editrice compositori
international physics series

g. bellini, l. bertocchi and p. g. rancoita editors

high-energy collisions involving nuclei

trieste september 1974

Proceedings of the Topical Meeting on

HIGH-ENERGY COLLISIONS INVOLVING NUCLEI

Trieste, 9-13 September 1974

Edited by

G. BELLINI

Istituto di Fisica dell'Università, Milano
Istituto Nazionale di Fisica Nucleare, Sezione di Milano

L. BERTOCCHI

Istituto di Fisica Teorica dell'Università, Trieste
Istituto Nazionale di Fisica Nucleare, Sezione di Trieste
International Centre for Theoretical Physics, Miramare - Trieste

P. G. RANCOITA

Istituto di Fisica dell'Università, Milano
Istituto Nazionale di Fisica Nucleare, Sezione di Milano

1975

EDITRICE COMPOSITORI - BOLOGNA

BACKWARD MESON PRODUCTION IN THE p(d) - NUCLEUS COLLISION or THE EXPERIMENTAL INVESTIGATION OF CUMULATIVE MESON PRODUCTION ON NUCLEI BY PROTONS AND DEUTERONS

A. M. BALDIN, N. GHIORDANESCU, V. S. STAVINSKY
J.I.N.R.
(Presented by N. Ghiordanescu)

The fragmentation of nuclei D, ^{6}Li, ^{7}Li, C, Al, Cu, ^{144}Sm, ^{154}Sm, ^{182}W, ^{186}W, Pb, into mesons by 6 and 8.4 GeV/c protons and deuterons has been studied by measuring the invariant production cross section of the inclusive reactions $p(d)+A \to \pi^{\pm}(K^{+})\ldots$ at an angle of 180°. In the antilaboratory system the reactions correspond to the processes of the interaction of relativistic nuclei with protons (deuterons). In this system most of the experimental data refers to mesons of a much higher energy than that per one nucleon of the relativistic nucleus.

The observed "cumulative effect" to the 4^{th} order inclusive is described by simple regularities, and the scaling behaviour of the invariant cross section is thus established.

FORMULATION OF THE PROBLEM

This is a brief of works devoted to an experimental investigation of cumulative meson production (5,7,8). This effect is being studied because investigations of relativistic nuclei are started at the Dubna synchrophasotron. Generalization of basic ideas of strong interaction in relativistic nuclei collision open up broad possibilities for nontrivial tests of important concepts in high energy physics.

A study (1,2) of the energy spectrum of particles in the reaction

$$(1) \qquad d + Cu \to \pi^{-} +$$

has lead to the discovery of the meson production effect for three-nucleon collisions. In agreement with previous estimates (3,4), this effect turnes out to be so significant that it is accessible not only to experimental study but is also of practical importance. The same estimates (3,4) show that the cumulative meson production processes of higher order cumulativity must have sufficiently large cross sections. The collision process of a relativistic nucleus with a target, in which the particle produced has an energy substantially exceeding that per one nucleon of an incident nucleus, is called cumulative effect.

As the order of cumulativity we define the number of nucleons of the incident relativistic nucleus participating in the collision.

This effect is separated from those which are due to the motion of nucleons inside the bombarding nucleus on the basis of the scale invariance and asymptotic properties of the matrix elements.

We expect [5,6] that the part of the invariant cross section $2E\, d\sigma/d\vec{p}$, which is due to the Fermi motion, does not have a scale invariance property and decreases with increasing E_A faster than $1/E_A^2$ (or $1/s^2$). Taking this into consideration we can give a method of separation of the cumulative effect from those of Fermi motion: it is necessary that the invariant cross section $R_A = 2E \frac{d\sigma}{d\vec{p}}$ should be expanded in a power series $(1/s)$; a zero term of this series separates the N-th order of the cumulative effect at $q_{N-1}^{max} - q - q_N^{max}$, where is the momentum of secondary particle and q_N^{max} is its maximum value for the collision of N-nucleons inside the relativistic nucleus.

