Very Peripheral Interactions of Relativistic ^{8}B, ^{9}Be and ^{14}N Nuclei in Nuclear Track Emulsion

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Abstract

The technique of nuclear track emulsions is used to explore fragmetation of light relativistic nuclei down to most peripheral interactions - nuclear ”white” stars. Complete pattern of relativistic dissociation of a ^{8}B nucleus with target fragment accompaniment is presented. Relativistic dissociation ^{9}Be→2α is explored using significant statistics and relative contribution of ^{8}Be decays from 0^{+} and 2^{+} states is established. Target fragment accompaniments is shown for relativistic fragmentation ^{14}N→3He+H and ^{22}Ne→5He. The leading role of electromagnetic dissociation on heavy nuclei with respect to break-ups on target protons is demonstrated in al these cases. It is possible to conclude that peripheral dissociation of relativistic nuclei in nuclear track emulsion is a unique tool to study many-body composed of lightest nuclei in energy scale relevant for nuclear astrophysics.

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I. INTRODUCTION

Nuclear beams of an energy higher than 1 A GeV are recognized as a modern tool for the nuclear structure studies (reviewed in [1]). Among the nuclear interactions the peripheral dissociation bears a uniquely complete information about the excited states in vicinity of particle decay thresholds. The peripheral dissociation is revealed as a narrow jet of relativistic fragments the summary charge of which is close to the charge of the primary nucleus. In spite of the relativistic velocity of fragment motion in a laboratory system the internal velocities inside the jet are non-relativistic [2]. In principle, information about the generation of such fragment ensembles can be used in nuclear astrophysics (indirect approaches), as well as in develoments of nucleosynthesis scenarios on the basis of few-particle fusion. To utilize this novel possibility it is necessary to provide a completeness in observation of the relativistic fragments.

The difficulties of principle are here as follows. An increase in the dissociation degree of a relativistic nucleus leads to a decrease in the response of an either fragment detector. This circumstance makes the wholesome analysis of relativistic fragments, which is necessary up to the He and H isotopes, hardly accessible. Nextly, the excited state of the produced fragment system is defined by the invariant mass of the relativistic fragment jet. Therefore the most accurate measurements of the emission angles of fragments are needed. The accuracy of measurements of the momenta is not so rigid, it is possible to assume that the fragments conserve the primary momentum per nucleus. In addition, the selection of extremely peripheral collisions which are most ineteresting ones requires the detection threshold to be as low as possible for the target fragments over a total solid angle.

The nuclear emulsion technique solves these problems and makes it possible to perform effectively survey investigations on newly produced beams [4, 5]. Unique information about the structure of peripheral dissociation of many nuclei has already been obtained [6–21]. Limitations imposed to statistics are compensated by the fact that the fragment jets are inaccessible for complete observation in any other techniques.

The complex emulsion compound provides special convinience to explore just peripheral interactions. Since it includes both the Br, Ag and H nuclei in comparable concentrations allowing one to compare fragmentation patterns of various nature. The relative content of these nuclei is about 1/1/3. for the BR-2 type emulsion. Under the same conditions it is possible to observe the very peripheral break-up in the electromagnetic field on a heavy target nucleus (EM dissociation) [3] as well as in collisions with target protons.

The emulsion response is described the multiplicity of heavily ionizing fragments from α particles up to light recoil nuclei C, N, and O - n_b and non-relativistic H nuclei - n_g. Besides, the reactions are characterized by the multiplicity of produced mesons n_s. The events in which there are no tracks of target nucleus fragmentation belong to EM dissociation and are named "white" stars (n_b=0, n_g=0, n_s=0) [7]. Dissociation on a proton must lead to the appearance of its track, that is, n_b=0, n_g=1, and n_s=0. The structure of the events of these two types is just the subject of the present paper.

