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Correlations between production of charged pions and formation of light nuclei in ^{16}Op collisions at $3.25A\,\mathrm{GeV}/c$

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Correlations between production of charged pions and formation of light nuclei in collisions of oxygen nuclei with protons at $3.25A\,\mathrm{GeV}/c$ were investigated. It was deduced that the mechanisms of formation of light fragments with $A = 2$–4 and the processes of generation of charged pions do not depend on each other.

Keywords: Production of pions; formation of light nuclei; fragmentation of nuclei; relativistic hadron–nucleus collisions.

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1. Introduction

It is well known that the processes of nucleus fragmentation dominate in nuclear collisions at incident energies of the order of a few GeV per nucleon. At peripheral collisions, colliding nuclei acquire quite small excitation energies, resulting in a breakup of these nuclei into fragments, which practically "preserve" the initial cluster structure of fragmenting nuclei. In recent years, the experiments on investigation of cluster structure of light stable and radioactive nuclei with $A \leq 12$

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were conducted[1–6] intensively by "BECQUEREL" collaboration, founded on the basis of Nuclotron of the Laboratory of High Energies (LHE) at Joint Institute for Nuclear Research (JINR, Dubna). For light and medium nuclei, the structures such as n^4He, n^4He+m^2H, n^4He+m^3H, n^4He+m^3He, and n^3H+m^2H (here $n \geq 1$ and $m \geq 1$, and they depend on mass number and type of fragmenting nucleus) are observed.[1–6] The composition of cluster structure is determined by the mass number and type of a fragmenting nucleus, that is, by whether the total number of nucleons in a nucleus is even or odd.

In hadron–nucleus collisions at incident energies of about a few GeV/nucleon, the mean number of produced particles (mostly pions) per collision event is not large. These pions are predominantly generated as a result of inelastic charge exchange of a nucleon of a projectile or target nucleus, or they come from decay of baryon resonances,[7–14] produced in fragmenting nuclei. At the same time, at such incident energies the contribution of pair ($\pi^+\pi^-$) production to multiplicity of produced pions is quite small.

Due to the peculiarities of experiments on nuclear emulsions,[1–6] the correlations between multiple generation of particles and processes of fragmentation of relativistic nuclei were not studied in such experiments. The other experiments[15–19] (with the target nucleus at rest) did not permit to study simultaneously the processes of fragmentation of nuclei and processes of multiple generation of particles (mostly pions), because, for example, nuclear emulsion experiments did not allow identification of fragments by their masses. On the other hand, the conducted electronic experiments on nuclear fragmentation did not allow registration of all the fragments of reactions because of quite small (solid angle) coverage of the used detectors. Our experiment is a unique one,[20] since it allows registration and identification by charge and mass of all the charged particles and fragments of ^{16}Op collision events, measured at 4π (full) solid angle. Emission angles and momenta of the charged fragments and particles were measured with a good enough precision.[20] In our case, the fragmenting oxygen nucleus is a projectile impinging on a hydrogen target, and, therefore, we could measure the momenta of all the charged fragments and produced particles (pions), starting from a zero momentum in the oxygen nucleus rest frame.[20] The conditions of our experiment permit us to study simultaneously the fragmentation of oxygen nucleus and generation (production) of particles (mostly pions) and, hence, investigate correlations between the processes of nuclear fragmentation and production of pions. To our best knowledge, correlations between formation of fragments (light nuclei) and production of pions were not studied in relativistic nuclear collisions. The main aim of the present work is to establish the possible links between mechanisms of fragmentation of oxygen nucleus and production of pions.

2. Experiment

Our experiment on 1 m hydrogen bubble chamber of the Laboratory of High Energies (LHE) of Joint Institute for Nuclear Research (JINR, Dubna) allows for a quite precise identification of masses of secondary charged particles and fragments with $A \leq 9$. The predominant fraction ($> 95\%$) of produced particles in $^{16}\mathrm{O}p$ collisions at $3.25A\,\mathrm{GeV}/c$ consists of pions. Therefore, in the present work, we investigated the correlations in the production of charged pions and formation of light ^{1}H, ^{2}H, ^{3}H, ^{3}He, and ^{4}He nuclei in $^{16}\mathrm{O}p$ collisions at $3.25A\,\mathrm{GeV}/c$.

