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TECHNOLOGY OF NUCLEAR MATERIALS

The Hoyle State in the Relativistic Dissociation of Light Nuclei

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Abstract—In the context of the search for the triples of relativistic α particles in the Hoyle state, the analysis of available data on the dissociation of the ^{12}C, ^{16}O, and ^{22}Ne nuclei in a nuclear track emulsion was carried out. The Hoyle state is identified by the invariant mass calculated from the pair opening angles in α triples in the approximation of the conservation of the momentum per nucleon of the parent nucleus. The contribution of the Hoyle state to the $^{12}\mathrm{C} \to 3\alpha$ dissociation is 10%. In the case of the $^{16}\mathrm{O} \to 4\alpha$ coherent dissociation, it reaches 22% when the portion of the $^{16}\mathrm{O} \to 2^8\mathrm{Be}$ channel is 5%.

Keywords: nuclear track emulsion, invariant mass, relativistic fragments, ^{12}C nucleus, Hoyle state, alpha particles

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INTRODUCTION

Irradiations of stacks of nuclear track emulsion (NTE) in the beams of light relativistic nuclei were performed in the 1970s–1980s at the synchrophasotron of the Joint Institute for Nuclear Research and at Bevalac (LBL, USA). The use of NTE for studying the interactions of gold and lead nuclei continued in the 1980s–1990s at the AGS (BNL, USA) and SPS (CERN) accelerators. Observations of tracks of charged particles in the NTE in the full solid angle and practically with no threshold have made it possible to determine the contours of a complex picture of the collision of relativistic nuclei. Special attention was paid to central nuclear collisions. The subsequent development of this area on the basis of large-scale electronic experiments is widely known. At the same time, the results obtained by the NTE method, as well as the irradiated layers themselves and the files with measurement results, retain their uniqueness with respect to the structure of nuclear fragmentation.

In the peripheral interactions of nuclei, in which the charge of the incident nucleus is distributed between its fragments, the individual features of the incident nuclei are reflected. They are observed in the NTE as often and completely as the central collisions; therefore, in the cone of relativistic fragmentation, there is the fundamental possibility to study the nuclear structure. However, in this aspect, it turned out that the use of traditional spectrometers was extremely limited. The difficulties encountered in their use are of a fundamental nature. They are caused by a dramatic decrease in the ionization of relativistic fragments in an extremely narrow fragmentation cone and, often, by an approximate coincidence of the magnetic rigidity of fragments and nuclei of the beam. For these reasons, the measurements were carried out with registration of single relativistic fragments with charges whose value is close to that of the nucleus under study.

The pause in obtaining data on the structure of relativistic fragmentation has motivated the further experiments on NTE irradiations at the JINR nuclotron in the beams of light nuclei, including radioactive ones. In the early 2000s, the BECQUEREL experiment aimed at systematic study of peripheral interactions of relativistic nuclei by the NTE method was started. The analysis of peripheral interactions in longitudinally irradiated NTE layers allowed us to study the cluster features of a family of light nuclei, including neutron-deficient nuclei, in a single approach (reviews [1, 2]). The possibility of analyzing such ensembles is a prerequisite for testing the concepts developed in nuclear physics and nuclear astrophysics. The role of unstable nuclei ^{8}Be and ^{9}B in their structure was established. In the dissociation of the ^{10}C nucleus, an indication of the existence of the ^{9}Bp resonance at energy of about 4 MeV was found.

The decisive factor for reconstructing the decays of ^{8}Be and ^{9}B nuclei among fragments of a relativistic projectile nucleus is the best spatial resolution (about 0.5 μm) and the entire range of sensitivity provided only by the NTE technique. The decays of ^{8}Be and ^{9}B are identified by the invariant mass M^* determined by the sum of all products of 4-momenta P_i of relativistic fragments He and H. The subtraction of the sum of masses of fragments $Q = M^* - M$ is a matter of convenience. The components P_i are determined from the emission angles of fragments He and H on the assumption that they conserve their momentum per nucleon of the projectile nucleus (or its velocity). Then the invariant mass of the considered ensemble of fragments is determined by their opening angles. The $^9\mathrm{B} \to {}^8\mathrm{Be}p$ decays can be considered as a pure source of ^{8}Be nuclei. Their analysis made it possible to corroborate the criterion $Q_{2\alpha} < 0.2$ MeV for the selection of ^{8}Be which takes into account the used approximation and resolution of the method [3].

