

# Peripheral fragmentation of relativistic $^{11}\text{B}$ nuclei in photoemulsion

D. A. Artemenkov, V. Bradnova, A. D. Kovalenko, A. I. Malakhov,  
P. A. Rukoyatkin, S. Vokál, A. Vokálová, and P. I. Zarubin\*  
*Joint Insitute for Nuclear Research, Dubna, Russia*

M. Karabová and J. Vrláková  
*University of P. J.Šafárik University, Košice, Slovak Republic*

G. I. Orlova  
*Lebedev Institute of Physics, Russian Academy of Sciences, Moscow, Russia*

(Dated: October 18, 2006)

## Abstract

Experimental results on peripheral fragmentation of relativistic  $^{11}\text{B}$  nuclei are presented. In the experiment the emulsions exposed to  $^{11}\text{B}$  beam with momentum 2.75 A GeV/c at the JINR Nuclotron are used. The relative probability of various fragmentation channels for nucleus breakups (class A) and more violent peripheral interactions (class B) have been determined. For classes under investigations the sum of the fragment charges in narrow forward cone is equal to the projectile charge, but in the events of class A there are no secondary particles and in the events of class B there are. In both classes the main channels is  $^{11}\text{B} \rightarrow 2\text{He} + \text{X}$ : 62% and 50%, corresponding.

The main channel  $^{11}\text{B} \rightarrow 2 \cdot (Z_{fr}=2) + (Z_{fr}=1)$  was investigated in details. Momentum measurements of single-charged fragments have been done to determine number of p, d and t in the channel. This way it was found that the ratio  $N_p : N_d : N_t$  is about 1:1:1 for  $^{11}\text{B}$  nuclei dissociation and about 15:5:1 for peripheral interactions of  $^{11}\text{B}$  nuclei.

PACS numbers: 21.45.+v, 23.60+e, 25.10.+s

---

\*Electronic address: zarubin@lhe.jinr.ru; URL: <http://becquerel.jinr.ru>

## I. INTRODUCTION

The study of peripheral interactions of light odd-even nuclei  ${}^7\text{Li}$  and  ${}^{11}\text{B}$  in nuclear track emulsion can provide a ground for including tritons as clusters into the general pattern of multiple fragmentation of heavier nuclei [1]. It is established that in the “white” stars produced by relativistic  ${}^7\text{Li}$  nuclei in most peripheral collisions, the  ${}^7\text{Li}^* \rightarrow \alpha + t$  channel constitutes as high as 50% [2, 3]. In this way a dominant role a triton as a cluster with lowest separation energy (2.47 MeV) has been revealed for the case of relativistic  ${}^7\text{Li}$  nuclei. The present  ${}^{11}\text{B}$  experiment is a logical continuation of the  ${}^7\text{Li}$  study aiming to establish the probabilities of the low threshold channels, namely,  ${}^7\text{Li} + \alpha$  (8.67 MeV),  $t + 2\alpha$  (11.22 MeV), and  ${}^{10}\text{Be} + p$  (11.23 MeV). In particular, it will allow one to verify whether exists a correlation between a channel threshold value, fragment number and composition, and the corresponding propability.

The  ${}^{11}\text{B}$  nucleus is a daughter one in the  $\beta$  decay of its mirror nucleus  ${}^{11}\text{C}$  having a very similar level structure. As application, the present study will provide a comparison ground to explore in future the  ${}^3\text{He}$  role as a cluster in low threshold breakups of a  ${}^{11}\text{C}$  nucleus:  ${}^7\text{Be} + \alpha$  (7.54 MeV),  ${}^3\text{He} + 2\alpha$  (9.22 MeV), and  ${}^{10}\text{Be} + p$  (8.69 MeV) and to evaluate a Coulomb effects in a few-body fragmentation.

