Vol. B18 (1987) ACTA PHYSICA POLONICA No 8

ON THE MECHANISM OF CUMULATIVE PROTON AND NUCLEAR FRAGMENT PRODUCTION

By Yu. B. Prilepsky and V. L. Shmonin

High Energy Physics Institute of the Kazakh Academy of Sciences, Alma-Ata*

(Received March 21, 1986; revised version received October 21, 1986)

The model of cumulative proton and nuclear fragment production based on subsequent account of space-time factors of the process of high-energy particle interaction with nuclei, is formulated. The cumulative proton and fragment sources are the baryon subsystems in this model. These subsystems are formed by recoil nucleons passing through the nuclear matter which are produced by multi-particle process in the nucleus. It is shown that the model satisfactorily reproduces main observable characteristics in a wide range of primary energies and masses of nuclei.

PACS numbers: 13.85.-t

1. *Introduction*

Recently, a discussion on the interpretation of the process of cumulative proton and nuclear fragment production has sharpened markedly. A spectrum of model interpretations presented for the explanation of this process ranges from standard mechanisms with Fermi-motion and rescattering, to the exotic ones assuming the existence of multi-nucleon quark bags in the nucleus before the interaction.

To understand the most general properties and to select the correct mechanism that provides a main contribution to the cross-section of the cumulative proton and light fragment production it is necessary to consider the following arguments.

1. There are many facts and arguments which allow one to state that the nature of this process differs from the nature of production of newly born cumulative particles. The most important experimental proof for this statement is a qualitative difference for the cross-section dependence on the mass of the target nucleus [1–4].

For the cumulative pion-production this dependence at any order of cumulation, beginning from the second one, has a volume form, but it is significantly stronger for the cumulative protons and fragments.

* Address: High Energy Physics Institute of the Kazakh Academy of Sciences, Alma-Ata 82, USSR.

In such a case, the A-dependence of the cross-section increases with the increase of the number of nucleus and rapidly increases with the transition to the highest orders of cumulativity.

This difference is not reproduced by any model using the universal mechanism for A-dependence (A is the nucleus number).

The different nature of π-meson and proton production also follows from the criterion of cumulative processes selection by means of their correlation characteristics in four--dimensional velocity space [5].

2. Models based on the hypothesis that the cumulative processes are conditioned by the presence of the associated nucleon groups in a nucleus [6–8] lead to the same A-dependence of the production for nucleon and fragment cross-section of different masses.

Indeed, in these models the absorption of cumulative particles in nuclear matter is not taken into account and A-dependence is determined only by the fluction production probability. The latter contains the geometrical factor $\left(\frac{V_0}{V}\right)^{n-1} \sim A^{-(n-1)}$ (V_0 is a volume in which nucleons should gather to produce the flucton, V is a nucleus volume, n is the number of nucleons in the flucton) and the combinatorical factor $C^A_{n,A \gg n} \sim A^n$. Hence, for any n this probability is directly proportional to A^1. So, these models cannot claim to give a dominant contribution to cumulative proton and fragment cross-section.

3. It should be also taken into account that the A-dependence is the same for cumulative proton production cross-section and the total cross-section of g-particle (nonrelativistic protons) production characterizing the "nucleus response" to the fast production processes in it.

We present these dependences in a form:

$$\left(\frac{d^3\sigma_p}{dp^3}\right)_{x>1} \sim A^{\alpha p}, \tag{1}$$

$$\sigma_g^{tot} = \int d^3p \, \frac{d^3\sigma(\mathrm{p+A \to g+x})}{dp^3} = \langle n_g \rangle \sigma_{pA} \sim A^{\alpha g}. \tag{2}$$

Then,

$$\alpha_p \approx \alpha_g. \tag{3}$$

We get $\alpha_p \approx 1.4$ [4] and $\langle n_g \rangle \sim A^{0.7}$ [9] and $\sigma_{pA} \sim A^{0.7}$ [10].

This similarity seems to indicate the universal mechanism which produces the cumulative and noncumulative protons in nucleus destroyed by the multiparticle production process.