The successful reconstruction of the ^{8}Be and ^{9}B decays allows taking the next step, which consists in searching for the triples of α particles in the Hoyle state (HS) in the relativistic dissociation $^{12}\mathrm{C} \to 3\alpha$. This state is the second (and the first unbound) 0_2^+ excitation of the ^{12}C nucleus. The significance of this short-lived state of three real α particles and the status of its study are presented in [4]. The features of the HS such as the isolation in the initial part of the ^{12}C excitation spectrum and low energy of the decay and its narrow width (378 keV and 8.5 eV) indicate its similarity to the 2α-particle nucleus ^{8}Be (91 keV and 5.6 eV). ^{8}Be is an indispensable product of HS decays. It can be assumed that the HS is not reduced to ^{12}C excitation but it can also occur as a 3α-particle analog of ^{8}Be in the relativistic fragmentation of heavier nuclei.

The interest in the HS is motivated by the concept of the α-particle Bose–Einstein condensate (review [5]), the status of which is presented in [6]. The ground state of the unstable ^{8}Be nucleus and, after it, the HS are considered as the simplest forms of such a condensate. Continuing the ^{8}Be and HS branches, it is assumed that the condensate 4α-state is the 6th excited state 0_6^+ of the ^{16}O nucleus located 700 keV above the 4α threshold. Then, it would be possible for the condensate decay to proceed in the following sequence: $^{16}\mathrm{O}(0_6^+) \to {}^{12}\mathrm{C}(0_2^+) \to {}^8\mathrm{Be}(0_2^+) \to 2\alpha$.

The fact of HS generation may both reflect the presence of three weakly bound α particles in the 0S state in the parent nucleus and occur through the excited fragment $^{12}\mathrm{C}^*(\to 3\alpha)$ or be a product of the interaction of α particles in the final state. These variants require theoretical consideration. Experimentally, the general question is as follows. Can the fragmentation of relativistic nuclei serve as a "factory" for the generation of ensembles of α particles of increasing multiplicity at the lower limit of nuclear temperature? Below, in the context of the HS problem, the distributions of invariant mass $Q_{(2-4)\alpha}$ of α-particle pairs, triples, and quartets generated in the dissociation of ^{12}C, ^{16}O, and ^{22}Ne nuclei will be presented.

DISSOCIATION OF ^{12}C NUCLEI

For the ^{12}C nucleus at an energy of 3.65 *A* GeV, there are measurements of emission angles of α particles performed by the groups under the leadership of G.M. Chernov (Tashkent) [7] and A.Sh. Gaitinov (Alma-Ata) for, respectively, 72 and 114 events of $^{12}\mathrm{C} \to 3\alpha$ coherent dissociation, not accompanied by fragments of the target nucleus or produced mesons. The stars of this type are briefly referred to as "white" stars. The search for such events was carried out in an accelerated manner along the transverse strips of NTE layers. In such a way, the contribution of $^8\mathrm{Be} \to 2\alpha$ decays was determined from the smallest opening angles of α particles [7]. Figure 1 shows the distribution over the α-pair invariant mass $Q_{2\alpha}$. In the region $Q_{2\alpha} < 0.2$ MeV, the contribution of ^{8}Be decays is pronounced and its value is 17 ± 1%.

Recently, in collaboration with the group under the leadership of N.G. Peresad'ko (FIAN), the data on 238 3α stars, including 130 "white" stars, have been added. In addition, there are the NTE layers irradiated in the ^{12}C beam at the booster of the Institute for High Energy Physics (Protvino) at energy of 420 *A* MeV, which allow using an approach based on the invariant mass variable [5]. In the latter case, the emission angles are measured in 86 3α events found, including 36 "white" stars.

The $Q_{3\alpha}$ distribution for all 510 stars is shown in Fig. 2. The region $Q_{3\alpha} < 10$ MeV covering the α-particle excitations of ^{12}C below the nucleon separation threshold is described by the Rayleigh distribution with the parameter $\sigma_{Q3\alpha} = (3.9 \pm 0.4)$ MeV. There is a peak in the region $Q_{3\alpha} < 1$ MeV (51 stars) where the HS signal is expected. For the events at 3.65 *A* GeV that made their contribution to this peak, the average value $\langle Q_{3\alpha}\rangle$ (RMS) is 397 ± 26 (166) keV; at 420 *A* MeV, 346 ± 28 (85) keV, respectively. According to the condition $Q_{3\alpha} < 0.7$ MeV, at 3.65 *A* GeV, 42 out of 424 events can be attributed to the HS decays; at 420 *A* MeV, 9 (out of 86) events, including 5 (out of 36) "white" stars. As a result, the contribution of HS decays to the $^{12}\mathrm{C} \to 3\alpha$ dissociation is 10 ± 2%.

COHERENT DISSOCIATION OF ^{16}O NUCLEI

The $Q_{2\alpha}$ distribution for all 2α combinations in 641 "white" stars, $^{16}\mathrm{O} \to 4\alpha$, according to the data [8], is presented in Fig. 3. As in the case of the $^{12}\mathrm{C} \to 3\alpha$ dissociation, at $Q_{2\alpha} < 0.2$ MeV, there is a contribution of ^{8}Be decays which manifests itself in 15 ± 1% events.