The presence of strongly ionizing particle (n_b >0) tracks in the vertex or relativistic particle (n_s >0) tracks outside the fragmentation cone makes it possible to define the interaction as the one which is occurred with an overlap of the densities of colliding nuclei or with C, N and O nuclei in the cases of extremely short tracks of recoil nuclei. In principle, mutual excitation and simultaneous fragmentation of both colliding nuclei are possible. The discussion of these events is outside the scope of the present paper and their statistics is given for the sake of an illustration.

In what follows, a target fragment accompaniment for the relativistic ^{8}B, ^{9}Be and ^{14}N dissociations is presented. The results are obtained in a BR-2 emulsion with relativistic sensitivity which was exposed to the JINR nuclotron beams. The secondary ^{8}B and ^{9}Be beams were produced in the fragmentation of the primary ^{10}B beam at an energy about 1.2 A GeV [5].

II. FRAGMENT ACCOMPANIMENT OF ^{8}B DISSOCIATION AND PROSPECT STUDIES OF ^{9,10}C NUCLEI

Due to the extremely weak proton binding the ^{8}B nucleus is appears to be a very sensitive probe of the interaction type down to the lowest momentum transfers which are typical for EM processes. The study of the events with a total relativistic fragment charge of ΣZ_{fr}=5 in an emulsion exposed to ^{8}B nuclei enabled one to establish the leading contribution of the "white" stars $^{8}B \rightarrow {}^{7}B+p$ as compared with the stars containing the target fragments [17, 21]. This conclusion is a qualitative distinction from ^{10}B case for which 3-prong "white" stars 2He+H were predominant [14].

TABLE I: The distribution of the peripheral interactions with ΣZ_{fr}=5 and 6 obtained in an emulsion exposed to a ^{8}B enriched secondary beam versus target fragment numbers n_b and n_g.

n_b	0	0	1	2	3	4	5
n_g	0	1	0	0	0	0	0
He+3H	12	6	3	3	2	3	-
2He+H	14	3	8	2	4	-	1
Be+H	25	1	3	3	1	-	-
2He+2H	3	-	-	2	-	1	-
He+4H	-	1	3	1	1	-	1

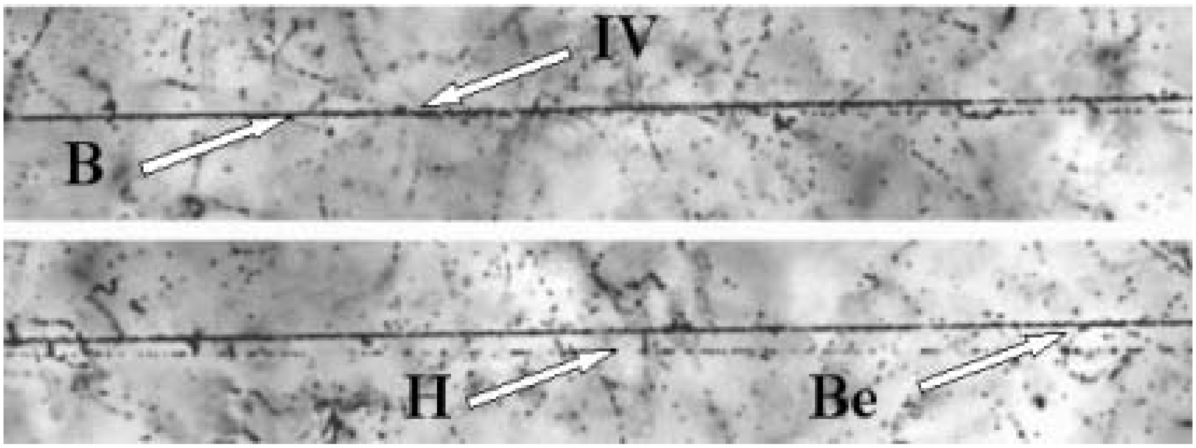

FIG. 1: Example of peripheral interaction of a 1.2 A GeV $^8B \to ^7Be+p$ in a nuclear track emulsion ("white" star). The interaction vertex (indicated as **IV**) and nuclear fragment tracks (**H** and **Be**) in a narrow angular cone are seen on the upper and bottom microphotograph.

