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MECHANISMS OF CUMULATIVE PROTON PRODUCTION IN PION-NUCLEUS INTERACTIONS AT 5 GeV/c. A PHENOMENOLOGICAL ANALYSIS

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Processes of hadron-nucleus scattering hA at high energies, leading to emission of relatively fast (cumulative) baryons from nuclei into the backward hemisphere ($B\downarrow$) have been objects of intensive experimental and theoretical investigation for many years[1,2]. The attention to reactions of emission of "backward baryons $B\downarrow$" is attracted first of all by an opportunity of obtaining essentially new information on the properties of intranuclear nucleons, their associations into close groups[3,4], and the interaction of the primary or cascade hadron with clusters of the d, α, ... type[5-8] or with considerably closer objects, such as quark bags[9,10] in nuclei.

To find a relative contribution of the above-mentioned mechanisms to the process of cumulative baryon production, one usually studies multi-particle correlations within certain limited regions of the phase space for secondary particles.

Our investigations in this field[11] allowed us in 1976 to reveal an opening angle correlation of two protons, angle between them being close to 180° (one of the protons was emitted into the back hemisphere in the lab.frame). Study of this effect showed[5] that it can be partially due to absorption of slow cascade pions by an associated pair of nuclear nucleons, i.e., due to the process $\pi + (NN) \to P\downarrow + N$. Then this point of view was confirmed by other experiments[12-16].

Comparison of experimental data with the cascade-evaporation model showed[5,12] that three mechanisms can make the main contribution to the $P\downarrow$ production:

(a) rescattering on intranuclear nucleons (including processes of elastic and nonelastic rescattering, charge-exchange, pion production, etc.);

(b) descruction of the excited residual nucleus;

(c) absorption of slow π-mesons by a correlated pair of intranuclear nucleons.

Full description of experimental data requires also allowance for other possible mechanisms of cumulative proton production, which, however, arouses certain methodical difficulties (e.g., see Ref.[17]).

Irrespective of the $B\downarrow$ production mechanisms, phenomenological description of their energy distributions was given in a series of papers published by ITEP group[2,18,19]. The authors point out to scaling behaviour of the structure function ρ for the $B\downarrow$ production process with the energy (momentum) E(P) in the inclusive reaction $hA \to B\downarrow + \ldots$ with the cross section σ_{in}:

$$\rho = \frac{1}{\sigma_{in}} \cdot \frac{E}{p^2} \cdot \frac{d^2\sigma}{dp \cdot d\Omega} . \qquad (1)$$

In Ref.[2,18] it is indicated that invariant function (1) is parametrised fairly well in the form:

$$\rho = A_0 \cdot \exp(-Bp^2). \qquad (2)$$

The parameter B does not depend on energy, sort of the incident particle h and type of the nucleus; A_0 does not depend on energy and hadron sort.

While checking the hypothesis of nuclear scaling it is of importance, however, to find out if the invariant function is parametrised by one exponent or a sum of exponents. Presence of several exponents may mean that in various kinematic regions there are various processes, leading to $B\downarrow$ production. In a number of experiments there were attempts to describe the invariant function ρ as a sum of two[20] or even three[16] exponents. In Ref.[20] there are no conclusions on mechanisms of cumulative proton production, while results of the work[16] have confirmed our earlier conclusions[5,12] on manifestation of three "backward" proton production mechanisms.

This paper deals with the study of the structure function behaviour for protons, emitted into the backward hemisphere in lab. frame in the reaction

$$\pi^- + C^{12} \to P\downarrow + \ldots \qquad (3)$$

at 5 GeV/c, aimed at discriminating contributions of various mechanisms responsible for production of such protons.

Contributions of mechanisms (a), (b) and (c) to cumulative proton production were discriminated by means of the cascade-evaporation model (CEM) with allowance for variations of the number of nucleons in the nucleus due to their knocking-out in the process of the intranuclear cascade. The evaporation stage was calculated by the "desctruction" model, based on Fermi' statistical model. Unlike of Refs.[5,12,13], we use the present modification of CEM in which the cross section for pion absorption of the nucleon pair is reduced according to the data of Ref.[23]. From 95000 Monte-Carlo generated non-elastic π^-C interactions about 50000 events with $\approx$14000 "backward" protons were chosen with allowance for experimental criteria for selection of π^-C events.