The main characteristics of the cumulative effect are related to the following model representations [2,3,4]; we consider it necessary to test them thoroughly in experiments. The spectra of high energy secondary particles in the collision of relativistic nuclei are determined by local properties of hadron matter (nuclei form-factors are insignificant). As an hypothesis it has been proposed that these spectra are described by the same universal function as those of secondary particles which are produced, for example, in the collision of protons. The cross section is defined by two factors: the probability of finding the nucleon group in the region of many-particle interaction (determined by the nucleon density inside the nucleus, equal for different nuclei) and the universal scale-invariant function into which, as an initial momentum, the nucleon momentum is substituted. Below we present and discuss the experimental data on the reactions

(2) $$A + p(d) \to \pi^{\pm}(K^{+}), (0°)$$

obtained in the coordinate system where nucleus A is at rest, and mesons are detected at an angle of 180°. This approach to the problem makes it possible to get informations about the main features of the cumulative effect before the beams of relativistic nuclei will be available with $A > 4$ and with the energy permitting one to separate the cumulative effect from the effects of the Fermi motion. In the reaction (2) D, ^{6}Li, ^{7}Li, C, al, Cu, ^{144}Sm, ^{154}Sm, ^{182}W, ^{186}W, Pb were taken as nuclei A. The momentum of protons was 6 GeV/c or 8.4 GeV/c and of deuterons 8.4 GeV/c. The energy of secondary mesons varied from 100 to 1070 MeV. This corresponds to the discovery of the cumulative effect up to the 4^{th} order inclusive (as many as 4 nucleons out of A take part in the collision).

Thus this paper is devoted, in principle to the following problems:

1. Spectra shape for the inclusive reaction:

$$p(d) + A \rightarrow \pi^{\pm}\ (180°)\ \ldots \tag{3}$$

2. Dependence of the spectra on the atomic weight;
3. Scaling behaviour of the invariant cross section for the process (3).

EXPERIMENTAL DATA

We present the experimental data on the invariant production cross section

$$R_A = 2\ E_\pi\ d^3\sigma/dp^3 \tag{4}$$

or the inclusive density

$$\rho = \frac{2\ E_\pi}{\sigma_{tot}} \cdot \frac{d^3\sigma}{dp^3} \tag{5}$$

The experimental layout, detecting apparatus and details of calculating the cross section are described in refs.(5,7). The total systematic error in measuring R_A is about 10% (5). In refs.(5,8) one can see the tables of the experimental data on the invariant cross section (R_A) of the inclusive process

$$p + A \rightarrow \pi^-\ (180°) \tag{6}$$

when nuclei D, ^{6}Li, ^{7}Li, C, Al, Cu, ^{144}Sm, ^{154}Sm, ^{112}W, ^{186}W, and Pb are excited by 6.0 GeV/c protons and 8.4 GeV/c protons, or by 8.4 GeV/c deuterons. The kinetic energy of negative pions produced by 6 GeV/c protons

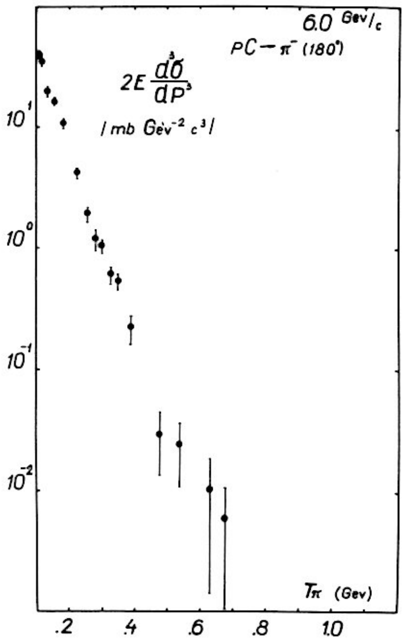

Fig. 1 - Experimental data on the reaction $p+C \to \pi^-(180°)$ for primary protons with momentum 6 GeV/c.

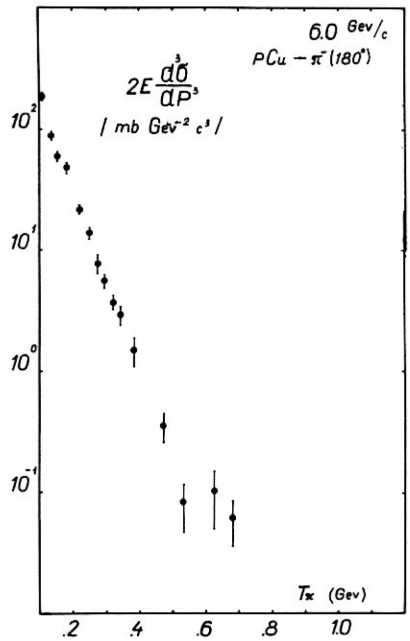

Fig. 2 - Experimental data on the reaction $p+C \to \pi^-(180°)$ for primary protons with momentum 6 GeV/c.