## II. EXPERIMENT

A stack of BR-2 photoemulsion layers, the dimensions and the thickness of which being  $10 \times 20 \text{ cm}^2$  and  $600 \mu\text{m}$ , repectively, was exposed to a beam of  ${}^{11}\text{B}$  nuclei accelerated to a momentum  $2.75A \text{ GeV}/c$  at the JINR Nuclotron. An example of the central interaction of relativistic  ${}^{11}\text{B}$  in emulsion is given in Fig. 1. The  ${}^{11}\text{B}$  beam was directed parallel to the long side of the emulsion plane. Interactions were sought by viewing along the primary nucleus track. Over the total viewed -track length of 7141.5 cm we found 542 interactions of  ${}^{11}\text{B}$  with emulsion nuclei used in this analysis. In such a way, the mean free path was found to be  $\lambda = (13.2 \pm 0.6) \text{ cm}$ . This value agrees well with the calculations by the geometric model.

The relativistic fragment charge was determined by the method of counting the number of  $\delta$  electrons on the fragment track. The results of the determination of the charges  $Z_{fr}=3-5$  by this method are given in Fig. 2, which illustrates its high reliability.

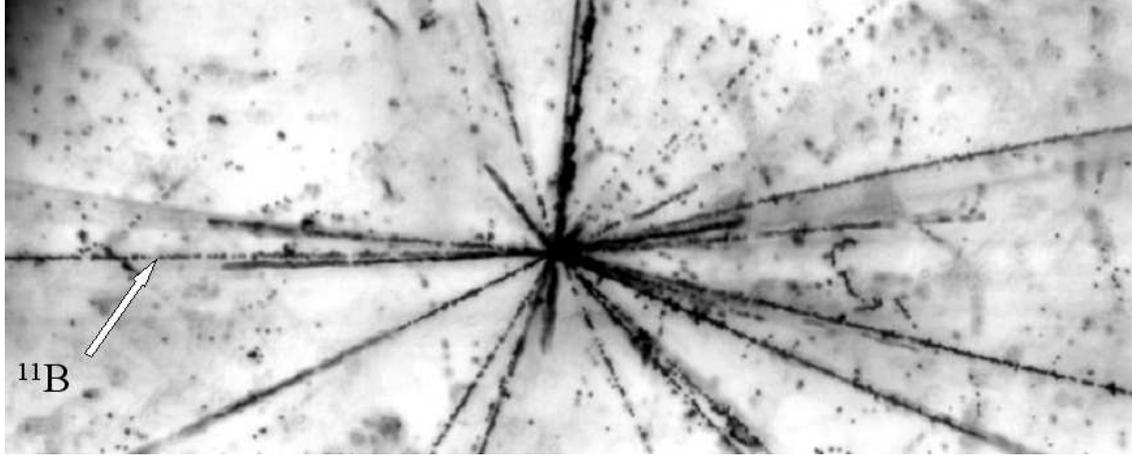


FIG. 1: An event of central interaction of relativistic  $^{11}\text{B}$  nucleus with emulsion nucleus.

