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Some peculiarities of formation of ^{4}He nuclei in ^{16}Op collisions at 3.25A GeV/c

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The new experimental data on dependences of the mean multiplicities and kinematical characteristics of ^{4}He nuclei, formed in ^{16}Op collisions at 3.25A GeV/c, on degree of excitation of the fragmenting nucleus are presented. It is shown that the initial (α cluster) structure of oxygen nucleus is retained at small excitation levels. It is established that the kinematical characteristics of ^{1}H, ^{2}H, ^{3}H and ^{3}He fragments do not depend on availability or absence of α particles in a collision event, which indicates the independence of mechanisms of formation of such fragments and ^{4}He nuclei.

Keywords: Fragmentation of nuclei; structure of nuclei; excitation of nuclei; formation of light nuclei.

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It is known that α cluster structure prevails in even–even light nuclei. This structure should manifest itself mainly in fragmentation processes of such relativistic nuclei at peripheral collisions with nucleons and nuclei when the excitation energy of fragmenting nucleus slightly exceeds the value of threshold energy of nucleus breakup into the constituents of initial structure.

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In recent years, it was shown experimentally by International BEQUEREL Collaboration that not only α cluster structure, but also clusters including light ^{2}H, ^{3}H and ^{3}He nuclei in combination with ^{4}He nuclei may exist in light nuclei.[1–6] Information on existence of such cluster structures can be obtained by studying various correlations among final products of fragmentation, which can partly be formed from breakup of intermediate excited nuclear remnants (for example,^{6}Li*, ^{7}Li*,^{7}Be*,^{9}Be*, ^{10}B*, ^{12}C*, ^{14}N*),[3,7,8] as well as from decay of unstable ^{8}Be and ^{9}B nuclei.[9] Besides it, the experimentally observed α particles can be the conserved constituents of the initial α cluster structure (especially at small excitations of the fragmenting nucleus). Therefore, it seems interesting to investigate the various characteristics of α particles as a function of excitation levels of the fragmenting nucleus.

It was observed, while studying the fragmentation of oxygen nuclei in interactions with protons at $3.25\,A\,\text{GeV}/c$ in Refs. 10 and 11, that formation of doubly charged fragments dominates among multi-charged fragments, the predominant part (≈80%) of which consists of α particles. Inclusive cross-section of formation of α particles proved to be $164 \pm 1.9\,\text{mb}$, which is approximately half of inelastic cross-section of $^{16}\text{O}p$ interactions at $3.25A\,\text{GeV}/c$ ($334 \pm 6\,\text{mb}$). The total number of possible topological channels of breakup (fragmentation) of oxygen nuclei in $^{16}\text{O}p$ interactions equals 22. The topologies with the final fragment charges (35), (44) and (233) with conservation of the charge of an initial nucleus are not observed. Interpretation of absence of such topologies is given in Ref. 12. Here the single digits denote the charges of multi-charged fragments and their number is the total number of such fragments with the exception of topology (1), which means the breakup of oxygen nucleus on singly charged fragments only. From the experimentally observed 19 topologies of breakup of oxygen nuclei ((1), (2), (3), (4), (5), (6), (7), (8), (22), (23), (24), (25), (26), (222), (223), (224), (2222), (33), (34)) — 10 topologies include doubly charged fragments.[13] The total cross-section of topologies, containing one or more doubly charged fragments, equals $134.6 \pm 2\,\text{mb}$, which is approximately 40% of inelastic cross-section of $^{16}\text{O}p$ reaction at $3.25A\,\text{GeV}/c$.

It is interesting to note that from the experimentally observable three channels ((26), (224) and (2222)) with the total charge of fragments 8, only in two of topologies ((26) and (2222)) all the nucleons of the initial oxygen nucleus are conserved. In topological channel (224), the fragments with the charge 4 consist only of ^{7}Be nuclei.[14] The main fraction (2/3) of cross-section of breakup of oxygen nucleus on α particles and ^{12}C nuclei proceeds through the process of peripheral knocking out of one of the α clusters of oxygen nucleus, while the remaining three α clusters fuse into carbon-12 nucleus.[15] This result is interpreted as an evidence for an α cluster structure of ^{16}O nucleus.

Continuing the series of investigations of formation of light fragments[16–22] in interactions of oxygen nuclei with protons at $3.25A\,\text{GeV}/c$, we studied the peculiarities of formation of ^{4}He nuclei in these collisions at different levels of excitation of impinging nucleus.

