Light nucleus clustering in fragmentation above 1 A GeV

N. P. Andreeva[a], D. A. Artemenkov[b], V. Bradnova[b], M. M. Chernyavsky[c], A. Sh. Gaitinov[a], N. A. Kachalova[b], S. P. Kharlamov[c], A. D. Kovalenko[b], M. Haiduc[d], S. G. Gerasimov[c], L. A. Goncharova[c], V. G. Larionova[c+], A. I. Malakhov[b], A. A. Moiseenko[e], G. I. Orlova[c], N. G. Peresadko[c], N. G. Polukhina[c], P. A. Rukoyatkin[b], V. V. Rusakova[b], V. R. Sarkisyan[e], T. V. Schedrina[b], E. Stan[e], R. Stanoeva[b,f], I. Tsakov[f], S. Vokal[h], A. Vokalova[b], P. I. Zarubin[b], and I. G Zarubina[b]

[a]Insitutute for Physics and Technology, Almaty, Kazakh Republik.
[b]Joint Institute for Nuclear Research, Dubna, Russia.
[c]Lebedev Institute, Physics, Russian Academy of Sciences, Moscow, Russia.
[d]Institute of Space Sciences, Bucharest-Magurele, Romania.
[e]Yerevan Physics Institute, Yerevan, Armenia.
[f]Institute for Nuclear Research and Nuclear Energy, Bulgarian Academy of Sciences, Sofia, Bulgaria.
[g]P. J. Safarik University, Kosice, Slovak Republik.

[+] deceased

The relativistic invariant approach is applied to analyzing the 3.3A GeV ^{22}Ne fragmentation in a nuclear track emulsion. New results on few body dissociations are obtained from the emulsion exposures to 2.1A GeV ^{14}N and 1.2A GeV ^{9}Be nuclei. The first observations of fragmentation of 1.2 A GeV ^{8}B and ^{9}C nuclei in emulsion are described.

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 to1 MeV per nucleon. The observations allow one to justify the development of few body aspects of nuclear astrophysics.

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 of a dilute quantum gas since the composing nuclei have values of a de Broglie wave length which exceed their sizes. In this sense, lightest nucleus fusions imply their phase transitions to «drops» of a quantum liquid, that is, to heavier nuclei. The fusions can proceed via 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 nucleus breakups via the excitation close to the few body decay threshold.

In the present paper, production of systems consisting of few H and He nuclei will be described in terms of relativistic invariant variables [2]. The invariant presentation makes it possible to extract qualitatively new information about few cluster systems from fragmentation of relativistic nuclei in peripheral interactions [3]. Systematic data on charged topology states for a number of light nuclei and experiment details can be found in [4, 5]. The fragment correlation studies are presented for ^{12}C→3α in [6] and for ^{16}O→4α in [7].

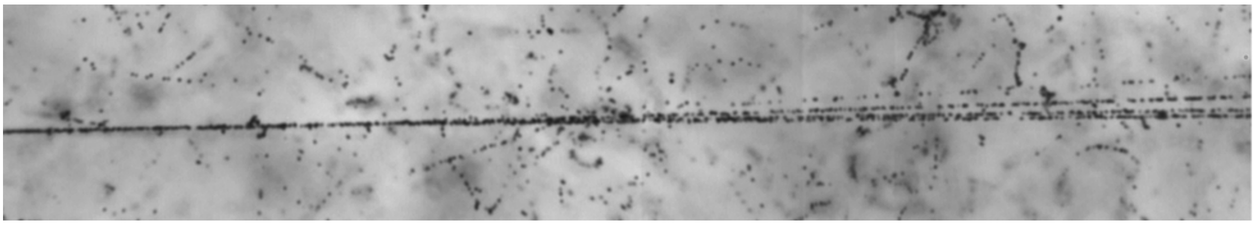

Fig. 1. Fragmentation of ^{14}N nucleus at 1.2 A GeV in emulsion. The interaction vertex and a fragment jet in a narrow angle cone are seen on the photograph. Following the direction of the fragment jet it is possible todistinguish 1 singly and 3 doubly charged fragments.

