NEW TRENDS IN HIGH-ENERGY PHYSICS

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Diffractive dissociation of relativistic nuclei in nuclear track emulsion

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Abstract

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 are 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 mean of obtaining conclusions about the behavior of systems involving a few He nuclei at a relative energy close to 1 MeV per nucleon. The observations allow one to justify the development of few body aspects of nuclear astrophysics.

1 Introduction

Few body systems consisting of more than two H and He nuclei can contribute to the stellar nucleosynthesis. A macroscopic medium at a stellar temperature can possess the properties analogous to those of dilute quantum gases of atomic physics since the composing nuclei can have the values of the de

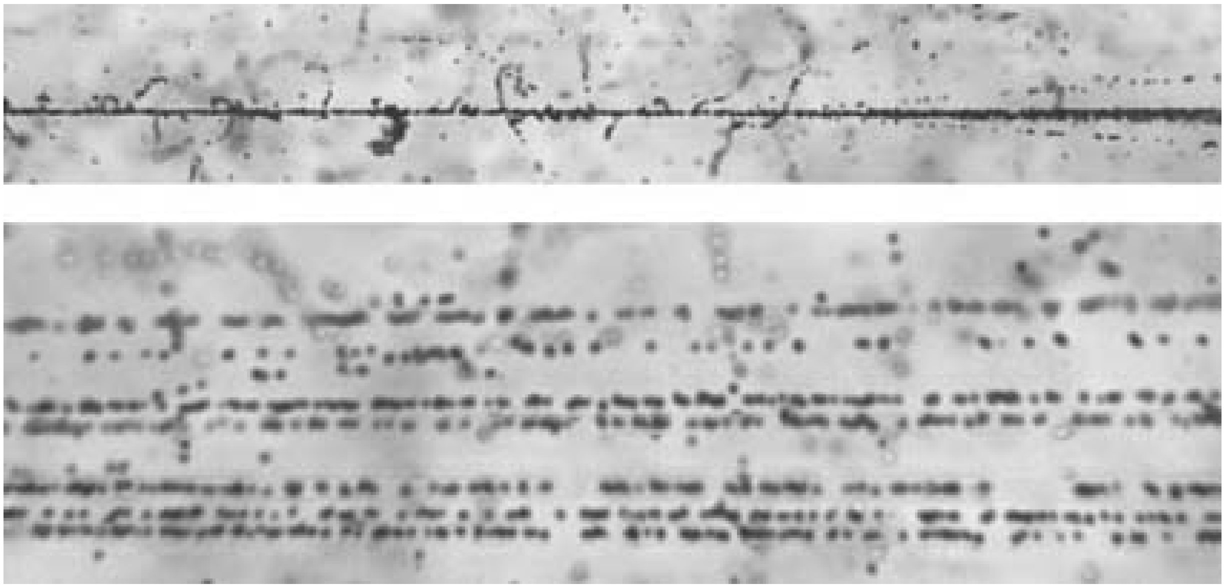

Figure 1: Peripheral interaction of a 3.65 A GeV ^{28}Si nucleus in a nuclear track emulsion. The interaction vertex, target recoil, a pair of singly charged particles and projectile fragment jet are seen on the upper microphotograph. Following the direction of the fragment jet (about 1 mm away the vertex), it is possible to distinguish 1 singly and 6 doubly charged fragments (bottom microphotograph).

Broglie wave length which exceed their sizes. In this sense, fusions of lightest nuclei imply their phase transitions 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 light nuclei.

The phase transition in stellar plasma 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. In such extended systems, bonding between charged clusters is set in at a reduced Coulomb repulsion. At the first glance, exploration of such transitions in the laboratory conditions seems to be impossible. Nevertheless, such reactions can indirectly be studied in the inverse processes of relativistic nucleus breakups via the excitation close to the few body decay threshold. In the present paper, production of relativistic systems consisting of few H and He nuclei will be presented and described in terms of invariant variables [15]. The invariant presentation makes it possible to extract qualitatively new information about few cluster systems from fragmentation of relativistic nuclei in peripheral interactions.

