Unstable nuclei in coherent dissociation of relativistic nuclei $^{7,9}Be$, ^{10}B and $^{10,11}C$

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Unstable nuclei in coherent dissociation of relativistic nuclei ^{7,9}Be, ^{10}B and ^{10,11}C

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Abstract. Contribution of the unstable nuclei ^{7}Be, ^{8}Be and ^{9}B into coherent dissociation events (“white” stars) of relativistic nuclei ^{7,9}Be, ^{10}B and ^{10,11}C is under study on the basis of a nuclear track emulsion exposed to beams of the JINR Nuclotron. Distributions over the opening angle of α-pairs indicate to a simultaneous presence of virtual ^{8}Be$_{g.s.}$ and ^{8}Be$_{2+}$ states in the ground states of the ^{9}Be and ^{10}C nuclei. The core ^{9}B is manifested in the ^{10}C nucleus with a probability of (30 ± 4)%, Selection of the ^{10}C “white” stars accompanied by ^{8}Be$_{g.s.}$ (^{9}B) leads to the appearance in the excitation energy distribution of 2α2*p* “quartets” of the distinct peak with a maximum at 4.1 ± 0.3 MeV. ^{8}Be$_{g.s.}$ decays are presented in 21% 2He + 2H and 19% in the 3He of the all ^{11}C “white” stars. ^{9}B$_{g.s.}$ decays are identified in “white” stars ^{11}C → 2He + 2H constituting 14% of the ^{11}C “white” stars. The ^{9}B nucleus. is manifested in the “white” stars ^{10}B → 2He + 2H with a probability of (9 ± 1)%. For the ^{10}B case yield of ^{8}Be$_{g.s.}$ nuclei with the respect to ^{9}B is about a factor of 3 higher than ^{9}B.

1. Introduction

The group of nuclei at the beginning of the table of isotopes provides a recognized laboratory of nuclear quantum mechanics allowing one to study the coexistence and evolution of cluster and shell degrees of freedom. Light nuclei can be presented as all possible superpositions of lighter nuclear cores, lightest nuclear clusters having no excited states (α-particle, triton, ^{3}He nucleus, and deuteron), and nucleons that coexist in dynamical equilibrium. Interlacing cluster and shell degrees of freedom do a “laboratory” of nuclear quantum mechanics from a group of nuclei in the beginning of the table of isotopes.

Consideration of the nucleosynthesis chains toward ^{10,11}B, ^{11,10}C and ^{12}N via the “hot breakout” ^{7}Be(^{3}He,γ)^{10}C(e^{+},ν)^{10}B assists to recognize the relationship of their structures. The ^{10}C synthesis processing due to increase of α-clustering provides an energy “window” for formation of the intermediate states with unstable nuclei ^{9}B + *p*, ^{8}Be$_{2+}$ + 2*p* and ^{6}Be + α. These clusters are preserved in subsequent reactions ^{10}C(e^{+},ν)^{10}B(*p*,γ)^{11}C(e^{+},ν)^{11}B. The “window” of the reaction ^{7}Be(^{4}He,γ)^{11}C allows only an association of the ^{7}Be and ^{4}He clusters, also contributing to the ^{11}C and ^{10}B structure. Thus, a hidden variety of the virtual configurations in the nuclei ^{10,11}C and ^{10,11}B can be populated via electromagnetic transitions from the real ones. In turn, these nuclei provide a basis for capture reactions of protons or the He isotopes (or in neutron exchange) for synthesis of the subsequent nuclei which leads to a translation of the preceding structures.

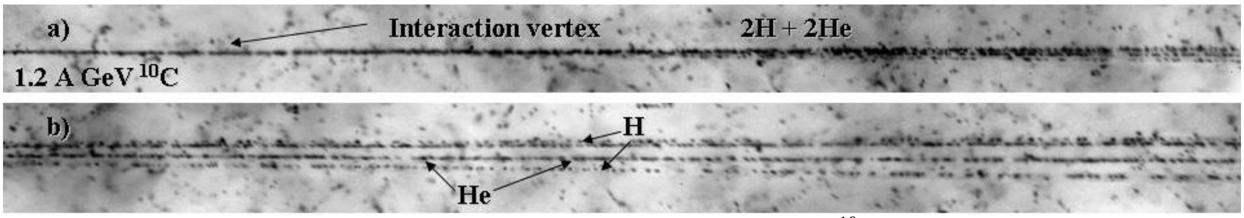

Figure 1. Macrophoto of the coherent dissociation event of 1.2 *A* GeV ^{10}C nucleus into pairs of He and H nuclei; a) primary track, approximate position of interaction vertex and appearance of fragment tracks and b) tracks of fragments are resolved; opening angles between tracks are Θ_{2He} = 5.9 mrad, Θ_{HeH} = 8.6, 16.6, 3.0, 17.6 mrad, Θ_{2p} = 20.1 mrad. Both 2HeH triples in the event correspond to ^{9}B decays.

