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Study of the Cluster Structure of Light Relativistic Nuclei via Dissociation

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Abstract. In the paper are presented the capabilities of relativistic nuclear physics for the development of the physics of nuclear clusters. Nuclear track emulsion continues to be an effective technique for pilot studies that allows one, in particular, to study the cluster dissociation of a wide variety of light relativistic nuclei within a common approach. Despite the fact that the capabilities of the relativistic fragmentation for the study of nuclear clustering were recognized quite a long time ago, electronic experiments have not been able to come closer to an integrated analysis of ensembles of relativistic fragments. The continued pause in the investigation of the "fine" structure of relativistic fragmentation has led to resumption of regular exposures of nuclear emulsions in beams of light nuclei produced for the first time at the Nuclotron of the Joint Institute for Nuclear Research (JINR, Dubna). To date, an analysis of the peripheral interactions of relativistic isotopes of beryllium, boron, carbon and nitrogen, including radioactive ones, with nuclei of the emulsion composition, has been performed, which allows the clustering pattern to be presented for a whole family of light nuclei.

1 Introduction

Collective degrees of freedom, in which groups of few nucleons behave as composing clusters, are a key aspect of nuclear structure. The fundamental "building blocks" elements of clustering are the lightest nuclei having no excited states $-$ first of all, the ^{4}He nucleus (α particles) as well as the deuteron (d), the triton (t) and the ^{3}He nucleus (h, helion). This feature is clearly seen in light nuclei, where the number of possible cluster configurations is small (Figure 1). In particular, the cluster separation thresholds in the nuclei of ^{7}Be, ^{6,7}Li, ^{11,10}B, ^{11,12}C and ^{16}O are below the nucleon separation thresholds. The stable ^{9}Be, and unbound ^{8}Be and ^{9}B nuclei have a clearly pronounced cluster nature. In turn, the cluster nuclei ^{7}Be, ^{7}Li, and ^{8}Be serve as cores in the isotopes ^{8}B and $^{9-12}$C. Descriptions of the ground states of light nuclei in the shell and cluster models are complementary. In the cluster pattern the light nuclei are represented as superpositions of different cluster and nucleon configurations. The interest in such states is associated with the prediction of their molecular-like properties [1, 2].

Nuclear clustering is traditionally regarded as the prerogative of the physics of nuclear reactions at low energies [3].

According to NTE observations, the degree of dissociation of light nuclei as well as of the heaviest ones can reach a total destruction into the lightest nuclei and nucleons. Until now, information about this phenomenon has been fragmentary, and its interpretation has not been offered. Light nuclei are sources for the generation of the simplest configurations of the lightest clusters and nucleons. Being interesting by itself, their study provides a basis for understanding the dynamics of multiple fragmentations of heavy nuclei. The nuclear track emulsion exposed to relativistic radioactive nuclei makes it possible to diversify qualitatively the “tomography” of nuclear structure.

The study of cluster structure by relativistic dissociation has both fundamental and practical importance. First of all, the probabilities with which the cluster states are shown in dissociation are related to the fundamental parameters of the ground and excited states of light nuclei. The knowledge of probabilities allows one to determine possible initial configurations of nuclear clusters, which is important for the analysis of the whole variety of nuclear reactions. Clustering is the basis of the underlying processes accompanying the phenomenon of the physics of nuclear isobars, hypernuclei and quark degrees of freedom. The ideas about nuclear clustering obtained in high-energy physics are important for applications in nuclear astrophysics, cosmic ray physics, nuclear medicine, and perhaps even nuclear geology. In particular, the probability distributions of the final cluster states may suggest new ways of multiple particle nuclear fusion, as inverse processes to their dissociation.