The experimental data were obtained using 1 m hydrogen bubble chamber of LHE of JINR, irradiated by oxygen nuclei, accelerated at Dubna synchrophasotron to momenta of $3.25\,\mathrm{GeV}/c$ per nucleon, and based on statistics of 10,042 measured inelastic $^{16}\mathrm{O}p$ collision events. For identification of mass of the fragments, the following momentum intervals in laboratory frame were introduced. Singly charged fragments with momenta $1.75\,\mathrm{GeV}/c < p \leq 4.75\,\mathrm{GeV}/c$ were considered to be protons, those with $4.75\,\mathrm{GeV}/c < p \leq 7.75\,\mathrm{GeV}/c$, and $p > 7.75\,\mathrm{GeV}/c$ were taken to be ^{2}H and ^{3}H nuclei, respectively. Doubly charged fragments having the momenta $p \leq 10.75\,\mathrm{GeV}/c$ were identified as ^{3}He nuclei, and those falling in momentum interval $10.75\,\mathrm{GeV}/c < p \leq 16\,\mathrm{GeV}/c$ were taken to be ^{4}He nuclei. Such an upper constraint on momentum of ^{4}He nuclei is due to instability of "invisible" ^{5}He nuclei, which decay quite fast through $^5\mathrm{He} \to \alpha + n$ reaction into neutron and ^{4}He, which we can "see" and detect in experiment. Due to quite small cross-section of formation of ^{6}He nuclei ($1.03 \pm 0.23\,\mathrm{mb}$[21]), we did not consider them in present analysis. At such a selection, the admixture of neighboring isotopes among selected fragments due to overlap of their momentum spectra does not exceed 3–4%.[22,23] The other methodological issues of the experiment can be found in Ref. 20.

3. Analysis and Results

For analysis of correlations in the production of charged pions and formation of light fragments in $^{16}\mathrm{O}p$ collisions at $3.25A\,\mathrm{GeV}/c$, we divided the whole ensemble of $^{16}\mathrm{O}p$ collisions into the following two groups: (a) there is no any charged pion in a collision event ($n_{\pi\pm} = 0$); (b) there is at least one charged pion in a collision event ($n_{\pi\pm} \geq 1$).

Fraction of collision events, the mean number per event of light fragments and a recoil proton for the above mentioned groups are presented in Table 1. As seen from Table 1, charged pions are not produced in approximately 45% of collision events, whereas production of at least one charged pion is observed in about 55% of events. The mean multiplicities per event of light ^{1}H,^{2}H,^{3}H,^{3}He, and

Table 1. Fraction of collision events (%), mean number per event of light fragments with $A \leq 4$, and of a recoil proton (n_{rc}) depending on availability of a charged pion in a collision event.

Availability of a $\pi^\pm$ in an event	Fraction of events (W), (%)	Type of a particle or fragment					
		^{1}H	^{2}H	^{3}H	^{3}He	^{4}He	n_{rc}
$n_{\pi\pm} = 0$	44.7 ± 0.7	1.58 ± 0.03	0.28 ± 0.01	0.11 ± 0.01	0.12 ± 0.01	0.46 ± 0.02	0.70 ± 0.01
$n_{\pi\pm} \geq 1$	55.3 ± 0.7	1.94 ± 0.03	0.37 ± 0.01	0.17 ± 0.01	0.16 ± 0.01	0.54 ± 0.02	0.59 ± 0.01

^{4}He fragments proved to be noticeably larger in a group of collision events with $n_{\pi\pm} \geq 1$ as compared to those in events without production of a charged pion ($n_{\pi\pm} = 0$). This is likely due to the fact that production of at least one charged pion in a collision event occurs at a significantly larger amount of momentum-energy transferred to a fragmenting nucleus, and consequently at higher degree of destruction of a nucleus, as compared to events without production of any charged pion. The mean values of the total charge of the fragments ($\langle Q_{38}\rangle$) with the charges $3 \leq z \leq 8$ in the considered groups of collision events further support this statement. For the group of events without production of a charged pion ($n_{\pi\pm} = 0$), this quantity proved to be $\langle Q_{38}\rangle = 4.92 \pm 0.04$, whereas in collision events with production of at least one charged pion ($n_{\pi\pm} \geq 1$) it was $\langle Q_{38}\rangle = 3.88 \pm 0.04$. Regardless of availability of a charged pion in a collision event ($n_{\pi\pm} = 0$ or $n_{\pi\pm} \geq 1$), the mean multiplicities per event of the "mirror" ^{3}H and ^{3}He nuclei coincided within statistical uncertainties in each analyzed group of events. It is worth mentioning that such a coincidence for mean multiplicities of "mirror" ^{3}H and ^{3}He nuclei was observed also earlier in inclusive ^{16}Op reaction.[22,24]

