ANALYSIS OF THE DECAY OF THE ^{9}B NUCLEUS IN THE DISSOCIATION OF THE ^{10}C NUCLEUS

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ABSTRACT

The creation of beams of radioactive nuclei opens qualitatively new opportunities for studying their structural features and excited states. In the study of interactions at high energies, a significant role is played by the nuclear photo emulsion method, which is characterized by unique capabilities. Due to its extremely good spatial resolution (0.5 μm) compared to other methods and depending on the primary impulse, an angular accuracy of the tracks of relativistic fragments of about 10^{-3} radians can be obtained. This provides complete observation of all possible fragmentation decays of relativistic nuclei. In the current study, results are presented for the analysis of the decay of the unbound nucleus ^{9}B in the dissociation of ^{10}C nuclei. A comparative study is also performed between experimental data and Monte Carlo model calculations.

Keywords: Monte Carlo modelling, radioactive beams, nuclear track emulsion technique, peripheral interactions of nuclei.

INTRODUCTION

The nuclear emulsion technique remains an effective research method, in particularly allowing to study the cluster dissociation of a wide variety of light relativistic nuclei in a unified approach. Even though the possibilities of relativistic fragmentation for studying nuclear clustering have been known for a long time, modern experiments have not been able to come close to a comprehensive analysis of the ensemble of relativistic fragments.

Of particular interest are the peripheral interactions of nuclei at energies above 1 A GeV as optimal for measurement and interpretation. The most significant for clustering studies are the interactions of relativistic nuclei, occurring with minimal mutual excitation of the colliding nuclei without the formation of charged mesons. In this case, an accurate separation of the products by momentum is achieved during fragmentation of the projectile nuclei and the target nuclei. The main criterion for selecting such events is the condition for preserving the electric charge and mass number of the impinging nucleus in a narrow angular fragmentation cone.

To date, an analysis of peripheral interactions of the relativistic isotopes' beryllium, boron, carbon and nitrogen, including radioactive ones, with nuclei from the composition of the emulsion has been performed, which allows us to present a picture of clustering in an entire family of light nuclei [1].

The current work is a continuation of the study, which is based on experimental results and is devoted to a comparative analysis of the characteristics of reaction $^{10}C \rightarrow {}^{9}B + p$ [2]. This study focuses on the identification of the unbound nucleus ^{9}B as a product of the coherent dissociation of the ^{10}C nucleus. In such peripheral interactions, the projectile nucleus dissociates without significant excitation or fragmentation of the target, favouring the formation of intermediate unbound states. The nucleus ^{9}B, unstable with respect to proton emission, decays into ^{8}Be + p, with ^{8}Be subsequently decaying into two α particles. These sequential decays can be reconstructed using nuclear track emulsion, allowing for detailed analysis of the reaction topology and providing insights into the cluster structure and decay dynamics of light nuclei.

EXPERIMENTAL

The nucleus ^{10}C exhibits a unique "super-Borromean" property, meaning that the removal of any one of its four constituent clusters (two alpha particles and two protons) results in an unbound state.

Events involving the ^{10}C nucleus have been observed for the first time using the nuclear track emulsion method [2]. The formation of some stars with $\Sigma Z_{fr} > 5$ could be associated with the admixture of ^{10}C nuclei in the beam used. These nuclei could be produced via charge-exchange $^{10}B \rightarrow {}^{10}C$ in the target intended for generating ^{8}B and captured in the secondary beam due to the small difference in magnetic rigidity with ^{8}B (about 4 %) and the spread of nuclei in their momentum. Identification of the charges of the primary traces made it possible to select events with $Z_{pr} = 6$. The charge topology of these events is presented. "White" stars with $\Sigma Z_{fr} = 6$ do not contain fragments with charge $Z > 2$. Their topology corresponds to the dissociation of the ^{10}C nucleus, which has a base in the form of ^{8}Be, through the most probable channel $^{10}C \rightarrow {}^{8}Be + 2p$. In this experiment an indication has been obtained that the dissociation channel $^{10}C \rightarrow$ 2He + 2H is dominant in events that do not involve the production of target-nucleus fragments or charged mesons ("white" stars). For 7 events, it was possible to measure all emission angles of relativistic fragments, including 2 "white" stars. An example of the interaction of projectile nuclei in a nuclear track emulsion is shown in Fig. 1. The figure displays a "white" star $^{10}C \rightarrow 2He + 2H$ with the values $Q_{2He} = 6$ MeV, $Q_{2HeH} = 10$ MeV, $Q_{2He2H} = 17$ MeV and $P_T(^{10}C^*) = 53$ MeV/c.