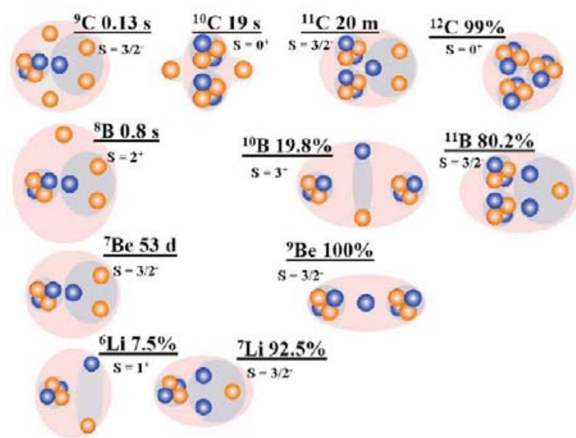

Figure 1. Diagram of cluster degrees of freedom in stable and neutron-deficient nuclei; abundances or lifetimes of isotopes, their spins and parities are indicated; orange circles correspond to protons and blue ones to neutrons; clusters are marked as dark background.

At the JINR Nuclotron in 2002, the newly formed BECQUEREL collaboration launched a program of irradiation of NTE stacks in the beams of relativistic isotopes of beryllium, boron, carbon and nitrogen, including radioactive ones (Figure 1). Coinciding with the name of the famous scientist, the project acronym indicates its key tasks – **Be**ryllium (**B**oron) **C**lustering **Que**st in **Rel**ativistic Multifragmentation [21]. The physical design of the program consisted in a systematic verification of the assumption that in the dissociation of light relativistic nuclei it is possible to study the characteristics of their cluster structure. This idea is not obvious, and its implementation by means others than NTE face objective difficulties. Analysis of NTE exposures can best explore the structure and kinematical characteristics of a variety of ensembles of relativistic clusters. The ultimate goal of NTE application is the most complete identification and metrology of unusual configurations of clusters. Detailed information about the structure of dissociation will be very useful for the feasibility studies of electronic experiments with high statistics of events.

2 First Exposures at the JINR Nuclotron

2.1 ^{10}B nucleus

The $\alpha + d$ clustering of the ^{6}Li nucleus, which was demonstrated with remarkable detail [4], led to an idea to identify a more complicated clustering – $2\alpha{+}d$ – in the next odd-odd nucleus – ^{10}B [5]. The thresholds of separation of nucleons and lightest nuclei are close for this nucleus – $E_{th}(^{6}\mathrm{Li}{+}\alpha) = 4.5$ MeV, $E_{th}(^{8}\mathrm{Be}{+}d) = 6.0$ MeV, $E_{th}(^{9}\mathrm{Be}{+}p) = 6.6$ MeV. It was found that in approximately 65% of peripheral interactions ($\sum Z_{fr} = 5$, $n_s = 0$) of $1A$ GeV ^{10}B nuclei occur via the 2He+H channel. A singly charged particle in ≈40% of these events is the deuteron. The abundant deuteron yield is comparable with the ^{6}Li case and points to the deuteron clustering in the ^{10}B nucleus. Events in the He+3H channel constitute 15%. 10% of the events contain both Li and He fragments. The presence (or absence) of fragments of the target nucleus has practically no effect on the charge topology of the projectile nucleus fragmentation.

Just 2% of the events contain fragments with charges $Z_{fr} = 4$ and 1, *i.e.* the ^{9}Be nucleus and the proton. This "negative" observation merits attention because it serves as a test of the relation of the shell and cluster description of the ^{10}B nucleus. Indeed, the spin of this nucleus is equal to 3, which explains the p-shell filling order. Removal of a proton from the p-shell leads to the formation of the ^{9}Be nucleus with spin 3/2. Thus, the separation of the proton does not require the transfer of the angular momentum. However, this channel is suppressed, which indirectly favors the leading role of the $2\alpha + d$ structure in the ^{10}B ground state.

A valuable finding of the exposure is an event of the coherent dissociation ^{10}B→3He. Associated with the rearrangement of nucleons in α clusters, the process ^{10}B$\rightarrow$ 2^{3}He+^{4}He could proceed via the charge-exchange reaction ^{10}B$\rightarrow$^{6}Li+^{4}He$\rightarrow$^{3}H+^{3}He+^{4}He$\rightarrow$2^{3}He+^{4}He (E$_{th}$ = 20 MeV). By the charge composition this event is almost certainly identified as ^{10}B$\rightarrow$ 2^{3}He+^{4}He, since the threshold of breakup of the second α cluster ^{10}B$\rightarrow$ 3^{3}He+n is even 16 MeV higher. The measurements of multiple scattering of the He tracks have confirmed this interpretation.

