ANALYSIS OF ANGULAR DISTRIBUTIONS OF CHARGED PARTICLES PRODUCED BY NEGATIVE PIONS ON NUCLEI AT 300 GeV*

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The angular distribution of particles produced in 2115 π^--emulsion interactions at 300 GeV has been analysed. The inclusive distribution of shower particles exhibits a pronounced plateau in the central region which extends for about two units of pseudorapidity. Taking advantage of the relation between the number of slow particles emitted from the struck nucleus and the average number of collisions of the projectile inside the target, the dependence of the pseudorapidity distribution on the effective thickness of the target nucleus was investigated.

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1. Introduction

In our previous paper [1], where one can find some details of the Fermilab experiment E 574, the general characteristics of more than two thousands interactions of negative pions in nuclear emulsion at 300 GeV were presented. The multiplicity distributions of the disintegration products of the target nucleus as well as the produced particles were analysed and compared with the results obtained at lower energies. Also presented was the inclusive pseudorapidity distribution of shower particles, which revealed a pronounced plateau in the central region.

In this paper we will continue the analysis of the pseudorapidity distributions of shower particles produced in the interactions of 300 GeV negative pions on emulsion nuclei. It is not our intention to support any particular model of particle production on nuclei. However, we would like to test a general idea of the particle production mechanism based on the assumption that in hadron-nucleus interactions the projectile undergoes multiple collisions with the target nucleons. This multiple rescattering may occur on

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a particle or quark-parton level. The basic parameter in all models adopting this idea is the number ν of the projectile-nucleon collisions inside the nucleus which measures the thickness of nuclear matter viewed by the impinging hadron.

There are two experimental possibilities to investigate the characteristics of hadron--nucleus interactions as a function of ν. One method is to vary the atomic number of target nucleus [2]. In this approach the average number of hadron-nucleon collisions inside the nucleus of atomic number A equals

$$\bar{\nu}_A = \frac{A\sigma_{hp}}{\sigma_{hA}}$$

where σ_{hp} and σ_{hA} are the hadron-proton and hadron-nucleus inelastic cross-sections respectively. The probability distribution $P(\nu_A)$ is broad and its dispersion is given by

$$\sigma(\nu_A) \simeq 0.7\bar{\nu}_A.$$

The second method involves selection of events based on the number of collisions of the projectile inside a given target nucleus. This number cannot be measured directly. However, it was argued in several papers [3–9] that the number of disintegration products emitted from the struck nucleus is related to the number of projectile collisions.

The unique advantage offered by nuclear emulsions as target and detector is the sensitivity to slow particles from disintegration of the target nucleus. Thus, using emulsion technique it is possible to investigate the correlation between the number of slow particles and the number of inelastic collisions of the projectile inside the nucleus.

2. *Correlation between the average number of collisions of the projectile inside the nucleus and the nuclear response of the target nucleus*

A nucleus hit by high energy hadron disintegrates into several fragments which are classified as gray and black tracks according to their visual appearance in nuclear emulsion. Gray particles are chiefly recoil protons which in turn initiate the low energy intranuclear cascade [3, 4]. Their velocities fall into the interval $0.25 < \beta \leqslant 0.7$ and the corresponding energies of protons are $30\text{ MeV} < E \leqslant 400\text{ MeV}$. The remaining excited nucleus evaporates into nucleons, deuterons, alpha particles and heavier fragments. The evaporation products are called black particles, and their velocities are $\beta \leqslant 0.25$, which corresponds to proton energy less than 30 MeV.

The number of gray or black particles emitted in hadron-nucleus interactions are denoted by N_g and N_b, respectively, and the sum $N_g + N_b$ is called N_h where the subscript "h" stands for heavy ionizing particles ($I > 1.4\, I_0$, where I_0 is the ionization of singly charged relativistic particle). We shall introduce the general notation N_{sl} for the number of disintegration products of the target nucleus, where N_{sl} ($\beta \leqslant 0.7$) may denote either N_g, N_b or N_h. Particles produced in hadron-nucleus interaction are contained within the shower particles ($\beta > 0.7$) denoted by n_s.