varies from 109 to 673 MeV. According to the kinematics of the nucleon-nucleon interaction

$$N + N \to \pi^- \ (180°)$$

the energy of secondary pions must not exceed T_{max} = 244 MeV. As an example figures 1, 2, 4 present the experimental data on the invariant cross sections $2E\ d^3\sigma/dp^3$ for nuclei C, Al and Cu as a function of the kinetic energy of negative pions. The majority of our experimental data corresponds to cumulative meson production. One can see from the figures that the dependence of the cross sections on the pion kinetic energy is of an exponential character, the spectra of various nuclei being similar and, in a first approximation, differing in constant.

In Figs. 3, 4 one can see the experimental data on the positive pion production on target-nuclei C and Cu by 8.4 GeV/c protons. As is seen, the energy spectra of pions are of an exponential character as well, and similar for various nuclei.

For comparison Fig. 3 shows the energy spectrum of protons (+) for the carbon target ([9]) exposed to 6.6 GeV/c protons. We can also see the preliminary data on the invariant yield of positive kaons for carbon and copper nuclei. It is seen from the figures that at equal kinetic energies of the produced mesons, the kaon yield is approximately two orders less than the meson one. The kinematic limit of kaon production in the nucleon-nucleon interaction is equal to ~40 MeV. Consequently, the observed kaons have an energy (T_k = 200-300 MeV), which is significantly higher than the kinematic limit for the nucleon-nucleon interaction and correspond to the 3d order cumulative effect.

In Fig. 5 we present the experimental data on the invariant cross sections of the negative pion production when nuclei D, C, Al, Cu and Pb are excited by protons with momentum 8.4 GeV/c. The kinetic energy of created pions varied from 119 to 1072 MeV. The kinetic limit corresponding to the nucleon-nucleon interaction is equal to 269 MeV. It is seen

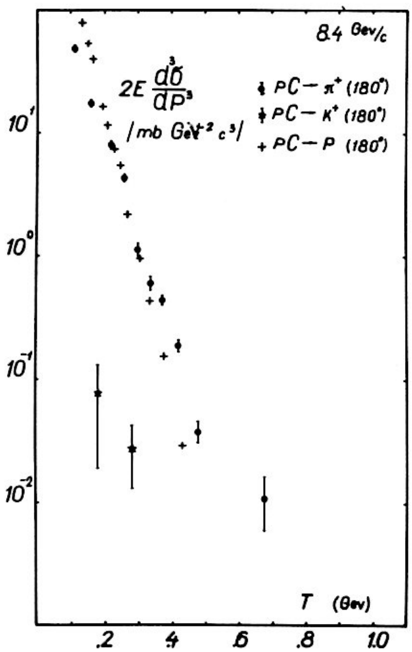

Fig. 3 - Experimental data on the reaction p+C → π^+(180°) for primary protons with momentum 8.4 GeV/c.

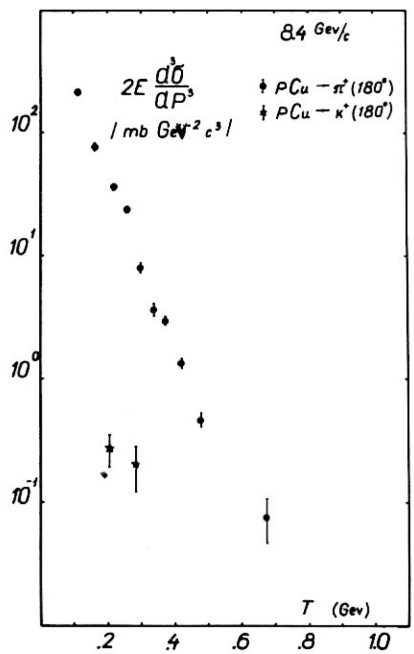

Fig. 4 - Experimental data on the reaction p+Cu→π^+(180°) for primary protons with momentum 8.4 GeV/c.

that if the energies of produced pions are lower than 700 MeV, the energy spectra, as before, are of an exponential character and similar for various nuclei. However, if the energies of produced pions are higher, a deviation from the exponential dependence is observed. According to our definition, the observed pions correspond to the observation of the 4^{th} order cumulative effect. Although the errors of measurement are large (~50%) in this range of energy, the deviation from the exponential is observed for all the investigated nuclei. Possible systematic errors have been tested experimentally (5).

