Charge topology of coherent dissociation of ^{11}C and ^{12}N relativistic nuclei

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The charge topology of the events of coherent dissociation of ^{11}C and ^{12}N of an energy of 1.2 A GeV in nuclear track emulsion is presented and its compared is given with the appropriate data on the nuclei ^{7}Be, ^{8,10}B, ^{9,10}C and ^{14}N.

Light nuclei, are represented as virtual superpositions of lighter core nuclei, the lightest cluster nuclei (α-particle, triton, ^{3}He nucleus or helion, deuteron) and nucleons, which coexist in a balance. This variety makes the group of nuclei at the beginning of the table of isotopes a nuclear clustering "laboratory". The study of the ^{11}C nucleus is of a fundamental importance due to the combination of cluster and shell features in it. The isotope ^{11}C is a link between stable nuclei with a pronounced α-particle clustering of nucleons and nuclei at the boundary of proton stability, where clustering based on the isotope ^{3}He is not less important. Interactions of clusters and exchange by a neutron between them result in the formation of structures with a core nucleus along with the 3-cluster configuration 2^{4}He + ^{3}He. The weakly bound configurations ^{7}Be + α (7.6 MeV), ^{10}B + p (8.7 MeV) and ^{3}He + ^{8}Be (9.2 MeV) are more expected, and ^{9}B + d (14.9 MeV), ^{9}Be + 2p (15.3 MeV) and ^{8}B + t (27.2 MeV) are less expected.

A balanced co-existence of these modes determines the properties of the ^{11}C ground state. The fact of its bondage is important for understanding light isotope abundances. The ^{11}C isotope can be synthesized in a mixture of isotopes ^{3}He and ^{4}He either through the ^{7}Be or ^{8}Be followed by a partial clustering into ^{10}B + p. The decay of ^{11}C leads to the formation of a stable isotope ^{11}B observed in cosmic rays. Such a scenario is not recognized – isotopes ^{10,11}B are considered as products of bombardment of carbon stars surfaces by high-energy protons. Observations of the ^{7}Be + α and ^{3}He + ^{8}Be dissociations will confirm the existence of states genetically related to the ^{11}C synthesis. Understanding of the ^{11}C structure is required for the interpretation of the existing data for ^{12}N and, potentially, for ^{13}O in which ^{11}C plays the role of core. In rapid processes of nucleosynthesis ("hot break outs"), these isotopes act as genetically related "waiting stations". The formation of the ^{12}C isotope or heavier ones can proceeds through them by attaching of protons. It is worth to notice that knowledge of the relativistic ^{11}C fragmentation is indispensable for the application of intense beams of these nuclei in nuclear medicine.

The cluster structure of light nuclei is studied in relativistic fragmentation processes by nuclear track emulsion (NTE) methods in the framework of the BECQUEREL Project at the JINR Nuclotron [1-11]. Development of the research and illustrations are presented in the review [12]. Among the events of the relativistic nucleus fragmentation, the events of coherent dissociation in narrow jets of fragments are particularly valuable for the study of the clustering of nucleons. They have neither tracks of slow fragments of target nuclei nor mesons. This feature reflects a minimum excitation of the relativistic nucleus under investigation in a "glancing" collision with a heavy nucleus from the NTE composition. The mechanism of coherent dissociation in NTE is a nuclear diffraction interaction [13] occurring without angular momentum transfer.

The experimental approach is based on a record spatial resolution and sensitivity of NTE, the layers of which are exposed longitudinally to the beams of relativistic nuclei. It has already provided obtaining of wholesome information regarding the aspects of the cluster structure of the family of light nuclei including radioactive ones. One of the key nuclei – ^{11}C – was found to be missed due to circumstances of a practical nature. Filling of this gap is the motivation to start a new cycle of research on the BECQUEREL Project. The methods of analysis of ^{11}C are to be rather complex due to existence of many possible configurations.

The coherent dissociation events got a short name of the "white" stars due to the absence of strongly ionizing particle tracks. The name well reflects a sharp "breakdown" of the ionization density in the vertex of the interaction in the transition from the primary nucleus track to a narrow cone of secondary tracks. This feature is a fundamental difficulty for electronic methods, because the larger the degree of dissociation in the event, the harder to register it. On the contrary, such events in NTE are observed and interpreted in the most obvious way, and their distribution via the interactions with different compositions of charged fragments are determined fully exhaustively. This probability distribution is a main observed characteristic of the cluster structure of the nucleus in question.

