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Peripheral Fragmentation of Relativistic Nuclei ^{11}B in Nuclear Track Emulsion

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Abstract—Data obtained from a nuclear track photoemulsion exposed to a beam of ^{11}B nuclei with a momentum of 2.75 GeV/c per nucleon are reported. Peripheral interactions where the total charge of particles emitted within the forward cone of relativistic fragmentation is equal to the charge of the projectile nucleus are analyzed to study the clustering of the ^{11}T nucleus. It is found that the three-body breakup of $2 + 2 + 1$ charge configuration is a leading process. Tritons are revealed to play a crucial role in the most peripheral interactions of this type. Events interpreted as charge exchange of the ^{11}B nucleus to excited states of the ^{11}C* nucleus above the nucleon-coupling threshold were observed for the first time. Prospects for studying the ^{11}C nucleus are discussed.

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INTRODUCTION

Studying peripheral interactions of relativistic nuclei ^{7}Li and ^{11}B in nuclear emulsion, one can gain grounds for the inclusion of tritons as clusters in multiple fragmentation of nuclei beginning with the lightest ones [1, 2]. Earlier, it was found that the branching fraction of the channel $^{7}\text{Li} \to \alpha + t$ in the most peripheral events of the dissociation of ^{7}Li nuclei in nuclear emulsion without the formation of target fragments and charged mesons (so-called white stars) is as large as 50% [3]. Thus, the role of the triton as a nucleon cluster with the lowest separation threshold (2.47 MeV) is revealed. The present experiment on the fragmentation of the ^{11}B nucleus, which is heavier, is a logical continuation of the studies of the ^{7}Li nucleus. It is aimed at revealing the relative role of channels characterized by low fragment-separation thresholds—namely, $^{7}\text{Li} + \alpha$ (8.7 MeV), $t + 2\alpha$ (11.2 MeV), and $^{10}\text{Be} + p$ (11.2 MeV).

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EXPOSURE OF EMULSION TO A BEAM OF ^{11}B NUCLEI

A stack of layers of BR-2 nuclear track photoemulsion was exposed to a beam of ^{11}B nuclei

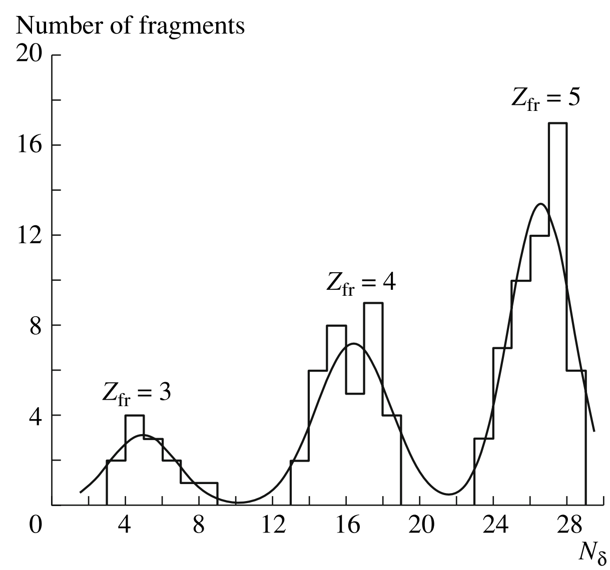

Fig. 1. Distribution of $Z_{fr} = 3$, 4, and 5 relativistic fragments in interactions of ^{11}B nuclei in terms of the average number of δ electrons per 100 μm of the track length. The curve is an approximation by the sum of three Gaussian functions.

with a momentum of 2.75 GeV/c per nucleon from the nuclotron of the Joint Institute of Nuclear Research (JINR, Dubna). The emulsion layers were 10×20 cm^2 in size and about 600 μm thick. During the exposure, the beam was running parallel to the emulsion plane along the longer side of the layers.

The method of viewing along primary tracks was used to seek the events of interest. There were 542 ^{11}B interaction events detected over the total viewed track length of 7141.5 cm, this yielding the mean path of $\lambda = 13.2 \pm 0.6$ cm. This value agrees with the calculations based on the geometric model.

The charges of relativistic fragments produced in interactions of ^{11}B nuclei were determined by a method that involves calculating the δ-electron density. The results of applying this method to determining relativistic-fragment charges $Z_{\rm fr} = 3$, 4, and 5 are presented in Fig. 1.

