TRITIUM FORMATION AT THE FRAGMENTATION OF AN ^{16}O NUCLEUS WITH A MOMENTUM OF 3.25A GeV/c

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New experimental data concerning the formation of tritium at ^{16}Op-collisions with a momentum of 3.25A GeV/c have been reported, and the interpretation of the mechanisms of the relevant reactions has been offered. Correlations between the multiplicities of secondary nuclei and the produced pions associated with the formation of the ^{3}H$_1$ nucleus have been established. Strong positive correlations between the nucleus ^{3}H$_1$ multiplicity and the formation of π^+-mesons, which evidence for their multiplication during the inelastic recharge of nucleons at their multiple intranuclear rescattering, have been found. The process of fusion of cascade nucleons, knocked out quasielastically from the oxygen nucleus, was demonstrated to be the basic mechanism of formation of fast ($T \geq 70$ MeV) ^{3}H$_1$ nuclei.

Studying the correlation characteristics of the yield of fragmented nuclei, which have been formed at interactions between hadrons and high-energy nuclei, allows one to obtain the additional and rather helpful information concerning the states of the intermediate excited nuclear matter and the dynamics of formation of the final fragments of the initial nucleus.

This work continues the cycle of researches dealing with the processes of fragmentation of oxygen nuclei at ^{16}Op-collisions with a momentum of 3.25A GeV/c and is devoted to studying the single-particle momentum and angular spectra of ^{3}H$_1$, as well as to revealing the correlations (many-particle phenomena) between the individual characteristics of events and the mechanism of formation of ^{3}H$_1$ nuclei. The experimental body for the statistical treatment comprised 13759 measurements of ^{16}Op-events. The methodological issues concerning the identification of charged particles and fragments were discussed in the earlier works [1–3].

The process of formation of light nuclei ($A < 3$) is governed by a complicated superposition of several mechanisms, including the interaction between a projectile proton and the nucleons of an oxygen nucleus, the formation of quasi-free associations of a few nucleons, and the decay of the excited fragments with $A > 4$. For example, the nucleus of tritium can be formed owing to the fusion of a cascade nucleon and a deuteron or three cascade nucleons (two neutrons and one proton), or by knocking out a proton from the α-cluster of the oxygen nucleus. The latter statement follows from the fact that light nuclei with the mass numbers divisible by four and possessing identical numbers of neutrons and protons predominantly have the α-cluster structure. In order to reconstruct the whole scenario of the formation of ^{3}H$_1$ nuclei, we have analyzed their momentum and angular spectra.

Figure 1 exhibits the momentum spectrum of tritium nuclei in the antilaboratory coordinate system (ALCS), i.e. in the coordinate system, where the oxygen nucleus is at rest. One can see that the spectrum has a single-mode asymmetric shape with the maximum at $p \approx 250$ MeV/c and a "tail" in the range of high momenta. Although the average value of the momentum is (447 ± 7) MeV/c, the spectrum extends up to 1500 MeV/c. The existence of such fast tritium nuclei can be explained, as was indicated in our work [7], by the mechanism of fusion