The HS decays can manifest themselves in the $^{16}\mathrm{O} \to {}^{12}\mathrm{C}^* (\to 3\alpha) + \alpha$ dissociation. Figure 4 shows

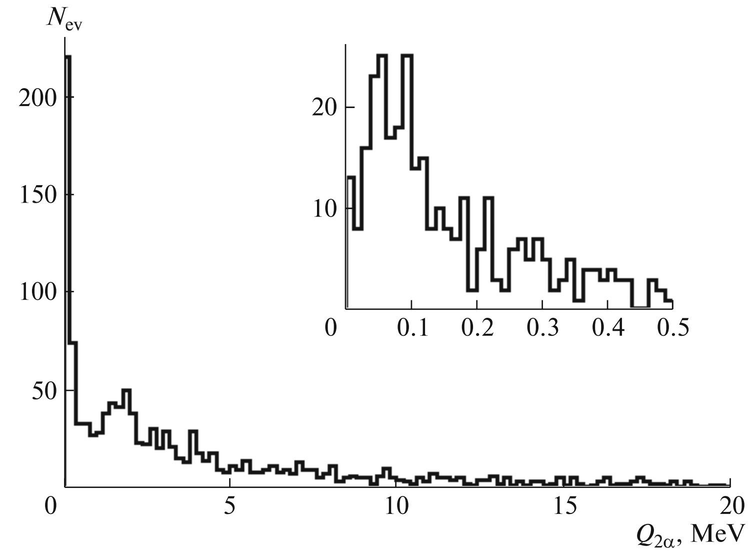

Fig. 1. Distribution of α pairs in the $^{12}C \to 3\alpha$ coherent dissociation over the invariant mass $Q_{2\alpha}$ at 3.65 A GeV (shaded); in the inset: a part of the distribution for $Q_{2\alpha} < 0.5$ MeV.

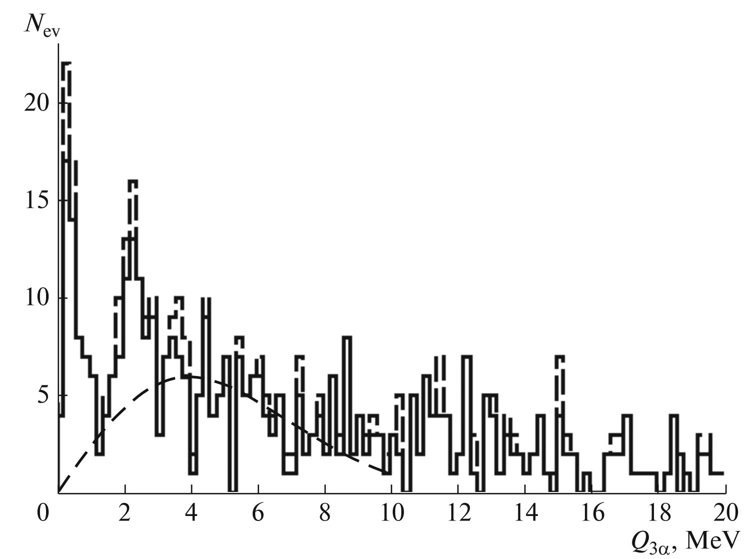

Fig. 2. Distribution of α triples in the $^{12}C \to 3\alpha$ dissociation over the invariant mass $Q_{3\alpha}$ at 3.65 A GeV (shaded) and 420 A MeV (dotted); the line is the Rayleigh distribution.

the $Q_{3\alpha}$ distribution of all 3α combinations. As in the case of ^{12}C, its main part at $Q_{3\alpha} < 10$ MeV is described by the Rayleigh distribution with the parameter $\sigma_{Q3\alpha} = (3.8 \pm 0.2)$ MeV. It also has a peak at $Q_{3\alpha} < 700$ keV. The condition $Q_{2\alpha} < 200$ keV, meaning that there is at least one ^{8}Be decay in a 4α event, does not influence on the statistics in this $Q_{3\alpha}$ range. The contribution of the combinatorial background, estimated at 8%, to the peak is excluded. The remaining 139 events have an average value $\langle Q_{3\alpha}\rangle = (349 \pm 14)$ keV corresponding to the HS and RMS of 174 keV. In 9 events out of them, more than one 3α-combination corresponds to the condition $Q_{3\alpha} < 700$ keV. In sum, the contribution of HS decays to the $^{16}O \to 4\alpha$ coherent dissociation is $22 \pm 2\%$. The distribution of α triples of the HS over the total transverse momentum P_T(HS) (Fig. 5) is described by the Rayleigh distribution with the parameter $\sigma_{PT}(HS) = (191 \pm 8)$ MeV/c, the value of which is characteristic of nuclear diffraction.

