Vol. B8 (1977) ACTA PHYSICA POLONICA No 6

CORRELATIONS IN HADRON-NUCLEUS COLLISIONS

By B. Wosiek

Laboratory of High Energy Physics, Institute of Nuclear Physics, Cracow*

(Received January 13, 1977)

The correlations between the particles produced in interactions of hadrons with emulsion nuclei were investigated. The data are in qualitative agreement with the models which describe the interactions with nuclei as subsequent collisions of the fast part of excited hadronic matter inside the nucleus.

1. Introduction

Particle-nucleus collisions are by now a very rapidly developing branch of both particle and nuclear physics. The growing interest is caused by the belief that interaction inside the nucleus can give us information which is not available in elementary particle collisions [1-4].

In this paper we present data on the correlations between secondaries produced in interactions of hadrons with emulsion nuclei. Apart from the investigation of the conventional two-particle correlation function we propose another way of looking at the data, which has not usually been applied[1]. The point is to split the particles produced between the two hemispheres, look at their multiplicity distributions separately and investigate the possible correlations between the two sets of secondaries.

The data presented here are in qualitative agreement with the current models of particle production in collisions with nuclei [1-4].

2. Experimental material

The analysis described below was done on a sample of about a thousand proton-emulsion nuclei inelastic interactions at 200 GeV [6] as well as for a thousand π^- interactions at the same energy [7]. To explore the energy dependence the data for 67 GeV proton interactions and 60 GeV π^- interactions in emulsion were used [6, 7]. In these samples all elastic and coherent interactions were removed. For all that remained the

* Address: Zakład V, Instytut Fizyki Jądrowej, Kawiory 26a, 30-055 Kraków, Poland.

[1] To our knowledge the only exception is the analysis carried out by Pisa-Stony Brook Collaboration for p-p only [5].

angles of the shower tracks were measured. We chose as a polar angle variable the pseudo-rapidity $\eta^L \equiv -\ln\tan\frac{\theta_L}{2}$, which approaches the rapidity y for m^2 negligible compared to $p_\perp^2$. θ^L in the definition of η is the laboratory polar angle.

3. *Forward-backward correlations*

First of all we define the two hemispheres in the center of mass of the colliding nucleons. The forward hemisphere is the one which contains the secondaries with $\eta > \eta_0$ where $\eta_0^{CM_{hN}} = 0$ (e.g. at 200 GeV $\eta_0^L = 3.0$); $\eta < \eta_0$ defines the backward hemisphere.

In Fig. 1a we show the average multiplicity in the forward cone $\bar{N}_F$ (backward $\bar{N}_B$) as a function of the multiplicity in the opposite cone for 200 GeV proton-nuclei interactions. The analogous dependence for p−p is also sketched out there. The graph for π^- collisions with emulsion nuclei is presented in Fig. 1b. It is seen that for $p-p$ interactions the average multiplicity in one hemisphere is independent of the multiplicity in the opposite hemisphere (the two protons fragment independently). However, for hadron-nucleus collisions the situation is different[2]. The multiplicity in one hemisphere depends on the

