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Charged-particle multiplicity and angular distributions in proton-emulsion interactions at 800 GeV

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The interaction of 800-GeV protons in nuclear emulsion has been investigated. The multiplicities and angular distributions of charged particles emitted by both the projectile and the target nucleus have been measured for 1718 inelastic events and are compared with the data obtained in proton-emulsion collisions at 67, 200, and 400 GeV. The target excitation is found to be independent of energy while the production of secondary particles continues to increase with incident proton energy.

I. INTRODUCTION

The investigation of nucleon-nucleus (pA) interactions is fundamental for understanding the nature of the interaction process, and these collisions have been studied at ever increasing energy as new accelerator beams become available. In this paper, we present results on the inelastic interactions of protons at 800 GeV, an energy a factor of 2 beyond previous investigations, in nuclear photographic emulsion. Over 1700 inelastic interactions have been analyzed and, combined with previous results, the sample now spans more than a decade in incident energy and allows the energy dependence of the parameters to be investigated. A preliminary report with lower statistics has been presented.[1]

II. EXPERIMENTAL MATERIAL

Several emulsion stacks composed of GOSNIIHIM-FOTOPROEKT BR-2 emulsion pellicles, 10 cm × 20 cm and 600 μm thick, were exposed to the 800-GeV proton beam at Fermi National Accelerator Laboratory (experiment No. E508). Nuclear emulsion was employed because its excellent spatial resolution and high sensitivity enables the simultaneous investigation of both the multiparticle production and the target-nucleus excitation processes. This is the reason it is still frequently used as a nuclear target and particle detector in many pA interaction experiments.

Along-the-track microscope scanning was employed to locate a sample of 1718 inelastic interactions (excluding coherent events). The scanning and measurements were performed in the same laboratories using the same criteria as were used in the proton-emulsion studies at 67 (Ref. 2), 200 (Refs. 3–6), and 400 GeV (Ref. 7) and have, at least, the same (if any) biases. Thus, the different experiments can be compared directly to study the energy dependence of the collision process.

For each interaction, the number of shower particles (n_s) corresponding to singly charged relativistic secondaries ($\beta > 0.7$, an ionization less than 1.4 times the ionization of the beam particle) and the number of slow ($\beta \leq 0.7$) heavily ionizing particles (N_h) were counted. Slow particles are subdivided into gray tracks N_g ($0.25 \leq \beta \leq 0.7$) and black tracks N_b ($\beta \leq 0.25$). Gray

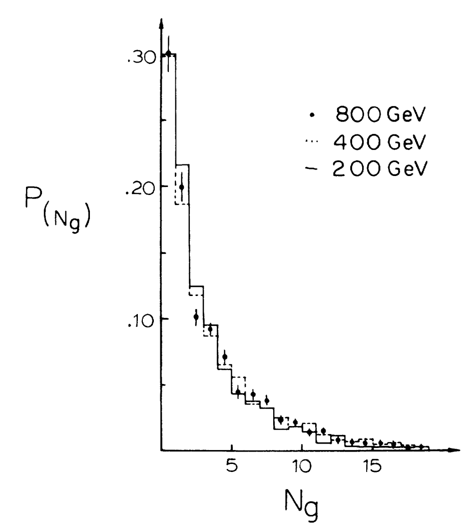

FIG. 1. Distribution of the number of gray tracks in proton-emulsion interactions at 200, 400, and 800 GeV.

