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Cumulative protons in hadron-nucleus and nucleus-nucleus interactions

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New experimental data on the formation of cumulative protons in hadron-nucleus and nucleus-nucleus collisions in the range of 3-300 GeV are presented. It was found that the average multiplicity of cumulative protons and share of cumulative events for the same fragmenting nucleus do not depend on the energy and the mass number of the projectile.

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An investigation of the processes of cumulative production of hadrons, emitted into the kinematically forbidden region of collision of free nucleons in the hadron-nucleus and nucleus-nucleus interactions, can provide information about the mechanisms of nuclear interaction and the details of nuclear structure at small distances.

In the pioneering work, where cumulative effect was observed experimentally, it was studied the reaction

$$d + Cu \rightarrow \pi^- + X$$

at the momentum of 10 GeV/c with the formation of π^- - mesons which have zero emission angles [1]. Here it was revealed the formation of negative pions with energies much higher than the energy per nucleon of deuteron. Since then, one can see an impressive number of papers (see eg., Reviews [2-7]), devoted to the study of these processes. Investigation of regularities of production for cumulative particles has lead to the hypothesis of the limiting fragmentation of nuclei ("nuclear scaling") [8]. For the interpretation of formation of cumulative protons in the nuclear reactions, A.M. Baldin hypothesized [9] that their appearance occurs due to the interaction of the incident particle with a few-nucleon nuclear association ("fluctons"). He also offered two scenarios of appearance fluctons in nuclei. They are a "cold" scenario, in which they arise in the ground state of the nucleus due to the fluctuation of the nucleon density, and a "hot" scenario where they arise because of convergence of nucleons with each other at a distance less than 1 fm under the influence of the incident particle. Experimental verification for the feasibility of these scenarios can be carried out in the investigation of formation of cumulative protons in the interaction of different types of primary particles and nuclei with nuclei with the same mass number.

The present work is devoted to the study of formation of cumulative protons in order to determine the preference of mentioned scenarios of their formation in the ^{16}Op interactions at 3.25 GeV/c, in the $\pi^- C$ collisions at 40 GeV/c, in pC interactions at 4.2 and 9.9 GeV/c, in ^4HeC- and CC-collisions at 4.2 GeV/c, as well as in pNe interactions at 300 GeV/c.

Experimental data for π^- C, pC, ^{4}NeC- and CC-collisions obtained by 2 metres propane bubble chamber LHE JINR (Dubna), ^{16}Op collisions, obtained by 1 m hydrogen bubble chamber LHE JINR (Dubna), and data on pNe interactions, obtained by the 30-inch neon-hydrogen bubble chamber, irradiated by a proton beam, accelerated in Fermi National accelerator Laboratory (Batavia). General statistics of experimental data includes more than 93,000 events, measured in full 4π-geometry.

It is considered that the cumulative are the protons, flying to the rear hemisphere with parameter $\beta \geq 1.2$, where $\beta = (E - Pcos\theta)/m_n$ (E is total energy, P is total momentum, θ is a proton emission angle, m_n is a nucleon mass). The lower limit for the cutoff in the momentum is associated with the need to exclude the evaporated protons, which appear much later of the act of interaction in the process of thermalization of the residual nucleus. This boundary is different for different mass of the fragmenting nuclei. For the carbon nucleus the upper limit of the Fermi momenta is 0.2 GeV/c for oxygen and it is 0.22 GeV/c for neon.

As an example, Fig.1 shows the inclusive cross sections for protons as a function of the cumulative number of β for $\beta > 1.2$ in the CC- and π^-C collisions at the momentum of 4.2 A GeV/c and 40 GeV/c, respectively, and in Fig.2 they are given the invariant structural functions for pNe

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interactions at 300 GeV/c and for ^{16}Op collisions at 3.25 A GeV/c; the straight lines show the results of fitting of the experimental data by the function

$$f(\beta) = a\, e^{-b\beta} \quad . \tag{1}$$

The results of the approximation of the experimental data for the distribution of protons on the number of β in accordance with the expression, as well as the average multiplicity of cumulative protons are shown in Table.1.

It is seen that the values of slope parameter b within the statistical errors coincide for all considered types of collisions and primary energies. The average value of b in all the ensemble in question is 8.1 ± 0.1.

It is interesting to note that not only invariant inclusive cross sections for the production of cumulative protons with dependence on the cumulative number of β have an exponential law, but also the distribution of protons on β have the same character.

