Vol. B5 (1974) ACTA PHYSICA POLONICA No 2

EXPERIMENTAL TESTS OF GOTTFRIED'S MODEL FOR MULTIPLE PRODUCTION OF PARTICLES IN HADRON-NUCLEUS COLLISION

By R. Hołyński, S. Krzywdziński, K. Zalewski

Institute of Nuclear Physics, Cracow*

(Received December 28, 1973)

Gottfried's theory of multiple production of particles in hadron-nucleus collisions is compared and found consistent with experimental data. The theory and the data are used to predict the inclusive distribution in $-\ln \tan \Theta_{lab}/2$ for particles produced in proton--arbitrary nuclear target collisions at 67 and 200 GeV/c incident momentum.

Recent experiments at Serpukhov and Batavia [1, 2, 3] have confirmed the amazing discovery of cosmic ray physicists (*cf.* the reviews [4, 5] and references contained there) that the average multiplicities of particles produced in hadron-nucleus collisions are much lower than those expected from standard cascade theories [6, 7, 8, 9]. In Ref. [4] this and other phenomena indicating strong suppression of the nuclear cascade were interpreted in terms of a small cross-section of interaction of the produced clusters with nucleons inside the nucleus.

A new model for multiple production on nuclei has recently been proposed by Gottfried [10]. In the present paper we show that our data from Refs [2, 3] support Gottfried's model. We find from the data, and discuss from the point of view of the model, the inclusive distributions in the parameter $\eta = -\ln \tan \Theta_{lab}/2$ [1] (Θ_{lab} is the laboratory production angle, thus $\eta \approx$ rapidity) for the particles originating from Gottfried's hard hadron and from his soft hadron. Further, we use the model and the data to predict the inclusive η-distributions for proton-arbitrary nuclear target collisions at 67 GeV/c and 200 GeV/c incident momentum.

The model describes the scattering on a nucleus as a series of collisions with individual nucleons. In the first collision an "energy flux" is produced, which soon materializes into a hard hadron and a soft hadron. These hadrons (and not the incident particle) undergo further collisions. The hard hadron behaves like the incident hadron *i.e.* in each subsequent collision with a nucleon it produces an energy flux, which materializes, reproducing the

* Address: Instytut Fizyki Jądrowej, Kawiory 26 A, 30-055 Kraków, Poland.

[1] The sign convention is different from that used in Ref. [3].

original hard hadron and producing a new soft hadron. The cross-section for this process equals that for the incident hadron-nucleon scattering. Given enough time, the hard hadron decays into ordinary particles with an average multiplicity equal to two thirds of that expected from the first (incident hadron-nucleon) collision. This decay is assumed to occur outside the nucleus. Collisions of the soft hadron with other nucleons, if any, do not change it appreciably and produce no further particles. Thus the collisions of the soft hadron may be ignored and after ν collisions there is one hard hadron and ν soft hadrons. The soft hadron, given enough time, decays into ordinary particles with an average multiplicity twice smaller than that for the hard hadron.

Incidentally, the partition of the final particles between the two hadrons is not Lorentz invariant. This is easily seen by comparing high energy pp scattering in the rest frame of the first and of the second nucleon. Such interpretation problems are not discussed in the present paper.

The tests discussed here do not sharply distinguish between the Gottfried model and alternative models, with different ratios of the decay multiplicities for the soft and hard hadrons, provided the mean free path of the hard hadron in nuclear matter is always adjusted so as to yield the correct value for the ratio R (see Eq. (2)).

The expected average multiplicity of final particles produced in a hadron-nucleus collision consisting of ν elementary collisions is

$$n = \tfrac{2}{3}\, n_p + \tfrac{1}{3}\, \nu n_p, \tag{1}$$

where n_p is the average multiplicity for the incident hadron-nucleon collision at the same energy. Since formula (1) is linear in n and ν, it remains valid when ν denotes the average number of collisions for a sample of events and n the average multiplicity for the sample. This interpretation will be assumed further [10]. For a given nucleus the average number of collisions ν is a known function [10] of the nuclear radius and of the incident hadron--nucleon cross-section.