The HS can occur as a decay product of the 0_6^+ excited state of the ^{16}O nucleus [5, 6] (by analogy with the HS decay ^{8}Be + α). In 641 "white" stars, the total

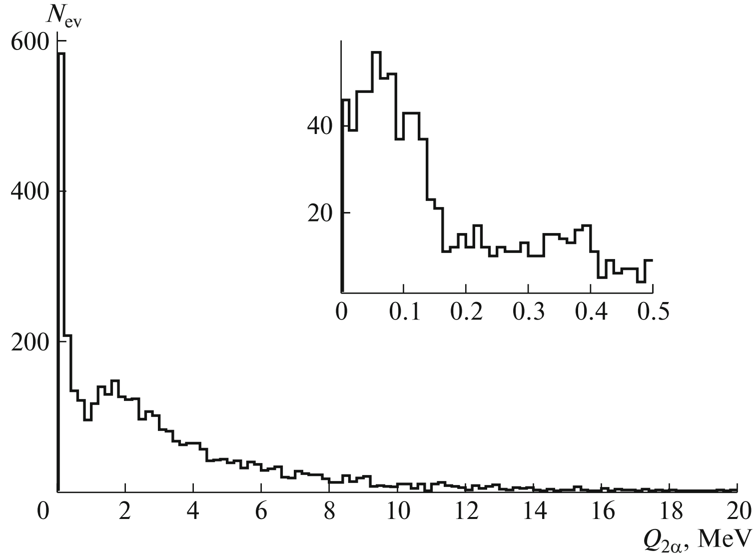

Fig. 3. Distribution of all α pairs in “white” stars $^{16}O \to 4\alpha$ over the invariant mass $Q_{2\alpha}$ at 3.65 *A* GeV; in the inset: a part of the distribution for $Q_{2\alpha} < 0.5$ MeV.

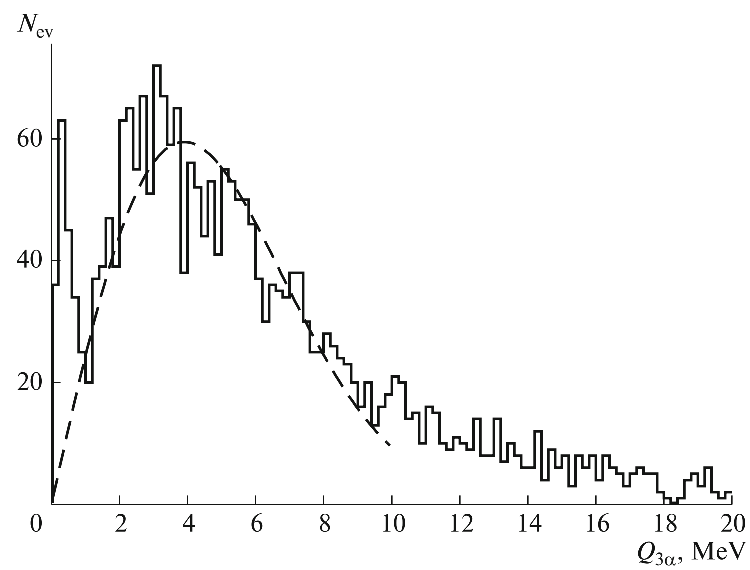

Fig. 4. Distribution of all α triples in the $^{16}O \to 4\alpha$ “white” stars over the invariant mass $Q_{3\alpha}$ at 3.65 *A* GeV; the line is the Rayleigh distribution.

$Q_{4\alpha}$ distribution of α quartets (Fig. 6) is described mainly by the Rayleigh distribution with the parameter $\sigma_{Q4\alpha} = (6.1 \pm 0.2)$ MeV. The condition for the presence of at least one α triple with $Q_{3\alpha} < 700$ keV in a 4α event (αHS) shifts the $Q_{4\alpha}$ distribution toward the low-energy direction (Fig. 6) and the parameter $\sigma_{Q4\alpha} = (4.5 \pm 0.5)$ MeV. It can be assumed that, in the decay of an integral object, the HS and α will be correlated in their direction. Figure 7 shows the distribution of αHS over $Q_{4\alpha}$ and the azimuth angle ε(αHS) between the HS and α-particle directions. It is worth noting that $Q_{4\alpha}$ and ε(αHS) are functionally related. The condition ε(αHS) < 45° selects 9 events that satisfy condition $Q_{4\alpha} < 1$ MeV with the average value $\langle Q_{4\alpha} \rangle = (624 \pm 84)$ keV at RMS of 252 keV (Fig. 6). On their basis, the estimate for the contribution of the 0_6^+ state is 7 ± 2%.

