ISSN 1063-7788, Physics of Atomic Nuclei, 2008, Vol. 71, No. 9, pp. 1565–1571. © Pleiades Publishing, Ltd., 2008.

ELEMENTARY PARTICLES AND FIELDS
Experiment

Fragmentation of Relativistic Nuclei in Peripheral Interactions in Nuclear Track Emulsion*

D. A. Artemenkov[1)], V. Bradnova[1)], M. M. Chernyavsky[2)], L. A. Goncharova[2)], M. Haiduc[3)], N. A. Kachalova[1)], S. P. Kharlamov[2)], A. D. Kovalenko[1)], A. I. Malakhov[1)], A. A. Moiseenko[4)], G. I. Orlova[2)], N. G. Peresadko[2)], N. G. Polukhina[2)], P. A. Rukoyatkin[1)], V. V. Rusakova[1)], V. R. Sarkisyan[4)], R. Stanoeva[5)], T. V. Shchedrina[1)], S. Vokál[1)], A. Vokálová[1)], P. I. Zarubin[1)***], and [1)]**

Received March 26, 2008

Abstract—The technique of nuclear track emulsions is used to explore the fragmentation of light relativistic nuclei down to the most peripheral interactions: nuclear "white" stars. A complete pattern of the relativistic dissociation of a ^{8}B nucleus with target fragment accompaniment is presented. Relativistic dissociation $^9\mathrm{Be} \to 2\alpha$ is explored using significant statistics, and a relative contribution of ^{8}Be decays from 0^+ and 2^+ states is established. Target fragment accompaniments are shown for relativistic fragmentation $^{14}\mathrm{N} \to 3\mathrm{He} + \mathrm{H}$ and $^{22}\mathrm{Ne} \to 5\mathrm{He}$. The leading role of the electromagnetic dissociation on heavy nuclei with respect to breakups on target protons is demonstrated in all these cases. It is possible to conclude that the peripheral dissociation of relativistic nuclei in nuclear track emulsion is a unique tool to study many-body systems composed of the lightest nuclei and nucleons in the energy scale relevant for nuclear astrophysics.

PACS numbers: 21.45.+v, 23.60.+e, 25.10.+s
DOI: 10.1134/S1063778808090111

1. INTRODUCTION

Nuclear beams of an energy higher than 1 *A* GeV are recognized as a modern tool used for the study of the structure of atomic nuclei (for a recent, review, see [1]). Among the variety of nuclear interactions, the peripheral dissociation bears uniquely complete information about the excited states above particle decay thresholds. The peripheral dissociation is revealed as a narrow jet of relativistic fragments whose total charge is close to the charge of the primary nucleus. In spite of the relativistic velocity of motion, the internal velocities in the jet are nonrelativistic [2]. Information about the generation of such fragment ensembles can be useful in nuclear astrophysics (indirect approaches), as well as in developments of nucleosynthesis scenarios on the basis of multiparticle fusion. It is necessary to provide a complete observation of fragments to utilize this possibility.

The difficulties in principle here are as follows. An increase in the dissociation degree of a relativistic nucleus leads to a decrease in the response of the fragment detector. This circumstance makes the complete analysis of relativistic fragments, which is necessary up to the He and H isotopes, rather difficult. The excited state is identified 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 requires that the threshold of detection of the target fragments in a total solid angle be reduced to a minimum.

The nuclear emulsion technique solves these problems and makes it possible to perform rather effectively survey investigations on newly produced beams [3]. Unique information about the structure of peripheral dissociation of many nuclei has already

*The text was submitted by the authors in English.