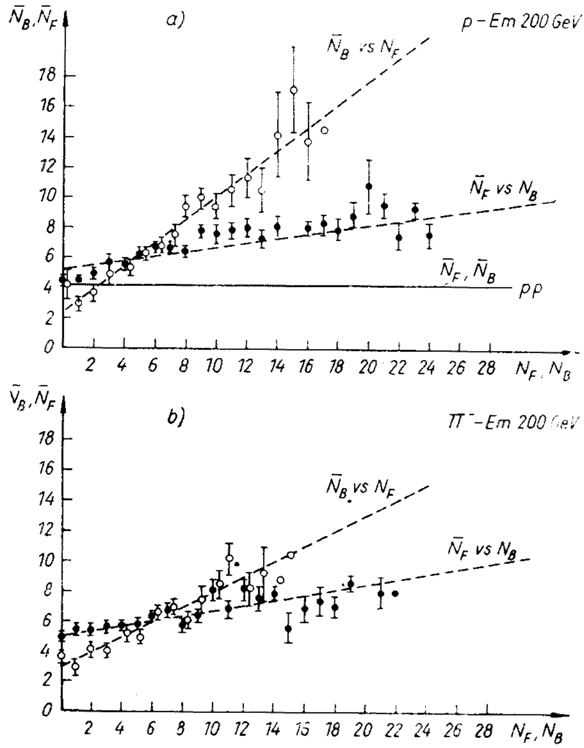

Fig. 1. Average multiplicity in the backward cone vs multiplicity in the forward cone and vice versa at 200 GeV proton (1a) and π^- (1b) interactions with nuclei. Full line in Fig. 1a represents the pp data at $\sqrt{s}$ = 30 GeV (from Ref. [5], the multiplicity is measured over the angular ranges: $4° \leqslant \theta^- \leqslant 31°$, $54° \leqslant \leqslant \theta \leqslant 90°$). The dashed lines are the linear fits to the experimental points for hadron-nucleus interactions

multiplicity in the opposite one. This correlation is rather weak for the average multiplicity in the forward cone as a function of the multiplicity in the backward one, but there is a strong correlation between the average multiplicity in the backward hemisphere and the multiplicity in the forward one (see Fig. 1a, b). The same effect is seen when one parametrizes these dependences analytically

$$\bar{N}_F = (5.19 \pm 0.13) + (0.15 \pm 0.01) N_B \quad \text{p}-\text{Em},$$

$$\bar{N}_F = (5.03 \pm 0.14) + (0.17 \pm 0.02) N_B \quad \pi^- - \text{Em}, \tag{1}$$

$$\bar{N}_B = (2.42 \pm 0.32) + (0.76 \pm 0.05) N_F \quad \text{p}-\text{Em},$$

$$\bar{N}_B = (2.94 \pm 0.24) + (0.49 \pm 0.05) N_F \quad \pi^- - \text{Em}. \tag{2}$$

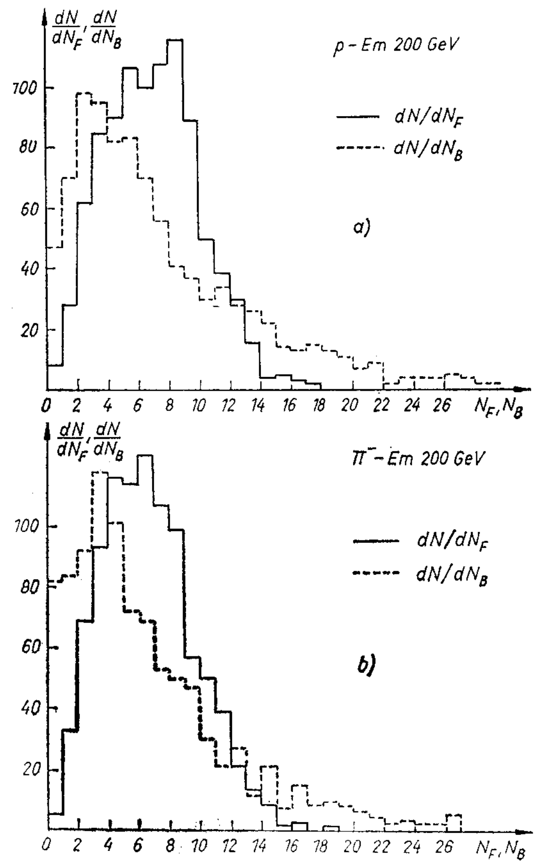

Fig. 2. **Multiplicity distributions for the forward hemisphere (full histogram) and for the backward one (dashed histogram), for proton (2a) and π^- (2b) interactions in emulsion at 200 GeV**

[2] The pp data shown in Fig. 1a do not cover the whole range of η. It is claimed [12] that the correlations in question depend on the cuts in rapidity. Even if it is so our correlations between $\bar{N}_F$ and N_B are comparable to the ones observed in [12] (where no cuts are introduced), while the correlations between $\bar{N}_B$ and N_F are definitely stronger than in pp case of Ref. [12].

