

## Progress of analysis of dissociation of $^{10}\text{C}$ , $^{10}\text{B}$ and $^{12}\text{C}$ nuclei in nuclear track emulsion

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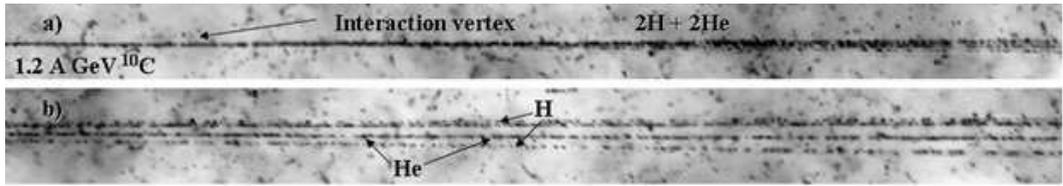
**Abstract.** Recent findings related with the unstable nuclei  $^8\text{Be}$  and  $^9\text{B}$  in the coherent dissociation of relativistic nuclei  $^{10}\text{C}$ ,  $^{10}\text{B}$  and  $^{12}\text{C}$  in nuclear track emulsion (“white” stars) are highlighted. Selection of the  $^{10}\text{C}$  “white” stars accompanied by  $^8\text{Be}$  ( $^9\text{B}$ ) leads to appearance of the distinct peak with a maximum at  $4.1 \pm 0.3$  MeV in the excitation energy distribution of  $2\alpha 2p$  ensembles. The  $^8\text{Be}_{g.s.}$  nucleus is manifested in the coherent dissociation  $^{10}\text{B} \rightarrow 2\text{He} + \text{H}$  with a probability of  $25 \pm 5$  % including  $13 \pm 3$  % of  $^9\text{B}$  decays. A probability ratio of the mirror channels  $^9\text{B} + n$  and  $^9\text{Be} + p$  is estimated to be  $10 \pm 1$ . Reanalysis of relativistic  $^{12}\text{C}$  dissociation in lead enriched emulsion revealed 9  $3\alpha$ -events corresponding to the Hoyle state.

### 1 Introduction

The family of nuclei composing the beginning of the isotope table provides a wholesome “laboratory” which allows one to study the evolution from cluster to shell nuclear structure (figure 1). As “building blocks” the light nuclei include the lightest clusters having no excited states, namely,  $\alpha$ -particles, tritons,  $^3\text{He}$  nuclei, and deuterons, and nucleons which virtual associations coexist in dynamical equilibrium. A pair of  $\alpha$ -particles can constitute the unstable  $^8\text{Be}$  nucleus in the ground  $^8\text{Be}_{g.s.}$  or 1st excited  $^8\text{Be}_{2+}$  states. The stable  $^7\text{Be}$  and  $^7\text{Li}$  nuclei are important in the structure of the neutron deficient and neutron rich nuclei, respectively. When the nucleons or clusters are added to the  $^8\text{Be}$ ,  $^7\text{Be}$  and  $^7\text{Li}$  nuclei the last ones serve as cores in the subsequent stable and radioactive isotopes. Then, the unstable  $^9\text{B}$  and stable  $^9\text{Be}$  can possess core roles of an equal importance in heavier nuclear structures. A balanced superposition of the cores, clusters and nucleons in appropriate spin-parity states determine ground state parameters of a corresponding nucleus.

The cluster structure of light nuclei including radioactive ones is under study by means of 0.5 mm pellicles of nuclear track emulsion (NTE) exposed longwise to primary and secondary beams of relativistic nuclei of the JINR Nuclotron (reviewed in [1], [2]). The studies are focused on coherent dissociation events (called “white” stars) which do not feature either slow fragments or charged

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**Figure 1.** Macrophoto of the coherent dissociation event of 1.2 A GeV  $^{10}\text{C}$  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 2HeH triples in the event correspond to  $^9\text{B}$  decays.

mesons. This empirical feature allows one to assume a glancing character of such collisions and that excitations of relativistic nuclei under study are minimal. A main underlying mechanism of coherent dissociation is nuclear diffraction interaction processing without nuclear density overlap and angular momentum transfer.

