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Features of 3α-particles formation in dissociation of ^{12}C nuclei in nuclear track emulsion

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The features of three α-particles formation in dissociation of ^{12}C nuclei at 3.65 and 0.42 *A* GeV in nuclear track emulsion are investigated. The invariant mass approach based on precision angular emission measurements of secondary fragments and approximation of the momentum conservation per nucleon of the parent nucleus is applied. On this basis, the contribution of production of unstable ^{8}Be nucleus and α-particle triples in the Hoyle state (the second excited state 0_2^+ of ^{12}C) in dissociation of ^{12}C nucleus are estimated.

Keywords: relativistic dissociation, nuclear track emulsion, light nuclei, Hoyle state.

INTRODUCTION

The main object of the experimental investigation of the dissociation of the relativistic ^{12}C nucleus into three α-particles is the famous state of the ^{12}C nucleus with spin-parity $I^\pi = 0^+$ at excitation energy of 7.65 MeV. This state was named Hoyle's state (HS) after the British astrophysicist Fred Hoyle, who predicted the existence of this resonance in 1957 [1] to explain the prevalence of the ^{12}C isotope in the Universe. Synthesis of ^{12}C nuclei occurs in fusion reactions of α-particles and the unstable ^{8}Be nucleus through the HS in stars with temperature and density corresponding to the phase of red giants. The most important consequence of the existence of the HS is the emergence of organic life. The HS is located at 378 keV above the three α particles mass threshold. This state is unstable with a width equal 8.5 eV. Such small value corresponds to the lifetime (~10^{-19} s) of several orders of magnitude greater than nuclear processes. It is comparable with the lifetimes of ^{8}Be and π^0 meson. The status of the new experimental and theoretical studies of the ^{12}C nucleus in the second excited state is presented in [2]. Materials for the study were nuclear track emulsion (NTE) samples exposed in beams of relativistic ^{12}C nuclei in the 70-80s at the Synchrophasotron of the Joint Institute for Nuclear Research (JINR, Dubna) with 3.65 *A* GeV and in 2017 at the booster of the Institute of High Energy Physics (IHEP, Protvino) with 420 *A* MeV. The NTE is a kind of photographic film which is a substrate made of plastic or glass coated with nuclear emulsion gel containing silver halide crystals dispersed in gelatin. The NTE technique has demonstrated its effectiveness in research of nucleus-nucleus interactions for more than 50 years [3]. Compared with the electronic methods for detecting charged particles, NTE retains its relevance due to unsurpassed spatial (0.5 μm) and angular (10^{-4} rad) resolution, as well as a wide range for registration of charged fragments beginning from highly ionizing short-range ions up to single-charged relativistic particles with minimal ionization. There are no electronic methods for the detection of charged particles that can compete with NTE in spatial and angular resolution.

A topical application of the NTE technique consists in studying the structure of light nuclei including radioactive ones on the basis of the advantages of the relativistic approach [4, 5]. Distributions of peripheral interactions of studied nuclei over channels of dissociation into relativistic charged fragments convey features of their structure. This possibility is lacking in electronic experiments.

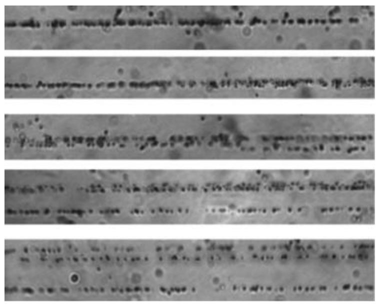

Fig. 1. Consecutive frames of dissociation $^{12}C \rightarrow 3\alpha$ at 1 *A* GeV/*c*; arrows indicate interaction vertex.

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The NTE makes it possible to observe the breakdown of relativistic nuclei up to a coherent dissociation, in which the target nuclei are not visibly destroyed in an obvious track (the example in Fig. 1). Such kinds of events are called "white" stars accounting for several percent of the total number of interactions. They are most valuable for interpreting the structure since in them distortion of an initial state of a nucleus that experiences dissociation can be considered minimal. Among the key results of the Becquerel [6] [experiment is the determination of contribution of unstable ^{8}Be and ^{9}B nuclei in dissociation of relativistic nuclei ^{10,11}C and ^{10}B. In general, the energy of a few-particle system Q is defined as the difference between the invariant mass of the system M^* and the mass of the primary nucleus or the sum of masses of the particles M, that is, $Q = M^* - M$. M^* is defined as the sum of all products of 4-momenta $P_{i,\ k}$ fragments $M^{*2} = (\Sigma P_j)^2 = \Sigma(P_iP_k)$. Subtraction of mass is a matter of convenience and Q is also invariant mass. In the case of relativistic nucleus fragmentation, the 4-momenta $P_{i,k}$ are determined in the conservation approximation by fragments of an initial momentum per nucleon (or the conservation of longitudinal velocity by fragments).