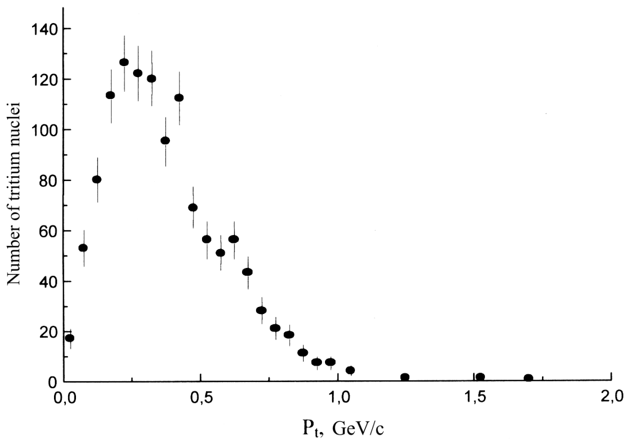

Fig. 1. Momentum spectrum of tritium nuclei in the ALCS

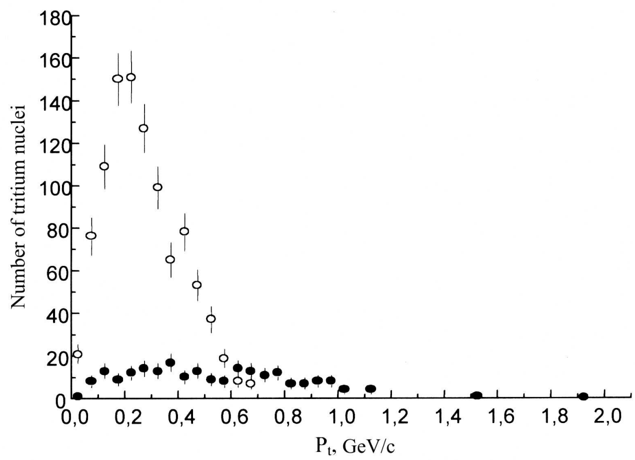

Fig. 2. Distributions of fast ($T > 70$ MeV, hollow circles) and slow ($T < 70$ MeV, solid circles) tritium nuclei over the transverse momentum

of cascade nucleons, which escaped from the oxygen nucleus at the intra-nuclear cascading of a target proton, and other secondary particles. However, the satisfactory description of the process by the coalescence model, which suggests the fusions of cascade nucleons possessing close vectors of momentum and finding themselves at the same moment inside a sphere about 1 fm in radius (the structural function of tritium nuclei in the range $T > 70$ MeV) does not mean yet that all these fast nuclei were formed only due to the mechanism of fusion. In the range $T > 70$ MeV, as was indicated above, the processes, where a target proton knocks out a proton from the α-cluster, may manifest itself.

For the further analysis, we use the value of the kinetic energy equal to 70 MeV in the rest coordinate system of the oxygen nucleus, as a conventional threshold between fast and slow tritium nuclei.

Figure 2 demonstrates the distributions of fast ($T >$ 70 MeV) and slow ($T < 70$ MeV) tritium nuclei over the transverse momentum. One can see that the spectra of these groups differ drastically: the average value of the transverse momentum for fast nuclei is (435 ± 17) MeV/c, which is almost twice as large as the corresponding quantity for slow nuclei ((225 ± 7) MeV/c), while the distribution dispersion for the first group is 2.7 times as much as that for the second one. Therefore, in the course of formation of fast tritium nuclei, the essential role is played by the transverse motion of their constituent nucleons, resulting in so high values of the transverse momentum. This conclusion testifies that the formation of fast tritium nuclei is impossible in soft processes, e.g., through the decay of α-clusters owing to the absorption of pions. Fast tritium nuclei can acquire high transverse momenta only provided that three cascade nucleons, or nucleons escaped owing to the absorption of π-mesons by a system with a few nucleons, fuse with a deuteron.

The angular distributions of tritium in two considered kinematic ranges may serve a sound argument in favor of the assumption that $^3H_1$ nuclei with the kinetic energy $T > 70$ MeV are formed as a result of the fusion of cascade nucleons. The average value of the $^3H_1$ departure angle turned out equal to $(1.35 \pm 0.02)^\circ$ at $T < 70$ MeV and $(3.04 \pm 0.14)^\circ$ at $T > 70$ MeV. Such a large difference between the angles of departure also testifies that $^3H_1$ nuclei with $T > 70$ MeV were formed as a result of the fusion of cascade nucleons.

The average values of the momentum for fast and slow tritium nuclei in the laboratory coordinate system (LCS) amount to (8.83 ± 0.01) and (9.78 ± 0.03) GeV/c, respectively. A practically full conservation of the initial momentum of a three-nucleon system in the latter case evidences for a dominating role of soft processes in the formation of slow tritium nuclei or for their formation through a direct knock out of a proton from an α-cluster.

