Study of inelastic interactions of 340-GeV/c pions with emulsion nuclei

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Results from a study of interactions of a 340-GeV/c π^- beam with emulsion nuclei at the CERN SPS are presented. Some characteristics of heavy- and shower-particle multiplicity distributions are reported. The Koba-Nielsen-Olesen scaling hypothesis has been tested. Single-particle pseudorapidity distributions and rapidity-gap distributions have been studied in detail. The pseudorapidity distributions show a bimodal structure in all $\pi^- A$ interactions and the rapidity-gap distributions indicate the production of clusters during the multiparticle production process. The production of heavy clusters has also been studied using the rapidity-interval method proposed by Adamovich *et al.* The result shows that 340 GeV is below the threshold energy at which heavy clusters may begin to produce.

I. INTRODUCTION

The multiparticle production process in high-energy hadron-nucleus interactions is a complex phenomenon and its study can provide a number of unique physics opportunities that are not available from a study of hadron-hadron interactions alone. Using heavy nuclei as targets, one can study the properties of hadrons at the time of their production and the space-time development of the hadronic process. Various theoretical models[1–6] have been proposed in order to explain the experimental results on multiparticle production in high-energy collisions of elementary particles. Most of the results presented in this paper are compared with the predictions of these models. It should be emphasized that the accumulation of accurate experimental data is still a current problem. It is also noted that the pion-nucleus ($\pi^- A$) interactions are much less investigated than proton-nucleus (pA) interactions. So keeping this in mind, an investigation of the multiparticle production phenomenon in pion-nucleus interactions at 340 GeV/c was undertaken.

In the present paper, we report some interesting results on 340-GeV/c π^--emulsion interactions.

II. EXPERIMENTAL DETAILS

In this investigation, we have used emulsion plates of size $\sim 7.5\times 7.5\times 0.063$ cm^3 exposed to a 340-GeV/c negative-pion beam at the CERN SPS. The flux of the beam is not uniform and varied from $(0.5-1.5)\times 10^4$ particles/cm^2. The events were searched by the method of area scanning using Cooke's M4000 series microscopes with $15\times$ eyepieces and $20\times$ objective. For measurements a $100\times$ oil immersion objective was used. The following criteria were used to select the interactions.

(1) Interactions were picked up after leaving 3 mm from the edges of pellicles in order to avoid the distortions at the edges.

(2) The beam track must lie within 2° of its mean direction in the pellicle.

(3) In order to facilitate the measurements, the stars which were produced within ~ 35 μm from the top or the bottom surfaces of the pellicle were excluded from the data.

(4) All the primaries of the selected events were followed back to ensure that the events chosen did not include secondary interactions.

(5) The secondary tracks were grouped into three categories based on their ionization. The tracks with specific ionization $g^* < 1.4$, $1.4 \le g^* \le 10$, and $g^* > 10$ have been taken as shower, grey, and black tracks, respectively.

Based on the above criteria a sample of 815 events with $N_h \ge 2$ and 200 events with $N_h = 0$ or 1 were picked up. The events with $N_h = 0$ or 1 are considered to represent pion-nucleon ($\pi^- N$) collisions. Thus, the results presented here are based on the analysis of 1015 interactions.

III. RESULTS AND DISCUSSION

A. Multiplicity of charged secondaries

In Table I, the values of $\langle n_s \rangle$, $\langle n_g \rangle$, $\langle n_b \rangle$, and $\langle N_h \rangle$ as obtained in the present experiment are compared with their values at other energies.[7–11] It is seen that the average values of these quantities for proton-emulsion collisions are higher than the corresponding values for pion-emulsion collisions, except for the $\langle n_b \rangle$, which is higher in the case of pion-emulsion collisions at 340 GeV. The ratios $\langle n_s \rangle_{\pi^- A}/\langle n_s \rangle_{pA}$, $\langle n_g \rangle_{\pi^- A}/\langle n_g \rangle_{pA}$, $\langle n_b \rangle_{\pi^- A}/\langle n_b \rangle_{pA}$, and $\langle N_h \rangle_{\pi^- A}/\langle N_h \rangle_{pA}$ at about the same momenta for pion and protons are 0.84, 0.83, 1.07, and 0.96, respectively, which may be compared to[12] $\langle \nu \rangle_{\pi^- A}/\langle \nu \rangle_{pA} \simeq 0.81$.