The first attempts to find the correlation between N_{sl} and the number ν of projectile collisions inside the nucleus were purely phenomenological. Since the gray particles include the recoil protons, it was natural to investigate the correlation between N_g and ν [5–7]. In this approach the distribution of N_g for a single encounter $P^A_{\nu=1}(N_g)$ was postulated. Then under the assumption that each collision of the projectile in the target nucleus contributes independently to the distribution of N_g, the probability $P(\nu, N_g)$ of finding an event with ν collisions and N_g gray particles was derived. This probability function can be used to calculate the average number of collisions $\bar{\nu}$ for the sample of events with a given N_g.

In the particular model [6] it was postulated that the distribution of gray particles for a single collision is of a geometrical form

$$P^A_{\nu=1}(N_g) = (1-X)X^{N_g}, \text{ where } X = \frac{Y}{1+Y} \text{ and } Y = \frac{\bar{N}_g}{\bar{\nu}}. \tag{1}$$

From the assumption of independence of collisions, the N_g distribution for ν collisions is

$$P^A_\nu(N_g) = \binom{N_g+\nu-1}{N_g}(1-X)^\nu X^{N_g}. \tag{2}$$

Thus the probability of finding an event with ν hadron-nucleon collisions and N_g gray particles is

$$P^A(\nu, N_g) = P(\nu)P^A_\nu(N_g), \tag{3}$$

where $P(\nu)$ is the probability distribution for ν. Finally the mean number of collisions in an event with a given number of N_g equals

$$\bar{\nu}_{N_g} = \frac{\sum_\nu \nu P^A(\nu, N_g)}{\sum_\nu P^A(\nu, N_g)}. \tag{4}$$

It is worthwhile to mention that the $\bar{\nu}_{N_g}$ vs. N_g relation is not universal but depends on the nature of the primary particle [9] since the $P(\nu)$ distributions for primary pions and protons are different. The above model was extented in Ref. [8] to obtain the dependences of $\bar{\nu}$ on N_b and N_h.

A totally different approach was adopted in Ref. [9]. The authors parametrized the pseudorapidity distribution of shower particles for a given energy using the number of slow particles emitted from the struck nucleus [10], i.e.,

$$\varrho(\eta) = a_I(\eta)+b_I(\eta)N_{sl}, \tag{5}$$

where $\eta = -\ln\tan\frac{\Theta}{2}$, subscript I denotes the incoming particle and $\varrho(\eta) = \frac{1}{N}\frac{dn_s}{d\eta}$ is the shower particle density determined from N events. The coefficients $a_I(\eta)$ and $b_I(\eta)$ were extracted from emulsion data. It was shown that these coefficients for a chosen N_{sl} parameter do not depend on the mass number A of the target nucleus. In other words the particle density in hadron-nucleus interactions for a given primary particle at a given energy does not depend on the target nucleus, provided the same number of slow particles

N_{sl} has been emitted. The experimental particle densities in pion and proton interactions in different targets were taken from Ref. [2] and N_{sl} for a given nucleus was fitted in Eq. (1). Using this procedure the relation between $\bar{\nu}_A$ and N_{sl} was found.

The correlation between $\bar{\nu}$ and N_{sl} obtained by the two methods described above are compared in Fig. 1a, b. The agreement for proton induced reactions is apparent. For pion-nucleus collisions the values of $\bar{\nu}$ for a given N_{sl}, calculated according to the model described in Ref. [8], are systematically a few percent higher than those obtained in Ref. [9].