The differences between the two above cases (1) and (2) can be understood on the basis of models which describe the interactions with nuclei as subsequent collisions of the fast part of excited hadronic matter inside the nucleus [1–4]. From Eqs (2) we see that the correlation between the average number of particles moving backward and the number of particles moving forward is weaker for pion-nucleus interactions. The inverse dependence ($\overline{N}_F$ on N_B) is similar for both projectiles.

We have also looked for the energy dependence of this effect, and we have found that for the lower energy data (60 GeV π^- and 67 GeV p), both correlations i.e. $\overline{N}_B$ on N_F and $\overline{N}_F$ on N_B are weaker than that for 200 GeV interactions. The main differences between pion and proton interactions are the same for the lower energy data as they are for 200 GeV data.

We have also investigated the multiplicity distributions for each hemisphere separately. For p–p collisions these distributions should be the same due to the symmetry of the initial state. But for collisions with nuclei we may expect differences. In Fig. 2 we present these two distributions for 200 GeV proton-nucleus (a) and π^--nucleus (b) interactions. Some parameters of these distributions are presented in Table I. For proton-nucleus

TABLE I

Average multiplicity $\overline{N}_F(\overline{N}_B)$, dispersion D and $D/\overline{N}_F$ $(D/\overline{N}_B)$ ratio for multiplicity distribution in forward (backward) hemisphere for proton and pion interactions with emulsion nuclei at 200 GeV and 67 (60) GeV

Inter-action	Primary energy [GeV]	Forward hemisphere			Backward hemisphere		
		$\overline{N}_F$	D	$D/\overline{N}_F$	$\overline{N}_B$	D	$D/\overline{N}_B$
p-Em	200	6.29±0.10	3.22±0.07	0.51±0.01	7.19±0.21	6.68±0.15	0.93±0.03
π-Em	200	5.94±0.11	3.11±0.08	0.52±0.02	5.74±0.19	5.40±0.14	0.94±0.04
p-Em	67	4.50±0.09	2.38±0.07	0.53±0.02	5.31±0.19	4.81±0.13	0.91±0.04
π-Em	60	4.45±0.08	2.29±0.06	0.51±0.02	4.13±0.14	3.86±0.10	0.93±0.04

collisions the well known evidence for backward asymmetry is seen ($\overline{N}_B > \overline{N}_F$). The observed symmetry for pion induced collisions ($\overline{N}_B \approx \overline{N}_F$) is probably due to the cancellations of two effects: one is the backward asymmetry expected for pion-nucleus collisions, the other one is the existing forward asymmetry in the elementary pion-nucleon collisions. Another parameter on which the nuclear target has an important impact [8] is the $D/\overline{N}$ ratio. It is seen that the multiplicity distribution of particles in the forward cone (connected with projectile) has a $D/\overline{N}$ ratio similar to the value observed in hadron-nucleon collisions. The distribution in the backward hemisphere, connected with the target nucleus has a significantly larger $D/\overline{N}$ ratio. These distributions differ from one another independently of the primary particle and of energy. We expect that a closer investigation of the properties of the two sets of secondaries mentioned above will help us to understand the differences between particle-nucleus and particle-particle collisions.

It is an interesting question how the effects discussed depend on the value of η_0[3]. In Fig. 3 we show how the $D/\overline{N}$ ratio changes with η_0, for 200 GeV p and π^- interactions

[3] This question was pointed out to us by Prof. A. Białas.

with nuclei. As can be seen, the $D/\bar{N}$ ratio for the forward part is independent of η_0 within the η_0 range from 2.0 to 4.0 (Fig. 3a). For the backward hemisphere it decreases with increasing η_0 in the same η_0 interval (Fig. 3b), no matter what the projectile is. In the explored η_0 range $D/\bar{N}_B$ and $D/\bar{N}_F$ differ significantly from each other. The dependence of the forward-backward correlations on η_0 is given in Table II. For the large values