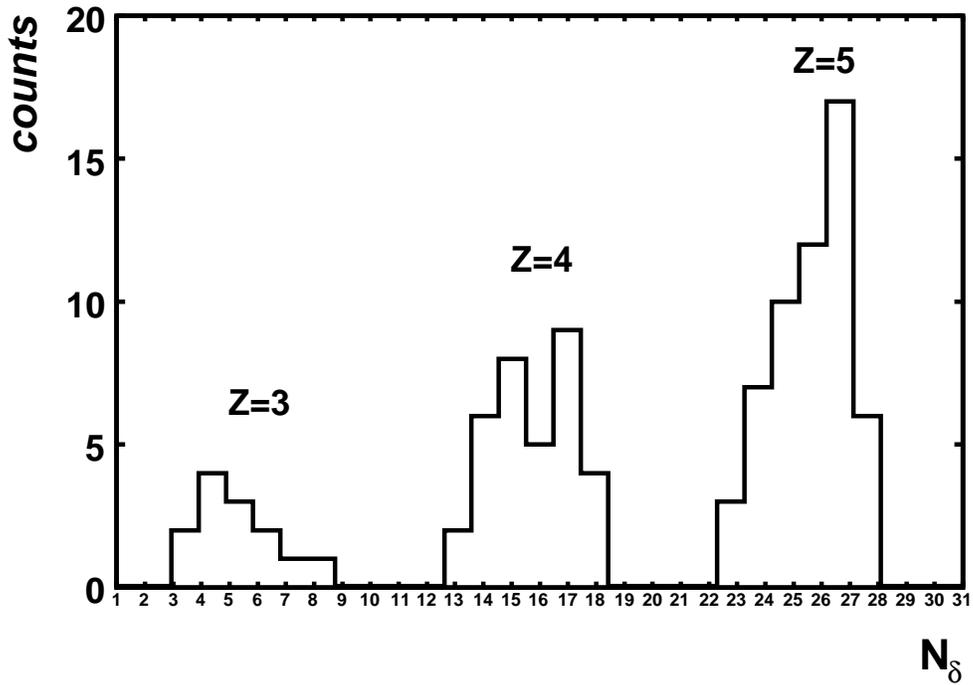


FIG. 2: Distribution of number of  $\delta$  electrons per 100  $\mu\text{m}$  length on the tracks of relativistic fragments with charges  $Z_{fr}=3, 4,$  and  $5$ .

The angular distributions of the  $^{11}\text{B}$  fragments are presented in Fig. 3 separately for singly, doubly, and multiply,  $Z_{fr} > 2$  charged fragments. The emission angles for  $Z_{fr} > 2$  are restricted in interval  $\theta < 3^\circ$ , and the ones for doubly charged fragments to an interval  $< 5^\circ$ . The angles for singly charged particles were measured in an interval  $< 15^\circ$ . Fig. 3

(above) shows that the angular distribution changes its shape at about  $\theta=6^\circ$ . This shape of the angular distribution may be due to the fact that the singly charged particles are a mixture of the particles of the two kinds: relativistic hydrogen isotopes and produced mesons the angular distributions of which are displaced relatively to one another. As momentum measurements show the distribution for singly charged fragments occupy a region  $\theta < 6-8^\circ$ . Basing on the momentum measurements, the angular distribution shape and the estimation of the projectile fragmentation angle by the equation

$$\sin\theta_{fr} = 0.2/p_0 = 0.073 \rightarrow \theta_{fr} = 4.16^\circ$$

a limiting angle for singly charged fragments was chosen to be  $\theta=6^\circ$ .

### III. $^{11}\text{B}$ CLUSTERING

In order to study  $^{11}\text{B}$  cluster degrees of freedom use was made of the events in which the total charge of particles emitted within the fragmenting cone is equal to the charge of the projectile nucleus  $Q=\Sigma Z_{fr}$ . Such events were divided into two classes A and B. Class A implies the breakup of a projectile not accompanied by the production of new particles,  $n_s=0$ . In their turn, the A class events can be subdivided into two groups: interactions without breakup of a target,  $n_h=0$  ( $n_h=n_b+n_g$ ) or “white” stars, and interactions accompanied by the breakup of a target,  $n_b < 8$ ,  $n_g=0$  in which the presence of several low-energy fragments is allowed. These group which possess close characteristics are united into common class in order to increase statistics. Events of the class A are notable for a low energy transferred to the projectile which results mostly in violations of intrinsic intercluster bonds. Therefore they are most interesting for the study of nuclear clustering.

Class B implies peripheral but violent interactions of nuclei. In the events of this class, there can exist newly produced particles with emission angles  $\theta > 15^\circ$ , as well as any quantity of the target fragments,  $n_h > 0$ . The fragmentation channels for both classes are given in Table I.

We can note some features in the data of Table I for events of classes A and B.

