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Recent Findings in Relativistic Dissociation of ^{10}B and ^{12}C Nuclei

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Abstract Recent findings related with the unstable nuclei ^{8}Be and ^{9}B in the coherent dissociation of relativistic nuclei ^{10}C, ^{10}B and ^{12}C in nuclear track emulsion (“white” stars) are highlighted 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 ± 5% including 14 ± 3% of ^{9}B decays. A probability ratio of the mirror channels $^{9}\text{B} + \text{n}$ and $^{9}\text{Be} + \text{p}$ is estimated to be 6 ± 1. Reanalysis of relativistic ^{12}C dissociation in lead enriched emulsion revealed nine 3α-events corresponding to the Hoyle state.

1 Introduction

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 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. 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 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

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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}Be and ^{9}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}Be nuclei the assumption that He fragments correspond to ^{4}He nuclei (α). Then ^{8}Be and ^{9}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.

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

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

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. For ^{10}C "white" stars it have to be assumed that ^{6}Be and ^{8}Be$_{g.s.}$ are produced as interfering parts of $2\alpha 2$p ensembles due to impossibility of separation of the ^{6}Be and ^{8}Be$_{g.s.}$ decays [1,2].

In a charge state distribution of fragments the share of the channel ^{10}B → 2He + H is 77%. On the basis of measurements of fragment emission angles it is determined that unstable nucleus ^{8}Be$_{g.s.}$ manifests itself with a probability of 25 ± 5% where 14 ± 3% of them occur in decays of the unstable nucleus ^{9}B. Channel Be + H appeared subdued accounting for about 2% of "white" stars.

^{8}Be$_{g.s.}$ decays are presented in 24 ± 7% of 2He + 2H and 27 ± 11% of the 3He of the ^{11}C "white" stars. ^{9}B decays are identified in "white" stars ^{11}C → 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 ^{9}B decays. On this ground the channel ^{9}B + H amounts 14 ± 3% [1,2].

2 Asymmetry in Mirror Channels for the ^{10}B Nucleus

The early analysis of the NTE exposured to 1 A GeV ^{10}B nuclei has pointed out that triples 2He + 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 2He + H triple dominance indicate the possible presence in ^{10}B of structures ^{9}B$_{g.s.}$ + n side by side with the mirror one ^{9}Be + p. It is interesting to verify whether they have equal contributions or not. Another opportunity is that the ^{10}B nucleus can incorporate the "dilute" ^{9}Be cluster in the superpositions ^{8}Be$_{g.s.}$ + n and ^{8}Be$_{2+}$ + n. Both them are leading to 3-prong "white" stars out of ^{9}B$_{g.s.}$ decays. Thus, a new round of the ^{10}B analysis is started recently which progress is summarized below.

The distribution of α pairs over the opening angle $\Theta_{2_{He}}$ in an interval $0 < \Theta_{2_{He}} < 10.5$ mrad allows one to count 57 decays ^{8}Be$_{g.s.}$ in all found events ^{10}B → 2He + H including 36 in the "white" stars (Fig.1, left). These numbers give 19 ± 3% and 25 ± 5% in the respective statistics. Then, the condition on the opening angle $\Theta(^8Be_{g.s.} + H)$ <25 mrad (Fig.1, right) allows one to identify 30 decays ^{9}B in all found events and 20 in the "white" stars which constitute, respectively, 10 ± 2% and 14 ± 3% contributions of the subset ^{8}Be$_{g.s.}$ + H in the channel 2He + H. Thus, in the "white" star case decays ^{9}B explains just 56 ± 16 % of decays ^{8}Be$_{g.s.}$. This way, the idea about simultaneous coexistence in ^{10}B of superposition of cores ^{8}Be$_{g.s.}$–^{8}Be$_{2+}$ and ^{9}B obtain a ground.

