PHYSICAL REVIEW D VOLUME 15, NUMBER 7 1 APRIL 1977

Nuclear interactions of 300-GeV protons in emulsion

J. Hébert, C. J. D. Hébert, and H. Areti
University of Ottawa, Ottawa, Canada

O. Adamovic and M. Juric
University of Belgrade, Belgrade, Yugoslavia

G. Baroni, S. Di Liberto, S. Petrera, and G. Romano
University of Rome, Rome, Italy

G. Baumann and R. Devienne
Université de Nancy, Nancy, France

J. M. Bolta and G. Rey
Instituto de Fisica Corpuscular, Valencia, Spain

R. Kaiser, J. P. Massué, and R. Pfohl
Centre de Recherches Nucléaires, Strasbourg, France

J. Lory, C. Meton, D. Schune, Tsai-Chü, and B. Willot
Laboratoire de Physique Générale, Université de Paris VI, Paris, France

R. Haglund and I. Otterlund
University of Lund, Lund, Sweden

R. Schmitt
Laboratoire du Rayonnement Cosmique, Lyon, France

A. Van Ginneken
Fermi National Accelerator Laboratory, Batavia, Illinois

M.-A. Vincent
CRESALA, Université du Québec, Montréal, Canada
(Received 17 December 1976)

Results from a study of p-nucleus interactions in emulsion at an incident energy of 300 GeV are presented. The observed events were separated into those belonging to the light (C,N,O) and the heavy (Ag, Br) groups of target nuclei. Some characteristics of the fast-charged- (shower-) particle multiplicity and angular distributions for the light and heavy groups, as well as for emulsion, are reported and compared with the results from our previous experiments at 200 GeV. The average number of shower particles, $\langle n_s\rangle$, has the values $\langle n_s\rangle_{\rm CNO} = 12.1 \pm 0.5$, $\langle n_s\rangle_{\rm AgBr} = 16.7 \pm 0.5$, and $\langle n_s\rangle_{\rm em} = 15.1 \pm 0.2$. The quantity R_A, defined as the ratio of created charged particles in p-nucleus and p-p collisions, is consistent with the relation $R_A = A^{0.19}$ While the width of the shower-particle distribution as measured by the dispersion D is greater at 300 GeV than at 200 GeV, the value of $\langle n_s\rangle/D$ is about 1.68 at both energies. The average number of slow charged particles resulting from the evaporation of the target nucleus remains virtually unchanged at the two energies. The angular distributions of shower particles plotted in terms of $\eta = -\ln\tan(\theta/2)$ show that, for a given nucleus, there are more particles at smaller angles at the higher energy, while there is no change in the distribution at large angles. In addition, for a given energy, the number of shower particles at larger angles increases with increasing size of the target nucleus.

I. INTRODUCTION

Nuclear targets have gained wide acceptance as tools for probing the multiparticle production process at high energies. In recent years, emulsion experiments with Fermilab hadron beams have stimulated considerable theoretical activity, which has resulted in the development of new models of particle production and also in the revival of older models, such as the hydrodynamical model. The theories, successful in describing some of the gross features of hadron-nucleus collisions, can be divided into two classes: those requiring an intermediate stage, such as the formation of "hadronic matter," preceding particle production, and those not requiring any such intermediate stage. In order to differentiate between the predictions of the two types of model (coherent and incoherent production models), extensive experimental data are required for different target elements over a wide range of energies. Indeed, it is instructive to use target nuclei differing greatly in their atomic weights. Nuclear emulsions provide such targets, since they contain a light group ($A \approx 14$) and a heavy group ($A \approx 94$) of nuclei. Although separation of events into these two groups is not exact, one can still obtain qualitative information regarding the dependence of the production mechanism on the size of the target nucleus.

