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TECHNOLOGY OF NUCLEAR MATERIALS

# Application of Nuclear Track Emulsion in Search for the Hoyle State in Dissociation of Relativistic $^{12}C$ Nuclei[1]

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**Abstract**—In dissociation in nuclear track emulsion of 4.5 and 1 *A* GeV/*c* $^{12}C$ nuclei, the formation of triplets of α particles in the Hoyle state (the second excited state $0^+$) is observed. This state is identified by the invariant mass, calculated from pair angles in the α triples in approximation of conservation of momentum per nucleon of the parent nucleus. An estimate of the contribution of the Hoyle state to the dissociation of $^{12}C \to 3\alpha$ is 10–15%.

**Keywords:** nuclear emulsion, dissociation, invariant mass, relativistic fragments, $^{12}C$ nucleus, Hoyle's state, alpha particles

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## INTRODUCTION

Exposures of nuclear track emulsion (NTE) to newly formed beams of relativistic nuclei, which began in the 1970s at the JINR Synchrophasotron of and LBL Bevalac (Berkeley, USA), since the early 2000s have found a continuation at the JINR Nuclotron in the BECQUEREL Experiment [1]. A topical application of the NTE technique consists in studying the structure of light nuclei, including radioactive ones, on the basis of advantages of the relativistic approach [2, 3]. 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. 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 way (the example in Fig. 1). Events of this kind, called "white" stars, account for several percent of the total number of interactions. They are the 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 experiment is determination of contribution of unstable $^{8}Be$ and $^{9}B$ nuclei in dissociation of relativistic nuclei $^{10,11}C$ and $^{10}B$. The meaning of this fact is as follows. As is known, nucleosynthesis involving $^{8}Be$ and $^{9}B$ is suppressed because of absence of bound ground states. Nevertheless, this circumstance does not prevent the substantial contribution of $^{8}Be$ and $^{9}B$. The obtained experience of reconstruction of $^{8}Be$ and $^{9}B$ is applicable to the search for relativistic decays of the Hoyle state (HS).

The status of the experimental and theoretical study of the second excited state of the $^{12}C$ nucleus is presented in the review [4]. This excitation is named after the astrophysicist F. Hoyle, who postulated its existence to explain the prevalence of the $^{12}C$ isotope in Universe as a synthesis product in stars. Following an accurate prediction of the HS energy, it was experimentally confirmed that the $^{12}C$ nucleus has an excited state located at only 378 keV above the mass threshold of three α particles. Although it is unstable, its width is only 8.5 eV. Such a small value indicates a lifetime of 5–6 orders of magnitude greater than that characteristic of nuclear processes. It is comparable with the lifetimes of $^{8}Be$ and $\pi^0$ meson. The prohibition of the fusion of $\alpha + {}^{12}C$ due to improper parity of low-lying levels in the $^{16}O$ nucleus determines the ratio of the prevalence of the isotopes $^{12}C$ and $^{16}O$. The transition of one of the merging $^{12}C$ nuclei into the HS is considered as a "gateway" for the synthesis of the $^{16}O$ isotope.

The structure of the HS remains in the focus of modern nuclear physics. In particular, the concept of

[1] The article was translated by the authors.

