Unstable nuclei in coherent dissociation of relativistic nuclei

7,9Be, 10B and 10,11C

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Abstract. Contribution of the unstable nuclei 7Be, 8Be and 9B into coherent dissociation events (“white” stars) of relativistic nuclei 7,9Be, 10B and 10,11C 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 8Be gs and 8Be2+ states in the ground states of the 9Be and 10C nuclei. The core 9B is manifested in the 10C nucleus with a probability of (30 ± 4)%.

Selection of the 10C “white” stars accompanied by 8Be gs (B) leads to the appearance in the excitation energy distribution of 2α2p “quartets” of the distinct peak with a maximum at 4.1 ± 0.3 MeV. 8Be gs decays are presented in 21% 2He + 2H and 19% in the 3He of the all 11C “white” stars. 9B gs decays are identified in “white” stars C → 2He + 2H constituting 14% of the 11C “white” stars. The 9B nucleus is manifested in the “white” stars 10B → 2He + 2H with a probability of (9 ± 1)%.

For the 11B case yield of 8Be gs nuclei with the respect to 9B is about a factor of 3 higher than 9B.

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, 3He 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 10,11B, 11,10C and 12N via the “hot breakout” 7Be(3He,γ)10C(e+,ν)10B assists to recognize the relationship of their structures. The 10C synthesis processing due to increase of α-clustering provides an energy “window” for formation of the intermediate states with unstable nuclei 9B + p, 8Be2+ + 2p and 8Be + α. These clusters are preserved in subsequent reactions 10C(e+,ν)11B(p,γ)11C(e+,ν)11B. The “window” of the reaction 7Be(He,γ)11C allows only an association of the 7Be and 4He clusters, also contributing to the 11C and 10B structure. Thus, a hidden variety of the virtual configurations in the nuclei 10,11C and 10,11B 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 $\Theta_{2\text{He}} = 5.9$ mrad, $\Theta_{\text{HeH}} = 8.6, 16.6, 3.0, 17.6$ mrad, $\Theta_{2p} = 20.1$ mrad. Both $2\text{HeH}$ triples in the event correspond to $^9\text{B}$ 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° 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 $^8\text{Be}$ and $^9\text{B}$ nuclei is possible by the energy variable $Q = M^* - M$, where $M^2 = \sum(P_i^2)$, $M$ 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 $^9\text{Be}$ and $^{10}\text{C}$ nuclei the assumption that He fragments correspond to $^4\text{He}$ nuclei (α), and H ones in $^{10}\text{C} - ^1\text{H}$ is justified. Then $^8\text{Be}$ and $^9\text{B}$ 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.
Distributions over the opening angle $\Theta_{2\text{He}}$ for pairs of He fragments of “white” stars $^9\text{Be} \rightarrow 2\text{He}$ and $^{10}\text{C} \rightarrow 2\text{He} + 2\text{H}$ (82% of the $^{10}\text{C}$ statistics) produced at energy of 1.2 A GeV are presented in Fig. 2. In both cases the values of $\Theta_{2\text{He}}$ of 75-80% of the pairs are distributed about equally in the intervals of $0 < \Theta_{\text{arrow}} < 10.5 \text{ mrad}$ and $15.0 < \Theta_{\text{wide}} < 45.0 \text{ mrad}$. The remaining pairs are attributed to intervals $10.5 < \Theta_{\text{medium}} < 15.0$ and “widest” of $15.0 < \Theta_{\text{very wide}} < 45.0 \text{ mrad}$. The distribution over the $Q$ variable is directly correlated with the $\Theta_{2\text{He}}$ one. It is pointing out that “narrow” pairs of $\Theta_{n}$ are produced via $^{8}\text{Be}^{+}$, while pairs $\Theta_{w}$ via $^{8}\text{Be}^{-}$ or $^{8}\text{Be}^{0}$. Besides, for the $^9\text{Be}$ case there is a peak in the interval $\Theta_{\text{m}}$ reflecting its level $5/2^{-}$ ($2.43 \text{ MeV}$). Fractions of events in the intervals $\Theta_{n}$ and $\Theta_{w}$ are equal to $0.56 \pm 0.04$ and $0.44 \pm 0.04$ for $^9\text{Be}$, while for $^{10}\text{C}$ $0.49 \pm 0.06$ and $0.51 \pm 0.06$, i.e. they practically coincide. They indicate to a simultaneous presence of virtual $^{8}\text{Be}^{+}$ and $^{8}\text{Be}^{-}$ states in the ground states of the $^9\text{Be}$ and $^{10}\text{C}$ nuclei. Elongation above 40 mrad of the $^{10}\text{C}$ $\Theta_{2\text{He}}$ distribution can be due to the channel $^4\text{He} + ^6\text{Be}$.

