Physics of Atomic Nuclei, Vol. 68, No. 3, 2005, pp. 455–465. Translated from Yadernaya Fizika, Vol. 68, No. 3, 2005, pp. 484–494.

Topology of "White Stars" in the Relativistic Fragmentation of Light Nuclei

N. P. Andreeva[1], V. Bradnova[2], S. Vokal[2),3], A. Vokalova[2], A. Sh. Gaitinov[1], S. G. Gerasimov[4], L. A. Goncharova[4], V. A. Dronov[4], P. I. Zarubin[2]*, I. G. Zarubina[2], A. D. Kovalenko[2], A. Kravchakova[3], V. G. Larionova[4], O. V. Levitskaya[5], F. G. Lepekhin[5], A. I. Malakhov[2], A. A. Moiseenko[6], G. I. Orlova[4], N. G. Peresadko[4], N. G. Polukhina[4], P. A. Rukoyatkin[2], V. V. Rusakova[2], N. A. Salmanova[4], V. R. Sarkisyan[6], B. B. Simonov[5], E. Stan[2,7], R. Stanoeva[2,8], M. M. Chernyavsky[4], M. Haiduc[7], S. P. Kharlamov[4], I. Tsakov[8], and T. V. Schedrina[2]
The BECQUEREL Collaboration

Received May 24, 2004; in final form, August 27, 2004

Abstract—Experimental observations of the multifragmentation of relativistic light nuclei by means of emulsions are surveyed. Events that belong to the type of "white stars" and in which the dissociation of relativistic nuclei is not accompanied by the production of mesons and target-nucleus fragments are considered. An almost complete suppression of the binary splitting of nuclei to fragments of charge in excess of two, $Z > 2$, is a feature peculiar to charge topology in the dissociation of Ne, Mg, Si, and S nuclei. An increase in the degree of nuclear fragmentation manifests itself in the growth of the multiplicity of singly and doubly charged fragments ($Z = 1, 2$) as the charge of the unexcited fragmenting-nucleus part (which is the main part) decreases. Features of the production of systems formed by extremely light nuclei α, d, and t are studied in the dissociation of the stable isotopes of Li, Be, B, C, N, and O to charged fragments. Manifestations of ^{3}He clustering can be observed in "white stars" in the dissociation of neutron-deficient isotopes of Be, B, C, and N. © *2005 Pleiades Publishing, Inc.*

INTRODUCTION

The charge topology of fragments in peripheral interactions of light nuclei at a primary energy in excess of 1 GeV per nucleon may serve as an efficient characteristic of nuclear multifragmentation. In this energy region, one reaches the regime of limiting nuclear fragmentation—that is, the spectrum of fragments becomes independent of the collision energy and of the composition of target nuclei.

In studying multifragmentation in the region of relativistic energies, the possibilities of observation and of spectroscopy of final states of a product system formed by charged fragments are determined by the accuracy achieved in measuring angles. Owing to the best spatial resolution (0.5 μm), nuclear emulsions provide an angular resolution of about 10^{-5} rad for tracks of relativistic fragments. This ensures complete observability of all possible decays of excited nuclear states to fragments. By way of example, we indicate that, over a length of 1 mm, one can distinguish with confidence the process $^8\mathrm{Be} \to 2\alpha$, which manifests itself at a momentum of 4.5 GeV/c per nucleon as a pair of tracks within an angular cone of about 2×10^{-3} rad. Such narrow decays are rather frequently observed in the fragmentation of relativistic oxygen and heavier nuclei.

Topological features of events involving the dissociation of light nuclei in peripheral interactions were investigated in emulsions for ^{12}C [1–6], ^{22}Ne [7–12], ^{24}Mg [13], ^{28}Si [14–16], ^{16}O [17, 18], ^{6}Li [19–22], and ^{10}B [23–25] nuclei at energies of about a

1) Institute for Physics and Technology, Kazakh Academy of Sciences, Almaty, Republic of Kazakhstan.
2) Joint Institute for Nuclear Research, Dubna, Moscow oblast, 141980 Russia.
3) P.J. Šafárik University, Košice, Slovak Republik.
4) Lebedev Institute of Physics, Russian Academy of Sciences, Leninskii pr. 53, Moscow, 117924 Russia.
5) Petersburg Nuclear Physics Institute, Russian Academy of Sciences, Gatchina, 188350 Russia.
6) Yerevan Physic Institute, ul. Brat'ev Alikhanyan 2, Yerevan, 375036 Armenia.
7) Institute of Space Sciences, Bucharest-Maguerele, Romania.
8) Institute for Nuclear Research and Nuclear Energy, Bulgarian Academy of Sciences, Blvd. Tsarigradsko chausse 72, BG-1784 Sofia, Bulgaria.
*E-mail: zarubin@lhe.jinr.ru

