HADRONIC COMPOUND-SYSTEMS IN CUMULATIVE PRODUCTION PROCESSES

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A modified version of the model of cumulative particle production in hadron-nucleus interactions based on the mechanism of nucleons "gathering" into hadronic compound-system is presented. The model results are compared with the new experimental data. A connection of the compound-system formation characteristics with the confinement of colour charges is considered.

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1. *Introduction*

The experimental investigation of cumulative production processes expanded greatly during the last decade. However it is not clear so far what kind of information the acquired data contain. The answer to this question depends on the preference to one of the basic groups of models.

The first group contains the models based on the assumption that the cumulative production takes place due to the interaction of the initial particle with some kind of "flucton" [1–3]. It can be a multinucleon or multiquark formation which appears fluctuatively in nucleus before interaction. In the framework of this representation the cumulative processes contain the information on the details of nuclear structure which are sensible at high energies.

Another group of models assumes that the hadronic system which radiates a cumulative particle is formed during the process of the incident particle interaction with the nucleus [4–6]. In the framework of this representation the nucleus serves as a detector of the space-time development of production process. In particular it will be shown below that the questions of colour tube life-time and the character of its interaction with the nucleons of the target nucleus may be considered in the framework of the "gathering" model [4, 5].

It must be stressed that so far there is no crucial experiment which evidently confirms

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a dominant role of one of these two pictures. The fact of cumulative μ-on production in μ-nucleus interactions is not an exception. In Ref. [1] this fact was considered as the stronger argument against the "gathering" model. However in this model the cumulative leptons may be produced due to the decays of short living cumulative hadrons (J/ψ for instance). Then the spectra of cumulative leptons and hadrons must be similar. It has been noted in [1] that such similarity was observed experimentally.

We consider that both schemes of the process are to be developed since they may supplement each other giving the contributions of equal orders of magnitude to the observed cross sections.

The aim of this paper is to present a corrected version of "gathering" model to verify its correspondence to new experimental data and to consider the arguments pro- and contra this model which have been suggested during the last years in connection with the appearance of new ideas and results.

2. *The "gathering" scheme*

The "gathering" scheme arises as an extreme in the general approach to the space--time development description of the multihadron production process on nuclei [7–10] which corresponds to production of particles with extremely large momenta. In accordance with [7–10] a hadronic compound-system (cluster) is created when an incident particle interacts with one of the nucleus nucleons. As this compound-system moves inside the nucleus it collides with nucleons and these collisions increase its mass.

A selection of cumulative particle production channel restricts the characteristics of interactions in which the compound-system is formed. The first restriction is connected with the leading particle effect. We consider it for the case when a compound-system is formed with participation of N nucleons of the target nucleus. Let P_0 be a momentum of the incident particle, δ_0 — the portion of P_0 which is spent for coumpound-system creation and δ_N — the corresponding momentum for each of N nucleons. Then the momentum P_c of the cumulative particle "c" is determined by the following equations

$$E_0+NE_N = E_0'+NE_N'+E_c+E_r, \tag{1}$$

$$P_0'+NP_N'+P_c+P_r = 0, \tag{2}$$

$$P_0' = (1-\delta_0)P_0, \quad P_N' = (1-\delta_N)P_N, \tag{3}$$

$$E_r^2 = P_r^2+M_r^2, \tag{4}$$

$$E_0' = 0 \quad \text{if} \quad \delta_0 = 1, \qquad E_N' = 0 \quad \text{if} \quad \delta_N = 1. \tag{5}$$

Here E_r, P_r and M_r are the energy, the momentum and the effective mass of hadronic system after radiation of the particle "c". Eq. (5) corresponds to the events when an incident particle or target nucleons are captured by compound-system.

The kinematical limit P_c^{max} for P_c corresponds to the minimal extreme of M_r which is determined by conservation of quantum numbers such as electric and barionic charges, strangeness etc.