2.2 ^{11}B nucleus

The determining role of the ^{3}H cluster in the fragmentation of ^{7}Li motivated a study of the triton cluster in the breakups of $2.75A$ GeV ^{11}B nuclei [6]. The experiment was aimed at the channels with low thresholds of cluster separation $-$ E$_{th}$(^{7}Li+α) $=$ 8.7 MeV, E$_{th}$($2\alpha + t$) $=$ 11.2 MeV and E$_{th}$(^{10}Be+p) $=$ 11.2 MeV. A leading channel, 2He+H, was also established for the ^{11}B nucleus. Similarly to the case of ^{10}B, a large proportion of tritons in the ^{11}B "white" stars favor its existence as a cluster. However, the increasing excess of neutrons that require (as in the case of ^{7}Li) an increasing volume of measurements of multiple scattering leads to a decrease in the effectiveness of our approach.

Eight "white" stars of the charge-exchange reaction ^{11}B$\rightarrow$^{11}C* $\rightarrow$^{7}Be+^{4}He have been found. Charge exchange events through other channels were not observed. This fact demonstrates that while a three-body channel leads in ^{10}B and ^{11}B breakups, the two-body leads in the ^{11}C case. These observations motivate a direct study of ^{11}C dissociation through the channels ^{7}Be+α (E$_{th}$ = 7.6 MeV), ^{10}B+p (E$_{th}$ = 8.7 MeV) and ^{3}He+2α (E$_{th}$ = 9.2 MeV).

One should note the practical value of information about the ^{11}C structure for nuclear medicine. In contrast to the ^{12}C nucleus there should also be a significant contribution of the ^{7}Be nucleus in the final states of ^{11}C fragmentation. This circumstance leads to less "spreading" of ionization from ^{11}C fragmentation products.

2.3 ^{7}Be nucleus

The next stage was peripheral interactions of the ^{7}Be nuclei obtained in charge-exchange reactions of $1.2A$ GeV ^{7}Li nuclei [7, 8]. Approximately 50% of the dissociation events occur without neutron emission, *i.e.*, when $\sum$A$_{fr}$ $= 7$. In general, the coherent dissociation $\sum$Z$_{fr}$ $= 4$ and $\sum$A$_{fr}$ $= 7$ is determined by the configuration of ^{4}He $+$ ^{3}He in the ^{7}Be structure. The channels with a high threshold, in which there is no ^{4}He cluster play a noticeable role. The statistics of the channels with He clusters shows a weak dependence on the values of dissociation thresholds. Apparently, the role of the ^{3}He cluster in the ^{7}Be nucleus goes beyond the ^{4}He+^{3}He bond.

2.4 ^{9}Be nucleus

The ^{9}Be nucleus having the properties of the loosely bound system $2\alpha + n$ is the "cornerstone" of cluster physics. Due to its low neutron separation threshold, dissociation of ^{9}Be can be a source of unstable ^{8}Be nuclei. The ^{8}Be isotope is known as the only nucleus whose ground state is characterized as the α-particle Bose condensate. Investigation of the ^{9}Be nucleus fragmentation in α-particle pairs seems to be an obvious starting point towards more complicated Nα-systems. However, there is a practical obstacle on the way of studying this stable nucleus. Beryllium is a toxic element which makes immediate acceleration of ^{9}Be nuclei impossible. Therefore, a secondary beam of relativistic ^{9}Be nuclei was obtained in the fragmentation reaction ^{10}B$\rightarrow$ ^{9}Be [8–10]. The share of ^{9}Be nuclei was approximately 2/3, while 1/3 fell on He and Li isotopes.