2 Clustering in relativistic fragmentation

The fragmentation of a large variety of light nuclei was investigated using the emulsions exposed to few A GeV nuclear beams at JINR [1 and ref. herein]. In this energy range, the pattern of the relativistic fragmentation loses sensitivity either to the collision energy or to the particular properties of a target nucleus. As an illustration, a 3.65 A GeV ^{28}Si fragmentation in emulsion is shown in fig. 1. The tracks of relativistic fragments remain in an emulsion sufficiently long for a 3D event image to be reconstructed. A system of 6 He and 1H fragments within a narrow cone is of our exploration interest. The cone is defined by the ratio of the transverse Fermi momentum to the primary nucleus one. The identification of relativistic H and He isotopes in emulsion is possible via the determination of the mean angle of multiple scattering. The excitation energy is defined by a fragment multiplicity, the produced fragment masses, and the emission angles. It can be estimated as the difference between the invariant mass of the fragmenting system and the mass of the primary nucleus that amounts to not more than 1 MeV per nucleon of the fragment. A collection of appropriate reaction images can be found in [16].

Existing experimental information on charged topology states for a number of light relativistic nuclei can be found in [2, 3, 4, 5, 6]. The common topological feature for fragmentation of the Ne, Mg, Si, and S nuclei consists in a suppression of binary splitting to fragments with charges larger than 2. The growth of the fragmentation degree is revealed in an increase of the multiplicity of singly and doubly charged fragments up to complete dissociation with increasing of excitation. This circumstance shows in an obvious way on a domination of the multiple cluster states having high density over the binary states having lower energy thresholds.

More specific correlation studies were performed for the leading fragmentation channels like ^{12}C$\rightarrow$3α [7], ^{16}O$\rightarrow$4α [8, 9], ^{6}Li$\rightarrow$dα [10, 11], ^{7}Li$\rightarrow$tα [12], ^{10}B$\rightarrow$d$\alpha\alpha$ [13], and ^{7}Be$\rightarrow$^{3}Heα [14]. In addition to the alpha clustering, a clustering of nucleons in the form of deuterons in ^{6}Li and ^{10}B decays, as well as of tritons in ^{7}Li decays has been revealed. Besides, the multiparticle dissociation is found to be important for these nuclei. Emulsions exposed to relativistic ^{14}N and ^{11}B isotopes are being analyzed with the aim to study clustering of these types. A ^{3}He clustering in ^{7}Be relativistic excitation is demostrated [6] and the next round of research, as to whether this kind of nuclear clustering is revealed in light neutron-deficient nuclei, is in progress now.