Among the $^{16}O \to 4\alpha$ “white” stars, 33 events were selected in which two ^{8}Be fragments ($Q_{2\alpha} < 0.2$ MeV) are present. The directions of expansion with respect to the azimuth angle ε(2^{8}Be) show their anticorrelation (Fig. 8), which indicates the binary production of these fragments. In 31 2^{8}Be events, there are no triples of

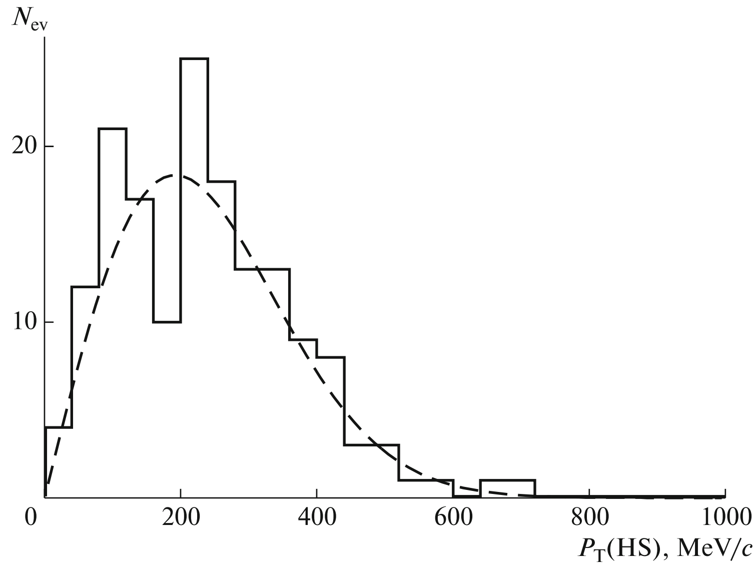

Fig. 5. Distribution of α triples with $Q_{3\alpha} < 0.7$ MeV (HS) in the $^{16}O \to 4\alpha$ "white" stars over the total transverse momentum P_T (HS) at 3.65 A GeV; the line is the Rayleigh distribution.

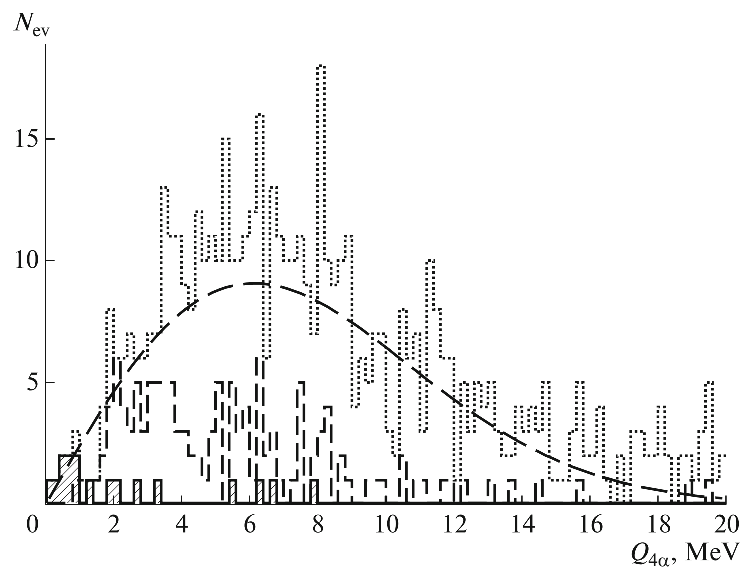

Fig. 6. Distribution over the invariant mass $Q_{4\alpha}$ of the $^{16}O \to 4\alpha$ "white" stars at 3.65 A GeV for all 4α quartets (points), αHS events (dotted line), and αHS events $\varepsilon(\alpha HS) < 45°$ (dashed areas); the line is the Rayleigh distribution.

α particles that satisfy the HS condition ($Q_{3\alpha} < 700$ keV), which gives an estimate for the contribution of the $^{16}O \to 2^8Be$ channel of $5 \pm 1\%$. The distribution of the pairs over their total transverse momentum $P_T(2^8Be)$ is described by the Rayleigh distribution with the parameter $\sigma_{PT}(2^8Be) = (161 \pm 2)$ MeV/c. Figure 9 shows the $Q_{4\alpha}$ distribution for the 2^8Be events for which the Rayleigh parameter is (4.3 ± 1.2) MeV. The ratio of the number of events in the $^{16}O \to \alpha HS$ channel to those in the $^{16}O \to 2^8Be$ channel is 4.5 ± 0.4, which means that the first of them is clearly leading.