B. Correlations between multiplicities of different particles

Correlations between multiplicities of different particles of type $\langle n_i(n_j) \rangle$, where n_i, $n_j = n_s$, n_b, n_g, N_h and $i \ne j$ are studied and the data at 340 GeV/c are found to be fitted satisfactorily by linear functions of the type

$$\langle n_i(n_j) \rangle = a_{ij} n_j + b_{ij} \quad (1)$$

TABLE I. Values of average multiplicities of different charged secondaries in π^--emulsion and p-emulsion collisions.

Energy (GeV)	Type of interaction	$\langle n_b \rangle$	$\langle n_g \rangle$	$\langle N_h \rangle$	$\langle n_s \rangle$	Refs.
50	π^--emulsion	4.48±0.09	2.71±0.07	7.19±0.16	8.27±0.12	7
200	π^--emulsion	4.42±0.07	2.38±0.04	6.90±0.04	12.01±0.05	8
300	π^--emulsion	4.71±0.25	2.89±0.20	7.60±0.45	14.09±0.42	11
340	π^--emulsion	5.21±0.07	2.00±0.04	6.95±0.07	14.22±0.12	This work
340	π^--N	0.22±0.03	0.09±0.02	0.31±0.04	10.29±0.22	This work
200	p-emulsion	5.03±0.10	2.70±0.06	7.36±0.16	13.31±0.30	9
300	p-emulsion	5.40	1.80	7.10±0.20	15.10±0.20	10
400	p-emulsion	4.87±0.20	2.39±0.21	7.26±0.22	16.86±0.51	7

with positive slopes. The values of a_{ij} and b_{ij} as obtained by a least-squares fit are listed in Table II. Variation of $\langle n_s \rangle$, $\langle n_b \rangle$, and $\langle N_h \rangle$ with n_g seems to be most interesting and is given in Fig. 1. These quantities vary linearly with n_g up to $n_g \simeq 8$ and there after the behavior becomes random. This may be due to the so-called saturation effect at $n_g \simeq 8$. Therefore, for establishing the dependence on n_g, the fit has been carried out only up to $n_g = 8$. It is clear from the table that the dependence of $\langle n_s \rangle$ is strongest on n_g in comparison to its dependence on n_b or N_h.

This indicates that n_g may be taken as the best measure of the intranuclear collisions, $\langle \nu \rangle$.

C. Charge multiplicity distributions and Koba-Nielsen-Olesen scaling

The Koba-Nielsen-Olesen (KNO) scaling[13] of shower particles in pion-nucleus interactions is tested here. For the scaling hypothesis to be valid, the normalized moments of the distributions, C_k, which are defined as $C_k = \langle n_s{}^k \rangle / \langle n_s \rangle^k$, where k can have values 1,2,3,4, etc., should be independent of energy. The values of the normalized moments C_2, C_3, and C_4 have been calculated for the shower multiplicity distributions of pion-emulsion collisions at 50 and 340 GeV/c. The values are given in Table III. For the sake of comparison the values of C_2 and C_3 obtained by Anzon *et al.* are also given in the table. A comparison of the values shows that these parameters do not change with energy.

The scaling functions due to Slattery and Buras[14] have been tried to fit the multiplicity distributions at 50 and 340 GeV/c. The Buras function given as

$$\psi(z') = A(z'+B)\exp(Cz'+Dz'^2) , \tag{2}$$

with $z' = n_s - \alpha / \langle n_s \rangle - \alpha$ is found to give the best fit to the data (Fig. 2). Taking[15] $\alpha = 0$, the values of the parameters for the best fit are $A = 2.033$, $B = -0.275$, $C = 2.526$, and $D = -2.217$ with $\chi^2/\mathrm{DF} = 1.42$.