Thus, we can conclude that the mechanism of formation of cumulative protons does not depend on the type of projectile or the primary energy

The average multiplicity of cumulative protons in cumulative ^{16}Op- and p^{20}Ne-events turned out to be 1.11 ± 0.02 and 1.16 ± 0.3, respectively, while in the interactions of π^--mesons, protons, α-particles and carbon nuclei with carbon nuclei (regardless of the type of incident particle) this value is 1.05 ± 0.01. Preliminary analysis of formation of cumulative protons in ^{12}C^{181}Ta collisions at 4.2 A GeV/c gave the value to the average multiplicity, in cumulative events, equals to 1.80 ± 0.06. Thus, in the cumulative events, the average multiplicity of cumulative protons increases slightly with increasing mass of the fragmenting nucleus and does not depend on the primary energy.

To study the A-dependences of the average multiplicity of cumulative protons we approximated it by the expression:

$$\langle n_{cum} \rangle = a + A^{\alpha} \quad ,$$

where A is the mass number of the fragmenting nucleus, a and α are the fitting parameters. Approximation of the experimental data gave a value of $a = -0.41 \pm 0.01$ and $\alpha = 0.15 \pm 0.01$ at a confidence level of more than 99 %. However, if the average multiplicity of cumulative protons is approximated by a function

$$\langle n_{cum} \rangle = a + Z^{\alpha}$$

on the number of protons (on the atomic number of Z) of the fragmenting nucleus, the parameter values are found to be $a = -0.32 \pm 0.01$ and $\alpha = 0.17 \pm 0.01$ also with a confidence level of more than 99 %. It is interesting to note that in both approximations, the values of the exponents are close to the value of 1.6, significantly different from the value of 2.3, which is characteristic for the A-dependence of mean multiplicities of all protons.

Formation of cumulative protons related to the number of fluctuations of the nuclear density, which in turn is proportional to the variance of the average multiplicity. Inside the target nucleus incident particle cuts out the "tube" having a size A$^{1/3}$. Within this "tube" the number of such fluctuations will be proportional to $\langle n \rangle^{1/2}$, and the average number of cumulative protons will be

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proportional to $A^{1/6}$. Thus, investigation of *A*-dependence of production of cumulative protons allows us to obtain a conclusion concerning the real scenario of their origin. In this case, the character of *A*-dependence confirms the scenario of a "cold" formation, based on the existence of fluctons.

In the discussed above ensembles of experimental data, it was defined the part of cumulative events (with the formation of cumulative protons) listed in Table. 2.

In Table. 2, along with the characteristics of the experimental material, it is given the fraction of number of events with the formation of cumulative protons in these collisions. An intriguing feature of these data is two things. Firstly, the share of cumulative events is independent of the mass of the incident particle (proton or nucleus). Secondly, there is an indication of the sensitivity of the share of number of cumulative events to the type of the incident particle (it is pion or system of baryons).

The first circumstance indicates on the possibility of combining the number of events with a cumulative proton in different ensembles of data for calculation of their average share for baryon systems (for $p^{12}C$-, $\alpha^{12}C$- and $^{12}C^{12}C$-collisions). In our case this value is $10.0 \pm 0.1\%$.

The independence of share of number of events with cumulative proton on the size of the incident baryon system may indicate the dominant role for single interaction of the incident particles with fluctons, the number of which, in accordance with the "cold" model, are unchanged in this case (the same target nucleus). Since the interaction of colliding objects is single, then its characteristics will be influenced by the properties of the primary particles (such as quark composition). It is interesting in this context to consider the ratio of the shares of number of cumulative events for the pion and baryon systems. It is easy to see that this ratio is 0.66 ± 0.02. The ratio of these shares for πC- and pC-collision is 2/3, reflecting the ratio of the number of valence quarks in the incident particle and, possibly, pointing to the realization of cumulative processes at the quark-parton level, that is , 2/3, which in turn coincides with the ratio of the number of valence quarks of the pion and proton.

Thus, at the study of *A*-dependence of shares of number of cumulative events, the following interesting regularities was obtained.

The share of cumulative events for the same fragmenting nucleus (in this case the carbon nucleus) was independent of the energy and mass number of the projectile (p, α, C) and was $10.0 \pm 0.1\%$. It proved to be sensitive to the type of incident particle (π, p) and amounted to $6.6 \pm 0.3\%$ for π^-C collisions. In favour of the script of "cold" production of cumulative protons there is the independence of share of number of cumulative events on type of the incident particle or nucleus, and also the independence of the average multiplicity of cumulative protons of target nucleus (with the same mass number) on the type of incident particle or nucleus.