In Fig. 1 the dependences of $(P_c^{max})_N$ on N, δ_0 and δ_N in L-system are presented for π^--mesons which fly out at an angle of 180° in p-A collisions at $E_0 = 9$ GeV. It is seen from Fig. 1, that $(P_c^{max})_N$ has a maximum at $\delta_N = 1$ and diminishes rapidly as δ_N decreases. Then tne nucleons "gathering" in the compound-system is necessary for production of a particle with extremely large momentum in the back hemisphere, since "gathering" corresponds to $\delta_N = 1$ for all nucleons participating in the compound-system formation. It is argued in [5] that the cross section for nucleon capture by the compound-system σ_c is about $(1/3 \div 1/4)\sigma^{in}$. The value $\sigma_c = 1/3\ \sigma^{in}$ is used in the calculations below.

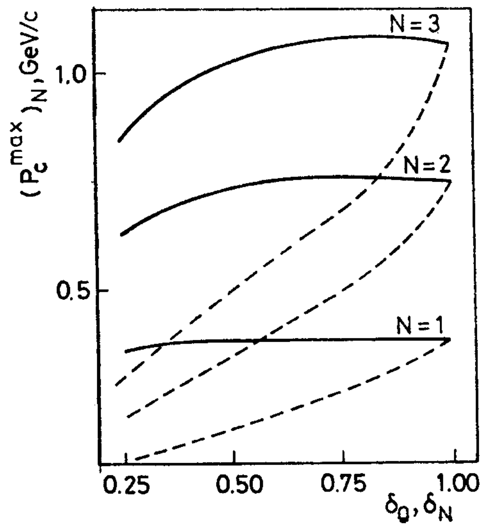

Fig. 1. Dependences of $(P_c^{max})_N$ on $\delta_0(\delta_N = 1)$ — solid lines and on $\delta_N(\delta_0 = 1)$ — dashed lines

In Fig. 1 one can also see that the values $(P_\pi^{max})_N$ vary slowly with δ_0. Therefore the cumulative particle production in the target fragmentation region does not impose kinematical restrictions on the leading effect for the incident particle and it preserves its character peculiar to multi-hadron production. This conclusion is in accordance with the results of the investigations of tne leading hadrons characteristics in cumulative production processes [11, 12]. Hence the target nucleons are "gathered" not by incident hadron but by a compound-system produced in the first interaction of this hadron with a nucleus nucleon. Then it is obvious that nucleons may be "gathered" by a hadronic system produced in a deep inelastic photon and lepton scattering.

The extension of the phase space by several nucleons participation in the compound-system formation is only a necessary condition for cumulative particle production but not a sufficient one. For such a process in each act of the compound-system formation the system is also required to preserve its ability to interact with nucleons as a single dynamically connected object not touched by dissipative processes. Such a state of the compound-system will be referred to as a coherent one.

In the framework of the multi-hadron production models based on the quark-glue model of hadron structure a coherent state of the compound-system is a non-broken colour tube or a string formed by colour charge exchange between interacting hadrons (see [13] for instance). As well as in [4, 5] we suppose that a coherent state decays exponentially i.e. the probability for the compound-system to be in a coherent state at a time t is

$$\eta = \exp(-t/\tau_c). \tag{6}$$

Here τ_c is a mean life-time of a coherent state.

In [4, 5] the life-time of this state was assumed to decrease inversely proportional to its mass:

$$\tau_c = \tau_0/M. \tag{7}$$

This assumption corresponds to the hypothesis of dynamical confinement of colour charges [14]. In accordance with this hypothesis the confinement forces not only depend on the distance between these charges but also grow with the increase of their relative motion energy M. As a result the density of the vacuum polarisation energy increases with M, and the colour tube is destroyed in shorter time intervals. The constant parameter τ_0 determines the tube life-time and is to be found experimentally.