In Fig. 6 we can see the experimental data on the invariant cross section of the inclusive process.

$$d + A \rightarrow \pi \tag{7}$$

The deuteron momentum is 8.4 GeV/c. The kinematic limit of pion production in the N-N interaction is equal to 209 MeV.

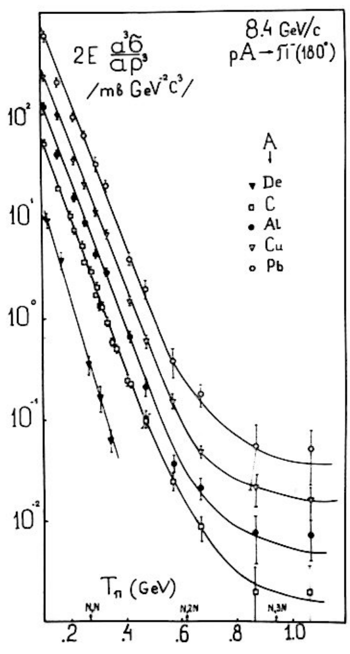

Fig. 5 - Experimental data on the reaction p+A → π^-(180°) for primary protons with momentum 8.4 GeV/c.

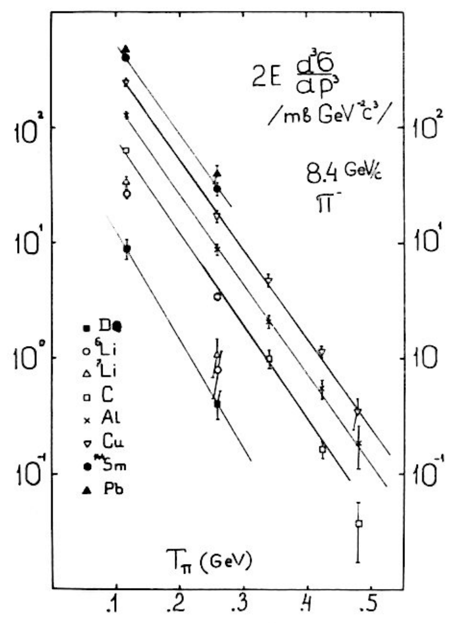

Fig. 6 - Experimental data on the reaction d+A→ π^- (180°) for primary ~~protons~~ with momentum 8.4 GeV/c.

The shape of the spectra for reaction (7) is similar to those for reaction (6).

EMPIRICAL REGULARITIES

1. - The similarity of the energy spectra for reactions (6) and (7) and their exponential character permit one to describe the function R_A by a simple exponential dependence. The experimental value $2E\,\frac{d^3\sigma}{dp^3}$ was fitted to the following functions:

$$2E\,\frac{d^3\sigma}{dp^3} = a_1\ \exp\left\{-\frac{T}{T_0}\right\} + a_2 \tag{8}$$

and

$$2E\,\frac{d^3\sigma}{dp^3} = a_1\ \exp\left\{-\frac{T}{T}\right\} \tag{9}$$

According to the criterion χ^2, the experimental data is well describ ed by the exponential functions (Maxwell distribution).

Table I presents the distribution parameters and their errors. It is seen from the table that the parameter T_0 ("temperature") is practically independent of the energy of primary protons and the charge sign of se= condary mesons. The parameter a_1 is also independent of the charge of secondary mesons and changes weakly with the energy of primary protons. One can see from Table I that a_1 practically linearly increases when the atomic number of target nucleus is increased.