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Figure captions

Fig. 1. Inclusive cross sections for protons as a function of the cumulative number of β for π^-C- and CC- collisions at 40 GeV/c (•) and 4.2A GeV/c (○), respectively . Straight lines are the results of approximation of experimental data by (1).

Fig. 2. Invariant structure function of cumulative protons depending on the cumulative number of β for $p^{20}Ne$- (•) and ^{16}Op - (■) collisions . Straight lines are the results of approximation of experimental data by (1).

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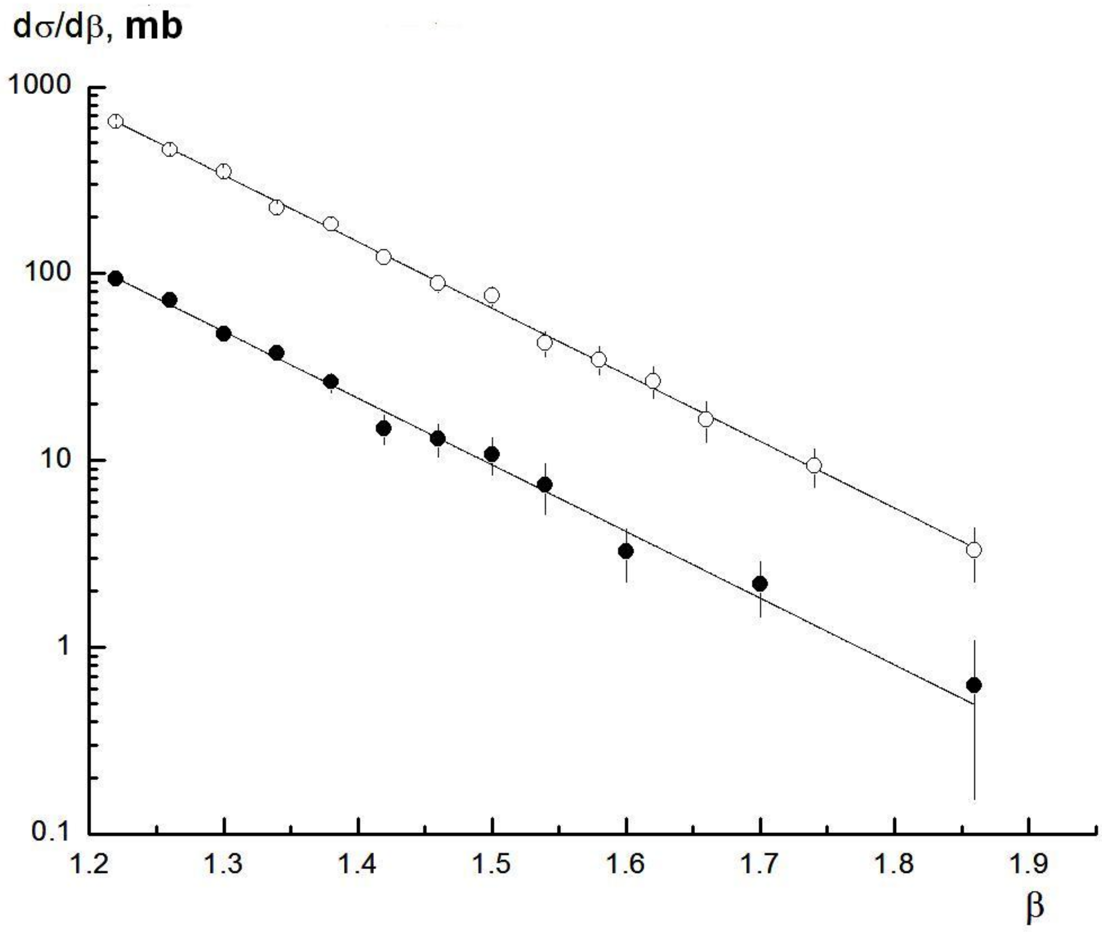

Figure 1:

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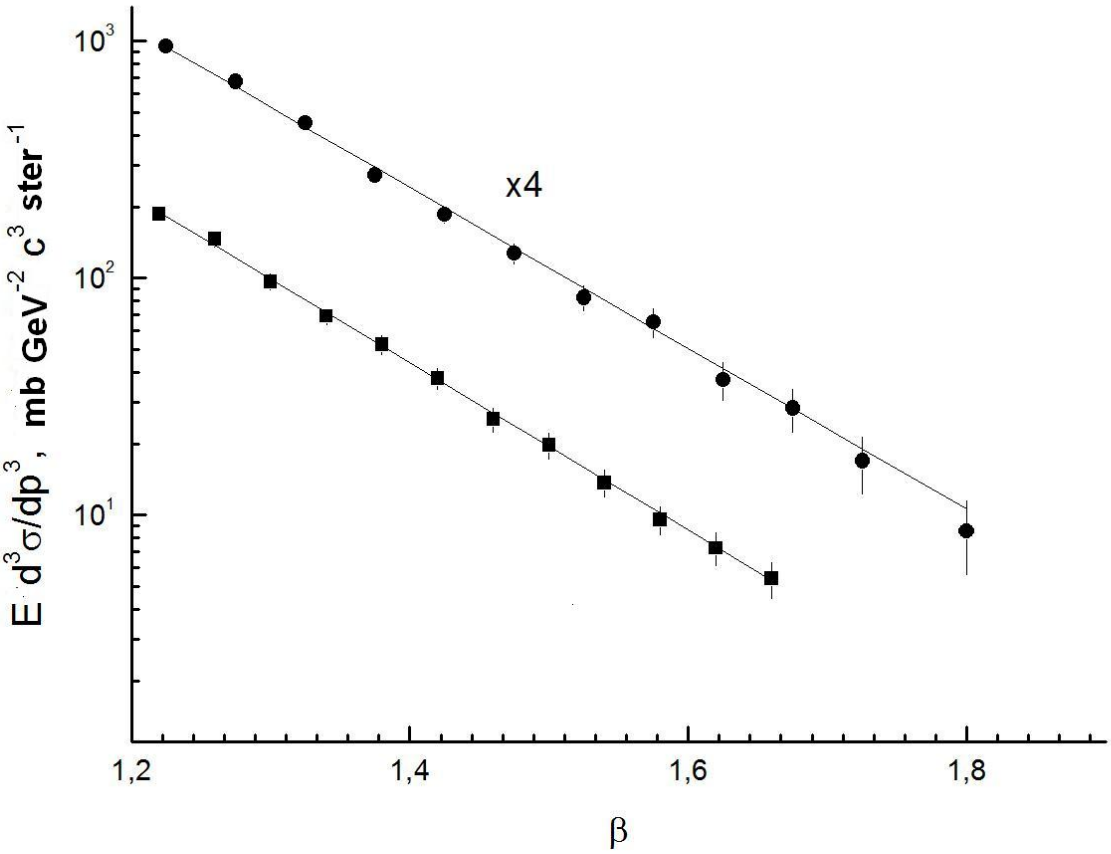

Figure 2:

Table 1: Slope parameters in the parameterization (1), the type of collision, the number of events and the average multiplicity of cumulative protons

Type of interaction, P_o(GeV/c)	The number of events	Slope parameter,b	χ^2/num.degr.freed.	The average number of cumulative protons
π^{12}C, 40.0	16657	8.18 ± 0.26	1.1	1.06 ± 0.03
p^{12}C, 4.2	6901	8.09 ± 0.49	1.0	1.04 ± 0.03
p^{12}C, 9.9	18325	8.10 ± 0.25	0.9	1.06 ± 0.03
^{4}He^{12}C, 4.2 A	12326	8.00 ± 0.28	1.2	1.06 ± 0.05
^{12}C^{12}C, 4.2 A	20530	8.14 ± 0.20	0.4	1.05 ± 0.04
^{16}Op, 3.25 A	12367	8.13 ± 0.21	0.4	1.11 ± 0.02
p^{20}Ne, 300	4990	7.99 ± 0.18	0.8	1.16 ± 0.03

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Table 2: The fraction of number of events with a cumulative proton as a function of the type of incident particle and the target nucleus

The type of interaction, P_o(GeV/c)	The total number of events	The number of events with cumulative proton	The share of events with cumulative proton, %
π^{12}C, 40.0	16657	1097	6.6 ± 0.2
p^{12}C, 4.2	6901	699	10.1 ± 0.4
p^{12}C, 9.9	18325	1825	10.0 ± 0.2
^{4}He^{12}C, 4.2 A	12326	1211	9.8 ± 0.3
^{12}C^{12}C, 4.2 A	20530	2070	10.1 ± 0.2
^{16}Op, 3.25 A	12367	1496	12.1 ± 0.4
p^{20}Ne, 300	4990	728	14.6 ± 0.6
^{12}C^{181}Ta, 4.2 A	2440	1013	41.5 ± 1.5

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