The invariant approach is applied to the existing data on 3.3A GeV ^{22}Ne interactions in nuclear track emulsion, as well as 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. The first observations of the fragment topology for neutron-deficient ^{8}B and ^{9}C nuclei in emulsion are described in this report. Recent emulsion exposures were performed at the JINR Nuclotron beams in the years 2002-2004 [8].

FRAGMENT JETS

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

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

with P and m being the 4-momenta and the masses of the i and k fragments. The jet is composed of the fragments having relative motion within the non-relativistic range $10^{-4}< b_{ik} <10^{-2}$ [2]. The lower limit corresponds to the ground state decay $^{8}Be\rightarrow 2\alpha$, while the upper one - to the limit 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. The example of a relativistic fragment jet is shown in fig. 1 («white» star). It corresponds to relativistic ^{14}N dissociation accompanied by neither a target fragment nor meson production.

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

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

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 the weight of the fragment system. The variable Q corresponds to a total excitation energy of fragment in their c. m. s. The useful option is

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

with M' being the sum of fragment masses and A the nucleon number in the system. The variable Q' characterizes a mean kinetic energy of fragments per nucleon in their c. m. s.

The values b_{ik} and Q is determined mostly by a scalar product of unit vectors defining the direction of the fragment emission. 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 to the primary nucleus value when normalized to the nucleon numbers. Secondly, the mass identification is possible only for relativistic H isotopes and much more hardly for He ones by multiple scattering measurements. 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.

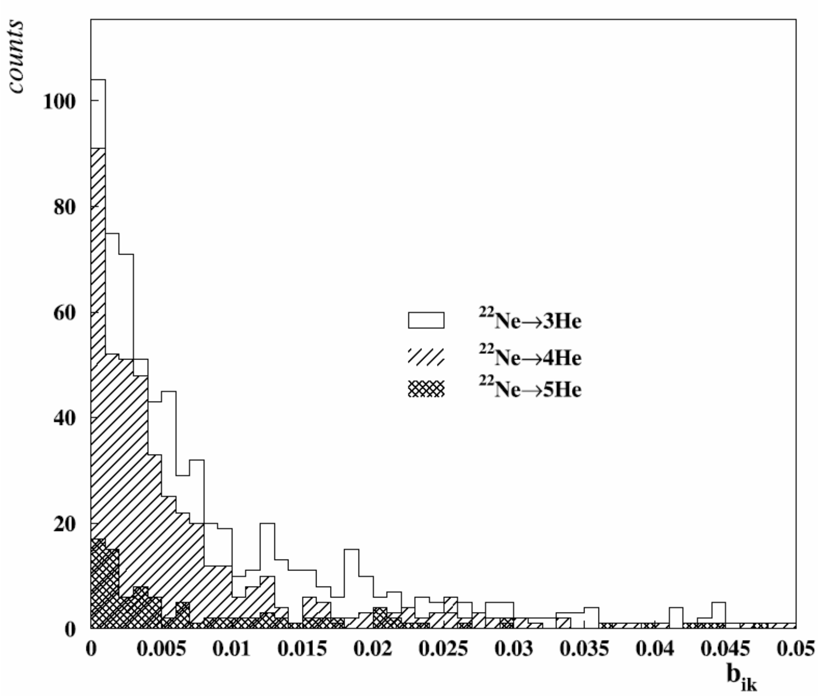

Fig. 2. The b_{ik} distribution for the fragmentation channels $^{22}Ne \to n\alpha$.

FRAGMENTATION OF ^{22}Ne NUCLEI

A nuclear state analogous to the dilute Bose gas can be revealed in the formation of *n*α particles 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]. Being originated from relativistic nuclei they can appear as narrow *n*α 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*α particle systems in a universal way.

We have data on 4100 events from 3.3A GeV ^{22}Ne nucleus interactions in emulsion which contain the classification of secondary tracks by ionization and angles. The feature for the ^{22}Ne fragmentation consists in a suppression of binary splitting to fragments with charges larger than 2 [5,9]. The fragmentation growth is revealed mostly in an increase of the multiplicity of doubly charged fragments. This circumstance can be treated as an indication of a preferred transition to the *n*α particle states having high density over the binary states having 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 $^{22}Ne \to n\alpha$ 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 ^{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. 3 presents the distribution Q’ (4) for them. Being considered as a distribution of the mean kinetic energy per nucleon in c. m. s., a major portion of the values of Q doesn’t exceed typical Coulomb barrier values. Thus, in spite of a rising *n*α multiplicity, the *n*α jets are seen to remain rather “cold” and similar.