A detailed distribution of the ^{8}B dissociation over the fragment configurations ΣZ_{fr} and the numbers of the target fragments n_b and n_g is given in Table I. First of all, the predominance of "white" stars $^8B \to ^7Be+p$ should be noted (example is shown in Fig. 1). In this channel, there is practically no dissociation on protons n_g=1. The difference is due to a rapid increase in the EM dissociation cross section with increasing target nucleus charge (like Z^2). Just half a number of "white" stars is associated with 3- and 4- particle dissociation modes having much higher thresholds. This implies that the multiple fragmentation can be initiated by an EM excitation of one of He clusters. It may also be noted that in the 2He+H

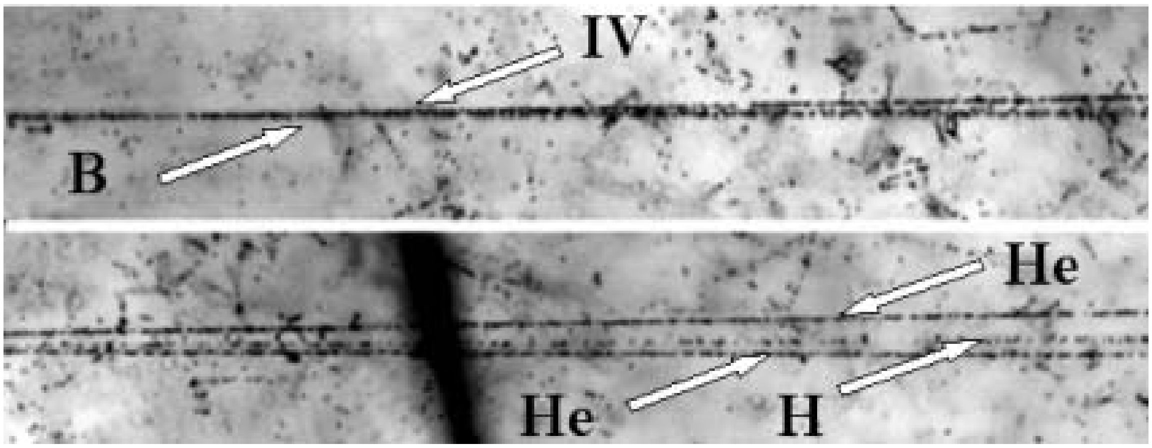

FIG. 2: Example of peripheral interaction of a 1.2 A GeV ^{8}B→2He+H in a nuclear track emulsion ("white" star). The interaction vertex (indicated as **IV**) and nuclear fragment tracks (**H** and **He**) in a narrow angular cone are seen on the upper microphotograph. Following the direction of the fragment jet, it is possible to distinguish 1 singly (the central track) and 2 doubly charged fragments on the bottom microphotograph.

and He+3H channels the fraction of the events on protons (n_g=1) and the events with target fragments (n_b >0) with respect to the ^{7}Be+p channel becomes the major one and increases by a factor of 5 as compared with the case of "white" stars (n_b=0, n_g=0). It is obvious that such a tendency is connected with an increase of direct proton-nucleon collisions.

A further accumulation of statistics on "white" stars ^{8}B→2He+H is of special interest (example is shown in Fig. 2). As is known, multiple scattering measurements can be used to identify relativistic ^{1,2,3}H and ^{3,4}He isotopes. In spite of the fact that these measurements are labour demanding, the appropriate efforts can be compensated by the identification of a 3-particle mode ^{8}B→2^{3}He+^{2}H (threshold of 20 MeV). This possibility is non-trivial because it is connected with a deep rearrangement of the ^{8}B cluster structure. The properties of this state near the threshold may turn out to be important for an inverse fusion process too. A particular feature of the 2^{3}He^{2}H fusion process might consist in a larger number of vacancies for a neutron to be captured in the ^{4}He cluster formation.

