PRODUCTION OF CUMULATIVE ^{3}H NUCLEI IN COLLISIONS OF OXYGEN NUCLEI WITH PROTONS AT A MOMENTUM OF 3.25 GEV/c PER NUCLEON

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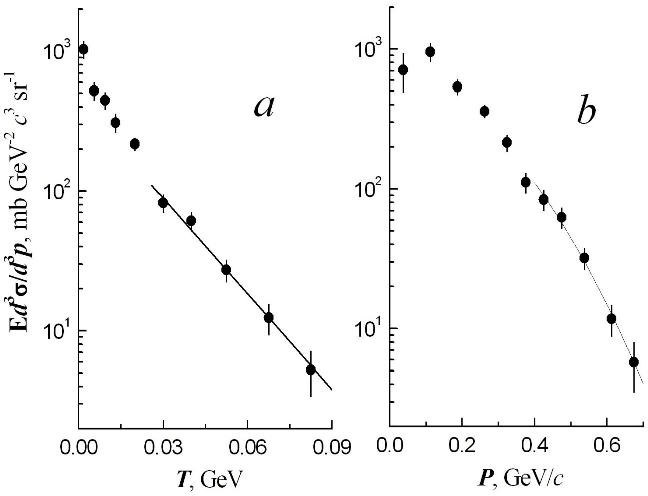
The production of cumulative ^{3}H nuclei in ^{16}Op-collisions at a momentum of 3.25 GeV/c per nucleon are studied for the first time under the conditions of 4π-geometry. We determined the slope parameters of invariant cross sections for cumulative ^{3}H nuclei and obtained new data on correlations of the escape of cumulative ^{3}H nuclei and charged particles and fragments in ^{16}Op-interactions. Noticeable differences between the characteristics of cumulative and non-cumulative events are revealed.

1. Introduction

The study of the processes of cumulative production of hadrons and light fragments escaping at large angles in hadron-nucleus interactions and collisions of relativistic nuclei represents an urgent problem aimed at obtaining the important information on mechanisms of the nuclear interaction and details of a nuclear structure at small distances along with the information on manifestations of quark degrees of freedom in nuclei. Systematic investigations of cumulative processes were initiated by Baldin [1] in 1971, while the cumulative effect was experimentally discovered by the group led by Stavinskii at the LHE JINR (Laboratory of High Energies of the Joint Institute for Nuclear Research, Dubna) synchrophasotron in the reaction ^{2}H(10 GeV/c) + Cu $\rightarrow \pi^-(0^\circ) + X$[2], in which pions with the energy considerably exceeding that per nucleon of a deuteron were observed. The first experimental indications of unusual phenomena in the processes of hadron-nucleus interactions were the results on the elastic pd-scattering of 660-MeV protons [3] and quasielastic knock-out of deuterons from light nuclei by a 675-MeV proton beam [4]. A great number of works cited in reviews [5–10] are devoted to investigations of these processes. The basic regularities of the production of cumulative particles allowed Leksin to formulate the hypothesis of limiting fragmentation of nuclei (nuclear scaling) [11] that was tested for a wide range of primary energies and mass numbers of fragmenting nuclei. However, the majority of works on cumulative processes available in the literature (see, e.g., [10]) are devoted to the investigation of the production of cumulative nucleons (mainly protons), deuterons, and mesons (mainly pions and kaons). At the same time, there is much less information on the cumulative production of light fragments with $A > 2$, and, as far as we know, no correlations of the escape of light cumulative nuclei and accompanying particles and nuclei were analyzed. Meanwhile, there are a lot of works [12–24] devoted to correlations in the processes with the production of cumulative nucleons and pions.

The recent work [25] deals with the investigation of the cumulative production of nucleons and light fragments (d, ^{3}H, and ^{3}He) in ^{4}Hep-interactions at a momentum of 5 GeV/c. In this work, the invariant cross sections for the production of protons, neutrons, and light nuclei d, ^{3}H, and ^{3}He escaping to the backward half-sphere in the ^{4}He nucleus rest-frame were determined in the 4π-geometry, and the slopes of their spectra in the cumulative region (the so-called temperature) were obtained. The spectra of the invariant cross sections of cumulative nuclei d, ^{3}H, and ^{3}He were in a good agreement with the predictions of the nuclear fusion model, and it was established that the radii of the fusion region in the ^{4}Hep-interactions are mainly determined by the radius of the escaping fragment [25]. It is worth noting that the