[1)]Joint Insitute for Nuclear Research, Dubna, Moscow oblast, 141980 Russia.
[2)]Lebedev Institute of Physics, Russian Academy of Sciences, Moscow, Russia.
[3)]Institute of Space Sciences, Magurele, Romania.
[4)]Institute of Physics, Erevan, Armenia.
[5)]Institute of Nuclear Research and Nuclear Energy, Bulgarian Academy of Sciences, Sofia, Bulgaria.
**E-mail: artemenkov@lhe.jinr.ru
***E-mail: zarubin@lhe.jinr.ru

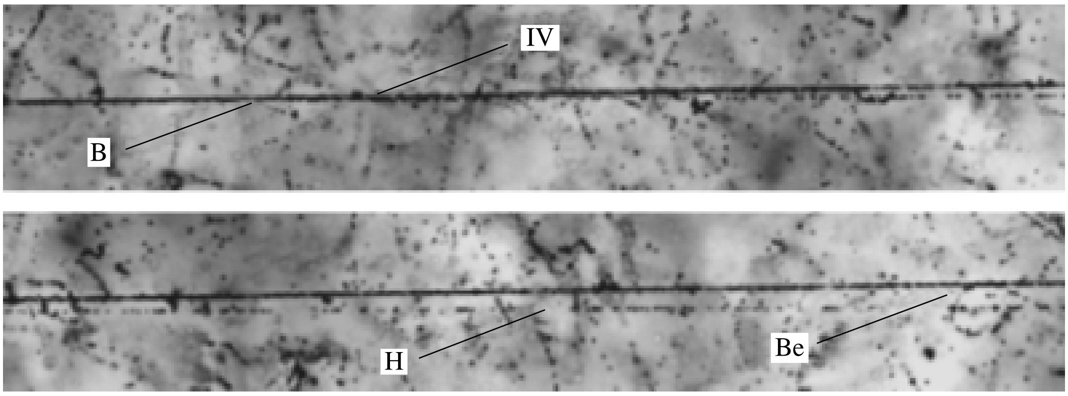

Fig. 1. Example of peripheral interaction of a 1.2 A GeV ^{8}B $\to$ ^{7}Be $+ p$ in a nuclear track emulsion ("white" star). The interaction vertex (indicated as IV) and fragment tracks (Be and H) in a narrow angular cone are seen in the microphotograph.

been obtained in [4, 5] and elsewhere. Limitations imposed on statistics are compensated by the fact that the fragment jet structures are inaccessible for observation in other approaches. In addition, an emulsion compound containing H, Ag, and Br nuclei in comparable concentrations (ratio of about 3.2/1/1) turns out to be useful for comparing interactions. Under the same conditions, it is possible to observe the very peripheral breakup in the EM field of a heavy target nucleus as well as in collisions with target protons.

The response of the emulsion nuclei includes the multiplicities of strongly ionizing target fragments from α particles up to recoil nuclei, n_b, and nonrelativistic H nuclei, n_g. In addition, 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 dissociation on Ag and Br and are named "white" stars ($n_b = 0$, $n_g = 0$, $n_s = 0$) [5]. 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 one which occurs 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 are given for the sake of illustration.

In what follows, the dissociation channels of ^{8}B, ^{9}Be, and ^{14}N are discussed. 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 of about 1.2 A GeV [6].

Table 1. The distribution of the peripheral interactions with $\sum Z_{\text{fr}} = 5$ 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

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

Owing to the small values of the proton binding energy, the ^{8}B nucleus is a sensitive probe of the type of the interaction up to the lowest momentum transfers. The study of the events with a total relativistic fragment charge of $\sum Z_{\text{fr}} = 5$ in an emulsion exposed to ^{8}B nuclei enabled one to establish the leading contribution of the "white" stars ^{8}B $\to$ ^{7}B $+ p$ as compared with the stars containing the target fragments [7, 8]. This fact shows a qualitative difference from ^{10}B nuclei for which "white" stars 2He + H were predominant [9].

A detailed distribution of the ^{8}B dissociation over the fragment configurations $\sum Z_{\text{fr}}$ and the numbers of