The conclusions about the EM dissociation of the ^{8}B and ^{7}Be nuclei [18] form the basis for a comparative analysis of the ^{9}C nucleus as the next step. The beam of these nuclei is created in the fragmentation of ^{12}C nuclei of an energy of 1.2 GeV, it is used to expose emulsion. In all probability, the pattern for ^{8}B and ^{7}Be nuclei with the addition of one or,

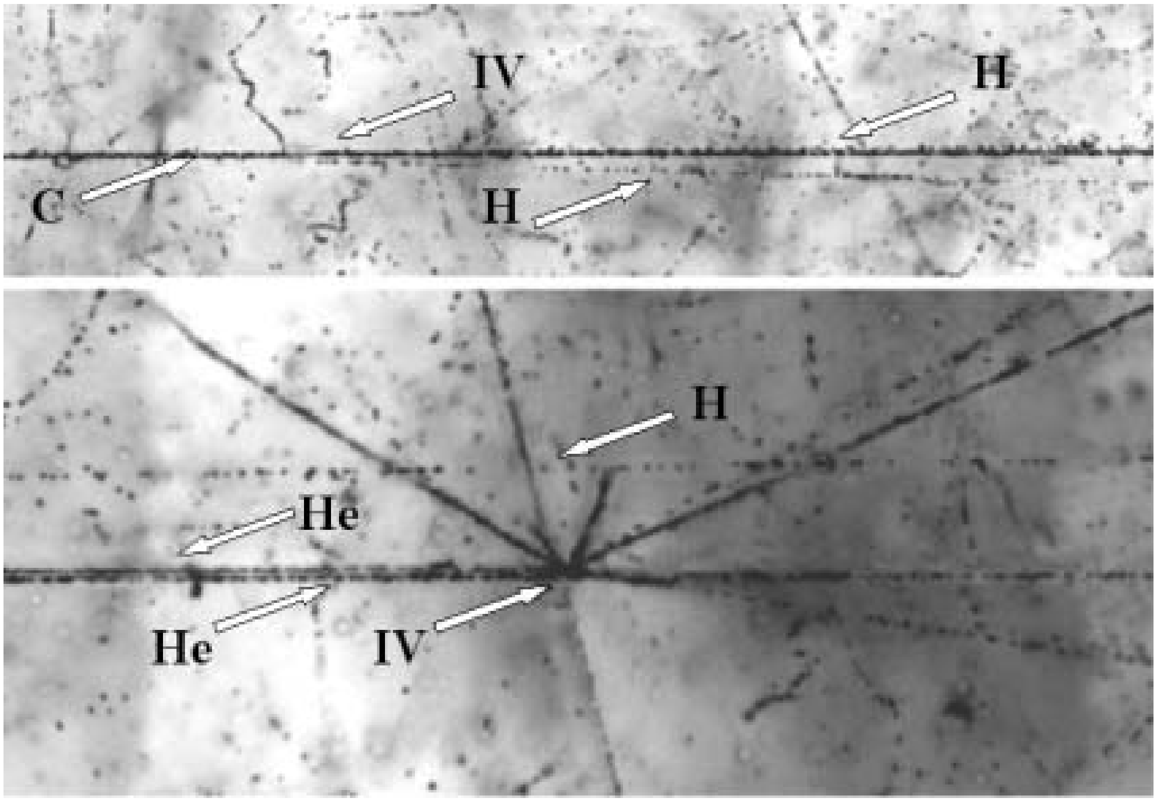

FIG. 3: Example of peripheral interaction of a 1.2 A GeV ^{10}C$\rightarrow$2He+2H in a nuclear track emulsion (“white” star). The interaction vertex (indicated as **IV**) and nuclear fragment tracks (**H** and **He**) in a narrow angular cone are seen on the upper microphotograph. Following the direction of the fragment jet, it is possible to distinguish 2 doubly charged fragments (^{8}Be decay) on bottom microphotograph. One of He tracks ended in the secondary star.

respectively, two protons must be reproduced for the ^{9}C dissociation. In addition the EM dissociation ^{9}C$\rightarrow$3^{3}He (threshold of 16 MeV) will become accessible for observation. The observation of 3^{3}He population near the threshold would allow one to put the ground for an extension of the well-known 3α fusion process toward 3^{3}He one.