The obtained experience of reconstruction of ^{8}Be and ^{9}B is applicable to the search for relativistic decays of the HS. Decays of the HS at ^{8}Be + α at a contrast of relativistic energy and the minimum possible stored energy of 3α ensembles could demonstrate the HS as an integral object similar to ^{8}Be. Despite the unique capabilities of the NTE technique, its history seemed complete in the 2000s. However, since 2012, the company Slavich (Pereslavl Zalessky, Russia) has resumed production of NTE layers with a thickness from 50 to 200 μm on a glass base. At the present time, production of baseless layers 500 μm thick is being mastered. The solution of this problem will make it possible to fully resume the methodological culture.

EXPOSURE OF NTE STACKS IN BEAM OF ^{12}C NUCLEI

Exposures of the NTE layers were carried out in two sessions at the U-70 accelerator complex of IHEP. The beam of ^{12}C nuclei with energy of about 450 A MeV was formed in the channel of the U-70 booster of IHEP used for biomedical research. The channel provides the required uniformity of

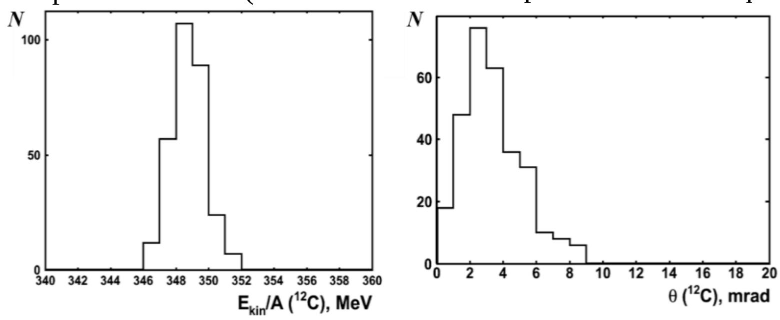

Fig. 2. Estimation of ionization losses during the passage of ^{12}C nuclei (E_{kin} = 450 A MeV) through the air volume (distance 30 m) calculated by modeling in Geant4.

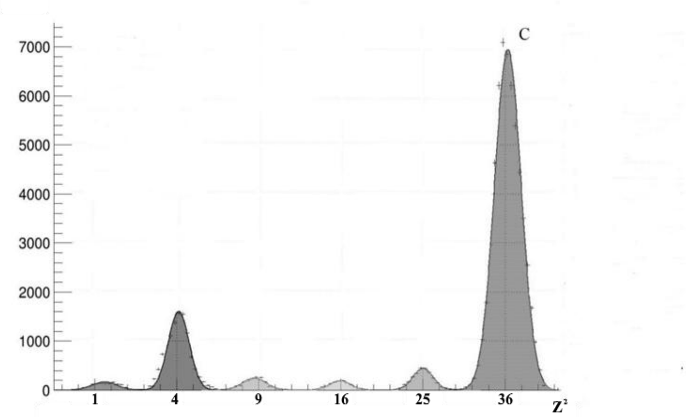

Fig. 3. The amplitude spectrum of the beam composition at the site of irradiation of nuclear emulsions [*Error! Reference source not found.*].

exposure by means of rotating electrostatic diffusers. Theoretical calculations of the cross sections for electromagnetic dissociation of light nuclei indicate a broad maximum in the region of several hundred MeV per nucleon. A number of practical conveniences arise with a decrease in the energy of nuclei. Firstly, the visual contrast between fragment α-pairs and narrow pairs due to $^{8}Be_{g.s}$ decays increases. Secondly, the share of background events with the production of charged mesons decreases. Thirdly, the leveling of the beam profile at the entrance to the NTE stack is simplified. The mode of slow extraction was changed in order to ensure that the density of particles at the irradiation site is about 2000-4500 nuclei / cm^2. The exposure point of the NTE stacks was shifted an additional 30 meters in the beam direction. Estimation of the ionization losses and the angular spread during the beam transfer through the scintillator, beryllium plate and the air volume (distance about 30 m) is presented in Figure 2.