Within the BECQUEREL project [1] the cluster structure of light nuclei is studied in relativistic-fragmentation processes on the basis of the nuclear track emulsion exposed to primary and secondary beams of the JINR Nuclotron [2, 3]. Among the events of fragmentation of relativistic nuclei, those of their coherent dissociation to narrow jets of fragments are especially important for studying nuclear clustering. They do not feature tracks of either slow fragments of emulsion nuclei or charged mesons. This special feature reflects the fact that the excitation of the relativistic nucleus under investigation is minimal in the case of a glancing collision with a heavy track-emulsion nucleus. Nuclear diffraction interaction processing without nuclear density overlaps and not accompanied by an angular momentum transfer is a main underlying mechanism of excitation of coherent dissociation in nuclear track emulsions.

The experimental method in question is based on a record spatial resolution and sensitivity of nuclear track emulsion whose layers are exposed longitudinally to beams of relativistic nuclei including radioactive ones. It has already furnished unique information about cluster aspects of the structure of the whole family of light nuclei, including radioactive ones. Because of the absence of tracks of strongly ionizing particles, events of coherent dissociation were called “white” stars (example in fig. 1). The term “white” star reflects aptly a sharp “breakdown” of the ionization density at the interaction vertex upon going over from the primary-nucleus track to secondary tracks within a 6^0 cone at 1.2 *A* GeV.

This special feature generates a fundamental problem for electronic methods because more difficulties should be overcome in detecting events where the degree of dissociation is higher. On the contrary, such events in nuclear-track emulsions are observed and interpreted in the most straightforward way, and their distribution among interaction channels characterized by different compositions of charged fragments is determined exhaustively. This probabilistic distribution is a basic feature that is observed for the virtual cluster structure of the nucleus under consideration.

The probability distribution of the final configurations of fragments in white stars makes it possible to reveal their contributions to the structure of nuclei under consideration. We assumed that, in the case of dissociation, specific configurations arise at random (random-phase approximation) without sampling and that the dissociation mechanism itself does not lead to the sampling of such states via angular-momentum or isospin exchange. By and large, available results confirm the assumption that cluster features of light nuclei determine the picture of their relativistic dissociation. At the same time, events that involve the dissociation of deeply bound cluster states and which cannot arise at low collision energies are detected.

Reconstruction of the decays of relativistic ^{8}Be and ^{9}B nuclei is possible by the energy variable $Q = M^* - M$, where $M^{*2} = \sum(P_i \cdot P_k)$, M is the total mass of fragments, and $P_{i,k}$ are their 4-momenta defined under the assumption of conservation of an initial momentum per nucleon by fragments. When the identification of relativistic fragment can be reasonably supposed the quasi-invariant variable Q allows one to estimate the excitation energy of their complex ensembles uniting all angular measurements in an event. For the “white” stars of ^{9}Be and ^{10}C nuclei the assumption that He fragments correspond to ^{4}He nuclei (α), and H ones in ^{10}C – ^{1}H is justified. Then ^{8}Be and ^{9}B identification is reduced to measurements of the opening angles between the directions of fragment emission. The experimental details and development of these investigations and their illustrations are presented in the recent review article [12]. Below further progress of this research is discussed.