The production of ^{10}C nuclei is possible through charge-exchange reactions involving of accelerated ^{12}C nuclei and in their fragmentation [3]. Nuclear emulsions were exposed to relativistic ^{12}C nuclei at the JINR Nuclotron [4]. This publication presents experimental results obtained for relativistic ^{10}C nucleus at a beam energy of 1.2 A GeV. Events were sought by microscope scanning over the emulsion plates. In the used BR-2 photoemulsion, single- and double-charged relativistic particles are visually identified. Nuclei with charges $Z \geq 3$ are determined by the method of calculating the δ - electrons (N_δ) per unit length of the investigated track. Calibration was achieved by assessing the δ-electron density along the tracks of beam particles that formed "white" star events with fragment combinations of 2He + 2H, 2He and He + 2H.

Among "white" stars (N_{ws}) with a total fragment charge $\sum Z_{fr} = 6$, the dominant dissociation channel corresponded to 95 occurrences of the 2He+2H configuration, which aligns with theoretical predictions for ^{10}C. In contrast, the He + 4H channel was strongly suppressed (14 events), due to the high energy barrier required for α-cluster separation in ^{10}C. In our experiment, the coordinate method of angular measurements was used. Irradiation details and a special analysis of interactions in the BR-2 emulsion are presented in refs.

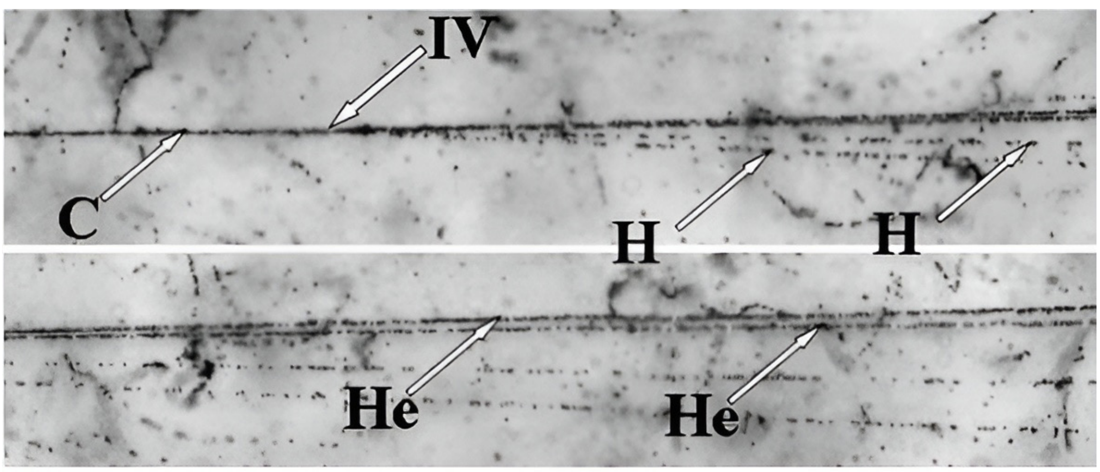

Fig. 1. Fragmentation of a ^{10}C nucleus with an energy of 1.2 A GeV in a peripheral interaction on an emulsion nucleus, detected in the composition of the used beam. The top photograph shows the interaction vertex (indicated as IV) and a jet of fragments in a narrow angular cone. When shifting in the direction of the jet of fragments, 2 He fragments and 2 H fragments can be distinguished.

[3, 4]. A detailed account of all experimental procedures is beyond the scope of this report.