In the two-body model used for the calculation of the magnetic moment [11, 12] of the ^{9}Be nucleus, the latter is represented as a bound state of the neutron and ^{8}Be core in the 0^+ (g.s.) and 2^+ states with neutron separation thresholds being E$_{th}$ $=$ 1.67 and 4.71 MeV. The weights of these states are 0.535 and 0.465. Therefore, in the ^{9}Be dissociation it is possible to observe the ^{8}Be 0^+ and 2^+ states with a similar intensity and in the simplest terms. In the ^{8}Be nucleus there is a clear separation in energy E$_{ex}$ and width Γ of the ground 0^+ (E$_{ex}$ $= 92$ keV, $\Gamma = 5.6$ eV), the first 2^+ (E$_{ex}$ $= 3.1$ MeV, $\Gamma = 1.5$ MeV) and second excited 4^+ (E$_{ex}$ $= 11.4$ MeV, $\Gamma = 3.5$ MeV) states. Observation of these states can serve as a test of NTE spectroscopic capabilities. The excitation structure of ^{9}Be itself is much more complicated $-$ there are 10 levels from the threshold to 12 MeV. There is uncertainty about the contribution of the + ^{5}He state.

An accelerated search for ^{9}Be$\rightarrow$2He events was carried out "along the strips". Focusing on a simple topology allowed bypassing the complicated problem of the identification of the secondary beam nuclei. As a result of scanning, 500 α-particle pairs were found in the projectile fragmentation cone. Measurements of immersing angles and angles in the emulsion plane were performed for all α-pair tracks which made it possible to determine the pair opening angles Θ. A peculiarity of the resulting Θ distribution is the formation of two peaks. About 81% of the events formed two roughly equal groups $-$ "narrow" α-pairs in the interval $0 < \Theta_{n(arrow)} < 10.5$ mrad and "wide" ones $-15.0 < \Theta_{w(ide)} < 45.0$ mrad. The remaining 19% of the events are classified as "intermediate" pairs $10.5 < \Theta_{m(ediuum)} < 15.0$ mrad and "wider" pairs $-$ $45.0 < \Theta_{v(ery)w(ide)} < 114.0$ mrad.

The physical meaning of this observation is explicitly manifested in the distribution of the α-pair energy Q$_{2\alpha}$. (75$\pm$10)% of events with "narrow" opening angles Θ_n are characterized by mean $\langle$Q$_{2\alpha}\rangle = (86 \pm 4)$ keV with a standard deviation $\sigma($Q$_{2\alpha}) = (48 \pm 2)$ keV. This value $\langle$Q$_{2\alpha}\rangle$ corresponds to the ^{8}Be$_{g.s.}$ 0^+ state decay. The value $\sigma($Q$_{2\alpha})$ can serve as an estimate of resolution. For events with "wide" opening angles Θ_w the value $\langle$Q$_{2\alpha}\rangle$ is equal to (3.1$\pm$0.11) MeV with $\sigma($Q$_{2\alpha})$=(1.30$\pm$0.08) MeV. In this case $\langle$Q$_{2\alpha}\rangle$ and $\sigma($Q$_{2\alpha})$ correspond to the ^{8}Be 2^+ state. Events with "intermediate" opening angles Θ_m, may be associated with the formation of ^{5}He, and Θ_{vw} $-$ with the decay of the ^{8}Be 4^+ state. For events Θ_{vw} an important factor is the accuracy of the determination of energy and of identification of He isotopes. Thus, the formation of Θ_n pairs is matched to decays of the ^{8}Be 0^+ ground state and Θ_w pairs $-$ of the first excited 2^+ state. The shares of the events Θ_n and Θ_w constitute 0.56$\pm$0.04 and 0.44$\pm$0.04, respectively. These values demonstrate the compliance with the weights of the ^{8}Be 0^+ and 2^+ states adopted in [11,12] and point to the presence of these states as components of the ^{9}Be ground state.

2.5 ^{14}N nucleus

The ^{14}N nucleus is of interest as intermediate between the cluster nucleus ^{12}C and the doubly magic nucleus ^{16}O. The study of ^{14}N nuclei can expand understanding of the evolution of increasingly complex structures beyond the α-clustering. The information about the structure of ^{14}N has an applied value. As a major component of the Earth's atmosphere the ^{14}N nucleus can be a source of the light rare earth elements Li, Be and B, as well as of deuterium. Generation of these elements occurs as a result of bombardment of the atmosphere during its lifetime by high-energy cosmic particles. Therefore, the cluster features of the ^{14}N fragmentation can determine the abundances of lighter isotopes. Beams of ^{14}N nuclei can be used in radiation therapy, which also gives a practical interest in obtaining detailed data about the characteristics of the ^{14}N fragmentation.