It is seen from Table 1 that the mean multiplicity per event of recoil protons is larger in collisions events without pion production as compared to that in events where at least one charged pion is generated. It can be explained by the fact that some parts of π^+ come from inelastic charge exchange decay of a target proton into neutron and positive pion. Using data of Table 1, one can determine the fraction of a charge lost by a target proton via its inelastic charge exchange according to reaction $p \to n + \pi^+$ and through its charge exchange $pn \to np$ with a neutron of projectile nucleus. The fraction of a charge lost by a proton target was calculated using

$$W(p \to n) = W(n_{\pi\pm} = 0)(1 - n_{\rm rc}(n_{\pi\pm} = 0)) + W(n_{\pi\pm} \geq 1)(1 - n_{\rm rc}(n_{\pi\pm} \geq 1))$$

which proved to be $W(p \to n) = 0.36 \pm 0.02$. This result agrees well with the coefficient of inelastic charge exchange of a target proton (0.37 ± 0.01) in ^{16}Op reaction, obtained in Ref. 25.

To find out whether the correlations observed in Table 1 between multiplicities of light fragments and availability of a charged pion in an event are connected with the dependencies between production mechanisms of charged pions and mechanisms of formation of light fragments, we investigated the kinematical characteristics of light fragments separately in each analyzed group of collision events.

In Table 2, the average values of the total and transverse momenta and their widths are given for light ^{1}H, ^{2}H, ^{3}H, ^{3}He, and ^{4}He fragments with $A \leq 4$ depending on availability or absence of a charged pion in a collision event. Due to coincidence of the mean multiplicities and kinematical characteristics of the "mirror" ^{3}He and ^{3}H nuclei in ^{16}Op reaction,[22,24] for better statistics, we united the data for these two nuclei in this and the following tables.

Table 2. The average values of the total and transverse momenta and their widths (D) (in MeV/c) for light fragments with $A \leq 4$ depending on availability of a charged pion in a collision event.

Quantity	Availability of a $\pi^{\pm}$ in an event	Type of a fragment		
		^{2}H	^{3}H+^{3}He	^{4}He
$\langle P \rangle$	$n_{\pi^\pm} = 0$	352 ± 7	367 ± 8	293 ± 4
	$n_{\pi^\pm} \geq 1$	351 ± 5	362 ± 6	296 ± 3
$D(P)$	$n_{\pi^\pm} = 0$	243 ± 9	236 ± 9	180 ± 7
	$n_{\pi^\pm} \geq 1$	241 ± 6	229 ± 9	179 ± 5
$\langle P_t \rangle$	$n_{\pi^\pm} = 0$	257 ± 6	234 ± 6	189 ± 3
	$n_{\pi^\pm} \geq 1$	253 ± 5	236 ± 4	189 ± 3
$D(P_t)$	$n_{\pi^\pm} = 0$	215 ± 8	173 ± 8	149 ± 8
	$n_{\pi^\pm} \geq 1$	207 ± 6	175 ± 7	143 ± 6
$\langle P_L \rangle$	$n_{\pi^\pm} = 0$	116 ± 8	122 ± 10	21 ± 6
	$n_{\pi^\pm} \geq 1$	118 ± 6	129 ± 7	29 ± 5
$D(P_L)$	$n_{\pi^\pm} = 0$	234 ± 4	282 ± 8	244 ± 3
	$n_{\pi^\pm} \geq 1$	239 ± 5	288 ± 10	239 ± 4

From Table 2, it follows that:

- the average values of the total and transverse momenta and their widths for light fragments do not depend within statistical uncertainties on availability or absence of a charged pion in a collision event;
- the average values of the total and transverse momenta and their widths coincide within statistical errors for deuterons and "mirror" (^{3}H+^{3}He) nuclei;
- all the analyzed kinematical characteristics of α particles proved to be smaller than those of deuterons and "mirror" (^{3}H+^{3}He) nuclei, which is due to the peculiar character of formation of ^{4}He nuclei in ^{16}Op collisions. ^{4}He nuclei, being initial composite structure of a projectile oxygen nucleus,[26] are formed in peripheral interactions at quite small excitation energies of fragmenting ^{16}O nucleus;
- the average value of the total momentum of the "mirror" (^{3}H+^{3}He) nuclei proved to be less than that of deuterons, which is due to relatively smaller average emission angle of (^{3}H+^{3}He) nuclei as compared to that of ^{2}H nuclei.