1063-7788/05/6803-0455$26.00

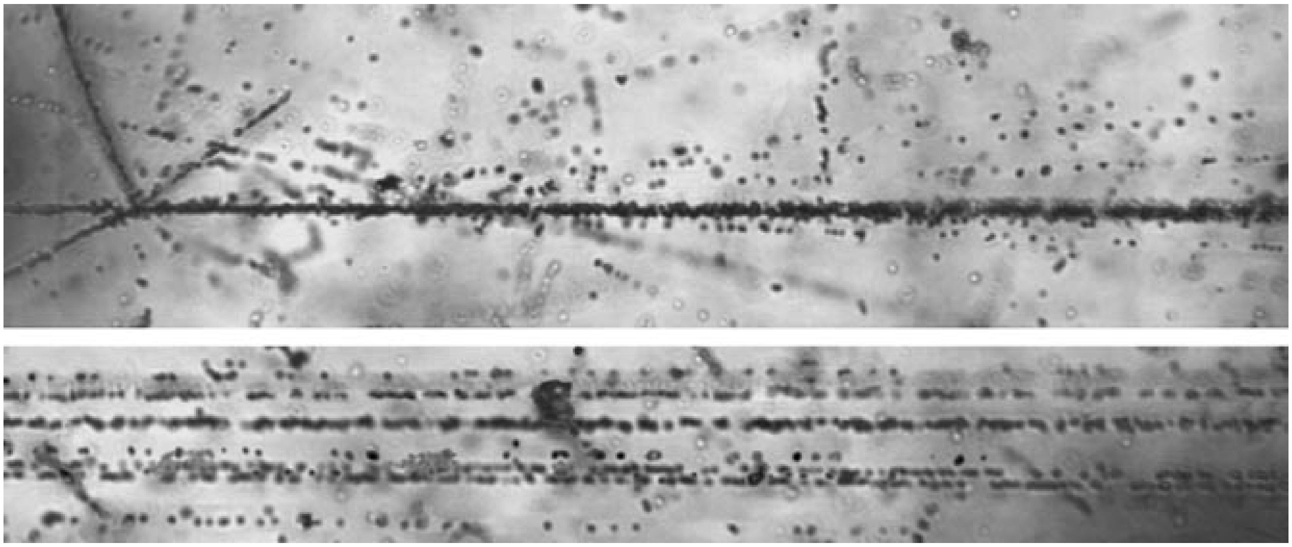

Fig. 1. Event of the fragmentation of a ^{28}Si nucleus having an energy of 3.65 GeV per nucleon and participating in a peripheral interaction with an emulsion nucleus. The upper photograph shows the interaction vertex and a jet of fragments within a narrow angular cone, along with four accompanying singly charged particles within a broad cone and three target-nucleus fragments. Upon a shift in the direction of the jet of fragments (lower photograph), one can distinguish three H and five He fragments. An intense track on the lower photograph (the third one from top to bottom) is identified as a pair of $Z = 2$ fragments that occurs in very narrow angular cone and which corresponds to the decay of a ^{8}Be nucleus. The three-dimensional image of events was reconstructed as a plane projection with the aid of an automated microscope entering into the composition of the PAVIKOM complex at the Lebedev Institute of Physics (Moscow).

few gigaelectronvolts per nucleon. The dissociation of ^{16}O and ^{32}S nuclei was investigated at an energy of 200 GeV per nucleon [17, 26, 27]. These results are complete and highly reliable and can be useful in planning investigations of nuclear multifragmentation that are characterized by a high statistical significance.

In this article, we present data on dissociation channels for a broad range of light nuclei in events belonging to the “white star” type. Experimental data on the branching fractions of observed nuclear-dissociation channels give an idea both of the general regularities of the nuclear-fragmentation process and of the special features of fragmentation that are associated with the structure of individual nuclei. For ^{24}Mg, ^{14}N, and ^{7}Be nuclei, the results in question are given for the first time. Data on the other nuclei discussed below were obtained on the basis of events from experimental results published previously that had passed more stringent selection criteria. The irradiation at energies of about a few gigaelectronvolts per nucleon was performed at the synchrophasotron and nuclotron of the Joint Institute for Nuclear Research (JINR, Dubna, Russia), while the irradiation at the energy of 200 GeV per nucleon was conducted at CERN (Switzerland).

In order to illustrate the criteria of event selection, an event of silicon-nucleus multifragmentation at a momentum of 4.5 GeV/c per nucleon is displayed in Fig. 1. A group of projectile fragments that travel within a narrow cone of angle about a few degrees and having the total charge of $Z = 13$ is of particular interest. The size of the cone is determined by the ratio of the transverse Fermi momentum to the projectile momentum per nucleon. The tracks of relativistic fragments remain within a single emulsion layer for a long time, and this is sufficient for reconstructing a continuous three-dimensional image of this group of tracks. Within emulsions, a mass identification of relativistic hydrogen and helium isotopes can be performed by using the mean angle of scattering of tracks and the total momentum associated with this angle.

The longitudinal momenta of fragments per nucleon are equal, to within a few percent, to the momenta of projectile nucleons. The excitation energy of the system of fragments is determined by their multiplicity and angles of divergence. This energy can be determined as the difference of the invariant mass of the fragmenting system and the projectile mass and is about 1 MeV per fragment nucleon. Angular correlations of fragments reflect the angular momentum of the product system. Minimum-ionization tracks of product mesons are seen within a broader cone in Fig. 1. In addition, tracks from strongly ionizing target-nucleus fragments of energy about a few tens of megaelectronvolts are present in the interaction vertex. Thus, the separation of the kinematical regions of fragmentation of colliding nuclei clearly manifests itself in the interaction being considered.

Multifragmentation in White Stars

In accumulating statistics of multifragmentation of nuclei, one selects events featuring no charged particles emitted between the projectile- and target-fragmentation regions. As a rule, the projectile charge is completely transferred in such events to the narrow angular cone of fragmentation. The interpretation is the clearest for events that do not involve target fragments either. They are produced in the case of a minimum energy transfer to the fragmenting nucleus. Events of this type are referred to as "white stars." Their fraction among the total number of inelastic events is about a few percent. This term reflects not only a general view of the tracks of such events but also a sharp decrease in ionization losses (by the factor Z in the limiting case) upon going over from the projectile track to the narrow cone of secondary tracks. White stars are formed in the electromagnetic interactions of target nuclei with virtual photons and in diffractive scattering on perpheral target neutrons.

The requirement of charge conservation is a circumstance of practical convenience in seeking events of this type, since this makes it possible to exclude the contribution from an admixture of lighter particles in the beam that have a close charge-to-mass ratio. This is of importance in exposing emulsions to secondary beams of radioactive nuclei, because the composition of such beams is rather complex. We note that the above criteria for selecting white stars can be used, along with the condition requiring the energy-flux conservation in the fragmentation cone, in future experiments aimed at studying global special features of the fragmentation of heavy nuclei in processes of peripheral dissociation.

Loosely Bound Cluster Systems

The objective of our experiments was to study, in the vicinity of the thresholds for the reactions being discussed, the pattern of the phase transition of nuclear matter from the state of a quantum liquid to the state of a quantum gas consisting of a large number of nucleons and extremely light nuclei. By extremely light nuclei, we mean deuterons, tritons, and ^{3}He and ^{4}He nuclei—that is, stable systems that do not have excited states below the threshold for their decay to nucleons.

Current interest in studying phase transitions in nuclear systems is motivated by the prediction of such states as loosely bound cluster systems [28–30]. The spatial extension of such systems may exceed the fragment sizez significantly {Efimov's states [28] in the vicinity of the threshold for the decay of a three-body system, light nuclei of molecular-type structure (for an overview, see [29]), or a Bose condensate of a dilute gas of alpha particles in $N\alpha$ nuclei [30]}. The multifragmentation process involving adiabatic excitation transfer can be interpreted in terms of the disappearance of the Coulomb barrier owing to a simultaneous increase in the distance between charged clusters.

Investigation of multiparticle states on scales that are characteristic of the nucleon and cluster structure of a nucleus is of interest for nuclear astrophysics. By way of example, we indicate that, owing to a significant decrease in Coulomb repulsion in extended nuclear systems, such states may play the role of intermediate states in the processes of nuclear fusion in stars. The topologies found here may prove to be useful for clarifying versions of nuclear fusion as the process inverse to nuclear fragmentation.