Four stacks with 13 NTE layers and one stack with 12 NTE layers were packed. The dimensions of the NTE layers are 9×9 cm^2, the thickness is ≈ 200 μm. The control of exposure of NTE stacks was carried out using three counters: on the basis of scintillators produced by IHEP (plastic polystyrene type SC-301) measuring 10×10 mm^2 with a thickness of 1 mm and PMTs - 85. NTE stacks were installed over the counters. The fraction of nuclei with a charge of $Z_N = 6$ was about 78%, Z_N = 5 – 2%, Z_N = 4 – 2%, Z_N = 3 – 2%, Z_N = 2 – 14%, Z_N = 1 – 2% (see Figure 3). The NTE stacks were exposed in several cycles with a common intensity of 10^5 nuclei per one stack (according to a scintillation counter).

ANGULAR DISTRIBUTION IN $^{12}C \rightarrow 3\alpha$ EVENTS

Manual search for events of ^{12}C nuclei dissociation into three α-particles was carried out by means of the microscope MBI-9 with objective magnification of ×60. Accelerated method "view by strips" was chosen for this task. NTE allows to observe and distinguish all tracks of charged particles in 4π-geometry (even for opening angle less than 1 mrad). The search was carried out in a narrow part (strip with a width of 200 μm) of NTE layer in the direction perpendicular to the direction of the beam (Figure 4). When finding the alpha track or narrow jet of alpha particles the track(s) was pulled to the interaction vertex and fixed its position. Thus, the search provided statics of 720 events of ^{12}C dissociation into three α-particles.

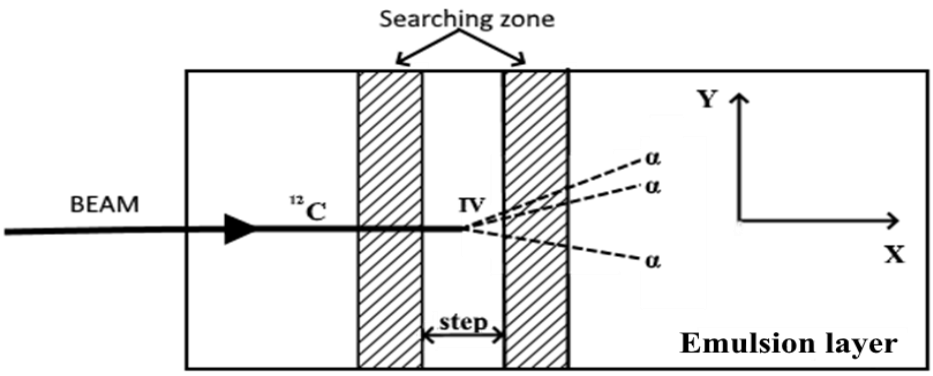

Fig. 4. Scheme of the search for $^{12}C \rightarrow 3\alpha$ event in NTE. Beam – direction of incoming beam, searching zone – strips for searching events, step – distance between strips, IV- interaction

Measurements of the emission angles of α-particles were performed for 86 events $^{12}C \rightarrow 3\alpha$, including 39 events of the "white" star. The angular measurement procedure was carried out by microscope for measurement of nuclear tracks KSM - 1 (VEB Carl Zeiss Jena). In addition, angular measurements made in the 1990s are available for 72 (G.M. Chernov's group, Tashkent) [7] and 114 "white" stars $^{12}C \rightarrow 3\alpha$ (A. Sh. Gaitinov's group, Alma-Ata) in NTE layers irradiated at the JINR Synchrophasotron at 4.5 *A* GeV/*c*. At that time, the problem of observing the HS was not posed. Recently, in collaboration with the group of N. G. Peresadko (FIAN), data on 238 3α-stars, including 130"white", have been added. Thus, the analysis is provided with statistics of 510 $^{12}C \rightarrow 3\alpha$ events.