Taking (7) into account one gets the following expression for quantities η_N in the nucleus rest system.

$$\eta_N = \exp\left\{-\frac{tM_N}{\tau_0\gamma N}\right\} = \exp\left\{-\frac{(z-z_0)M_N^2}{\tau_0\delta_0P_0}\right\} = \exp\{-a_N(z-z_0)\}. \tag{8}$$

Here N is the number of "gathered" nucleus nucleons, z_0 is the coordinate of the point where the compound-system was born or its mass was increased, z is the running coordinate; M_N and γ_N are the mass and Lorence-factor of the compound-system:

$$M_N = \sqrt{2Nm\delta_0E_0+N^2m^2}, \tag{9}$$

$$\gamma_N = \frac{\delta_0E_0+Nm}{M_N}. \tag{10}$$

At high energies the quantities a_N approach the limit

$$a_N = 2Nm/\tau_0, \tag{11}$$

which does not depend on δ_0.

The dependences of $a_N\tau$ on δ_0 at $E_0 = 9$ GeV are shown in Fig. 2. One can see that these dependences are quite weak. This is in agreement with the above mentioned non--distortion of leading particle effect in cumulative production processes. The dependences of quantities $(P_\pi^{max})_N$ and $a_N\tau_0$ on E_0 are shown in Fig. 3a and 3b. They exhibit plateaus of almost constant heights as E_0 increases. This results in an analogous behaviour of cumulative particle production cross section.

To describe produced particle spectra we assume the invariant inclusive cross section for production of i particle in the interaction of the compound-system with N^{th} nucleon

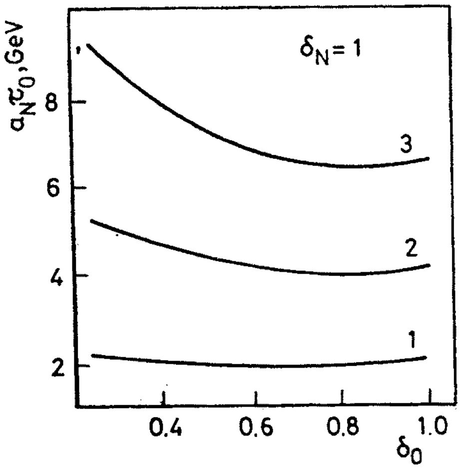

Fig. 2. Dependences of values $a_N\tau_0$ on δ_0

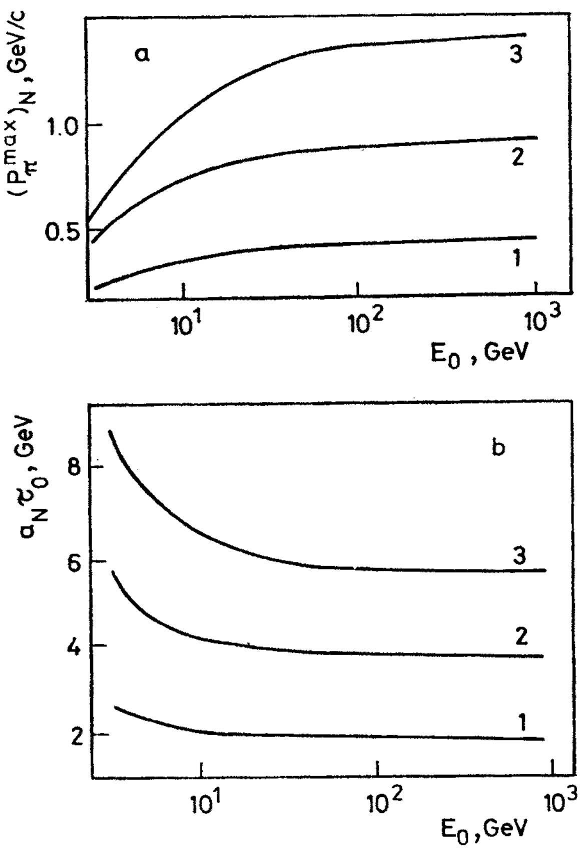

Fig. 3. Values of $(P_\pi^{max})_N$ (a) and $a_N\tau_0$ (b) vs E_0

to be identical to the corresponding cross section in hadron-nucleon collision at $\sqrt{S} = (\sqrt{S})_N$. Then the invariant cross section for the i particle production on nucleus is determined by the equation

$$E \frac{d^3\sigma_i^A}{dP^3}(x, P_\perp, E_0) = \sum_N W_A^N F_i(x_N, P_\perp, \sqrt{S_N}). \tag{12}$$