SPECIAL FEATURES OF THE FRAGMENTATION OF Mg, Ne, Si, AND S NUCLEI

Multifragmentation of ^{24}Mg Nuclei

Searches for white stars in the dissociation of ^{24}Mg nuclei with a kinetic energy of 3.65 GeV per nucleon were performed by following the projectile track up to an interaction vertex with the aid of microscopes (see, for example, [25]). This resulted in finding 83 events of the type in question, where almost all of the secondary tracks were within a cone of angle not larger than 4° with respect to the primary-track direction. The charge of a particle that generated a track in the emulsion used was determined on the basis of the density of gaps and the number of delta electrons. The distribution of events with respect to the charge topology of fragments is given in Table 1. The charge of a $Z > 2$ fragment, the number of singly charged fragments, the number of doubly charged fragments, and the observed number of events that have this topology are quoted in each column of the table in the rows from top to bottom. The efficiency of the observation of events characterized by $11 + 1$ charge topology is estimated at 50% because of the screening of singly charged tracks by secondary tracks of high ionization.

Table 1 presents data concerning channels of the production of white stars that cover the cases from the separation of singly and doubly charged fragments from a cold nuclear residue of the primary nucleus to its complete breakup to extremely light nuclei. None of such events involves more than one track from a $Z > 2$ relativistic fragment. An obvious special feature of the processes being considered is that they do not produce events of the binary or ternary

Table 1. Charge-topology distribution of white stars in the dissociation of ^{24}Mg nuclei with an energy of 3.65 GeV per nucleon

Z_f	11	10	10	9	9	8	8	8	7	7	6	5	5	5	4	4	3	–	–	–
$N_{Z=1}$	1	2	–	3	1	4	2	–	3	1	2	5	3	1	6	4	5	6	4	2
$N_{Z=2}$	–	–	1	–	1	–	1	2	1	2	2	1	2	3	1	2	2	3	4	5
$N_{\rm ev}$	10	14	8	5	9	1	7	4	4	2	4	2	1	1	2	1	3	1	2	2

Table 2. Charge-topology distribution of white stars in the dissociation of ^{22}Ne nuclei with an energy of 3.3 GeV per nucleon

Z_f	9	8	8	7	6	6	5	5	$5+3$	4	$4+3$	–	–
$N_{Z=1}$	1	–	2	1	–	2	1	3	–	–	3	2	–
$N_{Z=2}$	–	1	–	1	2	1	2	1	1	3	–	4	5
$N_{\rm ev}$	22	51	6	7	5	2	1	1	1	2	1	1	3

Table 3. Charge-topology distribution of white stars in the dissociation of ^{28}Si nuclei with an energy of 3.65 GeV per nucleon

Z_f	13	12	12	11	11	10	10	10	9	9	9	8	8	8	7	7	7	6	6	6	6	5	5	4	–	–	–
$N_{Z=1}$	1	–	2	1	3	–	2	4	1	3	5	6	2	4	3	5	7	2	4	6	8	3	5	2	2	8	10
$N_{Z=2}$	–	1	–	1	–	2	1	–	2	1	–	–	2	1	2	1	–	3	2	1	–	3	2	4	6	3	2
$N_{\rm ev}$	9	3	15	11	6	2	7	2	2	8	3	2	5	6	1	3	3	3	5	8	1	1	3	1	1	2	3

splitting of light nuclei to fragments heavier than the alpha particle, this being indicative of a crucial role of the multifragmentation process here. Previously, only one event of the disintegration process $\mathrm{Mg}^* \to \mathrm{B} + \mathrm{N}$ without an additional emission of charged particles was found in analyzing 1666 interactions [31]. The dominance of multifragmentation processes despite high energy thresholds for them can be explained by a high density of multiparticle states.

It is planned to perform an analysis of events of a complete breakup of Mg nuclei on the basis of substantially vaster statistics and to identify simultaneously extremely light nuclei originating from this breakup. This would provide the possibility of reconstructing the invariant mass of a decaying system and its subsystems (for example, $N\alpha$-particle ones). Two events of the decay of magnesium nuclei to six helium nuclei have been found so far. One of these was identified as a $5^4\mathrm{He} + {}^3\mathrm{He}$ event. Since these events are accompanied by single target-nucleus fragments, they were not included in the data presented in Table 1. Nevertheless, their existence provides sufficient grounds to continue seeking 6α configurations over a large length of primary tracks of ^{24}Mg nuclei.

Multifragmentation of ^{22}Ne Nuclei

We will compare special features of the fragmentation of ^{24}Mg nuclei with data on neighboring nuclei, in which case we have vast statistics of interactions at our disposal. Table 2 displays the charge-topology distribution of 103 white stars generated by ^{22}Ne nuclei of energy 3.3 GeV per nucleon and selected among 4100 inelastic events [7]. There are no events of binary splitting in this case inclusive. Bogdanov *et al.* [31], who used a different sample of 4155 events, did not observe the binary splitting of ^{22}Ne either.

A much more pronounced role of helium isotopes in the fragmentation of ^{22}Ne nuclei may be due to the fact that, in contrast to the symmetric magnesium nucleus, the nucleus in question involves a pair of extra outer neutrons. In initiating multiparticle dissociation via the knockout of external neutrons, this circumstance can be used for a more efficient generation and detection of systems containing a large number of alpha particles. Three events of the decay of ^{22}Ne nuclei to five helium nuclei whose tracks are within a cone of 3° were found (Table 2). In two of these events, all tracks are even within 1°. These observations indicate once again that nuclear emulsions provide unique possibilities in studying multiparticle systems consisting of extremely light nuclei that have minimum relative 4-velocities (relative Lorentz factors).

Multifragmentation of ^{28}Si and ^{32}S Nuclei

A sample of 116 white stars generated by ^{28}Si nuclei of energy 3.65 GeV per nucleon exhibits the same regularity—a transition to multifragmentation (Table 3) without binary splitting [14]. In [31], only one event of the process $\mathrm{Si}^* \to \mathrm{O} + \mathrm{C}$ was observed in a different sample of 1900 inelastic interactions. It is interesting to note that the transition to the complete breakup of ^{28}Si nuclei is accompanied by an increase in the contribution to the final states of hydrogen isotopes in relation to helium isotopes. It is desirable to find out whether this is a consequence of a decrease in the degree of alpha-particle clustering in nuclei with increasing A. The results in Table 3 represent an improved sample of events from data obtained previously in [7, 14]. We note that those articles contain rich information, which may be of use in planning experiments where the degree of inelasticity of selected collisions is varied.

We will also present results obtained by irradiating emulsions with ^{32}S nuclei accelerated to an energy of 200 GeV per nucleon. In this case, the angular size of the fragmentation cone is 0.5°. Table 4 demonstrates that the channels of hydrogen-isotope separation are dominant. Although the data sample used is insufficiently vast, multifragmentation manifests itself in the topology of 193 white stars.