Figure 2 shows the distributions of measured emission angles of fragments of ^{11}B nuclei with different charges $Z_{\rm fr}$. The angles for $Z_{\rm fr} > 2$ fragments fall within the range $\theta < 3°$; for doubly charged fragments ($Z_{\rm fr} = 2$), they are smaller than 5°. For singly charged particles ($Z_{\rm fr} = 1$), the angles were measured over the range $\theta = 15°$. The selection criterion for the $Z_{\rm fr} = 1$ relativistic fragments subjected to analysis was taken to be $\theta \leqslant 6°$. This corresponds to the traditional definition of the fragmentation cone: the angular distribution for $Z_{\rm fr} = 1$ changes its shape approximately at $\theta = 6°$. This shape is governed by the contribution from the isotopes ^{1,2,3}H originating from the fragmentation of ^{11}B nuclei and by the contribution from protons participating in the interaction and from product mesons, whose angular distributions are very different.

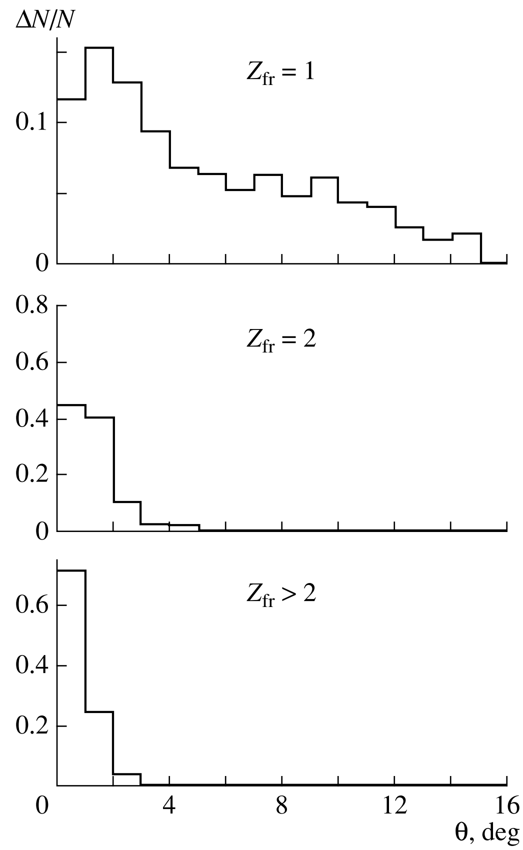

Fig. 2. Emission-angle distributions of relativistic fragments with charge $Z_{\rm fr} = 1$, $Z_{\rm fr} = 2$, and $Z_{\rm fr} > 2$ in interactions of ^{11}B nuclei. The distributions are normalized to the number of fragments with charge $Z_{\rm fr}$.

CLUSTERING IN THE DISSOCIATION OF ^{11}B NUCLEI

The clustering of the ^{11}B nucleus was studied in peripheral interactions, where the total charge of particles emitted within the forward fragmentation cone was equal to the charge of the projectile nucleus—that is, $\sum Z_{\rm fr} = 5$. In those events, the production of particles having emission angles in the region $\theta \geqslant 15°$ and the production of target fragments are admissible. Table 1 presents their statistical sample, including white stars, in different charge channels. It can be concluded that three-body breakup of charge configuration $2 + 2 + 1$ is a leading process despite its higher threshold in relation to the Li + He channel. A similar pattern has already been established for the ^{10}B nucleus [4]. In just the same way in the cases of ^{12}C [5], ^{6}Li [6], and ^{7}Li [3] nuclei, α-particle clustering plays an important role in the peripheral fragmentation of these boron isotopes.

ISOTOPIC COMPOSITION OF ^{11}B FRAGMENTS

In order to study the $\Sigma Z_{\rm fr} = 2 + 2 + 1$ fragmentation channel, which is dominant, the momenta $p\beta c$

Table 1. Distribution of the number of events of ^{11}B dissociation in terms of fragment charge states $\sum Z_{\rm fr} = 5$ (N_Z is the number of fragments with charge $Z_{\rm fr}$ in an event; the statistics of white stars are given in parentheses)

N_5	N_4	N_3	N_2	N_1	$\sum$
1	–	–	–	–	2
–	1	–	–	1	11
–	–	1	1	–	3
–	–	1	–	2	5
–	–	–	1	3	17 (1)
–	–	–	2	1	43 (6)
–	–	–	–	5	0

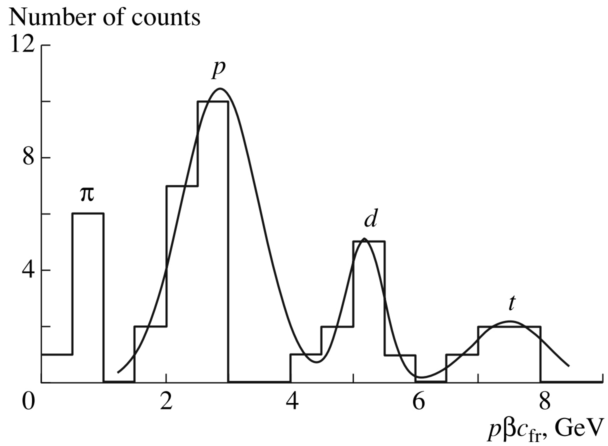

Fig. 3. Distribution of relativistic singly charged fragments of the ^{11}B nucleus in terms of measured values of $p\beta c$. The solid curve is the least squares approximation by Gaussian functions.