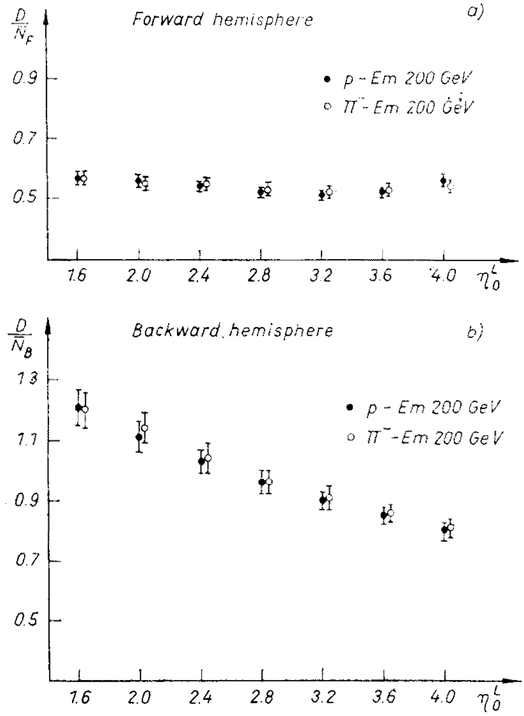

Fig. 3a). Dependence of the $D/\bar{N}_F$ ratio for the forward hemisphere on the value of η_0 for proton (black symbols) and π^- (open symbols) interactions at 200 GeV. b). The same for the backward hemisphere

TABLE II

Dependence of forward-backward correlations on the value of η_0 for 200 GeV proton and pion interactions with emulsion nuclei. Parameters $a(\eta_0)$ and $b(\eta_0)$ are determined by the least-square fit to the data

η_0^L	Projectile	$\bar{N}_F = a(\eta_0)N_B+b(\eta_0)$		$\bar{N}_B = a'(\eta_0)N_F+b'(\eta_0)$	
		$a(\eta_0)$	$b(\eta_0)$	$a'(\eta_0)$	$b'(\eta_0)$
2.0	p	0.80 ± 0.04	6.75 ± 0.18	0.39 ± 0.02	0.22 ± 0.15
	π^-	0.46 ± 0.04	7.10 ± 0.17	0.24 ± 0.02	1.15 ± 0.16
3.0	p	0.15 ± 0.01	5.19 ± 0.13	0.76 ± 0.05	2.42 ± 0.32
	π^-	0.17 ± 0.02	5.03 ± 0.14	0.49 ± 0.05	2.94 ± 0.24
4.0	p	0.01 ± 0.01	3.30 ± 0.10	0.13 ± 0.15	9.75 ± 0.61
	π^-	-0.01 ± 0.01	3.50 ± 0.09	0.06 ± 0.11	8.44 ± 0.47

of η_0 (very forward direction) there are practically no correlations between the forward and backward hemispheres. However, for $\eta_0 = 2.0$ the correlations between $\overline{N}_F$ and N_B ($\overline{N}_B$ and N_F) are strong. That is, $\eta_0 \approx 3.0$ is the point at which $\overline{N}_F$ starts to be independent of N_B. This indicates that the $\eta_0 = 3.0$ was a good choice indeed (i.e. the particles going to the right of $\eta_0 = 3.0$ are really different from those going to the left).

4. Two-particle correlations

The investigation of the two-particle correlations for proton-nucleus interactions at 300 GeV in emulsion was carried out by Baroni et al. [9]. We present a similar analysis for our data. In addition we can look at the dependence of the correlation function on the primary particle. Since only angles are available in our data, we report on the correlations integrated over the absolute magnitude of the particles momenta and over the azimuthal angle. We have analysed the correlation function defined as:

$$R(\eta_1, \eta_2) = \frac{\sigma_{\text{inel}} \dfrac{d^2\sigma}{d\eta_1 d\eta_2}}{\dfrac{d\sigma}{d\eta_1} \dfrac{d\sigma}{d\eta_2}} - 1$$

$$= \frac{N_{\text{inel}} N_2(\eta_1, \eta_2)}{N_1(\eta_1) N_1(\eta_2)} - 1. \tag{3}$$