The same function has been found to give a fairly good fit to the data for the distribution obtained by dividing the sample in different N_h or n_g bins.

D. Rapidity distributions

The true rapidity variable of a particle at sufficiently high energies reduces to the form $Y \simeq \eta = -\ln \tan\theta/2$ and is generally called its pseudorapidity, where θ is the space angle of the particle with respect to the primary particle.

Figure 3 shows rapidity distributions of showers observed in $\pi^- A$ and $\pi^- N$ interactions at 340 GeV/c. In Fig. 4 the rapidity distributions of showers in different n_g bins for $\pi^- A$ interactions are given. Figure 5 presents the differences

$$d(\eta) = \left[\frac{1}{N} \frac{dn}{d\eta} \right]_{\pi^- A} - \left[\frac{1}{N} \frac{dn}{d\eta} \right]_{\pi^- N} \tag{3}$$

and the ratios

$$r(\eta) = \left[\frac{1}{N} \frac{dn}{d\eta} \right]_{\pi^- A} \Big/ \left[\frac{1}{N} \frac{dn}{d\eta} \right]_{\pi^- N} \tag{4}$$

for different n_g groups of $\pi^- A$ interactions. From these distributions the following observations can be made.

(i) The pseudorapidity distributions of $\pi^- A$ and $\pi^- N$ interactions differ in the sense that the former are en-

TABLE II. Results of the approximation to experimental data on multiplicity correlations by the dependence $\langle n_i(n_j) \rangle = a_{ij} n_j + b_{ij}$ in 340-GeV/c π^--emulsion interactions.

$\langle n_i(n_j) \rangle$	n_j: N_h	n_s	n_g[a]	n_s
$\langle N_h \rangle$		$1.31n_b + 0.04$	$2.26n_g + 3.59$	$0.64n_s - 1.28$
$\langle n_b \rangle$	$0.41N_h + 5.13$		$1.21n_g + 3.69$	$0.45n_s - 0.80$
$\langle n_g \rangle$	$0.29N_h - 0.36$	$0.233n_b + 0.59$		$0.18n_s - 0.59$
$\langle n_s \rangle$	$0.35N_h + 12.02$	$0.48n_b + 11.86$	$1.02n_g + 12.32$	

[a]For n_g dependence, the fit has been done up to $n_g = 8$.

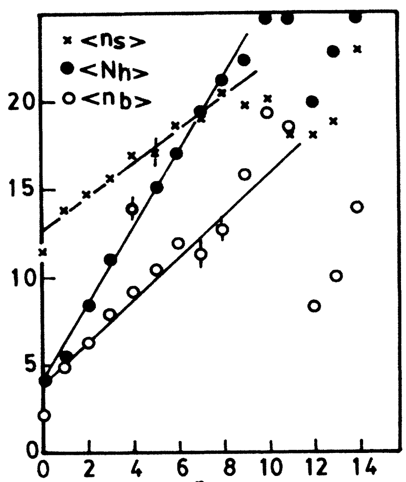

FIG. 1. Multiplicity correlations of shower $\langle n_s \rangle$, heavy $\langle N_h \rangle$, and black $\langle n_b \rangle$ tracks as a function of the number of grey tracks n_g. The straight lines represent an approximation with the function $\langle n_i(n_j) \rangle = a_{ij} n_g + b_{ij}$.

riched with particles of small rapidity (η) while the latter are enriched with particles of higher rapidity. The larger the value of n_g, the stronger is the deformation in the angular spectrum. This indicates that the number of medium fast particles is related to the influence of the target on the particle production process.

