# CUMULATIVE PION PRODUCTION IN COLLISIONS OF RELATIVISTIC NUCLEI

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The model of the cumulative-type processes in nucleus-nucleus collisions is formulated. It is based on the "gathering" scheme applied earlier for describing the cumulative particle production in hadron-nucleus interactions. Invariant cross sections for pion production are calculated and compared with the experimental data obtained at initial kinetic energy of 2.1 GeV/nucleon. The predictions of the model are given for primaries available at Dubna accelerator.

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Cumulative particle production processes continue to attract an attention both of theorists and experimentalists. However, in spite of considerable amount of experimental information about these processes obtained mainly in hadron-nucleus interactions the problem of their unique interpretation is yet nondecided.

In [1] the existing approaches to the description of these processes were divided in two groups. The basis of the first group of models is some variant of the flucton hypothesis [2–4]. According to it a multinucleon object (flucton) arises in the nucleus before the interaction. The cumulative particle is formed due to interaction of the projectile with such an object.

Another group of models is based on the idea that the system emitting a cumulative particle is produced during the multiple process development in nuclear matter [5–7].

An analysis of the experimental data on the cumulative production in collisions of high energy particles with nuclei within mentioned models did not lead to the unique choice of a dominant mechanism of the process. That is why it is reasonable to extend the sphere of the model consequence comparison with experimental data on cumulative pion production in relativistic ion collisions.

The study of production of the cumulative $\pi^-$ mesons flying away at 0° in A-A interactions has revealed an unusual dependence of invariant cross section on atomic weights of colliding nuclei [8]. If one approximates this by an expression of the type

$$E\frac{d^3\sigma}{dp^3} \sim A^{\alpha}, \tag{1}$$

the exponent $\alpha_T$ for the target is close to 1/3 and for the beam it is $\alpha_B \gtrsim 1$. This means that the whole volume of the projectile and only peripherical region of the target take part in cumulative $\pi^-$ meson production.

It is difficult to understand such a fact within the framework of flucton models [2–4] because in accordance with the logic of these models the cumulative pion or quark (pion is produced by hadronization of this quark) is directly formed in hadron-flucton interactions inside nucleus. Really, the ability of such models to reproduce a number of regularities of the cumulative production in hadron-nucleus interactions is conditioned by the hypothesis that there is no absorption of cumulative particles (or quarks) in nuclear matter. Therefore it follows from this hypothesis that the exponent $\alpha_T$ should not be less than 2/3 for A-A interactions. But this value contradicts the observed $A_T$-dependence [8].

Thus the results of cumulative meson production study in A-A collisions are crucial to the choice of the process scheme. Further we shall consider that process within the "gathering" model formulated in [5–6] and developed in [1].

Before one proceeds to the more complicated process of relativistic nuclei interaction we explain the main principles of the model on the base of cumulative particle production in hadron-nucleus collisions.

The "gathering" model is the extreme situation in the general picture of space-time development of the multiple production on nuclei [9]. It corresponds to the channel of coherent interaction of projectile with a target nucleon group as a whole. The probability of such a channel realization is determined by the following relationships. According to [1, 5, 6] the mean life-time of compound-system which is formed by interaction of projectile with one of the target nucleons in the coherent state is inversely proportional to the mass $M$ of the compound-system:

$$\bar{\tau}_c \approx \tau_0/M, \tag{2}$$

where $\tau_0 \approx 2$ GeV $\cdot$ fm/$c$. The state of the system in which the dissipative processes have not been developed yet we call the coherent state.

Corresponding to $\bar{\tau}_c$ the mean coherent length is:

$$\bar{L}_c \approx c\tau_c\sqrt{\gamma_{cs}^2-1} = \frac{c\tau_0 p}{M^2} \approx \frac{c\tau_0}{2m} \approx 1 \text{ fm}. \tag{3}$$

In (3) $\gamma_{cs}$ is the Lorentz-factor of the compound-system.

Since $\bar{L}_c$ is less than the mean distance between nucleons in the nuclei: $\bar{r}_{NN} \approx 2\,R_A/A^{1/3} \approx 2r_0 \approx 2.5$ fm, production of compound-system and its consequent collisions with intranuclear nucleons are mostly separated in time by the processes of dissipation, consequently they must be considered as a series of incoherent interactions.