Earlier, basing on the $Q_{2\alpha}$ energy distribution of the triples $2\alpha + p$ from the “white” stars $^{10}\text{C} \rightarrow 2\alpha + 2\text{H}$ it is concluded that in the $^{10}\text{C}$ nucleus the core $^{9}\text{Be}$ is manifested with a probability of $(30 \pm 4)\%$, and the $^{8}\text{Be}^{+}$ decays are arise always through the $^{8}\text{Be}$ 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 $^{10}\text{C} \rightarrow 2\alpha + 2\text{H}$ which appears at a first glance to be scattered. However, selection of the stars accompanied by $^{8}\text{Be}^{+}$ (equally $^{9}\text{Be}$) leads to appearance in the $Q_{2\alpha 2p}$ distribution of the distinct peak with a maximum at $4.1 \pm 0.3 \text{ MeV}$ and RMS of $2.0 \text{ MeV}$. Such a value of the peak maximum is corresponding to the $4.2 \text{ MeV}$ state established in low energy experiment and interpreted as a molecular-like state $^{4}\text{He} + 2\text{p} + ^4\text{He}$ while the width is determined by the accepted momentum approximation. The peak statistics present $17 \pm 4 \%$ of the total number or $65 \pm 14 \%$ of the stars containing $^{9}\text{Be}$ decays.

Distribution over a total momentum $P_{2\alpha 2p}$ of all $2\alpha 2p$ ensembles is described by a Rayleigh function with the parameter $\sigma = 175 \pm 10 \text{ MeV}/c$ while in a case of the $^{8}\text{Be}^{+}$, $^{9}\text{Be}$ presence it is significantly less $\sigma = 127 \pm 16 \text{ MeV}/c$. 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 $0.77 \text{ MeV}$ in which both $2\alpha p$ triples correspond to $^{8}\text{B}$ decays with $Q_{2\alpha p}$ of 0.22 and 0.67 MeV, $Q_{2\alpha}$ of 0.14 MeV and $Q_{2\alpha 2p}$ of 0.64 and 0.6 MeV (fig. 1).
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%), $^4$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 $Q_{2\alpha 2p}$ (fig. 4). Since angular measurements are used only to search for this narrow resonance the rough condition $Q_{2\alpha 2p} < 6$ 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, $^8$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.
Figure 5. Distributions of “white” stars $^{10}\text{C} \rightarrow 2\text{He} + 2\text{H}$ over energy $Q_{\alpha\alpha}$ and $Q_{\alpha p}$ (a, expected regions of decays $^8\text{Be}$, $^8\text{Be}_{g.s.}$ ($^7\text{Be}$) and $^8\text{Be}_2^+$ are shown) Distributions of $\alpha p$ triples over energy $Q_{\alpha p}$ in all “white” stars $^{10}\text{C} \rightarrow 2\text{He} + 2\text{H}$ (b, dashed histogram) and with presence of $^8\text{Be}_{g.s.}$ ($^7\text{Be}$) decays in them (b, solid histogram).