Here $x_N = P_\parallel/(P_i^{\max})_N$ and

$$F_i(x, P_\perp, \sqrt{S}) = \frac{E}{\sigma_{hN}^{\text{in}}} \cdot \frac{d^3\sigma_i^{hN}}{dP^3}(x, P_\perp, \sqrt{S}). \tag{13}$$

The quantities W_A^N are the cross sections of the formation process of a compound-system containing $N-1$ nucleons and its interaction with N^{th} nucleon.

Taking (8) into account one gets the following equation for W_A^N

$$W_A^N = 2\pi \int_0^\infty bdb \int_{-\infty}^\infty dz\sigma_c\varrho(b, z) \exp\left[-\sigma_c \int_{-\infty}^\infty dz\varrho(b, z)\right]$$

$$\times \int_{z_1}^\infty dz_2\sigma_c\varrho(b, z_2) \exp\left[-\sigma_c \int_{z_1}^{z_2} dz\varrho(b, z)\right] \exp\left[-a_1(z_2-z_1)\right]$$

$$\ldots \int_{z_{N-1}}^\infty dz_N\sigma_{hN}^{\text{in}}\varrho(b, z) \exp\left[-\sigma_{hN}^{\text{in}} \int_{z_{N-1}}^{z_N} dz\varrho(b, z)\right] \exp\left[-a_{N-1}(z_N-z_{N-1})\right]. \tag{14}$$

It differs formally from the corresponding equation for W_A^N in [4, 5] in one point: in the last integral the cross section σ_c is replaced by σ_{hN}^{in}. This replacement is stipulated by the following circumstance. In papers [4, 5] the function $F(x, P_\perp, \sqrt{S})$ was used in a sense of inclusive spectrum of particles produced by a decay of the compound-system of mass M_N. But actually the invariant cross section (13) taken from hadron-nucleon interaction is a sum over all the mass spectrum of compound-system which corresponds to inelasticity distribution in these interactions. The usage of (13) as a cross section for particles produced by compound-system with a certain decay mass is not quite correct. A more precise definition of the model [4, 5] given here eliminates this discrepancy.

Fermi's distribution for nucleon density in nuclei ϱ was used in (14). In papers [4, 5] the uniform sphere approximation was applied.

To calculate a cumulative π production cross-section, we use for F the approximation obtained in [15]:

$$F_\pi(x, P_\perp, \sqrt{S}) = F_\pi(x, P_\perp) = f(x) \exp\left[a_6(-P_\perp+P_\perp x-P_\perp^2x^2)\right], \tag{15}$$

where

$$f(x) = a_1 \frac{\exp(-a_2x)}{1+\exp\left(\dfrac{x-a_3}{a_4}\right)} (1-x)^{a_5}. \tag{16}$$

It takes into account the scaling of π spectra in pp-interactions and satisfies the experimental data. The values of a_i are the following: $a_1 = 0.92$, $a_2 = 3.9$, $a_3 = 0.65$, $a_4 = 0.083$, $a_5 = 0.69$, $a_6 = 6.12$.