The experimental data were obtained using 1 m hydrogen bubble chamber of the Laboratory of High Energies (LHE) of Joint Institute for Nuclear Research (JINR), irradiated by oxygen nuclei with momenta $3.25A$ GeV/c accelerated at Dubna synchrophasotron, and consist of 8712 fully measured inelastic ^{16}Op collision events. For more reliable identification of α particles, we considered those events in which the lengths of tracks of particles in the chamber were not less than 35 cm, which provided the high enough precision of momentum measurements. While determining the mean multiplicities of ^{4}He nuclei, we accounted for the losses of α particles due to their interaction with the hydrogen nuclei in the chamber at the length $L \leq 35$ cm. The methodological issues of obtaining the experimental data are presented in detail in Refs. 10, 17, 23 and 24. For extraction of ^{4}He nuclei among doubly charged fragments of oxygen nuclei, we selected the momentum interval $10.75 \leq p \leq 15.75$ GeV/c. At such a selection, the admixture of ^{3}He nuclei among identified ^{4}He nuclei does not exceed 3–4%.[17]

Let us consider the formation of ^{4}He nuclei at different levels of excitation of fragmenting oxygen nucleus. As a measure of degree of nucleus excitation or peripherality of a collision we can take the value of the total charge (Q) of multi-charged fragments with $z \geq 2$. In our experiment, the Q value changes from 0 (the complete breakup of oxygen nucleus on singly charged fragments — ^{1}H, ^{2}H, ^{3}H) to 8. It should be mentioned that, due to selection criteria, ^{4}He nuclei are not formed in collision events with $Q = 0$ and 3.

The dependence of mean multiplicity per event of helium-4 nuclei, $\langle n(^4\text{He})\rangle$, on the total charge of multi-charged fragments with $z \geq 2$, Q, in ^{16}Op collisions at $3.25A$ GeV/c is presented in Fig. 1. As seen from Fig. 1, the value of $\langle n(^4\text{He})\rangle$ depends nonmonotonically on Q — its maximum value is observed at $Q = 4$, i.e., in the group of events with topologies (22) and (4), and its minimal value is reached at $Q = 7$. It is obvious that the value of $\langle n(^4\text{He})\rangle$ is determined by several factors: by the law of charge conservation, cross-sections of topological channels of

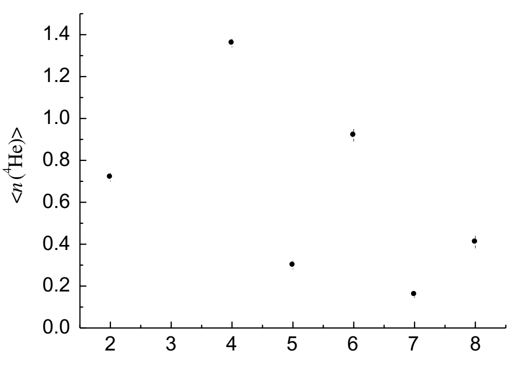

Fig. 1. The dependence of the mean multiplicity of ^{4}He nuclei on the total charge of fragments with $z \geq 2$.

formation of doubly charged fragments, multiplicity of doubly charged fragments in the given topology and by the fraction of ^{4}He nuclei among them, and by the ratio of contributions of topological channels with formation of doubly charged fragments and with their absence. For example, though the minimal multiplicity of helium-4 nuclei, $\langle n(^4\text{He})\rangle$, according to the degree of destruction of oxygen nucleus, should be observed in the group with $Q = 2$, its relatively small value is due to events with formation of only one doubly charged fragment. In this case, the mean multiplicity of helium-4 nuclei is determined by the fraction of these nuclei among doubly charged fragments. The maximal value of $\langle n(^4\text{He})\rangle$ in the group of events with $Q = 4$ is caused by the fact that the main contribution for this group is given by topology (22) with cross-section 36.44 mb, whereas the contribution of topology (4) is only 5.6 mb. The mean multiplicity of helium-4 nuclei for topology (22) is 1.56, and, on the whole, it equals 1.35 for $Q = 4$. The group of events with $Q = 5$ consists of topologies (23) and (5). The relatively small value of $\langle n(^4\text{He})\rangle$ in this group compared with the multiplicity in the group with $Q = 6$ is due to the cross-section of topological channel (23), in which ^{4}He nuclei can be formed, which is 1.5 times smaller than the cross-section of the topology (5) with an absence of ^{4}He nuclei. The group of events with $Q = 6$ is due to topologies (222), (24), (33) and (6), and formation of helium-4 nuclei is not observed at all in the last two topologies. The total inclusive cross-section of formation of doubly charged fragments in topologies (222) and (24) equals 105.34 mb, whereas the total cross-section of topological channels (33) and (6) is 55.42 mb, i.e., almost two times lesser. The behavior of the value of $\langle n(^4\text{He})\rangle$ at $Q = 7$ and 8 can also be explained by the analogous arguments about topological cross-sections with (and without) formation of doubly charged fragments.

