Clustering in light nuclei in fragmentation above 1 A GeV

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The relativistic invariant approach is applied to analyzing the 3.3 A GeV ^{22}Ne fragmentation in a nuclear track emulsion. New results on few-body dissociations have been obtained from the emulsion exposures to 2.1 A GeV ^{14}N and 1.2 A GeV ^{9}Be nuclei. It can be asserted that the use of the invariant approach is an effective means of obtaining conclusions about the behavior of systems involving a few He nuclei at a relative energy close to 1 MeV per nucleon. The first observations of fragmentation of 1.2 A GeV ^{8}B and ^{9}C nuclei in emulsion are described. The presented results allow one to justify the development of few-body aspects of nuclear astrophysics.

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I. INTRODUCTION

Interactions in few-body systems consisting of more than two ^{1,2}H and ^{3,4}He nuclei can contribute to a nucleosynthesis pattern. A macroscopic medium composed of the lightest nuclei having energy of a nucleosynthesis scale can possess the properties analogous to those of dilute quantum gases of atomic physics. In this sense, few-body fusions imply a phase transition to “drops”of a quantum liquid, that is, to heavier nuclei. Fusions can proceed via the states corresponding to low-lying cluster excitations in forming nuclei.

On a microscopic level the phase transition can proceed through the production of quasi-stable and loosely bound quantum states. Among candidates for such states one can consider the dilute α particle Bose condensate [1] as well as radioactive and unbound nuclei along a proton drip line. At first glance, exploration of few-body transitions in the laboratory conditions seems to be impossible. Nevertheless, such processes can indirectly be explored in the inverse processes of relativistic nucleus breakups in a nuclear track emulsion by selecting the excitations close to the few-body decay threshold.

Experimental data on charged topology for the final states of a number of light nuclei have been described in [2, 3, 4, 5, 6]. More specific studies were performed for the leading channels like ^{12}C→3α [7], ^{16}O→4α [8, 9], ^{6}Li→dα [10, 11], ^{7}Li→tα [12], ^{10}B→d$\alpha\alpha$ [13], and ^{7}Be→^{3}Heα [14]. A collection of appropriate reaction images can be found in [15, 16].

In the present paper the behaviour of relativistic systems consisting of several H and He nuclei will be described in terms of invariant variables of a 4-velocity space as suggested in [17]. The invariant presentation makes it possible to extract qualitatively new information about few-cluster systems from fragmentation of relativistic nuclei in peripheral interactions. The invariant approach is applied to the existing data on 3.3 A GeV ^{22}Ne interactions in a nuclear track emulsion, as well as to new data for 2.1 A GeV ^{14}N and 1.2 A GeV ^{9}Be nuclei extracted from a portion of recently exposured emul-

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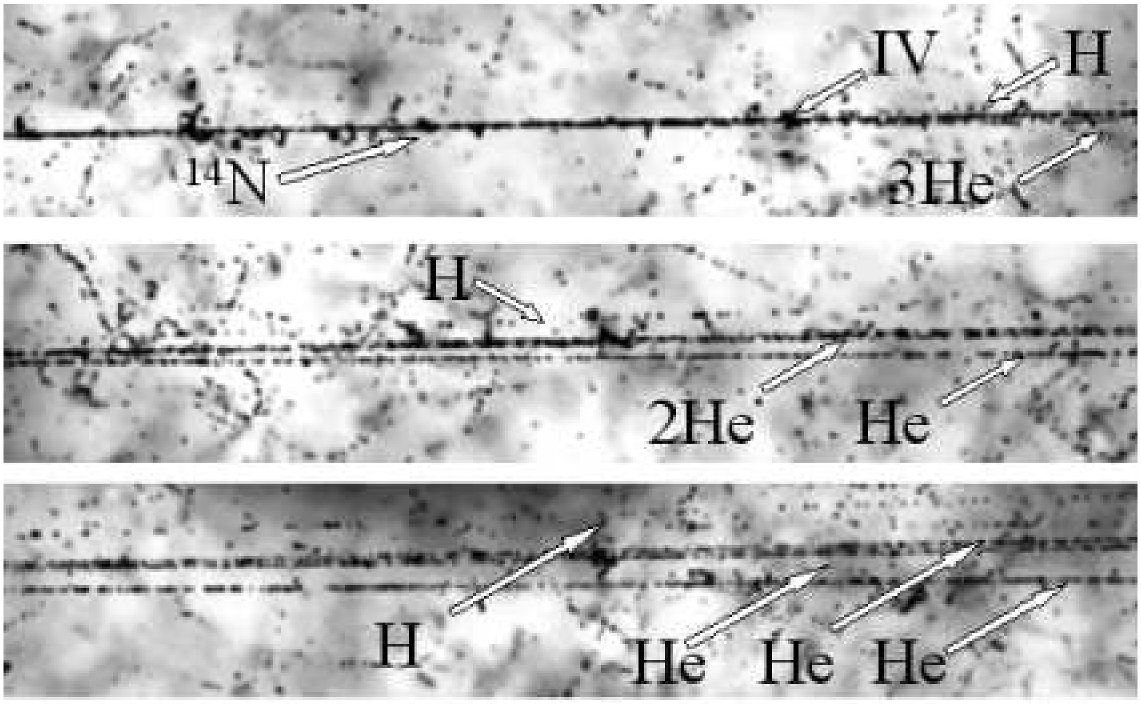