It is of interest to study the topology of white stars for heavy nuclei. Single events of a complete breakup of lead nuclei were observed in emulsions irradiated at CERN with ultrarelativistic lead nuclei of energy 160 GeV per nucleon. However, a detailed investigation of heavy nuclei within the fragmentation cone is beyond the potential of even the emulsion method. In all probability, this can be done in intense relativistic beams of heavy nuclei by measuring total ionization and energy fluxes in a complete solid angle.

SPECIAL FEATURES OF THE FRAGMENTATION OF C, O, B, AND N NUCLEI

Multifragmentation of ^{12}C and ^{16}O Nuclei

The probabilities of the production and the properties of systems consisting of a small number of $Z = 1$, 2 fragments can be studied by selecting white stars in the fragmentation of B, C, N, and O isotopes. Detailed information about the multifragmentation of nuclei belonging to this group may form a basis for understanding corresponding processes in heavier nuclei. The dissociation of B and C nuclei to three-particle systems can proceed either via the separation of extremely light nuclei (alpha particles, deuterons, tritons, and ^{3}He nuclei) from the core in the form of the unstable nucleus ^{8}Be or via a direct fragmentation to hydrogen and helium isotopes.

The white stars from the process $^{12}\mathrm{C}^* \to 3\alpha$ at an energy of 3.65 GeV per nucleon were studied in [4–6]. These investigations resulted in demonstrating the role of the channel involving a ^{8}Be nucleus and in drawing the conclusion that, with increasing total energy of the system of three alpha particles, there occurs a transition to direct multifragmentation. In [31], no event of binary splitting through the only possible channel $^{12}\mathrm{C}^* \to {}^6\mathrm{Li} + {}^6\mathrm{Li}$ was observed in the statistical sample of 2757 inelastic interactions.

In [18], the white stars from the process $^{16}\mathrm{O}^* \to 4\alpha$ were studied at a high statistical level (641 events). The analysis of angular correlations that was performed there suggested that there is angular-momentum transfer to fragment systems and that the role of cascade decays through ^{8}Be and $^{12}\mathrm{C}^*$ is insignificant. Tables 5 and 6 present the results obtained by selecting white stars in the sample of 2159 interactions of ^{16}O nuclei at energies of 3.65 (72 stars) and 200 GeV (86 stars) per nucleon.

Multifragmentation of ^{10}B Nuclei

The study of the deuteron contributions to the decays of odd–odd nuclei ^{6}Li [19–22], ^{10}B [23–25], and ^{14}N was a continuation of the investigation into the multifragmentation of light even–even nuclei that involves dissociation only to alpha particles. The role of a deuteron as a cluster was the most pronounced in the white stars from ^{6}Li nuclei at an energy of 3.65 GeV per nucleon (the branching fraction of the decays $^6\mathrm{Li}^* \to d\alpha$, $^6\mathrm{Li}^* \to {}^3\mathrm{He}t^*$ and $^6\mathrm{Li}^* \to tdp$ are, respectively, 74, 13, and 13% [21]).

The topology of white stars for ^{10}B nuclei was studied at an energy of 1 GeV per nucleon. Table 7 presents the charge-topology distribution of 41 white stars, where the secondary tracks are within the angular cone of 15°. The fraction of the decays $^{10}\mathrm{B}^* \to d\alpha\alpha$ among events of $2+2+1$ charge topology was 40%. The contribution of the channel $^{10}\mathrm{B}^* \to {}^8\mathrm{Be}d \to d\alpha\alpha$ was estimated at a level of $18 \pm 3\%$. The decay of an unstable nucleus ^{9}B is not the main source of events having this topology. This is suggested by a low probability of $4+1$ topology in the decay $^{10}\mathrm{B}^* \to {}^9\mathrm{Be}p$ and by a moderately small contribution of ^{8}Be to the decay $^{10}\mathrm{B} \to {}^8\mathrm{Be}p$. We can conclude that direct three-body decays having the $2+2+1$ configuration of white stars play a

Table 4. Charge-topology distribution of white stars in the dissociation of ^{32}S nuclei with an energy of 200 GeV per nucleon

Z_f	15	14	14	13	13	12	12	11	11	10	10	10	9	8	8	7 + 3	7	5 + 3
$N_{Z=1}$	1	–	2	1	3	2	4	3	5	2	4	6	3	–	6	4	3	4
$N_{Z=2}$	–	1	–	1	–	1	–	1	–	2	1	–	2	4	1	1	3	2
$N_{\rm ev}$	99	11	48	7	6	3	4	4	1	1	2	1	1	1	1	1	1	1

decisive role. Thus, the decay $^{10}\mathrm{B}^* \to d\alpha\alpha$ is similar in topology to the decay $^{12}\mathrm{C}^* \to 3\alpha$.

In order to refine our ideas of the relationship between the direct three-body decay and decays through ^{8}Be, we irradiated emulsions with relativistic ^{9}Be nuclei. A beam of ^{9}Be nuclei that have a momentum of 2 GeV/c per nucleon was formed at the JINR nuclotron in the fragmentation process $^{10}\mathrm{B} \to {}^9\mathrm{Be}$. The formation of white stars involving two alpha particles is initiated in the fragmentation process accompanied by the stripping of one neutron. An analysis of data would make it possible to assess the degree of clustering in the ^{9}Be nucleus and the probability of the formation of a ^{8}Be nucleus. This must be manifested in the yield of alpha-particle pairs through the excitation of n–^{8}Be and α–n–α configurations.

Multifragmentation of ^{14}N Nuclei

It is of interest to reveal the role of three-body decays here, which was established for the processes $^{10}\mathrm{B}^* \to d\alpha\alpha$, $^{12}\mathrm{C}^* \to 3\alpha$, and $^{16}\mathrm{O}^* \to 4\alpha$, and to extend the concepts of clustering in nuclei that involves deuterons. For this, we irradiated emulsions with ^{14}N nuclei of energy 2.1 GeV per nucleon. The main objective here was to study $^{14}\mathrm{N}^* \to d\alpha\alpha\alpha$ white stars in the forward cone of angular size up to 8°. The statistics of 540 interactions of nitrogen nuclei with photoemulsion nuclei, including 25 white stars, have been accumulated thus far. The charge-topology distribution of these events is given in Table 8. There is an indication of an important role of the $2 + 2 + 2 + 1$ configuration, which is associated with the decay $^{14}\mathrm{N}^* \to d\alpha\alpha\alpha$. The $6 + 1$ configuration seems to contribute considerably, which is analogous to what we have in events involving the separation of $Z = 1$ fragments in the dissociation of heavier symmetric nuclei.

