Inelastic interactions of 340-GeV/c π^- with emulsion nuclei

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Pion-nucleus interactions in nuclear emulsions from 340-GeV/c π^- H2 beam at CERN SPS are studied. The average values of produced showers $\langle n_s \rangle$, gray $\langle n_g \rangle$, black $\langle n_b \rangle$, and heavily ionizing particles $\langle n_h \rangle$ are measured. Linear correlations between these numbers were obtained. The Koba-Nielsen-Olesen—type scaling behavior of the shower particles is investigated. A test of the collective tube model is carried out. The gray particles are studied in the framework of the Pomeron interaction with nuclei applying the tree approximation.

The use of heavy nuclei as targets in relativistic particle collisions enables us to study the hadronic production mechanism. The investigation of the multiplicities of the different produced charged particles (secondaries) and their dependence on the space-time development of hadron-hadron collisions enables us to test the different current theoretical models.[1–3] For the π^- interactions with nuclei, experimental data exist for energies up to 200 GeV/c incident π^- momentum.[4–6] Accurate measurements at higher momenta are very rare.[7] In this work, data concerning the multiplicities of the different charged secondaries produced in π^--emulsion interactions at 340 GeV/c are presented.

A (6 cm$\times$15 cm$\times$22$\times$600 μm) stack of Ilford G-5 emulsion was exposed to the CERN SPS H2 π^- beam at 340 GeV/c. Pellicles were oriented parallel to the beam, so that the length of the beam tracks is many centimeters per single pellicle. The incident flux was about 7×10^4 particles/cm^2. The emulsions were processed at CERN EP division. The number of grains per 100 μm for the incident pion tracks $\simeq$19 (i.e., in the plateau). In an along the track scanning, 1000 interactions were systematically collected. The value of the mean free path of inelastic interactions of 340-GeV/c π^- in emulsions was found to be $\lambda=40.09\pm1.5$ cm. Samples collected in that way have a natural composition of all topologies. For each event, the number of heavily ionizing particles n_h (gray particles n_g+ black particles n_b) and relativistic charged shower particles n_s were carefully counted (for definition of tracks see Ref. 8). Events with a single relativistic track emitted at an angle ≤ 7 mrad were excluded from our sample. Following known criterion,[9] events due to π^--nucleon interactions (these are events with at most one gray track; for protons, this corresponds to kinetic energy between 25 and 400 MeV, in the forward laboratory hemisphere, and without a visible recoil nucleus) were separated. The events due to π^- coherent interactions with emulsion nuclei are thus automatically separated, since they are contained among the odd-prong-number π^--nucleon events. All the events due to π^- interactions with emulsion nuclei were accurately examined.

In Table I, the average multiplicities of the dif-

TABLE I. The average values of the different charged secondaries emitted in π^- and p interactions with emulsion nuclei.

	π^- 340 GeV/c	π^- 200 GeV/c	p 200 GeV/c	p 400 GeV/c
$\langle n_s \rangle$	13.38$\pm$0.18	12.01$\pm$0.10	14.00$\pm$0.20	16.74$\pm$0.17
$\langle n_g \rangle$	2.25$\pm$0.10	2.38$\pm$0.04	2.70$\pm$0.06	2.99$\pm$0.06
$\langle n_b \rangle$	5.69$\pm$0.11	4.52$\pm$0.07	5.00$\pm$0.10	5.00$\pm$0.09
$\langle n_h \rangle$	7.90$\pm$0.13	6.89$\pm$0.11	7.70$\pm$0.10	7.99$\pm$0.14
$\langle n_b \rangle / \langle n_g \rangle$	2.53$\pm$0.12	1.89$\pm$0.05	1.86$\pm$0.06	1.67$\pm$0.06