Invariant cross sections $Ed^3\sigma/d^3p$ (•) of ^{3}H nuclei escaping to the backward half-sphere ($\vartheta_{\rm alab} > 90°$) depending on their kinetic energy (*a*) and total momentum (*b*) in the rest-frame of the oxygen nucleus. Solid curves – results of the approximation of the experimental data in the region $T > 26$ MeV by the function $f = A_0 \exp(-T/T_0)$ (*a*) and in the region $P > 383$ MeV/c by the function $f = A_0 \exp(-B_0 \cdot P^2)$ (*b*)

slope parameters of cumulative ^{3}H and ^{3}He nuclei [25] produced in ^{4}Hep-interactions at a momentum of 5 GeV/c coincided within error limits.

The present work continues the cycle of our investigations [26–29] of the production of cumulative particles in hadron- and nucleus-nucleus collisions at high energies. It is devoted to the researches of the production of cumulative ^{3}H nuclei in ^{16}Op-interactions at a momentum of 3.25 GeV/c per nucleon. We analyze the spectra of invariant cross sections of cumulative ^{3}H nuclei and also present new results on correlations of the escape of cumulative tritium nuclei and charged particles and fragments in ^{16}Op-collisions.

The experimental material was obtained with the help of a 1-meter hydrogen bubble chamber (the LHE of JINR) irradiated with relativistic ^{16}O nuclei at the Dubna synchrophasotron. The data of the given work are based upon the analysis of 8712 completely measured ^{16}Op-events at a momentum of 3.25 GeV/c per nucleon. The target homogeneity and a low density of the working liquid of the chamber allowed us to unambiguously identify the charges of all secondary fragments and to measure their momenta to a high accuracy. In the given experiment, we use a beam of nuclei falling on a target-proton. In this case, the produced cumulative particle or a nucleus is fast in the chamber rest-frame, and the efficiency of its registration is close to 100%. We considered single- and double-charge fragments with the lengths of their tracks in the working volume of the chamber exceeding $L = 35$ cm. In the case of such a selection, the mean relative error in the determination of the momenta of such fragments does not exceed 3.5%. When determining the mean multiplicities, we took into account the corrections for fragment losses due to the interaction with the working liquid of the chamber at the length $L \leq 35$ cm. In the case of fragments with charges $z \geq 3$, their track lengths were not restrained in such a way, as we did not identify their masses. It is worth noting that, among the whole experimental material, we did not register any event with the total charge of multicharged fragments (with $z \geq 2$) exceeding the charge of the fragmenting oxygen nucleus.

As protons-fragments and deuterium and tritium nuclei, we accepted positive single-charged particles in the range of momenta in the laboratory system of coordinates $p = 1.75$–4.75 GeV/c, p=4.75–7.75 GeV/c, and $p \geq 7.75$ GeV/c, respectively. Such a selection with respect to the momentum range allows one to identify isotopes of single-charged fragments with the probability ≥96%. Doubly charged fragments with the momentum $p < 10.75$ GeV/c were considered as ^{3}He nuclei, while those with the momentum $p \geq 10.75$ GeV/c – as ^{4}He ones. In this case, admixtures of ^{3}He and ^{6}He nuclei with respect to ^{4}He ones do not exceed 4% and 0.5%, respectively. The methodical peculiarities of the experiment are reported in more details in [30–32]. The inelastic cross section of ^{16}Op-collisions at a momentum of 3.25 GeV/c per nucleon determined according to the standard technique appeared to be equal to 334 ± 6 mb [32].