Does it follow from the experimentally observed coincidence of the average momentum characteristics of the analyzed nuclei in two group of events that the shapes of their momentum spectra are also identical? Our analysis showed that the shapes of the momentum spectra of the analyzed (^{2}H, ^{3}H, ^{3}He, and ^{4}He) fragments also coincide within statistical uncertainties for both groups of collision events. As an example, the spectra of the total (in oxygen nucleus rest frame) and transverse momenta of ^{2}H nuclei are shown in Figs. 1 and 2, respectively, for both considered groups of collision events. As observed from Figs. 1 and 2, the spectra of total momentum as well as those of transverse momentum of ^{2}H nuclei coincide within statistical error bars in both classes of analyzed events, which points out that mechanisms of formation of light fragments and processes of pion production do not depend on each other.

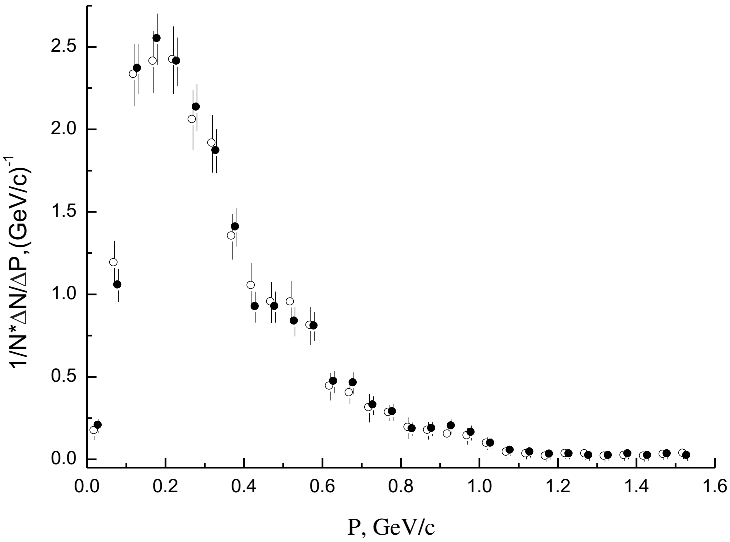

Fig. 1. Distribution of deuterons (^{2}H nuclei) on total momentum in oxygen nucleus rest frame in collision events with production of at least one charged pion (○) and without any charged pion (●). For better visibility, the experimental points were shifted (by 5 MeV/c) to the left and to the right along the P axis for the first and second group of events, respectively.

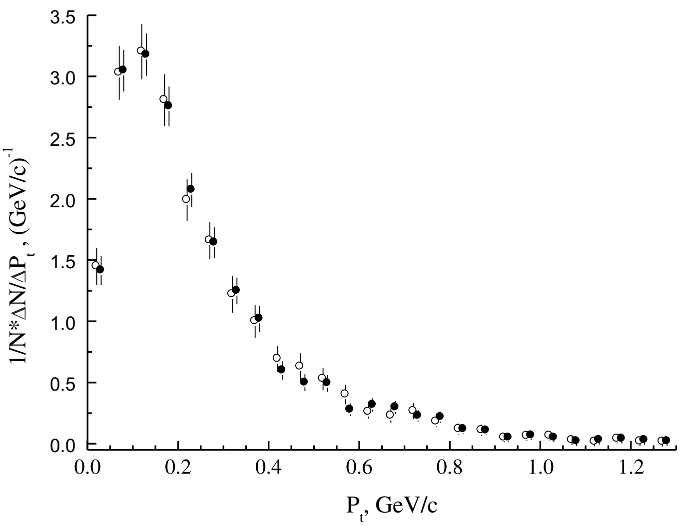

Fig. 2. Distribution of deuterons (^{2}H nuclei) on transverse momentum in collision events with production of at least one charged pion (●) and without any charged pion (○). For better visibility, the experimental points were shifted (by 5 MeV/c) to the right and to the left along the P_t axis for the first and second group of events, respectively.

From the above given analysis results, it follows that also the mean kinematical characteristics of charged pions should not depend on mechanism of formation of light fragments. It is known that the following mechanisms contribute mainly to formation of light nuclear fragments emitted into forward hemisphere ($\Theta \leq 90°$) in oxygen nucleus rest frame: "evaporation", Fermi breakup, quasi elastic knocking out by a target proton, and decays of highly excited nuclei with mass numbers $A \geq 3$. At the same time, the light fragments emitted into backward hemisphere ($\Theta > 90°$) in oxygen nucleus rest frame are formed mainly due to mechanisms of "evaporation" and Fermi breakup. To check the above assumption, we compared the mean values of the total and transverse momenta and their widths for π^- mesons depending on emission angle (in oxygen nucleus rest frame) of light fragments (see Table 3).