The distributions over the probability of finite configurations of fragments in "white" stars allow one to reveal their contributions to the structure of the studied nuclei. It is assumed that a specific configuration is fixed at dissociation randomly, without sampling, and the dissociation mechanism does not lead to sampling of such states through the exchange of an angular momentum or an isospin. In general, the available results suggest that the cluster features of light nuclei define the picture of their relativistic dissociation. However, the events of dissociation of deeply bound cluster states are detected which can not occur at a low collision energy.

For the ^{11}C nucleus dissociation channels with low binding energy – ^{7}Be + α, ^{10}B + p, and ^{3}He + ^{8}Be – are expected. From the experimental point of view the last channel is a 3-body one and can include decays of not only the ground state 0^+, but also the excited 2^+ state. In addition, channels corresponding to the charge topology dissociation of the ^{7}Be [3, 11] and ^{10}B [14] core nuclei are expected to appear. Thereby, the role of multiple channels of ^{11}C coherent dissociation should be significant and, therefore, the application of the NTE method is justified.

Table 1. Distribution over charge channels for the "white" stars produced by ^{7}Be nuclei.

Channel	^{7}Be [3]	^{7}Be [11]
2He	41 (44 %)	115 (40 %)
He + 2H	42 (45 %)	157 (54 %)
Li + H	9 (10 %)	14 (5 %)
4H	2 (2 %)	3 (1 %)

Table 2. Distribution over charge channels for the "white" stars produced by ^{10}B and ^{8}B nuclei.

Channel	^{10}B [14]	^{8}B [4]
Be + H	1 (2 %)	25 (48 %)
2He + H	30 (73 %)	14 (27 %)
He + 3H	5 (12 %)	12 (23 %)
Li + He	5 (13 %)	

Data on previously studied nuclei are valuable ingredients of this analysis, and deserve the description. A particular feature of ^{7}Be consists in the fact that the probabilities of the main channels 2He and He + 2H of coherent dissociation are about equal (Table. 1). According to the LPI Group their ratio is 1 ± 0.2 [3], and for more statistics of the JINR group – 0.7 ± 0.1 [11]. The 3-body channel 2He + H (about 75%) is a leader among the "white" stars ^{10}B (Table. 2). Events of the channel He + 3H are 12%. 10% of the events contain both fragments Li and He. Only 2% of the events contain fragments Be and H, which shows that probability of configuration ^{9}Be + p in the ^{10}B structure is insignificant. In contrast, the contribution of this channel to the ^{8}B coherent dissociation is predominate and indicates the existence of a configuration ^{7}Be + p with a proton halo. Thee joint contribution of the configurations containing only clusters of He and H is estimated at 50%.

A series of NTE samples produced by the workshop MICRON of OJSC "Company Slavich" [15] was exposed in the secondary beam of relativistic nuclei ^{11}C of the JINR Nuclotron in December 2013. The samples were prepared by pouring of NTE layers of about 200 micrometers on glass substrates measuring 9 × 12 cm^2. According to the main characteristics this NTE is close to NTE BR-2 which provided sensitivity up to relativistic particles.

Nuclei ^{11}C were produced in fragmentation of nuclei ^{12}C of energy 1.2 A GeV on a polyethylene target of thickness of 1.5 g/cm^2. The secondary ^{11}C beam was formed by separation in a magneto-optical channel of beam transportation of the having a momentum acceptance of about 2%. At the intensity of the primary beam of the order of 10^7 ^{12}C nuclei per cycle, the intensity of the ^{11}C beam was 10^4, which is optimal for a controlled exposure of the NTE stack. The beam profile was formed in such a way that the irradiation along the narrower side be possibly more uniform.

The nucleus flow outputted on an irradiated NTE stack was monitored by a scintillation counter. The presence of accompanying nuclei in the main beam allows one to estimate opportunities of separation of ^{11}C nuclei in the used magneto-optical channel [16]. Fig. 1 shows the amplitude spectrum of the monitor when conducting nuclei ^{12}C, the lower part of the spectrum is shown in an enlarged view. There is a contribution of lighter nuclei with the same charge-to-mass number like ^{12}C. They were mostly generated on a production target at the beginning of the separation channel. "Shoulder" on the left of the main peak corresponds to ^{10}B nuclei; Be nuclei does not appear (the ^{8}Be nucleus is an unbound one); the contribution of nuclei Li (^{6}Li) is distinguishable; and nuclei He (^{4}He) is well seen.

Fig. 2 shows a photograph of the spectrum when the channel is tuned for separation of ^{11}C nuclei with the same momentum per nucleon as in the case of ^{12}C. An increase of the bottom part of the spectrum is given in the left inset. This spectrum is given in logarithmic scale in the inset. The signals B, Be (^{7}Be), Li and He are weakly distinguishable and associated with fragmentation of ^{11}C nuclei. Disappearance of He nuclei is particularly revealing. With decreasing magnetic rigidity of the channel the ^{4}He nuclei have disappeared and the ^{3}He nuclei do not appear yet. All these facts show that the separation of ^{11}C nuclei is sufficient which allows one to neglect the contribution of other isotopes. 40 NTE layers are exposed to a beam of such a composition. To vary irradiation density the layers were assembled in 7 stacks exposed successfully.