Among 10 events $^{22}Ne \to 5\alpha$ it was found 3 “white” stars. i. e. accompanied by neither target fragments nor produced mesons. Of them, in 2 “golden” events α particle tracks are even within a 1° cone. For these two events 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 *n*α nuclei to the dilute Bose gas of α particles. It gives a special motivation to explore lighter *n*α systems produced as potential “building blocks” of a dilute α particle Bose gas.

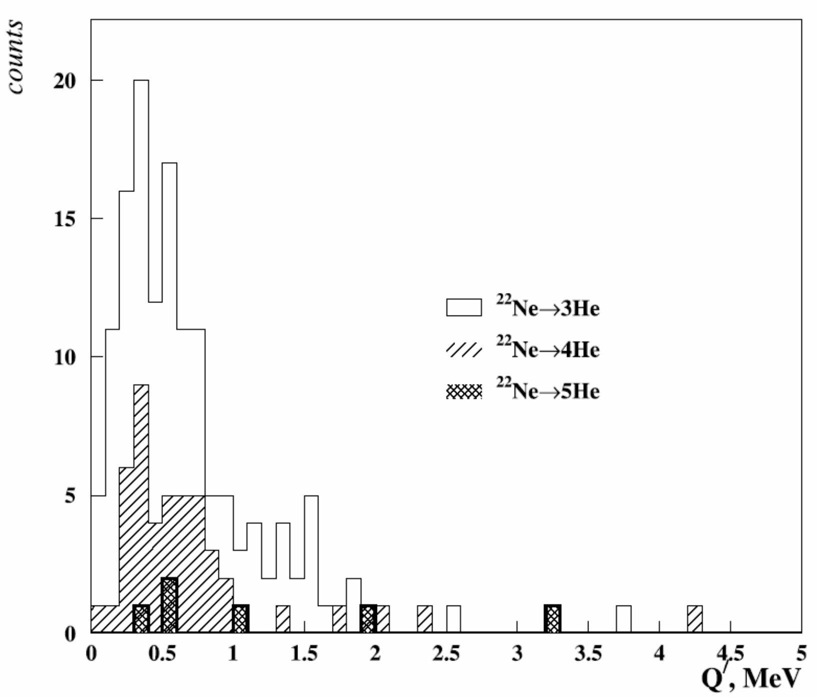

Fig. 3. The Q' distribution for the fragmentation channels ^{22}Ne→*n*α.

FRAGMENTATION OF ^{14}N NUCLEI

We are presently engaged in accumulating statistics on the interactions of 2.1A GeV ^{14}N nuclei in emulsion with an impact on a «white» stars search. By systematic scanning over primary tracks, 42 «white» stars have already been found among 540 inelastic events. The secondary tracks of «white» stars are concentrated in a forward 8° cone. They are distributed over the charge modes as follows: 3He+H - 33%, C+H - 31%, B+2H - 7%, B+He - 7%, Be+He+H - 2%, Li+He+2H - 2%, и Li+4H – 2%.

A leading role of the channel 3He+H among "white" stars implies that the exploration of the 3α systems originated in ^{14}N fragmentation is prospective. The distribution in which the excitation energy $Q_{3\alpha}$ is counted out from the ^{12}C nucleus mass is given in fig. 4. A 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 excitation pattern. 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 is of the same magnitude as in fig. 3. As a preliminary conclusion, we note that a contribution of α-^{8}Be configuration in the 3He one doesn't exceed 10% and this topic needs higher statistics.

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 dispersion angle in the few GeV range. 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 1.2A GeV ^{10}B beam. In scanning of emulsions exposed to ^{9}Be nuclei, 200 interactions are detected with He pair produced in a forward 8° cone. Fig. 5 shows the distribution $Q_{2\alpha}$ (3) for 50 measured events. 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^{+} having a 0.8 MeV width. A zoomed part of this distribution is presented in fig. 6. 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. 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 excitation spectrum. Identification of ^{8}Be production is of particular importance for justification of the spectroscopy a few body decays in relativistic beams.