We also studied the influence of the formation of $^3H_1$ nuclei on the multiplicity of accompanying particles (protons and charged pions) and fragments. The average values of the multiplicities for particles of various types and associated fragments, with a nucleus $^3H_1$ taking part in the event or not, are quoted in Table 1. The data of the table show that the multiplicities of all secondary nuclei and fragments correlate with the participation or absence of a $^3H_1$ nucleus in the event. These correlations are positive for nuclei with $Z_f \leq 2$ and negative for the group of fragments with $Z_f \geq 3$. The negative correlations, which are observed in the latter case, are explained, on the one hand, by the suppression, because of the baryon charge conservation, of the formation of multicharged fragments in events with the participation of a tritium nucleus and, on the other hand, by a large average value of the excitation energy of the initial nucleus when a $^3H_1$ nucleus is being formed, which induces a splitting of the excited nucleus into fragments with $Z_f \leq 2$.

The increase of the multiplicities of singly charged fragments ($^1H_1$, $^2H_1$, and $^3H_1$) at changing over from the group without a yield of the tritium nucleus to the group with it is also connected, generally speaking, with the growth of the excitation energy of an oxygen nucleus in the latter case. However, a drastic distinction between the multiplicities of fragmented nuclei $^1H_1$ and $^2H_1$ may be induced by the substantial contribution of the protons knocked out during the process of intra-nuclear rescattering of the target proton to the average multiplicity of $^1H_1$. The events with the formation of a $^3H_1$ nucleus can be attributed to non-peripheral collisions which are characterized by a large number of intra-nuclear rescattering events of the target proton, a large energy transfer to the residual nucleus, and, correspondingly, a more complete break-up of the nucleus. Therefore, considering these interaction events, one may expect the enhanced yield of singly charged fragments. In this case, the number of extra knocked out fragmented nucleons would be proportional to the number of intra-nuclear rescattering events. The events of the interaction without a departure of a $^3H_1$ nucleus are characterized by a smaller number of intra-nuclear rescattering events of the target proton; and it is reflected in a smaller value of the multiplicity of $^1H_1$ nuclei. Another source of extra protons is their emission in the course of the excitation relaxation ("evaporation" of protons). A comparison of the multiplicities of evaporated protons (with the momentum in the range of $0 - 0.22$ GeV/c in the ALCS) in the events with and without the formation of tritium nuclei demonstrates that, in the former group, it is higher by approximately a unity than that in the latter one, amounting to 1.84 ± 0.04 against 0.85 ± 0.00, respectively. This fact is an additional argument that the formation of tritium nuclei takes place under the condition of the strong excitation of the oxygen nucleus.

When a tritium nucleus is formed, the negative correlations with the average multiplicity of recoil protons are also observed. This circumstance can be connected, on the one hand, with the increase of the transferred momentum from a projectile nucleus to a target proton, when the former supplies the latter with a momentum in the range $p > 1.25$ GeV/c, so that the visual identification of the proton is complicated. On the other hand, owing to multiple rescattering of the proton, the probability of its inelastic recharge into a neutron and a π^+-meson increases, which also reduces the average number of recoil protons in events with the formation of $^3H_1$and increases the average multiplicity of π^+-mesons. The circumstance that the sum of the average multiplicities of π^+-mesons and recoil protons does not depend on the participation or absence of a tritium nucleus in the event, amounting to 1.05 ± 0.01 and 1.05 ± 0.02, respectively, testifies in favor of such a suggestion. This fact points at the local conservation of the electric charge in the recoil nucleon–π^+-meson system. Considering the events without the formation of a tritium nucleus as peripheral, with the truncated average number of intra-nuclear rescattering events being of about unity, and the events with the formation of tritium as those when a full set of rescattering events for the projectile proton is realized, the average multiplicity of recoil protons can be regarded as an indicator of the number of rescattering events. In this case, the probability for a proton to remain intact after the first scattering (see Table 1) is equal to $W = 0.58 \times 1.05 = 0.61$, and after $\langle\nu\rangle$ rescattering events to $W^{\langle\nu\rangle} \approx 0.45$. This brings about the value $\langle\nu\rangle \approx 1.6$, which, taking into account the crude evaluation, agrees rather well with the average number of intra-nuclear collisions $\langle\nu\rangle = A\sigma_{\rm in}^{pN}/\sigma_{\rm in}^{pA} = 1.54$. Therefore, the events with the formation of tritium nuclei are characterized by a larger number of intra-nuclear rescattering events of the initial proton and, correspondingly, by a higher level of development of cascade processes in the nucleus.