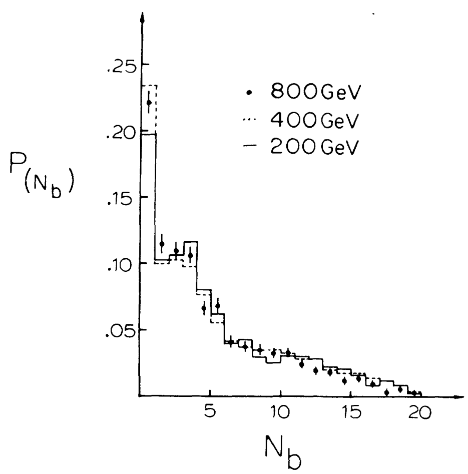

FIG. 2. Distribution of the number of black tracks in proton emulsion interactions at three primary energies.

tracks are due mainly to recoil protons with momenta 0.2–1.0 GeV/c with an admixture of low-momenta pions of less than a few percent. The black tracks are produced by low-energy fragments (protons, deuterons, alphas, and heavier fragments) emitted from the excited target nucleus.

The emission angles (θ) of the shower particles were recorded in each event under high microscope magnification with particular attention given to the smallest angles, of the order of 1 mrad. The angular measurements were made with respect to an appropriately chosen neighboring proton beam track, and the accuracy of the relative angle measurement is $\sim$0.1 units in the pseudorapidity variable ($\eta = -\ln\tan\theta/2$). In most of the events, the emission angles of heavily ionizing particles were also measured.

III. CHARGED-PARTICLE MULTIPLICITY

A. Heavily ionizing particles

In Figs. 1 and 2 the multiplicity distributions of gray and black tracks at 200, 400, and 800 GeV are compared. The mean values of these distributions are given in Table I. The 800-GeV results confirm the observation at lower energies that the distributions of heavily ionizing particles do not depend on the energy of the incoming particle, provided the same projectile is considered. It has been suggested[8-10] that the number of heavily ionizing particles measures the impact parameter of the collision and consequently is related to the number of nucleon-nucleon collisions inside the target nucleus. The observed scaling behavior of the N_g and N_b distributions for a wide range of primary energies supports this hypothesis and enables one to study the characteristics of proton interactions as a function of the number of collisions of the incident proton with target nucleons. Interactions with different mean number of intranuclear collisions can be selected by the observed number of heavily ionizing particles emitted from the target,[8] and this will be discussed in a forthcoming paper.

TABLE I. Average multiplicities of target fragments.

E_0 (GeV)	Number of events	$\langle N_g\rangle$	$\langle N_b\rangle$	$\langle N_h\rangle$
67	1183	2.74 ± 0.10	4.76 ± 0.14	7.50 ± 0.22
200	2595	2.60 ± 0.06	5.02 ± 0.10	7.62 ± 0.15
400	3482	2.79 ± 0.06	4.62 ± 0.08	7.41 ± 0.13
800	1718	2.90 ± 0.09	4.62 ± 0.12	7.52 ± 0.19

TABLE II. Multiplicity data for shower particles.

E_0 (GeV)	$\langle n_s\rangle$	D	$D/\langle n_s\rangle$	R
67	9.35 ± 0.16	5.62 ± 0.15	0.60 ± 0.03	1.45 ± 0.03
200	13.84 ± 0.16	8.15 ± 0.15	0.59 ± 0.02	1.64 ± 0.02
400	16.42 ± 0.17	10.03 ± 0.11	0.61 ± 0.01	1.66 ± 0.02
800	20.02 ± 0.29	11.98 ± 0.25	0.60 ± 0.02	1.75 ± 0.03

B. Shower particles

Table II gives the mean and the dispersion D [$D=(\langle n_s^2\rangle-\langle n_s\rangle^2)^{1/2}$] of the multiplicity distributions and the derived ratios $D/\langle n_s\rangle$ and $R=\langle n_s\rangle/\langle n_{ch}\rangle$, the normalized multiplicity. The quantity $\langle n_{ch}\rangle$ is the mean number of charged particles produced in a proton-proton interaction at the same energy and $\langle n_{ch}\rangle$ values were calculated from a fit to the pp experimental data.[11]

The mean multiplicity values in Table II increase with energy as

$$\langle n_s\rangle = -(10.8\pm1.2)+(4.15\pm0.19)\ln s \ ,$$

where s is the proton-proton center-of-mass (c.m.) energy squared, but $D/\langle n_s\rangle$ scales with energy. The behavior of $D/\langle n_s\rangle$ suggests that there are positive long-range correlations between the particles in inclusive spectra which may be due to the superposition of the different mechanisms of particle production. Note that the ratio R increases slowly with energy over the full energy range investigated.