1. In both classes, the major fragmentation channel is  $\Sigma Z_{fr}=2+2+1$ : 62 and 52%, respectively. For sake of comparison, this channel for “white” stars produced in fragmentation of  $^{10}\text{B}$  nuclei amounts to 65%.

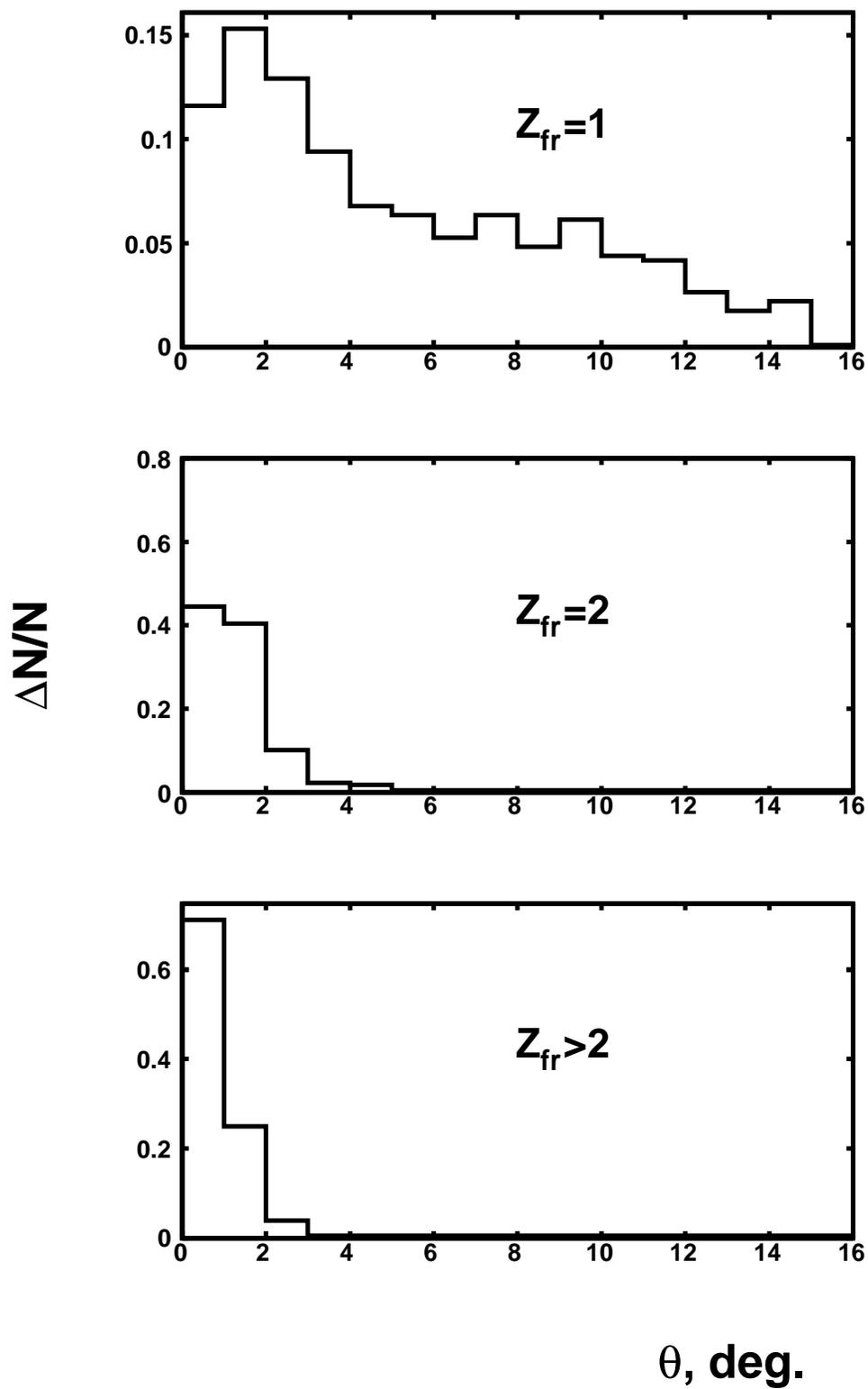


FIG. 3: Normalized angular distributions of fragments with charges  $Z_{fr}=1$  (above),  $Z_{fr}=2$  (in the middle) and  $Z_{fr} > 2$  (below).