FIG. 1: Example of peripheral interaction of a 2.1 A GeV ^{14}N nucleus in a nuclear track emulsion ("white" star). The interaction vertex (indicated as **IV**) and nuclear fragment tracks (**H** and **He**) in a narrow angular cone are seen on the upper microphotograph. Following the direction of the fragment jet, it is possible to distinguish 1 singly and 3 doubly charged fragments on the middle and bottom microphotograph.

sion. The first observations of the fragment topology for neutron-deficient ^{8}B and ^{9}C nuclei in emulsion are described in this report. Last emulsion exposures were performed at the JINR Nuclotron in the years 2002-4 [18].

II. NUCLEAR FRAGMENT JETS

The relativistic projectile fragmentation results in the production of a fragment jet which can be defined by invariant variables characterizing relative motion

$$b_{ik} = -\left(\frac{P_i}{m_i} - \frac{P_k}{m_k}\right)^2 \qquad (1)$$

with $P_{i(k)}$ and $m_{i(k)}$ being the 4-momenta and the masses of the i or k fragments. Following [17], one can suggest that a jet is composed of the nuclear fragments having relative motion within the non-relativistic range $10^{-4} < \mathrm{b}_{ik} < 10^{-2}$. The lower limit corresponds to the ground state decay ^{8}Be$\rightarrow 2\alpha$, while the upper one - to the boundary of low-energy nuclear interactions. The expression of the data via the relativistic invariant variable b_{ik} makes it possible to compare the target and projectile fragmentation in a common form. Fig. 1 shows the microphotograph of a special example of a projectile fragment jet - the "white"star as introduced in [3]. It corresponds to the case of a relativistic nucleus dissociation accompanied by neither a target fragment nor meson production.

The variable characterizing the excitation of a fragment jet as a whole is an invariant mass M^* defined as

$$M^{*2} = (\Sigma P_j)^2 = \Sigma(P_i \cdot P_k) \qquad (2)$$

The system excitation can be characterized also by

$$Q = M^* - M \qquad (3)$$

with M being the mass of the ground state of the nucleus corresponding to the charge and weight of the fragment system. The variable Q corresponds to the excitation energy of the system of fragments in their c. m. s. A useful option is

$$Q' = \frac{(M^* - M')}{A} \qquad (4)$$

with M' being the sum of fragment masses and A the total atomic weight. The normalized variable Q' characterizes a mean kinetic energy of fragments per nucleon in their c. m. s. Precision of the experimental b_{ik} and Q

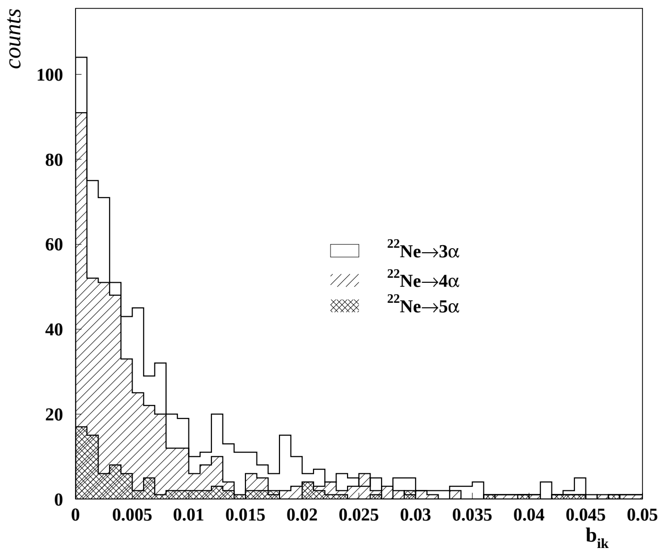

FIG. 2: Distribution of α particle pairs *vs* relative variable b_{ik} (1) for the fragmentation modes ^{22}Ne→ $n\alpha$.