ferent emitted charged secondaries, $\langle n_s \rangle$, $\langle n_g \rangle$, $\langle n_b \rangle$, $\langle n_h \rangle$, together with the ratio $\langle n_s \rangle / \langle n_g \rangle$ for the π^--A interactions at 340 GeV/c and at 200 GeV/c,[6(b)] as well as for p-A interactions at 400 GeV/c (Refs. 10,11) and at 200 GeV/c (Ref. 12), are presented. It is clear that all the average values in case p-A interactions are higher than the corresponding values for π^--A except for the $\langle n_b \rangle$ value, which is higher in case of π^--A interactions at 340 GeV/c. This leads to a higher value for the ratio $\langle n_b \rangle / \langle n_g \rangle$.

The ratios $\langle n_s \rangle_{\pi^- \text{-}A} / \langle n_s \rangle_{p\text{-}A}$, $\langle n_g \rangle_{\pi^- \text{-}A} / \langle n_g \rangle_{p\text{-}A}$, $\langle n_b \rangle_{\pi^- \text{-}A} / \langle n_b \rangle_{p\text{-}A}$, and $\langle n_h \rangle_{\pi^- \text{-}A} / \langle n_h \rangle_{p\text{-}A}$ at approximately the same momenta for pions and protons (~ 340 GeV/c) are 0.84 ± 0.02, 0.75 ± 0.05, 1.14 ± 0.04, and 0.99 ± 0.03, respectively. The mean number of intranuclear collisions $\langle \nu \rangle$ in case of π^--A and p-A was calculated for the average emulsion nucleus ($A \sim 70$) using the cross-section data of Ref. 13 and the ratio

$$\langle \nu \rangle_{\pi^- \text{-}A} / \langle \nu \rangle_{p\text{-}A} = \frac{\sigma^{\text{inel}}_{\pi^- \text{-}p} \sigma^{\text{inel}}_{p\text{-}A}}{\sigma^{\text{inel}}_{p\text{-}p} \sigma^{\text{inel}}_{\pi^- \text{-}A}} = 0.85$$

was obtained. It is clear that this value of $\langle \nu \rangle_{\pi^- \text{-}A} / \langle \nu \rangle_{p\text{-}A}$ is close only to the ratios $\langle n_s \rangle_{\pi^- \text{-}A} / \langle n_s \rangle_{p\text{-}A}$ and $\langle n_g \rangle_{\pi^- \text{-}A} / \langle n_g \rangle_{p\text{-}A}$, reflecting their direct relation and or strong dependence on $\langle \nu \rangle$. The deviation in case of b particles is due to their being related to the last step of the interaction, that is, the evaporation, beside the complexity of the mechanism of their emission. We believe that it is only the ratios of s and g particles which can be compared with $\langle \nu \rangle$.

The correlation between the different charged secondaries of the type $\langle n_i(n_j) \rangle$ ($n_i, n_j = n_s$, n_g, n_b, and n_h, $i \neq j$) is studied and the data at 340 GeV/c are fitted by linear functions with positive slopes

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

The results are presented in Table II. From this table it is clear that the strongest correlation is that of $\langle n_s(n_g) \rangle$. This fact confirms the above-mentioned result that the best experimental measure of the number of the intranuclear collisions $\langle \nu \rangle$ is given by the number of gray particles n_g. As an example Fig. 1 shows the correlation dependence of the multiplicities of showers, black, and heavily ionizing particles on gray particles, that is, $\langle n_i(n_g) \rangle$ with $n_i = n_s$, n_b, and n_h. A change in the slope at $n_g \simeq 6-8$ (the so-called saturation effect) is not as clear as that in case of p-A interactions.[11]

The value of the $\langle n_g \rangle$ is found to decrease logarithmically as the incident pion momentum P_0 increases:

$$\langle n_g \rangle = 3.5 - 0.21 \ln P_0 .$$

This relation is valid in the range of P_0 from 50 up to 340 GeV/c only for π^--nucleus interactions.