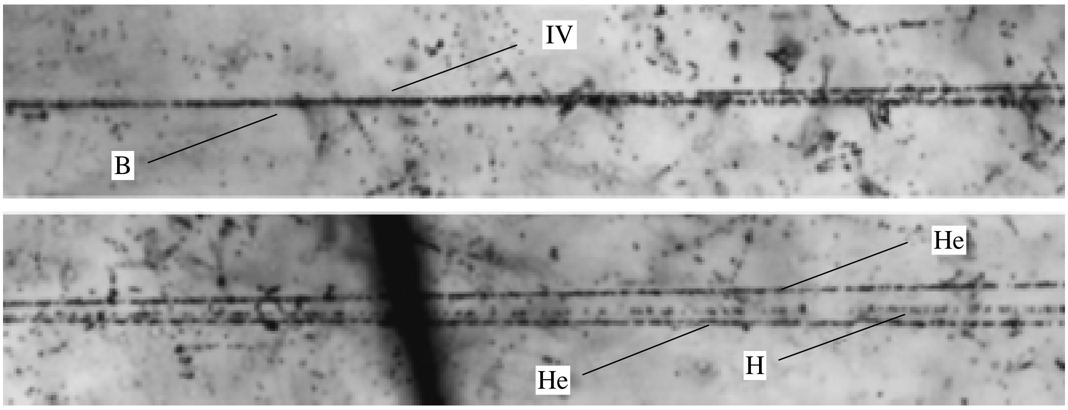

Fig. 2. Example of peripheral interaction of a 1.2 A GeV ^{8}B $\rightarrow$ 2He + H in a nuclear track emulsion ("white" star). The interaction vertex (indicated as IV) and nuclear fragment tracks (H and He) in a narrow angular cone are seen in the microphotograph.

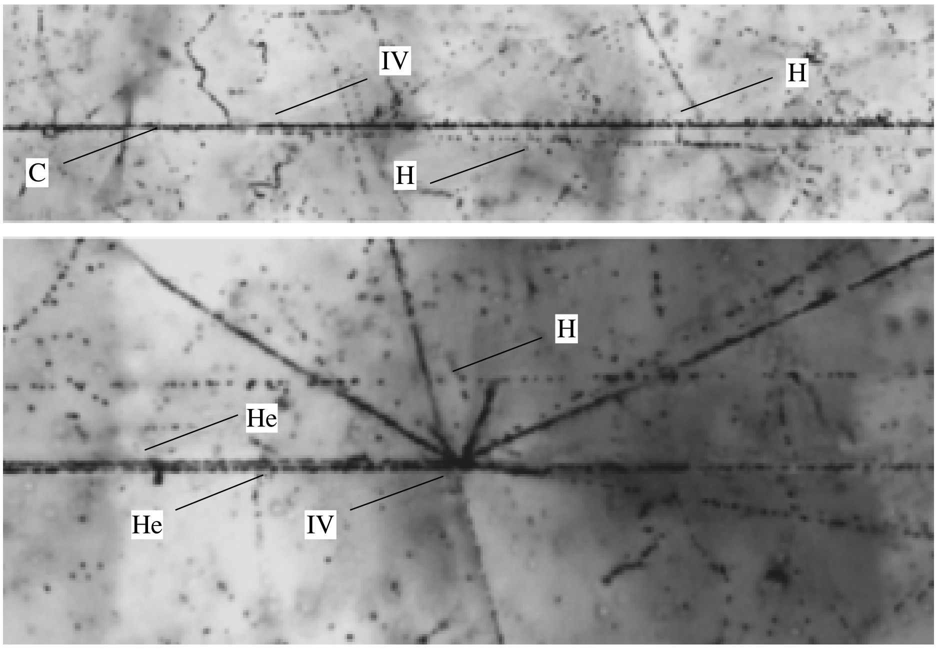

Fig. 3. Example of peripheral interaction of a 1.2 A GeV ^{10}C $\rightarrow$ 2He + 2H in a nuclear track emulsion ("white" star). The interaction vertex (indicated as IV) and nuclear fragment tracks (H and He) in a narrow angular cone are seen in the upper microphotograph. Following the direction of the fragment jet, one can distinguish two doubly charged fragments (^{8}Be decay) in bottom microphotograph. One of the He fragments produces a secondary star.

target fragments n_b and n_g is given in Table 1. First of all, the predominance of "white" stars ^{8}B $\rightarrow$ ^{7}Be + p should be noted (an 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). Half the number of "white" stars is associated with three- and four-particle dissociation modes having much higher thresholds. This implies that the multiple fragmentation can be initiated by an EM excitation. It may also be noted that, in the 2He + H 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 in direct proton–nucleon collisions.