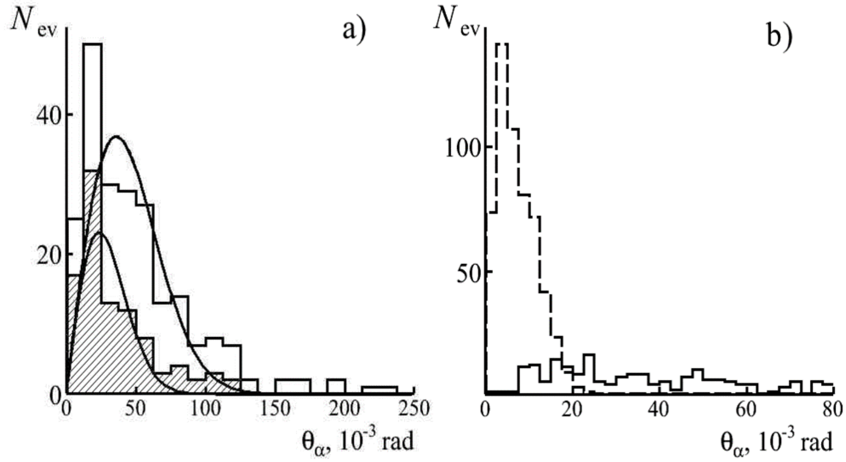

Fig. 5. (a) Distribution of the α-particle polar angle θ in events $^{12}C \rightarrow 3\alpha$. All events – solid line, "white" star – hatched. Curved lines are Rayleigh fit distribution function. (b) Distribution over the polar angle θ of α-particles in events $^{12}C \rightarrow 3\alpha$ at 4.5 *A* GeV / *c* (dashed) and $^{12}C \rightarrow 3\alpha$ at 1 *A* GeV/*c* (solid).

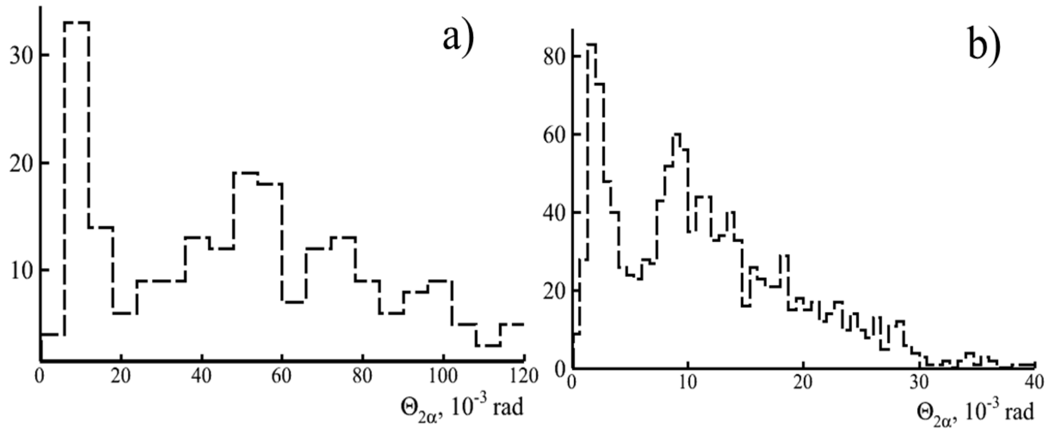

Fig. 6. Distribution over angle $\Theta_{2\alpha}$ of α-particle pairs in events of $^{12}C \rightarrow 3\alpha$ at 1 *A* GeV/*c* (a) and at 4.5 *A* GeV/*c* (b).

Single-particle distributions over the spatial angle of emission of α-particles in all measured events (Figure 5 (a)) are described by the Rayleigh distribution parameter σ_θ = (36 ± 3) mrad, for white-star events σ_θ = (23 ± 4) mrad. In the framework of the statistical model, the Rayleigh distribution parameter is σ_θ = 40 mrad. Figure 5 (b) jointly presents measurements on the polar angle of departure of θ_α α-particles for two values of the initial momentum.

The energy coverage from hundreds of MeV to several GeV per nucleon makes it possible to test the universality of identifying the formation of HS by the variable effective invariant mass of three α-particles $Q_{3\alpha}$.