In case of p-nucleus interactions, this relation was found to be

$$\langle n_g \rangle = 4.06 - 0.26 \ln P_0$$

in the range of P_0 from 5 up to 200 GeV/c.[2]

The multiplicity distribution of heavily ionizing particles n_h is shown in Fig. 2. The probability of emission of stars with $n_h \geq 28$ is rather small ($< 1.0\%$ from interactions with Ag and Br nuclei). This indicates that the probability of complete destruction in case of π^- interactions with Ag and Br nuclei is rather small relative to that in case of p interactions (which amounts to $2-3\%$).[8,11]

The integral n_h distribution is shown in Fig. 3. The limiting fragmentation of the target nucleus shown in Fig. 3 is considered as an evidence against the intranuclear cascade model.

In the framework of the models without any intranuclear cascade like the energy-flux-cascade model,[14] the two-phase model,[15] the collective tube model (CTM),[3] and the fragmentation model,[16] this limiting fragmentation of nuclei can be considered as a consequence of the constancy of the inelastic

TABLE II. Results of the approximation to experimental data on multiplicity correlations by the dependence $\langle n_i(n_j) \rangle = a_{ij} n_j + b_{ij}$.

	n_h	n_b	n_g	n_s
$\langle n_h \rangle$		$1.31n_b + 0.43$	$2.65n_g + 1.77$	$0.43n_s + 2.37$
$\langle n_b \rangle$	$0.70n_h + 0.21$		$1.69n_g + 2.25$	$0.36n_s + 0.07$
$\langle n_g \rangle$	$0.29n_h + 0.15$	$0.25n_b + 1.14$		$0.11n_s + 0.76$
$\langle n_s \rangle$	$0.50n_h + 9.52$	$0.89n_b + 7.93$	$1.18n_g + 10.46$	
R	$0.07n_h + 0.92$		$0.13n_g + 1.13$	

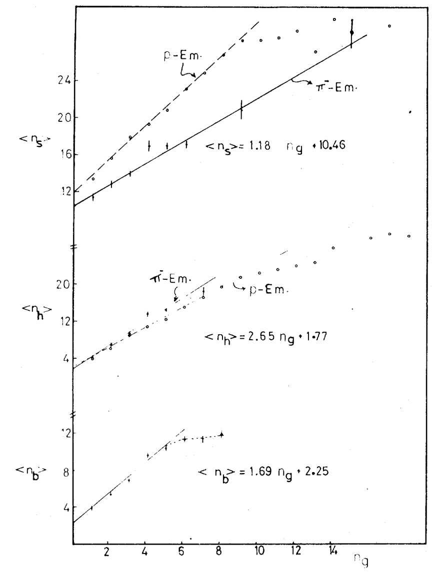

FIG. 1. Correlations of the average number of shower $\langle n_s \rangle$, heavy $\langle n_h \rangle$, and black $\langle n_b \rangle$ tracks as a function of the number of gray tracks n_g for the interaction of 340-GeV/c π^- with emulsion nuclei.

hadron-nucleon cross section σ_{hN} and the mean inelasticity coefficient in hN interactions.

The multiplicity distribution of shower particles is shown in Fig. 4. Figure 5 shows the values of the dispersion $D=[\langle n_s^2 \rangle - \langle n_s \rangle^2]^{1/2}$ of the shower multiplicity distribution against $\langle n_s \rangle$. The data of π^--A interactions at 100 and 175 Gev/c (Ref. 5) and that at 300 GeV/c (Ref. 7) are shown.