FRAGMENTATION of ^{22}Ne

The results of measurements of 4301 interactions of ^{22}Ne nuclei at energy of 3.22 A GeV are available for analysis. The events were sought by scanning the

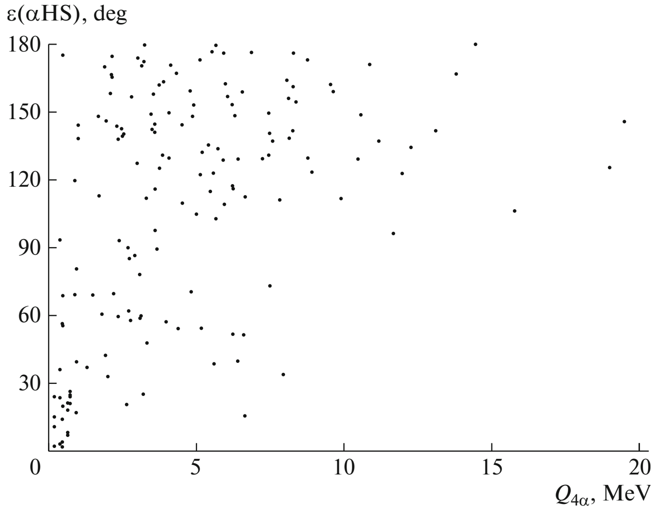

Fig. 7. Distribution of $^{16}O \to \alpha HS$ events over the invariant mass $Q_{4\alpha}$ and azimuth angle $\varepsilon(\alpha HS)$.

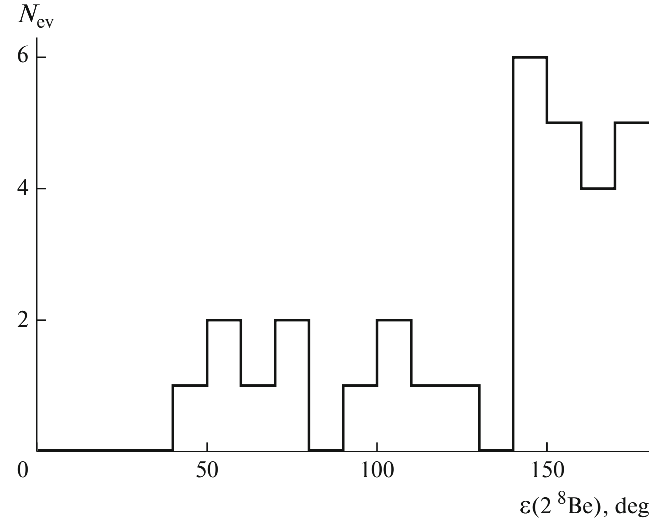

Fig. 8. Distribution of $^{16}O \to 2^8Be$ events over the azimuth angle $\varepsilon(2^8Be)$ between ^8Be fragments.

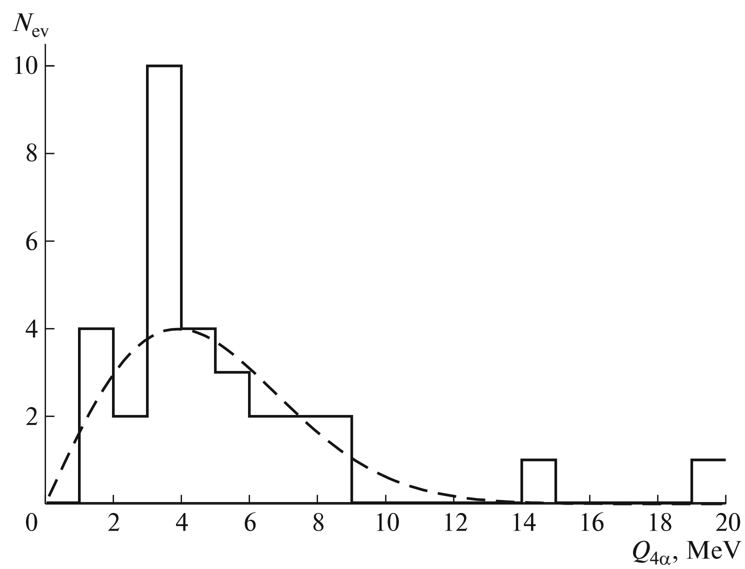

Fig. 9. Distribution of $^{16}O \to 2^8Be$ events over the invariant mass $Q_{4\alpha}$; the line is the Rayleigh distribution.

tracks of primary nuclei (i.e., without sampling), providing an overview of the ^{22}Ne fragmentation topology [9]. This set includes the measurements of the emission angles of relativistic α particles for 528 2α events, 243 3α events, 80 4α events, and 10 5α events, which allows us to perform the analysis in variables of the invariant mass $Q_{(2-5)\alpha}$. It is worth noting that measurements of the scattering angles of fragments were performed by the method that gives a worse relative accuracy than that in the cases presented above. Nevertheless, the $Q_{2\alpha}$ distribution allows us to separate the ^8Be signal in the region $Q_{2\alpha} < 0.2$ MeV (Fig. 10).