This point seems to be quite natural in the framework of the model [11, 12] where the cumulative pions are produced as a result of the multiparticle production process development in nuclear matter [13].

The cumulative protons are the result of the "nucleus response" to this process.

4. During the development of multiparticle production process in nucleus, most of the nucleons participating in this process will acquire kinetic energy of about few hundred

MeV (recoil nucleons). These nucleons can interact with other nucleus nucleons what increases the degree of nucleus destruction.

At the middle energies of recoil nucleons ($0.2 \div 0.3$ GeV) these nucleons interact mainly elastically. However, such collisions do not occur, what is limited by the time of nucleon-nucleon interaction τ_d. A character of processes during destruction of nucleus depends mainly on the difference between τ_d and the time during which the two-nucleon system passes the distance from one nucleon to another τ_r, and also the difference between τ_d and the time necessary for the system to leave the nucleus τ_R R_A/V (R_A is nucleus radius; V is a velocity of the system).

If $\tau_d \ll \tau_r$, the process of destruction is reduced to the superposition of two-nucleon collisions.

For such a case, when

$$\tau_d \sim \tau_r, \tag{4}$$

this process can be accompanied by the production of two-baryon subsystems consisting of three or more nucleons. Finally, if

$$\tau_d > \tau_R, \tag{5}$$

such subsystem captures all nucleus nucleons encountered on the way of recoil nucleon motion. These nucleons interact with the delay time of about τ_d.

To obtain a reasonable estimate of τ_d, one should take into account that the nucleons are the systems of quarks and gluons. The interaction between such systems in elastic channel can be of two types: the potential scattering which is not accompanied by mixing of quark colour degrees of freedom of nucleons and the scattering which passes through the stage of a single intermediate system bound by colour forces.

The life-time of such system can be large because it can decay only if the recombination of many colour degrees of freedom in relatively seldom white configurations occurs. Taking into account this peculiarity, the inherent excited states of intermediate multiquark system in a first approximation can be presented as lapped resonances. In this approximation, the interaction time delay in elastic channel is estimated as [14]

$$\tau_d \approx \pi \hbar \varrho_{res}, \tag{6}$$

where ϱ_{res} is the resonance density. In the frame of bag model [15] ϱ_{res} is estimated in a form

$$\varrho_{res} = \tfrac{1}{28} (\text{MeV})^{-1}. \tag{7}$$

If a recoil nucleon having produced two-nucleon system has a kinetic energy in a range $\varepsilon_K = 0.2$ to 0.3 GeV, one can get from (6) and (7):

$$\frac{\tau_d}{\tau_R} = \frac{\pi \hbar \varrho_{res}}{R_A \cdot m/\sqrt{2\varepsilon_K}} \gtrsim 2 \tag{8}$$

even for the very heavy nuclei.

In such a case the condition (5) is valid. Therefore, the recoil nucleons produced in multiparticle production process when passing through the nuclear matter, can initiate the "gathering" of some nucleons into baryon subsystem. The decay of these subsystems can be a source of cumulative protons and fragments.

5. The experimental investigation of correlations between non-relativistic products of the target nucleus destruction in relativistic nucleus central interactions, with complete destruction of photoemulsion heavy nuclei, led us to the discovery of the effects caused by the presence of baryon subsystems [16, 17]. In the cited papers these effects were interpreted as multinucleon systems bound in predecay state by colour forces.

In nucleus-nucleus collisions, the indication of the long-living multinucleon subsystem generation which possess universal properties, were obtained [18] when analysing spectrum-angle characteristics of secondary particles within the frames of formalism based on the introduction of time operator.

We will show below that the model admitting baryon subsystem formation can reproduce the most general characteristics of the process.

2. *The model*

Basing on the arguments presented in the Introduction, let us accept the following picture of interactions where the cumulative protons and fragments are produced. At the first stage, the multiparticle production processes proceed in nucleus, accompanied by the formation of recoil nucleons causing the baryon subsystem generation (see Fig. 1). At the second stage, these recoil nucleons, so-called "initiators", upon passing through the nuclear matter and "gathering" nucleons produce baryon subsystem which decays into protons and light nucleus fragments (see Fig. 2).

