

**Peripheral fragmentation of the  $^8\text{B}$  nuclei fragmentation at an  
energy of 1.2 A GeV in nuclear track emulsion**

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## Abstract

The results of investigations dealing with the charge topology of the fragments produced in peripheral dissociation of relativistic  $^8\text{B}$  nuclei in emulsion are presented. 55 events of peripheral dissociation of the  $^8\text{B}$  nucleus were selected from the events which do not involve the production of the target-nucleus fragments and mesons (“white” stars). A leading contribution of the  $^8\text{B} \rightarrow ^7\text{Be} + \text{p}$  mode having the lowest energy threshold was revealed on the basis of those events. Information on the relative probability of dissociation modes with a larger multiplicity was obtained. The dissociation of a  $^7\text{Be}$  core in  $^8\text{B}$  indicates an analogy with that of the free  $^7\text{Be}$  nucleus.

The transverse momentum distributions of the fragments from the  $^8\text{B} \rightarrow ^7\text{Be} + \text{p}$  dissociation mode were obtained. Their small average value,  $\langle P_t \rangle = 52 \text{ MeV}/c$ , in the c.m.s. suggests a low binding energy of the external proton in the  $^8\text{B}$  nucleus. An indication for a strong azimuthal correlation of the  $^7\text{Be}$  and p fragments was got.

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## I. INTRODUCTION

A peculiar feature of the  ${}^8\text{B}$  nucleus is known to consist in a low proton separation energy. This fact suggests that in  ${}^8\text{B}$  there can possibly exist a proton halo which is spacially separated from a core represented by the  ${}^7\text{Be}$  nucleus. In relativistic fragmentation processes  ${}^8\text{B}\rightarrow{}^7\text{Be}$  such a loose bound results in very narrow momentum distribution of  ${}^7\text{Be}$  nuclei [1, 2]. In just the same way as in the case of exotic nuclei, a possible increase in the  ${}^8\text{B}$  nucleus radius caused by the proton halo could have lead to a relative growth in its interaction cross section. However this increase is not observed experimentally. Therefore a more detailed study of the  ${}^8\text{B}$  nucleus, namely its cluster structure, is especially urgent. For example, a proton halo can arise on the basis of the deuteron cluster from an odd neutron with an external proton. The  ${}^7\text{Be}$  and  ${}^8\text{B}$  spins equal to  $3/2$  and  $2$ , respectively, point to this possibility.

The nature of the proton halo can be clarified by means of a more thorough analysis of the  ${}^8\text{B}$  relativistic fragmentation in peripheral interactions. The interactions of this type are provoked either in electromagnetic and diffraction processes, or in nucleon collisions at small overlapping of the colliding nucleus densities. A fragmenting nucleus gains an excitation spectrum near the cluster dissociation thresholds. In the kinetic region of fragmentation of a relativistic nucleus there are produced nuclear fragment systems the total charge of which is equal to the parent-nucleus charge. A relative intensity of formation of fragments of various configurations makes it possible to estimate the importance of different cluster modes. For the  ${}^8\text{B}$  nucleus the following modes  ${}^7\text{Be}+{}^1\text{H}$ ,  ${}^4,3\text{He}+{}^3\text{He}+{}^1,2\text{H}$ ,  ${}^6\text{Li}+{}^2,1\text{H}$ ,  ${}^4,3\text{He}+{}^2,1\text{H}+{}^2,1\text{H}$ , and  $5^2,1\text{H}$ . are possible.

The opening angle of the relativistic fragmentation cone is determined by the Fermi-momenta of the nucleon clusters in a nucleus. Being normalized to the mass numbers they are concentrated with a few percent dispersion near the normalized momentum of the primary nucleus. When selecting events with dissociation of a projectile into a narrow fragmentation cone we see that target-nucleus non-relativistic fragments either are absent (“white” stars in [3]), or their number is insignificant. The target fragments are easily separated from the fragments of a relativistic projectile since their fraction in the angular relativistic fragmentation cone is small and they possess non-relativistic momentum values.

In the peripheral fragmentation of a relativistic nucleus with charge  $Z$  the ionization

induced by the fragments can decrease down to a factor  $Z$ , while the ionization per one track - down to  $Z^2$ . Therefore experiment should provide an adequate detection range. In order to reconstruct an event, a complete kinematic information about the particles in the relativistic fragmentation cone is needed which, e.g., allows one to calculate the invariant mass of the system. The accuracy of its estimation decisively depends on the exactness of the track angular resolution. To ensure the best angular resolution, it is necessary that the detection of relativistic fragments should be performed with the best spacial resolution.