(ii) The shape of the η spectrum undergoes a very specific transformation with increasing n_g. The bimodal structure is present in all the n_g groups. The centroid of the distribution of the excess particles continuously shifts towards lower values of rapidity η as n_g increases. The bimodality is present in the case of pion-nucleus interactions at high energies, whereas no such bimodality is observed in proton-nucleus interactions.[7,16]

The observed change in the η spectrum with the target size, i.e., its dependence on n_g (or ν) and the bimodal structure of the distributions contradict the simple and naive versions of the tube model where hadron-nucleus interactions are considered to be identical to hadron-hadron interactions and, therefore, the structure of the distribution should not depend upon n_g. It may be mentioned that the composite nature of emulsion having two groups of nuclei (CNO and AgBr) cannot be responsible for the observed change in the η spectrum, since the events with $n_g \geq 3$ are essentially from heavy nuclei and also the pA collisions in emulsion do not show any bimodal structure. The change in the η spectrum towards the lower rapidity side with increasing target size and the shift of the centroid of the excess of particles is qualitatively inconsistent with the energy-flux-cascade (EFC) model, where the η spectrum from slow hadrons is independent of the number of collisions inside the nucleus and depends only on the incident energy.

TABLE III. Values of normalized moment in 50-, 200-, and 340-GeV/c π^--emulsion interactions.

Energy (GeV)	C_2	C_3	C_4	Refs.
50	1.31±0.04	2.14±0.06	3.92±0.03	15
200	1.33±0.03	2.22±0.09		8
340	1.47±0.05	2.23±0.09	3.97±0.10	This work

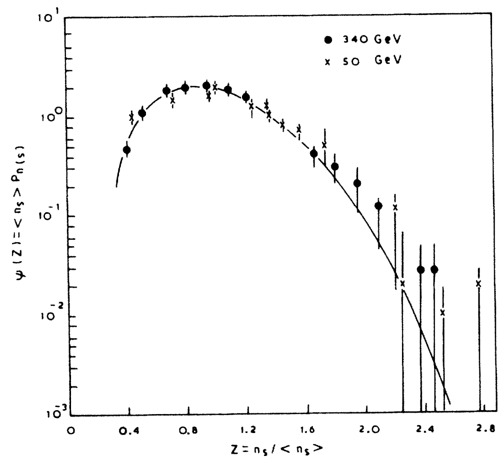

FIG. 2. The Buras scaling function (2) is represented by the solid line and is compared with the experimental data for the scaling function $\psi(z') = \langle n_s \rangle P_n(s)$ for π^--emulsion interactions at 50 and 340 GeV/c.

(iii) The study of differences $d(\eta)$ and the ratios $r(\eta)$ demonstrates that the pseudorapidity η_0 for which

$$\left[\frac{1}{N}\frac{dn}{d\eta}\right]_{\pi^- A} = \left[\frac{1}{N}\frac{dn}{d\eta}\right]_{\pi^- N}$$

is dependent on n_g. This observation is also inconsistent with the predictions of the energy-flux-cascade model.

E. Rapidity-gap distributions (cluster characteristics)

It is believed that the study of rapidity-gap distribution may lead to some information about the intermediate stage of the multiparticle production process.

For such a study, the pseudorapidity (η) of all the n charged particles of an event is arranged in increasing order ($\eta_1 < \eta_2 < \cdots < \eta_n$). The differences

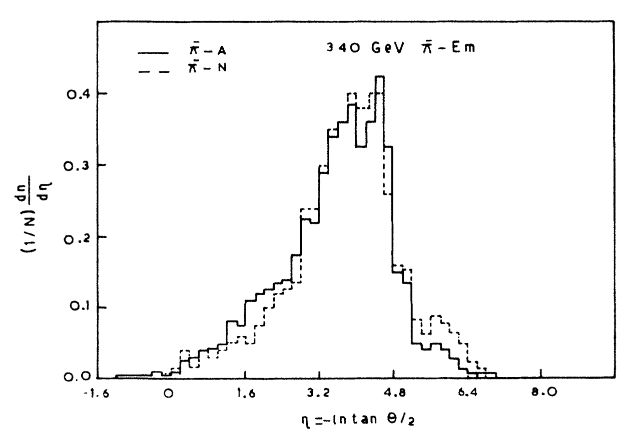

FIG. 3. Pseudorapidity distributions of shower particles from π^--emulsion and π^--N interactions.