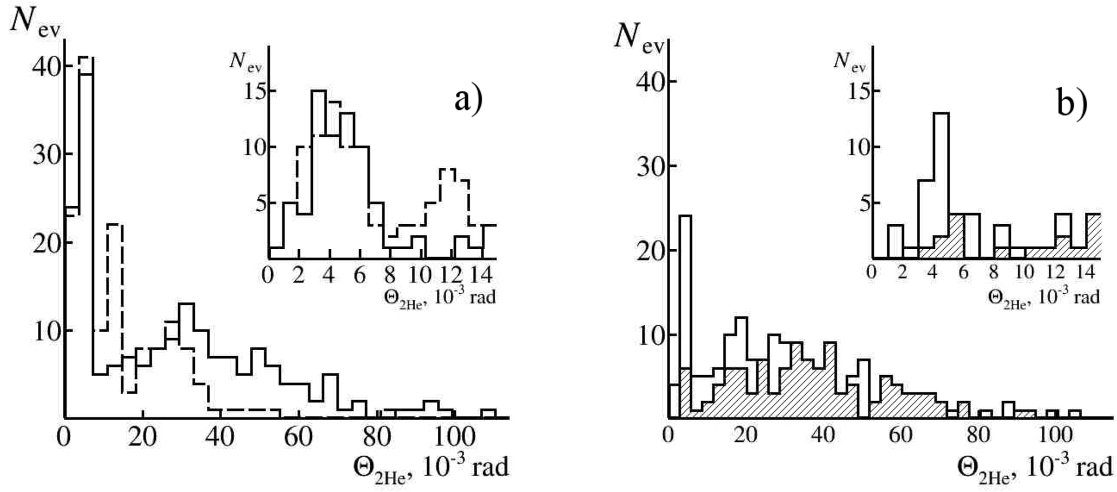

Figure 2. Distributions over the opening angle Θ_{2He} of α-particle pairs in "white" stars $^{10}C \to 2He + 2H$ (a, solid histogram) and $^{9}Be \to 2He$ (a, dashed histogram), $^{11}C \to 2He + 2H$ (b, solid histogram) and $^{11}C \to 3He$ (hatched histogram); on the insertions: the Θ_{2He} distribution in interval Θ_n.

2. The ^{8}Be and ^{9}B nuclei in dissociation of the ^{9}Be and ^{10}C nuclei

Distributions over the opening angle Θ_{2He} for pairs of He fragments of "white" stars $^{9}Be \to 2He$ and $^{10}C \to 2He + 2H$ (82% of the ^{10}C statistics) produced at energy of 1.2 *A* GeV are presented in Fig. 2. In both cases the values of Θ_{2He} of 75-80% of the pairs are distributed about equally in the intervals of $0 < \Theta_{n(arrow)} < 10.5$ mrad and $15.0 < \Theta_{w(ide)} < 45.0$ mrad. The remaining pairs are attributed to intervals $10.5 < \Theta_{m(edium)} < 15.0$ and "widest" of $15.0 < \Theta_{v(ery)w(ide)} < 45.0$ mrad. The distribution over the *Q* variable is directly correlated with the Θ_{2He} one. It is pointing out that "narrow" pairs of Θ_n are produced via $^{8}Be_{g.s.}$ while pairs Θ_w via $^{8}Be_{2+}$. Besides, for the ^{9}Be case there is a peak in the interval Θ_m reflecting its level $5/2^-$ (2.43 MeV). Fractions of events in the intervals Θ_n and Θ_w are equal to 0.56 ± 0.04 and 0.44 ± 0.04 for ^{9}Be, while for ^{10}C 0.49 ± 0.06 and 0.51 ± 0.06, i. e. they practically coincide. They indicate to a simultaneous presence of virtual $^{8}Be_{g.s.}$ and $^{8}Be_{2+}$ states in the ground states of the ^{9}Be and ^{10}C nuclei. Elongation above 40 mrad of the ^{10}C Θ_{2He} distribution can be due to the channel $^{4}He + ^{6}Be$.

Earlier, basing on the $Q_{2\alpha p}$ energy distribution of the triples $2\alpha + p$ from the "white" stars $^{10}C \to 2\alpha + 2p$ it is concluded that in the ^{10}C nucleus the core ^{9}B is manifested with a probability of (30 ± 4)%, and the $^{8}Be_{g.s.}$ decays are arise always through the ^{9}B decays.

Due to completeness of observation the $2\alpha 2p$ "quartets" is an interesting feature is manifested in their excitation energy distribution $Q_{2\alpha 2p}$. Fig. 3 shows distribution $Q_{2\alpha 2p}$ of all "white" stars $^{10}C \to 2He + 2H$ which appears at a first glance to be scattered. However, selection of the stars accompanied by $^{8}Be_{g.s.}$ (equally ^{9}B) leads to appearance in the $Q_{2\alpha 2p}$ distribution of the distinct peak with a maximum at 4.1 ± 0.3 MeV and RMS of 2.0 MeV. Such a value of the peak maximum is corresponding to the 4.2 MeV state established in low energy experiment and interpreted as a molecular-like state $\alpha + 2p + \alpha$ [4] while the width is determined by the accepted momentum approximation. The peak statistics present 17 ± 4 % of the total number or 65 ± 14 % of the stars containing ^{9}B decays.