In this paper, we review some general characteristics of proton-nucleus interactions in emulsions at an incident proton energy of 300 GeV and compare them with the results obtained at 200 GeV. Preliminary results at 300 GeV from the analysis of a smaller sample of events have already been published.[1,2]

II. EXPERIMENTAL DETAILS

Stacks of Ilford K-5 emulsion were exposed to the 300-GeV proton beam at the Fermi National Accelerator Laboratory. Two stacks, each containing 24 pellicles of dimensions 15 cm $\times$ 5 cm $\times$ 600 μm, were exposed horizontally, i.e., with the beam direction parallel to the emulsion surface. In addition, four small stacks, each containing 6 pellicles of dimensions 5 cm $\times$ 5 cm $\times$ 600 μm, were exposed vertically, i.e., with the beam direction normal to the emulsion surface. The vertical exposure has the following interesting features: Firstly, it gives an overall picture of the beam-flux distribution; secondly, it permits precise measurements of angles in a shorter time; and thirdly, higher beam flux can be chosen ($\approx 10^6$ protons/cm^2 compared with $\approx 2\times 10^4$ protons/cm^2 for the horizontal exposure) without confusing the secondary tracks with the primary tracks, thus reducing scanning time.

The 2633 events observed, while scanning the plates, were subjected to a rigorous depth cut-off criterion. In the horizontally exposed plates, events occurring in the top or bottom 50 μm of the emulsion were rejected, while in the vertically exposed plates, events within the top 90 μm or the bottom 140 μm of the emulsion were disregarded. The final number of accepted events was 1971, out of which 388 were from the vertically exposed plates.

The tracks associated with each one of the interactions were classified as shower, gray, or black tracks depending on the ionization, I, caused by the passage of the charged particle through emulsion. If I_0 is the ionization due to an extremely relativistic charged particle, then the tracks with (a) $I \leq 1.4 I_0$ are shower tracks (b) $1.4 I_0 < I \leq 4 I_0$ are gray tracks, and (c) $I > 4 I_0$ are black tracks. The number of shower tracks observed in an interaction is denoted by n_s. These tracks are due primarily to charged pions, although the incident proton and fast secondary protons may also be included, along with some kaons, etc. Less energetic protons ejected from the target nucleus appear mainly among gray tracks as do some slow-charged pions. The black tracks are attributed mainly to the evaporation or fragmentation of the target nucleus. The gray and black tracks together are referred to as heavy tracks or dense tracks. The number of heavy tracks, N_h, resulting from a collision is indicative of the energy imparted to the target nucleus by the incoming proton. N_h may also be used as a criterion for separating the target nuclei in emulsion into two groups: a light group (H, C, N, O) and a heavy group (Ag, Br). Interactions in a light nucleus are not likely to result in the emission of more than six fragments. Hence, the events attributed to the light group of nuclei are found among the stars with $N_h \leq 6$ and have to be separated from the peripheral interactions in silver and bromine. The characteristics of the two types of events are not very different, but the presence of a heavy recoiling nucleus (a black track, 1–2 μm long), is a useful criterion for selecting the interactions in the heavy nuclei.

Clean white stars, i.e., events with $N_h = 0$ and no nuclear recoil or an electron track at the vertex, were carefully examined for two reasons. Such events, having $n_s = 2$ or 3 may be due to energetic knock-on electrons or lepton pairs directly produced by the incoming proton and should be removed from genuine events. Secondly, this type of star with an odd number of shower tracks may be coherently produced. Elimination of coherent events from the rest of the white stars proved to be difficult, since the angular criterion for coherence $\sum_{i=1}^{n_s} \sin\theta_i \leq 0.3$ (θ_i is the angle between the directions for the ith shower track and the incoming proton) was equally well satisfied by many noncoherently produced events. However, the contribution of the coherently produced events to the inelastic mean free path is small (about 1.5–2%).[3]

III. RESULTS

The inelastic mean free path for proton-nucleus collisions in emulsion at 300 GeV is found to be 34.9 ± 0.7 cm, which is essentially the same as the value measured at 200 GeV.[4,5]

Another quantity which shows no appreciable change from 200 to 300 GeV is the average number of dense tracks, $\langle N_h \rangle$. In fact, $\langle N_h \rangle$ remains constant from 27 GeV (Ref. 6) ($\langle N_h \rangle = 7.5 \pm 0.4$) up to present Fermilab energies. The values of $\langle N_h \rangle$ are 7.4 ± 0.2 at 200 GeV and 7.1 ± 0.2 at 300 GeV. Also, the average numbers of black and gray tracks, separately, show little change from 200 to 300 GeV; the values are, respectively, $\langle N_b \rangle \approx 5.4$ and $\langle N_g \rangle \approx 1.8$.