For the first time the fragmentation of relativistic ^{14}N nuclei was studied in NTE exposed at the Bevatron in the 70s [16]. Limitations in measurement of angles and fragment identification [16] motivated a study of the dissociation of 2.9 A GeV/c ^{14}N nuclei in NTE exposed at the JINR Nuclotron [15]. The starting task was to reveal the role of external nucleon clustering in the form of a deuteron. This type of clusterization is expected for odd-odd light stable nuclei, whose number is small.

Events were selected in which the total charge of the fragments $\sum Z_{fr}$ was equal to the projectile nucleus charge $Z_{pr} = 7$ and there were no produced mesons. The main contribution is provided by the channels C+H, 3He+H, and 2He+3H (77%). The share of events C+H ($E_{th} = 7.6$ MeV) is sufficiently significant $-$ 25%. The share of B+He events ($E_{th} = 20.7$ MeV) turned out to be small $-$ only 8%. A significant reduction in the proportion of deuterons relative to protons in comparison with ^{6}Li and ^{10}B nuclei was demonstrated. A leading role both for "white" stars and events with the formation of target fragments is taken by the multiple channel ^{14}N$\to$3He+H ($E_{th} = 15$ MeV) having a probability of about 35%. Thus, the ^{14}N nucleus manifests itself as an effective source of 3α-systems. It was found that 80% of the 3α ensembles correspond to the excitations of the ^{12}C nucleus from the breakup threshold to 14 MeV. ^{14}N produces fragments in the channel 3He+H via the formation of ^{8}Be with approximately 20% probability. Events ^{11}C+^{3}H, ^{6}He+^{4}He+^{3}He+p, ^{4}He+2^{3}He+d have been identified; for these partial rearrangement of the α-structure is necessary.

2.6 ^{8}B nucleus

^{8}B fragments produced by $1.2A$ GeV ^{10}B nuclei were selected for exposure of NTE [8, 13]. The charge composition of the relativistic fragments for the events $\sum Z_{fr} = 5$ accompanied by target nucleus fragments and (or) produced mesons N_{tf} and "white" stars N_{ws} (example in Figure 2) show a qualitative difference. The main conclusion is that the contribution of the dissociation ^{8}B$\to$ ^{7}Be$+p$ is leading among "white" stars. This situation is qualitatively different from the dissociation of the ^{10}B isotope. Data on N_{ws} may be useful as estimates of the probabilities of few body configurations in the ^{8}B ground state.

Due to the record low binding energy of the external proton ($E_{th} = 138$ keV), the ^{8}B nucleus is the most sensitive probe of the electromagnetic interaction with the target nucleus. In the center of mass of the system ^{7}Be$+p$ the average transverse momenta of the particles is $\langle P_T^* \rangle = (62 \pm 11)$ MeV/c at RMS of 54 MeV/c. This small value indicates a weak bond of the proton and the core. The distribution of the total transverse momenta of the pairs in the "white" stars has an average value of $\langle P_T(^8\mathrm{B}^*) \rangle = (95 \pm 15)$ MeV/c at RMS of 73 MeV/c, and a significantly greater one for events with target nucleus fragments or produced mesons $\langle P_T(^8\mathrm{B}^*) \rangle = (251 \pm 29)$ MeV/c at RMS of 112 MeV/c.

Analysis of angular correlations allowed establishing the criteria of the electromagnetic dissociation events by the total transverse momentum $P_T(^8\mathrm{B}^*) <$ 150 MeV/c, energy $Q_{pBe} < 5$ MeV and by the azimuth angle $\varepsilon_{pBe} > \pi/2$ between the fragments. Because of Z^2 dependence of the electromagnetic cross-section on a nucleus target charge species, the proportional contribution can be assumed from Ag and Br nuclei. Then the obtained cross-sections comprise $\sigma_{Ag} = (81 \pm 21)$ mb and $\sigma_{Br} = (44 \pm 12)$ mb. Analysis of the ratio of the Coulomb and nuclear dissociation and stripping in the dissociation of ^{8}B$\to$ ^{7}Be$+p$ for the Pb target up to the energy of $\approx 2A$ GeV was carried out in [14]. Extrapolation σ_{Ag} to the Pb nucleus leads to the value $\sigma_{Pb} = (230 \pm 60)$ mb, which is close to the theoretical value of $\approx$210 mb [14].