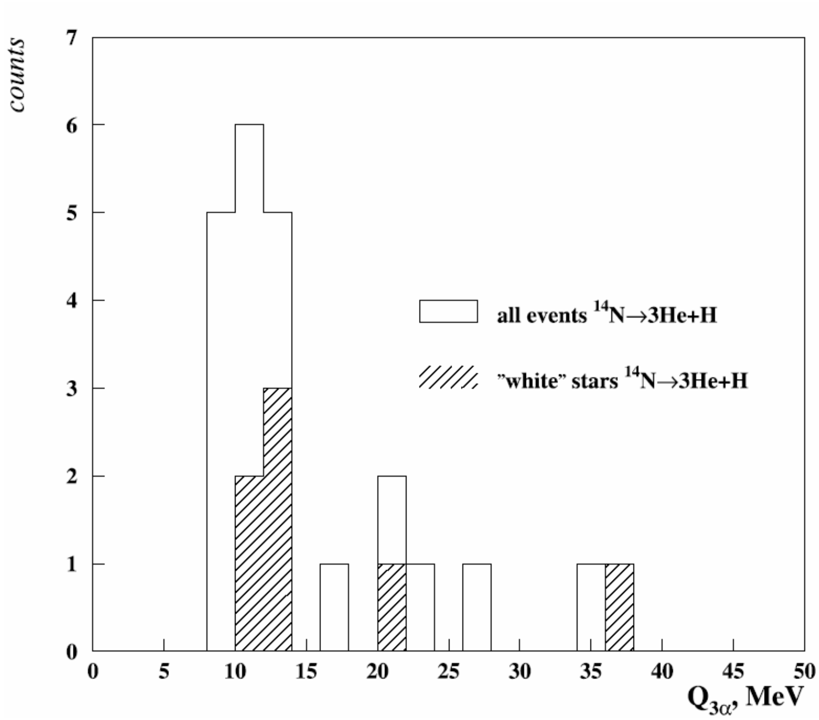

Fig. 4. The $Q_{3\alpha}$ distribution for the fragmentation channels $^{14}N \to 3\alpha$.

FRAGMENTATION OF ^{8}B NUCLEI

To expose an emulsion to an enriched ^{8}B beam use was made of the process of fragmentation of 1.2 A GeV ^{10}B nuclei. In this case, the absence of a bound ^{9}B state is found to be a good luck which results in a clear separation of the primary and secondary B beams by their magnetic rigidity. When scanning exposed emulsions, this fact was confirmed by the absence of stars with He+H charge topology which could be produced by background ^{6}Li nuclei having the same magnetic rigidity as ^{10}B nuclei have. The ^{7}Be interaction admixture was about 15% which was eliminated according to the final charge configuration. The main background is presented by ^{3}He nuclei the primary tracks of which are seen to be sharply distinct of B and Be nucleus ionization.

By the present time, a total of 80 stars are found by scanning over the beam particle tracks in which the total track charge in a forward 8° cone is equal to 5. Among them, 27 events are selected which contain no tracks of relativistic particles outside the fragmentation cone (that is, produced mesons). The event distribution by the charge modes is as follows: Be+^{1}H – 9, 2He+H – 8, ^{6}Li+2^{1}H – 1, He+3H – 1, 5H – 1. We note that the observation of the channels was very reliable and systematic.

One may conclude about the significance of the 3-body mode of ^{8}B fragmentation in just the same way as in the case of the ^{10}B nucleus. An evident difference consists in a large yield of the ^{7}Be+^{1}H channel which is due to the easy separation of a loosely bound proton. In the case of ^{10}B dissociations, a similar channel ^{9}Be+^{1}H is just about 3% which is due to a lower threshold of separation of a deuteron [10]. It is planned to increase statistics, identify the H and He isotopes, and reconstruct excitations.

Obtaining of accelerated ^{10,11}B nuclei will make it possible to proceed to the formation of a ^{10,11}C beam in a charge exchange reaction analogously to the earlier employed $^{7}Li \to ^{7}Be$ process [3]. The use of this reaction instead of the heavier nucleus fragmentation is optimal for the nuclear emulsion method where of importance is the simplicity of identification of nuclei rather than the beam intensity. We do intent to establish the existence and the cross sections of such processes in a separate experiment.