Opening angles of α-particle pairs are shown in Figure 6. The distribution shows a peak in the region of up to 20 mrad with $\langle\Theta_{2\alpha}\rangle$ = (10.6 ± 0.6) with RMS 3.9 mrad, which corresponds to (17 ± 1)% of the statistics. Cascade process of α - particles emitting through the unstable ^{8}Be nucleus in the ground 0^+ state characterizes such events. Next peak in the region of 35 < $\Theta_{2\alpha}$ <90 mrad can be assigned to the decay of ^{12}C through the formation of the ^{8}Be nucleus in the second excited state 2^+.

RECONSTRUCTION OF ^{8}Be AND HS DECAYS

Information about the mechanism of formation of the α-particle system is obtained by the spectrum of their invariant masses $Q_{N\alpha}$. Figure 7 shows the functional dependence of the invariant masses $Q_{2\alpha}$ of α-pairs on measured angles $\Theta_{2\alpha}$ for the dissociation of $^{12}C \rightarrow 3\alpha$ at 1 and 4.5 *A* GeV/*c*, $^{10}B \rightarrow 2\alpha + p$ at 1.6 *A* GeV/*c* and $^{11}C \rightarrow 2\alpha + 2p$ at 2.0 *A* GeV/*c*.The *Q* values for α pairs are calculated as follows:

(1)

assuming conservation of parent momentum per nucleon. Figure 8 shows the projection of this dependence in the variable $Q_{2\alpha}$ for the dissociation of ^{12}C nuclei at 1 and 4.5 *A* GeV/*c*. The region $Q_{2\alpha}$ < 0.2 MeV contains a peak corresponding to the contribution of ^{8}Be decays from the ground state 0^{+}. Table 1 summarizes the data for the mean values of $\langle\Theta_{2\alpha}\rangle$ ($Q_{2\alpha}$ < 300 keV) and $\langle Q_{2\alpha}\rangle$. For all previously studied nuclei the role of the ^{8}Be nucleus was established. Observation of ^{8}Be decays from the ground state demonstrates both the excellent resolution of the angular measurements in the emulsion and the convenience of the invariant representation. The average values of $\langle\Theta_{2\alpha}\rangle$ are related as inverse ratio of initial momenta of parent nuclei. Consideration of these events in the variable invariant mass *Q* of the 2α-particle system indicates the identity of the source of the appearance of narrow α-pairs in all cases with average values $\langle\Theta_{2\alpha}\rangle$ of the ^{8}Be decay energy from the ground state 0^{+}. RMS values $\Theta_{2\alpha}$ show the resolution of the method. Thus, reconstructed ^{8}Be nuclei become reference events for the search for HS events.

An important feature of HS identification, as well as of identification of decays of unstable ^{8}Be and ^{9}B nuclei is that the HS energy level is also quite separated from the nearest excitation thresholds of the ^{12}C nucleus (the next level from HS is 9.641 MeV). The previously tested invariant mass approach is applicable to the identification of HS events by the invariant mass of α-triples $Q_{3\alpha}$ according to the formula:

(2)

Table 1. Mean values of $\langle\Theta_{2\alpha}\rangle$ and $\langle Q_{2\alpha}\rangle$ ($Q_{2\alpha}$ < 200 keV)

Nucleus (P_0, *A* GeV/*c*)	$\langle\Theta_{2\alpha}\rangle$ (RMS), mrad ($Q_{2\alpha}$ < 200 keV)	$\langle Q_{2\alpha}\rangle$ (RMS), keV
^{12}C (4.5)	2.1 ± 0.1 (0.8)	109 ± 11 (83)
^{16}O (4.5)	1.8 ± 0.3 (0.6)	81 ± 2 (50)
^{22}Ne (4.1)	1.9 ± 0.1 (0.8)	82 ± 5 (52)
^{14}N (2.9)	2.9 ± 0.2 (1.9)	120 ± 10 (72)
^{9}Be (2.0)	4.4 ± 0.2 (2.1)	86 ± 4 (48)
^{10}C (2.0)	4.6 ± 0.2 (1.9)	63 ± 7 (83)
^{11}C (2.0)	4.8 ± 0.3 (1.9)	77 ± 7 (40)
^{10}B (1.6)	5.9 ± 0.2 (1.6)	101 ± 6 (46)
^{12}C (1.0)	10.4 ± 0.5 (3.9)	107 ± 10 (79)