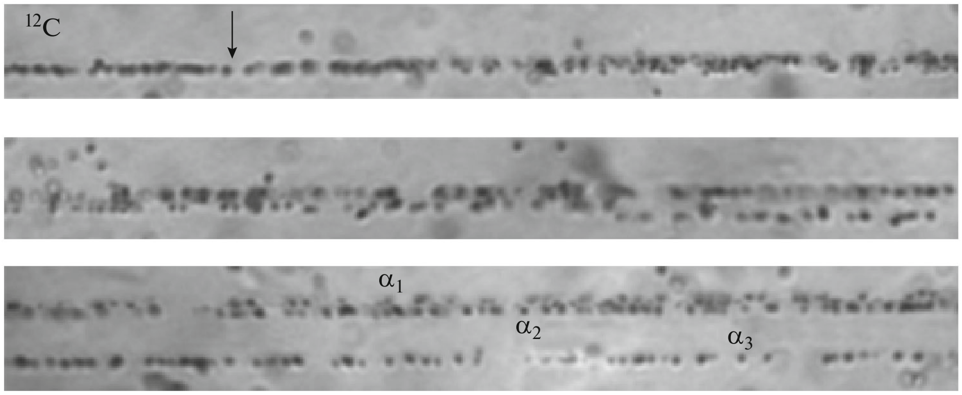


**Fig. 1.** Consecutive frames of coherent dissociation $^{12}C \rightarrow 3\alpha$ at 1 *A* GeV/*c* ("white" star); arrow indicate interaction vertex; grain sizes are about 0.5 μm.

the α-particle Bose–Einstein condensate is suggested [5]. As the simplest forms ("building blocks") of such a condensate, the ground state of the unstable $^{8}$Be nucleus and, subsequently, the HS are suggested. Observation of the HS at high energy can provide additional evidence of the nuclear-molecular pattern of the HS. First of all, it is necessary to establish the very possibility. 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. Within the framework of the BECQUEREL experiment, the NTE samples were tested in topical experiments in which there was a whole variety of ionization tracks from slow heavy ions to relativistic particles [6]. On the basis of photography on microscopes, the experience of computer recognition of short nuclear tracks in NTE was obtained. 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 that could be lost. At the present time, along with works on the HS problem, an exposure to relativistic muons is under study. In addition, preparations are in progress for analyzing the triple fission induced by thermal neutrons in NTE samples impregnated in a solution of uranyl nitrate. Such diverse tasks are combined by the application of novel NTE samples produced by Slavich. Results of the HS study are presented below.

## APPLICATION OF INVARIANT MASS APPROACH

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 $M^{*2} = (\Sigma P_j)^2 = \Sigma(P_i P_k)$. Subtraction of mass is a matter of convenience and $Q$ is also an 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). This approach is well established in the region of limiting fragmentation of relativistic nuclei [7]. The definition of $Q$ is reduced to determining the relative angles between the directions of emission of fragments. The required methods of three-dimensional coordinate measurements of tracks of relativistic particles in NTE on microscopes were developed at the beginning of studies on the physics of cosmic rays few decades ago [8]. Being almost invariant, the variable $Q$ allows one to compare the data for different values of projectile nucleus energy.

The ground state of $^{8}$Be is sufficiently separated from the first excited state $2^+$ [9] to identify $^{8}$Be in a fragmentation cone in the spectrum over the invariant mass $Q_{2\alpha}$ calculated on the opening angle of the α pair $\Theta_{2\alpha}$. The same approach is applicable to the identification of the HS with respect to the invariant mass of α triples $Q_{3\alpha}$. Like $^{8}$Be, it is also sufficiently separated from the nearest excitations of the $^{12}$C nucleus [9]. Therefore, the same approach is applicable to the identification of the HS with respect to the invariant mass of α-triples $Q_{3\alpha}$, according to the formula

$$Q_{3\alpha} = \sqrt{\sum_{i \neq j} (E_{\alpha_i} E_{\alpha_j} - P_{\alpha_i} P_{\alpha_j} \cos\Theta_{2\alpha})} - 3m_\alpha,$$

