CLUSTER STRUCTURE OF ^{10}C AND ^{12}N NUCLEI STUDIED IN COHERENT DISSOCIATION[*]

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Thanks to its record spatial resolution and sensitivity, nuclear track emulsion technique allowed one to carry out a “tomography” for light neutron deficient nuclei. It is found that for the ^{10}C nucleus the fraction of the coherent dissociation events $2\alpha + 2p$ is about 80%. About 30% of them belong to the channel $^{9}B_{g.s.} + p$ with a subsequent decay $^{8}Be + p$. There are no obviously leading channels in the coherent dissociation of ^{12}N. At the same time there is an intensive formation of fragments with a charge exceeding 3. Most probably, the role of the ^{12}N core can be attributed to the ^{7}Be nucleus.

1. Introduction

Despite the fact that the capabilities of relativistic fragmentation for the study of nuclear structure were recognized quite a long time ago, electronic experiments have not been able to come closer to an integrated analysis of ensembles of relativistic fragments. The continued pause in the investigation of the "fine" structure of relativistic fragmentation has led to resumption of regular exposures of nuclear track emulsion (NTE) in the beams of light nuclei produced for the first time at the Nuclotron of the Joint Institute for Nuclear Research (JINR, Dubna). To date, an analysis of the peripheral interactions of relativistic isotopes of beryllium, boron, carbon and nitrogen, including radioactive ones, with nuclei of the emulsion composition, has been performed, which allows their clustering features to be presented.[a]

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[a] More information and collection of images and videos of interactions in NTE: http://becquerel.jinr.ru.

At collisions of nuclei of the energy above 1A GeV, the kinematical regions of fragmentation of the projectile and target nuclei are clearly separated, and the momentum spectra of fragments come to asymptotic behavior. Thus, the regime of the limiting fragmentation of nuclei is reached, which also means that the isotopic composition of the fragments remains constant with increasing collision energy. Of particular value for the cluster physics are the events of peripheral dissociation of the incident nucleus with preservation of the number of nucleons in the region of its fragmentation. At a projectile energy above 1A GeV the probability of such dissociation reaches a few percent. Definition of interactions as peripheral is facilitated by increasing collimation of fragments. Thresholds of detection of relativistic fragments are absent, and their energy losses in the detectors are minimal. All these factors are essential for experimental studies. With the development of research in relativistic nuclear physics, magneto-optical channels of particle transportation were built at the JINR Nuclotron allowing secondary beams of 2A GeV/c nuclei to be formed. The channel used in our exposures has a length of about 50 m and consists of four bending magnets; its acceptance is about 2–3%.

An emulsion chamber is assembled as a stack of pellicles about 550 microns thick and 10x20 cm^2 in size. The factors in obtaining large event statistics are thickness reaching 80 g/cm^2 along the long side and complete detection efficiency of charged particles. Nuclear emulsions contain heavy nuclei Ag and Br as well as H nuclei in similar concentrations. By the density of hydrogen, nuclear emulsion is close to a liquid hydrogen target. This feature allows one to compare in the same conditions the disintegrations of projectile nuclei in diffraction or electromagnetic dissociation on heavy target nuclei as well as in collision with protons.

The fragments of the relativistic nuclei are concentrated in a cone limited by the angle $\theta_{fr} \approx p_{fr}/p_0$, where p_{fr} = 0.2 GeV/c is a quantity characterizing the Fermi momentum of nucleons, and p_0 is the momentum per nucleon of the projectile nucleus. If the beam is directed parallel to the pellicles, the tracks of all relativistic fragments can stay long enough in a single pellicle for 3-dimensional reconstruction. The distribution of events over the interaction channels with different composition of charged fragments (or charged topology) is a direct feature of the fragmentation of relativistic nuclei.