Invariant differential cross sections for "backward" protons $P\downarrow$, produced due to the mechanism of multiple rescattering in CEM, were parametrized in the form $\rho^a = A_1' \exp(-A_2' \cdot p)$ with $\chi^2/n \approx 1{,}1$ (the function $A_1' \cdot \exp(-A_2' \cdot p^2)$ describes model data with $\chi^2/n > 2$. In Fig.1 there parameters are plotted against

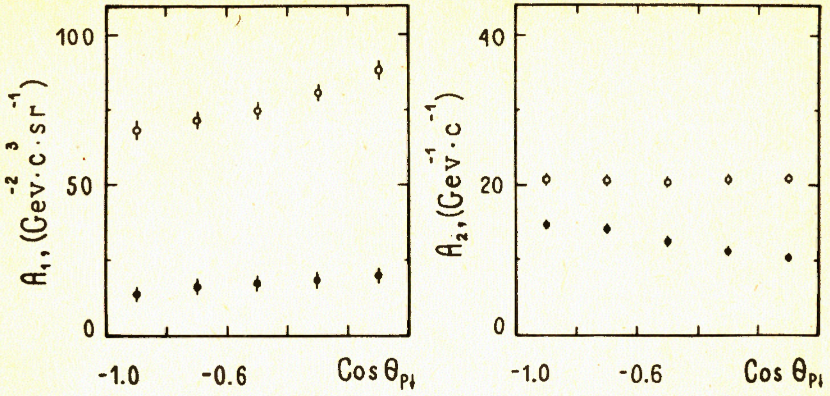

Fig.1. Dependence of the parameters a) A_1 and b) A_2 on the proton emission angle. Light points - for mechanism destruction of the residual nucleus; black points - for mechanism of multiple rescattering.

the emission angle of protons (black points). From Fig.1a one can see that the yield of protons decreases with larger emission angles θ, which seems natural, since the mechanism of multiple rescattering[22] provides a lower probability for production of the proton with a given momentum when the emission angle increases. Increase of the slope parameter (Fig.1b) with a larger θ is due to the fact that the maximum momentum of the emitted proton decreases as the rescattering number increases. This gives rise to the "softening" of the $P\downarrow$ momentum spectrum and, consequently, to increase of the slope parameter. Table 1 lists results of approximation of parameters A_1' and A_2' by a function $a + b \cdot \cos$

Table 1

Parameters	a	b	χ^2/n
A_1' $(GeV^{-2}\, c^3 sr^{-1})$	20.1 ± 0.5	5.8 ± 0.6	1.3
A_2' $(GeV^{-1}\, c)$	10.2 ± 0.2	-4.2 ± 0.5	1.1

Invariant cross sections for protons, emitted due to the destruction of the residual nucleus, were also approximated by a function $\rho^b = A_1'' \cdot \exp(-A_2'' \cdot p)$ with $\chi^2/n \approx 1.1$. Dependence of the parameters A_1'' and A_2'' on the proton emission angle (light points) is shown in Fig.1. As it is seen from Fig.1a, the amplitude of A_1'' decreases with larger angles according to the rule $a + b \cdot \cos\theta$, which is explained by forward motion of the excited residual nucleus while the slope parameter A_2'' does not depend on the proton emission angle (Fig.1b). Table 2 presents values of the parameters A_1'' and A_2'' for the nuclear destruction process.

Table 2

Parameters	a	b	χ^2/n
A_1'' ($GeV^{-2} c^3 sr^{-1}$)	91.2 ± 23.4	26.0 ± 4.1	1.1
A_2'' ($GeV^{-1} c$)		20.8 ± 0.7	0.3