RESULTS AND DISCUSSION

The experimental data are compared with the distribution of the emission angle θ for projectile fragments with charge $Z_{fr} = 1$ (Fig. 2), obtained from Monte Carlo modelling of induced interactions. It is assumed that the relativistic fragments ^{9}B and p are produced through the decay of the excited nucleus $^{10}C^*$ [5]. The mean emission angle for fragments with charge $Z_{fr} = 1$ is measured to be $(16 \pm 5) \times 10^{-3}$ rad, with an RMS value of $(11 \pm 4) \times 10^{-3}$ rad. The obtained experimental values for the average emission angle θ clearly reflect the difference in fragment masses. In the Monte Carlo - simulated events, the mean emission angle is 19×10^{-3} rad, which is in good agreement with the experimental results.

By measuring the emission angle θ, the transverse momenta P_T of relativistic fragments with mass number A_{fr} can be estimated using the approximate relation $P_T \approx A_{fr}P_0\sin\theta$, where A_{fr} is the mass number of the fragment, θ is the emission angle and $P_0 = 2.0$ A GeV s^{-1} is the momentum per nucleon of the ^{10}C nucleus. The P_T distributions for protons produced in peripheral interactions such as $^{10}C \rightarrow 2He + 2H$ and $^{10}C \rightarrow {}^{9}B + p$ are essentially similar, suggesting that proton fragmentation occur independently of the formation of the ^{9}B nucleus.

Fig. 3 shows the $Q_{2\alpha p}$ distribution for events in the 2He + 2H channel. This excitation energy is defined as the difference between the invariant mass of the three fragments 2α+p and the sum of the proton mass and the doubled the α-particle mass. The results are compared with the experimental data obtained from charge-exchange reaction $^{10}B \rightarrow {}^{10}C$ (dashed-line) [2]. About 30 % of the detected 2α + p triples show $Q_{2\alpha p}$ values below 500 keV. The average excitation energy for these triples is roughly 250 keV (± 15 keV), with a root-mean-square (RMS) deviation of 74 keV. These results are consistent with the known ground-state decay of ^{9}B into p + ^{8}Be (0^{+}), which has a measured energy of 185 keV and a resonance width of 0.54 ± 0.21 keV [6]. Within the region defined by $Q_{2\alpha} < 1$ MeV and $Q_{2\alpha p} < 1$ MeV, a pronounced correlation between ^{8}Be and ^{9}B formation is observed, suggesting that these triples originate from ^{9}B decay. Interestingly, one 2α + 2p event was detected in which both possible triples simultaneously correspond to ^{9}B decay.

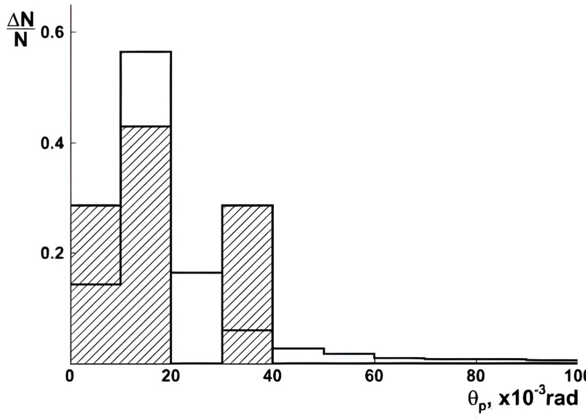

Fig. 2. Angle distribution for fragments with Z = 1 from the reaction $^{10}C \rightarrow {}^{9}B + p$ (Monte Carlo modelling). The shaded area of the histogram corresponds to the contribution from experimental data.

