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CLUSTERING IN RELATIVISTIC DISSOCIATION OF ^{9}Be, ^{9}C, ^{10}C AND ^{12}N NUCLEI

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The dissociation features in nuclear track emulsion of ^{9}Be, ^{9,10}C, and ^{12}N nuclei of 1.2 A GeV energy are presented. The data presented for the nucleus ^{9}Be can be considered as evidence that there is a core in its structure in the form of 0^{+} and 2^{+} states of the ^{8}Be nucleus having roughly equal weights. Events of coherent dissociation ^{9}C$\rightarrow$3^{3}He associated with the rearrangement of the nucleons outside the α-clustering are identified. A pattern of the charge fragment topology in the dissociation of ^{10}C and ^{12}N nuclei is obtained for the first time. Contribution of the unbound nucleus decays to the cascade process ^{10}C$\rightarrow$^{9}B$\rightarrow$^{8}Be is identified.

1. Introduction

The concepts of baryonic matter in a cold dilute phase with clustering of nucleons in the lightest nuclei ^{4}He, ^{3}He, ^{2}H and ^{3}H have been developed in the last decade.[1–4] Theoretical developments carried out in this direction orient towards the study of cluster groups as integral quantum systems and give motivation to a new generation of experiments on cluster spectroscopy.[5,6] Since the macroscopic cluster states can play the role of an intermediate phase in astrophysical processes, these studies assume the significance going beyond the framework of the nuclear structure problems.[7,9]

The method of nuclear track emulsion provides a uniquely complete observation of multiple fragment systems produced in dissociation of relativistic nuclei. Approximate conservation of the initial momentum per nucleon by relativistic fragments is used in the kinematical analysis of the events to compensate the lack of momentum measurements. The fragmenting system excitation can be defined as Q = M*-M, where M* is the invariant mass and the projectile mass or total fragment mass. The value M* is defined by the relation $M^{*2} = (\sum P_j)^2 = \sum(P_i \cdot P_k)$, where

$P_{i,k}$ 4-momenta fragments i and the k, determined in the approximation of the conservation of the primary momentum value per nucleon.

The most valuable events of coherent dissociation of nuclei in narrow jets of light and the lightest nuclei with a net charge as in the initial nucleus, occurring without the formation of fragments of the target nuclei and mesons (the so-called "white"stars),[10,11] comprise a few percent among the observed interactions. The data on this phenomenon are fragmented, and the interpretation is not offered. The dissociation degree of light O, Ne, Mg and Si, and as well as heavy Au, Pb and U nuclei may reach a complete destruction to light and the lightest nuclei and nucleons, resulting in cluster systems of an unprecedented complexity. The dissociation dynamics of heavy nuclei can be grounded on dissociation peculiarities established for light nuclei. An extensive collection of photographs of such interactions is gathered by the BECQUEREL collaboration.[12]

Despite the fact that the potential of the relativistic approach to the study of nuclear clustering is recognized long ago, e-experiments were not be able to get closer to the required detailed observation of the relativistic fragment ensembles. The related pause has led to the proposal to irradiate nuclear track emulsion in the JINR Nuclotron beams of the whole family of 1.2 A GeV light nuclei, including radioactive ones.[13,14] Studies with relativistic neutron-deficient nuclei have special advantages due to more complete observations. The dissociation features of ^{9}Be, ^{9,10}C, and ^{12}N nuclei, which are the sources of basic cluster configurations, will be presented in the present paper.

2. Dissociation ^{9}Be→2α

In order to justify the application of the relativistic fragmentation in the study of Nα-systems[11] it was suggested to investigate the dynamics of the formation of α-particle pairs at a high statistical level and under the simplest conditions (without combinatorial background) which are provided in the relativistic fragmentation ^{9}Be→2α.[13,16,17] The secondary ^{9}Be beam was obtained by fragmentation of accelerated ^{10}B nuclei.[21] When scanning the exposed emulsion 500 events ^{9}Be→2α in a fragmentation cone of 0.1 rad have been found. About 81% α-pairs form roughly equal groups on $\Theta_{2\alpha}$: "narrow"($0 < \Theta_n < 10.5$ mrad) and "wide"($15.0 < \Theta_w < 45.0$ mrad) ones. The Θ_n pairs are consistent with ^{8}Be decays from the ground state 0^+, and pairs Θ_w - from the first excited state 2^+. The Θ_n and Θ_w fractions are equal to 0.56±0.04 and 0.44±0.04. These values are well corresponding to the weights of the ^{8}Be 0^+ and 2^+ states $\omega_{0^+} = 0.54$ and $\omega_{2^+} = 0.47$ in the two-body model n - ^{8}Be, used to calculate the magnetic moment of the ^{9}Be nucleus.[22,23]

For the coherent dissociation ^{9}Be→2α+n, the average value of the total α-pair transverse momentum is equal to $< P_{Tsum} > \approx 80$ MeV/c, which can be assigned to the average transverse momentum carried away by neutrons. For the ^{9}Be coherent dissociation through the ^{8}Be 0^+ and 2^+ states there is no differences in the values $< P_{Tsum} >$, which points to a "cold fragmentation"mechanism. The whole complex of these observations may serve as an evidence of the simultaneous presence of the ^{8}Be 0^+ and 2^+ states with similar weights in the ground state of the nucleus ^{9}Be.