Contribution of the (c) mechanism of slow π-meson absorption by the pair of correlated nucleons in the nucleus is of special interest. At absorption of pions by a pair of intranuclear nucleons the kinetic energy of two nucleons, one of them flying into the backward hemisphere, is $T_N + T_{N\downarrow} = m_\pi + T_\pi$. The cross section for absorption of the positive pion on the deuteron [23,24] has a wide maximum (± 60 MeV) in the region $0.09 < T_\pi < 0.15$ GeV. Since the opening angle between the two nucleons at absorption is larger than 90°, dependence of the mean opening angle between the two nucleons $\bar{\psi}$ on their kinetic energy $T_N + T_{N\downarrow}$ must have maximum in the energy region $0.23 \div 0.29$ GeV. Figure 2 shows this dependence $\bar{\psi}(T_{2p})$; points stand for the experiment (pion-carbon interactions at 5 GeV/c). In the energy region $0.19 < T_{2p} < 0.26$ GeV a characteristic maximum is observed. The maximum becomes more distinct for pions with the momentum over 0.3 GeV/c (Fig.3). A similar dependence for interactions of π^--mesons with the mean nucleus $\bar{A} \approx 24$ (mixture of propane-freon) at 5 GeV/c is shown in Fig.1 where one also observes a maximum caused by absorption of the π^+ meson by the pair (np).

In Fig.5 the mean multiplicity of π^+ mesons is plotted against the sum of proton kinetic energies. Light points are pion-carbon interactions at 5 GeV/c; black points are interactions of pions with the mean nucleus $\bar{A} \approx 24$ at the same energy. At the energy range in which the $\bar{\psi}$ (T_{2p}) distribution has a maximum one can observe the $\bar{n}_{\pi^+}$ minimum; that means that absorption of π^+ mesons is effective in this very region. The data in Fig.5 allows one to estimate the contribution of the reaction π^+ "d"$\rightarrow p\downarrow p$ to production of cumulative protons. This contribution is $\sigma = (1.5 \pm 0.4)$ mb. Dependence of the π^+/π^- yield ratio on the momentum of π^+ mesons (see Fig.6) is also in favour of π^+ absorption.

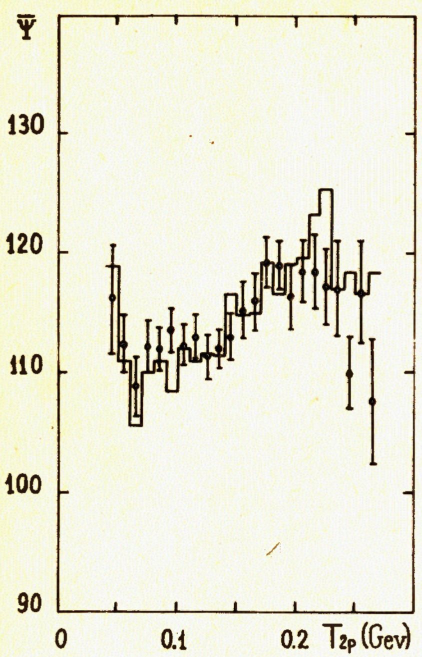

Fig.2. Dependence of the mean opening angle between the two protons $\bar{\psi}$ with the momentum $0.2 < P < 0.6$ GeV/c on their sum kinetic energies T_{2p}. Points stand for the experiment (pion-carbon interactions at 5 GeV/c), histogram - calculation by CEM).

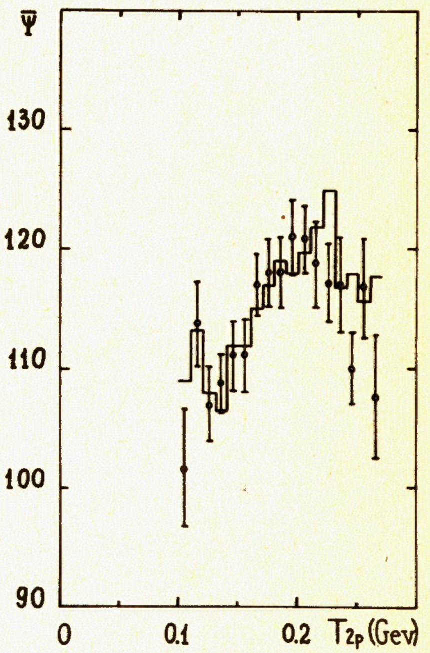

Fig.3. Dependence $\bar{\psi}$ (T_{2p}) for protons with the momentum $0.3 < P < 0.6$ GeV/c.