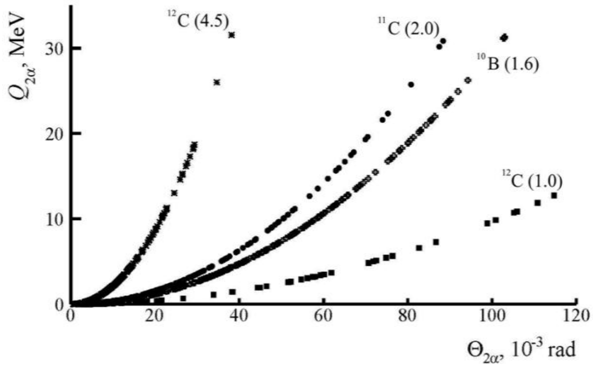

Fig. 7. Dependence of calculated invariant masses of α pairs $Q_{2\alpha}$ over opening angles in them $\Theta_{2\alpha}$ in events of dissociation of ^{12}C, ^{11}C, and ^{10}B nuclei; momentum values are indicated in parentheses (*A* GeV/*c*).

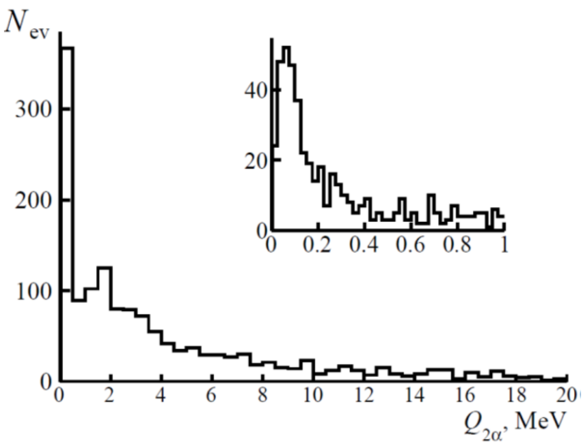

Fig. 8. Distribution over invariant mass of α pairs in the dissociation $^{12}C \to 3\alpha$ at 4.5 and 1 *A* GeV/*c*; in insert: region of $Q_{2\alpha} < 1$ MeV.

In the distribution over the invariant mass of the α triples $Q_{3\alpha}$ shown in Figure 9, there is a peak in the region $Q_{3\alpha} < 1$ MeV where the HS decays should be reflected. In the case of 424 events of $^{12}C \to 3\alpha$ at 4.5 *A* GeV / *c*, the average value for events at the peak is $\langle Q_{3\alpha} \rangle = (443 \pm 52)$ at RMS 186 keV and for 86 events at 1 *A* GeV/*c* $\langle Q_{3\alpha} \rangle = (348 \pm 32)$ at RMS 75 keV.

According to the condition of $Q_{3\alpha}$ <1 MeV in exposure of 4.5 *A* GeV/*c* 42 (out of 424) events can be attributed to HS and in the case of 1 *A* GeV/*c* - 9 (out of 86), including 5 “white” stars (from 36). As a result, the probability of observation of the α-particles triples in the HS in dissociation of ^{12}C nucleus into three α-particles is (10 ± 2)%.

The available measurements allow to make conclusions about the dynamics of the HS formation according to the distributions over the total transverse momentum P_{Tsum} of α-particle triples (Figure 10). For 316 “white” stars of $^{12}C \to 3\alpha$ at 4.5 *A* GeV/*c*, the mean value of the total transverse momentum P_{Tsum} of α-triples $\langle P_{Tsum} \rangle$ = (254 ± 9) with RMS 154 MeV/*c*, and for a sample of 37 events, $Q_{3\alpha} < 1$ MeV - $\langle P_{Tsum} \rangle$ = (200 ± 20) with RMS 122 MeV/*c*. For 36 events of peripheral dissociation $^{12}C \to 3\alpha$ at 1 *A* GeV/*c* is $\langle P_{Tsum} \rangle$ = (229 ± 21) with RMS 125 MeV/c, and for 5 of them corresponding to the HS - $\langle P_{Tsum} \rangle$ = (139 ± 18) with RMS 41 MeV/*c*. Obtained values of $\langle P_{Tsum} \rangle$ correspond to the nuclear diffraction reaction mechanism. In the case of electromagnetic dissociation into *quasi*-real photons of a heavy target nucleus the limitation would be P_{Tsum} < 100 MeV/*c*. It can be assumed that an increase in statistics will allow the formation of the HS to be recorded outside the fragmentation cone of the parent nucleus. Such events were observed in cases of $^9Be \to {}^8Be$ and $^{10}C \to {}^9B$.