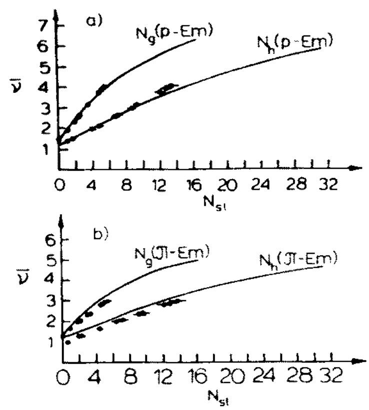

Fig. 1a, b. Average number $\bar{\nu}$ of projectile — nucleon collisions inside the target nucleus as a function of N_{sl} obtained in Ref. [8] (solid line) and Ref. [9] (circles) for proton-emulsion (Fig. 1a) and π^--emulsion (Fig. 1b) interactions

Analytical calculations of intranuclear cascade initiated by recoil nucleons [3, 4] support the phenomenological models [5–7] relating the number of gray particles N_g to the number $\bar{\nu}$ of projectile collisions inside the nucleus. It was shown in Ref. [4] that the distribution of N_g particles in a single encounter inside the nucleus is of the geometrical type shown in Eq. (1), as used in Ref. [6]. In this paper we will use the relation between $\bar{\nu}$ and N_{sl} as described in Ref. [8]. See Fig. 1a, b.

Finally we would like to point out that there are at least two advantages of using the number of disintegration products N_{sl} from the target nucleus as a measure of $\bar{\nu}$. First, the variation range possible in this method is much higher than that achieved by changing targets from hydrogen to uranium. Second, for example [3], the dispersion $\sigma(\bar{\nu}_{N_g})$ of the distribution ν_{N_g} is close to $0.6\sqrt{\bar{\nu}_{N_g}}$ and is considerably smaller than the dispersion of the ν_A distribution $\sigma(\nu_A) \simeq 0.7\bar{\nu}_A$.

3. *Pseudorapidity distributions of shower particles*

In Fig. 2 the inclusive angular distribution of shower particles produced in 2115 π^--emulsion interactions at 300 GeV is presented using the pseudorapidity variable η. The plateau in central region extends for about two units of pseudorapidity. For several years the existence of a plateau in π^--emulsion interactions was a subject of controversy. It was reported in Ref. [11] that in pion-emulsion interactions at 200 GeV the pseudorapidity distribution has a bimodal structure and that this property is a characteristic feature of pion-nucleus interactions at high energies. However, this is not the case in our high statistics experiment which was performed at higher energy.

We shall now divide our sample of π^- interactions into subsamples according to the number of disintegration products of the target nucleus, N_g or N_h. This procedure, as

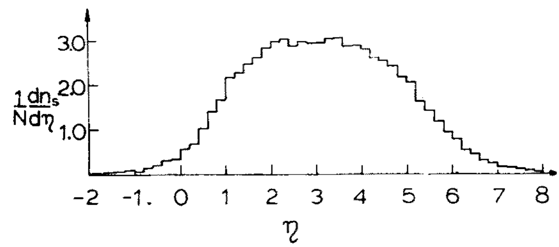

Fig. 2. The normalized inclusive pseudorapidity distribution of shower particles produced in 2115 π^--emulsion interactions

TABLE I

N_g-bins	No. of events	$\bar{N}_g$	$\bar{\nu}_{N_g}$	N_h-bins	No. of events	$\bar{N}_h$	$\bar{\nu}_{N_h}$
0	736	0	1.39	0–2	708	0.76	1.32
1	480	1	1.82	3–5	491	3.89	1.82
2–3	449	2.49	2.42	6–10	385	7.66	2.44
4–8	337	5.34	3.30	11–21	420	15.32	3.43
≥9	73	11.11	4.45	≥22	111	26.07	4.38

described in Chapter 2, selects subsamples characterized by different average number of collisions $\bar{\nu}$ of the projectile inside the target nucleus. The characteristics of the selected groups of events are given in Table I. The N_h-bins were chosen in such a way that $\bar{\nu}_{N_h} \simeq \bar{\nu}_{N_g}$. The pseudorapidity distributions for different values of $\bar{\nu}_{N_g}$ and $\bar{\nu}_{N_h}$ are presented in Fig. 3. One can see that irrespective of whether the events were selected according to N_g or N_h the pseudorapidity distributions are the same within the statistical errors. Thus, these two selection criteria are equivalent, and either N_g or N_h may be used to differentiate between events with different effective target thicknesses.