The investigation results [5,6] show that the momentum spectrum of protons, produced due to the absorption mechanism, has a bell-like shape which can be described by the Gaussian function with parameters c_1, c_2, c_3 independent of the proton emission angle. The exponent form of this function, as accepted in Ref. [16], cannot describe the full momentum spectrum of protons, produced as a result of the slow pion absorption.

Approximation of the proton invariant function distribution for the discriminated absorption mechanism in CEM yielded the following results for c_i : $c_1 = (0.038 \pm 0.005)$ $GeV^{-2} c^3 sr^{-1}$; $c_2 = (0.389 \pm 0.003)$ $GeV \cdot c^{-1}$; $c_3 = (0.129 \pm 0.003)$ $GeV^{-1} c$ with $\chi^2/n \approx 0.6$.

Thus, the total contribution of mechanisms (a)-(c) to production of protons, emitted into the backward hemisphere, can

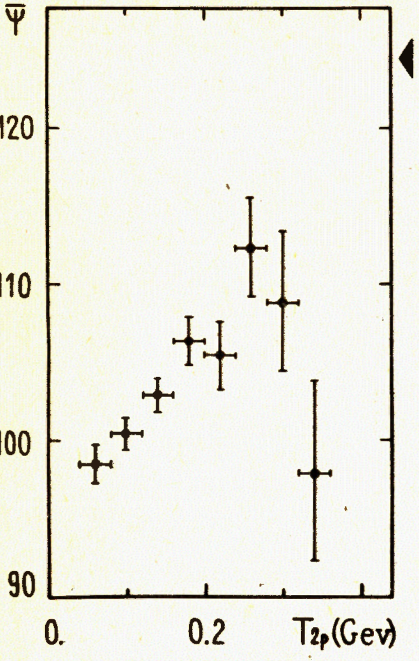

Fig.4. Similar dependence for interactions of π^--mesons with the mean nucleus $\bar{A} \simeq 24$ (mixture of propane-freon) at 5 GeV/c.

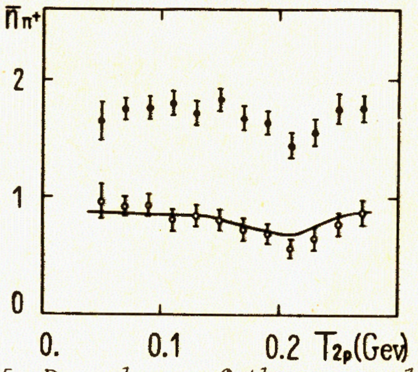

Fig.5. Dependence of the mean multiplicity of π^+-mesons against the sum of proton kinetic energies. Light points are pion-carbon interactions at 5 GeV/c; black points are interactions of pions with the mean nucleus $\bar{A} \simeq 24$ at the same energy.

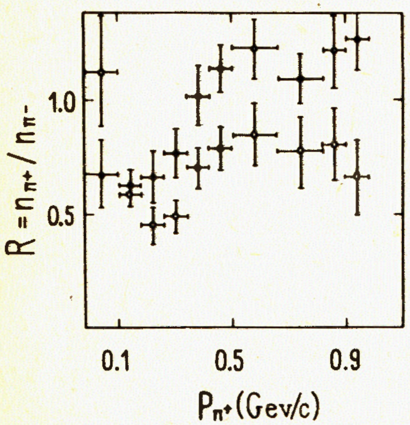

Fig.6. Dependence of π^+/π^- yield ratio on the momentum of π^+-mesons.

be written in the form

$$\frac{1}{\sigma_{in}} \cdot \frac{E}{p^2} \cdot \frac{d^2\sigma}{dp \cdot d\Omega} = (A_1 + A_2 \cdot \cos\theta) \cdot \exp(-(A_3 + A_4 \cdot \cos\theta) \cdot p) + (B_1 + B_2 \cdot \cos\theta) \cdot \exp(-B_3 \cdot p) + c_1 \cdot \exp(-(p - c_2)^2 / 2 \cdot c_3^2). \qquad (4)$$