Employing the criteria proposed by Lohrman and Teucher,[7] a subsample of ~400 events was separated into interactions occurring in the light group (C, N, O) and the heavy group (Ag, Br) of emulsion nuclei. The values of $\langle N_h \rangle$ from this analysis are 2.9 ± 0.2 and 9.9 ± 0.5 for the light and the heavy group, respectively. Within experimental errors the same values were obtained from a similar analysis of the 200-GeV data.

The frequency distribution of the heavy prongs in the 1971 events analyzed at 300 GeV is shown in Fig. 1, in which the average values of N_h for the light group, for the heavy group, and for emulsion are indicated by arrows.

The charged-shower-particle distribution, shown in Fig. 2, is wider than the 200-GeV distribution, as was to be expected. The average number of shower particles, $\langle n_s \rangle$, is 15.1 ± 0.2, as compared with 13.2 ± 0.2 at 200 GeV.[8] Some of the characteristics of the multiplicity distribution, along with the values of $\langle n_s \rangle$ for the light and the heavy groups of nuclei, are listed in Table I. The nearly linear relationship which exists between the number of shower tracks and the number of heavy prongs is illustrated in Fig. 3.

A characteristic of the shower-particle multiplicity distribution which is of considerable interest is the dispersion $D = (\langle n_s^2 \rangle - \langle n_s \rangle^2)^{1/2}$. In the energy range from 6.2 to 300 GeV, a simple relationship exists between D and $\langle n_s \rangle$, expressed by $D = (0.60 \pm 0.04)\langle n_s \rangle$ (see Ref. 2). This expression is similar in form to that given by Wroblewski[9] for proton-proton interactions. In the latter case, $\langle n_s \rangle$ is replaced by $\langle n_{ch} \rangle - 1$, where $\langle n_{ch} \rangle$ is the charged-particle multiplicity in proton-proton collisions. The correspondence between $\langle n_s \rangle$ and $\langle n_{ch} \rangle - 1$ has an important bearing on the comparison of multiplicities in proton-nucleus and proton-proton collisions. Since $\langle n_s \rangle$ is not equivalent to $\langle n_{ch} \rangle$, as has been generally assumed, it follows that the multiparticle production process is not correctly described by the commonly used ratio, $R = \langle n_s \rangle / \langle n_{ch} \rangle$. The reason is that, whereas the quantity $\langle n_{ch} \rangle$ includes all the created charged particles plus the incident and target protons, only the charged particles having $\beta \geq 0.7$ contribute to the value of $\langle n_s \rangle$.

If we consider the ratio of only the charged particles created in the interactions, it can be shown that this ratio for emulsion is $R_{em} = \langle n_s \rangle - 1.2 / \langle n_{ch} \rangle - 2$.[10] This expression is found to have essentially the same value as a ratio calculated on the basis of comparing the total numbers of particles in the final state, including neutrals, but the latter ratio is less accurate on account of the number of corrections to be applied.

This ratio, R_{em} (unlike the previously used ratio) is found to be energy-independent in the (30–300)-GeV energy range. The values of R_{em} are 2.12 ± 0.10 and 2.14 ± 0.07 at 200 and 300 GeV, respectively. The constancy of this ratio has an important implication concerning the atomic weight dependence of the multiparticle production process. For a target of atomic weight A, we can write $R_A = A^{\alpha}$, where the value of the exponent α has to be calculated from the expression

$$R_{em} = \sum_i p_i A_i^{\alpha};$$

p_i is the probability of an inelastic encounter

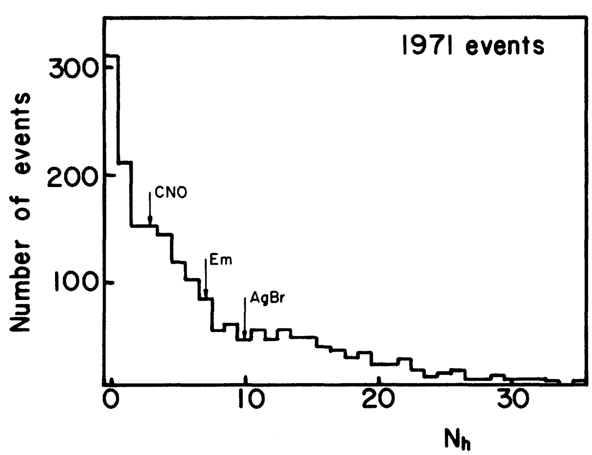


FIG. 1. Frequency distribution of heavy tracks at 300-GeV incident energy. The arrows indicate the average values of heavy tracks for CNO, AgBr, and emulsion samples.