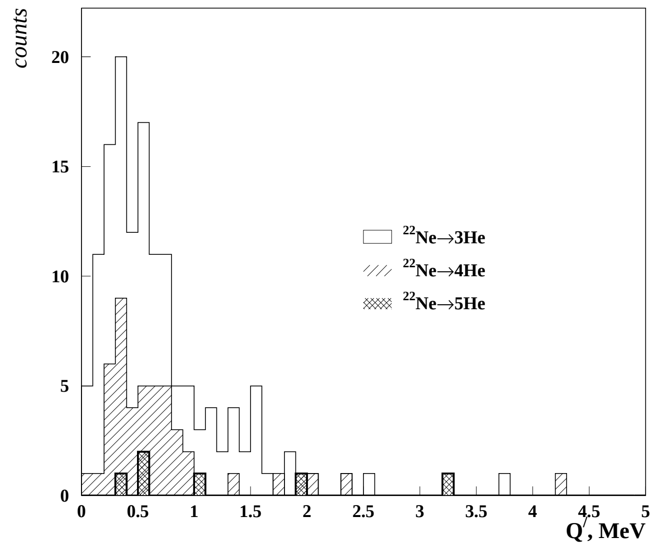

FIG. 3: Distribution of α particle pairs *vs* Q' (4) for the fragmentation modes ^{22}Ne→ $n\alpha$.

values is driven to a decisive degree by the angular resolution in the determination of unit vectors defining the direction of the fragment emission.

Due to excellent spatial resolution (about 0.5 μm) the emulsion technique is known to be most adequate for the observation and angular measurements of projectile fragments down to a total breakup of relativistic nuclei. Nevertheless, it has restrictions on the determination of the 4-momentum components of fragments. Firstly, the fragment spatial momentum in the projectile fragmentation cone is suggested to be equal within a few percent error to the primary nucleus value when normalized to the nucleon numbers. Secondly, by multiple scattering measurements it is possible to identify the mass only for relativistic H isotopes and much harder for He ones. Normally, the α particle mass is taken for the mass of doubly charged fragments in a narrow fragmentation cone. Both assumptions are proven to be reasonable for light stable nuclei.

III. FRAGMENTATION OF ^{22}Ne NUCLEI

A nuclear state analogous to the dilute Bose gas can be revealed in the formation of $n\alpha$ particle ensembles possessing quantum coherence near the production threshold. The predicted property of these systems is a narrow velocity distribution in the c. m. s. [1]. Originating from relativistic nuclei, they can appear as narrow $n\alpha$ jets in the forward cone defined by the nucleonic Fermi motion. The determination of the c. m. s. for each event is rather ambiguous while analysis of jets in the b_{ik} space enables one to explore $n\alpha$ particle systems in a universal way.

At our disposal there are data on 4100 events from 3.3 A GeV ^{22}Ne nucleus interactions with emulsion nuclei (presented in [2]) which contain the classification of secondary tracks by ionization and angles. The key feature for the ^{22}Ne fragmentation consists in a suppression of binary splittings into medium charge fragments with respect to He and H cluster formation. The increase of a fragmentation degree is revealed in a growth of the α particle multiplicity. Thus, transition to the $n\alpha$ particle states having a high level density predominate over the binary splittings occuring at lower energy thresholds.

In the present analysis, the doubly charged particles found in a forward 6° cone were classified as relativistic α particles. Fig. 2 shows the b_{ik} distribution (1) for the fragmentation channel ^{22}Ne→ $n\alpha$ for n equal to 3 (240 events), 4 (79 events), and 5 (10 events) which is rather narrow. The distribution "tails"appear to be due to the ^{4}He diffractive scattering or ^{3}He formation proceeding at higher momentum transfers. The events, satisfying the non-relativistic criterion b_{ik} $<10^{-2}$ for each α particle pair were selected for n equal to 3 (141 events), 4 (47 events), and 5 (6 events).