The emulsion exposed to ^{8}B nuclei allowed us to observe events with the total charge of relativistic fragments ΣZ_{fr}= 6 from the mixture of ^{10}C nuclei produced in the generating target due to the charge exchange process ^{10}B$\rightarrow$^{10}C. Their distributions over the charge track topology are given in the two lower lines of Table I. Even restricted statistics points out that the 2He+2H breakup accompanied by the conservation of α particle clusters in “white” stars is more preferable (example is shown in Fig. 3). A low ^{8}Be+2p channel threshold equal to 3.8 MeV is manifested in such a way.

The ^{10}B→^{10}C charge exchange can be used for further exposures of emulsions with the aim not only to explore the main channel of EM dissociation 2He+2H but also to establish existence of the dissociation mode ^{10}C→^{4}He+2^{3}He (threshold of 17 MeV). In just the same way as in the ^{9}C case its discovery can enlarge the picture of the 3He fusion process in nuclear astrophysics. To search for ^{8}B→2He+H and ^{9,10}C→3He related to the EM channels it is possible to perform a scanning over the area. This method was already used for accelerating the search for the events ^{12}C→3He [9] and ^{16}O→4He [10], as is discussed below, for ^{9}Be→2He.

III. FRAGMENT ACCOMPANIMENT OF ^{9}BE→2HE DISSOCIATION

The ^{9}Be nucleus is known to be the best source the unbound ^{8}Be nucleus in the ground and excited states. Most clear information about the generation of a relativistic 2α particle system without the presence of the combinatory background of any other α particle can be applied in understanding more complicated Nα systems. The present-day interest in such systems is inspired by the suggested search for the α particle Bose-Einstein condensate [22] in which a ground 0^{+} and the first excited 2^{+} states of the ^{8}Be nucleus must play the role of condensate basic elements. The proof of existence of such a quantum state of dilute nuclear matter would has very important consequences in the development of nucleosynthesis concepts. The peripheral dissociation to relativistic Nα jets may turn out to be the most convenient tool for searching for it [15].

In an emulsion exposed to relativistic ^{9}Be nuclei 371 events of fragmentation to a narrow pair of relativistic He nuclei were analyzed under the assumption of their correspondence to 2α [19, 21]. A subset of 237 events with n_s=0 is considered below. Clear apperance of two peaks in the distribution over the invariant mass above the α particle pair mass threshold $Q_{2\alpha}$ was identified. It was concluded that the 0^{+} and 2^{+} states of ^{8}Be are revealed in the spectra over $Q_{2\alpha}$.

The observed interaction vertices allows one to separate the population of these states for EM and direct nucleonic interactions. Table II gives the distribution of the ^{9}Be→2He events in the major intervals over $Q_{2\alpha}$ and the configurations of accompanying tracks. The principal feature of the distribution consists in an evident dominance of 144 "white" stars (n_b=0, n_g=0) amounting about 60%. Only 27 events (11 %) are ascribed to the stars resulting from ^{9}Be collisions with protons (n_b=0, n_g=1). The ratio of the "white" stars from the states 0^{+}

TABLE II: The distribution of the peripheral interactions ^{9}Be→2α over intervals $Q_{2\alpha}$ versus target fragment numbers n_b and n_g with corresponding mean values of α pair total transverse momentum $<P_T^{2\alpha}>$

n_b	0	0	1	2	3	4	5
n_g	0	1	0	0	0	0	0
$Q_{2\alpha}$ <1 MeV	98	10	21	8	1	3	1
$<P_T^{2\alpha}>$, MeV/c	133±16	166±40	154±14				
1 MeV<$Q_{2\alpha}$ <4 MeV	33	10	14	3	2	1	-
$<P_T^{2\alpha}>$, MeV/c	127±15	195±54	178±23				
4 MeV<$Q_{2\alpha}$	13	7	4	2	2	3	1
$<P_T^{2\alpha}>$, MeV/c	202±31	232±42	281±51				