2. Experimental Data and Their Discussion

Figure,*a* presents the experimental invariant cross sections $f(T) = Ed^3\sigma/d^3p$ for ^{3}H nuclei escaping to the backward half-sphere ($\vartheta_{\rm alab} > 90°$) depending on their kinetic energy in the rest-frame of the oxygen nucleus in ^{16}Op-collisions at a momentum of 3.25 GeV/c per nucleon. As one can see from Figure,*a*, the spectrum of the invariant cross section of ^{3}H nuclei contains, on the whole, two regions with different shapes of the spectrum: $T < T_c$ – spectator region and $T > T_c$ – cumulative one. Differentiating the spectrum of the invariant cross section of ^{3}H nuclei, we determined $T_c \approx 26$ MeV as the transition point of the spectrum from the spectator region to the cumulative one. The value $T_c \approx 26$ MeV (which is of the order of the Fermi-motion energy of ^{3}H nuclei in a ^{16}O nucleus) obtained for ^{3}H cumulative nuclei in ^{16}Op-collisions at a momentum of 3.25 GeV/c per nucleon appeared to be close to the corresponding value ($T_c^{^3\mathrm{H},^3\mathrm{He}} \approx 20$ MeV) for ^{3}H and ^{3}He nuclei in ^{4}Hep-interactions at a momentum of 5 GeV/c [25]. The statistics of events with the production of cumulative ^{3}H nuclei with the kinetic energy $T > 26$ MeV amounted to 148 events. The experimental spectrum $f(T)$ of ^{3}H nuclei in the cumulative region $T > 26$ MeV was approximated by the function $f = A_0 \exp(-T/T_0)$ with the slope parameter T_0 (or the temperature) representing one of the important characteristics of the cumulative production. The solid curve in Figure,a shows the result of such an approximation (fitting parameters: $A_0 = 433 \pm 71$ mb GeV^{-2} c^3 sr^{-1}, $T_0 = 19 \pm 2$ MeV, goodness measure χ^2/degr. freed. = 0.3). As follows from Figure,a and the value of χ^2, the spectrum $f(T)$ of cumulative ^{3}H nuclei is rather well described by the exponential function with the slope parameter $T_0 = 19 \pm 2$ MeV. The value of T_0 for cumulative ^{3}H nuclei produced in ^{16}Op-collisions at a momentum of 3.25 GeV/c per nucleon (which corresponds to the kinetic energy of protons $T_p \approx 2.5$ GeV in the rest-frame of the oxygen nucleus) appeared to be higher than T_0 for ^{3}H and ^{3}He cumulative nuclei (9.4 ± 0.9 and 9.1 ± 0.6 MeV, respectively) produced in ^{4}Hep-interactions [25] at a momentum of 5 GeV/c (which corresponds to $T_p \approx 0.62$ GeV in the rest-frame of the ^{4}He nucleus). This result is not surprising and agrees with the general tendency of decreasing the parameter T_0 with reducing the primary energy [25] in complete accordance with the hypothesis of nuclear scaling (limiting fragmentation) [10,11]. Figure,b shows the experimental invariant cross sections $f(P) = Ed^3\sigma/d^3p$ for ^{3}H nuclei escaping to the backward half-sphere ($\vartheta_{\mathrm{alab}} > 90°$) as a function of their total momentum in the rest-frame of the oxygen nucleus in ^{16}Op-collisions at a momentum of 3.25 GeV/c per nucleon. The experimental spectrum $f(P)$ of ^{3}H nuclei in the cumulative region $P > 383$ MeV/c (that corresponds to the region $T > 26$ MeV) was approximated by the generally accepted function $f = A_0 \exp(-B_0 \cdot P^2)$ with the slope parameter B_0. The solid curve in Figure,b presents the result of such an approximation (fitting parameters: $A_0 = 547 \pm 160$ mb GeV^{-2} c^3 sr^{-1}, $B_0 = 10 \pm 1$ (GeV/c)$^{-2}$, goodness measure χ^2/degr. freed. = 0.18). As follows from Figure,b and the value of χ^2, the spectrum $f(P)$ of cumulative ^{3}H nuclei is well described by the exponential function $f = A_0 \exp(-B_0 \cdot P^2)$ with the slope parameter $B_0 = 10 \pm 1$ (GeV/c)$^{-2}$.

As is well known, the investigation of various correlations with respect to yields of cumulative and noncumulative particles and fragments can provide the important information necessary for the identification of the mechanisms of cumulative production of particles and fragments [10]. In order to analyze the peculiarities of events with the production of a cumulative ^{3}H nucleus in more details, we compared the mean multiplicities of charged fragments and pions in events accompanied by the production of a cumulative ^{3}H nucleus (with $\vartheta_{\mathrm{alab}} > 90°$ and $T > 26$ MeV in the rest-frame of the oxygen nucleus) (hereinafter – cumulative events) with those in the events with the production of one or more noncumulative ^{3}H nuclei rather than the escape of a cumulative ^{3}H nucleus (hereinafter – noncumulative events). The mean multiplicities of charged fragments and pions in these two groups of events are presented in Table 1. As one can see from the table, the mean multiplicities of protons-fragments, ^{2}H and ^{3}He nuclei, as well as multicharged fragments with the charges z=3–6 and π^--mesons, practically coincide within error limits in cumulative and noncumulative events. However, as follows from the table, the mean multiplicity of ^{3}H nuclei in cumulative events appeared to be noticeably higher than that in noncumulative events. This result agrees with those obtained in early works [12–16,18–22] devoted to the study of the production of cumulative protons and pions. In [12–16,18–22], it was shown that the interactions with the emission of cumulative protons are accompanied by an increased multiplicity of all protons, whereas events with cumulative π-mesons are characterized by an increased multiplicity of all π-mesons. In our recent work [33], we demonstrated that the interactions with the formation of cumulative ^{4}He nuclei are also characterized by an increased multiplicity of all ^{4}He nuclei. The obtained results demonstrate that the regularity [12–16, 18–22] typical of the cumulative production of hadrons consisting in the increased mean multiplicity of hadrons in interactions with the emission