The nuclear photoemulsion method, which underlies the BECQUEREL project at the JINR nuclotron [4], well satisfies the above-mentioned requirements. It is aimed at a systematic search for peripheral fragmentation modes with statistical provision at a level of dozens events, their classification and angular metrology. Emulsions provide a record special resolution (about  $0.5 \mu\text{m}$ ) which allows one to separate the charged particle tracks in the three-dimensional image of an event within one-layer thickness ( $600 \mu\text{m}$ ) and ensure a high accuracy of angle measurements. The tracks of relativistic H and He nuclei are separated by sight. As a rule, in the peripheral fragmentation of a light nucleus its charge can be determined by the sum of the charges of relativistic fragments. Multiple-particle scattering measurements on the light fragment tracks enable one to separate the H and He isotopes. The analysis of the products of the relativistic fragmentation of neutron-deficient isotopes has some additional advantages owing to a larger fraction of observable nucleons and minimal Coulomb distortions. Irradiation details and a special analysis of interactions in the BR-2 emulsion are presented in [5, 6]. In what follows, we give the first results of the study of the  $^8\text{B}$  nucleus fragmentation at a  $1.2\text{A GeV}$  energy which are obtained with the use of a part of the material analyzed. In particular, we found the final charged state and fragment emission angle distributions. A comparison with the data for  $^{10}\text{B}$  [3, 6] and  $^8\text{B}$  [7] nuclei was made.

## II. EXPOSURE OF EMULSION TO A $^8\text{B}$ BEAM

In investigations with the use of emulsion exposed to secondary beams it is necessary that the identification of the nuclei being studied should be rather simple. For this purpose, to form a  $^8\text{B}$  beam at the JINR Nuclotron, use was made of the fragmentation process of a primary  $^{10}\text{B}$  nucleus beam of an energy of  $1.2\text{A GeV}$  on a polyethylene target. Such