The dependence close to (16) was obtained in [16] from the quark-parton model:

$$f(x) \sim (1-x)^4. \tag{17}$$

The comparison of (16) with (17) is given in Fig. 4. However, it has been shown in [17] that the expression like $(1-x)^n$ follows from the longitudinal phase space model

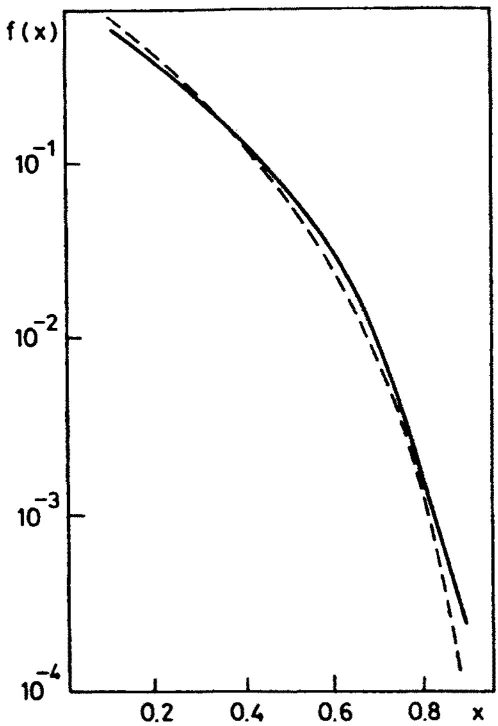

Fig. 4. Function $f(x)$ determined by expression (15) — solid line, and by (16) — dashed line

when the momentum conservation is taken into account. Then a power $n = 4 \div 5$ was obtained in the framework of a statistical model which takes into account the peculiarities of hadronization process in relativistic expansion of the compound-system [14]. Therefore cumulative particle production may be considered in the framework of a statistical approach applied to the compound-system decay[1].

Two important conclusions follow:

Firstly, the identity of the invariant cross sections of particle production in hadronic

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[1] A statistical model of cumulative particle production has been developed in [6]. However a thermodynamical approximation used there does not take into account the energy conservation law. This is inadmissible for description of the large x particle production.

collisions and in "gathering" scheme obtains a simple explanation based on statistical model: the decay properties of system are determined by its mass only.

Secondly, the statistical shape of cumulative particle spectrum agress with the assumption that their radiation does not take place at the early stage of the compound-system evolution but occurs as a result of hadronization process whose duration is long enough for the compound-system to fly out the nucleus [10]. Then a quite complicated question of cumulative particle absorption in nuclear matter is removed. This question arises inevitably when a cumulative hadron is born inside the nucleus. The absorption may be quite intensive since the momentum of cumulative pions observed in the majority of experiments is of the order 1 GeV/c. This value corresponds to the resonance region. Obviously such an absorption should decrease repeatedly the yield of cumulative particles and turns its A-dependence into the $A^{2/3}$ form.

It should be noted that by the logic of the most popular "flucton"-type models [1] the cumulative hadrons are born inside a nucleus and the problem of their absorption awaits its solution.

Another specification of the model [4, 5] presented here is the allowance of a core in nucleon-nucleon interaction which prevents the nucleons to approach a distance less than a core radius r_c. This brings Eq. (13) to the form

$$W_A^N = 2\pi \int_0^\infty bdb \int_{-\infty}^{\infty} dz_1 \varrho(b, z) \exp\left[-\sigma_c \int_{-\infty}^{z} dz \varrho(b, z)\right]$$

$$\times \int_{z_1+r_c}^{\infty} dz_2 \sigma_c \varrho(b, z_2) \exp\left[-\sigma_c \int_{z_1+r_c}^{z_2} dz \varrho(b, z)\right] \exp\left[-a_1(z_2-z_1)\right]$$

$$\times \int_{z_{N-1}+r_c}^{\infty} dz_N \sigma_{hN}^{in} \varrho(b, z_N) \exp\left[-\sigma_{hN}^{in} \int_{z_{N-1}+r_c}^{z_N} dz \varrho(b, z)\right] \exp\left[-a_{N-1}(z_N-z_{N-1})\right]. \quad (18)$$

The value $r_c = 0.6$ fm is used in the calculations.