T a b l e 1. Mean multiplicities of charged fragments and pions in events with production of a cumulative ^{3}H nucleus (Group 1) and in noncumulative events (Group 2)

Type	Group 1	Group 2
$\langle n(^1\mathrm{H})\rangle$	2.80 ± 0.12	2.88 ± 0.06
$\langle n(^2\mathrm{H})\rangle$	0.72 ± 0.07	0.70 ± 0.03
$\langle n(^3\mathrm{H})\rangle$	1.34 ± 0.04	1.19 ± 0.01
$\langle n(^3\mathrm{He})\rangle$	0.35 ± 0.05	0.32 ± 0.02
$\langle n(^4\mathrm{He})\rangle$	0.76 ± 0.07	0.87 ± 0.03
$\langle n(z=3)\rangle$	0.08 ± 0.02	0.08 ± 0.01
$\langle n(z=4)\rangle$	0.06 ± 0.02	0.05 ± 0.01
$\langle n(z=5)\rangle$	0.03 ± 0.02	0.03 ± 0.01
$\langle n(z=6)\rangle$	0.05 ± 0.02	0.06 ± 0.01
$\langle n(\pi^-)\rangle$	0.32 ± 0.04	0.35 ± 0.02
$\langle n(\pi^+)\rangle$	0.50 ± 0.06	0.60 ± 0.03

of the corresponding cumulative hadrons is also valid for the cumulative production of light nuclear fragments. Evidently, these results indicate the general universal feature in the mechanisms of cumulative production of hadrons and light nuclear fragments. In Table 2, we present the mean escape angles ($\langle\vartheta\rangle$), transverse momenta ($\langle p_t\rangle$), and kinetic energies ($\langle T\rangle$) of ^{2}H nuclei, noncumulative nuclei ^{3}H, and nuclei ^{4}He in the rest-frame of the oxygen nucleus in cumulative and noncumulative events. As one can see from Table 2, ^{2}H, noncumulative ^{3}H, and ^{4}He nuclei in cumulative events escape at noticeably larger angles as compared to those in noncumulative events. Moreover, ^{4}He nuclei in cumulative events exhibit a tendency to the predominant emission to the backward half-sphere, i.e. in the direction of the escape of ^{3}H cumulative nuclei. At the same time, ^{4}He nuclei in noncumulative events mainly escape to the forward half-sphere in the rest-frame of the oxygen nucleus. It is worth noting that ^{4}He nuclei accompanying the emission of cumulative ^{4}He nuclei in ^{16}Op-collisions at a momentum of 3.25 GeV/c per nucleon also tended to the predominant escape to the backward half-sphere in the rest-frame of the oxygen nucleus [33]. This common feature observed in the processes of cumulative production of tritium and ^{4}He nuclei is obviously related to the α-cluster structure of the oxygen nucleus. As follows from Table 2, ^{2}H and ^{4}He nuclei in cumulative events are characterized by considerably higher values of the transverse momentum and the kinetic energy as compared to those in noncumulative events; for noncumulative ^{3}H nuclei, these values in cumulative events are noticeably lower than those in noncumulative ones. It is worth noting that the similar characteristics of protons-fragments, ^{3}He nuclei, and charged pions practically coincided within the limits of statistical errors in cumulative and noncumulative events. The mean values of the escape angle, kinetic energy, and transverse momentum for cumulative ^{3}H nuclei in the rest-frame of the oxygen nucleus are presented in Table 3. As follows from the table, these parameters in the case of cumulative ^{3}H nuclei are considerably larger than those in the case of noncumulative ones (see Table 2) in cumulative events, as one would expect from the conditions of the selection of cumulative ^{3}H nuclei.

