Fragmentation of Relativistic Nuclei in Peripheral Interactions in Nuclear Track Emulsion


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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 $^9$Be $\rightarrow$ 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 $^{14}$N $\rightarrow$ $^3$He + H and $^{22}$Ne $\rightarrow$ $^5$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.

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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
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].

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 \(\sum Z_{fr} = 5\) 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 [7, 8]. This fact shows a qualitative difference from \(^{10}\)B nuclei for which “white” stars \(^{2}\)He + \(H\) were predominant [9].

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

<table>
<thead>
<tr>
<th>(n_b)</th>
<th>0</th>
<th>0</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td>(n_g)</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>He + 3H</td>
<td>12</td>
<td>6</td>
<td>3</td>
<td>3</td>
<td>2</td>
<td>3</td>
<td>--</td>
</tr>
<tr>
<td>2He + H</td>
<td>14</td>
<td>3</td>
<td>8</td>
<td>2</td>
<td>4</td>
<td>--</td>
<td>1</td>
</tr>
<tr>
<td>Be + H</td>
<td>25</td>
<td>1</td>
<td>3</td>
<td>3</td>
<td>1</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>2He + 2H</td>
<td>3</td>
<td>--</td>
<td>--</td>
<td>2</td>
<td>--</td>
<td>1</td>
<td>--</td>
</tr>
<tr>
<td>He + 4H</td>
<td>--</td>
<td>1</td>
<td>3</td>
<td>1</td>
<td>1</td>
<td>--</td>
<td>1</td>
</tr>
</tbody>
</table>
target fragments $n_b$ and $n_q$ is given in Table I. First of all, the predominance of “white” stars $^8B \rightarrow 7Be + p$ should be noted (an example is shown in Fig. 1). In this channel, there is practically no dissociation on protons $n_q = 1$. 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 ($n_q = 1$) and the events with target fragments ($n_b > 0$) with respect to the $7Be + p$ channel becomes the major one and increases by a factor of 5 as compared with the case of “white” stars ($n_b = 0, n_q = 0$). 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 $^8B \rightarrow 2He + H$ is of special interest (an example is shown in Fig. 2). As is known, multiple scatter-
The conservation of stars is more preferable (an example is shown in the inverse fusion process too. A particular feature of the threshold may turn out to be important for an cluster structure. The properties of this state near the threshold would allow one to establish the one. A particular feature of the 2\(^3\)He + 2H fusion process might consist in a larger number of vacancies for a neutron to be captured in the 4\(^4\)He cluster formation.

The conclusions about the EM dissociation of the 8\(^8\)B and 7\(^7\)Be nuclei [10] form the basis for a comparative analysis of the 9\(^9\)C nucleus as the next step. A beam of these nuclei is created in the fragmentation of 12\(^{12}\)C nuclei of an energy of 1.2 GeV, and it is used to expose the emulsion. In all probability, the pattern for 8\(^8\)B and 7\(^7\)Be nuclei with the addition of one or, respectively, two protons must be reproduced for the 9\(^9\)C dissociation. In addition the dissociation 9\(^9\)C + 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 establish the grounds for an extension of the well-known 3\(\alpha\) fusion process toward the 3\(^3\)He one.

The emulsion exposed to 8\(^8\)B nuclei allowed us to observe events with the total charge of relativistic fragments \(\sum Z = 6\) from the mixture of 10\(^{10}\)C nuclei produced in the generating target owing to the charge-exchange process 10\(^{10}\)B \(\rightarrow\) 10\(^{10}\)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 2\(^2\)He + 2H breakup accompanied by the conservation of \(\alpha\)-particle clusters in “white” stars is more preferable (an example is shown in Fig. 3). A low 8\(^8\)Be + 2p channel threshold equal to 3.8 MeV is manifested in such a way.

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

3. FRAGMENT ACCOMPANIMENT OF 9\(^9\)Be \(\rightarrow\) 2\(^2\)He DISSOCIATION

The 9\(^9\)Be nucleus is a source for the study of the ground and excited states of the 8\(^8\)Be nucleus. Information about the generation of a relativistic 2\(\alpha\) particle system without the presence of the combinatory background of other \(\alpha\) 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 \(\alpha\)-particle Bose–Einstein condensate [13] in which a ground 0\(^+\) and the first excited 2\(^+\) states of the 8\(^8\)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\(^9\)Be nuclei, 362 events of fragmentation to a narrow pair of relativistic He nuclei were analyzed under the assumption of their correspondence to 2\(\alpha\) [8, 15]. A subset of 283

**Table 2.** The distribution of the peripheral interactions 8\(^8\)Be \(\rightarrow\) 2\(\alpha\) over intervals \(Q_{2\alpha}\) versus target fragment numbers \(n_b\) and \(n_g\) with corresponding mean values of \(\alpha\) pair total transverse momentum \(P_T^{2\alpha}\)

| \(n_b\) | 0 | 0 | 1 | 2 | 3 | 4 | 5 |
| \(n_g\) | 0 | 1 | 21 | 8 | 1 | 3 | 1 |
| \(Q_{2\alpha} < 1\) MeV | 98 | 10 | 154 ± 14 |
| \(\langle P_T^{2\alpha}\rangle\) [MeV/c] | 133 ± 16 | 166 ± 40 | |
| 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 |
events with \( n_g = 0 \) is considered below. Clear appearance of two peaks in the distribution over the invariant mass above the \( \alpha \)-particle pair mass threshold \( Q_{2\alpha} \) was identified. It was concluded that the \( 0^+ \) and \( 2^+ \) states of \( ^9\text{Be} \) are revealed in the spectra over \( Q_{2\alpha} \).