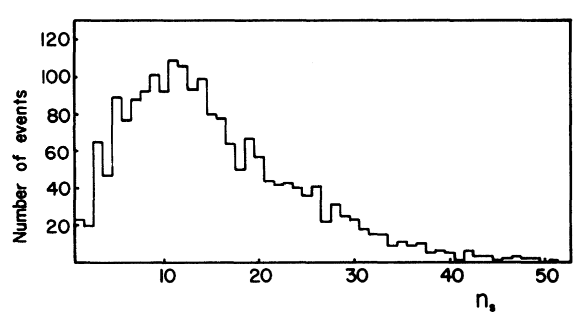


FIG. 2. Frequency distribution of shower tracks at 300-GeV incident energy.

TABLE I. Characteristics of the multiplicity distribution.

Energy (GeV)	$\langle n_s \rangle_{em}$	D	$\langle n_s \rangle / D$	$\langle n_s \rangle_{CNO}$	$\langle n_s \rangle_{AgBr}$
200	13.2 ± 0.2	7.8 ± 0.2	1.69 ± 0.07	10.7 ± 0.5	14.7 ± 0.5
300	15.1 ± 0.2	9.0 ± 0.2	1.68 ± 0.06	12.1 ± 0.5	16.7 ± 0.5

in a target nucleus of atomic weight, A_i. The experimental values of R_{em} lead to the result that $\alpha = 0.19 \pm 0.01$. This value of the exponent α is in excellent agreement with the prediction of the hydrodynamical model.[11]

IV. ANGULAR DISTRIBUTION

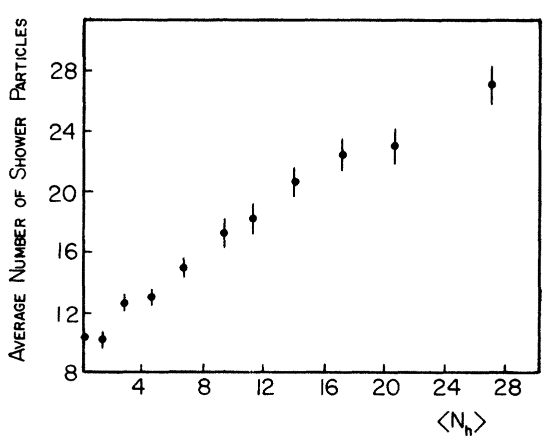
Angular distribution data from a sample of 887 events have been analyzed in terms of the pseudorapidity variable, $\eta = -\ln \tan(\theta/2)$, where θ is the space angle of a shower particle with respect to the direction of the incident proton. The data were divided into two categories based on (i) the target size, and (ii) the star size, indicated by the number of heavy prongs.

The η plots for the light and the heavy groups of emulsion nuclei are presented in Fig. 4(a) and Fig. 4(b) for incident proton energies of 300 and 200 GeV, respectively. It is evident from the figures that the angular distribution in the projectile-fragmentation region is independent of the size of the target nucleus. The excess of particles in the case of the heavier target appears at large angles, shifting the center of the distribution toward smaller values of η. The data, although insufficient to determine whether or not the angle at which the excess of particles appears depends on the target size, indicate that this angle is energy-dependent, the angle decreasing as the energy increases.

The angular distributions for the light group of nuclei at the two incident energies are compared in Fig. 5(a). A similar comparison for the heavy group is given in Fig. 5(b). It is evident that, in each case, the η distribution in the target-fragmentation region is independent of energy, the excess of particles at the higher energy appearing at smaller angles.

While separating the data for events with $N_h \leq 6$ into a light and a heavy group of nuclei, it was noticed that the angular distributions for the two groups were very similar.[12] This observation implies that the particle production process is influenced only by the number of collisions of the incident particle with the target nucleons and not by the size of the target.

The angular distributions classified according



Dependence of Average Number of Shower Particles on Star Size

FIG. 3. The dependence of the average number of shower particles on the average number of heavy tracks.