Figure 11 shows the $Q_{3\alpha}$ distribution for the 4α channel. In the region $Q_{3\alpha} < 1$ MeV, the average value is $\langle Q_{3\alpha}\rangle = (557 \pm 51)$ keV and RMS is 195 keV, which is close to the HS value. The values of the Rayleigh distribution parameters $\sigma_{Q3\alpha}$ in the approximations of the $Q_{3\alpha}$ distributions for channels 3α, 4α, and 5α in the energy range of up to 10 MeV are (4.0 ± 0.5), (4.3 ± 0.6), and (4.3 ± 0.4) MeV, respectively. These values are close to those in the cases of ^{12}C and ^{16}O. In the region $Q_{3\alpha} < 1$ MeV, the numbers of candidates to the HS decays (and their portion) in the 3α, 4α, and 5α

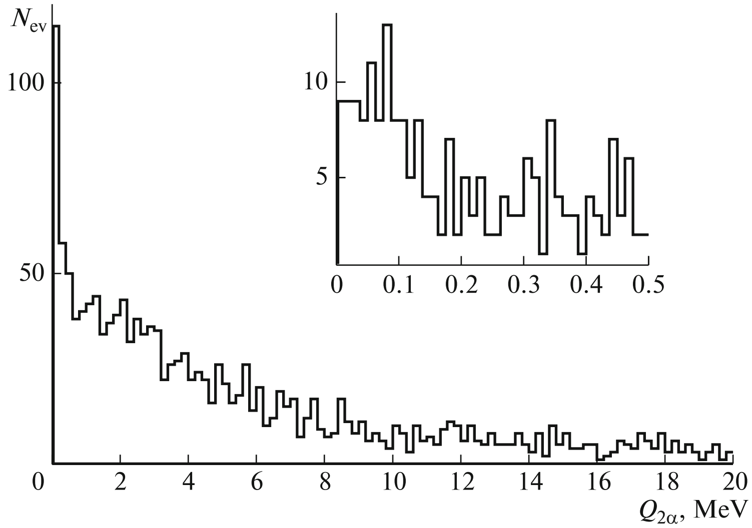

Fig. 10. Distribution of all α pairs in the ^{22}Ne → (2–5)α fragmentation channels over the invariant mass $Q_{2\alpha}$ at 3.22 *A* GeV.

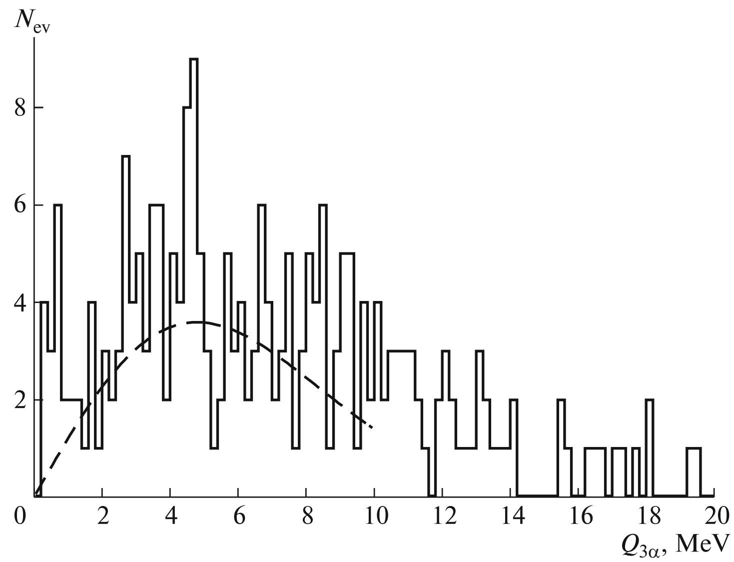

Fig. 11. Distribution of all α triples in the 4α channel in the fragmentation of ^{22}Ne nuclei over the invariant mass $Q_{3\alpha}$ at 3.22 *A* GeV; the line is the Rayleigh distribution.

channels are 3 (1.2 ± 0.7%), 12 (15 ± 4%), and 1 (10%), respectively. Therefore, only the 4α channel has a significant indication of the HS. The $\langle Q_{3\alpha} \rangle$ shift, compared to the cases of ^{12}C and ^{16}O, requires a better accuracy of measurements.

The $Q_{4\alpha}$ distribution in channels 4α and 5α is presented in Fig. 12. Its main part limited by $Q_{3\alpha} < 10$ MeV is described by the Rayleigh distribution with the parameter $\sigma_{Q4\alpha} = (4.9 \pm 0.9)$ MeV. In the 4α channel, there is a single event with $Q_{4\alpha} = 791$ keV in which all α triples meet the HS condition $Q_{3\alpha} < 1$ MeV. This α quartet can correspond to the decay of the 0_6^+ state of ^{16}O. It would obviously be interesting to increase the statistics in channels 4α and 5α. An additional possibility is provided by the existing NTE layers irradiated with ^{28}Si nuclei at energy of 3.65 *A* GeV.