The detailed description of this process demands the concrete definition of multiparticle production mechanism and the consideration of rather complicated geometry of initiating nucleon passage through nuclear matter. For this case, it is necessary to take into account the interactions between initiators and baryon subsystems, too. Therefore, in the first stage we do not use detailed definition. We construct very rough scheme which reflects only the most common features of the process.

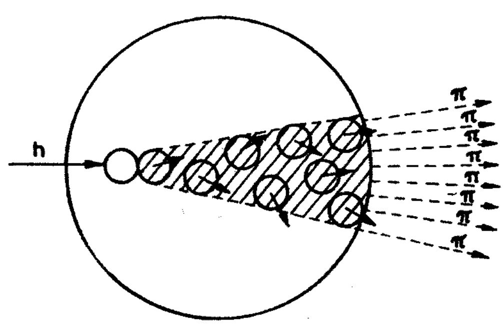

Fig. 1. The scheme of a fast stage of high energy particle interaction with nuclei

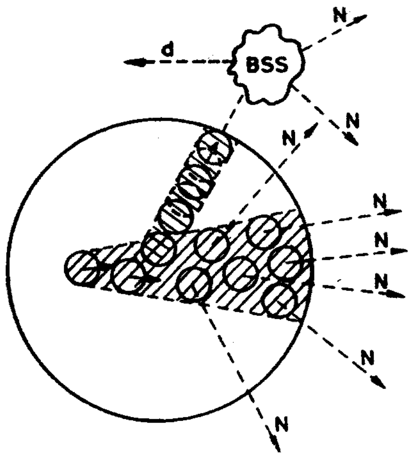

Fig. 2. The scheme of a slow stage — the "nucleus response" for fast production process in nucleus

Let L be the average path covered by initiating nucleon in nuclear matter with density ϱ_0. The possibility of "gathering" of n nucleons into baryon system is defined by the well-known expression:

$$F_1 = \int_0^L dz_1 \sigma^* \varrho e^{-\sigma^* \varrho z_1} \int_{z_1}^L dz_2 \sigma^* \varrho e^{-\sigma^* \varrho (z_2 - z_1)} \ldots$$

$$\int_{z_{n-1}}^L dz_n \sigma^* \varrho e^{-\sigma^* \varrho (z_n - z_{n-1})} e^{-\sigma^* \varrho (L - z_n)} = \frac{(\sigma^* \varrho L)^n e^{-\sigma^* \varrho L}}{n!} . \quad (9)$$

Here, σ^* is the cross-section of nucleon capture into baryon subsystem. Obviously, the distribution in n (9) is the Poisson distribution with the average value

$$\bar{n} = \sigma^* \varrho L. \quad (10)$$

Thus, according to (8), the length over which the generation of baryon subsystem proceeds is defined by the nucleus size.

We can write:

$$L = \kappa A^{1/3}, \quad (11)$$

where κ is a factor in units of length. It takes into account a very complicated geometry of initiating nucleon passing through the nucleus. Two unknown quantities σ^* and the coefficient of proportionality κ in (11) are the factors in (10). So, they can be combined in one parameter a.

Assume $\bar{n} = aA^{1/3}$ and present (9) in a form:

$$F_n = \frac{(\alpha A^{1/3})^n e^{-aA^{1/3}}}{n!} . \quad (12)$$

In the frames of such approximation the invariant cumulative proton and fragment production cross-sections can be presented in a form:

$$E\frac{d^3\sigma}{dp^3} \approx \sigma_{pA} N \sum_{n} F_n x f_n(x, \vec{p}_\perp). \tag{13}$$

Here $x = p_\parallel/(p_\parallel^{max})_{NN}$, where $p_\parallel$ is a longitudinal momentum of observable particle and $(p_\parallel^{max})_{NN}$ is the maximal value of this momentum for NN interaction. The lower summation limit in Eq. (13) is defined by kinematical limitations and equals the integer part of x. In (13) σ_{pA} is the cross-section of proton-nucleus interaction. We use the following expression [10] to determine it:

$$\sigma_{pA} = 44\, A^{0\ 69}\ \text{mb}. \tag{14}$$

It is the approximation of experimental data.