It is necessary to emphasize the importance of correct determination of M_r for Eq. (4). Let us consider, for instance, the ratio of K^+ and K^- meson production cross section

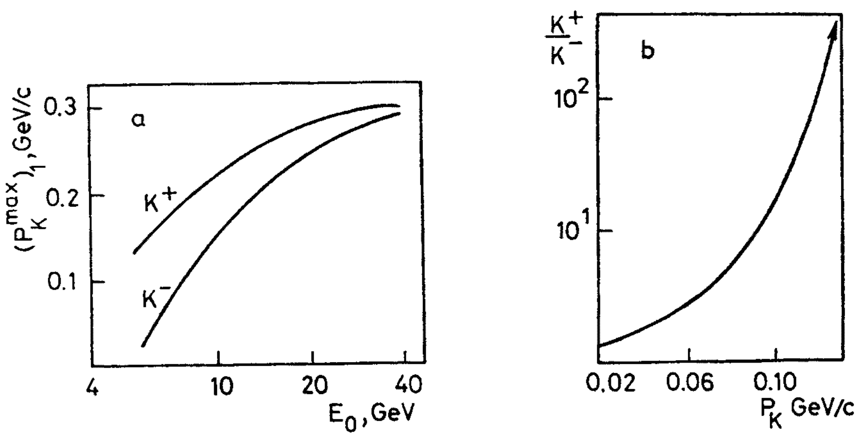

Fig. 5. Values of (P_K^{max}) on E_0 (a) and the ratio of K^+ and K^- production cross sections (b)

being used as one of the tests for cumulative particles production models [1]. There is a notable peculiarity in production of these particles in nucleon-nucleon interaction: K^+ may be produced in pair with Λ_0, but K^- in pair with K^+ only. Then M_r for K^--mesons is larger

$$\Delta M_r = m_K - (m_{\Lambda_0} - m_N) \approx 0.32 \text{ GeV}, \tag{19}$$

and the kinematical bounds are more restrictive. The influence of ΔM_r on these bounds grows with decrease of E. The dependences of $(P_K^{max})_1$ upon E_0' for K^+ and K^--production at an angle of 180° in pp-collisions are shown in Fig. 5a. The ratio of K^+ and K^- production cross sections at the same momentum may be arbitrary large due to this factor only.

The dependence of this ratio on P_K at $E_0 = 9$ GeV is shown in Fig. 5b. In our calculations the shape of K-meson spectra was assumed to be determined by (17). This factor was not taken into account in Ref. [1] and incorrect conclusion was made that the "gathering" model is unable to describe this ratio.

3. *Some consequences of the model and their comparison with experimental data*

In 1979 at JINR the new data were obtained for the invariant cross sections of cumulative particle production by proton interacting with various nuclei at $P_0 = 8.9$ GeV/c [18]. The previous results [19] were considerably changed, particularly for pions with kinetic energies $E_{kin} \gtrsim 0.6$ GeV. The difference between new and former results reaches three-to-four orders of magnitude (see Fig. 6). In Refs [4, 5] the parameters of the "gathering" model were fit to the data [19]. The results of our calculations are shown in Fig. 6 by curve *1*.

We have used the new data on cumulative pions production in p Pb interaction at $P_0 = 8.9$ GeV/c to choose the value of τ_0 in corrected version of the "gathering" model. The curve 2 in Fig. 6 corresponds to the value $\tau_0 = 2$ fm GeV/c. This value is used in all following calculations.

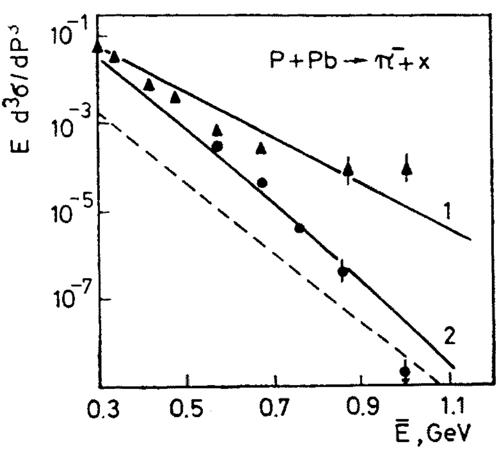

Fig. 6. The cross sections $E/Ad^3\sigma/dP^3$ in pPb-interactions: (▲) — the data from Ref. [19], (●) — the data from Ref. [18]; the curves are the model calculation