Distribution over a total momentum $P_{T2\alpha 2p}$ of all $2\alpha 2p$ ensembles is described by a Rayleigh function with the parameter σ = 175 ± 10 MeV/*c* while in a case of the $^{8}Be_{g.s.}$ (^{9}B) presence it is significantly less σ = 127 ± 16 MeV/*c*. Not competing in statistics and resolution [] our observation of such a state manifesting in extra narrow $2\alpha 2p$ jets is grounded on selection of evidently glancing collisions which reduce dramatically a continuum contribution. It is worth noting the observation of a single "white" star $2\alpha 2p$ having $Q_{2\alpha 2p}$ equal to 0.77 MeV in which both $2\alpha p$ triples correspond to ^{9}B decays with $Q_{2\alpha p}$ of 0.22 and 0.67 MeV, $Q_{2\alpha}$ of 0.14 MeV and $Q_{\alpha 2p}$ of 0.64 and 0.6 MeV (fig. 1).

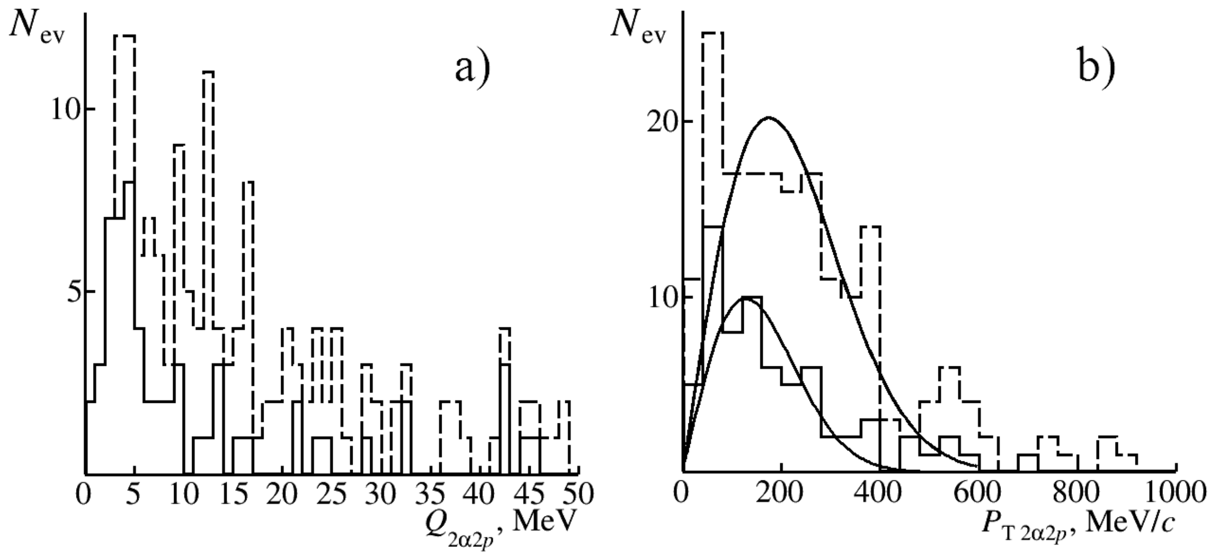

Figure 3. Distributions of all "white" stars $^{10}C \rightarrow 2He + 2H$ (dashed histogram) and the ones with the presence of $^{8}Be_{g.s.}$ (^{9}B) (solid histogram) over energy $Q_{2\alpha 2p}$ (a) and total transverse momentum $P_{T2\alpha 2p}$ (b).