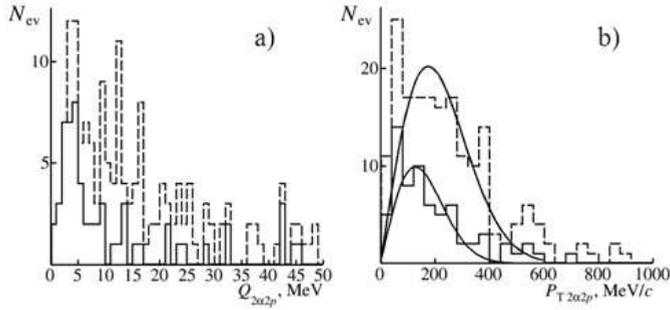
Events of coherent dissociation are called “white” stars because of the absence of tracks of strongly ionizing particles (figure 1). The term “white” star reflects aptly a sharp “breakdown” of the ionization density at the interaction vertex upon going over from the primary-nucleus track to secondary tracks within a  $6^\circ$  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 NTE 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.

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. In the case of dissociation, specific configurations arise at random 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 the cluster features of light nuclei determine the pattern 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 energy 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  $M^{*2} = \Sigma(P_i \cdot P_k)$ ,  $M$  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  $^9\text{Be}$  and  $^{10}\text{C}$  nuclei the assumption that He fragments correspond to  $^4\text{He}$  nuclei ( $\alpha$ ), and H ones in  $^{10}\text{C} - ^1\text{H}$  (p) 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. Recent and rather unexpected findings of these studies of nuclear clustering related with the unstable nuclei and obtained in relativistic experimental approach are highlighted below.

## 2 The unstable nuclei as cores

Contribution of the unstable nuclei  $^6\text{Be}$ ,  $^8\text{Be}$  and  $^9\text{B}$  into dissociation of relativistic nuclei  $^7,9\text{Be}$ ,  $^{10}\text{B}$  and  $^{10,11}\text{C}$  is under current study. The general pattern is as follows.



**Figure 2.** Distributions over energy  $Q_{2\alpha 2p}$  (a) and total transverse momentum  $P_{T2\alpha 2p}$  (b) of all “white” stars  $^{10}\text{C} \rightarrow 2\text{He} + 2\text{H}$  (dashed) and the ones with the presence of  $^9\text{B}$  (solid).

Weights of the configuration  $^6\text{Be} + n$  to the  $^7\text{Be}$  structure is estimated at a level of  $8 \pm 1\%$  which is near the value of  $5 \pm 1\%$  for the configuration  $^6\text{Li} + p$ .

Distributions over the opening angle of  $\alpha$ -pairs indicate to a simultaneous presence of virtual  $^8\text{Be}_{g.s.}$  and  $^8\text{Be}_{2+}$  states in the ground states of the  $^9\text{Be}$  and  $^{10}\text{C}$  nuclei.

The core  $^9\text{B}$  is manifested in the  $^{10}\text{C}$  nucleus with a probability of  $30 \pm 4\%$ .  $^8\text{Be}_{g.s.}$  decays in  $^{10}\text{C}$  “white” stars always arise through the  $^9\text{B}$  decays. For  $^{10}\text{C}$  “white” stars it has to be assumed that  $^6\text{Be}$  and  $^8\text{Be}_{g.s.}$  are produced as interfering parts of  $2\alpha 2p$  ensembles due to impossibility of separation of the  $^6\text{Be}$  and  $^8\text{Be}_{g.s.}$  decays.

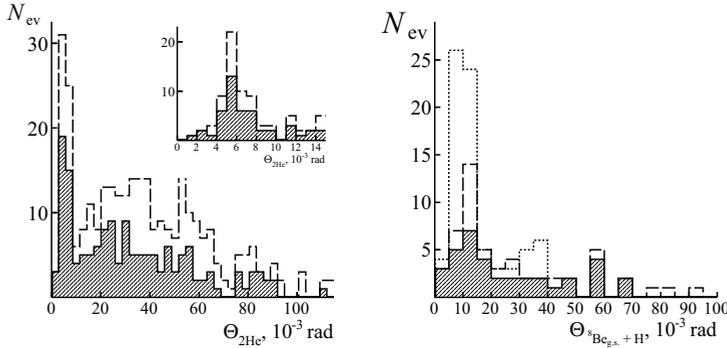
In a charge state distribution of fragments the share of the channel  $^{10}\text{B} \rightarrow 2\text{He} + \text{H}$  is 77%. On the basis of measurements of fragment emission angles it is determined that unstable nucleus  $^8\text{Be}_{g.s.}$  manifests itself with a probability of  $25 \pm 5\%$  where  $13 \pm 3\%$  of it occurs due to decays of the unstable nucleus  $^9\text{B}$ . Channel  $\text{Be} + \text{H}$  appeared subdued accounting for about 2% of “white” stars.