The observations of the \( ^9\text{Be} \) interaction vertices allow one to separate the population of these states for EM and direct nucleon interactions. Table 2 gives the distribution of the \( ^9\text{Be} \to \alpha \text{He} \) 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 \( ^9\text{Be} \) collisions with protons \(( n_b = 0, n_g = 1 )\). The ratio of the “white” stars from the states \( 0^+ (Q_{2\alpha,1} \text{ MeV}) \) and \( 2^+ (1 < Q_{2\alpha} < 4 \text{ MeV}) \) 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 \( \alpha \) particle pair via the ground \( ^9\text{Be} \) 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 \( ^9\text{Be} \) 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 \( \alpha \) particle clusters with angular momentum \( L = 2 \). The presence of a neutron gives the value for the \( ^9\text{Be} \) spin 3/2. When the neutron is knocked out by the target proton, there proceeds either a dispersion of the \( \alpha \)-particle pair from the \( D \) state or a radiation transition to the \( ^8\text{Be} \) ground state \( 0^+ \). An inverse \( ^9\text{Be} \)-synthesis process might be considered as a radiation transition \( 0^+ \to 2^+ \) in the presence of the neutron. In other words, the \( \alpha \) pair goes out from the mass surface with \( \gamma \) emission. Such a picture is worthy of checking in experiments with \( \gamma \) detection.

Figure 4 shows the total-transverse-momentum distribution transferred to \( \alpha \) pairs, \( P_T^{2\alpha} \), for \(( a ) \) “white” stars and from \(( b ) \) breakups on protons. The following average values are obtained: \( \langle P_T^{2\alpha} \rangle = 138 \pm 12 \text{ MeV/c} \) \(( n_b = 0, n_g = 0 )\) and \( 194 \pm 28 \text{ MeV/c} \) \(( n_b = 0, n_g = 1 )\). There is a noticeable difference in the average values and the distribution shapes, which points to different dynamics of \( \alpha \) pair production. The \( ^9\text{Be} \) 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 \( \alpha \)He event statistics owing to a destruction of the \( ^9\text{Be} \) structure.

4. FRAGMENT ACCOMPANYMENT OF \( ^{14}\text{N} \) AND \( ^{22}\text{Ne} \) DISSOCIATION

The study of the peripheral dissociation of \( ^{14}\text{N} \) nuclei of an energy of 2.1 \( \text{A GeV} \) in the fragment state \( Z_f = 7 \) [8, 16] has resulted in the conclusion about the leading part of the \( ^{14}\text{N} \to \alpha \text{He} \) channel. Therefore, the peripheral \( ^{14}\text{N} \) dissociation can be used as an effective source of \( \alpha \)S systems. The dominant part of the events was shown to be concentrated in the interval of the invariant \( 3\alpha \)-particle mass over the \( ^{12}\text{C} \) mass \( 7 < Q_{3\alpha} < 20 \text{ MeV} \) covering the \( \alpha \)-particle levels just above the \( ^{12}\text{C} \) dissociation threshold. Thus, the problems of few-body nuclear physics near the \( \alpha \) emission threshold can be explored using detection advantages of the relativistic collisions.

The pattern of the target fragment accompaniment in the \( ^{14}\text{N} \) dissociation (Table 3) is of the same nature.
as in the case for $^9\text{Be}$. In spite of some increase in the threshold over $Q$, the main $\alpha$-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 $^{14}\text{N}$ and $^9\text{Be}$ points out that the dissociation mechanisms for $2\alpha$ and $3\alpha$ ensembles are alike.

As an example of a more complicated system, Table 3 gives the description of the accompaniment of five events for $^{22}\text{Ne}$ for $3.2$ $A$ $\text{GeV}$ selected on the basis of $4100$ inelastic interactions [14]. In spite of a limited amount of data, one can conclude that the generation of $5\alpha$-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 $5\alpha$-particle systems in these events when normalized to the $\alpha$-particle number is located in the region typical for dissociation of light nuclei with a pronounced $\alpha$ 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 $10.6$ $A$ $\text{GeV}$ and Pb nuclei at $160$ $A$ $\text{GeV}$.

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 $^8\text{B}$ and $^9\text{Be}$ 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 $^{14}\text{N}$ nucleus to a $3\text{He}$ 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

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