In (13) N is a number of nucleons-initiators. To determine it, one could use the concrete representation of multiparticle production process in the matter. Here, we choose another technique which allows us to get rather rough estimation of N, but it does not demand specification of the multiparticle process. For this purpose in the first approximation let us assume that: (a) the baryon subsystem can decay only in protons and single charged fragments, (b) there are the products of their decay and the recoil protons that have not produced subsystems, that is all g-particles observed in the experiment.

In accordance with these assumptions

$$\frac{z}{A} N \sum_{n=0}^{\infty} (n+1) F_n = \bar{n}_g. \tag{15}$$

Executing summation in (15) and solving it with respect to n_g, we obtain:

$$N = \frac{A}{z} \cdot \frac{\bar{n}_g}{\bar{n}+1}. \tag{16}$$

At the energy of primary hadron of about 10 GeV and more, the n_g value practically does not depend on energy. Based upon the data [9] the n_g dependence on A can be approximated by the expression

$$\bar{n}_g \approx 0.13\, A^{0.7}. \tag{17}$$

To describe the proton spectrum produced in the decay of baryon subsystem we use the longitudinal phase volume model [19] which is added to the exponential cutting dependent on transverse momentum.

In this approximation, the proton distribution in x and $p_\perp$ is presented in a form:

$$f_n(x, \vec{p}_\perp) = \frac{B^2}{2\pi}\, \varphi_n(x) e^{-Bp_\perp} \quad (B = 4\ \text{GeV}^{-1}c), \tag{18}$$

where

$$\varphi_n(x) = \int_0^1 dx' \psi(x') \xi_n(\eta), \tag{19}$$

and

$$\xi_n(\eta) = 2n(n+1)(2n+1)\eta(1-\eta)^{2n-1}. \tag{20}$$

Here η is a portion of subsystem energy taken away by nucleon. η is connected with the value x determined in the experiment by the relation:

$$\eta = \frac{x}{n+x'}. \tag{21}$$

In (19), $\psi(x')$ is the x distribution for recoil nucleons [20]:

$$\psi(x') = 1{:}5\, x^{0.5}. \tag{22}$$

To describe tritium and deuterium spectra we took into account only the decrease of the phase space scale:

$$\xi^{(d)}(\eta) = n(2n-2)(2n-1)\eta(1-\eta)^{2n-3}, \tag{23}$$

$$\xi^{(t)}(\eta) = (n-1)(2n-4)(2n-3)\eta(1-\eta)^{2n-5}. \tag{24}$$

Obviously, in this approximation we can describe these spectra to an accuracy of structure factors determining the possibility of nucleons to be produced in a bound state. Such an approximation is sufficient to define A-dependence for the cumulative fragment production cross-section.

3. Some consequences of the model

A number of the most inportant qualitative consequences of the model are defined by the circumstance that the A-dependence for each next term in the sum (13) differs from that for the preceding term by the factor $A^{1/3}$ (see (12)). As the lowest limit of summation in (13) increases by a unit with the increase of the fragment mass per one nucleon, the A-dependence for fragment production cross-section increases approximately by a factor $A^{1/3}$. Just the same dependence was obtained when analyzing the experimental data [4].

For the same reason the A-dependence of the cumulative proton production increases $A^{1/3}$ times when passing to each next degree of cumulativity. The data [3] are in agreement with this conclusion.

These regularities are the direct consequence of the fact that baryon subsystems are formed in the space intervals of about nucleus size.

Fig. 3 shows the results of the invariant cross-section calculation for proton production at 160° angle in system where protons interact with different nuclei.