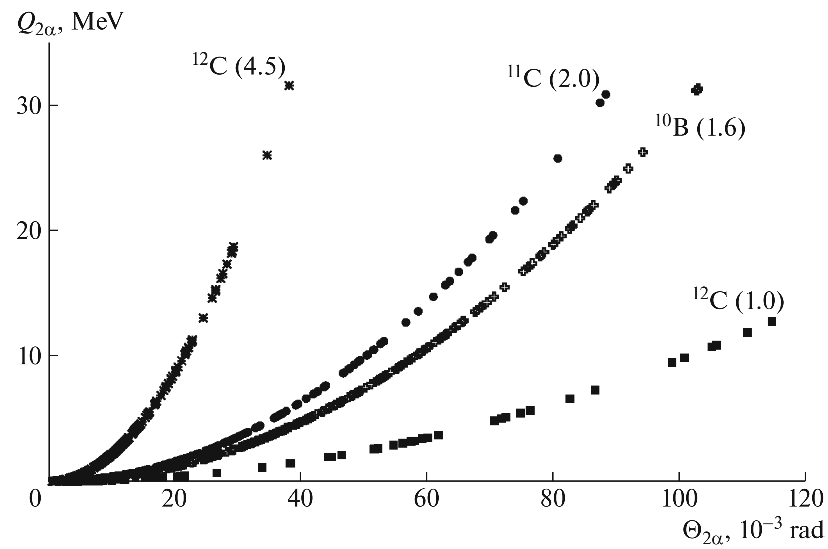


**Fig. 2.** Dependence of calculated invariant masses of α pairs $Q_{2\alpha}$ over opening angles in them $\Theta_{2\alpha}$ in events of dissociation of $^{12}$C, $^{11}$C, and $^{10}$B nuclei; momentum values are indicated in parentheses ($A$ GeV/$c$).

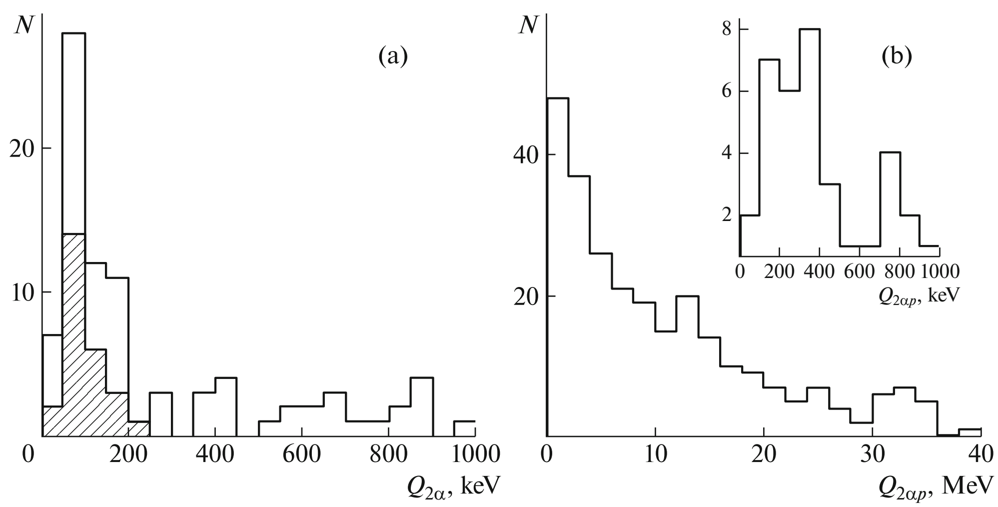


**Fig. 3.** Distributions over invariant mass of α pairs $Q_{2\alpha}$ < 1 MeV (a) and $2\alpha p$ triples $Q_{2\alpha p}$ (b) for fragmentation $^{10}$B → 2He + H at 1.6 $A$ GeV/$c$; in (b) insert, region $Q_{2\alpha p}$ < 1 MeV; contribution of identified decays $^{9}$B → $^{8}$Be (a) is shaded.

where $E_\alpha$ and $P_\alpha$ are energy and momentum values of the α particles $i$ and $j$, $\Theta_{2\alpha}$ is the angle of separation between them, and $m_\alpha$ is the mass of the α particle; $P_\alpha = 4P_0$, where $P_0$ is the momentum per nucleon of incident nuclei.

In the BECQUEREL experiment, data are obtained for the $^{10}$B and $^{11}$C nuclei making it possible to demonstrate resolution over the invariant mass for $^{8}$Be and $^{9}$B. Figure 2 shows the functional dependence of $Q_{2\alpha}$ on $\Theta_{2\alpha}$ for the dissociation of the $^{12}$C, $^{11}$C, and $^{10}$B nuclei discussed below. Decays of $^{8}$Be should manifest themselves in the region of minimum values of $\Theta_{2\alpha}$; the upper limit depends on the momentum of the parent nucleus. Examples of the reconstruction of $Q_{2\alpha}$ and $Q_{2\alpha p}$ are shown in Figs. 3 and 4 for $^{10}$B and $^{11}$C.