A further accumulation of statistics on "white" stars ^{8}B $\rightarrow$ 2He + H is of special interest (an example is shown in Fig. 2). As is known, multiple scatter-

Table 2. The distribution of the peripheral interactions $^9\mathrm{Be} \to 2\alpha$ over intervals $Q_{2\alpha}$ versus target fragment numbers n_b and n_g with corresponding mean values of α pair total transverse momentum $\langle P_T^{2\alpha} \rangle$

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
$\langle P_T^{2\alpha} \rangle$ [MeV/c]	133 ± 16	166 ± 40	154 ± 14				
$1 < Q_{2\alpha} < 4$ MeV	33	10	14	3	2	1	–
$\langle P_T^{2\alpha} \rangle$ [MeV/c]	127 ± 15	195 ± 54	178 ± 23				
4 MeV $< Q_{2\alpha}$	13	7	4	2	2	3	1
$\langle P_T^{2\alpha} \rangle$ [MeV/c]	202 ± 31	232 ± 42	281 ± 51				

ing 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 labor intensive, the appropriate efforts can be compensated by the identification of a three-particle mode $^8\mathrm{B} \to 2^3\mathrm{He} + {}^2\mathrm{H}$ (threshold of 20 MeV). This possibility is nontrivial 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 $2^3\mathrm{He} + {}^2\mathrm{H}$ 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 [10] form the basis for a comparative analysis of the ^{9}C nucleus as the next step. A beam of these nuclei is created in the fragmentation of ^{12}C nuclei of an energy of 1.2 GeV, and it is used to expose the emulsion. In all probability, the pattern for ^{8}B and ^{7}Be nuclei with the addition of one or, respectively, two protons must be reproduced for the ^{9}C dissociation. In addition the dissociation $^9\mathrm{C} \to 3^3\mathrm{He}$ (threshold of 16 MeV) will become accessible for observation. The observation of 3^3He population near the threshold would allow one to establish the grounds for an extension of the well-known 3α fusion process toward the 3^3He one.

The emulsion exposed to ^{8}B nuclei allowed us to observe events with the total charge of relativistic fragments $\sum Z_{\mathrm{fr}} = 6$ from the mixture of ^{10}C nuclei produced in the generating target owing to the charge-exchange process $^{10}\mathrm{B} \to {}^{10}\mathrm{C}$. Their distributions over the charge track topology are given in the two lower lines of Table 1. Even restricted statistics point out that the 2He + 2H breakup accompanied by the conservation of α-particle clusters in "white" stars is more preferable (an example is shown in Fig. 3). A low $^8\mathrm{Be} + 2p$ channel threshold equal to 3.8 MeV is manifested in such a way.

The $^{10}\mathrm{B} \to {}^{10}\mathrm{C}$ charge exchange can be used for further exposures of emulsions with the aim not only to explore the main channel of dissociation 2He + 2H, but also to establish existence of the dissociation mode $^{10}\mathrm{C} \to {}^4\mathrm{He} + 2^3\mathrm{He}$ (threshold of 17 MeV). In just the same way as in the ^{9}C case, its discovery could enlarge the picture of the 3He fusion process in nuclear astrophysics. To search for $^8\mathrm{B} \to 2\mathrm{He} + \mathrm{H}$ and $^{9,10}\mathrm{C} \to 3\mathrm{He}$ related to the fragmentation channels, it is possible to perform a scanning over the area. This method was already used for accelerating the search for the events $^{12}\mathrm{C} \to 3\mathrm{He}$ [11] and $^{16}\mathrm{O} \to 4\mathrm{He}$ [12], as is discussed below for $^9\mathrm{Be} \to 2\mathrm{He}$.

3. FRAGMENT ACCOMPANIMENT OF $^9\mathrm{Be} \to 2\mathrm{He}$ DISSOCIATION

The ^{9}Be nucleus is a source for the study of the ground and excited states of the ^{8}Be nucleus. Information about the generation of a relativistic 2α particle system without the presence of the combinatory background of other α particles can be utilized in analyzing more complicated $N\alpha$ systems. The present-day interest in such systems is inspired by the suggested search for the α-particle Bose–Einstein condensate [13] 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 should be very important in the development of ideas about nucleosynthesis. The peripheral dissociation to relativistic $N\alpha$ jets may turn out to be the most convenient tool for searching for it [14].