($Q_{2\alpha}$ <1 MeV) and 2^+ (1<$Q_{2\alpha}$ <4 MeV) is equal to $R_{0/2}$=3±0.6 and in the case of collisions with target protons (n_b=0, n_g=1) it is equal to $R_{0/2}$=1±0.5. Thus, in EM dissociation the production of an α particle pair via the ground ^{8}Be state proceeds more intensively than for n-p knockout processes. The same conclusion is also valid for the events in which only one target nucleus fragment (n_b=1, n_g=0) is revealed and $R_{0/2}$=1.5±0.5.

Following the concept about the ^{9}Be nucleus as a cluster system α−n−α it may be supposed that the ground state of this nucleus contains with a noticeable probability a pair of α particle clusters with angular momentum L=2. The presence of a neutron gives the value for the ^{9}Be spin 3/2. When the neutron is knocked out by the target proton there proceeds either a dispersion of the α particle pair from the D-state or a radiation transition to the ^{8}Be ground state 0^+. Apparently the α particle pair succeeds more often in performing such a transition in the case of ^{9}Be EM dissociation. An inverse ^{9}Be synthesis process might be considered as a radiation transition $0^+ \rightarrow 2^+$ in the presence of the neutron. In other words, the α pair goes out from the mass surface with γ emission. Such a picture is worthy of checking in experiments with γ detection.

Fig. 4 shows the total transverse momentum distribution transferred to α pairs $P_T^{2\alpha}$ for "white" stars (a) and from a break-ups on protons (b). The following average values are obtained - $<P_T^{2\alpha}>$=138±12 MeV/c (n_b=0, n_g=0) and 194±28 MeV/c (n_b=0, n_g=1). There is a noticeable difference in the average values and the distribution shapes which points to

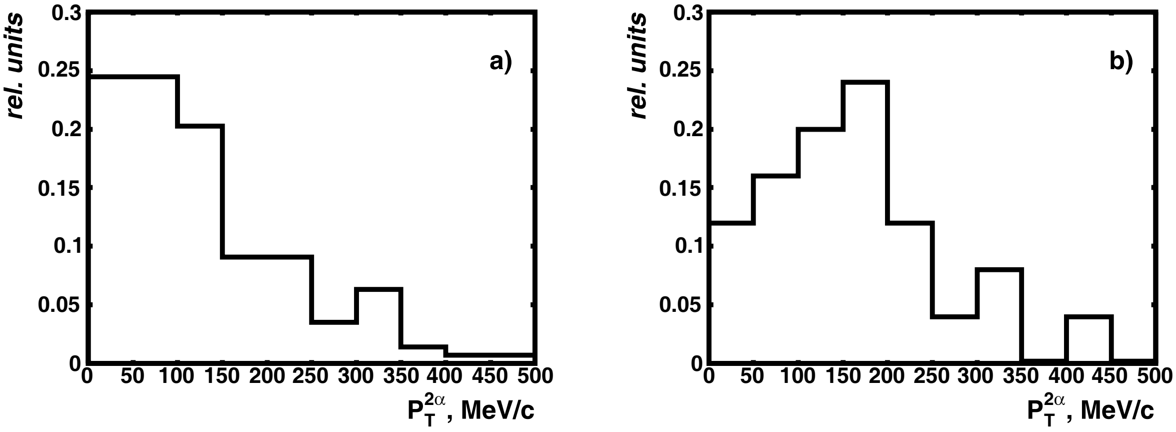

FIG. 4: The total transverse momentum distribution of α pairs $P_T^{2\alpha}$ in 1.2A GeV ^{9}Be→2α for "white" stars (a) and break-ups on protons (b).

different dynamics of α pair production. The ^{9}Be disintegration on a proton turns out to be a more rigid reaction mechanism as compared with EM dissociation. An increase in the target fragmentation multiplicity can be expected to result in an explicit increase in $<P_T^{2\alpha}>$ (Table II). A further growth of the multiplicity corresponding to a larger nucleus overlap leads to a suppression of the 2He event statistics owing to a destruction of the ^{9}Be structure destruction.