Table 5. Charge-topology distribution of white stars in the dissociation of ^{16}O nuclei with an energy of 3.65 GeV per nucleon

Z_f	7	6	6	5	5	4	4	–	–
$N_{Z=1}$	1	2	–	3	1	–	2	–	2
$N_{Z=2}$	–	–	1	–	1	2	1	4	3
$N_{\rm ev}$	18	7	21	2	10	1	1	9	3

Table 6. Charge-topology distribution of white stars in the dissociation of ^{16}O nuclei with an energy of 200 GeV per nucleon

Z_f	7	6	6	5	5	4	3	3	–	–	–
$N_{Z=1}$	1	–	2	1	3	2	1	3	–	2	4
$N_{Z=2}$	–	1	–	1	–	1	2	1	4	3	2
$N_{\rm ev}$	49	6	10	5	1	3	2	2	2	4	2

Clustering That Involves Tritons

Investigation of white stars generated by light odd–even stable nuclei (^{7}Li, ^{11}B, ^{15}N, and ^{19}F) can create a basis for including tritons in a general pattern. It was established that the contributions from various channels to white stars generated by relativistic ^{7}Li nuclei were the following: 50% from $^7\mathrm{Li}^* \to t\alpha$, 30% from $^7\mathrm{Li}^* \to dp\alpha$, and 20% from $^7\mathrm{Li}^* \to pn n\alpha$ [25]. As a further step in our investigations, we implemented an irradiation with ^{11}B nuclei of energy 1.2 GeV per nucleon and began an analysis of their dissociation. The main objective of the experiment is to study $^{11}\mathrm{B}^* \to t\alpha\alpha$ white stars.

PROSPECTS FOR STUDYING NEUTRON-DEFICIENT ISOTOPES OF C, B, N, AND Be

Searches for the "Ternary He Processes" in the Decays of ^{11}C, ^{10}C, and ^{9}C

The ^{11}B nucleus is the daughter nucleus in the beta decay of the mirror nucleus ^{11}C. Upon studying $^{11}\mathrm{B}^* \to t\alpha\alpha$ and $^{11}\mathrm{B}^* \to {}^7\mathrm{Li}\alpha$ white stars, it would therefore be of interest to clarify the role of ^{3}He in the decay of ^{11}C. The decays through the channels

Table 7. Charge-topology distribution of white stars in the dissociation of ^{10}B nuclei with an energy of 1 GeV per nucleon

Z_f	4	3	–	–
$N_{Z=1}$	1	–	3	1
$N_{Z=2}$	–	1	1	2
$N_{\rm ev}$	1	5	5	30

Table 8. Charge-topology distribution of white stars in the dissociation of ^{14}N nuclei with an energy of 2.1 GeV per nucleon

Z_f	6	5	4	3	–	–
$N_{Z=1}$	1	2	1	4	3	1
$N_{Z=2}$	–	–	1	–	2	3
$N_{\rm ev}$	6	3	1	1	2	12

^{11}C$^* \rightarrow$ ^{3}He$\alpha\alpha$ and ^{11}C$^* \rightarrow$ ^{7}Beα may be analogous to the channels ^{12}C$^* \rightarrow 3\alpha$ and ^{12}C$^* \rightarrow$ ^{8}Beα. Clustering in the decays ^{12}C$^* \rightarrow 3\alpha$ reflects the well-known ternary α process in nucleosynthesis in stars. Observation of the cluster decays ^{11}C$^* \rightarrow$ ^{3}He$\alpha\alpha$ would provide a basis for studying the possible role of the ternary He process in nucleosynthesis in stars via ^{3}He$\alpha\alpha$ fusion—that is, in helium media characterized by a mixed composition of helium isotopes.

The ^{10}C nucleus is formed from the ^{9}C nucleus via the addition of one neutron. However, the addition of a neutron is unlikely to result in the formation of deuteron or ^{3}He clusters in the ground state of ^{10}C. The formation of two-cluster structures in the form of ^{7}Be and ^{3}He nuclei or in the form of a ^{8}B nucleus and a deuteron is improbable because of a high binding energy of such clusters in the ^{10}C nucleus. In the case of one outer proton, the unstable nucleus ^{9}B may be a core of the ^{10}C nucleus. In a different possible structure featuring two outer protons, the core of the ^{10}C nucleus is formed by the ^{8}Be nucleus, which is also unstable. In all probability, such structures are similar to borromean structures of neutron-rich nuclei. In the case being considered, outer protons prevent the ^{10}C nucleus from decaying to fragments.

It is of interest to obtain experimental information about the channels ^{10}C$^* \rightarrow$ ^{3}He^{3}Heα and ^{10}C$^* \rightarrow$ ^{7}Be^{3}He, since this would make it possible to construct a generalization of the ternary He process. In the aforementioned irradiation of emulsions with ^{10}B nuclei, we have already observed two white stars interpreted in terms of the processes ^{10}B$^* \rightarrow$ ^{3}He$\alpha t \rightarrow (^{10}C^*)\pi^- \rightarrow \alpha^3$He^{3}He$\pi^-$. They suggest the existence of the mode of three-cluster excitation of the ^{10}C nucleus. By way of example, we also note that, in studying the charge-exchange process $t \rightarrow$ ^{3}He on photoemulsion nuclei, a high reliability of its observation was established in [22].

The dissociation of a ^{10}C nucleus may proceed via a cascade involving the production of unstable intermediate nuclei ^{9}B, ^{8}Be, and ^{6}Be in the intermediate state. In such decays, four charged fragments are formed in each final state. Thus, it is possible to study the decays of unstable nuclei ^{9}B, ^{8}Be, and ^{6}Be.

Table 9. Charge-topology distribution of white stars in the dissociation of ^{7}Be nuclei of energy 1.23 GeV per nucleon

Z_f	3	–	–	–
$N_{Z=1}$	1	4	2	–
$N_{Z=2}$	–	–	1	2
$N_{\rm ev}$	7	2	38	28

The beta-decay processes ^{11}C $\rightarrow$ ^{11}B and ^{10}C $\rightarrow$ ^{10}B lead to the formation of stable boron isotopes. In view of this, the participation of an extended ternary He process may affect the abundances of the isotopes of this element in cosmic rays and in matter. At the present time, it is generally believed that boron originates from the disintegration of heavier nuclei.

It is planned to form beams of ^{11}C and ^{10}C nuclei at the JINR nuclotron and to irradiate emulsions with them. The charge-exchange processes ^{11}B $\rightarrow$ ^{11}C and ^{10}B $\rightarrow$ ^{10}C rather than the fragmentation of heavier nuclei are chosen for their generation in order to suppress the contribution of nuclei close to those in ionization that they produce.