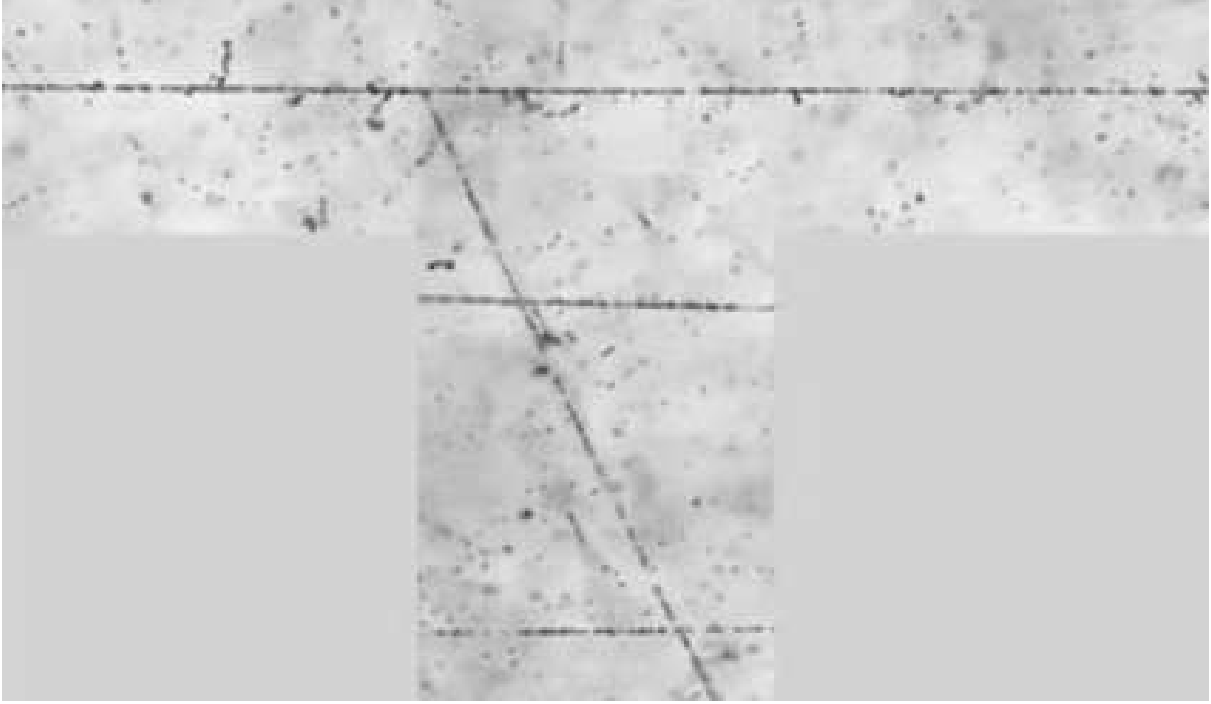


FIG. 1: Micro-photograph of the  $^{10}\text{B}$  fragmentation at an energy of 1.2 A GeV on a  $^1\text{H}$  nucleus in emulsion which was made by means of the PAVIKOM (FIAN) complex. The primary  $^{10}\text{B}$  nucleus track does not practically change its direction after the interaction point. The recoil proton track has a large emission angle. The process is identified as  $^{10}\text{B}+\text{p}\rightarrow^8\text{B}+2\text{n}+\text{p}$ .

processes were observed in the study of the  $^{10}\text{B}$  interactions in emulsion [6]. As an example, Fig. 1 displays a microphotograph of an event of the primary  $^{10}\text{B}$  nucleus fragmentation into a nucleus with a charge of 5 which entails the recoil proton track. As far as, on the one hand, a  $^9\text{B}$  isotope in the bound state does not exist and, on the other hand, it is necessary to compensate the recoil proton transverse momentum the most probable interpretation of this event is to suppose that two neutrons should escape from  $^{10}\text{B}$  and a  $^8\text{B}$  should be formed.

The absence of the  $^9\text{B}$  isotope among relativistic fragments turns out to be useful when separating the  $^8\text{B}$  beam from the  $^{10}\text{B}$  beam by the magnetic rigidity (the difference is about 20%). The beam channel at the JINR nuclotron which was used for irradiation was expected to have a suitable momentum acceptance of about 2-3%. This suggestion was confirmed when setting the channel to  $^9\text{B}$  separation: the boron nuclei practically vanished. But when setting to  $^{10}\text{B}$  and  $^8\text{B}$  separation they appeared anew. An analysis of irradiated emulsions gave an additional proof of this suggestion that was the absence of “white” stars with the

topology of the relativistic fragments of the H+He and He+Li pairs originating from possible  ${}^6\text{Li}$  and  ${}^{10}\text{B}$  admixtures. As a scintillation monitor showed the contribution from the  ${}^7\text{B}$  nuclei which have a close magnetic rigidity (the difference is about 10%) to the formed  ${}^{10}\text{B}$  beam was less than 10%. Their contribution to the number of “white” stars was excluded due to the charge topology. The most intense background from the beam tracks presented by the  ${}^3\text{He}$  nuclei was rejected in scanning emulsion by sight.

### III. THE CHARGE TOPOLOGY OF ${}^8\text{B}$ DISSOCIATION

Over the viewed-track length of 123 m we found 929 events of inelastic interactions. The mean free path was estimated to be  $\lambda=13.3\pm 0.4$  cm. The latter value correspond to the inelastic cross section for a  ${}^8\text{B}$  nucleus with a normal density. The method of viewing over the primary-particle track aimed at the search for interactions in emulsion shows that the frequency of emergence of the events with a given charge topology defines the probability of various dissociation channels. Among the found events there are 320 stars in which the total charge of the relativistic fragments in a  $8^\circ$  fragmentation cone  $Q$  satisfies the condition  $Q > 3$ . These stars were attributed to the number of peripheral dissociation events  $N_{pf}$ . The  $N_{pf}$  relativistic fragment distribution of over charges  $N_Z$  is given in Table I. There are given the data for 256 events containing the target-nucleus fragments -  $N_{tf}$ , as well as for 64 events which contain no target-nucleus fragments (“white” stars) -  $N_{pf}$ . The role of the channels with multiple relativistic fragments  $N_Z > 2$  is revealed to be dominant for the  $N$  “white” stars. Of peripheral events, the “white” stars  $N_{ws}$  (Table I) are of very particular interest. They are not accompanied by the target-nucleus fragment tracks and makes it possible to clarify the role of different cluster degrees of freedom at a minimal excitation of the nuclear structure.