IV. FRAGMENT ACCOMPANIMENT OF ^{14}N AND ^{22}NE DISSOCIATION

The study of the peripheral dissociation of ^{14}N nuclei of an energy of 2.1 A GeV in the fragment state Z_{fr}= 7 [20, 21] has resulted in the conclusion about the leading part of the ^{14}N→3He channel. The underlying reason is contribution of unbound ^{8}Be nucleus in the ground and excited states. Having much higher cross-section than in the ^{12}C case [9] the peripheral ^{14}N dissociation can be used as an effective source of 3α systems. The dominant part of the events was shown to be concentrated in the interval of the invariant 3α particle mass over the ^{12}C mass $7<Q_{3\alpha}<20$ MeV [20, 21] covering the α particle levels just above the ^{12}C dissociation threshold. Thus, the problems of a few-body nuclear physics near the α emission threshold can be addressed using detection advantages of the relativistic collisions.

The pattern of the target fragment accompaniment in the ^{14}N dissociation shown in Table

TABLE III: The distribution of the peripheral interactions ^{14}N→3He+H and ^{22}Ne→5He versus target fragment numbers n_b and n_g with corresponding mean values of α pair total transverse momentum $<P_T^{2\alpha}>$

n_b	0	0	1	2	3	4	5
n_g	0	1	0	0	0	0	0
^{14}N	41	6	23	16	3	2	1
$<P_T^{3\alpha}>$, MeV/c	222±21	217±51	262±31	378±54			
^{22}Ne	3	-	1	-	-	1	-
$<P_T^{5\alpha}>$, MeV/c	518±85						

III is of the same nature as in the case for ^{9}Be. In spite of some increase in the threshold over Q, the major channel of 3α jets is the EM dissociation on heavy nuclei. The "white" stars dominate while the hydrogen dissociation contribution is not large. The ratio of the numbers of events with n_b=0 and 1 for ^{14}N and ^{9}Be points out that the dissociation mechanisms for 2- and 3α ensembles are alike.

As an example of a more complicated system Table III gives the description of the accompaniment of 5 events ^{22}Ne for 3.2 A GeV selected on the basis of 4100 inelastic interactions [15]. In spite of a restricted amount of data one can conclude that the generation of 5α particle systems proceeds more preferably via EM dissociation (n_b=0, n_g=0). The value of the mean transverse momentum transferred to 5α particle systems in these events when normalized to the α particle number is located in the region typical for "white" stars originated by light nuclei. Quite probably that these fragmentation cases were initiated by coherent multiphoton exchanges [23] which simultaneously affected few α clusters.

The investigations with light nuclei provide a basis for the challenging studies of increasingly complicated systems He-H-n produced via multifragmentation of heavier nuclei in the energy scale relevant for nuclear astrophysics[24, 25]. In this respect, the motivated prospects are associated with a detailed analysis of the already observed fragment jets in the events of EM dissociation of Au nuclei at 10.6A GeV and Pb nuclei at 160A GeV [2].

V. CONCLUSIONS

Possessing a record space resolution the nuclear emulsion method keeps unique possibilities in studying the structure particularities of light nuclei, especially, of neutron-deficient nuclei. The presented results of an exclusive study of the interactions of relativistic ^{8}B and ^{9}Be nuclei in nuclear emulsion lead to the conclusion that the known features of their structure are clearly manifested in very peripheral dissociations. In spite of an extraordinarily large distinction from the nuclear excitation energy the relativistic scale not only does not impede investigations of nuclear interactions in energy scale typical for nuclear astrophysics, but on the contrary gives new methodical advantages. The maijor one of them is the possibility of principle of observing and investigating multi-particle systems. The study of the relativistic dissociation of ^{14}N nucleus to a 3He system confirm this prospect.