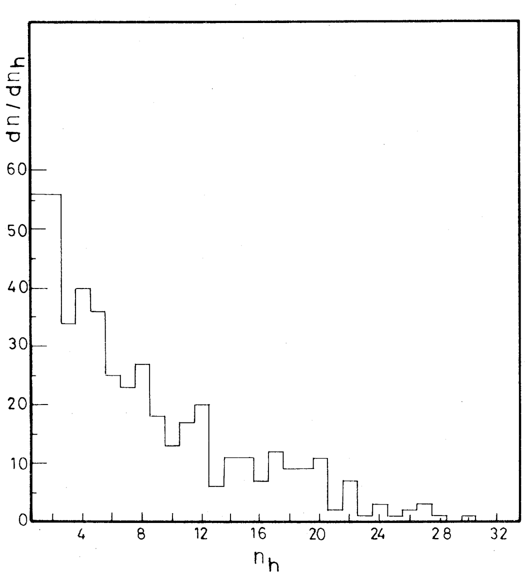

FIG. 2. Distribution of events as a function of heavily ionizing particles n_h.

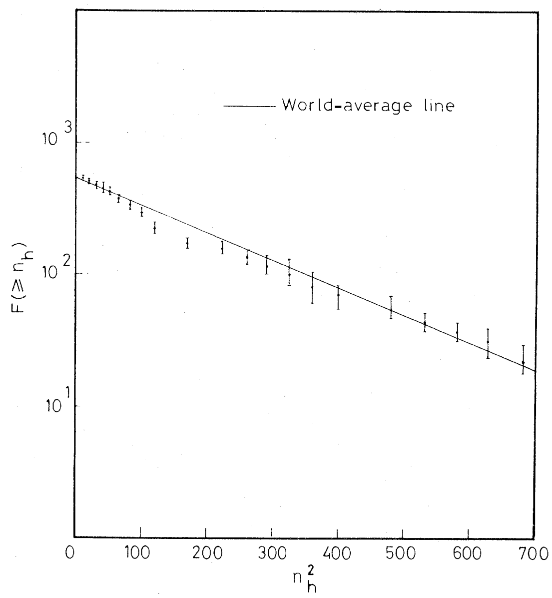

FIG. 3. Integral n_h distribution as a function of n_h^2 compared with the world-average line.

A least-squares fit to the data gave

$$D = 0.57\langle n_s \rangle - 0.73 .$$

This relation is very near to that of π^--p data (in the range 20–360 GeV/c),[5]

$$D = 0.56\langle n_s \rangle - 0.58$$

and to that of π^- interactions[5] given by

$$D = (0.54 \pm 0.16)\langle n_s \rangle - (0.59 \pm 0.2) .$$

This fact may reflect the nucleus transparency in case of π^--nucleus interactions especially at such high energies. It is clear from Fig. 5 that the Poisson distribution can not describe the data in that range of energy. The CTM (Ref. 3) calculations show deviations from the experimental data especially at lower values of $\langle n_s \rangle$. The big deviations from the general behavior of the D-$\langle n_s \rangle$ line of the points of the recent data[7] of the π^- interactions with ^{26}Al, ^{64}Cu, and ^{184}W at 300 GeV/c reflects the importance of the present results. The investigation of the dependence of the ratio $D/\langle n_s \rangle$ on the number of the gray particles n_g (related to the average number of collisions $\langle \nu \rangle$) is shown in Fig. 6. The decrease of that ratio $D/\langle n_s \rangle$ as n_g or $\langle \nu \rangle$ increases is clear and contradicts the CTM expectations. The deviation from the Koba-Nielsen-Olesen (KNO) scaling[17] behavior in hadron-nucleon collisions is seen and may be attributed to the energy loss as n_g increases. The same behavior was observed in a counter experiment[4,18] of π^- in-