Fig. 3 presents the normalized Q' distribution (4) for them. Being considered as estimates of the mean kinetic energy per nucleon in the center-of-mass of nα system, the Q values does not exceed the Coulomb barrier values. Thus, in spite of the high $n\alpha$ multiplicity, the $n\alpha$ jets are seen to remain rather "cold"and consimilar. Among 10 ^{22}Ne→5α events there were found 3 "white" stars. Of these, in 2 "golden"events α particle tracks are contained even within a 1° cone. For these two events the value of Q' is estimated to be as low as 400 and 600 keV per nucleon. The detection of such "ultracold" 5α states is a

TABLE I: Charge-topology distribution of the "white" stars originated from the dissociation of 2.1 A GeV ^{14}N nuclei.

Z_f	6	5	5	4	3	3	–	–
N_1	1	–	2	1	4	2	3	1
N_2	–	1	–	1	–	1	2	3
N_{ws}	6	2	3	1	1	1	1	10

serious argument in favor of the reality of the phase transition of α clusterized nuclei to the dilute Bose gas of α particles. It gives a special motivation to explore lighter nα systems produced as potential "building blocks"of the dilute α particle Bose gas.

IV. FRAGMENTATION OF ^{14}N NUCLEI

We are presently engaged in accumulating statistics on the interactions of 2.1 A GeV ^{14}N nuclei in emulsion impacted on "white" star searches. 25 "white" stars have already been found among 540 inelastic events by scanning over primary tracks. Such a systematic scanning allows one to estimate relative probabilities of various fragmentation modes. The secondary tracks of "white"stars were selected to be concentrated in a forward 8° cone.

Table I shows a number of the found "white"stars N_{ws} composed of a single heavy fragment having charge Z_f and of N_1 singly and N_2 doubly charged fragments. The predominant role of the 4-prong mode 3He+H among the "white" stars is clearly seen. It implies that the exploration of the 3α systems originated in ^{14}N fragmentation is rather promising.

Fig. 4 allows one to compare the b_{ik} distribution for the "white" 3α stars to the case of 3He+H events where a prohibition on a target fragmentation is lifted of. In both cases, the criterion of a non-relativistic character of fragment interactions is satisfied.

Fig. 5 shows the $Q_{3\alpha}$ distribution in which the excitation energy is counted out from the ^{12}C nucleus mass. It can be concluded that the major fraction of entries is concentrated within a range of 10 to 14 MeV covering the known ^{12}C nucleus levels. Softening of the selection conditions for 3He+H events, under which the target fragment formation is allowable, does not result in a shift of the position of the 3α excitation peak. This circumstance points out the universality of the mechanism of population of 3α particle states. Besides, one can readily estimate that the normalized values $Q'_{3\alpha}$ are of the same magnitude as in fig. 3. Another conclusion is that the contribution of the α-^{8}Be state in the 3α configuration does not exceed a 10% -level. This topic awaits for higher statistics allowing a reliable ^{8}Be identification.

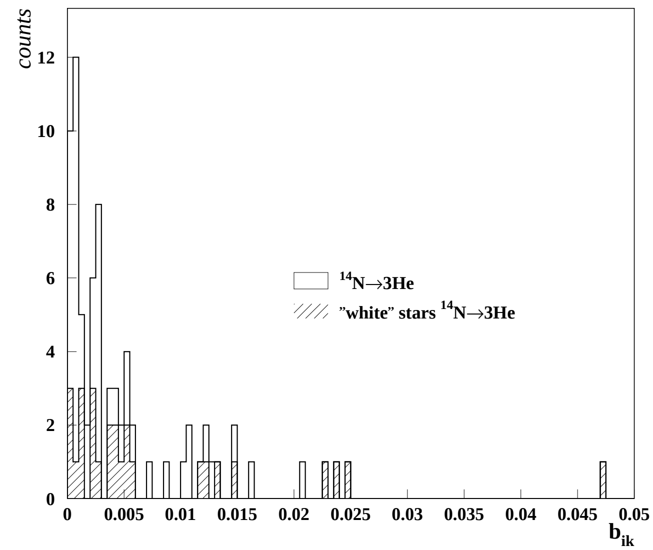

FIG. 4: Distribution of α particle pairs *vs* relative variable b_{ik} (1) for the fragmentation mode ^{14}N$\to$3α.