	8.4 Gev/c, $PA\to\pi^-(180^\circ)$				6.0 Gev/c, $PA\to\pi^-(180^\circ)$				8.4 Gev/c, $PA\to\pi^+(180^\circ)$			
	$2E\frac{d^3\sigma}{dp^3}(PA\to\pi(180^\circ)) = a_1\times\exp(-T/T_0)+a_3$ (mb·Gev^{-2}c^3)											
TARGET	C	Al	Cu	Pb	C	Al	Cu	Pb	C	Al	Cu	Pb
χ^2	1.1	1.7	0.9	0.9	0.82	0.75	0.73	—	5.3	7.0	4.0	5.7
a_1	356 ± 19	695 ± 56	1291 ± 100	2908 ± 333	295 ± 32	559 ± 51	1017 ± 108	—	388 ± 26	743 ± 43	1292 ± 80	2792 ± 229
T_0 (Mev)	56.6 ± 0.6	59.6 ± 1.0	62.4 ± 1.0	64.7 ± 1.5	53 ± 1.4	55.8 ± 1.25	58.3 ± 1.6	—	55.1 ± 0.9	55.8 ± 0.8	60.7 ± 1.0	62.7 ± 1.3
$a_3\times10^2$	0.28 ± 0.094	7.0 ± 2.1	1.67 ± 0.44	5.2 ± 2.0	0.63 ± 0.4	1.37 ± 0.86	4.0 ± 2.1	—	0.78 ± 0.65	0. ± 1.4	4.8 ± 3.0	0. ± 15
	$2E\frac{d^3\sigma}{dp^3}(PA\to\pi(180^\circ)) = a_1\times\exp(-T/T_0)$ (mb·Gev^{-2}c^3)											
χ^2	1.3	1.9	1.2	1.0	1.0	0.93	0.93	—	5.9	7.5	4.4	6.0
a_1	354 ± 19	681 ± 54	1261 ± 97	2893 ± 335	283 ± 29	535 ± 46	951 ± 93	—	383 ± 25	745 ± 43	1261 ± 73	2797 ± 229
T_0 (Mev)	56.7 ± 0.6	59.8 ± 1.0	62.8 ± 1.0	64.8 ± 1.5	53.6 ± 1.4	55.6 ± 1.2	59.5 ± 1.4	—	55.2 ± 0.9	55.8 ± 0.9	61 ± 1.0	62.6 ± 1.3

2. - Figures 7,8 show the experimental data on the production of negative pions by 8.40 GeV/c protons and by 8,4 GeV/c deuterons as a function of the atomic number A as plotted in the same figure (dotted line). The experimental data for various pion energies for 8,4 GeV/c and 6 GeV/c of protons, were fitted to the following relation

$$2E\,\frac{d^3\sigma}{dp^3}(T_\pi) = R_1(T_\pi)\;A^{n(x)}$$

where $x = T_\pi/T_\pi^{max}$ and T_π^{max} is the maximum kinetic energy of pion for the nucleon-nucleon interaction. Figure 9 shows the parameter n versus the variable x. The values of parameter a_1 are used to find the parameter n in the point x = 0 (fit 1) (Table I). From Fig. 9 it is seen that at $x = T_\pi/T_\pi^{max}$ the parameter n does not depend on the primary energy of protons and the charge sign of generated pions. If the energy of produced pions approaches 0, the parameter n tends to 2/3. By increasing the pion energy up to T^{max}, the parameter n increases achieving unity at x = 1.

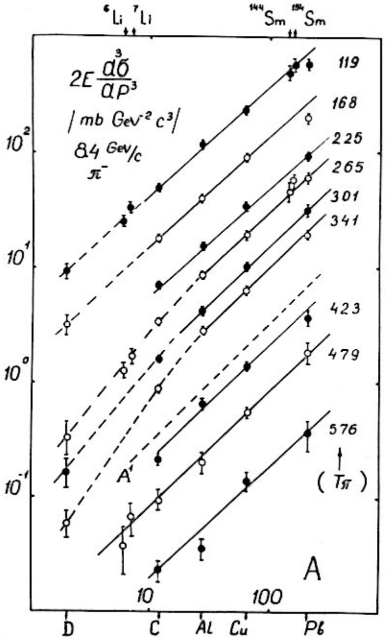

Fig. 7 - 2E $d^3\sigma/dp_3$ as a function of the atomic number for various energies of negative pions for the $p+A \rightarrow \pi^- + \ldots$

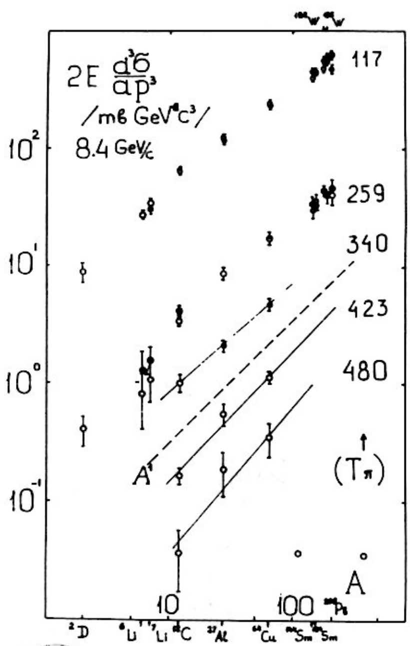

Fig. 8 - 2E $d^3\sigma/dp_3$ as a function of the atomic number for various energies of negative pions for the reaction $d+A \rightarrow \pi^- + \ldots$