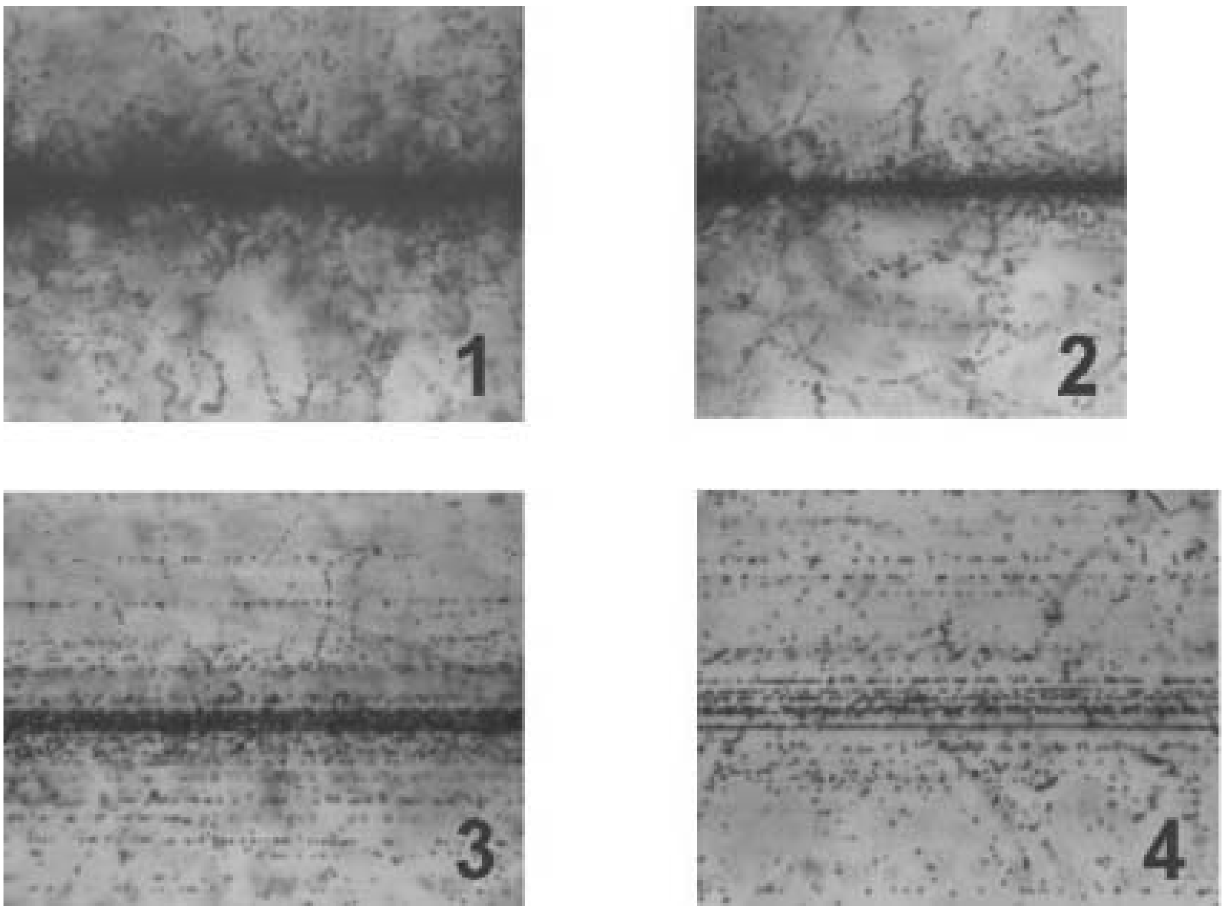

Figure 2: Event of peripheral interaction of a 158 A GeV ^{207}Pb nucleus in a nuclear track emulsion subsequently photoed on 3 cm path: 1 - primary nucleus track; 2 - interaction vertex without target recoils followed by projectile fragment jet; 3-jet kernel accompanied by singly and doubly charged particles; 4 - completely recognizable jet kernel.

The invariant approach is described below in application to the existing data on 3.3 A GeV ^{22}Ne for cluster dissociations in 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 exposed material. Clustering information of light nuclei can be considered as a ground for exploration of multiple fragmentation of heavy nuclei (example in fig. 2).

3 Nuclear fragment jets

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

$$b_{ik} = -(\frac{P_i}{m_i} - \frac{P_k}{m_k})^2 \quad (1),$$

with P and m being the 4-momenta and the masses of the i and k fragments. Following [15], one can suggest that a jet is composed of the nuclear fragments having relative motion within the non-relativistic range $10^{-4} < b_{ik} < 10^{-2}$. 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 and 2 show the microphotographs of a special examples of projectile fragment jets - the "white" stars (as introduced in [3]). It corresponds to the case of a relativistic nucleus dissociation not accompanied by target fragment tracks.

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

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

The system excitation can be characterized also by

$$Q = M^* - M \quad (3),$$

with M being the mass of the ground state of the nucleus corresponding to the charge and the 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

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

with M' being the sum of fragment masses and A the system nucleon number. The variable Q' characterizes a mean kinetic energy of fragments per nucleon in their c. m. s. Precision of the experimental b_{ik} and Q values is driven in a decisive degree by the angular resolution in the determination of unit vectors defining the direction of the fragment emission.

Due to an 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 more hardly for He ones. Usually, 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.