According to [9], the decay energy of $^{8}$Be is 91.8 keV with a width of 5.57 eV, and the values for $^{9}$B are 185.1 keV and 0.54 ± 0.21 keV, respectively. Figures 3 and 4 contain the $Q_{2\alpha}$ distributions for the identified decays of $^{9}$B, which gives the purest $^{8}$Be channel. Table 1 gives a summary of mean values of opening angles in α pairs $\langle\Theta_{2\alpha}\rangle$ and $\langle Q_{2\alpha}\rangle$ ($Q_{2\alpha}$ < 300 keV) which indicates their correspondence to the $^{8}$Be nucleus. Table 2

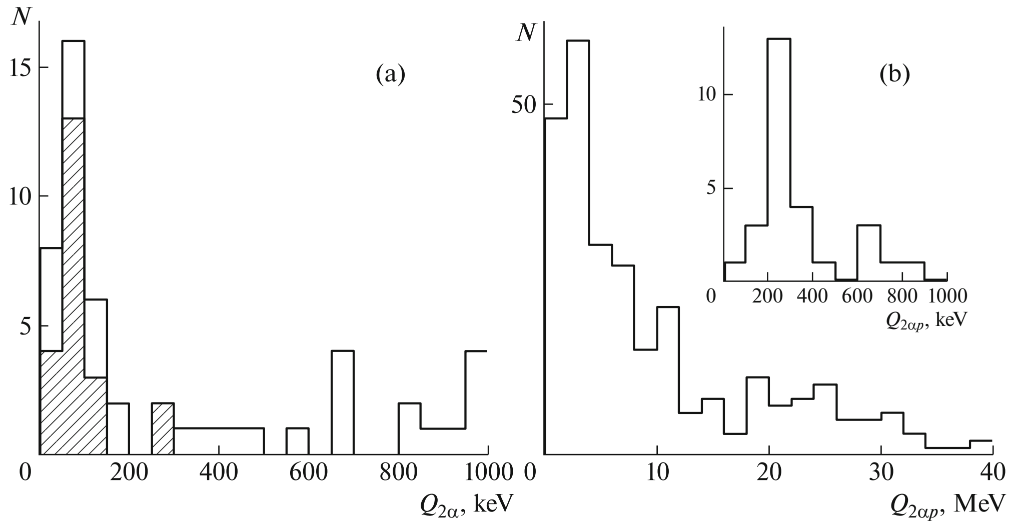


**Fig. 4.** Distributions over invariant mass of $Q_{2\alpha} < 1$ MeV; (a) and $2\alpha p$ triples $Q_{2\alpha p}$ (b) for "white" stars $^{11}C \rightarrow 2He + 2H$ at 2.0 *A* GeV/*c*; in (b) insert, region $Q_{2\alpha p} < 1$ MeV; contribution of identified decays $^{9}B \rightarrow {}^{8}Be$ is shaded (a).

shows the data for $2\alpha p$ triples. RMS values demonstrate that the resolution allows the certain identification of $^{8}Be$ and $^{9}B$. In the case of $^{10}B$ fragmentation, 42% of the $^{8}Be$ decays correspond to decays of $^{9}B$, and for $^{11}C$, 66%. For $^{10}C$, such a match was complete.

## RESULTS OF ANALYSIS

The current material for the investigation of the HS is 200-μm NTE layers on glass longitudinally irradiated with 1 *A* GeV/*c* $^{12}C$ nuclei in the biomedical beam of the Institute of High Energy Physics (Protvino). Accelerated search for $3\alpha$ events is carried out in them by accelerated scanning along bands that are transverse to the direction of the beam. At present, angular measurements in 86 events $^{12}C \rightarrow 3\alpha$ have been performed in the NTE layers, including in 36 "white" stars.