In Fig. 7 the results of these calculations are compared with the experimental data for cumulative pions at energies 9 GeV [18] and 400 GeV [20]. It is seen that the model correctly reproduces the energy dependence of invariant cross sections. As it has been repeatedly noted the parametrization of A-dependence of cumulative particle production cross section by the form A^{α} is not quite successful. It is dependent on nuclei which one uses for determination of α. In fact, the cross sections $E/A \times d^3\sigma/dP^3$ increase with A at $A \lesssim 20$ and become constant at $A \gtrsim 20$ (see Fig. 8). As it follows from Fig. 8 the model correctly

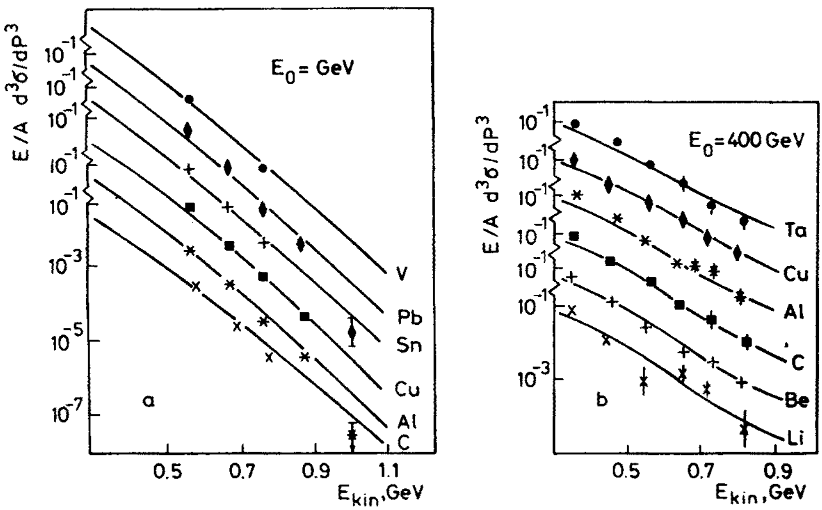

Fig. 7. Invariant cross sections of π^--meson production, the curves are the model calculation

reproduces this behaviour. It follows from such behaviour of cross-sections that determination of α with the use of a pair of heavy nuclei gives $\alpha \approx 1$. If the used pair contained a light nucleus then α should be considerably above unity.

There is a simple qualitative explanation of such A-dependence of the cumulative particle production in the context of "gathering" model. In accordance with (8) the probability for compound-system to be in the coherent state decreases exponentially with the distance from the point where it was born. Hence the probability for the next nucleon to be "gathered" in the compound-system rises with decreasing the mean internucleon distance in nuclei. In heavy nuclei this distance is almost independent of A. In light nuclei it diminishes when A increases and this implies the rise of the cross section. This explanation is confirmed by similarity of the cross section values for heavy nuclei and for ^{4}He [18] whose densities are almost equal.

In Fig. 9 the cross sections of cumulative π-meson production on Ta at $E_0 = 400$ GeV are shown for two angles of observation. It is seen that the model satisfactorily describes the angular dependence of these cross sections.