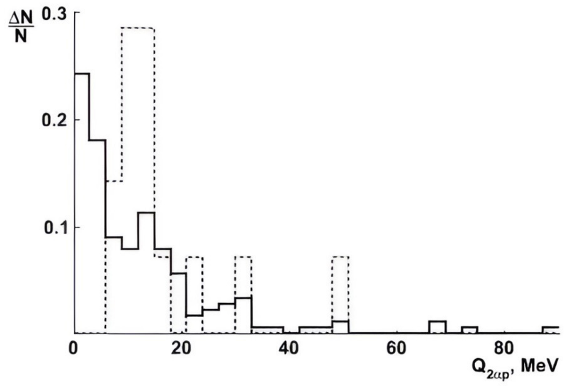

Fig. 3. $Q_{2\alpha p}$ distribution of the 2α + p system. The solid-line represents experiment data from charge-exchange and fragmentation reactions involving accelerated $^{12}C \rightarrow {}^{10}C$ nuclei, while the dashed-line corresponds to data from charge-exchange reaction $^{10}B \rightarrow {}^{10}C$.

The distribution of the total transverse momentum $P_T(^{10}C^*)$ for ^{9}B + p pairs is displayed in Fig. 4. The solid-line histogram shows Monte Carlo simulation results for the reaction $^{10}C \rightarrow {}^{9}B + p$, while the dashed-line histogram corresponds to experimental data from the reaction $^{10}C \rightarrow 2He + 2H$. The summary of the mean values of excitation energies and transverse momenta of $\langle P_T(^{10}C^*)\rangle$, generally confirms the similarity the distributions. For the $^{10}C \rightarrow 2He + 2p$ reaction, the average excitation energies are: $\langle Q_{2\alpha}\rangle = 7.3$ MeV, $\langle Q_{2\alpha p}\rangle = 12.2$ MeV, $\langle Q_{2\alpha 2p}\rangle = 19.9$ MeV, and the mean total transverse momentum is $\langle P_T(^{10}C^*)\rangle = 241.4$ MeV/c. The comparison demonstrates that applying the condition $P_T(^{10}C^*) < 100$ MeV/c effectively separates

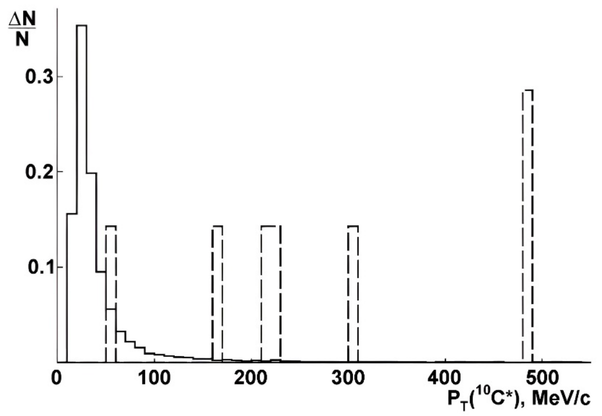

Fig. 4. Total transverse momentum distribution P_T ($^{10}C^*$) for ^9B + p pairs resulting from the reaction $^{10}C \rightarrow {}^9B$ + p (solid-line: Monte Carlo) and from the reaction $^{10}C \rightarrow$ 2He + 2H (dashed-line: experiment).

the kinematical region characteristic of ^9B + p events, which do not involve the production of target-nucleus fragments or mesons - so-called “white” stars.

CONCLUSIONS

The nuclear emulsion technique offers a unique approach to studying the cluster structure of light nuclei, especially when working with limited statistics. Despite this limitation, it allows direct observation of all charged fragments - an advantage over many other methods.

Monte Carlo modelling of the $^{10}C \rightarrow {}^9B$ + p reaction is used to interpret the data. The dissociation channel $^{10}C \rightarrow$ 2He + 2H is dominates in events without target-nuclei fragments or mesons. Angular correlations in both experimental and simulated peripheral events confirmed the selection of electromagnetic dissociation events based on the total transverse momentum, with the results in good agreement with the data.

These findings support the design of future experiments aimed at studying other light, proton-rich nuclei, using nuclear emulsions combined with modern detection systems for higher precision and broader event classification. Understanding the cluster structure and reaction mechanisms of light nuclei is also crucial for astrophysics, where such nuclei play a key role in stellar nucleosynthesis and energy generation processes in stars.

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Authors’ contributions:

R.S.: conceptualization, methodology, formal analysis, investigation, writing - original draft preparation, writing - review and editing, visualization.

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