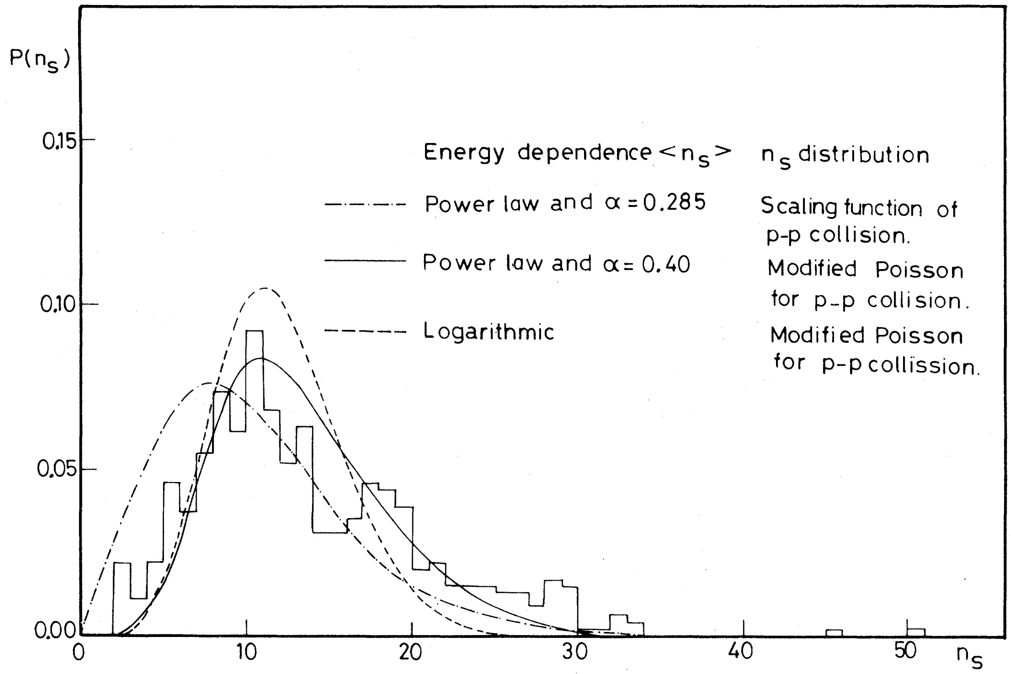

FIG. 4. Shower particles n_s multiplicity distribution (histogram) compared with the predictions of the CTM model. Different energy dependences of $\langle n_s \rangle$ as well as different distribution of showers produced in p-p collisions (as indicated in the figure) are used.

teractions with Al, Ag, and Pb nuclei at energies (20–37.5 GeV).

The KNO-type scaling[17] behavior of the topological cross section of shower particles in π^--nucleus interactions is tested here. The Buras scaling function[19] (which is valid for p-p interactions in a wide energy range)

$$\Psi(Z)=A(Z+B)\exp(CZ+DZ^2) , \qquad (1)$$

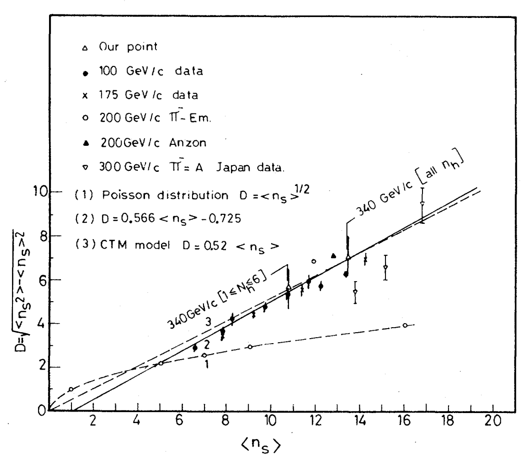

FIG. 5. The dispersion D of the showers multiplicity distribution as a function of $\langle n_s \rangle$.

with

$$Z=n_s-\alpha/\langle n_s \rangle-\alpha ,$$

is tested here using the data of π^--emulsion interactions at 17 (Ref. 20), 50 (Ref. 21), 60 (Ref. 22), 200 [Ref. 6(b)], and 340 GeV/c. A study of the central moments at these energies gave a value for the parameter $\alpha=0$. Figure 7 shows the scaling function (1) compared with the experimental data. The parameters giving the best fitting of Eq. (1) are $A=1.15$, $B=0.140$, $C=-0.059$, and $D=-0.659$. The same function was found to fit the p-emulsion data in the energy range from 6.0 up to 300.0 GeV/c.[23]