3. Coherent Dissociation of ^{9}C Nuclei

One can expect that the pattern established for the ^{7}Be[15] and ^{8}B[18,19] nuclei is reproduced for nucleus ^{9}C with the addition of one or two protons. In addition, the emergence of a 3^3He ensemble becomes possible. An intriguing hypothesis is that in the nuclear astrophysical processes the 3^3He system can be a 3α-process analog.

A secondary beam, optimized for ^{9}C nucleus selection was formed by fragmentation of accelerated ^{12}C nuclei.[20,21] It was important in this irradiation to avoid overexposure by the accompanying flux of ^{3}He nuclei. The intensity ratio of the nuclei with charges $Z_{pr} = 6$ and 2 amounted to 1 : 10. This factor has limited statistics and made the scan for ^{9}C interactions much more labor demanding.

Among the total number of “white”stars N_{ws}, detected in this exposure, 15 events ^{9}C→^{8}B+p and 16 events ^{7}Be+2p are found. Statistics in the channels ^{2}He+^{2}H (24), He+4H (28) and 6H (6) well corresponds to the ^{7}Be core dissociation. The event fraction ^{9}C→3^3He (16) was found to be the same as that of the channels ^{9}C→^{8}B+p and ^{7}Be+2p.

The latter fact can point to a significant admixture of a virtual 3^3He state in the ^{9}C ground state. This component can give a contribution to the ^{9}C magnetic moment, which has an abnormal value in terms of the shell model.[24]

4. Coherent Dissociation of ^{10}C and ^{12}N nuclei

The ^{10}C nucleus is the only example of the system, which has the “superboromean”properties, since the removal of one of the four clusters in the 2α+2p structure (threshold 3.8 MeV) leads to an unbound state. The particular feature of the ^{12}N nucleus consists in the low proton separation threshold (600 keV). Furthermore, the dissociation can occur through the channels α+^{8}B (8 MeV) , p+^{7}Be+α, as well as into more complicated ensembles with the ^{7}Be core break. Generation of ^{12}N and ^{10}C nuclei is possible in charge exchange and fragmentation reactions of accelerated ^{12}C nuclei.[21] The charge to weight ratio Z_{pr}/A_{pr} differs by only 3% for these nuclei, while the momentum acceptance of the separating channel is 2 - 3%. Therefore, their separation is not possible, and the ^{12}N and ^{10}C nuclei are simultaneously present in the secondary beam, forming a so-called beam “cocktail”. The contribution of ^{12}N nuclei is small in respect to ^{10}C ones in accordance with the cross sections for charge transfer and fragmentation reactions. Also, the beam contains ^{7}Be nuclei, differing by Z_{pr}/A_{pr} from ^{12}N nuclei only by 2%. Due to the momentum spread ^{3}He nuclei can penetrate in the separating channel. For neighboring ^{8}B, ^{9}C and ^{11}C nuclei the difference by Z_{pr}/A_{pr} from ^{12}N is about 10%, which leads to suppression in these isotopes. Identification of ^{12}N nuclei can be performed by δ-electron counting along the beam tracks. In the ^{10}C case, relying on the charge topology of the produced “white”stars it is necessary to be sure that the neighboring carbon isotope contribution is small. These considerations provided the justification to expose nuclear track emulsion in a mixed beam of ^{12}N, ^{10}C and ^{7}Be nuclei. The initial scanning phase consisted in visual search of beam tracks with charges Z_{pr}=1, 2 and Z_{pr} >2. The ratio of beam tracks with charges Z_{pr}= 1, 2 and Z_{pr} >2 is found to be equal $\approx 1 : 3 : 18$. Thus, the contribution of ^{3}He nuclei dramatically decreased compared with the ^{9}C irradiation, which radically raised the event search efficiency. The presence of fragments Z_{fr} >2 makes the charge identification of beam Z_{pr} and secondary Z_{fr} tracks necessary. For the calibration the average density of δ-electrons N_{δ} was measured along the beam tracks, which produced the "white" stars ^{2}He+^{2}H, ^{2}He and He+^{2}H, and also stars with fragments Z_{fr} >2 (^{12}N candidates). Thus, the correlation between the charge topology $\sum Z_{fr}$ and N_{δ} was established which permitted to determine beam track charges Z_{pr} and the fragment charges Z_{fr} >2. For "white" stars N_{ws} with charge topology $\sum Z_{fr}$=6 the most probable channel is represented by 91 events ^{2}He+^{2}H, which might be expected for the isotope ^{10}C. The channel He+4H is found to be suppressed (14 events), as in the ^{10}C case it is required to overcome the high threshold of the α-cluster break up. In this irradiation 20 "white" stars with Z_{pr}=7 and $\sum Z_{fr}$=7 are found, corresponding to the dissociation of ^{12}N nuclei. There are the following channels among them: C+H (1), ^{7}Be+He+H (2), ^{7}Be+^{3}H (4), ^{8}B+^{2}H (3), ^{3}He+H (2), ^{2}He+^{3}H (6), He+^{5}H (3). Thus, half of the events contain a fragment $Z_{fr} > 2$, clearly differing from the cases of nuclei ^{14}N[13,14] and ^{10}C.