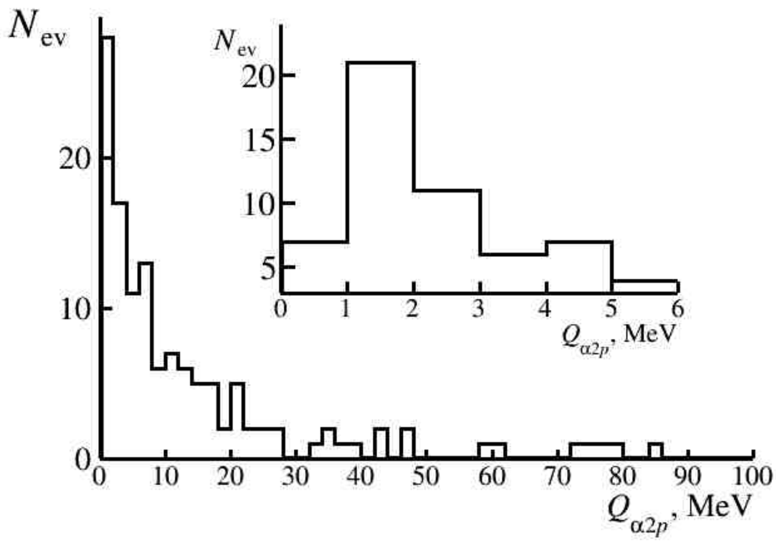

Figure 4. Distributions over energy $Q_{\alpha 2p}$ in measured "white" stars $^{7}Be \rightarrow He + 2H$; insertion; the enlarged $Q_{2\alpha p}$ distribution in the ^{6}Be region.

3. Search for ^{6}Be decays in dissociation of the ^{7}Be and ^{10}C nuclei

It is found that 289 "white" stars produced by 1.2 *A* GeV ^{7}Be nuclei [5] are distributed over the charge channels in the following way: He + 2H (54%), 2He (40%), ^{6}Li + H (1%), 4H (5%). The high statistics in the first channel allows one to estimate of the contribution of the unbound ^{6}Be nucleus in the left most peak of the distribution over $Q_{\alpha 2p}$ (fig. 4). Since angular measurements are used only to search for this narrow resonance the rough condition $Q_{\alpha 2p} < 6$ MeV is applied to estimate its contribution. 27% of 130 events in the channel He + 2H can be attributed to ^{6}Be decays in this way.

Determination of the ^{6}Be decay region in the accepted approximations gives opportunity to estimate a possible ^{6}Be contribution to the ^{10}C "white" stars. Fig. 5a shows correlation between $Q_{2\alpha}$ and $Q_{\alpha 2p}$. A peak at 3-4 MeV in the total distribution $Q_{\alpha 2p}$ is becoming profound when $^{8}Be_{g.s.}$ decays in the stars are demanded (Fig. 5b). Contrary to expectations on associated production of ^{4}He + ^{6}Be in energy continuum the dominant fraction of "^{6}Be" candidates correspond to their simultaneous decays altogether with $^{8}Be_{g.s.}$ (and, hence, ^{9}B) and $^{8}Be_{2+}$ decays. Surprisingly, but one can not separate the ^{6}Be and $^{8}Be_{g.s.}$ decays and have to assume that ^{6}Be and $^{8}Be_{g.s.}$ are produced as interfering parts of $2\alpha 2p$ ensembles.

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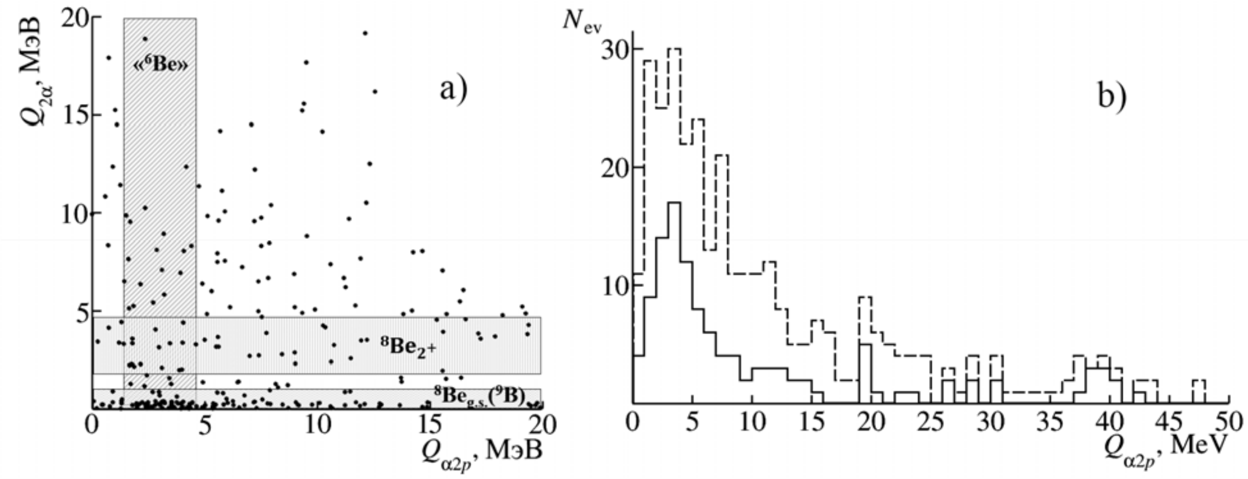