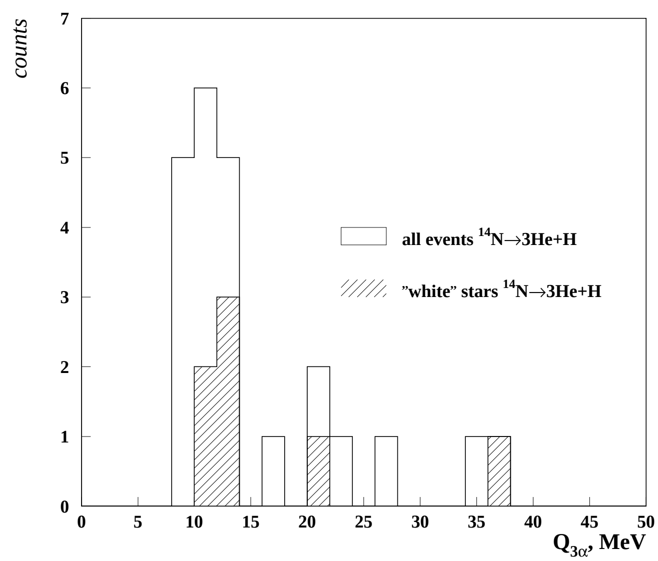

FIG. 5: Distribution of α particle triplets *vs* $Q_{3\alpha}$ (3) for the fragmentation mode ^{14}N$\to$3α+H.

V. FRAGMENTATION OF ^{9}Be NUCLEI

The relativistic ^{9}Be nucleus fragmentation is an attractive source for ^{8}Be generation due to the absence of a combinatorial background. The ^{8}Be nucleus reveals itself in the formation of α particle pairs having an extremely small opening angle of the order of a few 10^{-3} rad in the range of a few GeV. The estimation of the ^{8}Be production probability will make it possible to clear up the

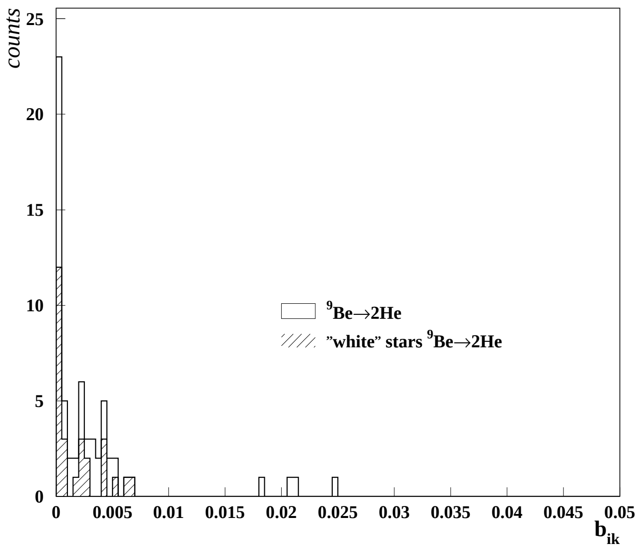

FIG. 6: Distribution of α particle pairs *vs* relative variable b_{ik} (1) for the fragmentation mode ^{9}Be→2α.

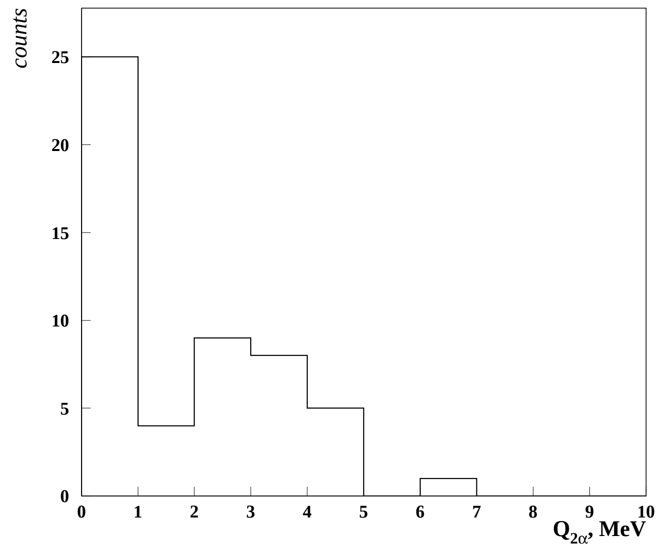

FIG. 7: Distribution of α particle pairs *vs* $Q_{2\alpha}$ (3) for the fragmentation mode ^{9}Be→2α.

interrelation between n-^{8}Be and α-n-α excitation modes which are important in understanding the ^{9}Be structure and fragmentation of heavier nuclei.