5. Production of ^{8}Be and ^{9}B Nuclei in ^{10}C Dissociation

The unbound ^{8}Be nucleus plays the role of the core in the ^{10}C structure, which should be manifested in the fragmentation intensity ^{10}C$\to$^{8}Be. Distribution α-pairs in the 91 "white" stars ^{2}He+^{2}H on the excitation energy $Q_{2\alpha}$ is presented in Fig. 1. In 30 events the $Q_{2\alpha}$ value does not exceed 500 keV (inset in Fig. 1). For them, the average value is $< Q_{2\alpha} > \approx 110\pm20$ keV and the mean-square scattering σ=40 keV, which well corresponds to the decays of the ^{8}Be 0^{+} ground state. The ^{8}Be 0^{+} contribution is approximately the same as for the neighboring cluster nuclei. The unbound ^{9}B nucleus can be another major product of the ^{10}C coherent dissociation. Fig. 2 shows the distribution of "white" stars ^{2}He+^{2}H on the excitation energy $Q_{2\alpha p}$, defined by the difference of the invariant mass of the three fragments 2α+p and the mass of the proton and the doubled α-particle mass. The $Q_{2\alpha p}$ values for one of two possible 2α+p triples do not exceed 500 keV in 27 events (inset in Fig. 2). The average value for these triples is $< Q_{2\alpha p} >=250\pm15$ keV with rms σ=74 keV. These values well correspond to the ^{9}B ground state decay via the channel p+^{8}Be (0^{+}) having the published values of energy 185 keV and width (0.54$\pm$0.21) keV.[25] In the region limited by $Q_{2\alpha}$ <1 MeV and time both triples correspond to the decay of the nucleus ^{9}B. In all other ^{9}B cases one of $Q_{2\alpha p}$ is above 500 keV. In addition, excitations α+2p are studied on the remaining statistics of "white" stars ^{2}He+^{2}H beyond ^{9}B decays. In the spectrum of $Q_{2\alpha p}$, there is no clear signal of ^{6}Be decays,[12]

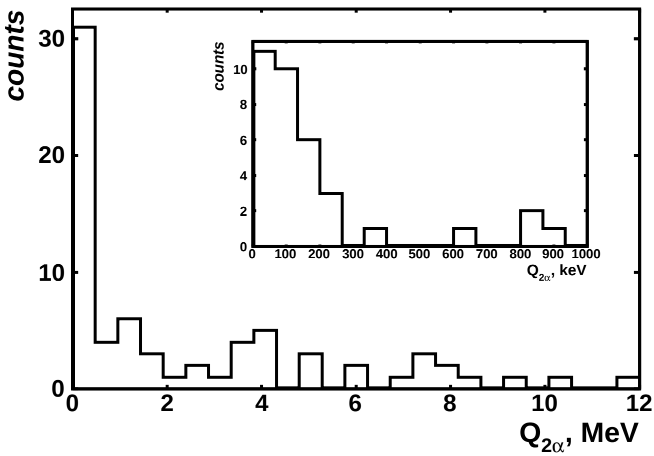

Fig. 1. Distribution number of "white"stars N_{ws} of the ^{2}He+^{2}H topology on the excitation energy $Q_{2\alpha}$ pairs of α-particles in the inset - enlarged distribution $Q_{2\alpha}$

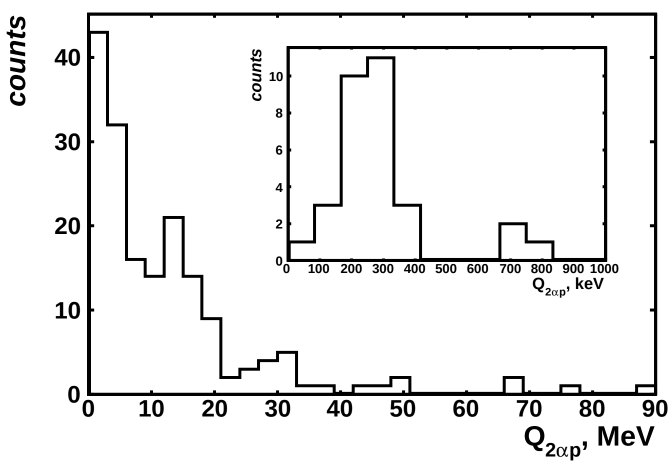

Fig. 2. Distribution number of "white"stars N_{ws} of the ^{2}He+^{2}H topology on the excitation energy $Q_{2\alpha p}$ triples 2α+p; in the inset - enlarged distribution $Q_{2\alpha p}$

and its estimated contribution does not exceed 20%. This aspect deserves further analysis taking the proton angular correlations into account.

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