Let us now investigate the pseudorapidity density of the relativistic charged particles $\varrho(\eta) = \frac{1}{N}\frac{dn_s}{d\eta}$ as a function of $\bar{\nu}_{N_g}$. The densities $\varrho(\eta)$ for ten η intervals are presented in Fig. 4. For $\eta > 3$ and for particles emitted backwards in the laboratory system ($\eta < 0$) the densities of particles can be satisfactorily parametrized by the linear relation

$$\varrho(\eta) = a(\eta)+b(\eta)(\bar{\nu}_{N_g}-1). \tag{6}$$

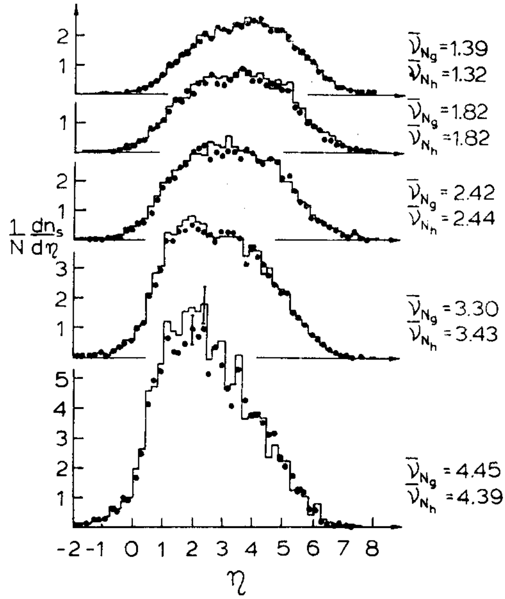

Fig. 3. Pseudorapidity distributions for different values of $\bar{\nu}_{N_g}$ (solid line) and $\bar{\nu}_{N_h}$ (dots)

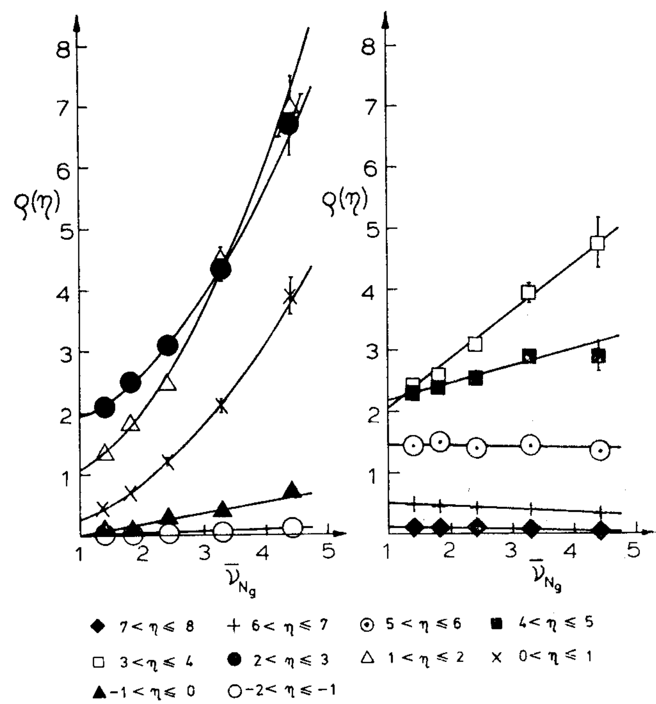

Fig. 4. Particle densities $\varrho(\eta)$ vs $\bar{\nu}_{N_g}$ for different η-bins

TABLE II

η-interval	$a(\eta)$	$b(\eta)$	χ^2 NDF = 3	$P(\chi^2)$
$7 < \eta \leqslant 8$	0.113 $\pm$0.012	$-$0.019 $\pm$0.007	3.2	0.37
$6 < \eta \leqslant 7$	0.504 $\pm$0.025	$-$0.054 $\pm$0.017	0.2	0.98
$5 < \eta \leqslant 6$	1.458 $\pm$0.047	$-$0.020 $\pm$0.033	1.9	0.59
$4 < \eta \leqslant 5$	2.183 $\pm$0.076	0.284 $\pm$0.054	1.2	0.74
$3 < \eta \leqslant 4$	1.586 $\pm$0.087	1.181 $\pm$0.080	2.3	0.51

The coefficients $a(\eta)$ and $b(\eta)$ as well as the confidence levels of the fits for $\eta > 3$ are listed in Table II. It is seen from Table II and Fig. 4 that for the highest rapidity values the particle density decreases with the increasing number of collisions. This effect is usually interpreted as a consequence of energy conservation.