In NTE the angular resolution for the tracks of relativistic fragments is of the order of 10^{-5} rad. Measurements of the polar angles θ of fragment emission are not sufficient for comparison of data for different values of the initial energy of nuclei. More generic is a comparison by the values of the transverse momentum P_T of fragments with the mass number A_{fr} according to the approximation of $P_T \approx A_{fr}P_0\sin\theta$, which corresponds to conservation by the fragments of the velocity of the primary nucleus (or momentum P_0 per nucleon). Obviously, the most important is the θ angle resolution, the θ distributions are “pressed against” zero. For α cluster-based nuclei, the assumption about the correspondence of a relativistic fragment with the charge $Z_{fr} = 2$ to the ^{4}He isotope is well justified. Separation of the isotopes ^{3}He and ^{4}He is required for neutron-deficient nuclei.

In coherent dissociation events there are no fragments of the target nuclei ($n_b = 0$, $n_g = 0$) and charged mesons ($n_s = 0$). Events of this type were informally named as "white" stars because of the lack of traces of strongly ionizing particles n_h ($n_h = n_b + n_g$). "White" stars are produced by nuclear diffraction and electromagnetic interactions on heavy target nuclei. Their proportion in the total number of inelastic events is a few percent. The name "white" stars aptly reflects the "breakdown" of ionization in the transition from the primary nucleus track to a narrow cone of the secondary tracks down to Z_{pr} times. This feature constitutes the main difficulty for electronic techniques, since the greater the degree of dissociation at the event, the harder it is to register. In nuclear track emulsions the situation is quite opposite.

The excitation energy of a fragment system, Q, is defined as the difference between the invariant mass of the fragmenting system M* and the mass of the primary nucleus M, i.e. $Q = M^* - M$. M* is the sum of all products of the fragment 4-momenta $P_{i,k}$ $M^{*2} = \Sigma(P_i \cdot P_k)$. 4-momenta $P_{i,k}$ are determined in the approximation of conservation of the initial momentum per nucleon by fragments.

Earlier relevant observations made in NTE exposures with the nuclei ^{12}C [1], ^{16}O [2], ^{22}Ne [3], ^{6}Li [4] and ^{7}Li [5] and were carried out at the JINR Synchrophasotron in the 70–90s. Within the BECQUEREL project, the peripheral interactions were analyzed in NTE exposed to the following set of nuclei: ^{6}He [6], ^{10}B [7], ^{7}Be [8], ^{14}N [9], ^{9}Be [10,11], ^{11}B [12], ^{8}B [13], ^{9}C [14], ^{10}C, and ^{12}N [15-17]. These experimental results allow to present a comprehensive picture of clustering for a family of nuclei at the beginning of the table of isotopes. The last two cases are presented below.

2. Exposure in a mixed beam of ^{12}N, ^{10}C and ^{7}Be nuclei

A secondary beam containing ^{12}N, ^{10}C and ^{7}Be nuclei can be formed by selection of products of charge-exchange and fragmentation reactions of relativistic ^{12}C nuclei. Such a composition is not so much desirable, but unavoidable since Z_{pr}/A_{pr} ratios of these nuclei differ by only 3%. Separation of these nuclei is not possible in a channel with the momentum acceptance of 2–3%, and they are simultaneously present in the beam, forming the so-called "beam cocktail". The contribution of ^{12}N nuclei is small relative to ^{10}C and ^{7}Be nuclei in accordance with the charge-exchange and fragmentation cross-sections. Because of the momentum spread ^{3}He nuclei can penetrate into the channel. For the neighboring nuclei ^{8}B, ^{9}C and ^{11}C the difference of Z_{pr}/A_{pr} from ^{12}N is about 10%, which causes their suppression in the secondary beam. An event-by-event identification of ^{12}N in the exposed NTE is possible for "white" stars by fragment topologies and beam nucleus charges determined by δ-electron counting on the beam tracks. In the case of the dominating ^{10}C nuclei it is sufficient to make sure that the contribution of the neighboring C isotopes by the overall pattern of the composition of "white" stars is small.