$^8\text{Be}_{g.s.}$  decays are presented in  $24 \pm 7\%$  of  $2\text{He} + 2\text{H}$  and  $27 \pm 11\%$  of the  $3\text{He}$  of the  $^{11}\text{C}$  “white” stars.  $^9\text{B}$  decays are identified in “white” stars  $^{11}\text{C} \rightarrow 2\text{He} + 2\text{H}$  constituting 14% of the  $^{11}\text{C}$  “white” stars. As in the  $^{10}\text{C}$  case  $^8\text{Be}_{g.s.}$  decays in  $^{11}\text{C}$  “white” stars almost always arise through  $^9\text{B}$  decays. On this ground the channel  $^9\text{B} + \text{H}$  amounts  $14 \pm 3\%$ .

### 3 Possibility of the $2\alpha 2p$ resonance around 4.1 MeV

An interesting feature is manifested in excitation energy distribution  $Q_{2\alpha 2p}$  of  $2\alpha 2p$  “quartets” provided by completeness of their observation. Figure 2a shows distribution  $Q_{2\alpha 2p}$  of all “white” stars  $^{10}\text{C} \rightarrow 2\text{He} + 2\text{H}$  which appears at a first glance to be scattered. The distribution  $Q_{2\alpha 2p}$  of the  $^{10}\text{C}$  stars containing  $^9\text{B}$  decays features the distinct peak with a maximum at  $4.1 \pm 0.3$  MeV at RMS of 2.0 MeV. Its width is determined by the accepted momentum approximation. The peak statistics present  $17 \pm 4\%$  of the total number of the  $^{10}\text{C}$  “white” stars or  $65 \pm 14\%$  of those containing  $^9\text{B}$  decays.

Distribution over a total momentum  $P_{T2\alpha 2p}$  of all  $2\alpha 2p$  ensembles (figure 2b) is described by a Rayleigh function with the parameter  $\sigma = 175 \pm 10$  MeV/c while in the case of the presence of  $^8\text{Be}_{g.s.}$  ( $^9\text{B}$ ) decays it is significantly less  $\sigma = 127 \pm 16$  MeV/c. 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  $^9\text{B}$  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 (figure 1).



**Figure 3.** Left: distributions over opening angle  $\Theta_{He}$  between directions of He fragments in all  $^{10}\text{B}$  stars  $2\text{He} + \text{H}$  (dashed) and “white” $^{10}\text{B}$  stars  $2\text{He} + \text{H}$  (hatched). Right: distributions over opening angle  $\Theta_{^8\text{Be}_{g.s.} + \text{H}}$  between directions of fragments  $^8\text{Be}_{g.s.}$  and H fragments in  $^{10}\text{C}$  “white”stars (dotted), all  $^{10}\text{B}$  stars (right, dashed) and “white” $^{10}\text{B}$  stars (right, hatched).

#### 4 Asymmetry in mirror channels for the $^{10}\text{B}$ nucleus

The early analysis of the NTE exposed to 1 A GeV  $^{10}\text{B}$  nuclei has pointed out that triples  $2\text{He} + \text{H}$  constitute about 65 % among 50 “white”stars found to that time. However, origin of this effect has not been studied being in a “shadow” of emerging studies with radioactive nuclei. Meanwhile, the  $2\text{He} + \text{H}$  triple dominance indicates the possible presence in  $^{10}\text{B}$  of structures  $^9\text{B}_{g.s.} + n$  side by side with the mirror one  $^9\text{Be} + p$ . It is interesting to verify whether they have equal contributions or not. Another opportunity is that the  $^{10}\text{B}$  nucleus can incorporate the “dilute” $^9\text{Be}$  cluster in the superpositions  $^8\text{Be}_{g.s.} + n$  and  $^8\text{Be}_{2+} + n$ . Both them lead to 3-prong “white”stars out of  $^9\text{B}_{g.s.}$  decays. Thus, a new round of the  $^{10}\text{B}$  analysis has been recently started which progress is summarized below.

The distribution of  $2\text{He}$  pairs over the opening angle  $\Theta_{2He}$  in an interval  $0 < \Theta_{2He} < 10.5$  mrad allows one to count 62 decays  $^8\text{Be}_{g.s.}$  in all found events  $^{10}\text{B} \rightarrow 2\text{He} + \text{H}$  including 39 in the “white”stars (figure 3, left). These numbers give  $19 \pm 3$  % and  $25 \pm 5$  % in the respective statistics. Then, the condition on the opening angle  $\Theta(^8\text{Be}_{g.s.} + \text{H}) < 25$  mrad (figure 3, right) allows one to identify 32 decays  $^9\text{B}$  in all found events and 21 in the “white”stars which constitute, respectively,  $9 \pm 2$  % and  $13 \pm 3$  % contributions of the subset  $^8\text{Be}_{g.s.} + \text{H}$  in the channel  $2\text{He} + \text{H}$ . Thus, in the “white”star case decays  $^9\text{B}$  explain just  $52 \pm 16$  % of decays  $^8\text{Be}_{g.s.}$ . This way, the idea about simultaneous coexistence in  $^{10}\text{B}$  of superposition of cores  $^8\text{Be}_{g.s.} - ^8\text{Be}_{2+}$  and  $^9\text{B}$  obtains a ground.