Statistics of "white" stars found without sampling one allows to compare the probability of dissociation in the channels ^{9}B + n and ^{9}Be + p (just two events). Measurements of fragment emission angles have become possible only in 65 of the 108 events 2He + H, which determines the reconstruction efficiency of the eight ^{9}B decays found among them. On this basis, a probability ratio of the mirror channels ^{9}B + n and ^{9}Be + p

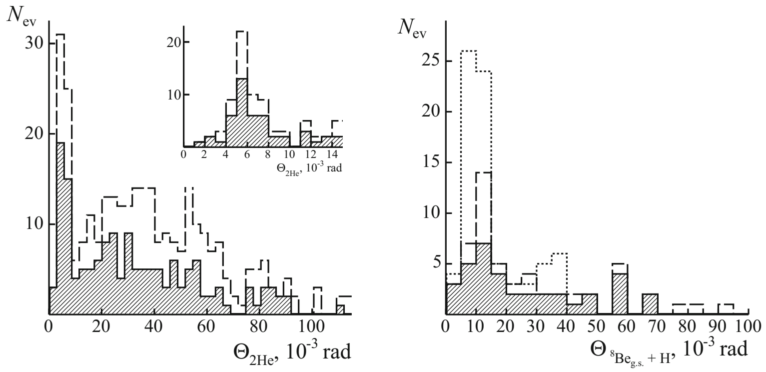

Fig. 1 *Left* distributions over opening angle Θ_{2He} between directions of He fragments in all ^{10}B stars 2He + H (*dashed*) and "white" ^{10}B stars 2He + H (*hatched*). *Right* distributions over opening angle $\Theta_{^8Be_{g.s.}}$ + H between directions of fragments ^{8}Be$_{g.s.}$ and H fragments in ^{10}C "white" stars (*dotted*), all ^{10}B stars (*right*, *dashed*) and "white" ^{10}B stars (*right*, *hatched*)

is estimated to be 6 ± 1. Accounting for observation efficiency of the "white" stars ^{9}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}Be core in nuclear molecular form 2α + n appearing in the dissociation channels containing ^{8}Be$_{2+}$ or ^{8}Be$_{g.s.}$ without ^{9}B decays. The core ^{9}B represents such a structure originally. Another explanation may be based on a broader spatial distribution of neutrons in the ^{10}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}Be$_{2+}$ + d can be a source of ^{8}Be$_{2+}$ decays. Besides, since the channel ^{10}B $\rightarrow ^6$Li + α is observed with 10% probability contribution of the "dilute" ^{6}Li cluster into the 2α + p(d) channel can be expected. Thus, with attraction of existing knowledge on ^{9}Be and ^{6}Li the pattern ^{10}B dissociation via decays ^{8}Be$_{g.s.}$, ^{8}Be$_{2+}$ and ^{9}B can be disentangled step by step. If successful, it will lead to better understanding for the neighbouring nuclei ^{11}C and, then, ^{12}N.

3 Search for the Hoyle State

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

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

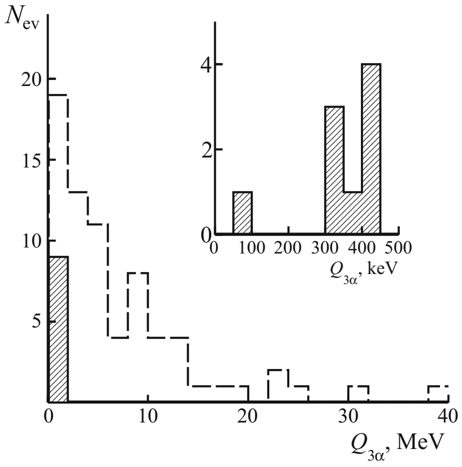

Fig. 2 Distiribution over excitation energy $Q_{3\alpha}$ of α-triples produced in coherent dissociation of ^{12}C of momentum of 4.5 A GeV/c

accompanied by a transfer of the angular momentum is a key parameter which should reflect the spin-cluster structure $^{12}C_{g.s.}$.

Importance of the discussed structure is determined not only by interest to describe $^{12}C_{g.s.}$, but also the fact that it is the starting configuration for the reverse process of generating 3α-particle ensembles in the Hoyle state. It is assumed that this state after $^{8}Be_{g.s.}$ is a Bose–Einstein condensate [3] consisting of α-particles with zero angular momentum. Its identification in breakups of ^{12}C allows one to advance to generation of condensate states of larger number of α-particles. Fundamental aspect seems related to the fact that in order to recreate the condensate it is necessary to "evacuate" two hidden rotations $^{12}C_{g.s.}$. 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}C nuclei revealed the following. Fraction of 3α events containing ^{8}Be is 40%. 9 events of 72 ones correspond to the Hoyle state in distribution over excitation energy $Q_{3\alpha}$ of α-triples (Fig. 2). 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 α-particles with zero angular moments in which all pairs are close to the unstable ^{8}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}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}C nuclei emission angles of α-particle triples will be measured with resolution allowing reconstruction of decays of the unstable ^{8}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.

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