From Eq. (1) the ratio $R = n/n_p$ does not depend on energy and equals

$$R = \frac{2}{3} + \frac{\nu}{3}. \tag{2}$$

The average number of collisions of incident proton with emulsion nuclei was calculated in [10] to be equal 3.2. A similar calculation for an incident pion yields the average number of collisions equal 2.4. In Fig. 1 the measured ratios n/n_p are compared with those calculated from Eq. (2). The numbers n are from Refs [2, 11, 12], the values for n_p were taken or obtained by interpolation from the data of Refs [13, 14, 15, 16, 17]. We confirm Gottfried's conclusion obtained by considering other data [10] that the agreement is satisfactory.

A formula analogous to (1) can also be written for particles produced into any η-interval:

$$n(\eta) = n_f(\eta) + \nu n_b(\eta). \tag{3}$$

Here $n_f(\eta)$ ($n_b(\eta)$) denotes the number of particles in the η-interval, originating from the hard (soft) hadron. This formula can be used to predict the inclusive η-distribution for an arbitrary nuclear target, provided one knows: the two inclusive η-distributions $n_f(\eta)$ and $n_b(\eta)$, which do not depend on the target and the parameter ν, which can be calculated either from the nuclear radius and the mean free path of the incident hadron in nuclear matter [10], or from Eq. (2), if the ratio R is known.

Relations very similar to (3) were found in the experimental data [3]. In order to test relation (3) for the present purposes we used the data on proton-emulsion interactions at 67 GeV/c and 200 GeV/c from Ref. [3]. The data also contain a small admixture of coherent 3-prong and probably 5-prong production [2]. This yields very fast particles,

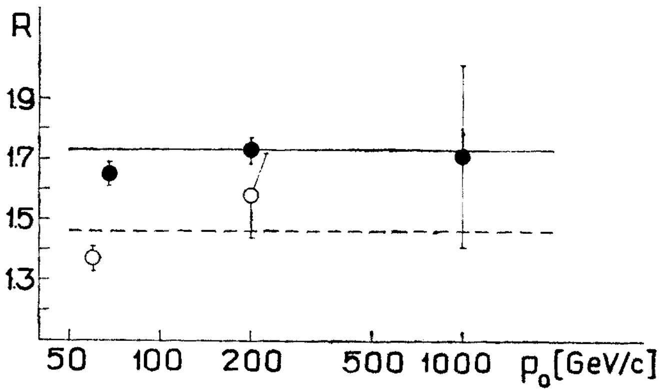

Fig. 1. The ratio R of the average multiplicity in hadron-emulsion collision to the average multiplicity in hadron-nucleon collision *vs* laboratory momentum. The full and broken lines represent the Gottfried prediction for incident proton and pion respectively. The measured values of R are denoted by: ● for incident proton, ○ for incident pion

with an inclusive spectrum depending on the nuclear radius, *i.e.* on ν. Consequently, it cannot be accommodated by the present model and has been removed from the data. For each energy, the events were divided into groups according to the number of evaporation tracks (tracks of slow particles $\beta > 0.7$, emerging from the nucleus; these are not included in the multiplicity n). For each group the average multiplicity n was found and used to evaluate ν from Eq. (2). Then for various η-intervals the linearity of $n(\eta)$ *versus* ν was tested and found to hold within errors (see Table 1). This is a further support for Gottfried's model.

Note here the implicit assumption that the number of evaporation tracks is mainly correlated with ν. In order to see that this assumption is necessary it is enough to imagine the same analysis applied to p—p collisions divided into groups according to multiplicity. This obviously would not make sense.