The linear dependence of particle densities on $\bar{\nu}$ for $\eta > 3$ indicates that no dramatic degradation of the energy of the primary pion is observed. Otherwise, there would be a flattening of $\varrho(\eta)$ for large values of $\bar{\nu}$. The ratio of the fitted coefficients b/a for $\eta > 3$ is always smallei than unity which means that no evidence of intranuclear cascading is observed in this region.

As can be seen from Fig. 4 linear parametrizations of particle densities in the interval $0 < \eta \leqslant 3$ are no longer acceptable. The higher order terms are needed i.e.

$$\varrho(\eta) = a(\eta)+b(\eta)\,(\bar{\nu}_{N_g}-1)+c(\eta)\,(\bar{\nu}_{N_g}-1)^2. \tag{7}$$

The corresponding coefficients of the fits to this relation are given in Table III. The numerical values in Table III indicate that the increase of multiplicities in the target fragmentation region is much faster than the multiplicity in elementary collision multiplied by $\bar{\nu}$. This may be interpreted as evidence for the existence of the cascading effects inside the target nucleus. Such cascades are due to the secondary interactions of pions produced in the target fragmentation region.

TABLE III

η-interval	$a(\eta)$	$b(\eta)$	$c(\eta)$	χ^2 NDF = 2	$P(\chi^2)$
$2 < \eta \leqslant 3$	1.879 $\pm$0.146	0.506 $\pm$0.282	0.251 $\pm$0.100	0.40	0.81
$1 < \eta \leqslant 2$	1.067 $\pm$0.119	0.589 $\pm$0.245	0.361 $\pm$0.090	3.20	0.20
$0 < \eta \leqslant 1$	0.262 $\pm$0.062	0.386 $\pm$0.134	0.189 $\pm$0.051	0.19	0.90

4. Conclusions

Using more than two thousand inelastic π^--emulsion interactions at 300 GeV primary energy we have checked the possibility of describing the hadron-nucleus interaction in terms of a number of independent collisions of the projectile inside the target nucleus. It has been shown that this number, or equivalently the thickness of nuclear matter as seen by the incoming hadron is related to the number of slow ($\beta \leqslant 0.7$) particles ejected from the hit nucleus. Thus, it is possible to select interactions with different mean numbers $\bar{\nu}$ of projectile collisions using the number of slow particles N_{sl} and then to investigate the various observables as functions of $\bar{\nu}$. It should be emphasized that this method allows analysis over a significantly greater interval of $\bar{\nu}$ than can be achieved by varying the atomic number of the target nucleus.

The dependence of particle densities $\varrho(\eta)$ as functions of $\bar{\nu}$ does not keep the same character throughout the pseudorapidity range. For the highest pseudorapidity values ($\eta \gtrsim 5$) the $\varrho(\eta)$ decreases with the increasing number of $\bar{\nu}$. For $\eta > 3$ the linear relation between $\varrho(\eta)$ and $\bar{\nu}$ holds and there is no evidence of intranuclear cascading. For $\eta < 3$ the increase of particle densities is faster than $\bar{\nu}$ and the relation $\varrho(\eta)$ vs. $\bar{\nu}$ is no longer linear. This may indicate cascading induced by slow produced pions inside the nucleus and/or specific correlations between particle densities and the number of intranuclear collisions of the projectile in this pseudorapidity region. Therefore, in our opinion, the promissing approach to discriminate between different superposition models is to compare the experimental results for the projectile fragmentation and forward central regions with the theoretical predictions. Such an attempt was made in Ref. [12].

In our data there is no evidence for any structure in the inclusive pseudorapidity distribution of shower particles, and a distinct plateau is observed.

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