of singly charged fragments were measured by the method of multiple Coulomb scattering. These measurements make it possible to divide singly charged fragments into protons, deuterons, and tritons, because spectator fragments of the projectile nucleus almost completely retain the initial momentum per nucleon. This method permitted a mass separation of singly charged fragments (Fig. 3).

The measured momenta for singly charged fragments of ^{11}B are satisfactorily approximated by the sum of three Gaussians functions peaked at 2.7, 5.2, and 7.5 GeV. The positions of the peaks correspond to the values expected for spectator protons, deuterons, and tritons. The region of $p\beta c$ values around 1 GeV corresponds to product pions. The ratio of the numbers of protons, deuterons, and tritons produced in peripheral interactions of the ^{11}B nucleus is 19 : 9 : 5; the corresponding ratio for white stars is 1 : 1 : 1. Even in the case of a small statistical sample, we can see an increase in the fraction of deuterons and tritons in white stars in relation to peripheral interactions. A large fraction of tritons in ^{11}B white stars suggests that the triton exists in the ^{11}B nucleus as a loosely bound cluster, which is readily destroyed in the interaction. These observations indicate that it is necessary to continue the accumulation of statistics for the $\Sigma Z_{\rm fr} = 2+2+1$ channel by the method of fast viewing emulsion-layer areas.

Table 2. Distribution of the number of ^{11}B charge-exchange events in terms of the fragment charge states $\sum Z_{\rm fr} = 6$ (the notation is identical to that in Table 1)

N_5	N_4	N_3	N_2	N_1	$\sum$
1	–	–	–	1	1
–	1	–	1	–	10 (8)
–	1	–	–	2	7
–	–	1	–	3	2
–	–	–	2	2	3

OBSERVATION OF ^{11}B $\to ^{11}$C* CHARGE-EXCHANGE EVENTS

Events where the charge of the primary track was determined to be $Z_{\rm pr} = 5$ and where the total charge within the fragmentation cone was $\Sigma Z_{\rm fr} = 6$ were observed in this experiment. They can be interpreted as those in which the ^{11}B nucleus goes over to excited states of the ^{11}C* nucleus above the nucleon-binding threshold via an inelastic charge-exchange process. The statistical sample of these events is presented in Table 2.

Ten ^{11}B $\to ^{11}$C* events followed by breakup into two fragments of charges $Z_{\rm fr} = 4$ and 2 were observed. These events are indicative of the charge exchange of the core in the form of the ^{7}Li cluster to ^{7}Be. To avoid a mistake, the track charges in these events were determined several times. The fraction of these charge-exchange events amounts to about 1.5% of all events found in primarily viewing the interactions.

Table 2 demonstrates that the most peripheral charge-exchange channel ^{11}B $\to ^{11}$C* is preferable: these are eight ^{11}B $\to$ Be + He white stars. They are identified as ^{7}Be + ^{4}He. The corresponding mean path is $\lambda_{\rm CE} = 8.9 \pm 3.2$ m. A microphotograph of one of these events is shown in Fig. 4. No events of ^{11}B charge exchange by ^{11}C dissociation via other channels were observed among the white stars. Even these limited statistics reveal the distinction between ^{11}C breakup, on one hand, and ^{10}B and ^{11}B breakup, on the other hand: for the ^{10}B and ^{11}B nuclei, the three-body decay channel is a leading process, while, for the ^{11}C* nucleus, two-body decays dominate, our statistics revealing no three-body processes. The difference may be due to a higher Coulomb barrier for the ^{11}C nucleus. This circumstance may point to a remarkable sensitivity of the relativistic dissociation mechanism to structural features of nuclei.