In Figs.7-11 one can see experimental structure functions (1), obtained by processing 15000 events of non-elastic interactions of π^- mesons with carbon nuclei. The interactions were detected in the 1-M propane bubble chamber of the Laboratory of Nuclear Problems, JINR. 4860 protons with the momentum $0.16 < P_{p\downarrow} < 0.75$ GeV/c and emission angle $\theta \geq 90°$ in the lab. frame were chosen for this analysis. In the same figure one can also see the curves, calculated by formula (4) in various intervals of the proton emission angle (the ordinates scale is logarithmic). Points are the experiment, the dash-and-dot line is the contribution of the mechanism (a), the dashed line is the contribution of the mechanism (b), the dotted line is the contribution of the mechanism (c), the solid line is the total contribution of three mechanisns.

Fig.12 presents the same data, but they are integrated over the proton emission angle in the interval (90°÷180°). Comparison of calculations, made by formula (4) with the experiment show the model describes quite well the experimental data. It should be noted that the calculated and experimental data are given in absolute units.

In our paper [25] and the paper [21] it was pointed out that the angular dependence of the slope parameter should be introduced in parametrization of structure function (1), which, as it follows from what was said above, is due to the process of nucleon rescattering inside the nucleus (the first term in formula (4)).

Table 3

Momentum (GeV/c)	Cross section	exp $\sigma_{P\downarrow}$ (mb)	mod $\sigma_{P\downarrow}$ (mb)	(a) $\sigma_{P\downarrow}$ (mb)	(b) $\sigma_{P\downarrow}$ (mb)	(c) $\sigma_{P\downarrow}$ (mb)
$P_{p\downarrow} >$	0.16	33.8±1.6	33.5	21.05	9.6	2.82
$P_{p\downarrow} >$	0.21	23.5±1.6	25.3	15.9	6.59	2.79
$P_{p\downarrow} >$	0.26	16.7±1.7	17.6	11.62	3.22	2.72
$P_{p\downarrow} >$	0.31	11.7±1.7	12.2	8.22	1.42	2.55
$P_{p\downarrow} >$	0.36	7.6±1.5	8.4	5.61	0.56	2.26

a) rescattering; b) destruction; c) absorption.

Tables 3 and 4 present cross sections for generation of cumulative protons in various intervals of momenta and emission angles. Cross sections $\sigma^{(a)}$, $\sigma^{(b)}$, $\sigma^{(c)}$ calculated by formula (4), are also given there. It is seen that at large emission angles $\cos\theta_P$ (-0.8; -1.0) and momenta $P_P \gtrsim 0.36$ GeV/c the contribution of the absorption mechanism amounts to 50%. Good agreement is also observed between the calculated and experimental data.

Table 4

Angle cosine	Momentum (GeV/c)	exp $\sigma_{P\downarrow}$ (mb)	mod $\sigma_{P\downarrow}$ (mb)	(a) $\sigma_{P\downarrow}$ (mb)	(b) $\sigma_{P\downarrow}$ (mb)	(c) $\sigma_{P\downarrow}$ (mb)
(-1.0,-0.6)	(0.21,0.74)	6.9±0.4	6.4	3.38	1.94	1.12
(-1.0,-0.6)	(0.26,0.74)	4.7±0.4	4.3	2.3	0.95	1.09
(-1.0,-0.6)	(0.31,0.74)	3.2±0.3	2.9	1.5	0.42	1.02
(-1.0,-0.6)	(0.36,0.74)	2.2±0.1	2.0	0.93	0.16	0.9
(-1.0,-0.8)	(0.21,0.74)	3.1±0.2	2.8	1.35	0.94	0.56
(-1.0,-0.8)	(0.26,0.74)	2.2±0.1	1.9	0.9	0.46	0.54
(-1.0,-0.8)	(0.31,0.74)	1.4±0.1	1.3	0.57	0.2	0.51
(-1.0,-0.8)	(0.36,0.74)	0.8±0.1	0.9	0.35	0.08	0.45

a) rescattering; b) destruction; c) absorption.