In the framework of the CTM, the probability $P_n(A,S)$ of producing n charged particles in the interaction of a hadron with a nucleus of mass number A at a center-of-mass energy $\sqrt{s}$ is given by[3,24]

$$P_n(A,s)=\sum_{i=1}^{A} P(i,A)P_n(i,s) . \qquad (2)$$

$P(i,A)$ is the probability of encountering a tube of i nucleons, $P_n(i,s)$ is the probability of producing n secondaries from the interaction of the hadron with a tube of i nucleons. Here the particle-tube collision looks like a particle-nucleon collision at the same center-of-mass energy, i.e.,

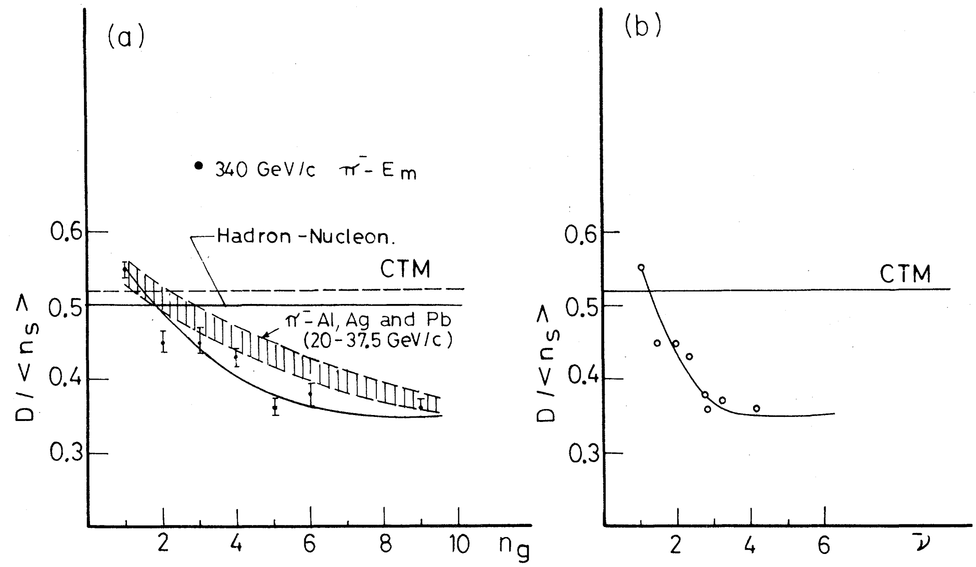

FIG. 6. The ratio $D/\langle n_s \rangle$ as a function of the number of gray tracks n_g (a) and the average number of collisions $\bar{\nu}$ (b) compared to the hadron-nucleon and CTM model (the shaded area represents the results of the π^- interactions with Al, Ag, and Pb target nuclei at momenta from 20 to 37.5 GeV/c).

$$P_n(i,s)=P_n(1,is) . \tag{3}$$

The average multiplicity of secondaries produced in the interaction of a hadron with a tube of i nu-