In an emulsion exposed to relativistic ^{9}Be nuclei, 362 events of fragmentation to a narrow pair of relativistic He nuclei were analyzed under the assumption of their correspondence to 2α [8, 15]. A subset of 283

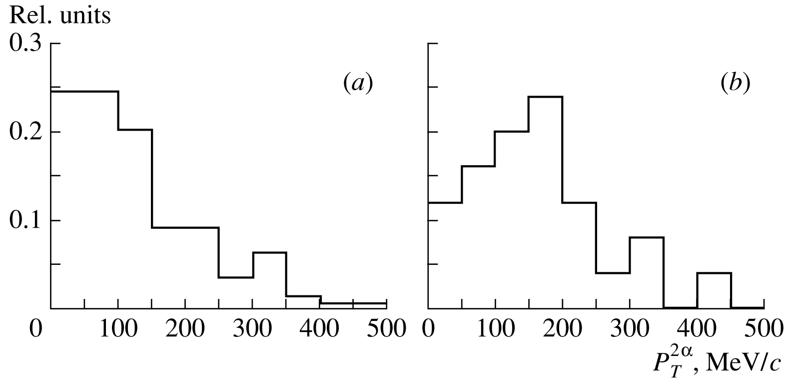

Fig. 4. The total transverse momentum distribution of α pairs, $P_T^{2\alpha}$, in 1.2 A GeV ^{9}Be $\to 2\alpha$ for (a) "white" stars and (b) breakups on protons.

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 observations of the ^{9}Be interaction vertices allow one to separate the population of these states for EM and direct nucleon interactions. Table 2 gives the distribution of the ^{9}Be $\to$ 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 to 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^+ ($Q_{2\alpha}1$ MeV) and 2^+ ($1 < Q_{2\alpha} < 4$ MeV) is equal to $R_{0/2} = 3 \pm 0.6$, and in the case of collisions with target protons ($n_b = 0, n_g = 1$), it is equal to $R_{0/2} = 1 \pm 0.5$. Thus, in peripheral fragmentation, 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 $R_{0/2} = 1.5 \pm 0.5$.

Following the concept about the ^{9}Be nucleus as a cluster system $\alpha{-}n{-}\alpha$, 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^+. An inverse ^{9}Be-synthesis process might be considered as a radiation transition $0^+ \to 2^+$ 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.

Figure 4 shows the total-transverse-momentum distribution transferred to α pairs, $P_T^{2\alpha}$, for (a) "white" stars and from (b) breakups on protons. The following average values are obtained: $\langle P_T^{2\alpha} \rangle = 138 \pm 12$ 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 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 disintegration on Ag and Br. An increase in the target fragmentation multiplicity can be expected to result in an explicit increase in $\langle P_T^{2\alpha} \rangle$ (Table 2). 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.

4. 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 $Z_{\rm fr} = 7$ [8, 16] has resulted in the conclusion about the leading part of the ^{14}N $\to$ 3He channel. Therefore, 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 covering the α-particle levels just above the ^{12}C dissociation threshold. Thus, the problems of few-body nuclear physics near the α emission threshold can be explored using detection advantages of the relativistic collisions.

The pattern of the target fragment accompaniment in the ^{14}N dissociation (Table 3) is of the same nature

Table 3. The distribution of the peripheral interactions $^{14}\text{N} \to 3\text{He} + \text{H}$ and $^{22}\text{Ne} \to 5\text{He}$ versus target fragment numbers n_b and n_g with corresponding mean values of α pair total transverse momentum $\langle P_T^{2\alpha} \rangle$

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
$\langle P_T^{3\alpha} \rangle$ [MeV/c]	222 ± 21	217 ± 51	262 ± 31	378 ± 54			
^{22}Ne	3	–	1	–	–	1	–
$\langle P_T^{5\alpha} \rangle$ [MeV/c]	518 ± 85	–	–	–	–	–	–

as in the case for ^{9}Be. In spite of some increase in the threshold over Q, the main α-particle channel of the systems is the EM dissociation on heavy nuclei. The "white" stars dominate, while the hydrogen dissociation contribution is not large. Within statistical errors, 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 2α and 3α ensembles are alike.