CONCLUSIONS

On the basis of the data obtained in the 1980s–1990s on dissociation of relativistic ^{12}C, ^{16}O, and ^{22}Ne nuclei in nuclear track emulsions, as well as the modern data in the case of ^{12}C, a search for the triples of relativistic α particles in the Hoyle state was performed. Determining the invariant mass of the α-par-

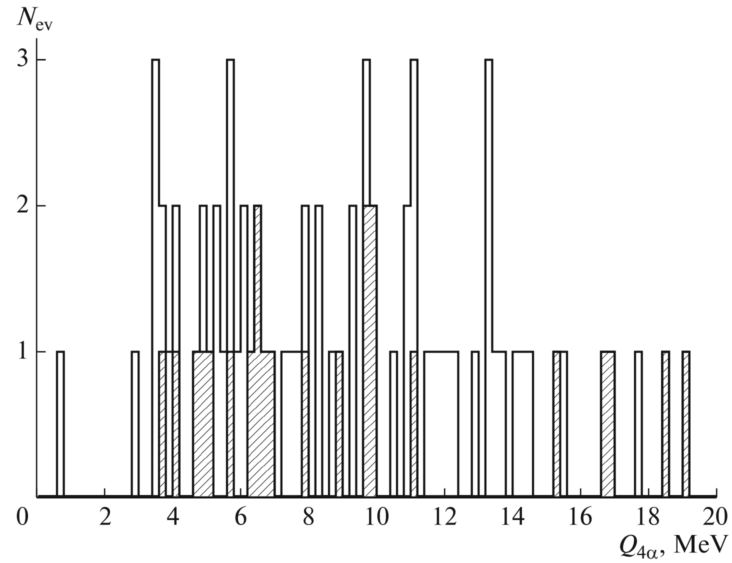

Fig. 12. Distribution of all α quartets in the 4α and 5α channels in the fragmentation of ^{22}Ne nuclei over the invariant mass $Q_{4\alpha}$ at 3.22 *A* GeV (5α channel, dashed).

ticle triples from their emission angles in the approximation of conservation of the velocity of the parent nucleus ensures a sufficient accuracy in identifying the HS against the background of higher 3α excitations of the ^{12}C nucleus. The contribution of the HS decays to the $^{12}\mathrm{C} \to 3\alpha$ dissociation is $10 \pm 2\%$.

In the $^{16}\mathrm{O} \to 4\alpha$ dissociation, the contribution of the HS decays is $22 \pm 2\%$. Attention is drawn to the fact that an increase in the α-particle combinations leads to a noticeable increase in the contribution of the HS to the $^{16}\mathrm{O} \to 4\alpha$ dissociation. Analyzing the invariant masses of α quartets, we find that the estimate of the contribution of the decays of the 0_6^+ state of ^{16}O is $7 \pm 2\%$. Hence, the direct dissociation α + HS dominates in the HS formation.

The analysis of the ^{22}Ne nucleus fragmentation has revealed the HS formation only in the 4α channel, for which the portion of events with the HS was $15 \pm 4\%$. Taking into account the insufficient statistics, this result serves as a guideline for continuing the search for α ensembles by fast-speed scanning over the area of NTE layers.

In general, the peculiarity of the HS as a universal and sufficiently long-lived object similar to the unstable ^{8}Be nucleus is confirmed. The closest source for verifying the HS universality is peripheral dissociation of the ^{14}N nucleus in which the 3He + H channel leads, with the contribution of ^{8}Be decays of about 25% [10]. Analysis of NTE layers irradiated with relativistic ^{14}N nuclei in the early 2000s was resumed in the context of the HS problem. A similar analysis will be performed in the NTE layers which were irradiated by relativistic ^{22}Ne and ^{28}Si nuclei at the JINR synchrophasotron in the late 1980s and used for the overall analysis. Despite the past decades, this experimental material has retained the necessary quality.

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The presented material is based on the analysis of experimental material and data obtained for the period from the beginning of the 1970s and up to the present time. In itself, this fact demonstrates the solidity of the nuclear track emulsion method and its ability to evolve. It is impossible to list all the participants in the emulsion cooperation at the JINR synchrophasotron in analyzing the interactions of relativistic nuclei. Behind this entire scientific heritage, there was the enormous amount of work and joy of being pioneers in this domain. Therefore, we hope that citing publications and the further use of materials and methods not only are useful in research but also will serve to preserve the memory about the era of the emergence of research on relativistic nuclear physics.

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CONFLICT OF INTEREST

The authors declare that they have no conflicts of interest.

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