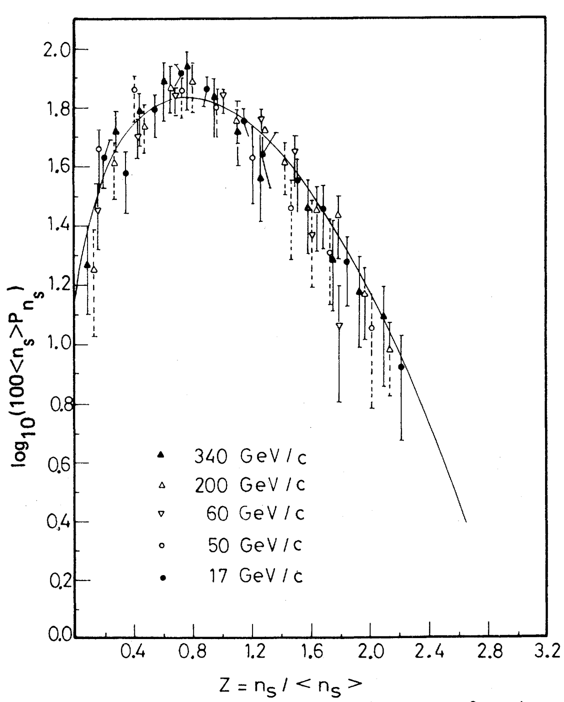

FIG. 7. The logarithm of the Buras scaling function (Ref. 19) $\psi(Z)=A(Z+B)\exp(CZ+DZ^2)$, represented by the solid line, is compared with the experimental data for the scaling function calculated by $\psi=\langle n_s \rangle P_{n_s}$, for the π^- interaction at different incident momenta.

cleons will be equal to that of the hadron-nucleon interaction at the same center-of-mass energy:

$$\langle n(s) \rangle_{hA} = \langle n(i,s) \rangle_{hN} . \tag{4}$$

Using Eq. (2), the multiplicity distribution of showers for the 340-GeV/c π^- interaction with emulsion nuclei is calculated using the following assumptions:

(1) $P(i,A)$ is calculated using Eq. (6) of Ref. 3.

(2) $P_n(1,is)$ is considered to be a Poisson function, taking into consideration the tube fragmentation[25,26] and the scaling function in both h-nucleon[27] and π^--nucleus interactions [Eq. (1) above].

(3) The energy dependence of $\langle n_s \rangle$ is considered to be a power law[3]

$$\langle n(s) \rangle_{hN} = \langle n(s_0) \rangle_{hN} \left[\frac{s}{s_0} \right]^{\alpha} \tag{5}$$

and a logarithmic function.[27]

Figure 4 shows the results of these calculations. While the general behavior of the multiplicity distribution can be predicted by the CTM, one is faced with a deviation from the experimental values of the average number of showers $\langle n_s \rangle$ and or the dispersion D. The same result was also obtained when we analyzed the data of the 200-GeV/c π^- interactions.

In all our trials the χ^2 test indicates a poor fit. It seems that the CTM as a whole can only reproduce qualitatively the multiplicity distribution of shower particles.

Considering the gray particles (protons of momenta $\simeq 30-400$ GeV/c) as being due to the knocked-out nucleons, it is interesting to test the theoretical calculations done for the multiplicity of these knocked-out nucleons and their correlation with the multiplicity of the produced mesons in particle-nucleus scattering.[28,29] These theoretical calculations were carried out considering the nucleus as a collection of independent nucleons acting coherently. In that case the effective coupling of the Pomeron to the nucleus is enhanced by $A^{1/3}$ with respect to the Pomeron-particle coupling. The tree approximation is applied and a Pomeron intercept $\alpha(0)=1+\mu>1$ is considered. Figure 8 shows the dependence of $P(n_g=0)$ on the momentum of the incident pion. It is clear that σ_0 approaches its asymptotic value ($\sigma_0=\frac{1}{2}\sigma_T$) at about $y=\ln s \simeq 6.0$, in accordance with the model.[28] All the other cross sections were found to vanish asymptotically as $s^{-\mu}$.