TABLE I: The charge topology distribution of the number of interactions of the classes A and B,  $N_A$  and  $N_B$ , which were detected in an emulsion exposed to a  $^{11}\text{B}$  nucleus beam. Here  $N_Z$  is the number of fragments with charge  $Z$ . Numbers of “white” stars are shown in brackets.

$N_5$	$N_4$	$N_3$	$N_2$	$N_1$	$N_A$	A, %	$N_B$	B, %
1	-	-	-	-	1	4.6	1	1.7
-	1	-	-	1	2	9.4	9	15
-	-	1	1	-	0	0	3	5
-	-	1	-	2	0	0	5	8.3
-	-	-	1	3	5 (1)	24	12	20
-	-	-	2	1	13 (6)	62	30	52
-	-	-	-	5	0	0	0	0

2. Only 14% of the events of the projectile breakup have fragments with charge  $Z_{fr} > 2$  while in peripheral interactions such events amount to 30%.
3. In the projectile breakup events (A) there was observed no Li fragments, while in peripheral interactions (B) such events constitute 13%.

The consimilar topology of “white” stars was investigated for  $^{10}\text{B}$  nuclei at the energy of 1.0 GeV per nucleon [2, 4]. The fraction of the  $^{10}\text{B}^* \rightarrow \text{d} + \alpha + \alpha$  decays is 40% of the events with a charge topology 2+2+1. The contribution of the  $^{10}\text{B}^* \rightarrow \text{d} + {}^8\text{Be} + \text{d} \rightarrow \alpha + \alpha + \text{d}$  channel is estimated to be  $18 \pm 3\%$ . The probability of observing a 4+1 topology in the  $^{10}\text{B}^* \rightarrow \text{p} + {}^9\text{Be}$  decay is found small (3%). Even being limited with current statistics one may conclude that the 3-body decays with a charge configuration 2+2+1 (Fig. 4) play a leading role in peripheral breakups of  $^{11}\text{B}$  as well as  $^{10}\text{B}$  nuclei in spite of higher threshold values with the respect to the Li+He mode ones. It may be noticed, that the both breakup patterns is indicative of an analogy with the 3-body dissociation  $^{12}\text{C}^* \rightarrow 3\alpha$  with one of  $\alpha$  particles substituted by a deuteron or triton [5].