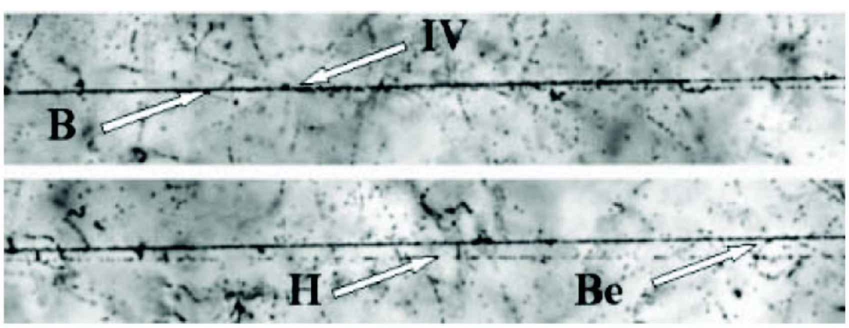

Figure 2. Coherent dissociation ^{8}B $\to ^7$Be$+p$ at $2A$ GeV/c (IV is interaction vertex).

2.7 ^{9}C nucleus

The ^{9}C nucleus became the next studied object on the proton border of nuclear stability. The coherent dissociation of ^{9}C can proceed through the channels ^{8}B+p (E$_{th}$ = 1.3 MeV) and ^{7}Be+2p (E$_{th}$ = 1.4 MeV) as well as the ^{7}Be core breakups (E$_{th}$ > 3 MeV). In the study of ^{9}C interactions there is a need to overcome two practical problems. First, the ^{3}He nuclei, having the same ratio of the charge Z$_{pr}$ to the mass number A$_{pr}$, are dominant in the generated beam. Thus, it was important to avoid NTE overexposure to ^{3}He nuclei. Second, it was necessary to ensure the ^{9}C dominance over the contributions of the ^{10,11}C isotopes. A comparative analysis of the coherent dissociation of the studied neighboring isotopes helped this problem to be solved.

^{12}C^{6+} ions, created by a laser source, were accelerated to $1.2A$ GeV and extracted to the production target. Further, the secondary beam tuned for selection of ^{9}C nuclei was guided on the emulsion stack [8, 17]. With dominance of C nuclei, the beam contained an insignificant admixture of ^{6}Li, ^{7}Be and ^{8}B.

The main branch of the coherent dissociation is represented by events $\sum$Z$_{fr}$ = 6, which is to be expected due to the dominance of C nuclei in the beam. The most valuable is the analysis of the channels corresponding to the ^{9}C nucleus dissociation with the lowest thresholds ^{8}B+p and ^{7}Be+2p, as well as the 3He channel. The events in the last channel could be eligible for the coherent dissociation ^{9}C $\rightarrow$ 3^{3}He. The events Z$_{pr}$ = 6 and Z$_{fr}$ = 5 and 4 are interpreted as ^{9}C→ ^{8}B+p and ^{7}Be+2p. The events 2He+2H and He+4H are dominant. In the case of ^{9}C, events in these channels occur with approximately equal probability as expected due to the dissociation of the ^{7}Be core [7]. This ratio does not correspond to the isotope ^{10}C, for which the probability of the 2He+2H channel is approximately by an order of magnitude higher than for the He+4H channel. Besides, “white” stars ^{6}Li+3p and 6H produced as a result the dissociation of the ^{7}Be core were observed.

The 3^{3}He states are the central subject of the current study. The dissociation probability via this channel ($\approx$14%) is comparable to the nucleon separation channels. The significant probability of the coherent dissociation channel ^{9}C→ 3^{3}He makes it an effective source for the search for a resonant 2^{3}He state near the threshold analogous to the ^{8}Be ground state.