Statistics of “white”stars found without sampling one allows to compare the probability of dissociation in the channels  $^9\text{B} + n$  and  $^9\text{Be} + p$  (just two events). Measurements of fragment emission angles became possible only in 82 of the 108 events  $2\text{He} + \text{H}$ , which determines the reconstruction efficiency of the ten  $^9\text{B}$  decays found among them. On this basis, a probability ratio of the mirror channels  $^9\text{B} + n$  and  $^9\text{Be} + p$  is estimated to be  $10 \pm 1$ . Accounting for observation efficiency of the “white”stars  $^9\text{Be} + p$  does not affect qualitatively this ratio.

This fact is quite unexpected and even intriguing. Perhaps it points to the predominance of the  $^9\text{Be}$  core in nuclear molecular form  $2\alpha + n$  appearing in the dissociation channels containing  $^8\text{Be}_{2+}$  or  $^8\text{Be}_{g.s.}$  without  $^9\text{B}$  decays. The core  $^9\text{B}$  represents such a structure originally. Another explanation may be based on a broader spatial distribution of neutrons in the  $^{10}\text{B}$  compared to protons.

Identification of He and H isotopes by a multiple scattering method progressing now will promote the analysis. In particular, the cluster configuration involving the deuteron  $^8\text{Be}_{2+} + d$  can be a source

of  ${}^8\text{Be}_{2+}$  decays. Besides, since the channel  ${}^{10}\text{B} \rightarrow {}^6\text{Li} + \alpha$  is observed with 10% probability contribution of the “dilute”  ${}^6\text{Li}$  cluster into the  $2\alpha + p(d)$  channel can be expected. Thus, with attraction of existing knowledge on  ${}^9\text{Be}$  and  ${}^6\text{Li}$  the pattern  ${}^{10}\text{B}$  dissociation via decays  ${}^8\text{Be}_{g.s.}$ ,  ${}^8\text{Be}_{2+}$  and  ${}^9\text{B}$  can be disentangled step by step. If successful, it will lead to better understanding for the neighbouring nuclei  ${}^{11}\text{C}$  and, then,  ${}^{12}\text{N}$ .

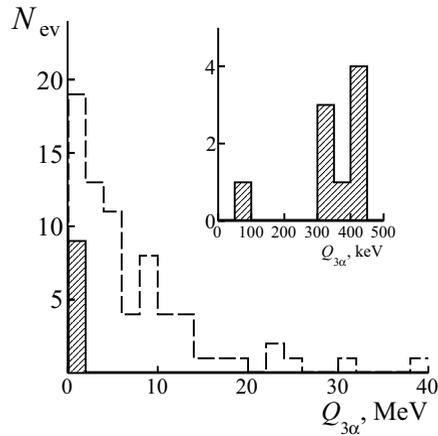
## 5 Search for the Hoyle state

Search for production of alpha-particle triples in the second excited state  $0_2^+$  of the  ${}^{12}\text{C}$  nucleus (the first unbound or Hoyle state) in dissociation of relativistic  ${}^{12}\text{C}$  nuclei in nuclear track emulsion (NTE) has been recently suggested. Traditionally the nucleus  ${}^{12}\text{C}$  is regarded as a “laboratory” for the development the  $\alpha$ -particle clustering concepts. It is a possible that in the ground state of  ${}^{12}\text{C}_{g.s.}$  there are two pairs of  $\alpha$ -clusters with orbital angular momenta equal to 2 (D-wave). In this case the basic configurations are  ${}^8\text{Be}$  nuclei in the first excited state  $2^+$ . In a classical pattern one may imagine a rotation in opposite directions of two  $\alpha$ -clusters with angular momenta equal to 2 around a common center represented by a third  $\alpha$ -cluster. Then the remaining combination of two  $\alpha$ -clusters should correspond to the ground state of the nucleus  ${}^8\text{Be}$  with spin and parity  $0^+$  (S-wave). As a result the superposition of the pair states in the ensemble of three  $\alpha$ -clusters leads to a zero spin in  ${}^{12}\text{C}_{g.s.}$ . Naturally, this simplified model requires a quantum-mechanical consideration. Nevertheless, its validity should be confirmed by an intensive formation of states  ${}^8\text{Be}_{2+}$  and  ${}^8\text{Be}_{g.s.}$  with a predominance of the former one in reactions of knocking out  $\alpha$ -particles from  ${}^{12}\text{C}$  nuclei.