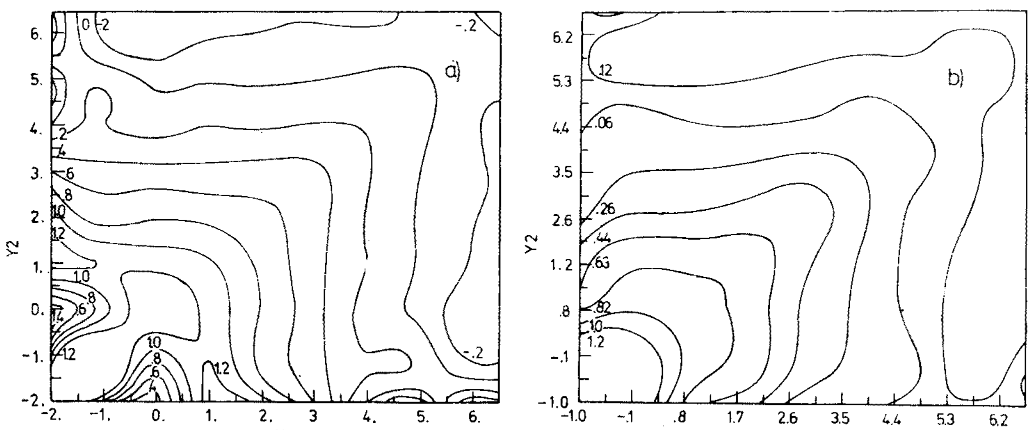

Fig. 4. Contour plot of the correlation function for proton-nucleus interactions (a) and for π^--nucleus interactions (b) at 200 GeV

Here N_{inel} is the total number of inelastic events in the sample, $N_1(\eta)$ is the number of charged particles at η and $N_2(\eta_1, \eta_2)$ is the number of pairs of charged particles at both η_1 and η_2 within the same event[4]. The contour plot of the function $R(\eta_1, \eta_2)$ is presented in Fig. 4. There is a striking difference between the behaviour of the correlations in hadron-

[4] η is defined in the laboratory frame.

-nucleus and hadron-nucleon collisions. The nuclear target has the greatest influence for small rapidities. For fixed η_1 and $\eta_2 < \eta_1$, R is constant as a function of η_2. As a result we obtain the contour plot given in Fig. 4 with characteristic rectangular contours instead of the elliptic ones observed in elementary particle collisions. In Fig. 5a, b we show $R(\eta_1, \eta_2)$ as a function of $(\eta_2 - \eta_1)$ for different values of η_1 for pion and proton interactions. Within the accuracy given there is no difference between π^--nucleus and p-nucleus collisions. In Fig. 6 we compare the proton-nucleus data with those for p−p taken from [5, 10].

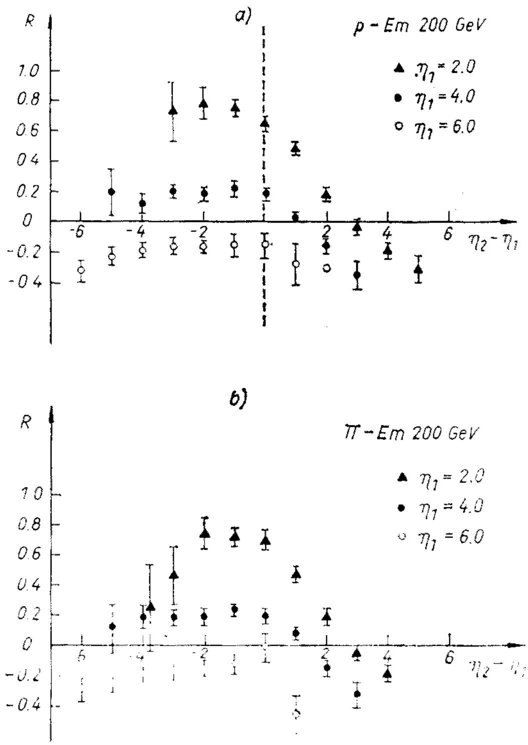

Fig. 5. Two-particle correlation function R in relation to $(\eta_2 - \eta_1)$ for different values of η_1. (a) p-nucleus 200 GeV, (b) π^--nucleus 200 GeV