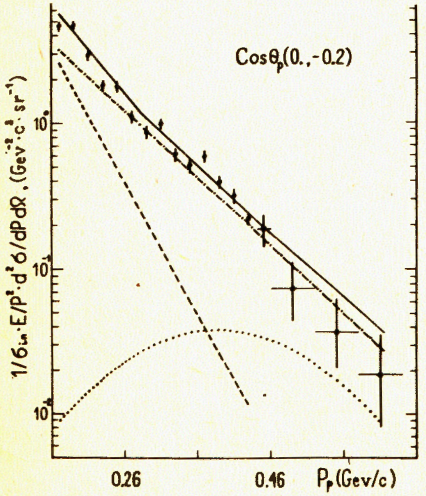

Fig.7

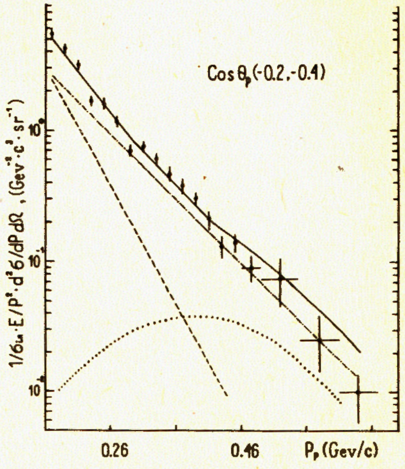

Fig.8

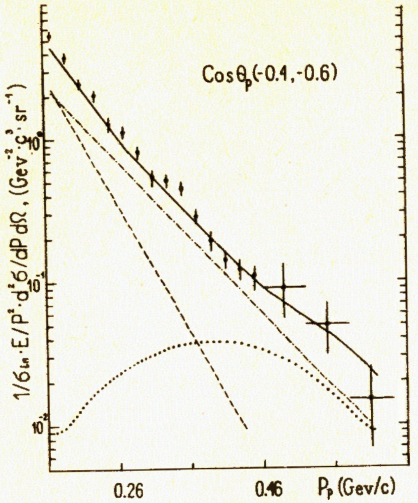

Fig.9

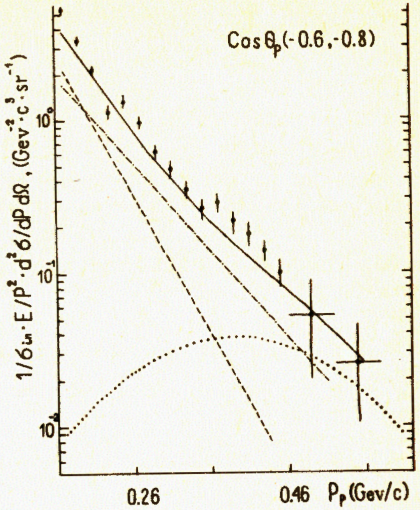

Fig.10

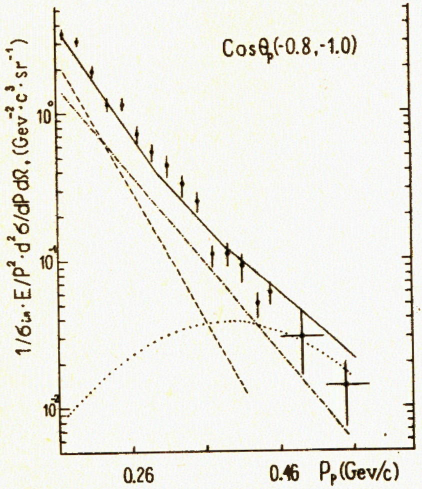

Fig.11

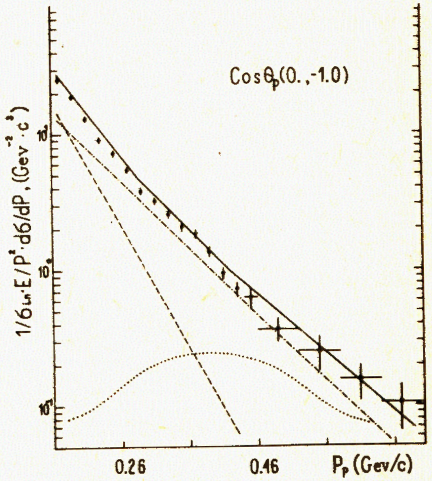

Fig.12

Figs.7-12. Structure function for protons in various interval of emission angle. Points are the experiment, the dash-and-dot line is the contribution of the mechanism (a), the dashed line is the contribution of the mechanism (b), the dotted line is the contribution of the mechanism (c), the solid line is the total contribution of three mechanisms.