4 Relativistic nα systems

A nuclear state analogous to the dilute Bose gas can be revealed as the formation of nα particle ensembles possessing quantum coherence near the production threshold. Being originated from relativistic nuclei it can appear in a form of narrow nα particle jets in the forward cone. The predicted property of these systems is a narrow velocity distribution in the c. m. s. [1]. 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 nα particle systems in a universal way.

We have at our disposal data on events from peripheral interactions of 4.1-4.5 A GeV/c ^{22}Ne, ^{24}Mg and ^{28}Si with emulsion nuclei which are relevant for the problem (10-15% of statistics). Data contain the classification of secondary tracks by ionization and emission angles. Peripheral nuclear interactions have been selected using the criterion: the sum charge of the projectile fragments in the forward narrow cone has to be approximately equal to that of projectile one - $\sum Z_{fr} = Z_0 \pm 1$, where Z_0 is projectile charge.

Angular distributions of He fragments normalized per number of events are given in fig. 3 (left column) for different channels of ^{22}Ne fragmentation with 3, 4, and 5 He fragments in final states. Practically all projectile fragments with $Z_{fr} \geq 2$ are emitted mostly within the fragmentation cone defined by a critical angle θ_b, where $\sin(\theta_b)= 0.2(\mathrm{GeV/c})/P_0$; for instance $\theta_b=2.55^\circ$ at P_0 =4.5 A GeV/c. Inclusive angular distributions for He fragments produced in reaction channels with $n_{He} \geq 3$ of ^{22}Ne, ^{24}Mg and ^{28}Si collision are shown in fig.5 (right column).