Two “white” stars with  $Q=4$  may be referred to the background  ${}^7\text{Be}$  nucleus contribution (Table I). An analysis of the emulsions exposed to a  ${}^7\text{Be}$  beam revealed [7] that the probability of peripheral  ${}^7\text{Be}$  interactions involving target-fragment production is about half as much as that involving no target-fragment production. This means that the main contribution to the number  $N_{tf}$  with  $Q=4$  must be given by the  ${}^8\text{B}$  interactions which occurred in the fragmentation cone with decreasing charge by unity.

The main dissociation branch are the events with  $Q=5$ . The key difference between  $N_{tf}$

and  $N_{us}$  for this group of events is revealed in a two-particle mode  $Z=4+1$ . The latter is unambiguously interpreted as  ${}^8\text{B}\rightarrow{}^7\text{Be}+p$  because of neutron deficiency. Its fraction sharply increases when selecting “white” stars: from 10% for the case of the presence of target fragments up to 44% for “white” stars. The threshold of this mode is the lowest one which is seen from the fact that it dominates the most peripheral events.

The distribution of the probability of the “white” stars production by  ${}^8\text{B}$  nuclei can be compared with similar data for the  ${}^{10}\text{B}$  nuclei of an energy of 1A GeV [3, 6]. The fraction of the 3-prong mode  ${}^{10}\text{B}\rightarrow 2\text{He}+{}^1,2\text{H}$  amounts to 73% for a 40% deuteron contribution. The probability of the 2-prong mode  ${}^{10}\text{B}\rightarrow{}^9\text{Be}+{}^1\text{H}$  was found to be as small as 2%. The difference is due to a lower binding energy of the deuteron as compared to that of the proton in the  ${}^{10}\text{B}$  nucleus. On the contrary, for the  ${}^8\text{B}$  isotope there is a large yield of the two-body mode  ${}^8\text{B}\rightarrow{}^7\text{Be}+p$  because the binding energy of the external proton is low enough. In such a way, the  ${}^8\text{B}$  nucleus manifests its structure through a more intense formation of “white” stars with  $N_Z=2$ . Among the  $Q=5$  and  $N_Z=2$  events, one event among  $N_{tf}$ , namely  $\text{Li}+\text{He}$ , may not be attributed to the  ${}^8\text{B}$  interaction.

The probabilities of the “white” stars fragmenting via the  $2\text{He}+\text{H}$  and  $\text{He}+3\text{H}$  channels for the  ${}^8\text{B}$  nucleus were turned out to be 22% and 25%, respectively, while for the  ${}^{10}\text{B}$  nucleus the probabilities of the same modes were 73% and 12%. Such a noticeable difference is due to the presence of a  ${}^3\text{He}$  cluster in  ${}^8\text{B}$  whose dissociation threshold is essentially lower than that for  ${}^4\text{He}$ .

The presence of the “white” stars with more than two  $N_Z > 2$  fragments may be explained by the  ${}^7\text{Be}$  core dissociation. In order to verify this suggestion, Table II gives the relativistic fragment charge distribution in the “white” stars for  ${}^7\text{Be}$  [3, 7] and  ${}^8\text{B}$  nuclei. The  ${}^8\text{B}$  events are presented without one single-charged relativistic fragment, that is a supposed proton halo. The identical fraction of the two main  $2\text{He}$  and  $\text{He}+2\text{H}$  dissociation channels is observed for  ${}^7\text{Be}$  and  ${}^8\text{B}$  nuclei which points out that the  ${}^8\text{Be}$  core excitation is independent of the presence of an additional loosely bound proton in the  ${}^8\text{B}$  nucleus.

The observation of 4 unusual  $Q=5$  “white” stars with a total  ${}^8\text{B}\rightarrow 5\text{H}$  disintegration is noteworthy (Table I). This process leads to a breakup of two He clusters and has a high energy threshold. Earlier, the events of such a type were already observed for  ${}^7\text{Be}\rightarrow 4\text{H}$  and  ${}^{10}\text{B}\rightarrow 5\text{H}$  [6]. The neutron deficiency in the  ${}^8\text{B}$  nucleus makes the observability of nucleons far better. In addition, the Coulomb repulsion in the fragment system becomes stronger.