The presented observations can also serve as an illustration of prospects of the nuclear track emulsion technique for nuclear astrophysics in the case of using of relativistic nuclei. Providing the 3D-observation of narrow dissociation vertices nuclear emulsions gives novel possibilities of moving toward more and more complicated nuclear systems. Therefore this technique deserves upgrade, without changes in its detection basics, with the aim to speed up the microscope scanning for ratther rare events of peripheral dissociation of relativistic nuclei.

Acknowledgments

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[1] T. Aumann, Eur. Phys. J. A, **26**, 441(2005).

[2] D. A. Artemenkov, G. I. Orlova, P. I. Zarubin, T. Čhechák at al.(eds.) Nuclear Science and Safety in Europe (2006) 189-200, Springer; arXiv:nucl-ex/0604007v2.

[3] G. Baur, K. Hencken, D. Trautmann, Prog. Part. Nucl. Phys. **51**, 487(2003); arXiv:nucl-th/0304041.

[4] Web site of the BECQUEREL project: http://becquerel.jinr.ru.

[5] P. A. Rukoyatkin et al., Czech. J. Phys., **56**, C379(2006).

[6] A. El-Naghy et al., J. Phys. G, **14**, 1125 (1988).

[7] G. Baroni et al., Nucl. Phys., A **516**, 673(1990).

[8] G. Baroni et al., Nucl. Phys., A **540**, 646(1992).

[9] V. V. Belaga et al., Phys. At. Nucl., **58**, 1905 (1995).

[10] N. P. Andreeva et al., Phys. At. Nucl., **59**, 106 (1996).

[11] M. I. Adamovich et al., Phys. At. Nucl., **62**, 1378 (1999).

[12] M. I. Adamovich et al., J. Phys. G, **30**, 1479 (2004).

[13] M. A. Jilany, Phys. Rev., **70** 014901(2004).

[14] N. P. Andreeva et al., Phys. At. Nucl., **68**, 455 (2005); arXiv:nucl-ex/0605015v2.

[15] N. P. Andreeva et al., Eur. Phys. J. A 27, s01, 295-300(2006); arXiv:nucl-ex/0604003v2.

[16] D. A. Artemenkov et al., arXiv:nucl-ex/0610023v1.

[17] R. Stanoeva et al., Phys. At. Nucl., **70**, 1216 (2007); arXiv:nucl-ex/0605013v3.

[18] N. G. Peresadko et al., Phys. At. Nucl., **58**, 1266 (2007); arXiv:nucl-ex/0605014v1.

[19] D. A. Artemenkov et al., Phys. At. Nucl., **70**, 1222 (2007); arXiv:nucl-ex/0605018v1.

[20] T. V. Shchedrina et al., Phys. At. Nucl., **70**, 1271 (2007); arXiv:nucl-ex/0605022v1.

[21] D. A. Artemenkov, T. V. Shchedrina, R. Stanoeva, and P. I. Zarubin, International Symposium on Exotic Nuclei (EXON-2006), 2006, Khanty-Mansiysk, Russia. To be published in AIP Proceedings; arXiv:0704.0384v1 [nucl-ex].

[22] P. Schuck, H. Horiuchi, G. Roepke, and Tohsaki, C. R. Physique **4**, 537 (2003).

[23] G. Baur, K. Hencken, A. Aste, D. Trautmann, and S. R. Klein, Nucl. Phys. **A729** 787(2003); arXiv: nucl-th/0307031.

[24] A.S. Botvina, I.N. Mishustin, Phys. Rev., **C72**, 048801 (2005); arXiv:nucl-th/0506061.

[25] A.S. Botvina, I.N. Mishustin, W. Trautmann, arXiv:nucl-th/0612055.