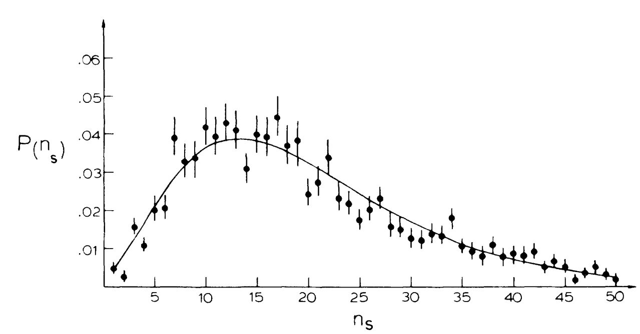

FIG. 3. Multiplicity distribution of shower particle for proton-emulsion interaction at 800 GeV. The curve represents the negative-binomial distribution.

TABLE III. Comparison of NBD with experimental n_s distribution.

E_0 (GeV)	k	χ^2/DF
67	3.952 ± 0.331	30.0/23
200	3.625 ± 0.188	46.6/33
400	3.213 ± 0.108	61.6/36
800	3.225 ± 0.182	67.4/37

The multiplicity distribution of shower particles at 800 GeV is presented in Fig. 3. Attempts have been made to describe the n_s distribution by the Koba-Nielsen-Olesen (KNO) function[12] as well as by the negative-binomial distribution (NBD) which is observed in hadron-hadron data at high energies.[13] In a previous paper[1] it was shown that the KNO function $\psi(z) = \langle n \rangle P_n$, where $z = n/\langle n \rangle$ is the scaling variable and P_n is the probability that n-charged particles are produced in the final state, fits the n_s distributions. The best fit to proton-emulsion data from 200–800 GeV is

$$\psi(z) = (2.52z + 30.9z^3 + 3.29z^5 + 1.04z^7)\exp(-4.08z) \ .$$

The NBD distribution

$$P(n,\langle n \rangle,k) = \frac{k(k+1)\cdots(k+n-1)}{n!} \frac{\langle n \rangle^n k^k}{(\langle n \rangle + k)^{n+1}} \ ,$$

where k is related to the dispersion by $D^2/\langle n \rangle^2 = 1/\langle n \rangle + 1/k$, is compared in Fig. 3 with the measured n_s distribution at 800 GeV, and fits the data satisfactorily. The NBD form also fits the multiplicity spectra at lower energies (67–400 GeV), and Table III gives the values of the parameter k and the χ^2 for the indicated number of degrees of freedom (χ^2/DF) for each primary energy. The largest contributions to the χ^2 values come from 1–3 bins with low n_s values. These bins have low statistics and may be influenced by diffractive phenomena.

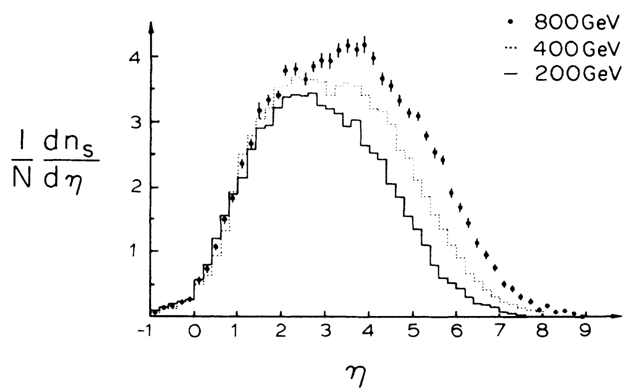

FIG. 4. Inclusive pseudorapidity distribution of shower particles in the laboratory frame at 200, 400, and 800 GeV.