A secondary ^{9}Be beam was produced through fragmentation of the primary 1.2 A GeV ^{10}B beam. In scanning emulsion layers exposed to ^{9}Be nuclei, about 200 interactions are detected with He pair produced in a forward 8° cone. As in the previously considered cases, the b_{ik} distribution for 50 measured events, which is shown in fig. 6, confirms the non-relativistic behavior of the relative motion of the produced α particles. In just the same way as in the case of the ^{14}N nuclei, softening of the criterion of selection of the 2He pairs less rigid does not lead to changes of the distribution shape.

Fig. 7 shows the $Q_{2\alpha}$ distribution (3) allowing one to estimate the excitation scale. There is an event concentration below 1 MeV which is relevant for the ^{8}Be ground state decay. Besides, one can resolve a bump at around 3 MeV corresponding to the ^{8}Be decay from the first excited state 2^+. A zoomed part of this distribution near zero is presented in fig. 8. A clear peak is seen as a concentration of 14 events around the mean value $Q_{2\alpha}$ equal to 88 keV which is close to the decay energy of the ^{8}Be ground state. Thus, the achieved identification of ^{8}Be production allows one to justify the spectroscopy of $n\alpha$ decays from the lowest decay energy.

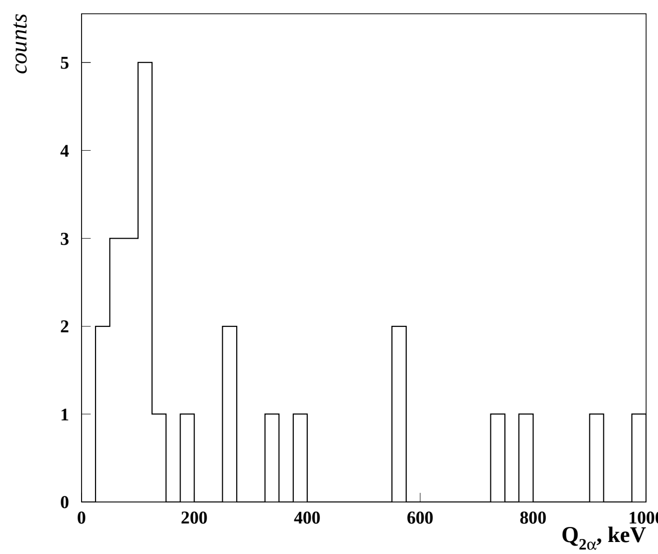

FIG. 8: Distribution of α particle pairs *vs* $Q_{2\alpha}$ (3) for the fragmentation mode ^{9}Be→2α zoomed between 0-1000 keV.

VI. CHARGED TOPOLOGY OF ^{8}B FRAGMENTATION

In order to expose an emulsion to ^{8}B nuclei, the use was made of fragmentation of 1.2 A GeV ^{10}B nuclei. In this case, absence of ^{9}B nuclei among secondary fragments turned out to be good luck, resulting in a clear separation of the primary and secondary beams by their magnetic rigidity. When scanning emulsions, this fact was indirecly

TABLE II: Charge-topology distribution of the "white" stars originated from the dissociation of 2.1 A GeV ^{8}B nuclei.

Z_f	4	3	–	–	–
N_2	–	–	2	1	–
N_1	1	2	1	3	5
N_{ws}	15	1	9	11	3

TABLE III: Charge-topology distribution of the "white" stars originated from the dissociation of 2.1 A GeV ^{9}C nuclei.

Z_f	5	4	–	–	–
N_1	1	2	–	2	4
N_2	–	–	3	2	1
N_{ws}	1	2	3	7	5

confirmed by the absence of "white" stars with a charge topology He+H. They could be produced by background ^{6}Li having the same magnetic rigidity as ^{10}B nuclei. A 15% -admixture of ^{7}Be nuclei was eliminated according to the charge topology of the found "white" stars. The most intensive background presented by ^{3}He nuclei was visually separated.

