PRODUCTION OF CUMULATIVE PROTONS AT HIGH-ENERGY ^{16}Op- AND p^{20}Ne-COLLISIONS

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Under 4π-geometry conditions and using a large statistical body of events, the production of cumulative protons at high-energy ^{16}Op- and p^{20}Ne-collisions has been studied for the first time. A weak increase of the average multiplicity of cumulative protons and a substantial growth of the fraction of cumulative events as the mass number of fragmenting nucleus becomes larger have been established.

1. Introduction

The study of the production of cumulative particles at hadron–nucleus and nucleus–nucleus collisions, which was predicted by A.M. Baldin [1] and experimentally discovered by Stavinsky in the early 1970s [2], has stimulated both a number of experimental researches and the development of theoretical approaches based on various assumptions concerning the existence of intranuclear quasiparticles (fluctons), whose mass exceeds the nucleonic one. According to those key assumptions, the available model approaches can be conventionally divided as "cold" [3] and "hot" models [4, 5]. The latter group includes, besides other models, quark-parton approaches which are developed successfully [6, 7] and provoke experimental researches of the new features of cumulative processes.

In this work, we continue our regular study of the production of cumulative particles at hadron–nucleus interactions. Earlier [8, 9], we studied the production of cumulative protons at interactions of π-mesons, protons, α-particles, and carbon nuclei with carbon nuclei in the initial energy interval 4–40 GeV. In those works, on the basis of a rather large statistical material, we have confirmed a universal regularity that the slope parameter of the invariant inclusive cross-sections of the given interactions at the cumulative number β is independent of the initial energy and the mass of a bombarding particle or nucleus. It is also of interest that the fractions of events with cumulative protons produced at a carbon nucleus are sensitive to the type of a bombarding particle (a pion or a system of baryons), but do not depend on the mass number of a bombarding particle with the mass $M \geq M_p$ (a proton or a nucleus). The average multiplicity of cumulative protons was also found to be dependent neither on the type of a bombarding hadron or nucleus nor on its initial energy. However, the dependence of cumulative events on the mass number of a fragmenting nucleus remained to be unstudied, although its behavior could allow the physical picture of cumulative processes to be specified.

This work is devoted to studying the production of cumulative protons at ^{16}Op-collisions at 3.25A GeV/c and p^{20}Ne-interactions at 300 GeV/c. It reports also the first results concerning the correlations between the yield of cumulative protons and the multiplicity of multicharged fragments in ^{16}Op-interactions.

The analyzed experimental material on ^{16}Op-collisions at 3.25A GeV/c – 12367 measured inelastic ^{16}Op-events – was obtained with the help of a 1-m hydrogen bubble chamber at the Laboratory of High Energies (the Joint Institute for Nuclear Research, Dubna, Russia), irradiated by relativistic oxygen nuclei produced by a Dubna synchrophasotron. The fragments with the measured track length $L > 35$ cm were selected for the analysis, which provided the reliable identification of fragments by their masses. Provided such a restriction on the track length, the mean relative error of momentum determination did not exceed 3.4% for every fragment.

For the ultimate identification of fragments by mass, the following momentum intervals were introduced: single-charged fragments with $p = 4.75 - 7.8$ GeV/c were classified as ^{2}H, and those with $p > 7.8$ GeV/c as ^{3}H; double-charged fragments with $p < 10.8$ GeV/c were classified as ^{3}He, and those with $p > 10.8$ GeV/c as ^{4}He. Provided such an identification of fragments, the admixture of isotopes close by mass, obtained owing to the overlapping of their momenta, did not exceed 3–4%. Positive single-charged relativistic particles with momenta 1.75 GeV/c<p<4.75 GeV/c were classified as protons. This selection of protons allowed the admixture of π^+-mesons to be neglected. For multicharged fragments with charges $Z_f \geq 3$, the lengths of their tracks were not restricted, because their identification by mass was not carried on. While determining the average multiplicities of single- and double-charged fragments, the losses of those fragments at the distance $L < 35$ cm, owing to their interaction with working liquid (hydrogen) in the chamber, were taken into account. Other methodical features of the experiment are reported in our works [10–12]. All characteristics of protons were studied in the antilaboratory coordinate system (ALCS), i.e. in the oxygen-nucleus rest system. The statistics of the analyzed material for ^{16}Op-collisions comprised 12367 measured inelastic events.