Of all nuclei considered here, the ^{9}C nucleus has the highest ratio of the number of protons to the number of neutrons. It has one extra proton in relation to the ^{8}B nucleus. The binding energy of this proton is much higher than the binding energy of the outer proton in the ^{8}B nucleus. This may be a manifestation of the interaction of the two protons, which is similar to the interaction of the two outer neutrons in the ^{6}He nucleus. Investigation of the probability of the decays ^{9}C$^* \rightarrow$ ^{3}He^{3}He^{3}He is of particular interest and importance in relation to ^{9}C$^* \rightarrow$ ^{8}Bp, ^{7}Bepp and other decay channels. It should be noted that the greater the ratio Z/N in the nucleus being studied, the more pronounced the advantages of the emulsion procedure in studying white stars. This is due to the possibility of more comprehensively observing nucleons originating from the fragmenting nucleus.

The fusion process ^{3}He^{3}He^{3}He $\rightarrow$ ^{6}Be^{3}He $\rightarrow$ ^{9}C is yet another version of a ternary He process. Its beta decay to the mirror nucleus ^{9}B, which is not bound, leads to the prompt decay ^{9}B $\rightarrow p\alpha\alpha$. Thus, we see that, in a stellar medium originally containing only ^{3}He, there can occur the production of ^{4}He. Under certain astrophysical conditions, the product nucleus ^{9}C can participate in the further fusion process ^{4}He^{9}C $\rightarrow$ ^{13}N(β^+) $\rightarrow$ ^{13}C.

In the fragmentation process ^{9}C $\rightarrow$ ^{8}C, the intersection of the proton drip line occurs. There then arises the possibility of studying nuclear resonance states in the multiparticle decay channels ^{8}C $\rightarrow$ ^{3}He^{3}Hepp, ^{4}He$pppp$, which possess clear-cut signatures. We cannot rule out the possibility that their investigation may give new impetus to the development of the physics of loosely bound nuclear systems.

A beam of secondary nuclei that have a magnetic rigidity that corresponds to the ratio $Z/A = 2/3$ was formed at the JINR nuclotron in accelerating ^{12}C nuclei of momentum 2 GeV/c per nucleon at an intensity of about 10^9 nuclei per spill. Data for an analysis of the interaction of ^{9}C nuclei in emulsions were obtained.

Clustering in the Decays of ^{8}B Nuclei

A uniquely low binding energy of one of the protons is a feature peculiar to the ^{8}B nucleus. Therefore, it is the most probable that the ^{8}B nucleus has a core in the form of a ^{7}Be nucleus and a loosely bound proton, whose spatial distribution determines, to a considerable extent, the radius of the ^{8}B nucleus.

The structural features of light neutron-deficient nuclei may underlie the so-called fast rp processes of proton capture. For example, the presence of a state belonging to the proton-halo type [32] (a proton far off the nuclear core) may increase the rate of synthesis of light radioactive nuclei along the proton drip line, which decay to stable isotopes. In particular, the halo of ^{8}B reduces the Coulomb repulsion in the ^{3}Heαp fusion of nuclei in mixtures of stable isotopes of H and He in astrophysical systems. The product ^{8}B nucleus can either "wait" for β^+ decay or, within certain astrophysical scenarios, participate in the fusion processes α^8B $\rightarrow$ ^{12}N(β^+) $\rightarrow$ ^{12}C. A much longer lifetime of ^{8}B is a feature that distinguishes this process from the synthesis of ^{12}C through ^{8}Be nuclei.

A beam of secondary nuclei that have a magnetic rigidity that corresponds to the ratio $Z/A = 5/8$ was formed in accelerating, at the JINR nuclotron, ^{10}B nuclei of momentum 1 GeV/c per nucleon and intensity about 10^8 nuclei per spill (the fragmentation process ^{10}B $\rightarrow$ ^{8}B, as was proposed in [25]). Results of irradiation for ^{8}B interactions in emulsion were obtained. It is planned to determine the probabilities of the formation of ^{8}B $\rightarrow$ ^{7}Bep, α^3Hep, ^{6}Lipp, αdpp white stars. In the fragmentation process ^{8}B $\rightarrow$ ^{7}B, the intersection of the proton drip line also occurs. Here, it becomes possible to study the decay channels ^{7}B $\rightarrow$ ^{3}He^{3}Hep (analog of ^{9}B), ^{4}Heppp. In order to study the structure of ^{12}N and to clarify the role of ^{8}B in this nucleus, it is planned to irradiate emulsions with a beam of such nuclei produced in the charge-exchange reaction ^{12}C $\rightarrow$ ^{12}N. In turn, the decays of yet another nucleus beyond the proton drip line can be studied in the fragmentation process ^{12}N $\rightarrow$ ^{11}N.

Clustering in the Decays of ^{7}Be Nuclei

It is of interest to study the fragmentation of a ^{7}Be nucleus, since this nuclear species can form a core in the ^{8}B nucleus. It would be instructive to employ a unified approach to compare, on the basis of the probabilities of white-star formation in the α^3He and ^{6}Lip channels, the cluster structure of this nucleus with those in ^{6}Li [21] and ^{7}Li nuclei, which are close to it in structure [25].

An emulsion was irradiated with ^{7}Be nuclei of energy 1.23 GeV per nucleon. The beam of these nuclei was formed at the JINR nuclotron on the basis of the charge-exchange reaction ^{7}Li $\rightarrow$ ^{7}Be. The procedure of following all primary tracks made it possible to find 75 white stars, where the total charge of secondary tracks within the cone of angular size 15° was $Z = 4$. Examples of such stars for $2+2$ topology with and without target excitation, as well as for $3+1$ and $1+1+1+1$ topologies, are given in Fig. 2. Table 9 presents the charge-topology distribution of these stars. One observes here a channel involving the separation of a singly charged fragment that is unambiguously interpreted as ^{6}Lip. As a special feature, one can indicate two cases of a complete breakup of the nucleus in question to singly charged fragments. For 36 events of $2+1+1$ topology, the method for assessing total momentum on the basis of multiple scattering made it possible to identify 20 $Z = 2$ tracks as ^{3}He and the remaining 16 tracks as ^{4}He. In the mass separation of He nuclei, use was made of $P\beta = 5.1$ GeV/c as the boundary value of the total momentum of fragments. As a continuation of our investigations, it is of interest to analyze the channel ^{7}Be $\rightarrow$ ^{6}Be(n) $\rightarrow$ ^{4}Hepp(n), which is accompanied by target-nucleus fragmentation induced by a neutron.