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

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

It is already established that 144 “white” stars produced by $^{11}\text{C}$ nuclei are distributed over the charge channels in the following way: $2\text{He} + 2\text{H}$ (50%), $3\text{He}$ (17%), $^7\text{Be} + \text{He}$ (13%), $\text{He} + 4\text{H}$ (11%), $\text{B} + \text{H}$ (5%), $\text{Li} + \text{He} + \text{H}$ (3%), $6\text{H}$ (2%). The distributions of He fragments over the opening angle $\Theta_{2\text{He}}$ (Fig. 2b) show that $^8\text{Be}_{g.s.}$ decays are presented in 21% of the $2\text{He} + 2\text{H}$ stars and in 19% of the $3\text{He}$ ones. These distributions allow one to assume a strong contribution of $^8\text{Be}_2^+$ decays but it is a subject of future consideration.
The virtual $^9\text{Be}_{g.s.}$ nucleus can exist in the $^{11}\text{C}$ nucleus as an independent component or as a component of a virtual core $^{10}\text{B}$. Decays $^9\text{Be}_{g.s.}$ in “white” stars $^{10}\text{C} \rightarrow 2\text{He} + 2\text{H}$ are identified in accordance with a limitation on the opening angle between directions of $^9\text{Be}_{g.s.}$ and each H fragments $\Theta(\text{Be}_{g.s.} + \text{H}) < 40$ mrad (Fig. 6) [3]. Application of such a condition to the “white” stars $^{11}\text{C} \rightarrow 2\text{He} + 2\text{H}$ allows one to identify 20 $^9\text{Be}_{g.s.}$ decays constituting 30% of events in this charge channel or 12% of the $^{11}\text{C}$ “white” star statistics.

An analysis of the NTE exposure to 1 A GeV $^{10}\text{B}$ nuclei has pointed out that triples $2\text{He} + \text{H}$ (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 $^9\text{Be}_{g.s.} + n$ as well as $^9\text{Be} + p$. In the $^{10}\text{B}$ nucleus a virtual $^9\text{Be}$ can exist in the superposition $^9\text{Be}_{g.s.} + n$ as well as $^8\text{Be}_{2s} + n$ one leading to 3-prong “white” stars out of $^9\text{Be}_{g.s.}$ decays. Then the cluster configuration involving the deuteron $^8\text{Be}_{2s} + d$ can be a source of $^8\text{Be}_{2s}$ decays. Since the channel $^{10}\text{B} \rightarrow \text{^6Li}$ is observed with 10% probability some virtual $^6\text{Li}$ contribution can be expected into the $2\alpha + p(d)$ channel. Thus, with attraction of existing knowledge the pattern $^{10}\text{B}$ dissociation via decays $^8\text{Be}_{g.s.}$, $^8\text{Be}_{2s}$ and $^9\text{Be}_{g.s.}$ can disentangled step by step. If successful, it will lead to better understanding for the neighbouring nuclei.

Figure 7. Distributions of “white” stars $^{10}\text{B} \rightarrow 2\text{He} + \text{H}$ over the opening angle $\Theta_{2\text{He}}$ of $2\alpha$ pairs (a) and over energy $Q_{2\alpha}$ of $\alpha 2p$ triples.

![Figure 7](image.png)

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

![Figure 8](image.png)
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$_{gs}$ decays (fig. 7) and 11 $^9$Be$_{gs}$ decays (fig. 6) accompanied by $^8$Be$_{gs}$. The distributions of the energy of $\alpha$-particle pairs $Q_{2\alpha}$ and triplets $2\alpha + p Q_{2\alpha}$ 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 $\alpha$ 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 $^{10}$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 $\alpha$-pairs indicate to a simultaneous presence of virtual $^8$Be$_{gs}$ and $^8$Be$_{2p}$ 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$_{gs}$ ($^8$B) leads to appearance in the excitation energy distribution of $2\alpha + 2p$ “quartets” of the distinct peak with a maximum at 4.1 ± 0.3 MeV. Distribution over the total momentum of $^8$Be$_{gs}$,2p ensembles is described by a Rayleigh function with the parameter $127 \pm 16$ MeV/c. A single $2\alpha + 2p$ “white” star in which both $2\alpha p$ triplets 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 $^7$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$_{gs}$ are produced as interfering parts of $2\alpha + 2p$ ensembles due to impossibility of separation of the $^6$Be and $^8$Be$_{gs}$ decays.

$^8$Be$_{gs}$ decays are presented in 21% 2He + 2H and 19% in the 3He of the all found $^{11}$C “white” stars. $^8$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 $^9$Be$_{gs}$, decays in $^{10}$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$_{gs}$ 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$_{gs}$,$^8$Be$_{2p}$ 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 $^9$Be in the ground $^8$Be$_{gs}$, and first exited $^8$Be$_{2p}$ 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 $^8$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.

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