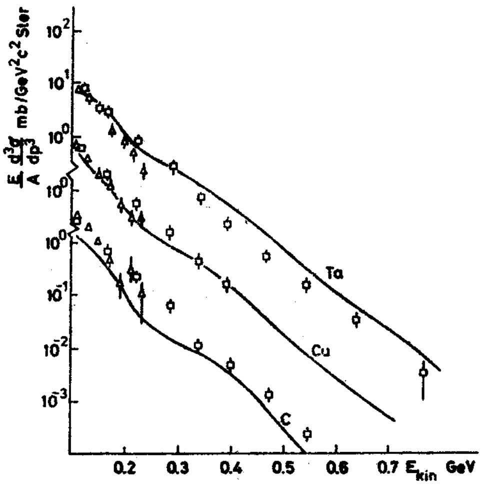

Fig. 3. The dependence of invariant cross-section of cumulative proton production in reaction $p+A \to p+X$ on kinetic energy. The angle of particle exit is 160° in the c.m.s. Experimental data are from Ref. [3] — (□) and [21] — (△). The curves result from the model calculation

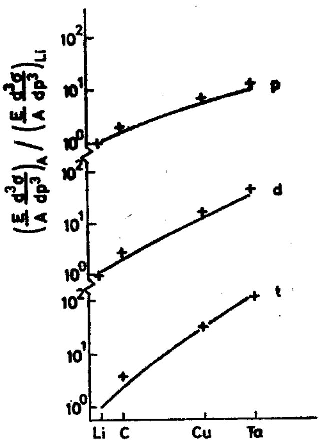

Fig. 4. The R-dependence on A for p ($E_k = 232$ MeV), d ($E_k = 100$ MeV) and t ($E_k = 90$ MeV), exit angle is 160° in the c.m.s. Experimental data are from Ref. [3]. The curves result from the model calculation

In calculation, parameter $a = 0.024$ is used in (12). Here, the experimental data obtained at two primary energies of 400 GeV and 9 GeV are presented [3, 21]. Comparison of experimental data with the results of calculation shows a qualitative agreement with the data. It should be noted that absolute values of model results for C and Ta deviate systematically from the experiment. We consider that the reason of these deviations is the absence in this rough model of an accounting of nonlinearity of the multiparticle production process development in nuclear matter [13] — its transverse spread which influences the range of nucleon-initiator path in nucleus. Such accounting should weaken slightly the A-dependence of value L in (11) and improve the agreement of curves in Fig. 3 with the experimental data. However, this accounting requires the concrete model of space-

-time development of production process in matter. But we seek to avoid such detailing on this stage of our consideration of the problem.

Fig. 4 demonstrates the A-dependence for the cross-section of cumulative proton and fragment production. The calculated curves correctly reproduce the increase of A-dependence with the increase of fragment mass.

4. Conclusion

The proposed model of the cumulative proton and fragment production is obviously very rough and it must be considered as a qualitative scheme. Based on this scheme one can formulate a more detailed description. This scheme seems to be quite vital as it is based on the realistic account of space-time factors of high energy particle interactions with nuclei, including the delay time intervals in hadron collisions when mixing of their colour degrees occurs.

Some of the features of this scheme have a technical character. For example, we may change the expressions (20), (23), (24) for a more exact calculation of phase-space volumes. Other specific features have not yet been solved. They arise when one attempts to describe successively the baryon subsystems passing through nuclear matter and also the collisions of such subsystems with each other. These difficulties are associated also with the problem of colour object interactions at large distances.

The inverse problem may be more productive. The aim is the get information about the character of such interactions from the experimental data on cumulative proton and light fragment production.

Our model contains one parameter in (12) which is defined by comparison with the experimental data. In principle, the value of this parameter may give an important information about σ^*, because in accordance with (10) and (11)

$$\sigma^* = \frac{a}{\varrho\kappa}. \tag{25}$$

But the precision of this information is restricted by rough approximations used in the model and by indeterminacy of value κ. The order of magnitude of κ can be estimated by the evident statement that the average path of initiating nucleon in nucleus (11) cannot be much more or much less than the nucleus radius

$$R \approx 1.2\,A^{1/3}. \tag{26}$$

Then, comparing (11) and (26) one can obtain that the order of κ magnitude is 1 fm. Substituting this value in (25) and taking into account $\varrho \simeq 0.14\ \mathrm{fm}^{-3}$ one obtains that the order of magnitude of σ^* is 1 mb. We consider this value as a low bound for σ^* because the more accurate calculation of phase-space volumes with accounting of particle mass finiteness would lead to necessity of increasing parameter a and consequently σ^*.

Authors are grateful to B. N. Kalinkin for useful discussions.