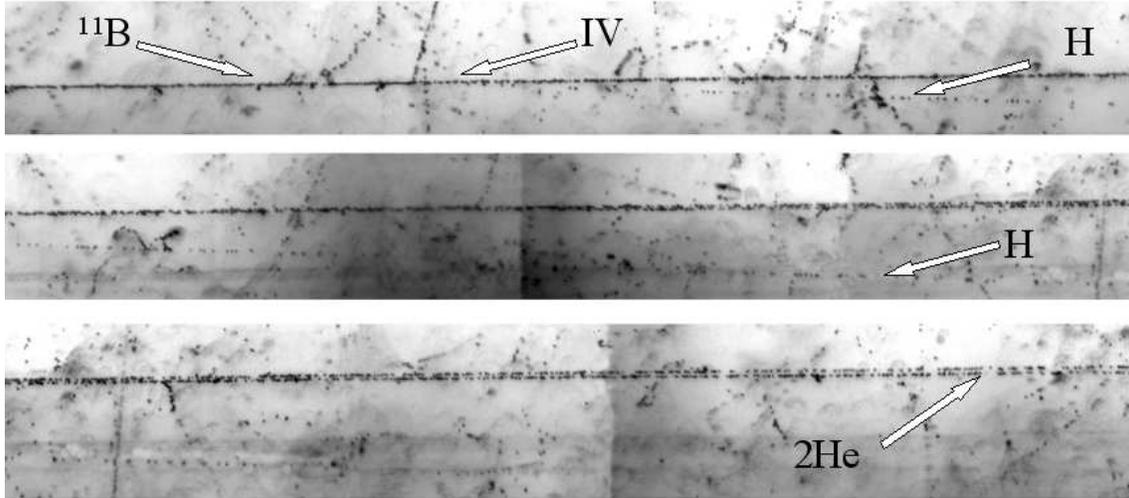


FIG. 4: Example of peripheral interaction of a  $2.75 \text{ A GeV}/c$   $^{11}\text{B}$  nucleus in a nuclear track emulsion. The interaction vertex (indicated as **IV**), nuclear fragment tracks (**H** and **He**) in a narrow angular cone, and fragment of target nucleus are seen on the upper microphotograph. Following the direction of the fragment jet, it is possible to distinguish 1 singly and 2 doubly charged fragments on the middle and bottom microphotograph.

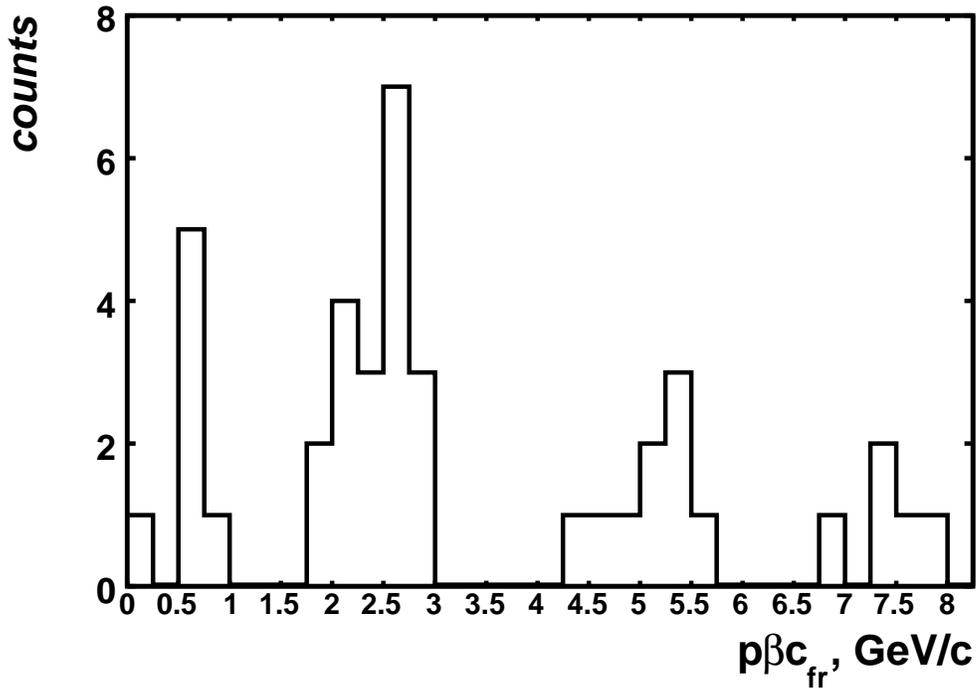


FIG. 5: Momentum distribution for singly charged fragments.