However, due to fluctuations of $L_c$ and $r_{NN}$ rare processes are possible in which a group of $N$ nucleons of nucleus takes part in coherent formation of compound-system. The cross sections of such processes are defined by expression (1) in "gathering" model:

$$W_N = 2\pi \int_0^\infty bdb \int_{-\infty}^\infty dz_1\sigma_c\varrho(b, z_1) \exp\left[-\sigma_c \int_{-\infty}^{z_1} \varrho(b, z)dz\right] \int_{z_1+r_c}^\infty dz_2\sigma_c\varrho(b, z_2)$$

$$\times \exp\left[-\sigma_c \int_{z_1+r_c}^{z_2} \varrho(b, z)dz\right]\eta_2(z_2 - z_1) \cdot \ldots \cdot \int_{z_{N-1}+r_c}^\infty dz_N\sigma^{in}\varrho(b, z_N)$$

$$\times \exp\left[-\sigma^{in} \int_{z_{N-1}+r_c}^{z_N} \varrho(b, z)dz\right] \cdot \eta_N(z_N - z_{N-1}). \tag{4}$$

In (4) $r_c \approx 0.6$ fm is a radius of core. Nucleons cannot draw closer to one another inside nucleus than $r_c$; $\eta_i$ are the probabilities for compound-system to "survive" in a coherent state between interactions

$$\eta_i = \exp\left[-\frac{z_i - z_{i-1}}{L_c}\right], \tag{5}$$

$\sigma_c \approx 1/3\sigma_{NN}^{in}$ is the cross section of process of nucleon "gathering" in a compound-system.

Taking into account (4) we can write the invariant cross section for large $x$ particle production on nucleus A in the form:

$$\left(E\frac{d^3\sigma}{dp^3}\right)^{pA} = \sum_N W_N \left(\frac{E}{\sigma_{pN}^{in}} \cdot \frac{d^3\sigma}{dp^3}\right)^{pN}_{\sqrt{s}=\sqrt{s_N}}. \tag{6}$$

A comparison of model calculations with experimental data on cumulative $\pi^-$ meson emission into back hemisphere in p-A collisions is presented in [1].

Cumulative production of pions in A-A collisions flying away at small angles occurs due to the "gathering" of two or more nucleons of projectile nucleus on one of the target nucleons. This task is reduced to N-A interaction with back flying cumulative pion in the antilab framework. A difference is that such a nucleon is surrounded by nuclear matter an interaction with which effectively corresponds to an absorption of both compound--system itself and the nucleon group forming the latter when they pass the nucleus before the "gathering" process.

Assuming approximately the cross section as the same for all stages of the process development and indicating it as $\sigma_a$ one obtains the following expressions for cross sections

$$W_N = 2\pi \int_0^\infty bdb \int_{-\infty}^\infty dx \int_{-\infty}^\infty dy w_N(b, x, y)T(x, y) \exp\left[-\sigma_a T(x, y)\right]. \tag{7}$$

Here $T(x, y)$ is an integral over the nuclear density distribution in the target:

$$T(x, y) = \int_{-\infty}^\infty \varrho_T(x, y, z)dz, \tag{8}$$

where $x$, $y$ are coordinates in the plane perpendicular to the collision axis.

Functions $w_N(b, x, y)$ are determined by the relationship:

$$w_N(b,x,y)=\int_{-\infty}^{\infty} dz_1\sigma_c\varrho_B(b,x,y,z_1)\exp\left[-\sigma_c\int_{-\infty}^{z_1}\varrho_B(b,x,y,z)dz\right]\int_{z_1+r_c}^{\infty}dz_2\sigma_c$$

$$\times\varrho_B(b,x,y,z_2)\exp\left[-\sigma_c\int_{z_1+r_c}^{z_2}\varrho_B(b,x,y,z)dz\right]\eta_2(z_2-z_1)\dots\int_{z_{N-1}+r_c}^{\infty}dz_N\sigma^{\text{in}}$$

$$\times\varrho(b,x,y,z_N)\exp\left[-\sigma^{\text{in}}\int_{z_{N-1}+r_c}^{z_N}\varrho(b,x,y,z)dz\right]\eta_N(z_N-z_{N-1}). \qquad (9)$$

In (9) $\varrho_B$ is the nucleon density distribution in the projectile. The Gauss- and Fermi--distributions are used for light and heavy nuclei respectively.

Cumulative pion production cross section is defined by a sum over $N$, similar to (6).

Experimental data [8] and calculations for $\pi^-$ production cross sections in HeC and CC collisions at $E_{\text{in}} \approx 3$ GeV/nucleon are presented in Fig. 1. The curves describe the experiment with good accuracy. It is assumed that $\sigma_a \approx \sigma_{NN}^{\text{in}} \approx 32$ mb. The exponent $\alpha_T \approx 0.37$ corresponding to that value of $\sigma_a$ is in satisfactory agreement with data [8]. As seen from Fig. 2 the observed dependence of $\alpha_B$ on $x$ is well reproduced by the model.

Thus the "gathering" model is able to describe both absolute values of cross sections and shape of cumulative $\pi^-$ meson spectra in nucleus-nucleus collisions and the dependence of the cross sections on atomic weights of colliding nuclei.