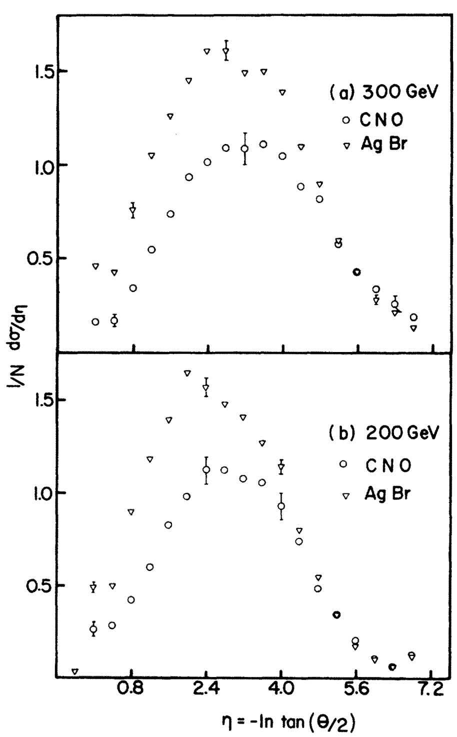


FIG. 4. Pseudorapidity distributions of shower particles from (a) 300-GeV and (b) 200-GeV proton interactions in CNO and AgBr. The events are normalized to 1. Typical errors are shown for different regions of the plot.

to star size (different N_h groups) are shown in Fig. 6 for incident proton energies of 300 and 200 GeV. For each N_h group, the η distributions in the target-fragmentation region are the same at the two energies. This feature of the distributions is readily apparent if we compare the average numbers of shower particles having values of $\eta < \eta_0$, where η_0 is taken to be equal to 3 (the center-of-momentum rapidity of proton-proton collisions at 200 GeV). This comparison is made in Table II(a). A similar comparison, presented in Table II(b), for $\eta > 3$ (small angles) shows that the average shower-particle multiplicity increases with increasing energy. The average angle of emission of the central particle decreases from $(0.61 \pm 0.04)°$ at 200 GeV to $(0.42 \pm 0.03)°$ at 300 GeV.

These features of the angular distributions may also be observed by plotting the integral distribution of $\eta_s(\eta, N_h)$, defined as the total number of shower particles with η less than some particular value, η_0, for all the events with a fixed number of heavy prongs. The linear dependence of $n_s(\eta, N_h)$ on N_h, represented by

$$n_s(\eta, N_h) = \alpha(\eta) + \beta(\eta) N_h ,$$

as illustrated in Fig. 7(a). The values of $\alpha(\eta)$

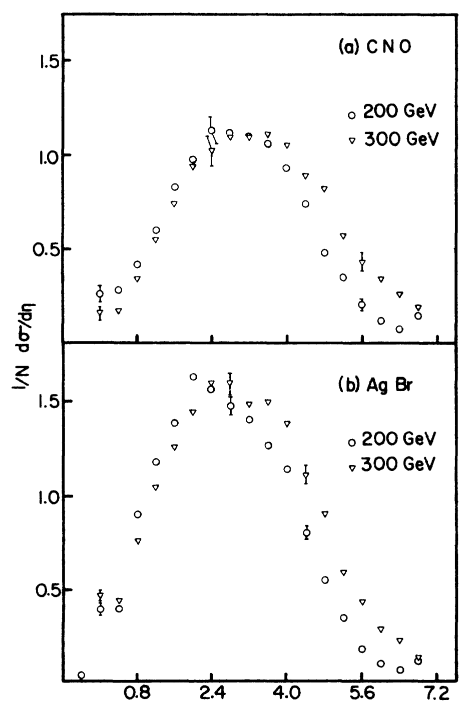


FIG. 5. Pseudorapidity distributions of shower particles for (a) p-CNO and (b) p-AgBr interactions at 300 and 200 GeV. The events are normalized to 1. Typical errors are shown for different regions of the plot.