TABLE II: Isotopic composition of singly charged fragments for events with  $\Sigma Z_{fr}=2+2+1$  of the classes A and B,  $N_A$  and  $N_B$ .

	p	d	t	$\pi$	$\Sigma$
$N_A$	4	4	4	0	13
A, %	33	33	33	0	
$N_B$	17	5	1	7	30
B, %	57	17	3	23	

#### IV. ISOTOPIC COMPOSITION OF SINGLY CHARGED FRAGMENTS

In order to study the basic  $^{11}\text{B}$  fragmentation channel,  $\Sigma Z_{fr}=2+2+1$  the singly charged fragment momenta were measured by the Coulomb multiple scattering method. The measurements enabled us to divide the singly charged fragments into protons, deuterons and tritons using the fact that the spectator fragments conserve the momentum per nucleon equal the primary one:  $A_{fr} = (p\beta c)_{fr}/p_0$ . The results of measurements are given in Fig. 5. As is seen, this method makes it possible to separate reliably the singly charged fragments by their mass.

Thus we had determined for this channel the ratio between protons, deuterons and tritons:  $N_p:N_d:N_t=4:4:4$  for  $^{11}\text{B}$  breakup events and  $N_p:N_d:N_t=17:5:1$  for the  $^{11}\text{B}$  peripheral interactions (Table II).

That is, it is possible to notice an essential decrease in the deuteron fraction and a practical disappearance of triton when passing on from breakups to interactions. A large part of fragment tritons in  $^{11}\text{B}$  breakups (about 1/3) testifies in favor of their existence as clusters weak internal bonds in  $^{11}\text{B}$  which are easily get destroyed in violent interaction processes. Besides, in 7 peripheral interactions (23%) the momentum of singly charged particles was less than 1 GeV/c, that is, they may be either newly produced particles, or scattered protons. Thus, it is confirmed that the breakups of nuclei are more effective for the study of their cluster structure as compared with the violent interactions of nuclei.

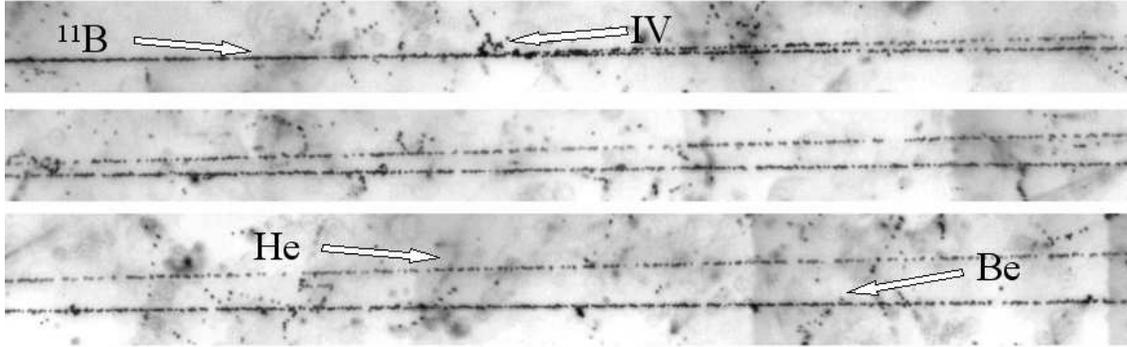


FIG. 6: Example of the charge exchange of  $^{11}\text{B} \rightarrow ^{11}\text{C}^*$  interaction in a nuclear track emulsion. The interaction vertex (indicated as **IV**), nuclear fragment tracks (**He** and **Be**) in a narrow angular cone are seen on the microphotographs.

## V. CHARGE EXCHANGE OF $^{11}\text{B}$ TO $^{11}\text{C}^*$

The events of the classes A and B in which the charge of the primary track was 5 and total charge in the fragmentation cone was  $\Sigma Z_{fr}=6$  were ascribed to the inelastic charge exchange events above a particle decay threshold of an excited  $^{11}\text{C}^*$  nucleus. The statistics of the events of an inelastic charge exchange of  $^{11}\text{B}$  to  $^{11}\text{C}^*$  is given in Table III. The particular feature of the present experiment was the observation of 8 events which can be considered as an inelastic charge exchange of  $^{11}\text{B}$  to  $^{11}\text{C}^*$  followed by a breakup into two fragments with charges  $Z_{fr}=4$  and  $Z_{fr}=2$  (Fig. 6). In order to avoid errors the charges in these events were measured several times. Of these, 6 events belong to class A, in 5 events there is none of the particles but the above mentioned fragments, and two events belong to the class B. The fraction of such events is about 1.5% of all events found in the initial scanning of the interactions, that is, the mean free path for the charge exchange of  $^{11}\text{B}$  to  $^{11}\text{C}^*$   $\lambda$  is equal to  $(0.89 \pm 0.32)$  m.