TABLE I: The charge topology distribution of the number of interactions of the peripheral  $N_{pf}$  type ( $N_{pf}=N_{tf}+N_{ws}$ ), which were detected in an emulsion exposed to a second  $^8\text{B}$  nucleus beam. Here  $Q$  is the total charge of relativistic fragments in a  $8^\circ$  angular cone in an event,  $N_Z$  the number of fragments with charge  $Z$  in an event,  $N_{ws}$  the number of white stars,  $N_{tf}$  the number of events involving the target fragments,  $N_{ws}$  the number of “white” stars.

Q	$N_5$	$N_4$	$N_3$	$N_2$	$N_1$	$N_{tf}$	$N_{ws}$
7	-	-	-	1	5	1	-
6	-	-	-	2	2	8	2
6	-	-	-	1	4	6	4
6	-	-	-	-	6	1	-
5	-	-	-	1	3	61	14
5	-	-	-	2	1	44	12
5	-	-	1	-	2	8	-
5	-	-	1	1	-	1	-
5	-	1	-	-	1	17	24
5	1	-	-	-	-	17	1
5	-	-	-	-	5	21	4
4	-	-	-	-	4	5	1
4	-	-	-	2	-	24	1
4	-	-	-	1	2	42	-

TABLE II: The charged dissociation mode distribution of the “white” stars produced by the  $^7\text{Be}$  and  $^8\text{B}$  nuclei. To make the comparison more convenient, for the  $^8\text{B}$  nucleus one H nucleus is eliminated from the charged mode and the channel fractions are indicated.

Z	$^7\text{Be}$	%	$^8\text{B}$ (+H)	%
2He	41	43	12	40
He+2H	42	45	14	47
4H	2	2	4	13
Li+H	9	10	0	0



The formation of such H nucleus ensembles can be the basis of the multiple fragmentation of heavier nuclei with a large number of fragments.

The production of “white” stars with  $Q=6$  (Table I) may be due to a  $^{10}\text{C}$  admixture in the composition of the beam used. The  $^{10}\text{C}$  nuclei could be produced through a  $^{10}\text{B}\rightarrow^{10}\text{C}$  charge exchange in the target intended for the  $^8\text{B}$  generation and could be captured to a second beam because of a small difference in the magnetic rigidity as compared with  $^8\text{B}$  (about 4%) and their proper momentum dispersion. The  $Q=6$  “white” stars contain no fragments with  $Z>2$ . Their topology does not contradict the assumption about the dissociation of a carbon isotope with a  $^8\text{B}$  core ( $^{10}\text{C}\rightarrow^8\text{Be}+2\text{p}$ ) or with the disintegration of one of the He clusters ( $^{10}\text{C}\rightarrow^4\text{He}+2\text{H}+2\text{p}$ ). This fact points to a possible formation of a  $^{10}\text{C}$  beam ( $^{10}\text{B}\rightarrow^{10}\text{C}$ ) under the conditions which are convenient for performing investigations in emulsion. A  $Q=7$  white star may be referred to the production of a charged meson pair.

#### IV. ANGULAR CHARACTERISTICS OF $^7\text{Be}+\text{P}$

The “white” stars of  $^8\text{B}\rightarrow^7\text{Be}+\text{p}$  (Table I) give a pair of observed tracks with a small angular deviation with respect to the primary nucleus track. Measurements gave the mean values of the polar emission angles  $\langle \theta_p \rangle = 2.0^\circ$  for protons and  $\langle \theta_{Be} \rangle = 0.4^\circ$  for  $^7\text{Be}$  nuclei.

The angular measurements permit one to reconstruct with a good accuracy the spectra of transverse momenta  $P_T$  by the equation  $P_T = AP_0 \sin\theta$ , where  $A$  is the mass number of a fragment,  $\theta$  its emission angle and  $P_0$  the momentum per  $^8\text{B}$  nucleon ( $P_0 = 2.0A \text{ GeV}/c$ ). Fig. 2 presents the  $P_t$  distribution for protons with the mean value  $\langle P_T \rangle = 73 \text{ MeV}/c$ . Going over to the c.m.s. of  $^7\text{Be}+\text{p}$  compensates the transverse momentum transferred to the  $^8\text{B}$  nucleus which results in a far more narrow  $P_t$  distribution (insertion in Fig. 2),  $\langle P_T^* \rangle = 52 \text{ MeV}/c$ . Such a small value of  $P_T$  is in agreement with data [2] in which for the longitudinal momentum distribution of fragments from  $^8\text{B}\rightarrow^7\text{Be}$  reaction there was obtained a FWHM value of  $91 \pm 5 \text{ MeV}/c$ . In this way, the loose bound of the proton with the core is revealed under the most clear conditions of observing fragmentation.