In addition, angular measurements made in the 1990s are available for 72 (G.M. Chernov's group, Tashkent) [10] 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. Figure 5 shows jointly the measurements over the polar emission angle $\theta_\alpha$ of α particles at these two

**Table 1.** Mean values of $\langle\Theta_{2\alpha}\rangle$ and $\langle Q_{2\alpha}\rangle$ ($Q_{2\alpha} < 300$ keV)

| Nucleus ($P_0$, *A* GeV/*c*) | $\langle\Theta_{2\alpha}\rangle$ (RMS), $10^{-3}$ rad ($Q_{2\alpha} < 300$ keV) | $\langle Q_{2\alpha}\rangle$ (RMS), keV |
|---|---|---|
| $^{12}C$ (4.5) | 2.1 ± 0.1 (0.8) | 109 ± 11 (83) |
| $^{14}N$ (2.9) | 2.9 ± 0.2 (1.9) | 119.6 ± 9.5 (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) | 4.7 ± 0.3 (1.9) | 77 ± 7 (40) |
| $^{11}C(2.0) \rightarrow {}^{9}B \rightarrow {}^{8}Be$ | | 94 ± 15 (86) |
| $^{10}B$ (1.6) | 5.9 ± 0.2 (1.6) | 101 ± 6 (46) |
| $^{10}B(1.6) \rightarrow {}^{9}B \rightarrow {}^{8}Be$ | | 105 ± 9 (47) |
| $^{12}C$ (1.0) | 10.4 ± 0.5 (3.9) | 107 ± 10 (79) |

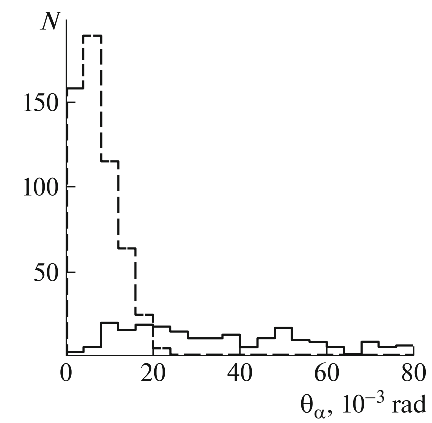


**Fig. 5.** Distribution over polar angle of emission of $\alpha$ particles $\theta$ in the $^{12}C \to 3\alpha$ events at 4.5 (dashed) and 1 *A* GeV/*c*.

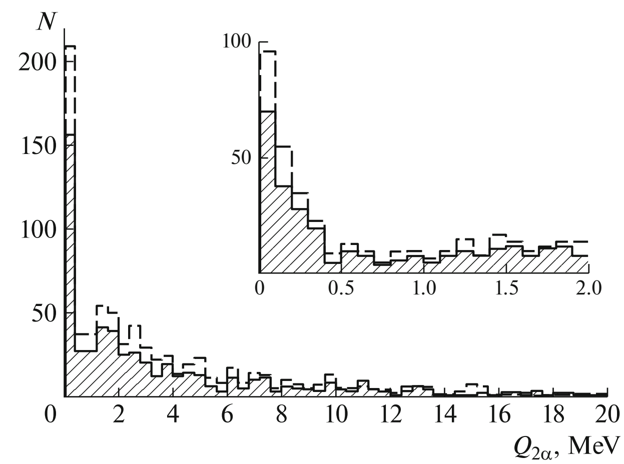


**Fig. 6.** Distribution over invariant mass of $\alpha$ pairs $Q_{2\alpha}$ <2 MeV in the dissociation $^{12}C \to 3\alpha$ at 4.5 (shaded) and 1 *A* GeV/*c* (added by dashed line); in insert: region of $Q_{2\alpha} < 1$ MeV.

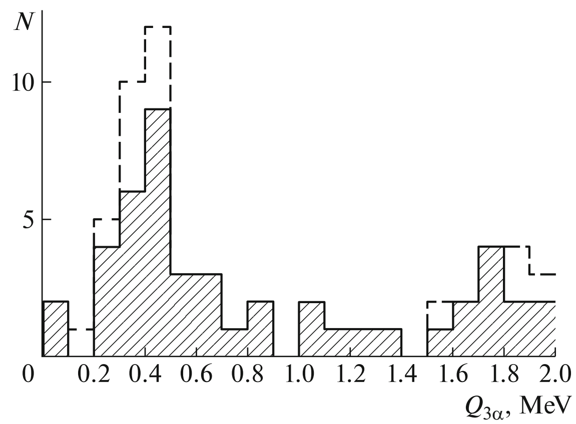


**Fig. 7.** Distribution over invariant mass of $\alpha$ triples $Q_{3\alpha}$ < 2 MeV in dissociation of $^{12}C \to 3\alpha$. at 4.5 *A* GeV/*c* (shaded) and 1 *A* GeV/*c* (added by dashed line).