Table 1. Average multiplicities of fragments and charged particles associated with the formation of $^3H_1$

Particle	The number of $^3H_1$ nuclei in the event		Particle	The number of $^3H_1$ nuclei in the event	
	$N(^3H_1)=0$	$N(^3H_1)\geq1$		$N(^3H_1)=0$	$N(^3H_1)\geq1$
$^1H_1$	1.48±0.02	2.73±0.05	π^+	0.468±0,006	0.605±0.020
$^2H_1$	0.293±0.006	0.695±0.024	π^-	0.282±0.005	0.329±0.016
$^3He_1$	0.110±0.003	0.285±0.015	$p_{\rm sep}$	0.580±0.005	0.451±0.017
$^4He_2$	0.553±0.010	0.840±0.024	$3\leq Z_f \leq8$	0.757±0.005	0.243±0.010

In order to reveal other possible reasons of the correlation between the average multiplicity of π^+-mesons and the $^3H_1$ yield, consider the average multiplicities of tritium nuclei against the participation or absence of π^+-mesons in the event (Table 2). One can see that the average multiplicity of $^3H_1$ in the events with the participation of π^+-mesons is more than twice higher than that in the events without the creation of a π^+-meson. On the one hand, this confirms a conclusion that some of π^+-mesons were formed as a result of the inelastic recharge of a proton into a neutron and a π^+-meson. Since a $^3H_1$ nucleus possesses the excess of neutrons, the increase of the number of neutrons due to the recharge leads to the growth of the tritium formation probability, as it does in experiment. On the other hand, a smaller multiplicity of tritium nuclei in the events without the participation of a π^+-meson at the final stage indicates that, owing to the absorption of this meson by the neutron phase of the nuclear matter, additional protons are formed, and the probability of either the formation of proton-excessive fragments, such as, e.g., helium-3 nuclei, or the direct yield of hydrogen nuclei increases.

The average multiplicity of $^3H_1$ nuclei in events without the participation of a π^--meson is also less than that if a π^--meson is present at the final stage, i.e. the absorption of π^-mesons by intra-nuclear clusters leads to their decay into nucleons. It can be, provided the cluster size does not exceed $A = 3$ (deuterons and helium-3), because if π^--mesons were absorbed – e.g., by an α-cluster – a tritium nucleus, which would be observed at the final stage, and a neutron would be formed.

Thus, absorption of $\pi^\pm$-mesons results in a reduction of the tritium nuclei yield, because of a finer fractionation of the initial nucleus owing to the additional pumping of energy to it. The circumstance that no dependence of the multiplicity of tritium nuclei on the momentum amplitude of π^+-mesons was observed within the limits of statistical errors confirms the importance of the very event of the absorption, rather than the kinematic characteristics of $\pi^\pm$-mesons.

It is remarkable that the average multiplicity of the formed tritium nuclei is weakly connected with the kinematic characteristics of protons which accompany the yield of tritium nuclei. Its minimal value equal to 0.195 ± 0.006 corresponds to the localizing of a trigger proton in the "evaporation" range ($P_{\mathrm{ALCS}} < 0.22$ GeV/c); and the maximal one equal to 0.229 ± 0.010 corresponds to $P_{\mathrm{ALCS}} \approx 0.25$ GeV/c. It can be explained by the fact that the processes with the emission of evaporated protons result in a stronger fractionation of the nucleus, which leads to some reduction of the tritium nucleus yield.

It was shown in work [8] that the invariant structural functions of $^2H_1$, $^3H_1$, and $^3He_2$ light fragments, formed as a result of ^{16}Op-collisions at $3.25A$ GeV/c, are described satisfactorily by the phenomenological model of coalescence in the range $T > 70$ MeV. Therefore, the fusion of cascade nucleons could be regarded as the mechanism of formation of $^3H_1$ nuclei with $T > 70$ MeV. The classification of $^3H_1$ nuclei with the kinetic energies $T < 70$ MeV and $T > 70$ MeV corresponds, in practice, to the consideration of mechanisms of formation of those nuclei through the Fermi-disintegration and the fusion of cascade nucleons, respectively.