Such a concept does not contradict the mechanism of the synthesis of the nucleus  ${}^{12}\text{C}$  accepted in nuclear astrophysics. Fusion of a triple of  $\alpha$ -particles occurs through its second excited state  $0_2^+$  (the Hoyle state) located at 290 keV above the breakup threshold  ${}^{12}\text{C} \rightarrow 3\alpha$ . Basically, each pair of  $\alpha$ -particles in it corresponds to  ${}^8\text{Be}_{g.s.}$ . In the transition  $0_2^+ \rightarrow 2_1^+$  with emission of a photon to the first excited state of  ${}^{12}\text{C}$ , which is bound one, an  $\alpha$ -pair in the D-wave should arise in a  $3\alpha$  ensemble in order to provide conservation of the angular momentum. The subsequent transition to  ${}^{12}\text{C}_{g.s.}$ , which is also accompanied by emission of a photon leads to the formation of another  $\alpha$ -particle pair in the D-wave state. This pair should have an opposite angular momentum with respect to the first pair to ensure zero spin value of the ground state  ${}^{12}\text{C}_{g.s.}$ . Thus, the nucleus  ${}^{12}\text{C}_{g.s.}$  does acquire polarization. Figuratively being expressed it does conserve an “invisible rotation”. The ratio of the yields of  $\alpha$ -particle pairs through the states  ${}^8\text{Be}_{2+}$  and  ${}^8\text{Be}_{g.s.}$  in disintegrations of nuclei  ${}^{12}\text{C}$  not accompanied by a transfer of the angular momentum is a key parameter which should reflect the spin-cluster structure  ${}^{12}\text{C}_{g.s.}$ .

Importance of the discussed structure is determined not only by interest to describe  ${}^{12}\text{C}_{g.s.}$ , but also the fact that it is the starting configuration for the reverse process of generating  $3\alpha$ -particle ensembles in the Hoyle state. It is assumed that this state after  ${}^8\text{Be}_{g.s.}$  is a Bose-Einstein condensate [3] consisting of  $\alpha$ -particles with zero angular momentum. Its identification in breakups of  ${}^{12}\text{C}$  allows one to advance to generation of condensate states of larger number of  $\alpha$ -particles. Fundamental aspect seems to be related to the fact that in order to recreate the condensate it is necessary to “evacuate” two hidden rotations  ${}^{12}\text{C}_{g.s.}$ . The Coulomb dissociation of a nucleus on a heavy nucleus appears to be the most suitable process since few photon exchanges in it are possible. In principle, contribution of electromagnetic interaction can be enhanced by addition of the lead.

Repeated analysis of early exposures of lead enriched NTE to relativistic  ${}^{12}\text{C}$  nuclei revealed the following. Fraction of  $3\alpha$  events containing  ${}^8\text{Be}$  is 40 %. 9 events of 72 ones correspond to the Hoyle state in distribution over excitation energy  $Q_{3\alpha}$  of  $\alpha$ -triples (figure 4). This observation motivates the search for the Hoyle state on statistics of hundreds events of electromagnetic dissociation. It is assumed that this state is the alpha Bose-Einstein condensate composed of  $\alpha$ -particles with zero



**Figure 4.** Distribution over excitation energy  $Q_{3\alpha}$  of  $\alpha$ -triples produced in coherent dissociation of  $^{12}\text{C}$  of momentum of 4.5 A GeV/c.

angular momenta in which all pairs are close to the unstable  $^8\text{Be}$  nucleus. Identification of the Hoyle state will open up perspective for search in relativistic approach of condensate states in dissociation of heavier nuclei.

Stacks of NTE pellicles exposed to  $^{12}\text{C}$  of energy in the range from hundreds MeV to few tenths GeV per nucleon at the JINR Nuclotron and the IHEP accelerator complex (Protvino) will serve as the material for this study. At a sufficient statistics of the coherent dissociation events of  $^{12}\text{C}$  nuclei emission angles of  $\alpha$ -particle triples will be measured with resolution allowing reconstruction of decays of the unstable  $^8\text{Be}$  nucleus. NTE pellicles will be enriched with lead because the Coulomb dissociation of a relativistic nucleus on a heavy target nucleus is relevant for the Hoyle state excitation.

## References

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