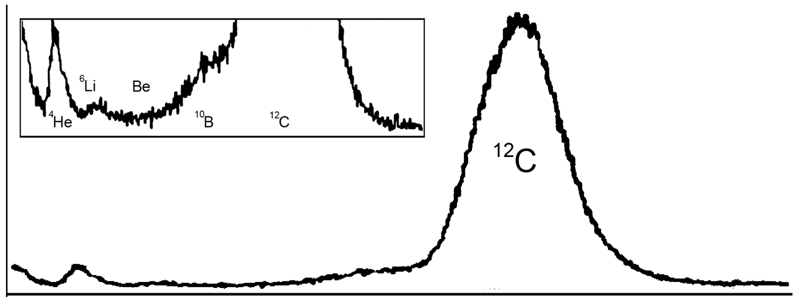

FIG. 1: Amplitude spectrum from a scintillation counter when transporting nuclei ^{12}C (arbitrary units)

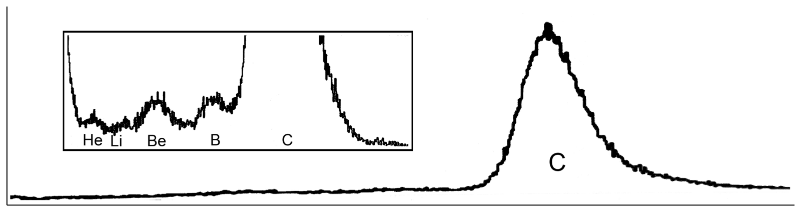

FIG. 2: Amplitude spectrum from a scintillation counter when transporting nuclei ^{11}C (arbitrary units)

The reduced thickness and the glass substrates of an experimental batch of NTE do not enable one to perform analysis with scanning along beam and secondary tracks without sampling. Therefore, scanning of the NTE layer was carried out on transverse strips in order to the find tracks of relativistic fragments with the total charge of at least 3 with a subsequent viewing up to the interaction vertices. Tracks corresponding to doubly and singly charged relativistic particles are determined visually. Dominance of C nuclei in the beam makes possible to specify charges of heavier fragments in “white” stars as values that does not reach six charge units.

Table 3. Distribution over charge channels for the ”white” stars produced by carbon isotopes.

Channel	^{11}C	^{10}C [9]	^{9}C [5]
B + H	6 (5 %)	1 (0.4 %)	15 (14 %)
Be + He	17 (14 %)	6 (2.6 %)	
Be + 2H			16 (15 %)
3He	22 (18 %)	12 (5.3 %)	16 (15 %)
2He + 2H	60 (48 %)	186 (82 %)	24 (23 %)
He + 4H	14 (11 %)	12 (5.3 %)	28 (27 %)
Li + He + H	4 (3 %)		
Li + 3H		1 (0.4 %)	2 (2 %)
6H	3 (2 %)	9 (4 %)	6 (6 %)

By the present time 126 “white” stars with a total charge of relativistic fragments equal to 6 are found in six scanned layers. Their distribution over charge states is given in Table. 3. Table. 3 also contains data on the isotopes ^{10}C [9] and ^{9}C [5], which indicate a specific nature of a “white” star distribution of each of the isotopes and the compliance of the performed exposures to the mass numbers of the C isotopes. In the study of the coherent dissociation of relativistic ^{12}C nuclei [17] all 100 “white” stars are found in a single channel $^{12}\text{C} \rightarrow 3\text{He}$ clearly reflecting the 3α-particle clustering of this nucleus. The decays of unbound relativistic ^{8}Be nuclei the contribution which was about 20% became the key observation.

Events containing only the relativistic isotopes of He and H (77%), in particular, 2He + 2H dominate among the ^{11}C “white” stars. The ratio of the statistics of this channel to the statistics of the channel He + 4H is 6 ± 3. It does not correspond to the idea about the only dissociation of the ^{7}Be core mentioned above. In contrast to the previously studied neutron deficient nuclei one can see a significant fraction of events Li + He + H is observed, which could correspond to ^{6}Li + ^{4}He + p. There are no events Be + 2H which could correspond to ^{9}Be + $2p$. However, there is a significant fraction of Be + He events. If the ^{4}He isotope is identified in them the isotope ^{7}Be is determined unambiguously. It is expected that the ^{3}He channel corresponds to the configuration 2^{4}He^{3}He which can arise from break-ups of both the core nuclei ^{8}Be and ^{7}Be and three-body states. An additional contribution to multiple channels can be made by dissociation of the ^{6}Li cluster, as an ^{11}C independent element in accordance to its bond structure α + d [16]. It can be said that the presented distribution over the charge topology have individual character for ^{11}C which differ from that of the other isotopes being a kind of "autograph".