As observed from Table 3, the average values of the total and transverse momenta and their widths for negative pions proved to be independent within statistical errors of the emission angle of light fragments. This supports our earlier finding that the mechanisms of formation of light fragments with $A = 2$–4 and the processes of production of charged pions do not depend on each other in $^{16}\mathrm{O}p$ collisions at $3.25A\,\mathrm{GeV}/c$. This conclusion is supported also by the independence of the mean multiplicities of charged pions (for events with production of at least one charged pion) on emission angle of light fragments in oxygen nucleus rest frame, which can be seen from Table 4.

Table 3. The average values of the total (in laboratory system) and transverse momenta and their widths (D) (in MeV/c) for π^- mesons depending on the emission angle (in oxygen nucleus rest frame) of light ^{2}H, ^{3}H+^{3}He, and ^{4}He fragments.

Quantity	Emission angle of a fragment	Type of a fragment		
		^{2}H	^{3}H+^{3}He	^{4}He
$\langle P\rangle$	$\Theta \leq 90°$, forward	653 ± 15	655 ± 17	622 ± 14
	$\Theta > 90°$, backward	654 ± 21	648 ± 22	613 ± 16
$D(P)$	$\Theta \leq 90°$, forward	428 ± 17	432 ± 18	411 ± 15
	$\Theta > 90°$, backward	414 ± 22	407 ± 22	424 ± 16
$\langle P_t\rangle$	$\Theta \leq 90°$, forward	189 ± 5	193 ± 5	186 ± 4
	$\Theta > 90°$, backward	189 ± 7	197 ± 7	189 ± 5
$D(P_t)$	$\Theta \leq 90°$, forward	125 ± 6	128 ± 6	127 ± 5
	$\Theta > 90°$, backward	124 ± 7	135 ± 8	130 ± 6

Table 4. The mean number per event of charged pions depending on emission angle of light fragments in oxygen nucleus rest frame.

Emission angle of a fragment	Type of a fragment		
	^{2}H	^{3}H+^{3}He	^{4}He
$\Theta \leq 90°$, forward	1.53 ± 0.02	1.56 ± 0.02	1.57 ± 0.02
$\Theta > 90°$, backward	1.53 ± 0.03	1.57 ± 0.03	1.53 ± 0.02

It follows from Table 4 that the average number per event of charged pions, accompanying the formation of light fragments, does not depend within statistical uncertainties on the fragment type. It is also seen that the mean multiplicities of charged pions do not depend within statistical errors on emission angle of these fragments. Taking into account that mechanisms of formation of light fragments emitted into forward and backward hemispheres differ from each other, we can conclude that mechanisms of formation of light fragments and processes of pion production are independent from each other.

4. Summary and Conclusions

The correlations between production of charged pions and formation of light fragments in $^{16}\mathrm{O}p$ collisions at $3.25A\,\mathrm{GeV}/c$ were investigated. For analysis of correlations in the production of charged pions and formation of light fragments in $^{16}\mathrm{O}p$ collisions at $3.25A\,\mathrm{GeV}/c$, the whole ensemble of $^{16}\mathrm{O}p$ collisions was divided into the following two groups: (a) there is no charged pion in a collision event; (b) there is at least one charged pion in a collision event.

The mean multiplicities per event of light ^{1}H, ^{2}H, ^{3}H, ^{3}He, and ^{4}He fragments proved to be noticeably larger in a group of collision events with production of at least one charged pion as compared to those in events without production of a charged pion. This was due to the fact that production of at least one charged pion in a collision event occurs at a significantly larger amount of momentum-energy transferred to a fragmenting nucleus, and consequently at higher degree of destruction of a nucleus, as compared to events without production of any charged pion.

The average values of the total and transverse momenta and their widths for ^{2}H, ^{3}H+^{3}He and ^{4}He nuclei proved to be independent on availability or absence of a charged pion in a collision event. Also, the shapes of momentum spectra of analyzed fragments (^{2}H, ^{3}H+^{3}He and ^{4}He) coincided within statistical uncertainties in both groups of collision events.

The average values of the total and transverse momenta and their widths for negative pions proved to be independent on emission angles (in oxygen nucleus rest frame) of light ^{2}H, ^{3}H+^{3}He and ^{4}He nuclei.

Hence, it can be concluded that mechanisms of formation of light fragments and processes of pion production are independent from each other. The correlations observed between multiplicities of light ^{2}H, ^{3}H+^{3}He and ^{4}He nuclei and an availability/absence of a charged pion in a collision event are due to the larger/smaller amount of energy-momentum transferred to a fragmenting nucleus.

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