Table 2. Mean escape angles ($\langle\vartheta\rangle$), transverse momenta ($\langle p_t\rangle$), and kinetic energies ($\langle T\rangle$) of ^{2}H nuclei, noncumulative ^{3}H nuclei, and ^{4}He nuclei in the rest-frame of the oxygen nucleus in events with production of a cumulative ^{3}H nucleus (Group 1) and in noncumulative events (Group 2)

Type	Group 1			Group 2		
Nucleus	^{2}H	^{3}H	^{4}He	^{2}H	^{3}H	^{4}He
$\langle\vartheta\rangle$, deg.	84±4	85±9	101±5	74±2	70±2	88±2
$\langle p_t\rangle$, MeV/c	301±27	183±19	228±16	248±9	221±6	208 ±6
$\langle T\rangle$, MeV	55± 10	20±4	31±6	44±3	29±2	25±3

Table 3. Mean escape angle ($\langle\vartheta\rangle$), transverse momentum ($\langle p_t\rangle$), and kinetic energy ($\langle T\rangle$) of cumulative ^{3}H nuclei (with $\vartheta_{\rm alab} > 90°$ and $T > 26$ MeV in the rest-frame of the oxygen nucleus)

Fragment	^{3}H
$\langle\vartheta\rangle$, deg.	139 ± 2
$\langle p_t\rangle$, MeV/c	333 ± 16
$\langle T\rangle$, MeV	69 ± 6

3. Conclusions

The basic conclusions of this work can be briefly summarized in the following way. The experimental invariant cross sections $f(T) = Ed^3\sigma/d^3p$ ($f(P) = A_0\exp(-B_0\cdot P^2)$) of ^{3}H nuclei escaping to the backward half-sphere ($\vartheta_{\rm alab} > 90°$) were obtained for the first time as functions of their kinetic energy (momentum) in the rest-frame of the oxygen nucleus in ^{16}Op-collisions at a momentum of 3.25 GeV/c per nucleon. The approximation of the $f(T)$ ($f(P)$) spectrum of ^{3}H nuclei in the cumulative region $T > 26$ MeV ($P > 383$ MeV/c) by the function $f = A_0\exp(-T/T_0)$ ($f = A_0\exp(-B_0\cdot P^2)$) allowed us to determine, for the first time, the slope parameters T_0 and B_0 of the spectra of cumulative ^{3}H nuclei that appeared to be equal to 19±2 MeV and 10 ±1 (GeV/c)$^{-2}$, respectively.

We have performed the comparative analysis of various characteristics of particles and fragments in cumulative events with the production of a cumulative ^{3}H nucleus and in noncumulative events without production of cumulative ^{3}H nuclei but with the production of at least one noncumulative ^{3}H nucleus. The results of such a comparison discovered significant distinctions in cumulative and noncumulative events. In particular, the mean multiplicity of ^{3}H nuclei in cumulative events appeared to be noticeably higher than that in noncumulative ones. This result agrees with numerous data obtained for the cumulative production of protons and pions, where events with the production of cumulative hadrons were also characterized by an increased multiplicity of the corresponding hadrons. A similar result was also obtained for cumulative ^{4}He nuclei formed in ^{16}Op-collisions at a momentum of 3.25 GeV/c per nucleon. It was also revealed that ^{2}H, ^{3}H, and ^{4}He nuclei that accompany the escape of a cumulative ^{3}H one are emitted, on the average, at noticeably larger angles in the rest-frame of the oxygen nucleus as compared to mean escape angles of the corresponding nuclei in noncumulative events.

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СТВОРЕННЯ КУМУЛЯТИВНИХ ЯДЕР ^{3}H У ЗІТКНЕННЯХ ЯДЕР КИСНЮ З ПРОТОНАМИ ПРИ ІМПУЛЬСІ 3,25 ГеВ/c НА НУКЛОН

Х.К. Олімов

Р е з ю м е

Вперше в умовах 4π-геометрії вивчено утворення кумулятивних ядер ^{3}H в ^{16}Op-зіткненнях при імпульсі 3,25 ГеВ/c на нуклон. Визначено параметри нахилу інваріантних перерізів кумулятивних ядер ^{3}H та наведено нові дані з кореляції виходу кумулятивних ядер ^{3}H і заряджених частинок та фрагментів в ^{16}Op-взаємодіях. Знайдено помітні відмінності характеристик кумулятивних і некумулятивних подій.