In general, these findings reflect the structure of ^{11}C as a superposition of the states based on the nuclei ^{10}B and ^{7}Be which sets future lines of this research. The discussed aspects motivate a new round of works on the basis of the performed exposure with the aim to enlargement the statistics of "white" stars ^{11}C, the He and H identify isotopes by measurements of their multiple scattering, determine the ^{8}Be decay contribution, and study the dissociation dynamics by angular measurements. The selection of the values of the total transverse momentum of relativistic fragments in limits typical for the diffraction dissociation will allow one to compensate indirectly the lack of a direct identification of isotopes heavier than He.

Table 4. Distribution over charge channels for the "white" stars produced by ^{12}N and ^{14}N nuclei.

Channel	^{12}N [10]	^{14}N [19]
C + H	4 (6 %)	13 (28 %)
B + He	3 (4 %)	4 (9 %)
B + 2H	11 (15 %)	3 (7 %)
Be + He + H	9 (13 %)	1 (2 %)
Be + 3H	10 (14 %)	
Li + He + 2H		1 (2 %)
Li + 4H		1 (2 %)
3He + H	2 (3 %)	17 (37 %)
2He + 3H	24 (33 %)	6 (13 %)
He + 5H	9 (13 %)	

These data make it possible to interpret more reliably the charge topology of "white" stars produced by relativistic nuclei ^{12}N [10]. Table 4 shows their statistics together with appropriate data for the "white" stars of ^{14}N [19]. For "white" stars ^{12}N of channels ^{11}C + p (0.6 MeV), ^{8}B + ^{4}He (8.0 MeV) and p + ^{7}Be + ^{4}He can have a significant part. There is a possibility of multiple dissociation via the unbound nucleus ^{9}B + ^{3}He (10 MeV). Interpretation of the channel B + 2H is more difficult due to the fact that the channel ^{10}B + 2p (9.2 MeV) becomes available. As exactly in the case of ^{11}C, multiple channels of ^{12}N can be associated with the dissociation of the cores ^{10}B and ^{7}Be. It is possible that the predominance of the channel 2He + 3H reflects a dissociation of the ^{11}C core with the participation of ^{10}B. A low probability of dissociation ^{10}B into the pair ^{9}Be + p allows one to determine Be in Table 4 as ^{7}Be. Limits on the mass number enable one to determine B in the channel B + He as ^{8}B (Table 4).

The restrictions of the statistics of "white" stars ^{12}N [10] (Table. 4) is due to the choice of the charge exchange reaction of relativistic ^{12}C nuclei for the formation of the ^{12}N beam. The main argument in favor of this choice was the desire to simplify the identification of "white" stars ^{12}N by the total charge of relativistic fragments of seven units on a more intensive background of events from the accompanying carbon isotopes. However, there are needs for a time-consuming determination of the charge beam tracks as corresponding to 7 charge units due to a significant contribution of the events of coherent dissociation of carbon isotopes with the formation of mesons in a narrow relativistic fragmentation cone. This fact drastically reduces the value of the exchange. However, a good separation of carbon isotopes at the Nuclotron confirmed by the data on their coherent dissociation indicates the possibility of exposure of NTE to isotopes ^{12,13}N produced in the fragmentation of relativistic nuclei ^{14}N with the aim to increase dramatically the statistics of "white" stars. New opportunities could open when accelerating nuclei ^{16}O for such studies using beams of neutron-deficient isotopes ^{13,14,15}O. A further promotion by the NTE technique to heavier neutron-deficient isotopes have prospects, although it is getting harder. Following this way a further diversity of the ensembles of p-^{3}He-α can grows. For its development it is necessary to study the experimental situation and have an accurate knowledge about the ^{11}C isotope.

It should be noted that the nuclei ^{11}C and ^{12}N initiate a restriction of the described approach which makes impossible a direct identification by the mass numbers of relativistic fragments heavier than He. The fractions of events with the participation of such fragments should increase rapidly with increasing mass number of a nucleus in question. This identification is possible in electronic experiments with a magnetic analysis in at energy of a few GeV per nucleon. The use of the NTE will be valuable for the orientation of electronic experiments on coherent dissociation of relativistic neutron-deficient nuclei. In perspective, identification is possible in the region of tens of GeV per nucleon in experiments with hadron calorimeters.

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