Fig. 3 gives the distribution along the total transverse momentum  $P_T(^8\text{B})$  which was acquired by the  $^8\text{B}$  nuclei in the formation of “white” stars  $^7\text{Be}+\text{p}$ ; its mean value is about  $100 \text{ MeV}/c$ . The distribution peak is located at the  $P_T(^8\text{B})$  value of about  $50 \text{ MeV}/c$ . This asym-

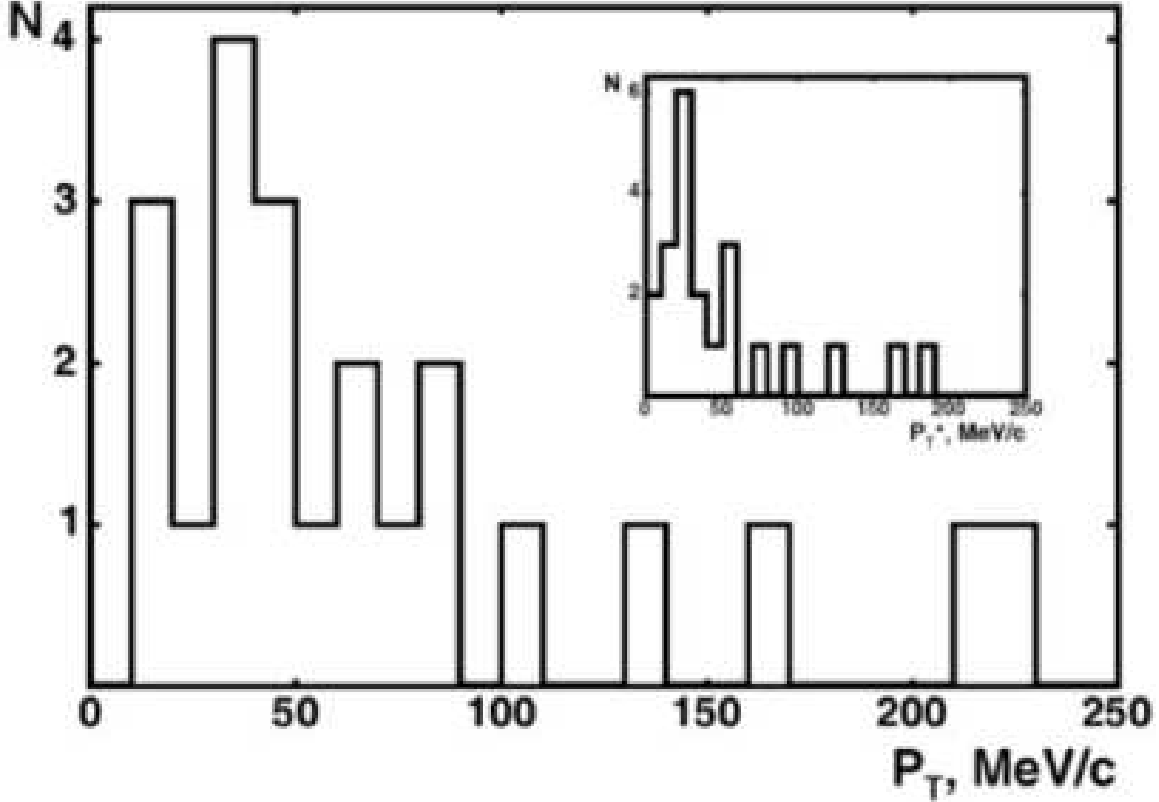


FIG. 2: The  $P_t$  transverse momentum distribution of the protons produced in “white” stars  ${}^8\text{B} \rightarrow {}^7\text{Be} + \text{p}$ . In the insertion the same  $P_t^*$  distribution is given in the c.m.s. of  ${}^7\text{Be} + \text{p}$ .

metry of the  $P_T({}^8\text{B})$  distribution may be associated both with the emission of neutrons by the target-nuclei and the contribution from the core excitation process  ${}^8\text{B} \rightarrow {}^7\text{Be}^* + \text{p} \rightarrow {}^7\text{Be} + \gamma + \text{p}$  [8].