Figure 5. Distributions of “white” stars $^{10}C \rightarrow 2He + 2H$ over energy $Q_{2\alpha}$ and $Q_{\alpha 2p}$ (a, expected regions of decays ^6Be, $^8Be_{g.s.}$ (^9B) and $^8Be_{2+}$ are shown) Distributions of $\alpha 2p$ triples over energy $Q_{\alpha 2p}$ in all “white” stars $^{10}C \rightarrow 2He + 2H$ (b, dashed histogram) and with presence of $^8Be_{g.s.}$ (^9B) decays in them (b, solid histogram).

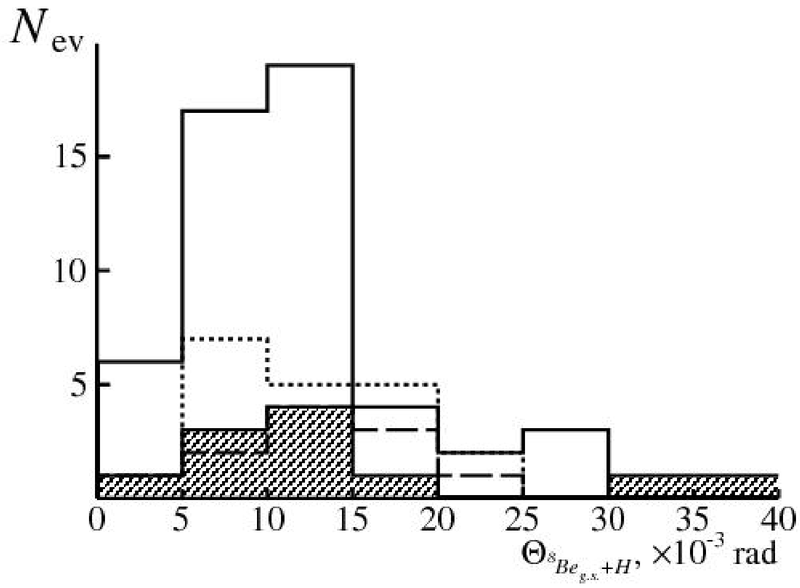

Figure 6. Distributions over the opening angle $\Theta(^8Be_{g.s.} + H)$ in “white” stars $^{10}C \rightarrow {}^8Be_{g.s.} + 2H$ (solid histogram), $^{11}C \rightarrow {}^8Be_{g.s.} + 2H$ (dashed histogram), $^{10}B \rightarrow {}^8Be_{g.s.} + H$ (hatched histogram) all found stars $^{11}C \rightarrow {}^8Be_{g.s.} + 2H$ (dotted histogram).

4. Progress of studies of dissociation of the ^{11}C and ^{10}B nuclei

It is already established that 144 “white” stars produced by ^{11}C nuclei are distributed over the charge channels in the following way: 2He +2H (50%), 3He (17%), ^{7}Be + He (13%), He + 4H (11%), B + H (5%), Li + He + H (3%), 6H (2%). The distributions of He fragments over the opening angle Θ_{2He} (Fig. 2b) show that $^8Be_{g.s.}$ decays are presented in 21% of the 2He + 2H stars and in 19% of the 3He ones. These distributions allow one to assume a strong contribution of $^8Be_{2+}$ decays but it is a subject of future consideration.