In the present analysis, the doubly charged particles found in a forward

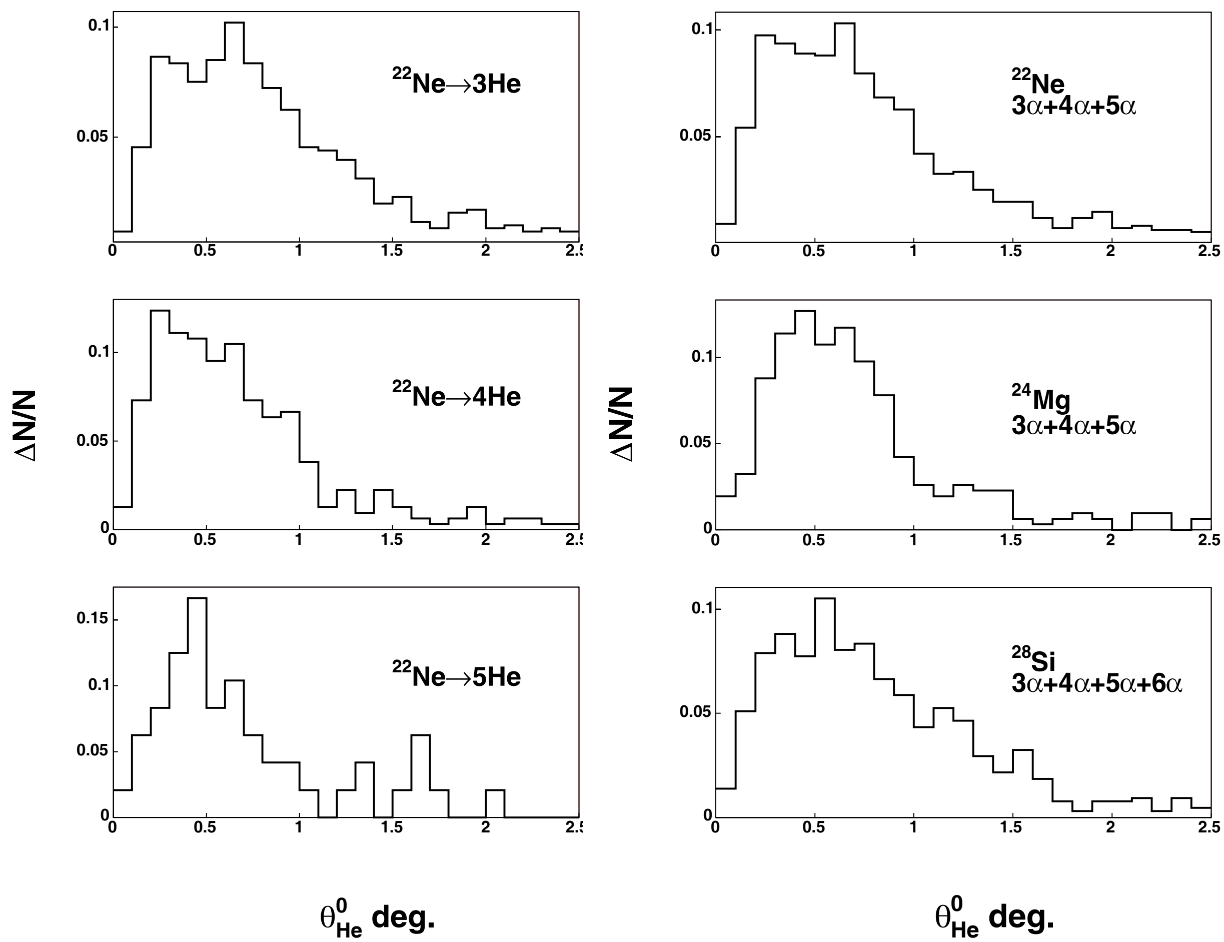

Figure 3: Normalized angular distributions of He fragments for different channels of ^{22}Ne collisions with 3, 4 and 5 He fragments in final state (left column) and for channels with $N_{He} \geq 3$ of ^{22}Ne, ^{24}Mg and ^{28}Si collisions (right column).

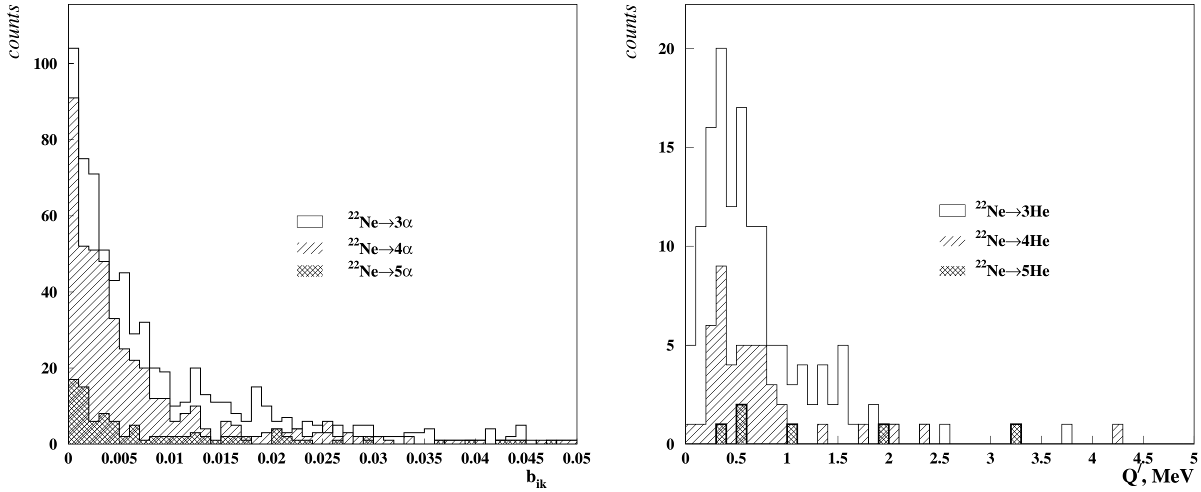

Figure 4: Distribution of α particle pairs *vs* invariant variables: left side - b_{ik} (1) and right side - Q' (4) for the fragmentation channels ^{22}Ne→nα.