By scanning over the incoming tracks, a total of 39 "white" stars, in which the charge in the 15°-cone is equal to 5, have been found. Their distribution by the charge modes is shown in table II in the same manner as in table I. The significance of the ^{8}B modes can be compared with the topology of "white" stars produced by the 1 A GeV ^{10}B nuclei [13]. The fraction of the 3-prong stars ^{10}B→ 2He+^{1,2}H was established to be equal to 80 % with 40% deuteron clustering. The probability of the 2-prong mode ^{10}B→ ^{9}Be+^{1}H was found to be equal only to 3%. Such a strong difference can be explained by the lower value of the ^{2}H binding energy.

As is shown in table 2, an obvious distinction of the ^{8}B case consists in a high yield of the 2-prong mode ^{8}B→ ^{7}Be+^{1}H. This feature is due to the weak ^{1}H binding. Thus, one can conclude that the loosely bound ^{8}B nucleus manifests its structure already in the charge-topology. Further it is planned to increase statistics, identify the H and He isotopes, and reconstruct emission angles.

Obtaining ^{10,11}B beams at the JINR Nuclotron makes it possible to form ^{10,11}C secondary beams by the use of charge-exchange reactions analogous to the ^{7}Li→ ^{7}Be process [15]. This method is optimal for the emulsion technique where of importance is the simplicity of identification of incoming nuclei rather than their intensity. The existence and the cross sections of such processes will be established in a separate experiment. The suggested emulsion exposures will allow one to explore the 3-prong modes ^{10,11}C→3He analogous to the case ^{12}C→3α [7]. Clustering in ^{12}C→3α reflects the ternary α process Study of the 3He clustering in ^{10,11}C fragmentation would serve as a basis for studying the possible role of the Hefusion process in nucleosynthesis, that is, in media with a mixed composition of He isotopes.

VII. CHARGED TOPOLOGY OF ^{9}C FRAGMENTATION

Unfortunately, it is impossible to use the approach based on a charge-exchange reaction for the formation of a ^{9}C nucleus beam. An emulsion was exposed to a secondary beam produced in fragmentation of the 2.1 A GeV ^{12}C nuclei and having a ^{9}C magnetic rigidity. A search was made for the events in which the total charge of tracks in a forward 15° cone is equal to 6. The presently found 17 events are distributed as shown in table III. The 3He mode, which dominantes the ^{12}C "white" stars, is seen to be suppressed. Besides, there is an indication that multiple dissociation channels predominate over possible candidates to the p+^{8}B and p+p+^{7}Be modes. Verification of this observation makes a farther increase in statistics to be particularly intriguing.

The cases, which might be interpreted as 3^{3}He, are of especial importance since they point to highly-lying cluster excitations associated with a strong nucleon rearrangement to produce the 3^{3}He system. Like the process ^{12}C→3α, this dissociation can be considered as a visible reflection of the inverse process of a ternary N_{ws}He fusion. It can provide a significantly higher energy output followed by ^{4}He pair production. Search for an ternary ^{3}He process appears to be a major goal of further accumulation of statistics.

VIII. CONCLUSIONS

The invariant approach is applied to analyzing the relativistic fragmentation of ^{22}Ne, ^{14}N and ^{9}Be nuclei having a significant difference in the primary energy. It is shown that doubly charged fragments having relative b_{ik} within the range b_{ik} <10^{-2} form well-separated $n\alpha$ jets. It corresponds to the relative motion of α particles with relative kinetic energy of the order of 1 MeV per nucleon in the jet center-of-mass system.

New experimental observations are reported from the emulsion exposures to ^{14}N and ^{9}Be nuclei with energy above 1 A GeV. Being applied to the fragmentation of these nuclei the invariant analysis is shown to be a promising means to study excited states of simple α particle systems. The internal energy of a system involving He fragments can be estimated in an invariant form down to the ^{8}Be nucleus decays.

The pattern of the relativistic fragmentation becomes more complete in the case of proton excess in the explored nucleus. It is shown that nuclear track emulsions provide unique possibilities to explore few-body decays of ^{8}B and ^{9,10,11}C nuclei. The paper describes the start of this work. The invariant approach applied for the stable nuclei will be of special benefit in the case of the neutron deficient nuclei.

In spite of statistical restrictions, nuclear track emulsions ensure the initial stage of investigations in an unbiased way and enable one to develop scenarios for dedicated experiments [16]. Our experimental observations concerning few-body aspects of nuclear physics can be described in the relativistic invariant form allowing one to enlarge nuclear physics grounds of the nucleosynthesis pattern.

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