CONCLUSIONS

1. For the first time contributions of individual mechanisms to production of cumulative protons in pion-carbon interactions at 5 GeV/c have been discriminated in the explicit form and described, using analytic expressions. Calculated data describe fairly well the experimental spectra.

2. The data, obtained at the mean nucleus $\bar{A} \approx 24$ at 5 GeV/c, confirm the results of Refs. /12-15/ regarding the presence of the mechanism of π^+-meson absorption by a correlated pair of nuclear nucleons and its contribution to cumulative proton production.

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Механизмы рождения кумулятивных протонов в пион-ядерных взаимодействиях при 5 ГэВ/с. Феноменологический анализ

Получены вклады отдельных механизмов в рождение кумулятивных протонов в π^-C-взаимодействиях при 5 ГэВ/с. Структурная функция имеет вид:

$$\frac{1}{\sigma_{in}} \cdot \frac{E}{p^2} \cdot \frac{d^2\sigma}{dp \cdot d\Omega} = (91{,}2 + 26{,}0 \cdot \cos\theta) \cdot \exp(-20{,}8 \cdot p) + (20{,}1 + 5{,}8 \cdot \cos\theta) \times$$
$$\times \exp(-(10{,}2 - 4{,}2 \cdot \cos\theta) \cdot p) + 0{,}038 \cdot \exp(-(p - 0{,}389)^2/2 \cdot 0{,}129^2),$$

где первый член представляет вклад механизма испарения возбужденного ядра-остатка; второй - механизма многократного ядерного рассеяния /включая процессы перезарядки, упругого и неупругого рассеяния/; третий - механизма поглощения медленных вторичных пионов парой внутриядерных нуклонов. Независимым образом из эксперимента оценен вклад реакции π^+"d" $\to P_{назад} + P$ в образование кумулятивных протонов $\sigma = /1{,}5 \pm 0{,}4/$ мбн. Получена зависимость угла разлета двух протонов /один из которых испускался в заднюю полусферу в л.с.к./ от суммы их кинетических энергий T_{2P} в пион-углеродных и пион-"фреоновых" ($\bar{A} \simeq 24$) взаимодействиях. В области $0{,}19 < T_{2P} < 0{,}26$ ГэВ наблюдается характерный максимум, обусловленный поглощением медленных пионов.

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Mechanisms of Cumulative Proton Production in Pion-Nucleus Interactions at 5 GeV/c. A Phenomenological Analysis

Separate mechanisms contributions to cumulative proton production were obtained for 5 GeV/c π^-C interactions. The structure function has the form:

$$\frac{1}{\sigma_{in}} \cdot \frac{E}{p^2} \cdot \frac{d^2\sigma}{dp \cdot d\Omega} = (91.2 + 26.0 \cdot \cos\theta) \cdot \exp(-20.8 \cdot p) + (20.1 + 5.8 \cdot \cos\theta) \times$$
$$\times \exp(-(10.2 - 4.2 \cdot \cos\theta) \cdot p) + 0.038 \cdot \exp(-(p - 0.389)^2/2 \cdot 0.129^2),$$

where the first term is the contribution of the evaporation mechanism of the excited residual nucleus, the second one is the contribution of the multiple nuclear scattering mechanism (including charge exchange, elastic and inelastic scattering processes) and the third one represents the mechanism of slow secondary pions absorption by the intranuclear nucleon pair. Contribution of the π"d" $\to P_{back} P$ reaction to cumulative proton production was estimated independently from the experiment: $\sigma = (1.5 \pm 0.4)$ mb. Dependence was obtained for the average angle between two protons (with one emitted to the backward hemisphere in lab.systems) upon its kinetic energy sum T_{2P} in pion-carbon and pion-"freon" ($\bar{A} \approx 24$) interactions. A characteristic maximum caused by absorption of slow pions has been obtained in the region $0.19 < T_{2P} < 0.26$ GeV.

The investigation has been performed at the Laboratory of Nuclear Problems, JINR.

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