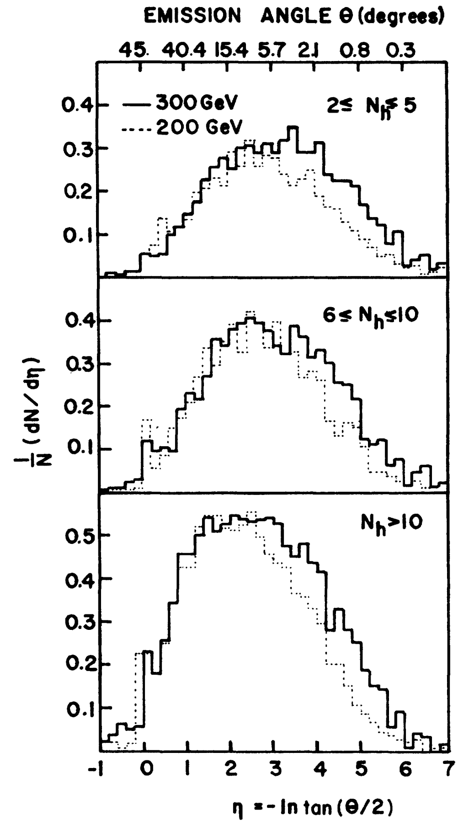


FIG. 6. Pseudorapidity distributions of shower particles for different star sizes (i.e., different N_h groups).

and $\beta(\eta)$, displayed in Fig. 7(b), are obtained from the angular distributions of events with $2 \leq N_h \leq 17$. Events with $N_h < 2$ were omitted since they contain coherent events and proton-proton interactions, while the exclusion of events with $N_h > 17$ eliminates the effects due to the total breakup of the target nucleus. The best-fit values of $\alpha = \alpha_{min}$ are 10.2 ± 0.6 and 8.7 ± 0.3 at 300 and 200 GeV, respectively. For events with $N_h = 0, 1$ the average shower-particle multiplicities (possible coherent events and proton-proton interactions

TABLE II. Shower-particle multiplicities.

N_h range	$\langle n_s \rangle$ 300 GeV	200 GeV
(a) Pseudorapidity region $\eta < 3.0$ ($\theta > 5.7°$)		
2–5	5.9 ± 0.3	5.8 ± 0.4
6–10	8.0 ± 0.6	8.0 ± 0.7
>10	13.7 ± 0.8	13.6 ± 1.0
(b) Pseudorapidity region $\eta > 3.0$ ($\theta < 5.7°$)		
2–5	7.1 ± 0.4	4.7 ± 0.3
6–10	7.7 ± 0.6	5.6 ± 0.5
>10	9.3 ± 0.5	6.4 ± 0.4

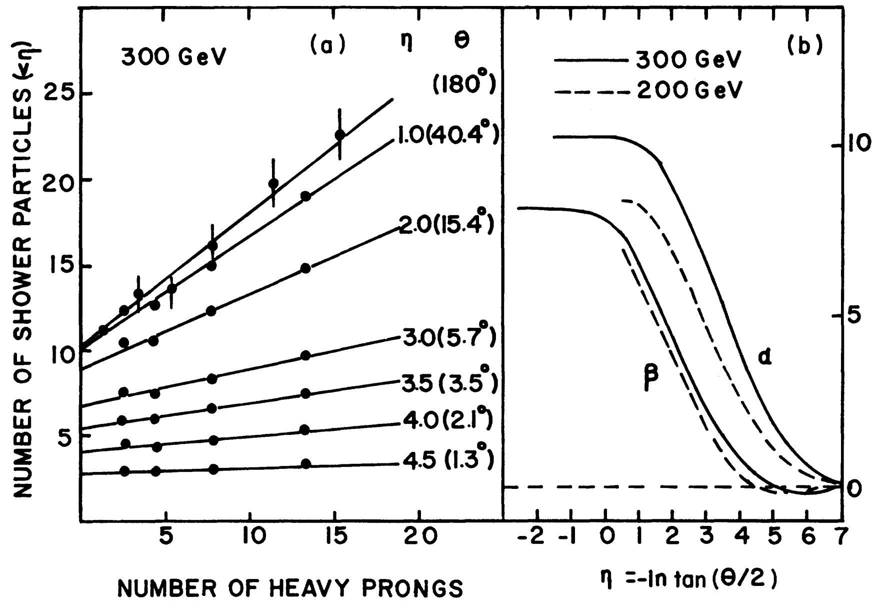


FIG. 7. (a) The effect of the star size on the number of shower particles emitted at various angles. (b) The coefficients α and β as functions of η. α is energy dependent, while β is essentially energy independent.

excluded) are 10.5 ± 0.6 at 300 GeV and 9.2 ± 0.4 at 200 GeV, in perfect agreement with the values of α_{min} obtained from Fig. 7(b), using only events with $N_h \leqslant 2$.