It is possible to estimate the role of the correlations by the azimuthal angle  $\epsilon_{pBe}$  between  ${}^7\text{Be}$  and  $\text{p}$ . This distribution has an asymmetry with respect to the angle  $\pi/2$   $A \approx 0.3$ , which points to a noticeable contribution of pairing dissociations. Fig. 4 presents the  $\epsilon_{pBe}$  distribution with the requirement of selection of the events  $P_T({}^8\text{B}) < 60$  MeV/c. One can note a sharp increase in the asymmetry up to  $A \approx 0.7$ , which points to a binary character of the  ${}^8\text{BB}$  breakup at small transverse momentum transfers.

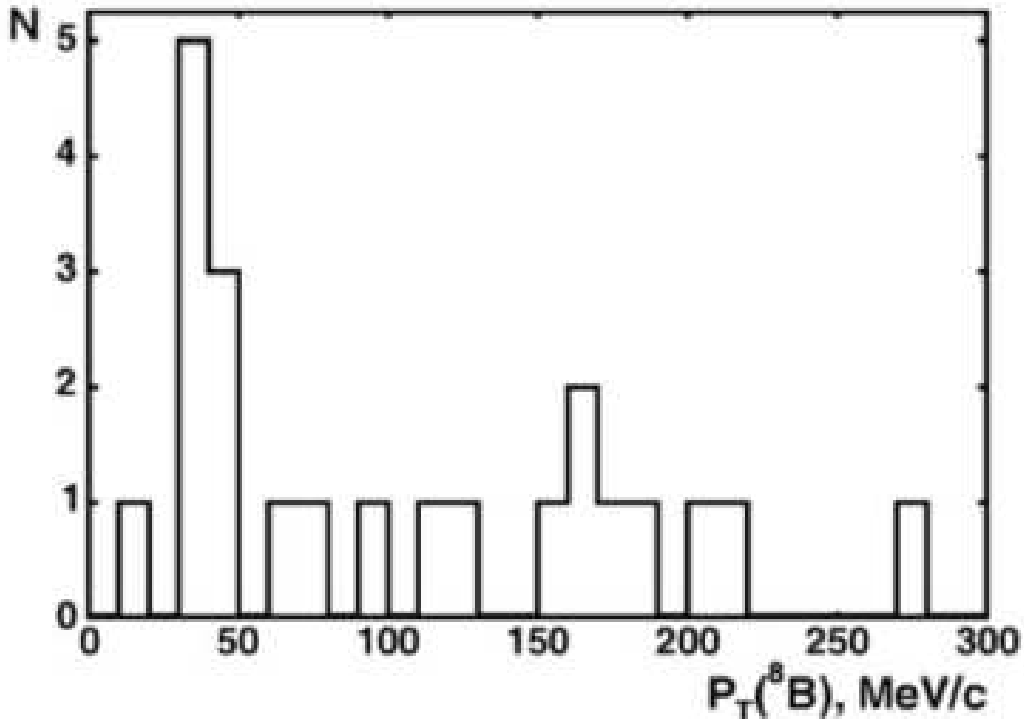


FIG. 3: The  $P_T(^8\text{B})$  total transverse momentum distribution of  $^7\text{Be}+p$  pairs produced in “white” stars  $^8\text{B}\rightarrow^7\text{Be}+p$ .

## V. CONCLUSIONS

For the first time, nuclear emulsions were exposed to a beam of relativistic  $^8\text{B}$  nuclei. We have obtained data on the probabilities of the  $^8\text{B}$  fragmentation channels in peripheral interactions. 55 events of the peripheral  $^8\text{B}$  dissociation which do not involve the production of the target-nucleus fragments and mesons (“white” stars) were selected. A leading contribution of the  $^8\text{B}\rightarrow^7\text{Be}+p$  mode having the lowest energy threshold was revealed on the basis of these events. Information about a relative probability of dissociation modes with larger multiplicity have been obtained. The  $^7\text{Be}$  core dissociation in  $^8\text{B}$  is found to be similar to that of the free  $^7\text{Be}$  nucleus. A further analysis of the fragmentation topology suggests the identification of the H and He isotopes.