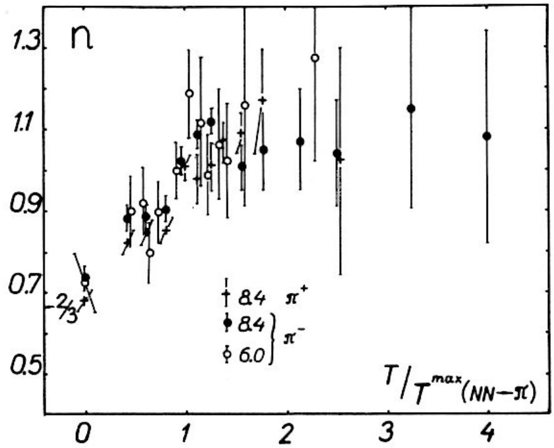

Fig. 9 - $n(R_A = R_1 A^{n(x)})$ as a function of $x = T/T^{max}$.

In the range of cumulative meson production ($x > 1$) the parameter n, within errors, remain constant at the level of unity. Such a behaviour of the parameter n indicates that in the range of ordinary (noncumulative) meson production ($x < 1$) the cross section of particle production is proportional to the nuclear surface ($n \sim 2/3$) and in the region of cumulative meson production ($x > 1$) the cross section of meson creation is proportional to the nucleus volume ($n \sim 1$).

3. - The experimental data for isotopes ^{6}Li and ^{7}Li, ^{154}Sm and ^{164}Sm, ^{182}W and ^{186}W obey, within the errors, the linear dependence on the atomic number A. Paper (8) shows that such a behaviour reflects that for the relativistic nuclei the local properties of hadron matter become important.

4. - The experimental data on the reaction $dA \rightarrow \pi^-(180°)$ (8) at 4.2 GeV/c for one nucleon together with our data on $pA \rightarrow \pi^-(180°)$ at 8.4 GeV/c, 6 GeV/c (5) and also data for 1.38 GeV/c (10) permit us to draw conclusions about the dependence of the cross section on the energy and scaling behaviour.

Figure 10 presents the extrapolated experimental data on the invariant cross sections, divided by the atomic weight of the target nucleus (R/A) for nuclei C, Al and Cu, and fixed $x = T/T^{\pi}_{max}$, as a function of the proton momentum. The curves (plotted by hand) correspond to different values of the variable x.

One can see that the function R_A/A tends to be constant for a momentum larger larger than approximatively 5 GeV/c.

We can suppose that for 1.38 GeV/c the effect of the internal motion of the nucleons is important in the matrix elements. However, for this energy, the invariant cross section has, within errors, the same dependence on x and A, as that for higher energy.

The experimental data on the reaction $p + D \to \pi^-(180°)$ (2,5,8) have a similar scaling behaviour.

CONCLUSIONS

1. - The experimental data for isotopes show that the form factor and the shape of the nucleus have no important parts in cumulative meson production (8).

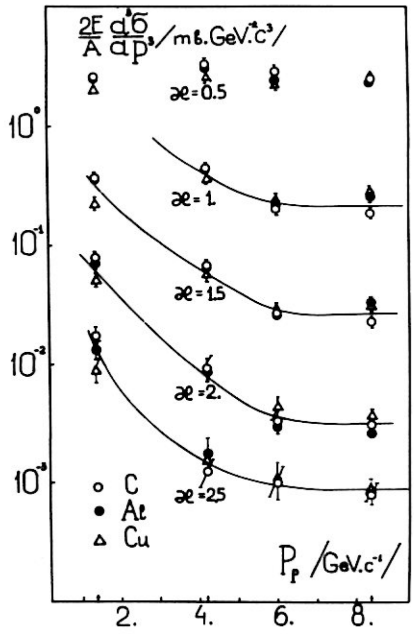

Fig. 10 - The invariant cross section, divided by atomic weight, as a function of the proton momentum for various parameter $x=T/T^{\pi}_{max}$.