Based on these considerations, it was suggested to expose NTE to a mixed beam of 2A GeV/c ^{12}N, ^{10}C and ^{7}Be nuclei [17]. The amplitude spectrum from a scintillation counter installed in the location of NTE irradiation pointed to the dominance of isotopes of He, Be, C, and a small admixture of N nuclei in the substantial absence of ^{8}B nuclei. A stack of 15 NTE layers was exposed to a secondary beam with such a composition. The initial stage of analysis was to search for beam tracks with charges $Z_{pr} = 1, 2$ and $Z_{pr} > 2$. The ratio of beam tracks $Z_{pr} = 1, 2$ and $Z_{pr} > 2$ was ≈ 1:3:18.

The analysis presented below is based on the search for events along the tracks of primary particles with charges visually valued as $Z_{pr} > 2$ over a length of about 1088 m. As a result, 7241 inelastic interactions were found, including 608 "white" stars, containing only relativistic particle tracks in the angular cone $\theta_{fr} < 11^{o}$. In the "white" stars, which might be created by ^{12}N nuclei, the average densities of δ-electrons N_{δ} were measured on the tracks of beam nuclei and secondary fragments with charges $Z_{fr} > 2$.

3. Dissociation of ^{10}C nuclei

The ^{10}C nucleus is the only example of a stable 4-body structure in which the removal of any of the constituent clusters or nucleons leads to an unbound state condition. The breakup threshold of the $^{10}C \rightarrow 2\alpha + 2n$ process is $E_{th} = 3.73$

MeV. The next threshold via $^8Be_{g.s.}$ + 2p is slightly higher – E_{th} = 3.82 MeV. Knocking out one of the protons (E_{th} = 4.01 MeV) leads to the formation of an unstable ^9B nucleus, which decays into a proton and a ^8Be nucleus. By way of α-cluster separation (E_{th} = 5.10 MeV), a ^6Be resonance can be formed, its decay energy being 1.37 MeV. The decay of ^6Be via the ^5Li resonance is impossible, because the threshold for the formation of $^5Li_{g.s.}$ + p is 0.35 MeV higher than the ^6Be ground state. In addition, the channel $^5Li_{g.s.}$ + α is closed since this threshold is 1.5 MeV higher than the ^9B ground state. Therefore, in the ^{10}C dissociation the resonances $^6Be_{g.s.}$ and $^5Li_{g.s.}$ can only be produced directly and not in cascade decays of ^9B.

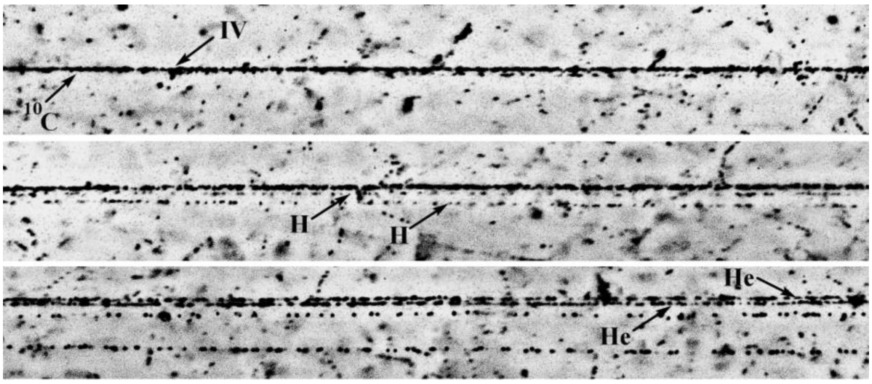

Figure 1. Coherent dissociation $^{10}C \rightarrow p + {}^9B_{g.s.}$ at 2A GeV/c.