We have obtained the transverse momentum distributions for the  $^8\text{B}\rightarrow^7\text{Be}+p$  dissociation fragments. Their small average value,  $\langle P_T^* \rangle = 52$  MeV/c, in the c.m.s. reflects a low binding

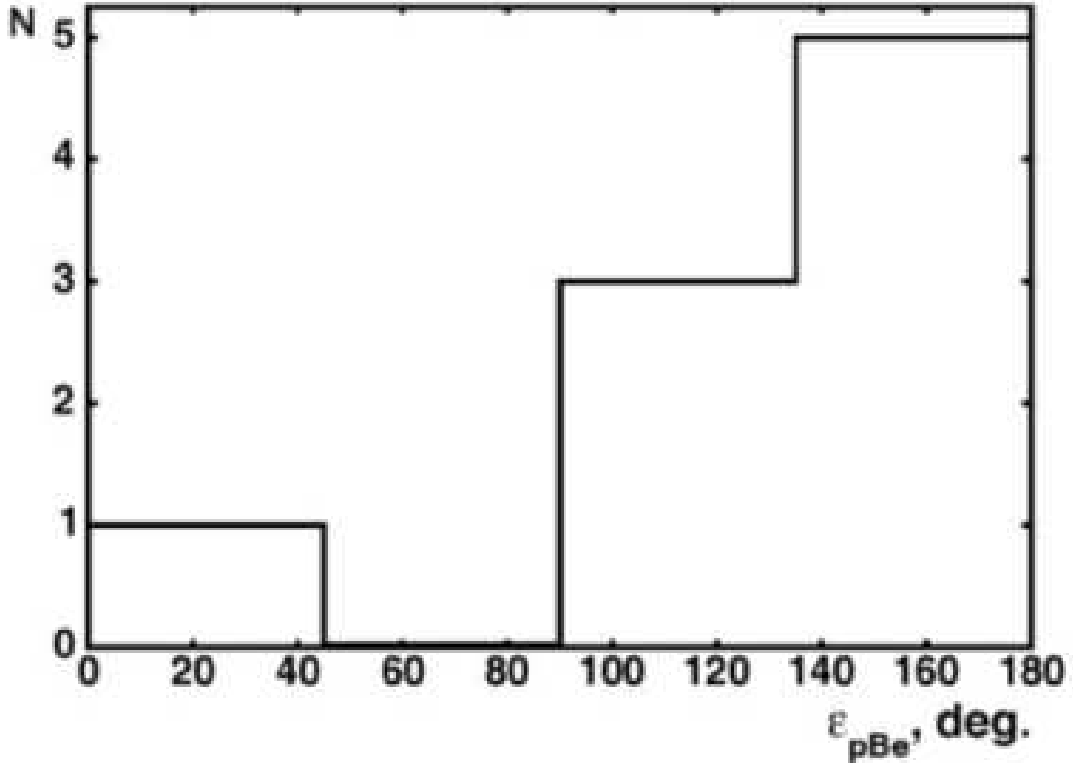


FIG. 4: The  $\epsilon_{pBe}$  azimuthal angle distribution in “white” stars  ${}^8\text{B} \rightarrow {}^7\text{Be} + \text{p}$  for  $P_T({}^8\text{B}) < 60$  MeV/c.

energy of the external proton in the  ${}^8\text{B}$  nucleus. In the selection of the events in which a transverse momentum of less than 60 MeV/c is transferred to the  ${}^8\text{B}$  nucleus there appears a strong azimuthal angle correlation between  ${}^7\text{Be}$  and p.

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- [1] W. Schwab et al Z. Phys. **A350**, 283(1995).
- [2] M. H. Smedberg et al. Phys. Lett. **B452** 1(1999).
- [3] M. I. Adamovich et al. Phys. At. Nucl. **67**, 455(2005).
- [4] The BECQUEREL Project Web-site <http://becquerel.jinr.ru/>.
- [5] M. I. Adamovich et al. Phys. At. Nucl. **62**, 1378(1999).
- [6] M. I. Adamovich et al. Phys. At. Nucl. 67, 514(2004).
- [7] N. G. Peresadko et al. In this volume.
- [8] M. Meister et al. Nucl. Phys. **A718**, 431c(2003).