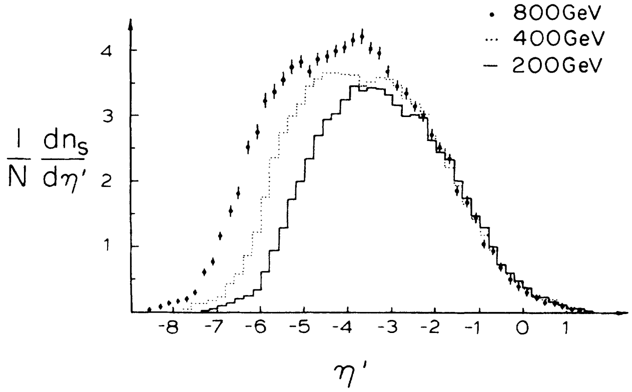

FIG. 5. Inclusive pseudorapidity distribution of shower particles in the projectile rest frame at 200, 400, and 800 GeV.

IV. ANGULAR DISTRIBUTION OF SHOWER PARTICLES

Figures 4 and 5 show the inclusive angular distributions of shower particles at 200, 400, and 800 GeV in the laboratory frame (η) and in the projectile rest frame (η'), respectively. For the projectile rest frame, $\eta' = \eta - y_p$ where y_p is the rapidity of the incoming proton. Positive values of η' are due mainly to the leading protons for which η is a poor approximation to rapidity. Figures 4 and 5 demonstrate that the inclusive distributions scale in both the target and projectile fragmentation regions, whereas the height of the central region increases with increasing energy. This dependence is shown in Fig. 6 where the pseudorapidity density of shower particles in the central region, ρ_c, is plotted versus s. The data is well represented by $\rho_c = (-0.10 \pm 0.18) + (0.55 \pm 0.03)\ln s$.

V. CONCLUSION

The analysis of pA collisions at 800 GeV, the highest energy currently available at accelerators for fixed-target

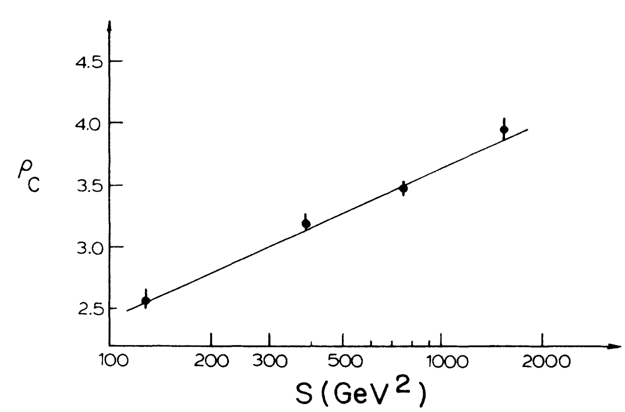

FIG. 6. Dependence of the pseudorapidity density, in the central region ρ_c, on s, the proton-proton c.m. energy squared. The central region corresponds to $|\eta_{c.m.}| \leq 0.8$, where $\eta_{c.m.}$ denotes the laboratory pseudorapidity transformed to the proton-proton c.m. systems.

experiments, when compared to existing data at lower energies shows that the target excitation is independent of projectile energy. For the produced particles, however, the average multiplicity and the pseudorapidity density in the central region continue to increase with increasing energy ($\propto \ln s$). The target and projectile fragmentation regions show pseudorapidity distributions that are independent of energy. The overall multiplicity distributions at all four energies can be fit by either the KNO or the NBD functions. Finally, for the derived quantities R, the normalized multiplicity at 800 GeV is in agreement with predictions of theoretical models,[14-16] and $D/\langle n_s \rangle$ is found to be independent of energy, indicating the possible existence of long-range correlations.

These results provide new data for understanding the physics of high-energy pA interactions and establish the energy dependences from data spanning more than a decade in energy (67–800 GeV).

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