Events ΣZ_{fr} = 6 were selected among the found peripheral interactions. The subject of the analysis was a sample consisting of 227 “white” stars N_{ws}. The peculiarity of this class of events is the dominance of the channel 2He + 2H, which is indeed the most expected one for the ^{10}C isotope. The channels N_{ws} requiring destruction of α-clustering in ^{10}C nuclei and having substantially higher thresholds are manifested with much lower probabilities. The macrophotography of a typical event is shown in Fig. 1. The interaction vertex (IV) in which a group of fragments formed is marked in the top photo. Further, one can distinguish two H (middle photo) and two He fragments (bottom photo). The most remote track originated in the dissociation $^{10}C \rightarrow {}^9B_{g.s}$. + p. The other tracks correspond to the decay of the unbound ^9B nucleus. The pair of the He tracks corresponds to the following decay of another unbound ^8Be nucleus.

Comparison of the N_{ws} topology distribution with the version for the 627 ^{10}C N_{tf} events accompanied by the production of mesons, fragments of target nuclei or recoil protons, points to the "turning on" of the He + 4H channel in the latter case (Table 1). First of all, a much smaller perturbation of the ^{10}C cluster structure in the "white" stars with the respect to the N_{tf} case is confirmed. In addition, the comparison shows that the probabilities of the fragmentation channels beyond the "pure" clustering 2α-2p do not differ too much in the cases N_{ws} and N_{tf} (Table 1). This fact indicates the existence in the ^{10}C structure of a small admixture of virtual states with participation of deeply bound cluster-nucleon configurations.

In 68 of the events N_{ws} α pairs with emission angles not exceeding 10^{-2} rad are observed. The distribution $Q_{2\alpha}$ of these α pairs with an average $<Q_{2\alpha}>$ = (63 ± 30) keV at RMS of 83 keV allows concluding that the formation of $^{8}Be_{g.s}$ is observed in these events. In turn, the distribution $Q_{2\alpha p}$ indicates that the dissociation $^{10}C \rightarrow 2\alpha + 2p$ is accompanied by the formation of unbound 9B nuclei. The average value $<Q_{2\alpha p}>$ = (254 ± 18) keV at RMS of 96 keV corresponds the energy and width of the decay $^{9}B_{g.s.} \rightarrow {}^{8}Be_{g.s.} + p$. A clear correlation between $Q_{2\alpha}$ and $Q_{2\alpha p}$ points to the cascade process $^{10}C \rightarrow {}^{9}B \rightarrow {}^{8}Be$. The contribution of these decays allows concluding that the ^{9}B nucleus manifests itself with a probability of (30 ± 4) % in the ^{10}C structure.

Table 1. Distribution over the charge configurations of relativistic fragments $\Sigma Z_{fr} = 6$ of ^{10}C fragmentation events for "white" stars N_{ws} and collisions with produced mesons, target fragments or protons N_{tf}

Channel	2He+2H	He+4H	3He	6H	Be+He	B+H	Li+3H	C+n
N_{ws} (%)	186 (81.9)	12 (5.3)	12 (5.3)	9 (4.0)	6 (2.6)	1 (0.4)	1 (0.4)	
N_{tf} (%)	361 (57.6)	160 (25.5)	15 (2.4)	30 (4.8)	17 (2.7)	12 (1.9)	2 (0.3)	30 (4.8)

4. Dissociation of ^{12}N nuclei

For ^{12}N "white" stars, the channels ^{11}C + p (E_{th} = 0.6 MeV), $^{8}B + {}^{4}He$ (E_{th} = 8 MeV) and p + $^{7}Be + {}^{4}He$ (E_{th} = 7.7) and the channels associated with the dissociation if the ^{7}Be core are expected to play a leading role. The threshold of the channel $^{3}He + {}^{9}B_{g.s.}$ is located at E_{th} = 10 MeV. A small difference in the binding energy compared with the channels containing fragments $Z_{fr} > 2$ suggests a possible duality of the ^{12}N nucleus. On the one hand, its basis can be represented by the bound ^{7}Be and ^{8}B nuclei, on the other hand by the unbound

^{8}Be and ^{9}B nuclei. Therefore, a particular feature of the coherent ^{12}N dissociation could be a competing contribution of ^{8}Be and ^{9}B decays.