The experimental data on p^{20}Ne-interactions at 300 GeV/c were obtained with the help of a 30-inch bubble chamber irradiated by a diffraction beam of protons with a momentum of 300 GeV/c produced by an accelerator at the Fermi National Accelerator Laboratory (Batavia) and consist of 4990 measured inelastic events. The bubble chamber was filled with a neon-hydrogen mixture (^{20}NeH$_2$), with the molar fraction of neon amounting to (30.9 ± 0.7)%. Protons and π^+-mesons in the momentum range $p \leq 1.25$ GeV/c were distinguished visually. The lower momentum limit for registered protons was determined by the minimal track length ($L > 2$ mm) and was equal to 0.11 GeV/c. Other issues dealing with the treatment of stereograms obtained on the 30-inch bubble chamber and the routines of plate scanning, measuring and restoring the kinematic characteristics of secondary particles are expounded in works [13, 14] in detail.

2. Experimental Results and Their Discussion

As cumulative were considered protons that flied into the back hemisphere, had the momentum $p >$ 0.22 GeV/c (i.e. evaporated protons were excluded), and were characterized by the parameter $\beta = (E - p\cos\vartheta)/m_n \geq 1.2$, E is the total energy of the proton, p its total momentum, ϑ its output angle, and m_n the mass of nucleon, which was taken to be equal to that of proton. Effectively, the value of the parameter β is an expected dimension of the target (a nucleon association) expressed in the units of nucleon mass.

Figure 1 exhibits the dependences of the invariant inclusive cross-sections of the production of cumulative protons on β for ^{16}Op-collisions at 3.25 GeV/c and for p^{20}Ne-interactions at 300 GeV/c. To enhance the visualization, the data on p^{20}Ne-collisions were multiplied by 4. The straight lines correspond to the results of approximations of experimental data by the

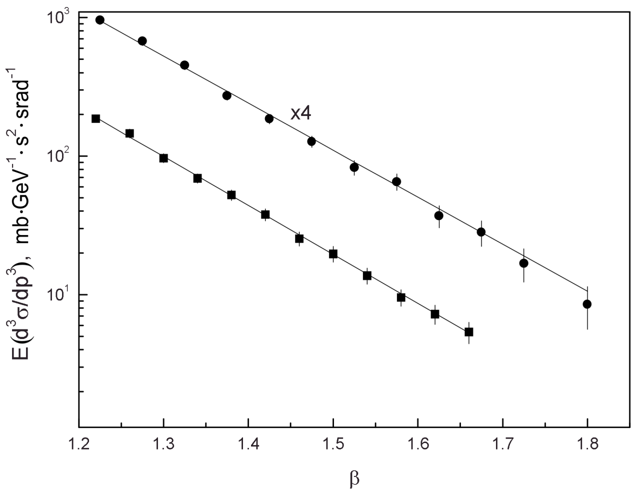

Fig. 1. Dependences of the invariant structural function of cumulative protons on the index of cumulativity β for p^{20}Ne- (●) and ^{16}Op- (■) collisions at high energies. The straight lines correspond to the results of approximation of experimental data by dependence (1)

dependence

$$f(\beta) = a\exp(-b\beta). \quad (1)$$

In the case of ^{16}Op-collisions, the best approximation of experimental data by function (1) was achieved for the parameter values $a = 3876134 \pm 999549$ and $b = 8.13 \pm 0.21$ ($\chi^2 = 3.8$, provided that the number of the degrees of freedom equals 10), while for p^{20}Ne-interactions, it occurred for $a = 17196526 \pm 3737945$ and $b = 7.99 \pm 0.18$ ($\chi^2 = 3.8$, provided the same number of the degrees of freedom). The coincidence of the values of the slope parameter b for ^{16}Op- and p^{20}Ne-interactions evidences for its dependence on neither the initial energy nor the mass of the fragmenting nucleus. Note that the value of the parameter b also coincides with the values obtained earlier for the interactions of π^--mesons, protons, α-particles, and carbon nuclei with carbon nuclei in the initial energy range $4 - 40$ GeV (8.1 ± 0.1) [8] and for pTa-collisions at 10 GeV/c (8.3 ± 0.7) [15].