Figure 5 shows the excitation-energy (Q) distribution for pairs of relativistic ^{4}He and ^{7}Be fragments produced in the ^{11}B $\to$ ^{7}Be + ^{4}He white stars with respect to the ground state of the ^{11}C nucleus. The

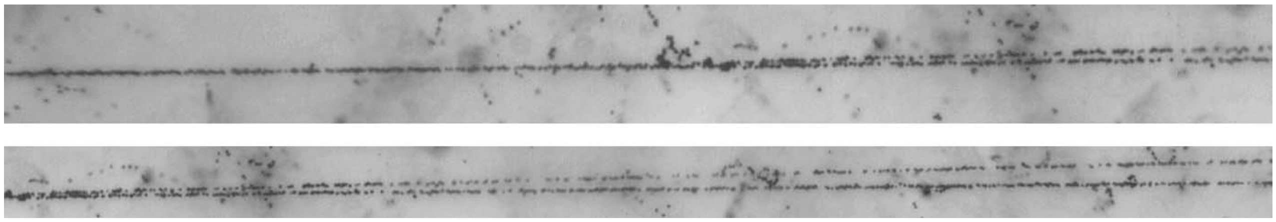

Fig. 4. Microphotograph of the charge-exchange fragmentation process $^{11}B \to {}^4He + {}^7Be$. In the upper picture, one can see the interaction vertex and formation of two relativistic fragments within a narrow angular cone. With a shift along the fragment-emission direction (lower picture), one can distinguish a He fragment (upper track) and a Be fragment.

quantity Q is defined in terms of the invariant mass of the system, M^* and the mass of the ^{11}C nucleus as

$$Q = M^* - M, \quad M^2 = (\sum P_j)^2 = \sum (P_i, P_k),$$

where P_j are the fragment 4-momenta determined under the assumption that the momentum per nucleon of the primary nucleus is conserved. The values of Q are in the region of low-lying excited states of the ^{11}C nucleus. The average transverse momenta of ^7Be and ^4He fragments in the laboratory frame are $\langle P_T(^7\mathrm{Be})\rangle = 185 \pm 27$ MeV/c and $\langle P_T(^4\mathrm{He})\rangle = 190 \pm 33$ MeV/c; in their c.m. frame, they are $\langle P_T^*(^7\mathrm{Be})\rangle = \langle P_T^*(^4\mathrm{He})\rangle = 145 \pm 21$ MeV/c. The average total transverse momentum of $^7Be + {}^4He$ pairs is $\langle P_T(^{11}\mathrm{C}^*)\rangle = 250 \pm 32$ MeV/c. These kinematical features are expected for diffractive-dissociation processes.

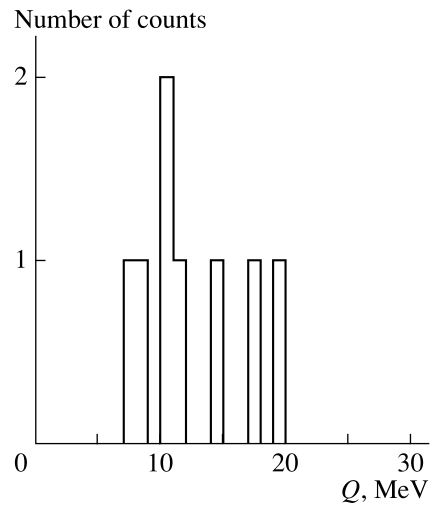

Fig. 5. Excitation-energy (Q) distribution for pairs of relativistic ^7Be and ^4He fragments formed in $^{11}B \to {}^7Be + {}^4He$ white stars with respect to the ground state of the ^{11}C nucleus.

The ^{11}C nucleus is a mirror nucleus for ^{11}B and has a similar structure of excitations. This study sets the stage for exploring the relativistic dissociation of the ^{11}C nucleus via channels characterized by low separation thresholds for nucleon clusters: $^7Be + \alpha$ (7.6 MeV), $^{10}B + p$ (8.7 MeV), and $^3He + 2\alpha$ (9.2 MeV). In this case, the ^3He nucleus can be a cluster like a triton in the ^{11}B nucleus. In events of the most peripheral dissociation, it will be possible to compare the effect of the Coulomb barrier on the picture of the dissociation of the ^{11}C nucleus with that for the ^{11}B nucleus. Earlier, the ^3He nucleus was found to play a leading role in the relativistic dissociation of the ^7Be nucleus [7], which is a mirror nucleus for ^7Li. In this connection, a transition to studying the ^{11}C nucleus by the nuclear-emulsion method seems a step as consistent as that of going over from the ^7Li nucleus to the ^{11}B nucleus.

It is of interest to seek manifestations of isotopic-invariance violation in the formation of white stars by relativistic nuclei ^{11}B and ^{11}C. This analysis can be performed by comparing the distributions in the population of similar channels and in their kinematical features. Nuclear diffractive processes must lead to the similarity of distributions, while electromagnetic interactions may lead to their difference in important details.

The reported observations are worth being studied more thoroughly with appreciably vaster statistics of events of ^{11}B and ^{11}C dissociation. With the latter nucleus, it is necessary to expose emulsion to a secondary beam, which is best formed by selecting products of the charge-exchange process $^{11}B \to {}^{11}C$.

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