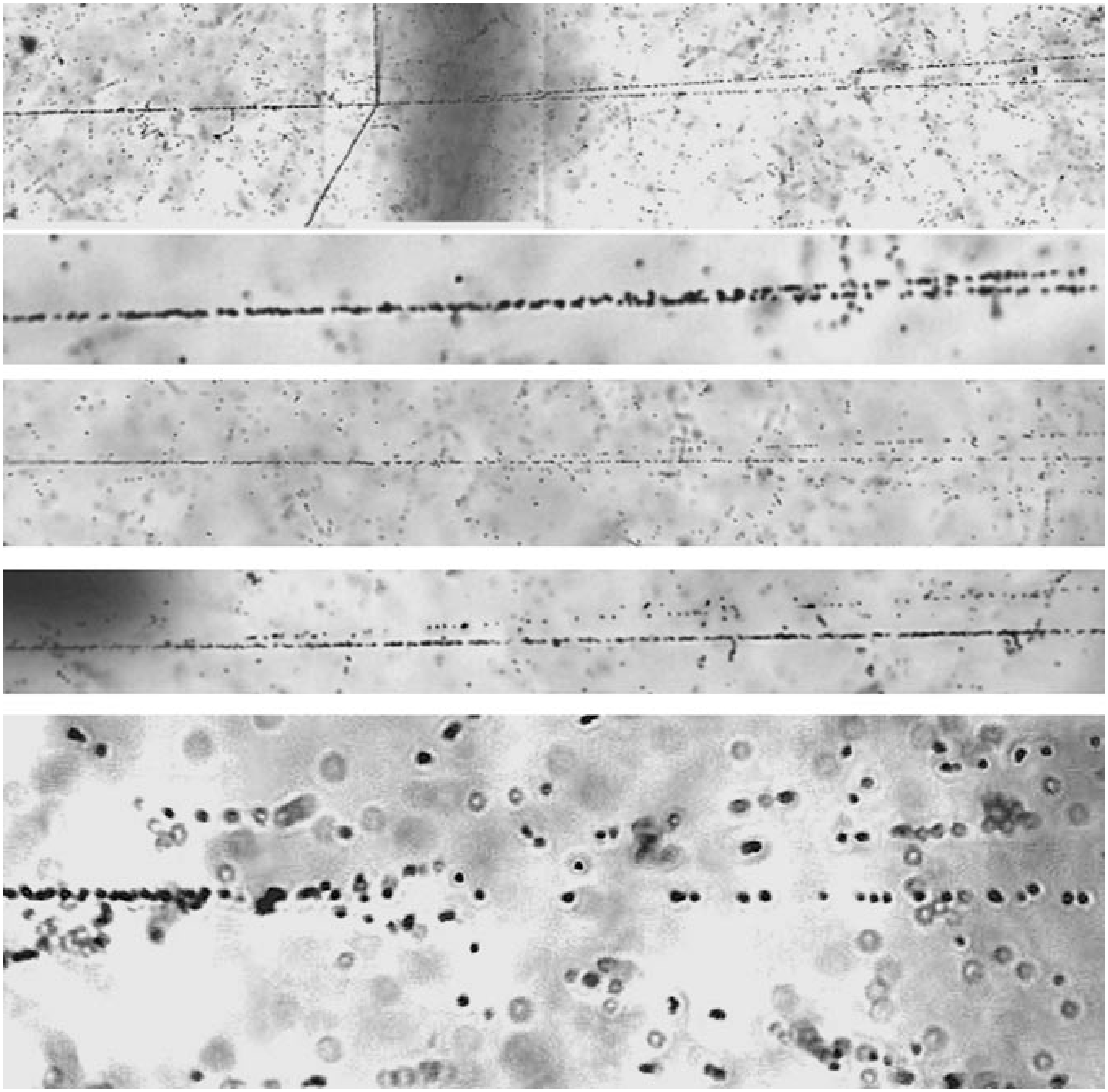

Fig. 2. Examples of events of the peripheral dissociation of ^{7}Be nuclei with an energy of 1.23 GeV per nucleon in emulsion. The upper photograph shows the process in which splitting to two He fragments is accompanied by the formation of two target fragments. In the lower photograph, one can see white stars corresponding to splitting to two helium fragments, one helium fragment and two hydrogen fragments, one lithium and one hydrogen fragment, and four hydrogen fragments.

In Fig. 3, two-particle decays are represented by points whose coordinates are defined as the total momenta $P\beta$ of $Z = 2$ fragments—more specifically, the maximum and the minimum value of $P\beta$ in an event are taken for the ordinate and the abscissa, respectively. The distribution is clearly seen to be anisotropic. The decay $^7\mathrm{Be}^* \to \alpha^3\mathrm{He}$, proceeding at a minimal excitation above the decay threshold, is dominant in 22 events of $2 + 2$ topology in relation to other channels. Within this topology, five events were identified as those of the decay $^7\mathrm{Be}^* \to (n)^3\mathrm{He}^3\mathrm{He}$. Thus, clustering accompanied by the production of a ^{3}He nucleus clearly manifests itself in white stars generated by ^{7}Be nuclei. This conclusion gives sufficient grounds to pose the question of clustering in neighboring neutron-deficient nuclei.

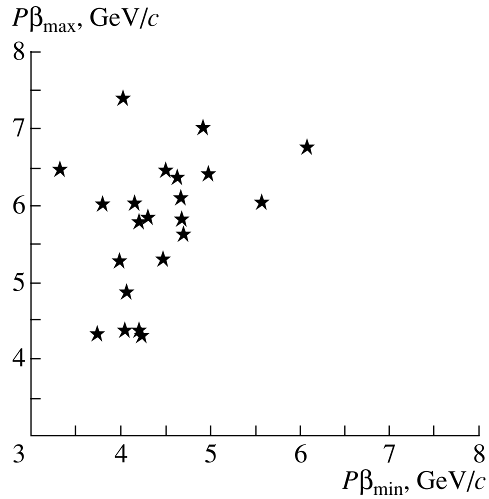

Fig. 3. Distribution of white stars generated by ^{7}Be nuclei of energy 1.23 GeV per nucleon for decays to two helium fragments in terms of the minimum and maximum momenta.

CONCLUSIONS

A review of experimental observations of the multifragmentation of light relativistic nuclei by means of emulsions has been given. Events of the white-star type that involve only tracks of fragments of a relativistic nucleus and which do not contain tracks of charged mesons or tracks of target-nucleus fragments have been selected. The topology of multifragmentation has been considered for these events.

An almost complete suppression of the binary splitting of nuclei to fragments of charge in excess of two, $Z > 2$, is a feature peculiar to charge topology in the fragmentation of Ne, Mg, Si, and S nuclei. Processes involving the separation of single fragments and proceeding at minimal excitation energies are dominant here. An increase in the degree of nuclear fragmentation manifests itself in the growth of the multiplicity of $Z = 1$ and 2 fragments as the charge of the unexcited part of the fragmenting nucleus (this is its main part) decreases.

Special features of the formation of systems of extremely light nuclei α, d, and t have been established in the multifragmentation of stable Li, Be, B, C, N, and O isotopes. For example, nucleon clustering in the form of deuterons in the decays of ^{6}Li and ^{10}B and in the form of tritons in the decays of ^{7}Li has been found in addition to alpha-particle clustering. Moreover, the important role of multiparticle dissociation has been proven for these nuclei.