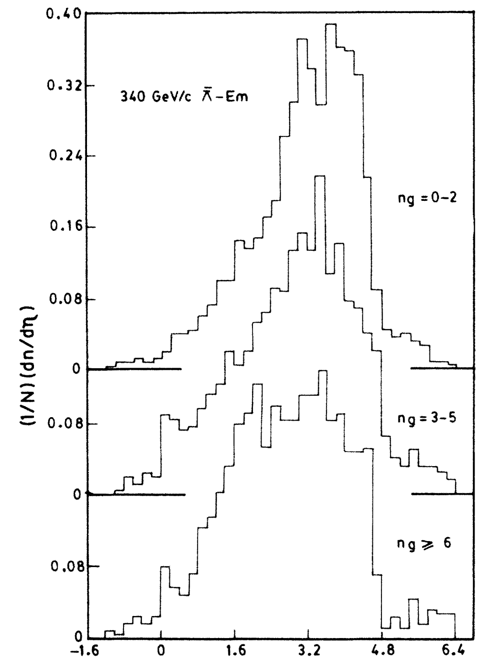

FIG. 4. Pseudorapidity distributions of shower particles in 340-GeV/c π^--emulsion interactions in different n_g bins.

$$r(2)=\eta_{i+1}-\eta_i, \text{ where } i=1,2,\ldots,n-1 \tag{5}$$

are calculated. This gives rise to two-particle rapidity-gap distribution. Similarly, the differences

$$r(3)=\eta_{i+2}-\eta_i, \text{ where } i=1,2,\ldots,n-2 \tag{6}$$

give the three-particle rapidity-gap distributions, and so on. Since the study of these correlations only in the central region is of interest, the particles at the two ends of the rapidity space are excluded while calculating the differences, as these correspond to the leading and target particles at high energies.

Figures 6(a) and 6(b) show the two-particle rapidity-gap distributions for events produced due to pion-nucleus and pion-nucleon collisions at 340 GeV/c. The presence of a sharp peak at small values of rapidity gaps gives evidence for strong short-range correlations which supports cluster formation. The existence of such a correlation has been reported in hadron-hadron and hadron-nucleus collisions at other energies.[18–21] In order to see the effect of phase space in these correlations, we have generated about 500 pseudoevents by randomly combining tracks from different events. The two-particle rapidity-gap distribution thus obtained for the generated events is shown in Fig. 7(a). The distribution for these pseudoevents visually looks similar to the experimental distribution. However, to see the difference between the two, we have plotted a difference distribution in Fig. 7(b). This figure shows a definite excess at small values of rapidity gaps. Thus, the correlations observed at small values of rapidity gaps cannot be attributed entirely to phase-space effects. As is evident from Figs. 6(a) and 6(b), the two-particle rapidity-gap distributions cannot be represented by a single exponential function. It has been shown that at high energies the rapidity-gap distributions in hadronic collisions can be well represented by the two-channel generalization of the Chew-Pignotti model[17] of the form