Let us consider the changes of the mean multiplicity of α particles in the topologies (2), (22), (222) and (2222), where the Q value varies linearly. It is interesting to know whether we will also observe the linear dependence of the mean multiplicity

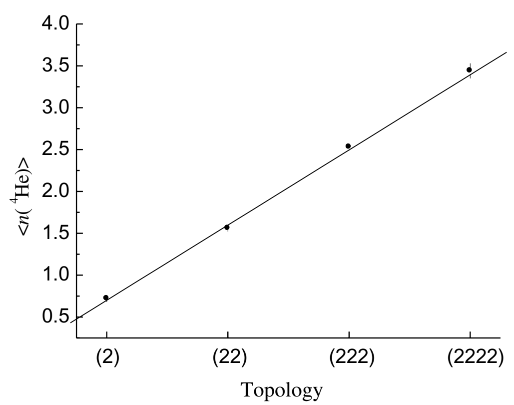

Fig. 2. The mean multiplicity of α particles in topologies (2), (22), (222) and (2222).

of α particles on Q. Such regularity would take place if the fraction of α particles remained the same with an increase of peripherality of a collision (in our case, with an increase of the total charge of doubly charged fragments in a collision event).

The mean multiplicity of α particles in topologies (2), (22), (222) and (2222) along with the results of its approximation (solid curve) are shown in Fig. 2. At first look, it seems that this dependence is fitted well by a linear function. However, the value of χ^2 per degree of freedom for this fit proved to be 1.75, which corresponds to 18% confidence level. The experimental data show (see Table 1) that the fraction of α particles among the doubly charged fragments increases with an increase of their number, i.e., with an increase of degree of peripherality of a collision, causing the deviation from the linear dependence of $\langle n(^4\text{He})\rangle$ on Q.

Thus, the deviation from the linear dependence of $\langle n(^4\text{He})\rangle$ on Q in the considered topologies is caused by an increase of probability of conservation of α particles with a decrease of degree of excitation of fragmenting nucleus, which, in its turn, confirms the existence of an α cluster structure of oxygen nucleus.

Let us proceed to an analysis of kinematical characteristics of α particles as a function of Q. The dependences of the mean values of the total and transverse momenta of α particles on the total charge of multi-charged fragments are shown in Fig. 3. It is necessary to note that only the topologies containing at least one α particle give the contribution to the total charge of multi charged fragments, because we deal with the kinematical characteristics of ^{4}He nuclei. So, for example, the point $Q = 2$ contains entirely α particles, the topology (22), containing at least

Table 1. The fraction of α particles among doubly charged fragments in topologies (2), (22), (222) and (2222).

Topology	(2)	(22)	(222)	(2222)
Fraction	0.72 ± 0.02	0.76 ± 0.01	0.82 ± 0.01	0.84 ± 0.02

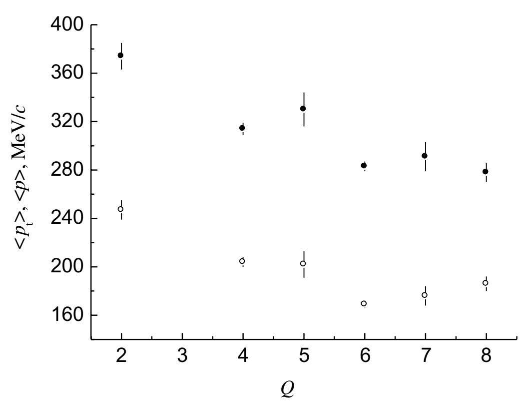

Fig. 3. The dependences of the mean values of the total $\langle p\rangle$ (closed circles) and transverse $\langle p\rangle$ (open circles) momenta of α particles on the total charge of fragments with $z \geq 2$.

one α particle, contributes to point $Q = 4$, and point $Q = 5$ is determined by only (23) topology, which has one α particle, and so on.

As observed from Fig. 3, the values of $\langle p \rangle$ as well as $\langle p_t \rangle$ show decreasing trend with an increase of Q, i.e., with a decrease of degree of excitation of oxygen nucleus. In case of $\langle p \rangle$ versus Q dependence, the deviation from the common regularity, seen for even Q values, is observed at points $Q = 5$ and 7. The possible reason for such behavior could be the regrouping of an initial α cluster structure, along with one α particle, to a fragment with the charge 3 or 5, which requires additional energy as compared to the points $Q = 4$ and 6. It should be noted that the topology (23) and combined topology (25) + (223) are realized with a noticeably lesser (more than three times) probability as compared to the topology (22) and combined topology (222) + (24).[13] The mean value of transverse momentum of α particles proved to be minimal at $Q = 6$, which is probably due to the dominant contribution of excited $^{12}C^*$ nuclei[8] to this point, which results in formation of three α particles. The matter is that the threshold of breakup of excited carbon-12 nucleus on three α particles is just 7.37 MeV, which brings about the small values of total and transverse momenta of decaying particles, emitted practically along the direction of movement of an initial oxygen nucleus.