Editorial note. This article was proofread by the editors only, not by the authors.

REFERENCES

[1] A. M. Baldin, V. K. Bondarev, N. Ghiordanescu, A. N. Khrenov, A. G. Litvinenko, A. N. Manaytovsky, N. S. Moroz, Yu. A. Panebratsev, M. Pentia, S. V. Rikhvitsky, V. S. Stavinsky, Preprint JINR E2-82-472, Dubna 1982.

[2] N. A. Nikiforov, Y. D. Bayukov, V. I. Efremenko, G. A. Leksin, V. I. Tchistilin, Y. M. Zaitsev, S. Frankel, W. Frati, M. Gazzaly, C. F. Perdrisat, *Phys. Rev.* **C22**, 700 (1980).

[3] Y. D. Bayukov, V. I. Efremenko, S. Frankel, W. Frati, M. Gazzaly, G. A. Leksin, N. A. Nikiforov, C. F. Perdrisat, V. I. Tchistilin, Y. M. Zaitsev, *Phys. Rev.* **C20**, 764 (1979).

[4] V. S. Stavinsky, *Fiz. Elem. Chastits At. Yadra* **10**, 949 (1979).

[5] A. M. Baldin, V. K. Bondarev, Yu. A. Panebratsev, M. Pentia, A. G. Litvinenko, V. S. Stavinsky, Proc. 7th Intern. Sem. High Energy Phys. Problems, Dubna 1984, p. 195.

[6] M. I. Strikman, L. L. Frankfurt, *Fiz. Elem. Chastits At. Yadra* **11**, 571 (1980).

[7] V. K. Lukjanov, A. I. Titov, *Fiz. Elem. Chastits At. Yadra* **10**, 815 (1979).

[8] A. V. Efremov, *Fiz. Elem. Chastits At. Yadra* **13**, 613 (1982).

[9] S. A. Azimov, K. G. Gulamov, V. Sh. Navotny, V. I. Petrov, L. P. Chernova, *The Particle Interactions with Nuclei at High Energy*, Tashkent 1981, p. 3.

[10] V. S. Barashenkov, V. D. Toneev, *High Energy Particle and Nucleus Interactions with Nuclei*, Moscow 1972.

[11] B. N. Kalinkin, A. V. Cherbu, V. L. Shmonin, *Fortschr. Phys.* **28**, 35 (1980).

[12] E. S. Golubyatnikova, G. A. Shakhanova, V. L. Shmonin, *Acta Phys. Pol.* **B15**, 585 (1984).

[13] B. N. Kalinkin, V. L. Shmonin, *Fiz. Elem. Chastits At. Yadra* **11**, 630 (1980).

[14] V. S. Olkhovsky, *Fiz. Elem. Chastits At. Yadra* **15**, 289 (1984).

[15] S. M. Dorkin, B. L. Reznik, A. I. Titov, *Sov. J. Nucl. Phys.* **36**, 1244 (1982).

[16] Yu. F. Gagarin, B. N. Kalinkin, V. A. Lukin, E. A. Yakubovsky, Preprint PTI N939, Leningrad 1981.

[17] Yu. F. Gagarin, N. S. Ivanova, V. A. Lukin, E. A. Yakubovsky, Preprint PTI N954, Leningrad 1985.

[18] K. Izumo, H. Araseki, *Prog. Theor. Phys.* **69**, 158 (1983).

[19] G. Berlad, A. Dar, G. Rilam, Preprint Technion — Israel Institute of Technology, Technion-PH-79-71, Haifa 1979.

[20] G. V. Alaverdyan, A. V. Tarasov, V. V. Uzhinsky, *Sov. J. Nucl. Phys.* **25**, 666 (1977).

[21] Yu. D. Bayukov, V. B. Gavrilov, N. A. Goryainov, Yu. G. Grishuk, O. B. Gushchin, P. V. Degtyarenko, N. L. Kornenko, G. A. Leksin, V. B. Fedorov, B. B. Shvartsman, S. V. Shevchenko, S. M. Shuvalov, Preprint ITEP N148, Moscow 1983; Preprint ITEP N143, Moscow 1984.