Table III clearly demonstrate appearance of low-lying cluster modes when collision inelasticity has a minimal observability. The decay of  $^{11}\text{C}$  nucleus into two particles with charges 4 and 2 can occur only in the  $^{11}\text{C} \rightarrow ^7\text{Be} + ^4\text{He}$ . In the events of the class A, there was found no inelastic charge exchange of  $^{11}\text{B}$  to  $^{11}\text{C}$  with a decay in other channels. However, in order to establish unambiguously the fact of the charge exchange it is required to carry out He momentum measurements. Nevertheless, in distinction to the considered above  $^{11}\text{B}$  case in Table I there is indication in on more important role of 2-body dissociations of excited

TABLE III: Fragmentation channels for events with charge exchange of  $^{11}\text{B}$  to  $^{11}\text{C}^*$  of the classes A and B,  $N_A$  and  $N_B$ . Here  $N_Z$  is the number of fragments with charge  $Z$ .

$N_5$	$N_4$	$N_3$	$N_2$	$N_1$	$N_A$	$N_B$
1	-	-	-	1	0	1
-	1	-	1	-	6	2
-	1	-	-	2	0	7
-	-	1	-	3	0	2
-	-	-	2	2	0	3

$^{11}\text{C}$  than 3-body ones - A class events with final state  $3\text{He}$  were not observed (Table III). This obvious difference may be originated due to a higher Coulomb barrier in a  $^{11}\text{C}$  nucleus. This feature has to be verified in special  $^{11}\text{C}$  study provided with emulsions exposed in a secondary beam of these nuclei produced in the charge exchange process  $^{11}\text{B} \rightarrow ^{11}\text{C}$ .

## VI. SUMMARY

This paper provides a framework for a longer time-demanding analysis. Already found  $^{11}\text{B}$  collisions will allow us to improve our statistics by factor 4-5 to strengthen the conclusions. Nevertheless, in spite of rather limited statistics analyzed to the present time one can derive the important features of peripheral fragmentation of  $^{11}\text{B}$  nuclei. Firstly, 3-cluster dissociations  $\text{H}+2\text{He}$  provide a leading contribution to the breakup cross-section. Secondly, there is an indication on a strong triton contribution comparable with  $^7\text{Li}^* \rightarrow \alpha + t$ . Thirdly, a  $^{11}\text{B}$  nucleus fragmentation is promising source to populate  $^{11}\text{C}^*$  excited states in charge exchange processes directly or via special formation of the  $^{11}\text{C}$  secondary beam in a charge exchange process.

## Acknowledgments

The work was supported by the Russian Foundation for Basic Research (grant 04-02-16593), VEGA N1/2007/05. Grant from the Agency for Science of the Ministry for Education of the Slovak Republic and the Slovak Academy of Sciences, and Grants from the JINR

Plenipotentiaries of Bulgaria, the Slovak Republic, the Czech Republic and Romania in the years 2002-2006.

---

- [1] Web site of the BECQUEREL Project, <http://becquerel.jinr.ru/>
- [2] M. I. Adamovich et al., Phys. At. Nucl., **67**, 514 (2004).
- [3] M. I. Adamovich et al., J. Phys. G, **30**, 1479 (2004).
- [4] N. P. Andreeva et al., Phys. At. Nucl., **68**, 455 (2005).
- [5] V. V. Belaga et al., Phys. At. Nucl., **58**, 1905 (1995).