interacting systems will fall on a universal straight line, with a slope only dependent on the incident energy. In Fig. 2(a) such a plot is shown for 200*A* GeV, and we find that this is indeed the case. We can now extrapolate into the region where one would expect central ^{208}Pb + ^{208}Pb interactions to fall and the obtained results can be directly compared to predictions from current models. In Fig. 2(b) this extrapolation is performed using the width s_1 for central events, and points corresponding to central events from VENUS 3.11 and FRITIOF 1.7 are inserted. We observe that the VENUS model shows an excess over the extrapolation, especially for the largest possible multiplicities, whereas the FRITIOF model is in good agreement with the extrapolation. The excess in the VENUS model is due to rescattering and creation of short strings in the repeated binary collisions.

We can now proceed one step further and predict the pseudorapidity distribution in central Pb + Pb interactions at 160*A* GeV in the CERN SPS perspective. From Table I we estimate $\sigma_{central} = s_1$ to be 1.38 at 160*A* GeV. If we consider events in which on the average 340 nucleons have participated (cf. FRITIOF and VENUS below), an estimate of the total charged particle multiplicity is 1300. Here we used the experimental observation [6,9] that the number of produced particles per participating nucleon is essentially constant for fixed energy, independent of the interacting system and centrality. A parametrization of the energy dependence of this number [6,10] is

$$n/P = 0.734 n_{ch} - 1.44 . \tag{5}$$

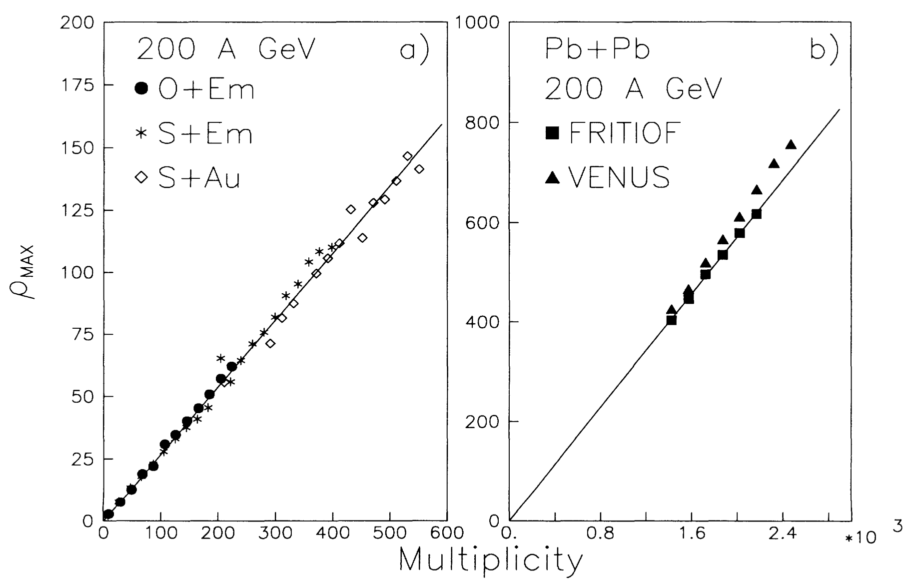

FIG. 2. The multiplicity dependence of the height of the pseudorapidity distributions, ρ_{max}, for (a) various systems at 200*A* GeV and (b) extrapolation to Pb + Pb interactions at 200*A* GeV. In (b) the extrapolation is compared to results from VENUS and FRITIOF calculations.

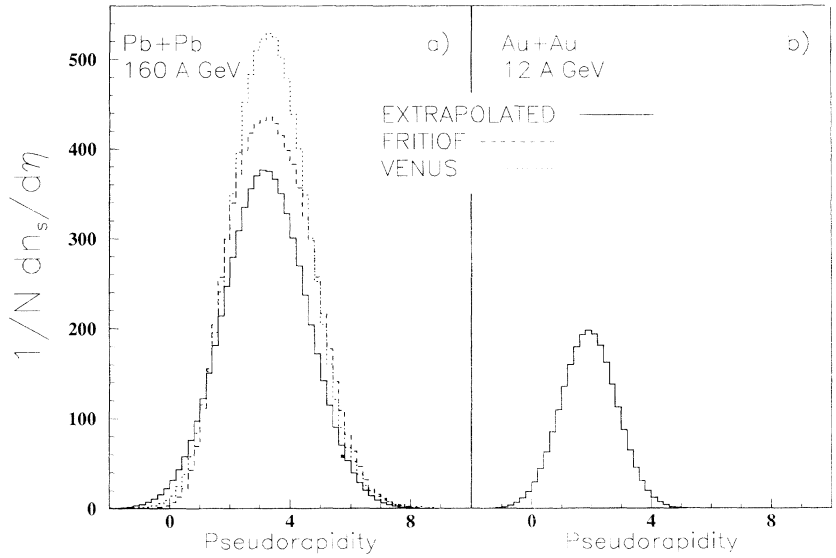

FIG. 3. Extrapolated pseudorapidity distributions for (a) central Pb+Pb interactions at 160*A* GeV and (b) central Au+Au interactions at 12*A* GeV. At 160*A* GeV the obtained distribution is compared with corresponding predictions from VENUS and FRITIOF.

Here P is the number of participating nucleons and n_{ch} is the charged particle multiplicity in pp collisions at the corresponding energy. For 200*A* GeV a value of 4.14 is obtained from Eq. (5), and taking the energy dependence into account gives 3.84 at 160*A* GeV. Finally Pb+Pb is a symmetric system and thus η_{peak} can be deduced from the peak position for the most peripheral events from our data on asymmetric systems. For such events we find that $\eta_{peak}=y_p/2+0.25$ is in good agreement with the data. In Fig. 3(a) predictions from this extrapolation are compared with predictions from VENUS and FRITIOF. For the two models a centrality criterion of $Q_{ZD}/Z_{beam} < 0.5$ is imposed corresponding to 13% and 10% of the total cross section for VENUS and FRITIOF, respectively. The average number of participants in the two cases is 341 and 334, respectively. We observe that VENUS predicts a much larger particle density in the central region than both FRITIOF and the extrapolation and is somewhat more narrow. The extrapolation and the FRITIOF prediction differ by about 15%, but agree rather well concerning the shape of the distribution [cf. Fig. 2(b)].

In the BNL AGS perspective we can similarly predict the pseudorapidity distribution for central ^{197}Au+^{197}Au interactions at 12*A* GeV, and the result is given in Fig. 3(b), assuming that all 394 nucleons participated.

In this Letter we have shown that for a given incident energy the shape of the pseudorapidity distributions is conserved independent of the projectile and target masses. When peripheral and central interactions are compared, the widths of the distributions only change about (10–20)%. The data thus suggest that a linear extrapolation from the presently available rather limited mass range up to Pb+Pb interactions may be valid. In the next few years data will exist which will make it possible to distinguish between such a linear extrapolation and models with nonlinear features exemplified here by the VENUS model.

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