6° cone were classified as relativistic α particles. Fig. 4 (left side) shows the b_{ik} distribution (1) for the fragmentation channel ^{22}Ne→nα 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 ^{3}He formation proceeding at a higher momentum transfer. To suppress this uncertainty the events satisfying a 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. 4 (right side) presents the distribution Q' (4) for them. Being considered as estimates of a mean kinetic energy per nucleon in c. m. s., the values of Q doesn't exceed typical Coulomb barrier values. Thus, in spite of a rising nα multiplicity, the nα jets are seen to remain rather "cold" and similar.

Among 10 ^{22}Ne→5α events it was found 3 "white" stars. Of them, in 2 "golden" events the 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 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.

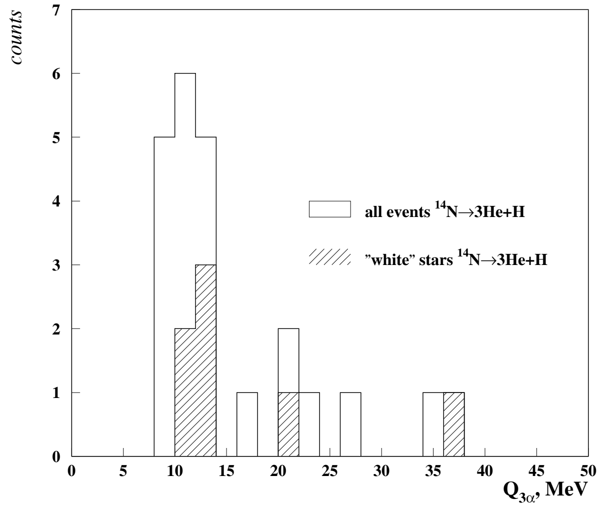

Figure 5: Distribution of α particle triplets *vs* $Q_{3\alpha}$ (3) for the fragmentation channel $^{14}N \rightarrow 3\alpha + H$.

5 Fragmentation of ^{14}N nuclei

We are presently engaged in accumulating statistics on the interactions of 2.1 A GeV ^{14}N nuclei with emulsion nuclei impacted on a "white" star search. The secondary tracks of "white" stars were selected to be concentrated in a forward 8° cone. 44 "white" stars have already been found among 950 inelastic events by scanning over primary tracks. Such a systematic scanning allows one to estimate relative probabilities of various fragmentation modes.

13 "white" stars are originated from the dissociations composed of a heavy fragment having charge Z_f=6 and a singly charged fragments corresponding separation proton or deuterog with low binding energy. 15 found "white" events with topology 3He+H demostrate importance of 4 and 5 body decay modes. It implies that the exploration of the 3α systems originated in ^{14}N fragmentation has a good prospective. The b_{ik} distributions are limited within b_{ik} <0.01 for the "white" 3α stars as well as in 3He+H events where a prohibition on a target fragmentation is lifted out. So, the criterion of a non-relativistic character of a projectile fragmenting system is satisfied.

The distribution in which the excitation energy $Q_{3\alpha}$ is counted out from the ^{12}C nucleus mass is given in fig. 5 (lower histogram). One is able to conclude that the major fraction of entries is concentrated within a range of 10 to 14 MeV corresponding to the known ^{12}C nucleus levels. Softening of the selection conditions for 3He+H events, under which the target fragment formation is allowable, doesn't result in a shift of the 3α excitation pattern (upper histogram in fig. 5). This circumstance points out the universality of the mechanism of population of the 3α particle states. Besides, one can easily estimate that the $Q'_{3\alpha}$ values are of the same magnitude as in fig. 5. As a preliminary conclusion, we note that the contribution of α-^{8}Be configuration in the 3α one doesn't exceed 10% level. The solution of this problem waits for higher statistics allowing a reliable ^{8}Be identification.

6 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 few 10^{-3} rad in the range of a few GeV's. The estimation of the ^{8}Be production probability will make it possible to clear up the interrelation between n-^{8}Be and α-n-α excitation modes which are important in understanding of the ^{9}Be nucleus structure and fragmentation of heavier nuclei.