A manifestation of ^{3}He clustering can be discovered in white stars from the dissociation of neutron-deficient isotopes of Be, B, C, and N. An analysis of white stars from ^{7}Be nuclei shows a manifestation of ^{3}He clustering.

Emulsions provide a unique basis for reconstructing relativistic multiparticle systems. Some of such systems can play the role of initial or loosely bound intermediate states in the fusion of more than two nuclei in nucleosynthesis in stars. The observational basis described in the present article can be used in searches for such states.

ACKNOWLEDGMENTS

In conclusion, we would like to recall our supervisors in investigations with relativistic nuclei, who, unfortunately, passed away. The basis of investigations along these lines was laid by Academician A.M. Baldin. For many years, M.I. Adamovich, V.I. Ostroumov, Z.I. Solov'eva, K.D. Tolstov, M.I. Tret'yakova, and G.M. Chernov were the leaders of investigations performed by the nuclear-emulsion method in beams from the JINR synchrophasotron.

The results presented here are based to a considerable extent on painstaking visual searches and measurements, which could hardly be possible without the generous contribution from technicians including A.V. Pisetskaya (Lebedev Institute of Physics); L.N. Tkach (Petersburg Nuclear Physics Institute); and N.A. Kachalova, I.I. Sosul'nikova, A.M. Sosul'nikova, and G.V. Stel'makh (JINR). I.I. Mar'in (JINR) ensured the maintenance of the microscopes used. A high-quality development of emulsions was performed by the Chemical Group of the V.I. Veksler and A.M. Baldin Laboratory of High Energies at JINR. Specialists from this laboratory who ensured a stable operation of the JINR nuclotron made a valuable contribution to our study. We are indebted to the Directorate of the G.N. Flerov Laboratory of Nuclear Reactions (JINR) for support in timely purchasing emulsions.

This work was supported by the Russian Foundation for Basic Research (project nos. 96-1596423, 02-02-164-12a, 03-02-16134, 03-02-17079, 04-02-16593, 04-02-17151); the Agency for Science at the Ministry for Education of the Slovak Republic and Slovak Academy of Sciences (grant VEGA no. 1/9036/02); and grants from the plenipotentiaries of the Slovak Republic, Czech Republic, and Romania at JINR in 2002 and 2003.

REFERENCES

1. M. I. Adamovich *et al.*, JINR Commun., No. E1-10838 (Dubna, 1977).
2. A. Marin *et al.*, Yad. Fiz. **32**, 1387 (1980) [Sov. J. Nucl. Phys. **32**, 716 (1980)].
3. U. A. Abdurazakova, R. A. Bondarenko, U. G. Gulyamov *et al.*, Yad. Fiz. **39**, 272 (1984) [Sov. J. Nucl. Phys. **39**, 169 (1984)].

4. V. V. Belaga *et al.*, Yad. Fiz. **58**, 2014 (1995) [Phys. At. Nucl. **58**, 1905 (1995)].
5. V. V. Belaga *et al.*, Pis’ma Zh. Éksp. Teor. Fiz. **62**, 385 (1995) [JETP Lett. **62**, 395 (1995)].
6. A. I. Bondarenko *et al.*, Yad. Fiz. **61**, 263 (1998) [Phys. At. Nucl. **61**, 214 (1998)].
7. N. P. Andreeva *et al.*, JINR Commun. OIYAI No. P1-85-692 (Dubna, 1985).
8. M. Karabova *et al.*, Acta Phys. Slov. **36**, 238 (1986).
9. N. P. Andreeva *et al.*, Yad. Fiz. **47**, 157 (1988) [Sov. J. Nucl. Phys. **47**, 102 (1988)].
10. N. P. Andreeva *et al.*, Pis’ma Zh. Éksp. Teor. Fiz. **47**, 20 (1988) [JETP Lett. **47**, 23 (1988)].
11. A. El-Naghy *et al.*, J. Phys. G **14**, 1125 (1988).
12. A. El-Naghy *et al.*, JINR Commun. No. E1-85-547 (Dubna, 1985).
13. A. I. Bondarenko, V. V. Rusakova, Dzh. A. Salomov, and G. M. Chernov, Sov. Phys. J. **34**, 400 (1991).
14. S. A. Krasnov *et al.*, JINR Commun. №. P1-88-252 (Dubna, 1988).
15. B. U. Ameeva *et al.*, Yad. Fiz. **51**, 1047 (1990) [Sov. J. Nucl. Phys. **51**, 669 (1990)].
16. M. I. Adamovich *et al.*, Z. Phys. A **351**, 311 (1992).
17. M. I. Adamovich *et al.*, Z. Phys. C **55**, 235 (1992).
18. F. A. Avetyan *et al.*, Yad. Fiz. **59**, 110 (1996) [Phys. At. Nucl. **59**, 102 (1996)].
19. F. G. Lepekhin, D. M. Seliverstov, and B. B. Simonov, Yad. Fiz. **58**, 881 (1995) [Phys. At. Nucl. **58**, 816 (1995)].
20. F. G. Lepekhin *et al.*, Eur. Phys. J. A **1**, 137 (1998).
21. M. I. Adamovich *et al.*, Yad. Fiz. **62**, 1461 (1999) [Phys. At. Nucl. **62**, 1378 (1999)].
22. M. I. Adamovich *et al.*, Part. Nucl. Lett. **110**, 29 (2003); nucl-ex/0206013.
23. V. Bradnova *et al.*, Few-Body Syst., Suppl. **14**, 241 (2003).
24. V. Bradnova *et al.*, Yad. Fiz. **66**, 1694 (2003) [Phys. At. Nucl. **66**, 1646 (2003)].
25. M. I. Adamovich *et al.*, Yad. Fiz. **67**, 533 (2004) [Phys. At. Nucl. **67**, 514 (2004)].
26. G. Baroni *et al.*, Nucl. Phys. A **516**, 673 (1990).
27. G. Baroni *et al.*, Nucl. Phys. A **540**, 646 (1992).
28. V. Efimov, Phys. Lett. B **32B**, 563 (1970).
29. F. Nunes, Comptes Rendus Physique **4**, 489 (2003).
30. P. Schuck, H. Horiuchi, G. Röpke, and A. Tohsaki, Comptes Rendus Physique **4**, 537 (2003).
31. V. G. Bogdanov *et al.*, Pis’ma Zh. Éksp. Teor. Fiz. **44**, 306 (1986) [JETP Lett. **44**, 391 (1986)].
32. W. Schwab *et al.*, Z. Phys. A **350**, 283 (1995).

Translated by A. Isaakyan