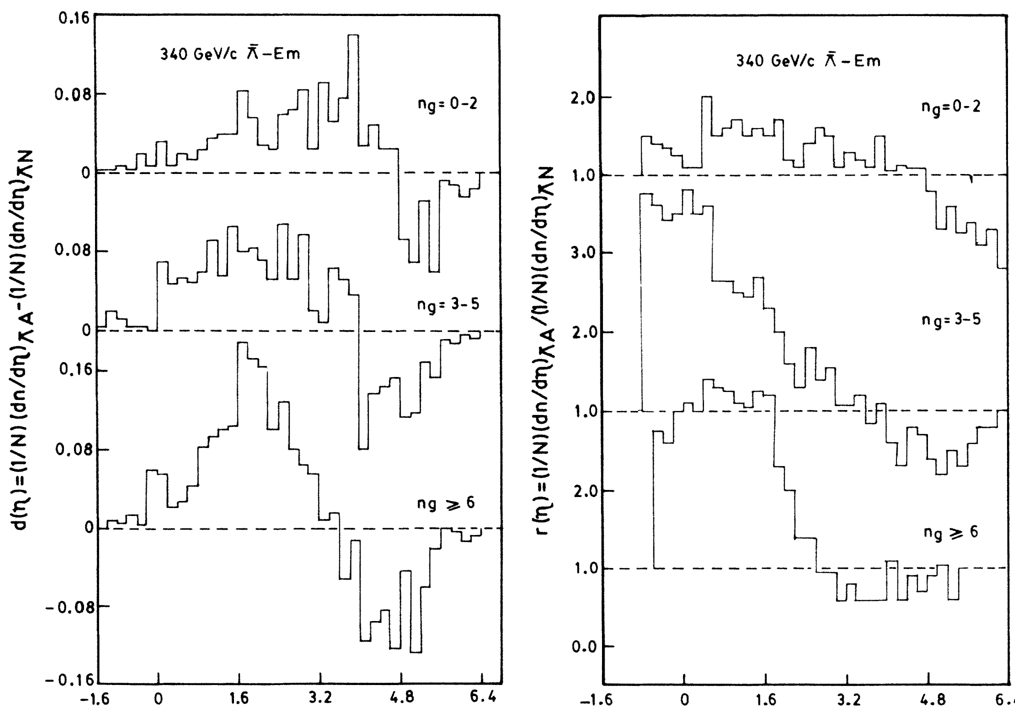

FIG. 5. Dependence of the difference $d(\eta)$ and the ratios $r(\eta)$ on η in different n_g groups of π^--emulsion interactions at 340 GeV/c.

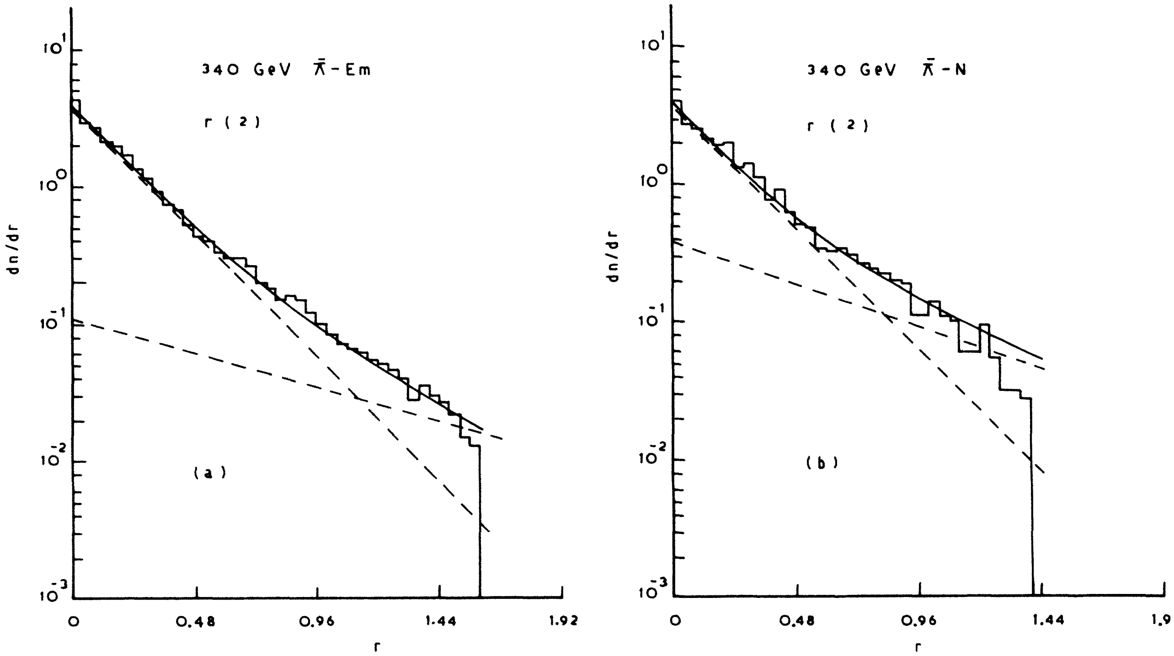

FIG. 6. Two-particle rapidity-gap distributions of shower particles (a) π^--emulsion and (b) π^--N interactions at 340 GeV/c.