Some interesting results were obtained from investigation of the cumulative process on carbon nuclei in the propane chamber [11, 12]. On the basis of these results it is possible

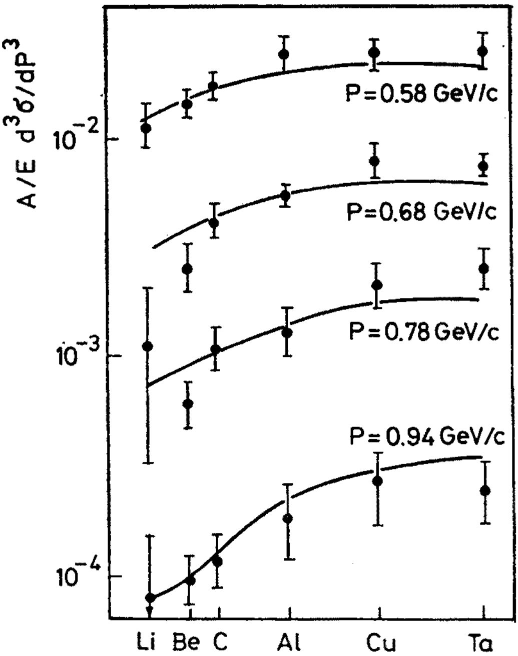

Fig. 8. Dependences of $Ed^3\sigma/dP^3$ on A; the curves are the model calculation

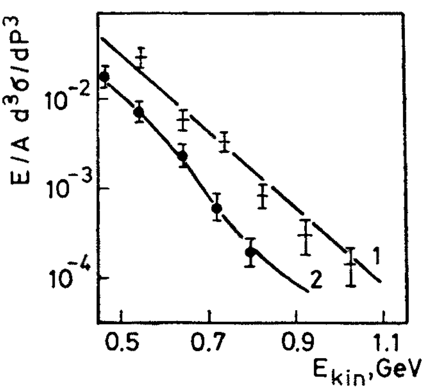

Fig. 9. $E/Ad^3\sigma_{\pi^+}/dP^3$ is at $\theta = 118°$ (line 1) and $\theta = 160°$ (line 2)

to estimate the rapidity y_s of hadronic system which radiates the cumulative particle. The mean cumulative meson momentum is 1 GeV/c, its angle is $\bar{\theta}_\pi \approx 120°$ and the mean rapidity of the rest particles is $y_r = 1.8$ when a cumulative number is $n_c \approx 1.5$ [12].

From here it follows:

$$y_s = \frac{y_r \frac{3}{2} N_{\pi^\pm} + y_\pi}{\frac{3}{2} N_{\pi^\pm} + 1} \approx 1.6. \tag{20}$$

Here $N_\pi = 6.5$ is the mean charge particle multiplicity, y_π is the rapidity of a cumulative π-pion. The value of y_s determined in the model is 1.55 for a compound-system containing two nucleus nucleons. This estimation agrees well with (20).

It should be noted that in the model [6] the velocity of a hadronic cluster radiating a cumulative particle is $\beta_K \approx 0.7$. Hence the rapidity of this cluster is

$$y_s \simeq \tfrac{1}{2} \ln \frac{1+\beta_K}{1-\beta_K} \approx 0.87, \tag{21}$$

which obviously contradicts (20).

However the constancy of β_K in the model [6] does not seem to be a crude approximation. One may abandon it and determine the speed and the mass of the cluster by the use of the equation of cluster motion in the nuclear matter [7–10]. By doing it, one not only excludes the adjustable parameter β_K but also, in contrast to [6], one obtains an absolute value of cumulative particle production cross section. The example of such calculation for pPb-interaction at $E_0 = 9$ GeV is shown in Fig. 6 by a dashed line. It is seen that contribution of such mechanism to cumulative particle production may be of the order of a few per cent.

4. *Conclusion*

The "gathering" model does not contradict the new experimental results of cumulative production process. If the output of the "gathering" channel dominates in the cross sections of cumulative production then using this model one can obtain the characteristics of the hadronic compound-systems in the coherent state: the life-time τ_c and the cross sections of their interaction with nucleus.

The coherent state of the compound-system may be considered as a colour tube. Hence τ_c is a time interval between creation and rupture of the tube. The τ_c-dependence on tube mass $(1/M)$ agrees with the hypothesis of dynamical confinement [14] and is an argument in favour of this hypothesis.

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