A secondary ^{9}Be beam was produced via fragmentation of the primary 1.2 A GeV ^{10}B beam. In scanning emulsion layers exposed to ^{9}Be nuclei, 200 interactions are detected with He pair produced in a forward 8° cone. Just as in the previously considered cases, the b_{ik} distribution for 50 measured events confirms a non-relativistic behavior of relative motion of the secondary α particles. In just the same way as in the case of the ^{14}N nuclei, making of the criteria of selection of the 2He pairs in the fragmentation cone less rigid doesn't change the distribution shape.

Fig. 6 shows the distribution $Q_{2\alpha}$ (3) allowing to estimate the exitation 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. 6 (left histogram). A clear peak is seen as a concentration of 14 events around $Q_{2\alpha}$ corresponding to the ^{8}Be ground state decay. The decay energy is estimated to be equal to 88 ± 10 KeV. Identification of ^{8}Be production is of particular importance for justification of the spectroscopy of a few body decays in relativistic beams.

7 Conclusions

In the present report, the invariant approach is applied to analyzing the relativistic fragmentation of ^{22}Ne, ^{14}N and ^{9}Be nuclei having a significant

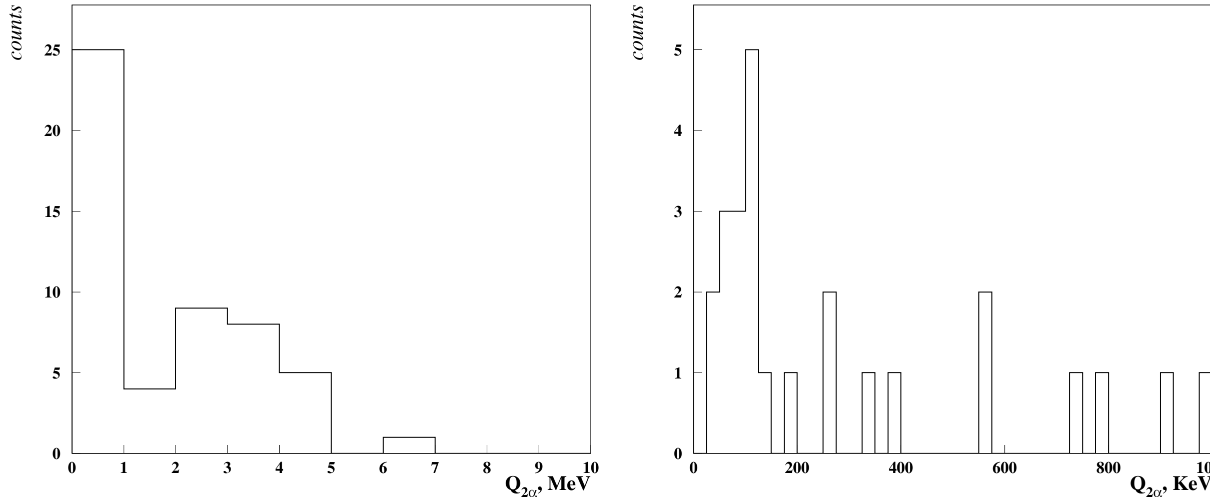

Figure 6: Left: distribution of α particle pairs *vs* $Q_{2\alpha}$ (3) for the fragmentation channel ^{9}Be$\rightarrow 2\alpha$. Right: the same distribution zoomed between 0-1000 KeV.

difference in the primary energy. Doubly charged fragments having relative b_{ik} within the range $b_{ik} < 10^{-2}$ are shown to form well separated nα jets. It corresponds to relative motion of α particles with relative kinetic energy of the order of 1 MeV per nucleon in the c. m. s. of the jet.

New experimental observations are reported from the emulsion exposures to ^{14}N and ^{9}Be nuclei with energy above 1 A GeV. The invariant analysis being applied to the fragmentation of these nuclei is shown to be a promising mean to study their decays into few lightest nuclei. The internal energy of a system involving He fragments can be estimated in an invariant form down to the ^{8}Be nucleus decays.

Nuclear track emulsions ensure the initial stage of investigations in an unbiased way and enable one to develop the scenarios for dedicated experiments [18]. Our experimental observations concerning few body aspects of nuclear physics can be expressed in the relativistic invariant form.

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