Eight narrow 2He pairs with opening angles limited to $\Theta_{2He} < 10^{-2}$ rad are reliably observed thanks to the NTE resolution. They are allocated in a special group with an average of $\langle\Theta(2^{3}\text{He})\rangle = (6 \pm 1) \times 10^{-3}$ rad at RMS of 3×10^{-3} rad. The energy distribution has a mean value $\langle\text{Q}(2^{3}\text{He})\rangle = (142 \pm 35)$ keV at RMS of 100 keV. Thus, despite the low statistics, this distribution points to an intriguing possibility of the existence of a resonant 2^{3}He state slightly above the mass threshold of 2^{3}He.

2.8 ^{10}C nucleus

The ^{10}C nucleus is the only example of a stable 4-body structure in which the removal of any of the constituent clusters or nucleons leads to an unbound state condition. The breakup threshold of the ^{10}C$\rightarrow$ $2\alpha + 2p$ process is E_{th} = 3.73 MeV. The next threshold via ^{8}Be$_{g.s.}$ + $2p$ is slightly higher $-$ E_{th} = 3.82 MeV. Knocking out one of the protons (E_{th} = 4.01 MeV) leads to the formation of an unstable ^{9}B nucleus, which decays into a proton and a ^{8}Be nucleus. By way of α-cluster separation (E_{th} = 5.10 MeV) a ^{6}Be resonance can be formed, its decay energy being 1.37 MeV. The decay of ^{6}Be via the ^{5}Li resonance is impossible, because the threshold for the formation of ^{5}Li$_{g.s.}$ + p is 0.35 MeV higher than the ^{6}Be ground state. In addition, the channel ^{5}Li$_{g.s.}$ + α is closed since this threshold is 1.5 MeV higher than the ^{9}B ground state. Therefore, in the ^{10}C dissociation the resonances ^{6}Be$_{g.s.}$ and ^{5}Li$_{g.s.}$ can only be produced directly and not in cascade decays of ^{9}B.

Events $\sum Z_{fr} = 6$ were selected among the found peripheral interactions [18, 20]. The subject of the analysis was a sample consisting of 227 "white" stars N_{ws}. A peculiarity of this class of events is the dominance of the channel 2He+2H, which is indeed the most expected one for the ^{10}C isotope. The channels N_{ws} requiring destruction of α-clustering in ^{10}C nuclei and having substantially higher thresholds are manifested with much lower probabilities.

Comparison of the N_{ws} topology distribution with the version for the 627 ^{10}C N_{tf} events accompanied by the production of mesons, fragments of target nuclei or recoil protons, points to the "turning on" of the He+4H channel in the latter case. First of all, a much smaller perturbation of the ^{10}C cluster structure in the "white" stars with the respect to the N_{tf} case is confirmed. In addition, the comparison shows that the probabilities of the fragmentation channels beyond the "pure" clustering $2\alpha - 2p$ do not differ too much in the cases N_{ws} and N_{tf}. This fact indicates the existence in the ^{10}C structure of a small admixture of virtual states with participation of deeply bound cluster-nucleon configurations.

2.9 ^{12}N nucleus

Clustering of the insufficiently explored ^{12}N nucleus is the next goal in the further development of the ^{7}Be, ^{8}B and ^{9,10,11}C studies in the relativistic dissociation approach. In an astrophysical aspect its existence provides an alternative scenario for the synthesis of the ^{12}C isotope via the fusion ^{11}C+p. For ^{12}N "white" stars, the channels ^{11}C+p ($E_{th} = 0.6$ MeV), ^{8}B+^{4}He ($E_{th} = 8$ MeV) and $p + {}^7$Be+^{4}He ($E_{th} = 7.7$ MeV) and the channels associated with the dissociation of the ^{7}Be core are expected to play a leading role. The threshold of the channel ^{3}He+^{9}B$_{g.s.}$ is located at $E_{th} = 10$ MeV. A small difference in the binding energy compared with the channels containing fragments $Z_{fr} > 2$ suggests a possible duality of the ^{12}N nucleus. On the one hand, its basis can be represented by the bound ^{7}Be and ^{8}B nuclei, on the other hand by the unbound ^{8}Be and ^{9}B nuclei. Therefore, a particular feature of the coherent ^{12}N dissociation could be a competing contribution of ^{8}Be and ^{9}B decays.