$$\frac{dn}{dr}=A\exp(-Br)+C\exp(-Dr)\ . \qquad (7)$$

The value of the slope B is a measure of the strength of the correlation and is termed the cluster density. The values of A, B, C, and D have been calculated by the method of least squares for π^-A and π^-N distributions at 340 GeV/c, using a VAX-11 computer, and are given in Table IV. The dashed lines in Figs. 6(a) and 6(b) represent contributions due to two individual terms of Eq. (7). It is seen although the observed distributions are described by the superposition of two exponential terms, the main contribution comes from the short-range term, i.e., the first term only. Several workers[18–21] have also studied the rapidity-gap distributions at other energies. From the reported results[18–21] it is seen that the value of B is nearly independent of energy and the nature of the projectile.

No sharp peak is observed in three- and four-particle

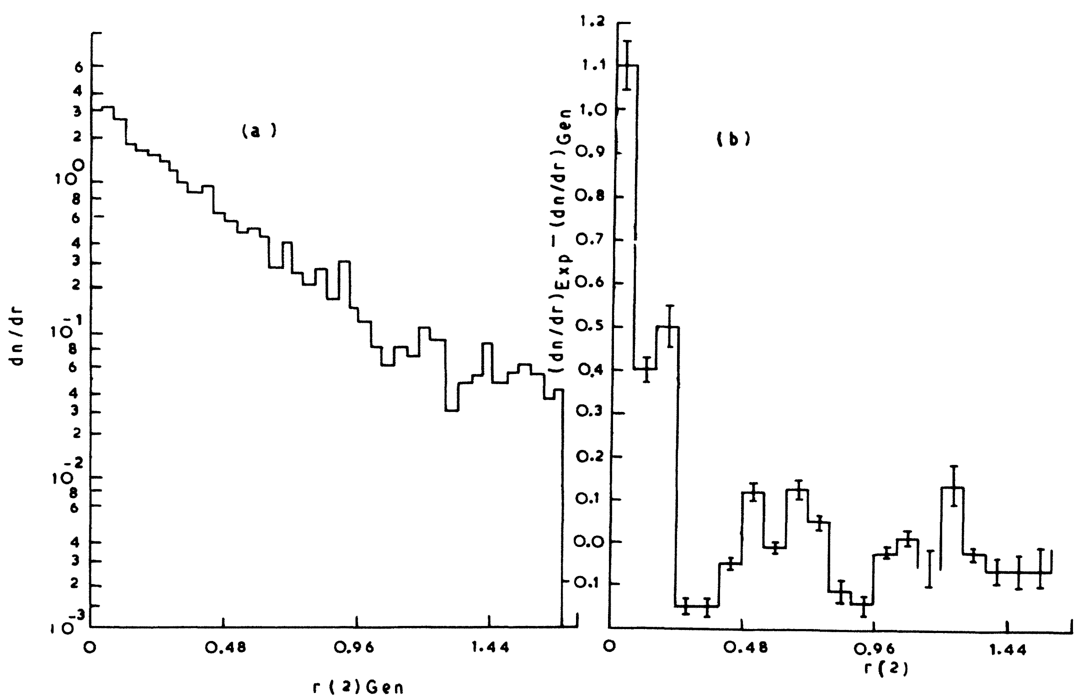

FIG. 7. (a) Two-particle rapidity-gap distribution of the generated events at 340 GeV/c. (b) Difference distribution at 340 GeV/c.

TABLE IV. Values of A, B, C, and D in 340-GeV/c π^--emulsion and π^--N interactions.