Considering the data at 200 and 340 GeV/c, μ was found to range from 0.1 at $n_g=1$ to 2.4 at higher n_g values. An average value $\bar{\mu}=0.21$ is obtained. The increase of μ indicates a Pomeron intercept >1, in accordance with the model.[28]

Figure 9 shows the dependence of $\langle n_s \rangle/\ln s$ on n_g. Averaging for values of $n_g \geq 4$ we get the relation

$$\langle n_s \rangle = 2.72 \ln s ,$$

which agrees with the expectations of this model, ($\langle n_s \rangle = 3 \ln s$) independent of n_g. The deviation from that line at $n_g=1$ and 2 may be attributed to the big contribution from interactions with light

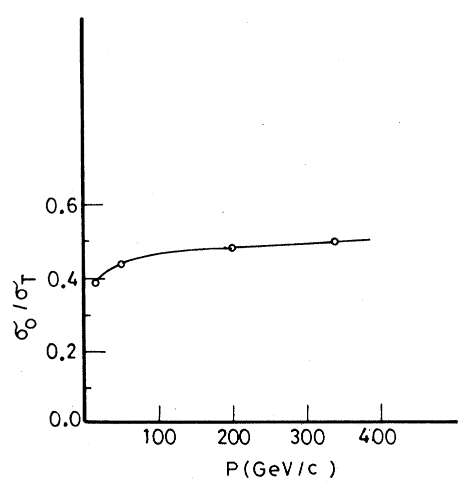

FIG. 8. Variation of σ_0/σ_T with the incident momenta.

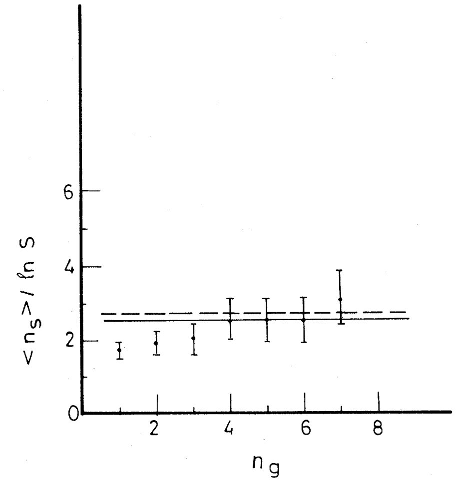

FIG. 9. The dependence of $\langle n_s \rangle/\ln S$ on n_g.

emulsion nuclei (CNO) and peripheral collisions with AgBr.

Figure 10 shows the KNO-type scaling behavior[17] of $\sigma(n_g)$. All topologies are approximately equal and satisfy the relation

$$P(n_g)2\langle n_g \rangle = e^{-n_g/\langle n_g \rangle} .$$

This is very near to

$$P(n_g)2\langle n_g \rangle = e^{-n_g/2\langle n_g \rangle}$$

as expected by the model.

In conclusion we can say that as a whole the coherent picture of hadron interaction with nuclei

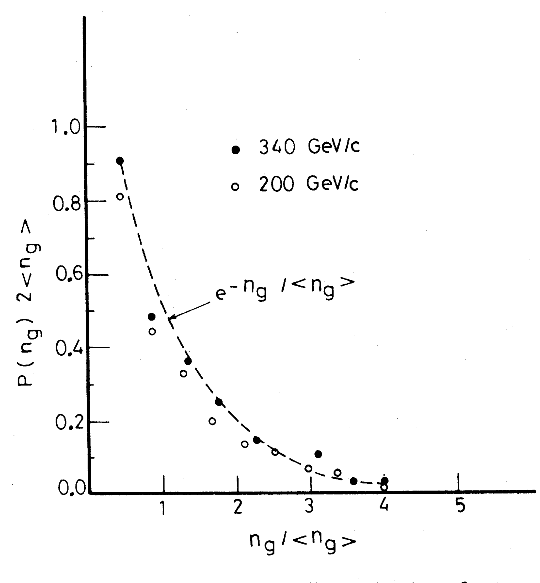

FIG. 10. The KNO-type scaling behavior of $P(n_g)$ at 340 and 200 GeV/c fitted by the relation:

$$P(n_g)2\langle n_g \rangle = e^{-n_g/\langle n_g \rangle} .$$

qualitatively represents the results of 340-GeV/c π^--emulsion interactions.

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