The distributions $n_f(\eta)$ and $n_b(\eta)$ found from fits to the data are shown in Fig. 2. According to Gottfried's model they are interpreted as decay distributions of the hard and of the soft hadron. The gross features are as expected from [10]:

1. The fast particles (large η) come almost exclusively from the decay of the hard hadron.

2. The slow particles come almost exclusively from the decay of the soft hadrons.

3. With increasing energy the (rather diffuse) boundary between the two decay distributions moves towards higher rapidities.

Some other features not included in the very simplified version of the model used here (work on more refined versions is in progress [10]) are, however, also visible in our data.

4. Because of energy conservation the hard hadron has to lose some energy at every collision. This, with increasing v, causes a small decrease in the number of fast final particles.

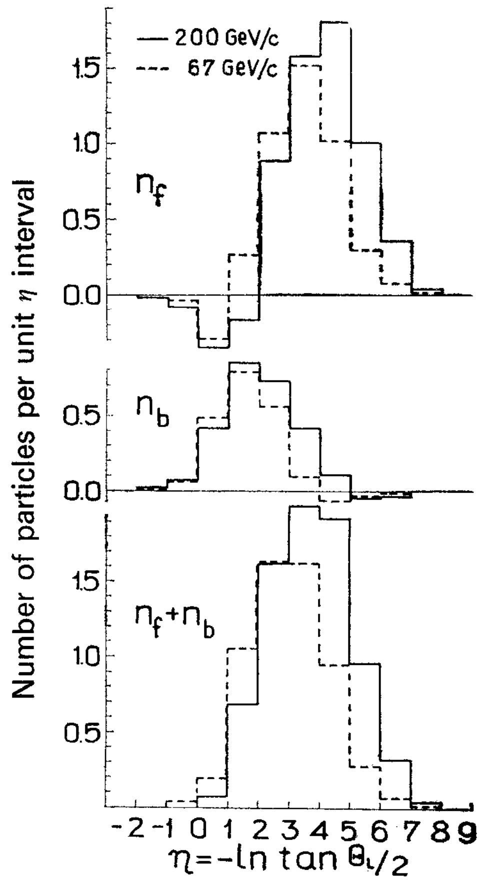

Fig. 2. Distributions $n_f(\eta)$, $n_b(\eta)$, and $n_f(\eta)+n_b(\eta)$ obtained from fits to the data at 67 GeV/c — broken line and 200 GeV/c — full line

In our parametrization it is reflected by the negative estimates of $n_b(\eta)$ in the last few bins ($4 \leqslant \eta \leqslant 7$).

5. Given enough nuclear matter to cross, the soft hadron should be able to produce some slow particles. Consequently, the multiplicity of slow particles should grow with v faster than indicated by Eq. (3). In our estimates this is reflected by the negative estimates of $n_f(\eta)$ in the first bins. Judging by the size of the negative estimate in the $0 \leqslant \eta \leqslant 1$ interval, this is the most important correction to the η-distribution.

TABLE I

Values of n_f and n_b per unit η interval

η interval	67 GeV/c			200 GeV/c		
	n_f	n_b	χ^2 NDF = 3	n_f	n_b	χ^2 NDF = 3
$-2<\eta<-1$	-0.007 ± 0.017	0.013 ± 0.006	1.27	-0.019 ± 0.009	0.016 ± 0.004	1.39
$-1<\eta<0$	-0.036 ± 0.025	0.074 ± 0.011	1.20	-0.055 ± 0.020	0.060 ± 0.008	1.53
$0<\eta<1$	-0.307 ± 0.057	0.497 ± 0.027	2.55	-0.397 ± 0.057	0.447 ± 0.022	8.83
$1<\eta<2$	0.251 ± 0.105	0.807 ± 0.041	3.25	-0.112 ± 0.094	0.828 ± 0.033	1.59
$2<\eta<3$	1.058 ± 0.118	0.575 ± 0.041	5.21	0.891 ± 0.111	0.732 ± 0.036	2.37
$3<\eta<4$	1.512 ± 0.104	0.102 ± 0.032	0.93	1.577 ± 0.109	0.420 ± 0.033	0.75
$4<\eta<5$	1.017 ± 0.074	-0.066 ± 0.021	1.06	1.805 ± 0.095	0.108 ± 0.026	3.79
$5<\eta<6$	0.307 ± 0.041	-0.032 ± 0.011	11.28	1.010 ± 0.060	-0.045 ± 0.015	0.36
$6<\eta<7$	0.074 ± 0.018	-0.012 ± 0.005	3.60	0.356 ± 0.033	-0.034 ± 0.007	2.67
$7<\eta<8$	0.014 ± 0.011	0.000 ± 0.004	1.55	0.043 ± 0.014	-0.002 ± 0.004	7.40