Type of interactions	A	B	C	D
π^--emulsion	3.83±0.07	4.42±0.13	0.115±0.03	1.16±0.41
π^--N	3.83±0.14	4.35±0.12	0.37±0.15	1.37±0.28

rapidity-gap distributions and thus higher-order correlations do not seem to exist in these interactions.

Adamovich *et al.*[22] have deduced that the rapidity-gap distributions can be represented by

$$\frac{dn}{dr} \sim e^{-\rho m r} \text{ (for small } r\text{)}, \quad (8)$$

$$\frac{dn}{dr} \sim e^{-\rho r} \text{ (for large } r\text{)}, \quad (9)$$

where m denotes the cluster decay multiplicity and ρ indicates the cluster density. Using the slope parameters B and D as obtained earlier, the value of m has been found to be 3.81 for pion-nucleus and 3.17 for pion-nucleon collisions. Our result strongly favors Snider's predicted value of m equal to 3.50 in 200-GeV pp interactions. Ludlam and Slansky have reported the value of m to be 4.0±0.8 at 205 GeV/c and 3.50±0.8 at 300 GeV/c by the fluctuation-analysis method.[23]

F. Production of heavy clusters

Recently, some workers have suggested that two- or three-particle correlations among showers could be due to the well-known resonances and that many particle correlations could be due to the production of fireball type of clusters.[24] To discriminate between these two cases, Adamovich *et al.*[22] have suggested a method of analyzing high-energy jets by the investigation of all available distributions of rapidity intervals. The rapidity interval $^n r_k$ between two particles, containing k particles in between, is defined as

$$^n r_k = \eta_{i+k+1} - \eta_i , \quad (10)$$

where $1 \le i \le n-k-1$, $0 \le k \le n-2$, and n is the total number of showers in an event. The distributions of these intervals can be obtained by summing up all possible choices of pairs of particles. According to Adamovich

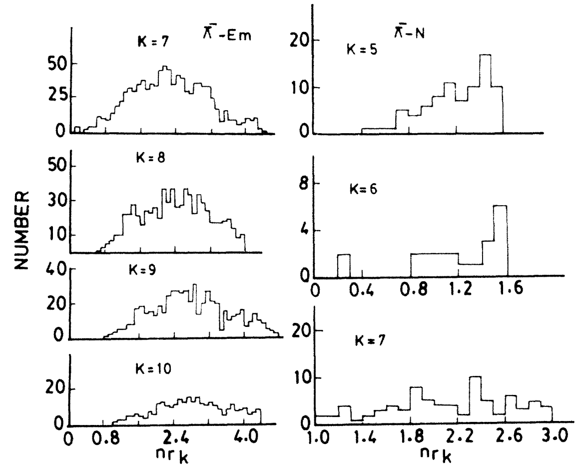

FIG. 8. Experimental distributions of rapidity intervals with $k=7$ to 10 for π^--emulsion and $k=5$ to 7 for π^--N interactions at 340 GeV/c.

et al., the comparison of theory and experiment can be best done if we confine our data to the events with n values close to $\langle n_s \rangle$ for the whole data. In the present work $\langle n_s \rangle = 14.22 \pm 0.12$ for π^--emulsion and 10.29 ± 0.22 for π^--N interactions. We have, therefore, selected 191 π^--emulsion interactions with $n_s = 13$, 14, 15, and 69 π^--N interactions with $n_s = 9$, 10, 11 which contributes to 2674 and 690 shower tracks for the present analysis. In the case of production of two heavy clusters a two-bump structure is observed in the distributions and this structure should be noticeable from $k \ge n/2$. In our case the two-bump structure should be observed from $k \ge 7$ in the case of π^--emulsion and $k \ge 5$ in case of π^--N interactions. The experimental rapidity interval distributions for π^--emulsion and π^--N interactions are shown in Fig. 8. No such bumps are observed. Goyal *et al.*[25] have reported that in 1000-GeV NN interactions some sharp bumps are observed for $k \ge n/2$. We therefore conclude that 340 GeV is below the threshold energy at which heavy clusters may be beginning to be produced and the production of heavy clusters is therefore energy dependent.

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