As an example of a more complicated system, Table 3 gives the description of the accompaniment of five events for ^{22}Ne for 3.2 A GeV selected on the basis of 4100 inelastic interactions [14]. In spite of a limited amount of data, one can conclude that the generation of 5α-particle systems proceeds more preferably via fragmentation on Ag and Br ($n_b = 0$, $n_g = 0$). 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 dissociation of light nuclei with a pronounced α clustering.

The investigations with light nuclei create a methodical basis for the study of exclusively complicated systems He–H–n for the energy scale relevant for nuclear astrophysics. In this respect, the motivated prospects are associated with a detailed analysis of the already observed fragment jets in the events of complete EM dissociation of Au nuclei at 10.6 A GeV and Pb nuclei at 160 A GeV.

5. CONCLUSIONS

Possessing a record spatial resolution, the nuclear emulsion method retains unique possibilities in studying the structural particularities of light nuclei, first of all, 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 particular features of their structure are clearly manifested in 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 on an energy scale typical of nuclear astrophysics, but, on the contrary, gives new methodical advantages. The main advantage is the possibility in principle of observing and investigating multiparticle systems. The study of the relativistic dissociation of ^{14}N nucleus to a 3He system confirms this prospect.

The presented observations can also serve as an illustration of unique prospects of the emulsion method for nuclear astrophysics using relativistic nuclei. Providing the three-dimensional observation of dissociation events, the nuclear emulsion method gives unique possibilities of moving toward more and more complicated nuclear systems generated in peripheral dissociations. Therefore, this method deserves upgrade, without changes in its basic designation for particle detection, with the aim to speed up the microscope search for rather rare events of peripheral dissociation of relativistic nuclei.

6. ACKNOWLEDGMENTS

The work was supported by the Russian Foundation for Basic Research (project nos. 96-159623, 02-02-164-12a, 03-02-16134, 03-02-17079, and 04-02-16593), VEGA 1/9036/02 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 the Republic of Bulgaria, the Slovak Republic the Czech Republic and Romania in the years 2002–2007.

REFERENCES

1. T. Aumann, Eur. Phys. J. A **26**, 441 (2005).
2. D. A. Artemenkov, G. I. Orlova, and P. I. Zarubin, in *Proceedings of the Nuclear Science and Safety in Europe, 2006* (Springer, 2006), p. 189; nucl-ex/0604007v2.
3. BECQUEREL Project: http://becquerel.jinr.ru
4. A. El-Naghy et al., J. Phys. G **14**, 1125 (1988).
5. G. Baroni et al., Nucl. Phys. A **516**, 673 (1990).

6. P. A. Rukoyatkin et al., Czech. J. Phys. **56**, 379 (2006).
7. R. Stanoeva et al., Phys. At. Nucl. **70**, 1216 (2007); nucl-ex/0605013v3.
8. D. A. Artemenkov, T. V. Shchedrina, R. Stanoeva, and P. I. Zarubin, in *Proceedings of the International Symposium on Exotic Nuclei (EXON-2006), Khanty-Mansiysk, Russia, 2006*; to be published in AIP Proc.; nucl-ex/0704.0384v1.
9. N. P. Andreeva et al., Phys. At. Nucl. **68**, 455 (2005); nucl-ex/0605015v2.
10. N. G. Peresadko et al., Phys. At. Nucl. **58**, 1226 (2007); nucl-ex/0605014v1.
11. V. V. Belaga et al., Phys. At. Nucl. **58**, 1905 (1995).
12. F. A. Avetyan et al., Phys. At. Nucl. **59**, 102 (1996).
13. P. Schuck, H. Horiuchi, G. Roepke, and C. R. Tohsaki, Physique **4**, 537 (2003).
14. N. P. Andreeva et al., Eur. Phys. J. A **27**S1, 295 (2006); nucl-ex/0604003v2.
15. D. A. Artemenkov et al., Phys. At. Nucl. **70**, 1222 (2007); nucl-ex/0605018v1.
16. T. V. Shchedrina et al., Phys. At. Nucl. **70**, 1230 (2007); nucl-ex/0605022v1.