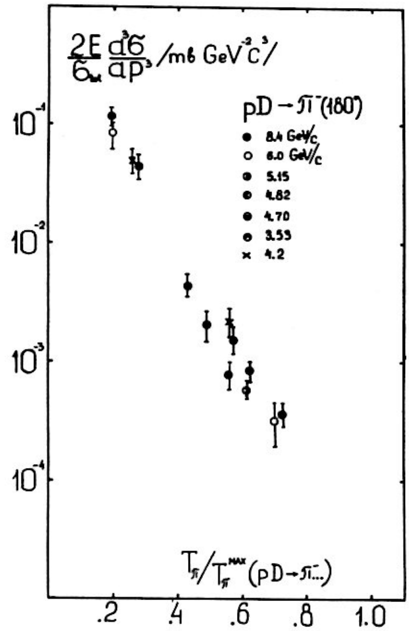

Fig. 11 - Experimental data on the reaction $p+d \rightarrow \pi^-(180°)$ for different energies protons.

2. - The energy spectrum of produced pions in the rest frame of the nucleus, is of an exponential character

$$2E \frac{d^3\sigma}{dp^3} \sim a_A \exp\left\{-\frac{T}{T_0}\right\} ,$$

parameter T_0 being practically independent of the energy of primary protons.

3. - The coefficient a_A depends on the atomic number of target nucleus ($a_A \sim a_o A^n$), the index n being dependent on the energy of produced pions. At low pion energies ($T \sim 0$) we have $n(T \sim 0) \approx 2/3$. In the range of cumulative meson production ($x \geq 1$) $n \simeq 1$.

4. - Figs. 10 and 11 show that the pion spectra for relativistic nuclei satisfy, in the limits of errors, the scale invariance requirement. The asymptotic behaviour becomes visible in the momentum region of 5 GeV/c/nucleon, for relativistic nuclei.

REFERENCES

(1) A.M. Baldin, N. Ghiordanescu, V.N. Zubarev, A.D. Kirillov, V.A. Kuznetsov, N.S. Moroz, V.B. Radomanov, R.N. Ramzhin, V.A. Sviridov, V.S. Stavinsky, M.I. Yatsuta, JINR, PI-5819, Dubna, 1971 and Proc. Rochester Meeting APS/OPF/ New York (1971) p. 131.

(2) A.M. Baldin, S.B. Gerasimov, N. Ghiordanescu, V.N. Zubarev, D.K. Ivanova, A.D. Kirillow, V.A. Kuznetsov, N.S. Moroz, V.B. Radomanov, V.N. Ramzhin, V.S. Stavinsky, M.I. Yatsuta, Yadernaya Fizika, 18, 41 (1974).

(3) A.M. Baldin, JINR, P7-5769, Dubna, 1971.

(4) A.M. Baldin, Brief Comm. on Physics No 1, AS US R·(1971),in Russian.

(5) A.M. Baldin, N. Ghiordanescu, L.K. Ivanova, N.S. Moroz, A.A. Pavtorejko, V.B. Radomanov, V.S. Stavinsky, V.N. Zubarev, JINR, E1-8054 (1974).

(6) S.B. Gerasimov, N. Ghiordanescu, Comm. JINR, P2-7687 (1974).

(7) A.M. Baldin, N. Ghirdanescu, V.N. Zubarev, L.K. Ivanova, A.D. Kirillov, V.I. Kotov, N.S. Moroz, S.A. Nezhdanova, A.A. Povtorejko, A.D. Rogal, V.S. Stavinsky, JINR, I-8028, Dubna, (1974).

(8) A.M. Baldin, N. Ghiordanescu, L.K. Ivanova, N.S. Moroz, A.A. Povtorejko, V.B. Radomanov, V.S. Stavinsky, V.N. Zubarev; Y.K. Bondarev, I.P. Iakovlev, P1-8249, JINR (1974).

(9) Yu.D. Bayukov, D.S. Verebiev, G.P. Kartashov, G.A. Leksin, V.B. Fyedorov, V.D. Khovansky, Izv. Akad. Nauk SSSR, ser.fiz. v.30, No 3, 521, (1966).

(10) D.R.F. Cochran, P.N. Dean, P.A.M. Gram, E.A. Knapp, E.R. Martin, D.F. Nagle, R.B. Perkine, W.J. Shlaer, H.A. Thiesson, K.D. Theriot Phys. Rev. D. v6, No 11, 3085 (1972).