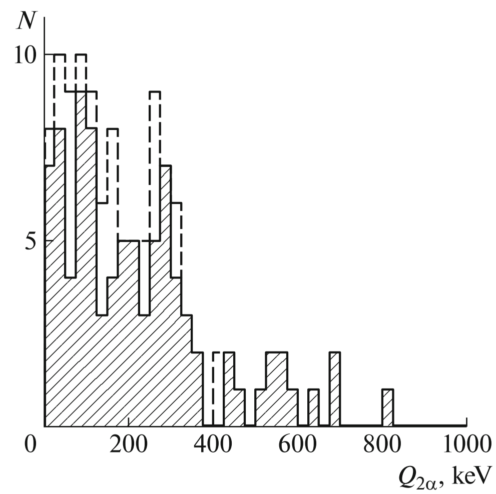


**Fig. 8.** Distribution over invariant mass of $\alpha$-pairs $Q_{2\alpha}$ < 2 MeV in the HS decays ($Q_{3\alpha}$ < 1 MeV) in dissociation of $^{12}C \to 3\alpha$ at 4.5 (shaded) and 1 *A* GeV/*c* (added by dotted line).

momentum values. The energy coverage—from hundreds of MeV to several GeV per nucleon—makes it possible to verify the universality of the HS identification in the variable $Q_{3\alpha}$.

Figure 6 shows the distribution of $Q_{2\alpha}$. The region $Q_{2\alpha}$ < 400 keV contains a peak pressed to the origin which corresponds to decays of $^8$Be. Although the $^8$Be signal is present, the distribution is significantly wider than in Figs. 3 and 4.

**Table 2.** Mean values of $\langle Q_{2\alpha p}\rangle$ ($Q_{2\alpha p}$ < 400 keV)

| Nucleus | $\langle Q_{2\alpha p}\rangle$ (RMS), keV |
|---|---|
| $^{10}$B | 249 ± 19 (91) |
| $^{10}$C | 254 ± 18 (96) |
| $^{11}$C | 273 ± 18 (82) |

In the distribution over the invariant mass of the $\alpha$ triples $Q_{3\alpha}$ shown in Fig. 7, there is a peak in the region $Q_{3\alpha}$ < 1 MeV where the HS decays should be reflected. For events at 4.5 *A* GeV/*c*, the mean value for the events at the peak $\langle Q_{3\alpha}\rangle$ (at RMS) is 441 ± 34 (190) keV, and at 1 *A* GeV/*c*, respectively, 346 ± 28 (85) keV. According to the "soft" condition $Q_{3\alpha}$ < 1 MeV, in the irradiation of 4.5 *A* GeV/*c*, 30 (of 186) events can be attributed to the HS, and at 1 A GeV/*c*, 9 (of 86), including 5 "white" stars (of 36).

When selecting $\alpha$ pairs from $\alpha$ triples in the entire available statistics that correspond to the HS criterion $Q_{3\alpha}$ < 1 MeV, the distribution over $Q_{2\alpha}$ acquires the form shown in Fig. 8. The average value of $\langle Q_{2\alpha}\rangle$ (RMS) is 210 ± 15 (156) keV, which is clearly different