From Fig. 7 we conclude that, for small angles, the number of shower particles $n_s(\eta, N_h)$ is insensitive to the value of N_h. In other words, $n_s(\eta, N_h)$ is independent of the path length of the leading particle in nuclear matter. However, for small values of η, i.e., for large angles, the shower multiplicity depends on the path length. The critical values of η separating the two effects are $\eta \approx 5$ ($\theta \approx 0.8°$) and $\eta \approx 4.3$ ($\theta \approx 1.6°$) at 300 and 200 GeV, respectively.

The coefficients $\alpha(\eta)$ and $\beta(\eta)$ may be interpreted as meaning that the differential distribution $d\alpha/d\eta$ mainly describes the angular distribution of shower particles from the leading particle, while $d\beta/d\eta$ describes the angular distribution of pions emitted in consecutive collisions: $d\alpha/d\eta$ is strongly energy-dependent, whereas $d\beta/d\eta$ is essentially independent of energy.

V. CONCLUSIONS

The characteristics of p-nucleus interactions show no apparent change as the incident energy is increased from 200 to 300 GeV, with the exception of the average shower-particle multiplicity which increases only slowly with increasing energy. The angular distributions of the shower particles indicate that the excess of particles at the higher energy is found in the projectile-fragmentation region. The average number of particles emitted in the target-fragmentation region is independent of energy and is determined by the number of repeated collisions of the leading particle. A comparison between the observed rapidity distributions and the predictions of the various theoretical models of multiparticle production requires more experimental data, covering a wider range of energies and a greater number of different target elements. However, the average number of charged pions created in proton-nucleus interactions is found to be in excellent agreement with the prediction of the hydrodynamical model.

ACKNOWLEDGMENTS

We wish to express our gratitude to Dr. J. Sanford and Dr. L. Voyvodic of the Fermi National Accelerator Laboratory for their valuable help and cooperation during the planning of the experiments and the exposure of the stacks. We should also like to thank the support staff of the Fermi National Accelerator Laboratory for their assistance. The financial help received from the award of grants by the National Research Council of Canada is gratefully acknowledged.

[1] I. Otterlund, University of Lund Report No. LUIP-CR-07-75 (unpublished).

[2] J. Hébert *et al.*, in *Proceedings of the XIVth International Cosmic Ray Conference, Munich, 1975,* edited by Klaus Pinkau (Max-Planck-Institut, München, 1975), Vol. 7, p. 2248.

[3] If the peaks at $n_s = 3$ and $n_s = 5$ in the multiplicity distribution are assumed to be due to coherently produced events, the latter would comprise about 2% of all the interactions. This indicates no drastic increase in coherent production from 200 to 300 GeV. See also Z. V. Anzon *et al.*, Zh. Eksp. Teor. Fiz. Pis'ma Red. 18, 19 (1973) [JETP Lett. 18, 10 (1973)].

[4] J. Hébert *et al.*, Phys. Lett. 48b, 467 (1974).

[5] Alma-Ata-Leningrad-Moscow-Tashkent collaboration, Yad. Fiz. 19, 1046 (1974) [Sov. J. Nucl. Phys. 19, 536 (1974)].

[6] A. Barbaro-Galtieri *et al.*, Nuovo Cimento 21, 469 (1961).

[7] E. Lohrman and M. W. Teucher, Nuovo Cimento 25, 957 (1962).

[8] These values of $\langle n_s \rangle$ include the contribution from coherent events. Exclusion of these events increases the value of $\langle n_s \rangle$ by about 0.2.

[9] A. Wroblewski, Acta Phys. Polon. B4, 857 (1973).

[10] J. Hebert, H. Areti, and C. J. D. Hébert (unpublished).

[11] S. Z. Belinkii and G. A. Milekhin, Zh. Eksp. Teor. Fiz. 29, 20 (1955) [Sov. Phys.—JETP 2, 14 (1956)].

[12] This feature was also noticed by M. I. Tretyakova *et al.*, report presented at the XVII International Conference on High Energy Physics, London, 1974 (unpublished).