Thus, it is possible to make conclusion that the value of the slope parameter of the invariant structural function of cumulative protons remains constant (with an accuracy of 2–3%) in a wide interval of initial energies β (3–300 GeV) and in the mass range of fragmenting nuclei, and amounts to 8.1 ± 0.1 on the average, which differs, within the limits of nine-fold errors, from the universal constant $b_0 = 7.1$ [16].

The average multiplicities of cumulative protons in cumulative ^{16}Op- and p^{20}Ne-events turned out equal to 1.11 ± 0.02 and 1.16 ± 0.3, respectively. Whereas, in the interactions of π^--mesons, protons, α-particles, and carbon nuclei with carbon nuclei (irrespective of the type of a bombarding particle), this value is equal to 1.05 ± 0.01. Thus, the average multiplicity of cumulative protons in cumulative events weakly grows with increase in the mass number of fragmenting nucleus.

The fractions of cumulative events in ^{16}Op- and p^{20}Ne-collisions turned out equal to (12.1 ± 0.2)% and (14.6 ± 0.4)%, respectively. For the interactions of protons, α-particles, and carbon nuclei with carbon nuclei, this quantity amounts to (10.0 ± 0.1)% [9]. These data testify that the fraction of cumulative events considerably increases with the mass number of a fragmenting nucleus A, pointing at the growth of the probability for the production of fluctons with the mass number A.

It is of interest to study the correlation between cumulative protons and particles of other types, as well as fragments. In the Table, the average multiplicities for various types of particles and fragments in events with and without production of cumulative protons, but with a number of created protons $n_p > 1$, are listed. The latter criterion for events "without cumulative protons" is necessary to provide the identical conditions of selection in these two classes of events, because, in cumulative events, at least one proton is formed. One can see that the average multiplicity of fragments with charges ranging from 1 to 3 is higher for cumulative rather than non-cumulative events. The average multiplicity of fragments with charges 4 and 5 does not depend on the presence of a cumulative proton in the event within the limits of statistical errors. The average multiplicity of fragments with charges 6 and 7 is lower for events with production of cumulative protons. All that together may probably indicate that the initial nucleus becomes more excited in the processes with cumulative protons production than without it. Naturally, the increase of the average multiplicity of fragments with $z_f \leq 3$, owing to the conservation laws of electric charge and baryon number, gives rise to a reduction of the average multiplicities of other multicharged nuclei with $Z_f = 6$ and 7.

An especially strong negative correlation was observed for fragments with charge 7. Events with the production of a nitrogen nucleus and a cumulative proton are mainly realized through the recharge of one or more neutrons of the projectile into a proton and a π^--meson. Probably, this mechanism is confirmed as well by the growth of the average multiplicity of π^--mesons (by a factor of about 1.4) in the events with production of cumulative protons in comparison with the events without production of such protons. The average multiplicity of π^+-mesons does not depend on the availability of a cumulative proton in the event within the limits of statistical errors.

It is interesting to study the dependence of the average multiplicities of secondary particles and fragments on the cumulative number β. In Fig. 2,*a*, the average multiplicities for non-cumulative protons, deuterons, π^+- and π^--mesons are depicted; in Fig. 2,*b*, exhibited are the average multiplicities for ^{4}He nuclei and nuclei with $Z_f \geq 3$, as well as the total average multiplicity for ^{3}He and ^{3}H nuclei. These figures make it evident that the average multiplicities of considered particles do not depend on the parameter β of the cumulative proton within the limits of statistical errors. Qualitatively, the same result for the average multiplicity of charged pions and non-cumulative protons has been obtained in work [15] as well.

Thus, one may conclude that the dependence of the invariant inclusive cross-sections of the production of cumulative protons on the cumulative number β is characterized by a universal regularity which consists in the dependence of the slope parameter on neither the initial energy, nor the type of a bombarding particle, nor the mass of fragmenting nucleus. The average multiplicities of secondary particles and fragments correlate with the yield of a cumulative proton, but, within the limits of statistical errors, do not depend on the parameter of proton cumulativity. It should be noted that these correlations have a kinematic character and do not point at the relation between the mechanisms of production of cumulative protons and other particles and fragments.