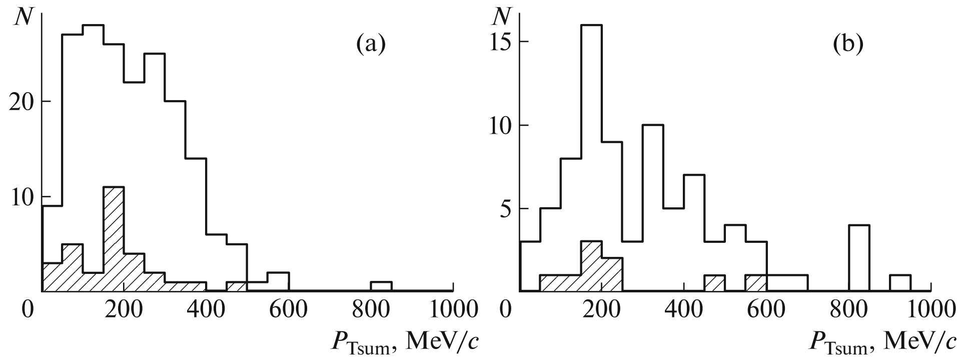


**Fig. 9.** Distribution of α triples over total transverse momentum $\langle P_{\rm Tsum}\rangle$ in dissociation $^{12}$C → 3α at 4.5 (a) and 1 *A* GeV/*c* (b); contribution of the HS decays is hatched.

from the data in Table 1. The form of the distribution becomes wider and it is difficult to identify there the $^8$Be peak. This change is caused by the increased contribution of nonresonance α pairs from the HS decays which mask the $^8$Be signal. In turn, this circumstance makes a more detailed analysis unattainable. It characterizes a limit for the approach used in the HS problem.

The available measurements make it possible to draw conclusions about the dynamics of the HS appearance according to the distributions over the total transverse momentum $P_{\rm Tsum}$ of triplets of α particles (Fig. 9). For 186 "white" stars $^{12}$C → 3α at 4.5 *A* GeV/*c*, the average value of the total transverse momentum of α triplet $\langle P_{\rm Tsum}\rangle$ (RMS) is 223 ± 9 (118) MeV/*c*, and for a sample of 30 events $Q_{3\alpha} < 1$ MeV, 176 ± 18 (101) MeV/*c*. For 36 "white" stars at 1 *A* GeV/*c*, $\langle P_{\rm Tsum}\rangle$ (RMS) is 229 ± 21 (125) MeV/*c*, and for 5 of them corresponding to the HS, 139 ± 18 (41) MeV/*c*. These values of $\langle P_{\rm Tsum}\rangle$ correspond to the nuclear-diffraction mechanism of the reaction.

## CONCLUSIONS

The Hoyle state is identified in dissociation $^{12}$C → 3α at 4.5 and 1 *A* GeV/*c* on the basis of the most precise measurements in NTE performed by different researchers at different exposures that are separated in time by two decades. In itself, this fact demonstrates the thoroughness of the NTE method. As a result of the studies, it can be concluded that the HS is observed with a contribution of about 10–15%. However, the method does not allow one to investigate the features of the HS decay. Reconstruction of the HS with respect to the invariant mass of relativistic α triples can be used to study processes with formation of the HS as an integral object at large momenta and for other fragmenting nuclei, except for $^{12}$C.

It seems surprising that such a "fragile" formation of three α particles as the HS can arise as an ensemble making a "bounce off" with the transverse momentum $P_{\rm Tsum}$ characteristic of strong interactions rather than electromagnetic ones. In the case of electromagnetic dissociation on the heavy nucleus of the target, the limitation would be $P_{\rm Tsum} < 100$ MeV/*c*. The increase in statistics may allow registration of the HS formation with large transverse momenta outside the angular cone of fragmentation of the parent nucleus. Such observations would clearly demonstrate the HS as a holistic and long-lived nuclear-molecular state. Similar events were observed in the cases $^9$Be → $^8$Be and $^{10}$C → $^9$B.

It is possible that the HS cannot be reduced to only the excitation of $^{12}$C, but can manifest itself as a universal object in the fragmentation of heavier nuclei, in much the same way as $^8$Be. In this respect, the closest source of the HS is the $^{14}$N nucleus. Even more convenient are the $^{13}$N and $^{13}$C nuclei, whose beams can be formed in the $^{14}$N fragmentation. It can be expected that the nuclear-molecular objects $^8$Be and the HS will become reference points for the search for more complex states of sparse nuclear matter in the relativistic approach.

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