We conclude that Gottfried's model yields a good description of our data. The simple version used here reproduces the gross features. The deviations, not very great though certainly significant, can be ascribed to obvious corrections not yet included in the model.

Combining formulae (1) and (3) it is possible to predict the inclusive η-distribution for an arbitrary nuclear target, provided the corresponding ratio R is known:

$$n(\eta) = n_f(\eta)+(3R-2)n_b(\eta). \tag{4}$$

The ratio R can be obtained either directly from the data, or calculated as shown in Ref. [10]. The coefficients $n_f(\eta)$ and $n_b(\eta)$ together with their statistical errors are listed in Table I.

One of the authors (K. Z.) acknowledges his indebtedness to Professor K. Gottfried, whose lecture in Aix-en-Provence stimulated his interest in the present problem, and to Professor H. J. Lubatti for impressing on him the importance of getting predictions for inclusive distributions of particles produced on heavy nuclear targets.

REFERENCES

[1] Barcelona – Batavia – Belgrade – Bucharest – Lund – Lyon – Mc. Gill – Ottawa – Paris – Quebec – Roma – Valencia Collaboration, paper presented at the *5th International Conference on High Energy Physics and Nuclear Structure*, Uppsala, Sweden, 18–22 June, 1973.
[2] J. Babecki *et al.*, INP *Report* No 842/PH (1973), *Phys. Lett.*, **B47**, 268 (1973).
[3] J. Babecki, Z. Czachowska, B. Furmańska, J. Gierula, R. Hołyński, A. Jurak, S. Krzywdziński, G. Nowak, B. Ślęzak, W. Wolter, *Acta Phys. Pol.*, **B5**, 315 (1974).
[4] M. Mięsowicz, *Progress in Elementary Particle and Cosmic Ray Physics*, **10**, 103 (1971).
[5] E. L. Feinberg, *Phys. Rep.*, **5C**, No 5 (1972).
[6] A. Dar, J. Vary, *Phys. Rev.*, **D6**, 2412 (1972).
[7] P. M. Fishbane, J. S. Trefil, *Phys. Rev.*, **D8**, 1467 (1973).
[8] I. Z. Artykov *et al.*, *Nucl. Phys.*, **B6**, 11 (1968) and references cited there.
[9] P. M. Fishbane *et al.*, *Phys. Rev. Lett.*, **29**, 685 (1972).
[10] K. Gottfried, CERN *preprint* TH 1735 (1973).
[11] J. Gierula, W. Wolter, *Acta Phys. Pol.*, **B2**, 95 (1971).
[12] J. Gierula *et al.*, *Acta Phys. Hung.*, **29**, 157 (1970).
[13] Soviet–French Collaboration, *Phys. Lett.*, **42B**, 519 (1972).
[14] G. Charlton *et al.*, *Phys. Rev. Lett.*, **29**, 515 (1972).
[15] M. Antinucci *et al.*, *Nuovo Cimento Lett.*, **6**, 121 (1973).
[16] V. V. Ammosov *et al.*, Soviet–French–CERN Collaboration, *Nucl. Phys.*, **B58**, 77 (1973).
[17] D. Bogard *et al.*, NAL-Conf.-73/30 EXP 7200–137 (1973).