Such observations would clearly demonstrate the HS as an integral and long-lived nuclear-molecular state.

Recently started reanalysis of data of the dissociation of $^{16}O \rightarrow 4\alpha$ nuclei at 4.5 *A* GeV/*c* [8]. allowed us to establish the contribution of the HS production ($^{16}O \rightarrow {}^{12}C^* (\rightarrow 3\alpha) + \alpha$) at the level of (22 ± 2)% (Figure 11). Thus, the identification of events in the HS in the dissociation of relativistic ^{12}C nuclei opens up the prospect for this method to search for condensate states with a large number of clusters and nucleons in the dissociation of heavier nuclei into ultra-narrow jets of the lightest nuclei.

CONCLUSION

Analysis of the exposed NTE layers by ^{12}C nuclei (1 *A* GeV/*c*) performed at the accelerator complex of U-70 in IHEP (Protvino) was carried out. The main goal of the analysis was focused on channel $^{12}C \rightarrow 3\alpha$. Such events were found to be 86. The statistics obtained were supplemented with 424 events $^{12}C \rightarrow 3\alpha$ (4.5 *A* GeV/*c*) from the early exposure of NTE layers performed at the JINR Synchrophasotron.

Angular analysis of the emission of α-particles indicated the possible contribution of the decay of ^{8}Be nuclei to the dissociation of ^{12}C nuclei with probability of (17 ± 1)%. The experience gained in the reconstruction of ^{8}Be and ^{9}B was applied to search for relativistic decays of the Hoyle's state. The contribution of HS decays to $^{12}C \rightarrow 3\alpha$ dissociation is (10 ± 2)% for the total statistics. However, the NTE method does not allow investigating the features of the HS decay. The reconstruction of the HS by the invariant mass of relativistic α-triples can be used to study the processes with the formation of the HS as an integral object at large momentum and for other nuclei, except ^{12}C.

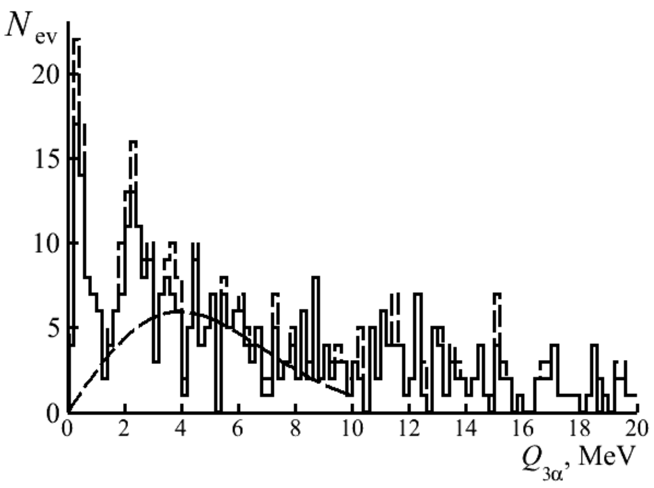

Fig. 9. Distribution over invariant mass $Q_{3\alpha}$ of α-triples in the dissociation $^{12}C \rightarrow 3\alpha$ at 3.65 *A* GeV (shaded) and 420 *A* MeV (added by a dotted line); line - Rayleigh distribution with the parameter $\sigma(Q_{3\alpha}) = (3.9 \pm 0.4)$ MeV .