Measurements of the charges of the beam nuclei Z_{pr} and relativistic fragments $Z_{fr} > 2$ in the candidate events of the ^{12}N dissociation made it possible to select 72 “white” stars which satisfy the condition $Z_{pr} = 7$ and $\Sigma Z_{fr} = 7$. The charge topology distribution of these stars is shown in Table 2. Accidentally, the mass numbers A_{fr} become definite for isotopes $Z_{fr}> 2$. According to “white” star statistics, the share of ^{12}N nuclei in the beam is estimated to be 14%, while those of ^{10}C and ^{7}Be nuclei are about 43% each (excluding H and He nuclei). These values do not reflect the ratio of the cross-sections of the charge-exchange and fragmentation reactions and have a technical importance. The significant contribution to the beam of charge-exchange products $^{12}C \rightarrow {}^{12}N$ compared with ^{10}C and ^{7}Be fragments of ^{12}C is explained by the fact that the beam was tuned to the ratio $Z_{pr}/A_{pr} = 5/12$ of ^{12}N, which is somewhat different from the values for ^{10}C and ^{7}Be.

Table 2. Distribution of the^{12}N "white" stars; middle row –selection with the condition $\theta_{fr} < 11^{o}$, bottom row – $\theta_{fr} < 6^{o}$.

He + 5H	2He +3H	3He +H	^{7}Be + 3H	^{7}Be+ He + H	^{8}B + 2H	^{8}B+ He	C+ H
9	24	2	10	9	11	3	4
2	12	2	5	8	9	3	4

For a further selection of events containing specifically ^{12}N fragments (not "participants") the condition on the angular cone of coherent dissociation was enhanced to $\theta_{fr} < 6^{o}$, which is determined by a “soft” constraint on the nucleon Fermi momentum. In the distribution of 45 selected events (Table 8) the share of the channels with heavy fragments $Z_{fr} > 2$ reaches approximately ⅔, and the contribution of the channels containing only He and H fragments is quite significant. A noticeable contribution of a very “fragile” ^{8}B points to a “cold” fragmentation with minimal perturbation of the ^{12}N structure. As judged by the facts of approximate equality of the probabilities of the channels 2He and He + 2H in the dissociation of the ^{7}Be nucleus [8], ^{7}Be core of ^{8}B [13] and ^{9}C [14], one would expect that for the ^{12}N nucleus the probabilities of the channels 2He + 3H and 3He + H are about equal. In contrast, the statistics in the 2He + 3H channel turned out to be unexpectedly large.

Angular measurements were used to study the contribution of ^{8}Be decays. Only two candidates for $^{8}Be_{g.s.}$ decays were found in the distribution on the opening angle Θ_{2He} for the “white” stars 2He + 3H and 3He + H. Thus, the contribution of $^{8}Be_{g.s.}$ to the ^{12}N structure is estimated to be only 4 ± 2%. For the neighboring nuclei ^{12}C, ^{10}C, ^{10}B and ^{14}N it amounted to about 20%. The data on Θ_{2He} for ^{12}N do not exclude a possibility of dissociation via ^{8}Be 2^{+} state decays. The latter question requires statistics at a new level.

When searching for an analogy between ^{9}C and ^{12}N nuclei by replacing one of the outer protons in the system 2p + ^{7}Be by an α-cluster, there arises the following difficulty. The probability of channels, which require the splitting of the outer α-cluster in the ^{12}N nucleus, roughly coincides with the values for channels that can be associated with the separation of only α-cluster. A "simple" picture of the ^{12}N nucleus as a p + ^{7}Be + ^{4}He structure appears to be insufficient. It is most likely that the cluster structure of the ^{12}N ground state constitute a complex mixture of the ^{7}Be core states and of the various configurations of lightest nuclei.

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