In Table 3, the average multiplicities for various types of particles and nuclei associated with the formation of $^3H_1$ nuclei with the kinetic energies either $T < 70$ MeV or $T > 70$ MeV are quoted. From this table, it follows that, within the limits of statistical errors, it is impossible to talk about any correlation between the mechanism of the formation of $^3H_1$ nuclei and the yield of particles and nuclei concerned. Therefore, one may draw a conclusion that the cascade knocking out of secondary nucleons occurs, mainly,

T a b l e 2. Average multiplicity of $^3H_1$ in events with the participation or absence of a charged pion

Trigger particle	without a pion	with a pion	with a pion $p > 0,6$ GeV/c	with a pion $p < 0,6$ GeV/c
π^--meson	0.103±0.004	0.143±0.010	0.144±0.013	0.133±0.015
π^+-meson	0.088±0.004	0.195±0.010	0.200±0.013	0.192±0.015

T a b l e 3. Average multiplicity of various types of particles and nuclei associated with the formation of $^3H_1$ nuclei in two kinematic ranges of their formation

Particle or fragment	$T < 70$ MeV	$T \geq 70$ MeV	Particleor fragment	$T < 70$ MeV	$T \geq 70$ MeV
$^1H_1$	2.79±0.05	2.59±0.10	π^+	0.63±0.02	0.55±0.05
$^2H_1$	0.68±0.03	0.69±0.05	π^-	0.31±0.02	0.32±0.03
$^3He_2$	0.29±0.02	0.27±0.03	p_{sep}	0.44±0.03	0.47±0.04
$^4He_2$	0.85±0.03	0.82±0.05	$3\leq Z_f \leq 8$	0.20±0.01	0.30±0.03

owing to the quasi-elastic scattering of the primary and secondary particles by the nucleons of the projectile nucleus.

To summarize, we list the basic conclusions that were made taking into account the results of our research of the formation of $^3H_1$ nuclei at ^{16}Op-collisions at $3.25A$ GeV/c. They can be formulated as follows:

1. The momentum spectrum of $^3H_1$ nuclei contains a component with anomalously large values of momenta, which is not explicable from the viewpoint of statistical models. The formation of such high-energy nuclei can be interpreted as an evidence for the participation of fast cascade nucleons in the formation of tritium nuclei.

2. Strong correlations have been discovered between the multiplicities of secondary nuclei and the generated pions associated with the formation of the $^3H_1$ nucleus. To a great extent, these correlations are caused by the conservation of the baryon and electric charges and are not sensitive to the mechanisms of formation of tritium nuclei.

3. Strong positive correlations have been discovered between the multiplicity of $^3H_1$ nuclei and the formation of π^+-mesons, which points at their multiplication in the processes of inelastic recharge of nucleons in the course of multiple intra-nuclear rescattering.

4. A negative correlation has been established between the multiplicity of recoil protons and the formation of $^3H_1$ nuclei, which indicates that events with the formation of tritium nuclei are characterized by a higher number of intra-nuclear rescattering events of the initial proton and, correspondingly, by a higher development level of cascade processes in the nucleus.

5. The basic mechanism of formation of fast ($T \geq$ 70 MeV) $^3H_1$nuclei is the process of fusion of cascade nucleons which were knocked out quasielastically from the oxygen nucleus.

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УТВОРЕННЯ ТРИТІЮ ПРИ ФРАГМЕНТАЦІЇ ЯДРА ^{16}O З ІМПУЛЬСОМ 3,25A ГеВ/c

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Р е з ю м е

Наведено нові експериментальні дані з утворення ядер тритію в ^{16}Ор-співударах при $3,25A$ ГеВ/c та запропоновано їхню інтерпретацію. Встановлено кореляції множинності вторинних ядер і народжених піонів, що пов'язані з утворенням ядра $^3H_1$. Виявлено сильні позитивні кореляції множинностей ядер $^3H_1$ з народженням π^+-мезонів, що свідчать про їх мультиплікацію у процесах непружної перезарядки нуклонів під час багаторазового внутрішньоядерного перерозсіяння. Показано, що основним механізмом утворення швидких ядер $^3H_1$ (з $T \geq$70 МеВ) є процес злиття каскадних нуклонів, квазіпружно вибитих з ядра кисню.