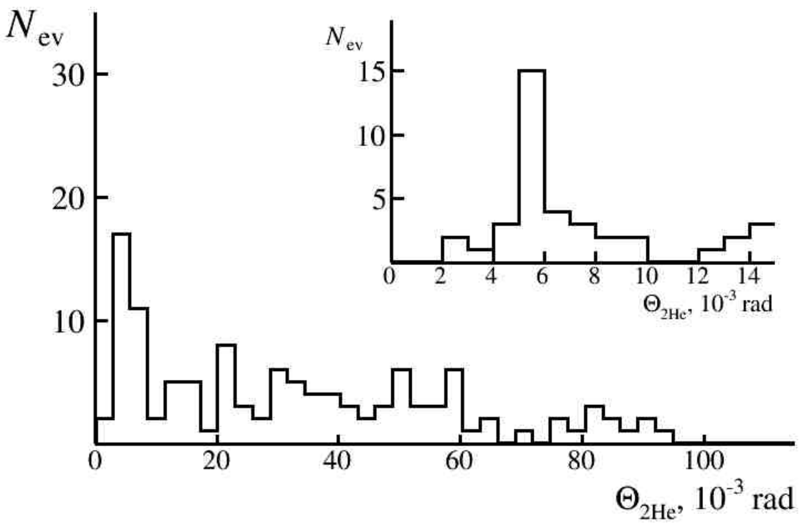

Figure 7. Distributions of "white" stars $^{10}B \rightarrow 2He + H$ over the opening angle Θ_{2He} of 2α pairs (a) and over energy $Q_{2\alpha p}$ of α2*p* triples.

The virtual $^9B_{g.s.}$ nucleus can exist in the ^{11}C nucleus as an independent component or as a component of a virtual core ^{10}B. Decays $^9B_{g.s.}$ in "white" stars $^{10}C \rightarrow 2He + 2H$ are identified in accordance with a limitation on the opening angle between directions of $^8Be_{g.s.}$ and each H fragments $\Theta(^8Be_{g.s.} + H) < 40$ mrad (Fig. 6) [3]. Application of such a condition to the "white" stars $^{11}C \rightarrow 2He + 2H$ allows one to identify 20 $^9B_{g.s.}$ decays constituting 30% of events in this charge channel or 12% of the ^{11}C "white" star statistics.

An analysis of the NTE exposure to 1 *A* GeV ^{10}B nuclei has pointed out that triples 2He + H (about 65%) dominate among "white" stars. However, origins of this effect have not been studied being in the "shadow" of studies with radioactive nuclei. This effect can indicate the possible presence of structures $^9B_{g.s.} + n$ as well as $^9Be + p$. In the ^{10}B nucleus a virtual ^9Be can exist in the superposition $^8Be_{g.s.} + n$ as well as $^8Be_{2+} + n$ one leading to 3-prong "white" stars out of $^9B_{g.s.}$ decays. Then the cluster configuration involving the deuteron $^8Be_{2+} + d$ can be a source of $^8Be_{2+}$ decays. Since the channel $^{10}B \rightarrow$ ^6Li is observed with 10% probability some virtual ^6Li contribution can be expected into the $2\alpha + p(d)$ channel. Thus, with attraction of existing knowledge the pattern ^{10}B dissociation via decays $^8Be_{g.s.}$, $^8Be_{2+}$ and $^9B_{g.s.}$ can disentangled step by step. If successful, it will lead to better understanding for the neighbouring nuclei.

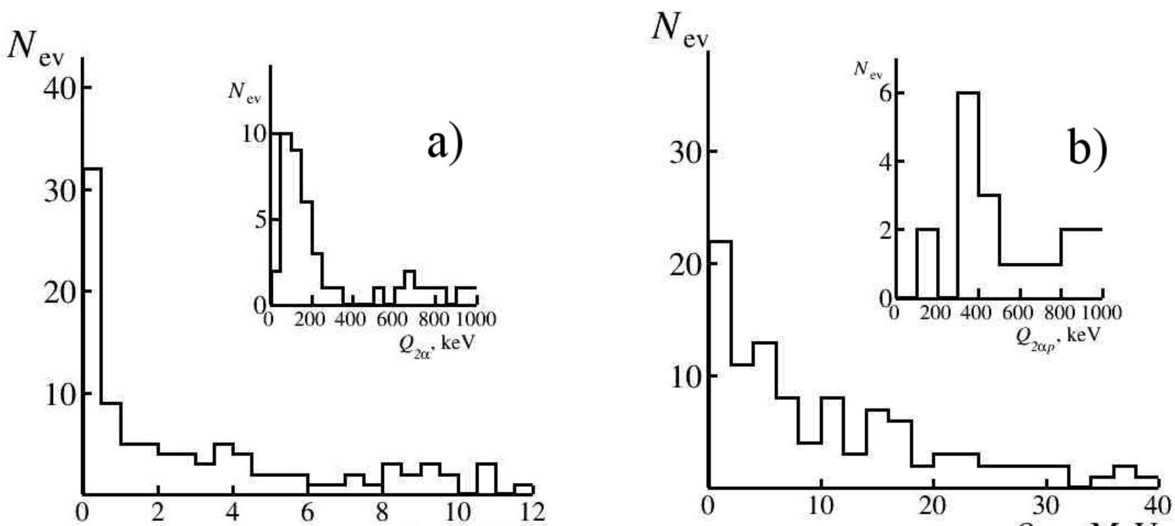

Figure 8. Distributions of "white" stars $^{10}B \rightarrow 2He + H$ over energy $Q_{2\alpha}$ of 2α pairs (a) and over energy $Q_{2\alpha p}$ of α2*p* triples.