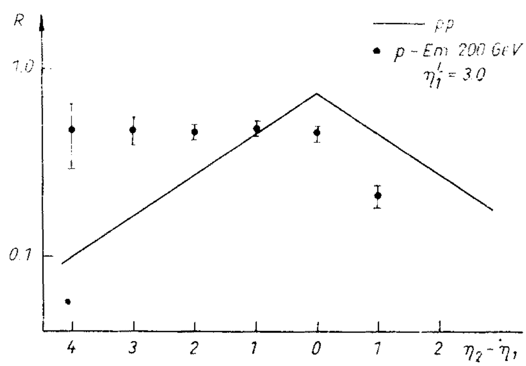

Fig. 6. Data on R for proton-nucleus interactions (points) compared with those for p-p (full line) from Ref. [5, 10]

What we emphasized in Fig. 4 appears here (Figs 5 and 6) as the flatness of the R for the negative values of $(\eta_2 - \eta_1)$ for hadron-nucleus interactions instead of the symmetrical decrease about $\eta_1 = \eta_2$ observed for p−p collisions. We did not compare the absolute magnitude of the correlations for p−p and for p-nucleus collisions. The emulsion data are an incoherent superposition of the interactions with different nuclei and we do not know how it affects the value of the correlation function.

5. *Conclusions*

While the data available on the one particle distributions do not show a very dramatic effect of the nuclear target [6, 7, 11] the data on the correlations presented here clearly indicate that the nucleus has a very strong influence on the two-particle distributions. The most important effects we have found are:

(*i*) Forward-backward correlations. The average number of particles moving forward (in the hadron-nucleon CM frame) weakly depends on the multiplicity in the backward hemisphere, while the average number of particles in the backward cone strongly increases with the multiplicity in the forward hemisphere. These correlations rise slightly with the incident energy and are independent of the projectile.

(*ii*) Correlation function. For fixed η_1, $R(\eta_1, \eta_2)$ is not symmetric around $\eta_2 = \eta_1$. It is almost flat for $\eta_2 < \eta_1$, decreasing for $\eta_2 > \eta_1$.

The observed differences between forward and backward moving secondaries suggest that the former come from a one-step elementary-like production process, while the latter are emitted in a more complicated multi-step way. The data on the correlation function are even more striking. Let us take one produced particle with fixed η_1. The probability of producing an associated particle with $\eta_2 < \eta_1$ (closer to the nucleus) is definitely greater than that with $\eta_2 > \eta_1$ and this behaviour differs greatly from that observed in p−p collisions.

The author would like to thank Professor A. Białas for valuable discussions and Drs W. Wolter and R. Hołyński for a critical reading of the manuscript.

REFERENCES

[1] M. Mięsowicz, *Progress in Elementary Particle and Cosmic Ray Physics*, Vol. X, 103 (1971).
[2] A. Białas, W. Czyż, *Phys. Lett.* **51B**, 179 (1974) and *Phys. Lett.* **58B**, 325 (1975).
[3] K. Gottfried, Ref. TH 1735–CERN 1973 and *Phys. Rev. Lett.* **32**, 957 (1974).
[4] P. M. Fishbane, J. S. Trefil, *Phys. Lett.* **51B**, 139 (1974).
[5] C. Belletini, Proc. 16th Int. Conf. on High Energy Physics, Batavia 1972, Vol. 1, p. 279; M. Jacob, ibid., Vol. 3, p. 373.
[6] J. Babecki et al., *Phys. Lett.* **47B**, 268 (1973); *Acta Phys. Pol.* **B5**, 315 (1974); *Phys. Lett.* **52B**, 247 (1974).
[7] J. Babecki et al., Raport No. 929/PH, Institute of Nuclear Physics, Kraków 1976.
[8] A. Białas et al., *Nucl. Phys.* **B100**, 103 (1975).
[9] G. Baroni et al., *Nucl. Phys.* **B103**, 213 (1976).
[10] S. R. Amendolia et al., *Phys. Lett.* **48B**, 359 (1974).
[11] W. Busza, *Acta Phys. Pol.* **B8**, 000 (1977).
[12] A. Derado, private communication.