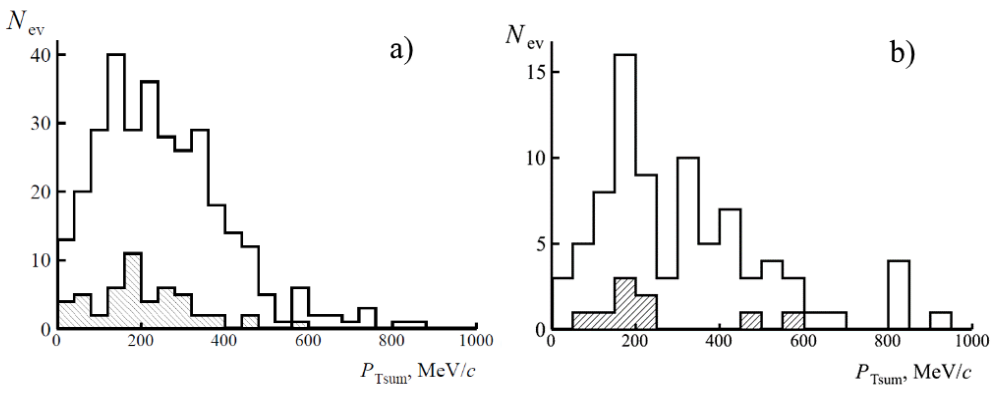

Fig. 10. Distribution of α triples over total transverse momentum P_{Tsum} in dissociation $^{12}C \rightarrow 3\alpha$ at 4.5 (a) and 1 *A* GeV/*c* (b); contribution of the HS decays is hatched.

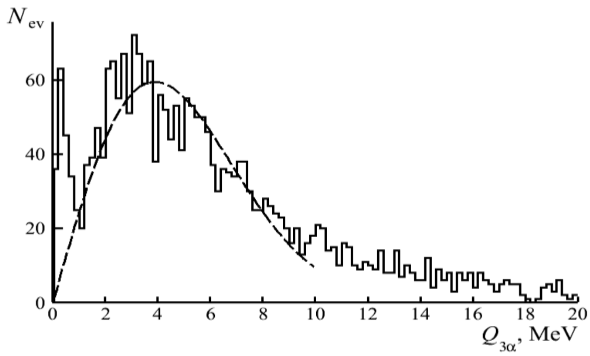

Fig. 11. Distribution of all α-triples in "white" stars $^{16}O \rightarrow 4\alpha$ at 3.65 *A* GeV over invariant mass $Q_{3\alpha}$; line - Rayleigh distribution.

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REFERENCES

1. E. M. Burbidge, G. R. Burbidge, William A. Fowler, and F. Hoyle, *Reviews of Modern Physics*, **29 (4)**, 547 (1957).
2. M. Freer, H. O. U. Fynbo, *Progr. Part. Nucl. Phys*. **78**, 1 (2014).
3. C. F. Powell, P. H. Fowler, D. H. Perkins, M. W. Friedlander, *Physics Today*, **13(9)**, 45 (1960).
4. D. A. Artemenkov, A. A. Zaitsev, P. I. Zarubin, *Phys. Part. Nucl*. **48**, 147 (2017).
5. P.I. Zarubin, Lect. Notes in Physics, Clusters in Nuclei, Springer Int. Publ., **875(**3**)**, 2014, p. 51,
6. The Becquerel Project, http://becquerel.jinr.ru/.
7. V. V. Belaga, A. A. Benjaza, V. V. Rusakova, J. A. Salamov, G. M. Chernov, *Physics of Atomic Nuclei*, **58**, 1905 (1995).
8. N. P. Andreeva, Z. V. Anzon, V. I. Bubnov, A. Sh. Gaitinov, G. Zh. Eligbaeva, L. E. Eremenko, G. S. Kalyachkina, E. K. Kanygina, A. M. Seitimbetov, I. Ya. Chasnikov, Ts. I. Shakhova, M. Haiduk, S. A. Krasnov, T. N. Maksimkina, K. D. Tolstov, G. M. Chernov, N. A. Salmanova, D. A. Salomov, A. Khushvaktova, F. A. Avetyan, N. A. Marutyan, L. T. Sarkisova, V. F. Sarkisyan, M. I. Adamovich, Yu. A. Bashmakov, V. G. Larionova, G. I. Orlova, N. G. Peresadko, M. I. Tretyakova, S. P. Kharlamov, M. M. Chemyavsky, V. G. Bogdanov, V. A. Plyushchev, Z. I. Soloveva, V. V. Belaga, A. I. Bondarenko, Sh. A. Rustamova, A. G. Chemov, N. N. Kostanashvili, S. Vokál, *Physics of Atomic Nuclei*, **59**, 102 (1996), arXiv:1109.3007.