Recently, 250 2He + H "white" stars are selected in an accelerated search. Angular measurements of the first 119 stars pointed already to 32 $^{8}Be_{g.s.}$ decays (fig. 7) and 11 $^{9}B_{g.s.}$ decays (fig. 6) accompanied by $^{8}Be_{g.s.}$. The distributions of the energy of α-particle pairs $Q_{2\alpha}$ and triples 2α + *p* $Q_{2\alpha p}$ from the $^{10}B \rightarrow$ 2He + H events are shown in Fig. 8a and 8b, respectively. For the moment correspondence of H to *p* and He to α is assumed. Identification of He and H isotopes by a multiple scattering method, are in progress now.

5. Conclusions

Contribution of the unstable nuclei ^{6}Be, ^{8}Be and ^{9}B into coherent dissociation events ("white" stars) of relativistic nuclei ^{7,9}Be, ^{10}B and ^{10,11}C is under study on the basis of a nuclear track emulsion exposed to beams of the JINR Nuclotron.

Distributions over the opening angle of α-pairs indicate to a simultaneous presence of virtual $^{8}Be_{g.s.}$ and $^{8}Be_{2+}$ states in the ground states of the ^{9}Be and ^{10}C nuclei. The core ^{9}B is manifested in the ^{10}C nucleus with a probability of (30 ± 4)%. $^{8}Be_{g.s.}$ decays in ^{10}C "white" stars always arise through the ^{9}B decays.

Selection of the ^{10}C "white" stars accompanied by $^{8}Be_{g.s.}$ (^{9}B) leads to appearance in the excitation energy distribution of 2α2*p* "quartets" of the distinct peak with a maximum at 4.1 ± 0.3 MeV. Distribution over the total momentum of $^{8}Be_{g.s.}2p$ ensembles is described by a Rayleigh function with the parameter 127 ± 16 MeV/*c*. A single 2α2*p* "white" star in which both 2α*p* triples correspond to a ^{9}B decay is observed.

On the basis of angular measurements 27% of events $^{7}Be \rightarrow$ He + 2H can be attributed to ^{6}Be decays by the condition on the excitation energy to be less than < 6 MeV.

For ^{10}C "white" stars it have to be assumed that ^{6}Be and $^{8}Be_{g.s.}$ are produced as interfering parts of 2α2*p* ensembles due to impossibility of separation of the ^{6}Be and $^{8}Be_{g.s.}$ decays.

$^{8}Be_{g.s.}$ decays are presented in 21% 2He + 2H and 19% in the 3He of the all found ^{11}C "white" stars. ^{9}B decays are identified in "white" stars $^{11}C \rightarrow$ 2He + 2H constituting 14% of the ^{11}C "white" stars. As in the ^{10}C case $^{8}Be_{g.s.}$ decays in ^{11}C "white" stars almost always arise through the ^{9}B decays.

The ^{9}B nucleus. is manifested in the "white" stars $^{10}B \rightarrow$ 2He + H with a probability of (9 ± 1)%. For the ^{10}B case yield of $^{8}Be_{g.s.}$ nuclei is about a factor of 3 higher than ^{9}B (in distinction to the ^{10,11}C cases). Thus, there appears a ground to assume the contribution in the ^{10}B structure of virtual superposition $^{8}Be_{g.s.}$- $^{8}Be_{2+}$ like in the ^{9}Be case. This is a subject of the ongoing study

On the ground of our studies the following pattern of nuclear clustering is emerging. As the fundamental elements of its structure atomic nuclei contain possible virtual associations of the nucleons and the lightest clusters. Their superpositions form cores consisting of the unstable ^{8}Be in the ground $^{8}Be_{g.s.}$ and first exited $^{8}Be_{2+}$ states and, then, ^{9}Be and ^{9}B nuclei which, in turn, serve as composing clusters in the structure of the heavier Be, B and C isotopes. Besides, the stable ^{7}Be and, probably, unstable ^{6}Be are important in the neutron deficient nuclei. A probability balance of such superpositions of possible core states with an appropriate spin and parity determine binding and ground state parameters of the corresponding nuclei.

Acknowledgements

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