In spite of extreme peripherality, the value of $\langle p_t \rangle$ at point $Q = 8$ slightly exceeds the corresponding value at point $Q = 6$. The topology (26) contributes 40% to the point $Q = 8$, the main part of which is realized through the direct knocking out of one α cluster of oxygen nucleus.[15] This statement follows from comparison of $\langle p_t \rangle = 174 \pm 8\,\mathrm{MeV}/c$ value for topology (2222) and $\langle p_t \rangle = 204 \pm 10\,\mathrm{MeV}/c$ value for topology (26). The analogous behavior is observed also at dependence of the mean emission angle of α particles on Q value (see Fig. 4).

Hence it may be concluded that the dependence of the mean multiplicity of ^{4}He nuclei on degree of excitation of fragmenting nucleus has nonmonotonous character,

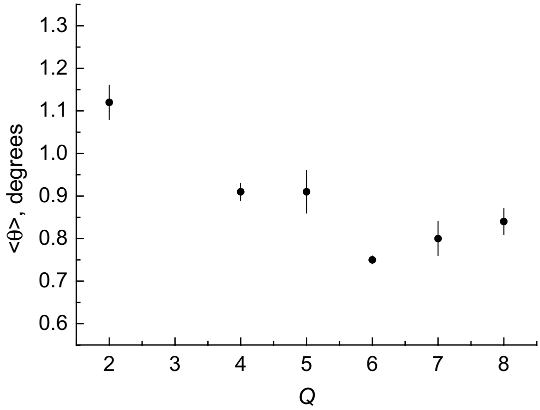

Fig. 4. The dependence of the mean value of emission angle of α particles in the laboratory frame on the total charge of fragments with $z \geq 2$.

indicating its complex dependence on the total charge of multi-charged fragments. The deviation from the linear dependence of $\langle n(^4\text{He})\rangle$ on the number of doubly charged fragments was observed, which was due to an increase of probability of conservation of an α particle with a decrease of degree of excitation of oxygen nucleus. The dependences of the mean total and transverse momenta of α particles, as well as their mean emission angles, on degree of excitation of fragmenting nucleus showed the qualitatively similar behavior. The minimal values of the mean transverse momentum and emission angles of α particles are observed at the channels of formation of three doubly charged fragments.

Let us analyze the momentum characteristics of light fragments — ^{1}H, ^{2}H, ^{3}H and ^{3}He in collision events with formation and an absence of ^{4}He nuclei. The mean values and widths of the total, longitudinal and transverse momenta (in oxygen nucleus rest frame) of proton fragments and deuterons in collision events with formation and absence of ^{4}He nuclei are presented in Table 2. It is seen that within statistical uncertainties the momentum characteristics of proton fragments as well as those of deuterons coincide for group of events with formation and absence of ^{4}He nuclei, i.e., the mechanisms of formation of these fragments do not correlate with formation of α particles in a collision event. Such independence is also observed for the widths (RMS) of momentum distributions of the considered fragments (see Table 2). Such a trend of independence of momentum characteristics on availability or absence of α particles in a collision event also holds for the light mirror ^{3}H and ^{3}He nuclei.

We may conclude that an initial α cluster structure of fragmenting oxygen nucleus is conserved at small excitations. The mean values of the total and transverse momenta as well as emission angles of ^{4}He nuclei depend on degree of excitation of oxygen nucleus and have the qualitatively similar character. The mean values and widths of momentum distributions of light ^{1}H, ^{2}H, ^{3}H, and ^{3}He fragments do not depend on availability or absence of α particles in a collision event, indicating an independence of formation of these fragments and α particles.

Table 2. The mean values and widths (RMS) of the total ($\langle p\rangle$), longitudinal ($\langle p_{\parallel}\rangle$), and transverse ($\langle p_t\rangle$) momentum distributions of protons and deuterons in collision events with formation and absence of ^{4}He nuclei.

The value, MeV/c	In events with ^{4}He formation		In events with absence of ^{4}He	
	Type of fragment		Type of fragment	
	^{1}H	^{2}H	^{1}H	^{2}H
$\langle p\rangle$,	388 ± 4	342 ± 5	387 ± 4	350 ± 5
RMS	312 ± 5	245 ± 6	307 ± 5	240 ± 6
$\langle p_{\parallel}\rangle$,	178 ± 3	126 ± 4	183 ± 2	122 ± 5
RMS	290 ± 4	239 ± 5	284 ± 3	235 ± 6
$\langle p_t\rangle$,	282 ± 3	243 ± 4	281 ± 2	250 ± 4
RMS	226 ± 4	213 ± 5	226 ± 4	208 ± 5

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