Average multiplicities for various types of particles and nuclei in events with and without production of cumulative protons, provided $n_p > 1$

Type of the particle or fragment	$n_{\rm cum} = 0$	$n_{\rm cum} \geq 1$
π^-	0.329±0.006	0.442±0.016
π^+	0.480±0.007	0.470±0.018
^{1}H	2.00±0.02	3.23±0.04
^{2}H	0.360±.0.008	0.588±0.0023
^{3}H	0.138±0.004	0.243±0.014
^{3}He	0.136±0.004	0.210±0.013
^{4}He	0.614±0.011	0.705±0.024
Z_f=3	0.090±0.003	0.118±0.010
Z_f=4	0.049±0.002	0.052±0.006
Z_f=5	0.086±0.003	0.081±0.008
Z_f=6	0.212±0.005	0.115±0.009
Z_f=7	0.194±0.005	0.041±0.005

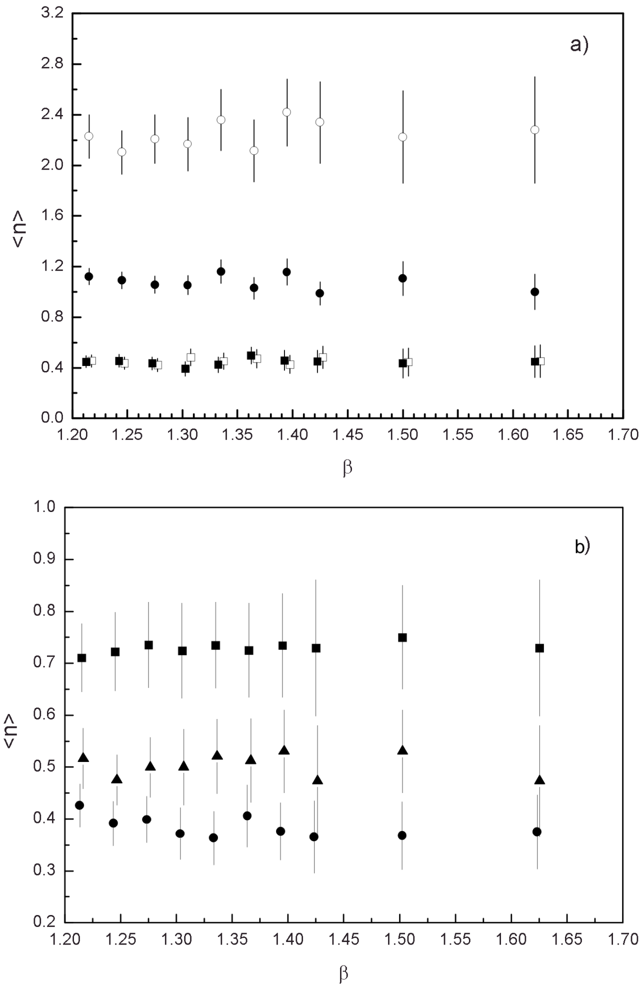

Fig. 2 (a) Dependences of the average multiplicities of noncumulative protons (○), deuterons (●), π^+-mesons (□), and π^--mesons (■) on the cumulative number β (here, to improve the data presentation, points ● are shifted upwards by 0.5). (b) The same as in panel a, but for nuclei-fragments $^4He_2$ (■), nuclei with $z > 3$ (▲), and the combined group of three-nucleon nuclei $^3He_2$ and $^3H_1$ (●)

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СТВОРЕННЯ КУМУЛЯТИВНИХ ПРОТОНІВ У ^{16}Op- І p^{20}Ne-ЗІТКНЕННЯХ ПРИ ВИСОКИХ ЕНЕРГІЯХ

Е.Х. Базаров

Р е з ю м е

Вперше в умовах 4π-геометрії на великій статистиці досліджено процеси утворення кумулятивних протонів у ^{16}Op- та p^{20}Ne-співударах при високих енергіях. Виявлено слабке збільшення середньої множинності кумулятивних протонів, а також значне зростання частки кумулятивних подій зі збільшенням масового числа фрагментуючого ядра.