Measurements of the charges of the beam nuclei Z_{pr} and relativistic fragments $Z_{fr} > 2$ in the candidate events of the ^{12}N dissociation made it possible to select 72 "white" stars which satisfy the condition $Z_{pr} = 7$ and $\sum Z_{fr} = 7$

[18, 19]. According to the "white" star statistics, the share of ^{12}N nuclei in the beam is estimated to be 14%, while those of ^{10}C and ^{7}Be nuclei are about 43% each (excluding H and He nuclei). These values do not reflect the ratio of the cross-sections of the charge exchange and fragmentation reactions and have a technical importance. The significant contribution to the beam of charge-exchange products ^{12}C→ ^{12}N compared with ^{10}C and ^{7}Be fragments of ^{12}C is explained by the fact that the beam was tuned to the ratio $Z_{pr}/A_{pr} = 5/12$ of ^{12}N, which is slightly different from the values for ^{10}C and ^{7}Be.

For a further selection of events containing specifically ^{12}N fragments (not "participants"), the condition on the angular cone of coherent dissociation was enhanced to $\theta_{fr} < 6°$, which is determined by a "soft" constraint on the nucleon Fermi momentum. In the distribution of 45 selected events the share of the channels with heavy fragments $Z_{fr} > 2$ reaches approximately 2/3, and the contribution of the channels containing only He and H fragments is quite significant. A noticeable contribution of a very "fragile" ^{8}B points to a "cold" fragmentation with minimal perturbation of the ^{12}N structure. As judged by the facts of approximate equality of the probabilities of the channels 2He and He + 2H in the dissociation of the ^{7}Be nucleus [7], ^{7}Be core of ^{8}B [13] and ^{9}C [17], one would expect that for the ^{12}N nucleus the probabilities of the channels 2He+3H and 3He+H are nearly equal. In contrast, the statistics in the 2He+3H channel turned out to be unexpectedly large.

Angular measurements were used to study the contribution of ^{8}Be decays. Only two candidates for ^{8}Be$_{g.s.}$ decays were found in the distribution on the opening angle Θ_{2He} for the "white" stars 2He+3H and 3He+H. Thus, the contribution of ^{8}Be$_{g.s.}$ to the ^{12}N structure is estimated to be only 4±2%. For the neighboring nuclei ^{12}C [21], ^{10}C [18, 20], ^{10}B [5] and ^{14}N [15] it amounted to about 20%. The data on Θ_{2He} for ^{12}N do not exclude a possibility of dissociation via ^{8}Be 2^{+} state decays. The latter question requires statistics at a new level.

3 Conclusion

In general, the presented results confirm the hypothesis that the known features of light nuclei define the pattern of their relativistic dissociation. The probability distributions of the final configuration of fragments allow their contributions to the structure of the investigated nuclei to be evaluated. These distributions have an individual character for each of the presented nuclei appearing as their original "autograph". The nuclei themselves are presented as various superpositions of light nuclei-cores, the lightest nuclei-clusters and nucleons. Therefore, the selection of any single or even a pair of configurations would be a simplification determined by the intention to understand the major aspects of nuclear reactions and nuclear properties rather than the real situation. The data presented are intended to help estimate the degree and effects of such simplifications.

The approach based on the dissociation of relativistic nuclei, opens new horizons in the study of the cluster structure of nuclei and unbound cluster systems. At present only first steps which nevertheless are quite necessary have been made. Dissociation of relativistic nuclei leads to the appearance of multiple particle combinations with kinematical characteristics that are of interest in nuclear astrophysics and that cannot be formed in other laboratory conditions. On the other hand, in multiple dissociations of neutron-rich nuclei into light fragments the presence of a significant neutron component becomes unavoidable which is caused by a symmetrical composition of light nuclei. Thus, there is a prospect of exploration of polyneutron states. Besides, an applied interest appears here too.

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