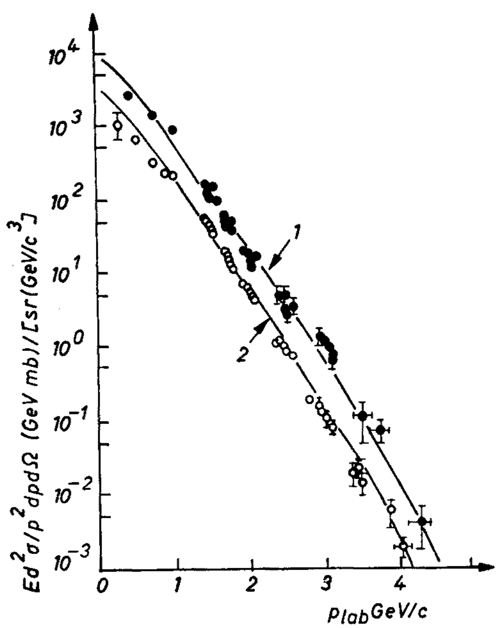


Fig. 1. Lorentz invariant negative pion inclusive cross section vs the lab momentum at 0° for 3 GeV/nucleon alphas (experiment [8] (○), theory (2)) and carbon nuclei (experiment [8] (●), theory (1)) interacting with a carbon target

The predictions of the model for cross sections of cumulative $\pi^-$ mesons emitted at 0° in $\alpha$C and CC interactions at $E^{in}$ = 4.6 GeV/nucleon are shown in Fig. 3. The dependence of $\alpha_B$ on X corresponding to that energy is shown by cross in Fig. 2. As seen from Fig. 4 the model predicts a noticeable breaking of scaling at large $x$ by transition from $E^{in}$ = 3 GeV/nucleon to $E^{in}$ = 4.6 GeV/nucleon.

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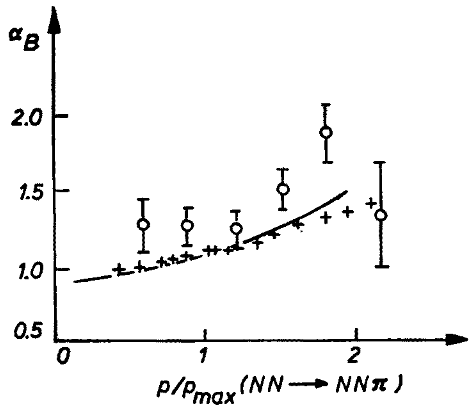


Fig. 2. The dependence of the exponent $\alpha_B$ from parametrization $E \frac{d^3\sigma}{dp^3} \sim A_B^{\alpha_B}$ vs the value $P/P_{max}$ (NN → NNπ) for $A_B = \alpha$, C at $E^{in}$ = 3.0 GeV/nucleon (experiment [8] (○), theory (solid line)) and $E^{in}$ = 4.6 GeV/nucleon (theory(+))

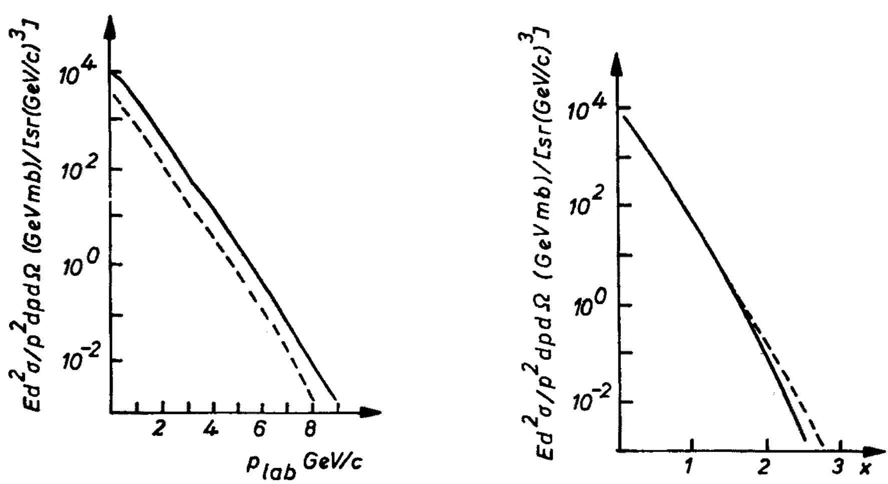


Fig. 3　　　　Fig. 4

Fig. 3. The same as Fig. 1 for 4.6 GeV/nucleon alphas (dotted line) and carbon nuclei (solid line) interacting with a carbon target

Fig. 4. Lorentz invariant $\pi^-$ inclusive cross section vs $x_F = P_L/P_L^{max}$ for carbon nuclei at $E^{in}$ = 4.6 GeV/nucleon (dotted line) and $E^{in}$ = 3.0 GeV/nucleon (solid line) interacting with a carbon target

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