FRAGMENTATION OF ^{9}C NUCLEI

It is impossible to use the approach based on a charge exchange reaction for the formation of a ^{9}C nucleus beam. Emulsion was exposed to a secondary beam produced in fragmentation of the 2.1A 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 8° cone is equal to 6. Presently found 17 events are distributed in the following way: 2He+2H – 7, He+4H – 5, 3He – 3, B+H – 1, and Be+2H – 1. The 3He mode, which is typical of the ^{12}C dissociation, is seen to be suppressed.

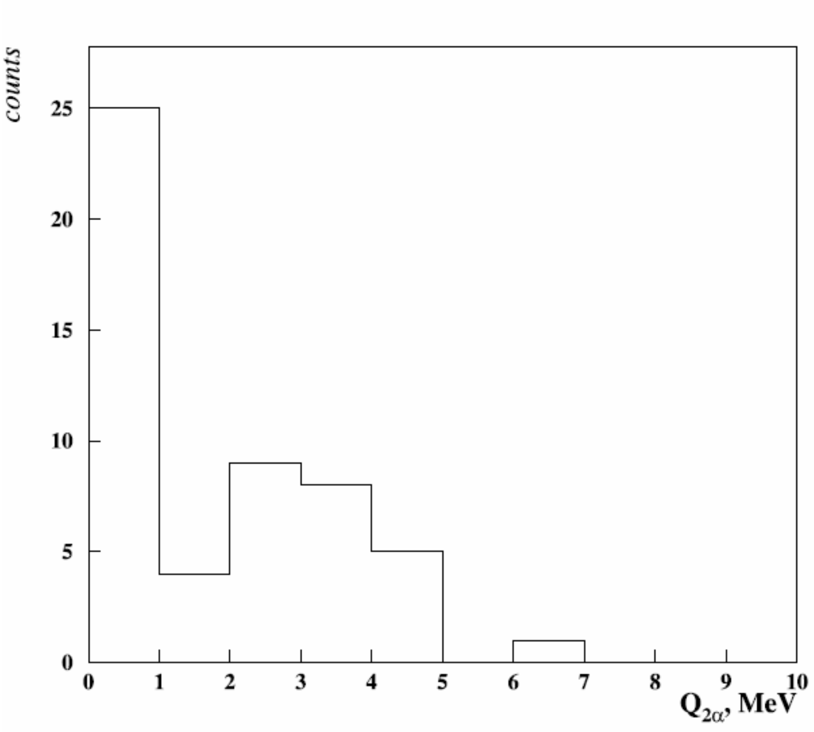

Fig. 5. The $Q_{2\alpha}$ distribution for the fragmentation channels $^{9}Be\rightarrow 2\alpha$.

The cases interpreted as $3^{3}He$ have a special importance since they point a highly-lying excitation associated with a nucleon rearrangement in the $3^{3}He$ system. As the process $^{12}C\rightarrow 3\alpha$, this dissociation can be considered as a visible reflection of the inverse process of a ternary ^{3}He fusion in stars. It can provide a significantly higher energy output followed by ^{4}He pair production. Search for reflections of an extended ternary He process makes a further accumulation of statistics and its presentation in relativistic invariant way to be especially topical.

CONCLUSIONS

In the present report the invariant approach is applied to analyzing the relativistic fragmentation of ^{22}Ne nuclei in a nuclear track emulsion. Doubly charged fragments of relativistic ^{22}Ne nuclei are shown to be concentrated mostly in the range of the invariantly defined variable $b_{ik}<10^{-2}$. The range covers nuclear interactions with a relative kinetic energy of the order a hundred KeV per nucleon.

New experimental observations are obtained from the emulsion exposures to ^{14}N and ^{9}Be nuclei with energy above 1A 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.

In spite of statistic restrictions, emulsions provide unique possibilities to explore a few body decays of relativistic ^{8}B and $^{9,10,11}C$ nuclei. This work star up is shown in the paper. The invariant approach justified for the stable nuclei will be of a special benefit in the cases of neutron deficient ones.

Nuclear track emulsions ensure the initial stage of investigations in an unbiased way and enable one to develop the scenarios for dedicated experiments [11]. Our experimental observations concerning few body aspects of nuclear physics can be expressed in the relativistic invariant form, and potentially they will allow one to extent nuclear physics grounds of nucleosynthesis pattern.

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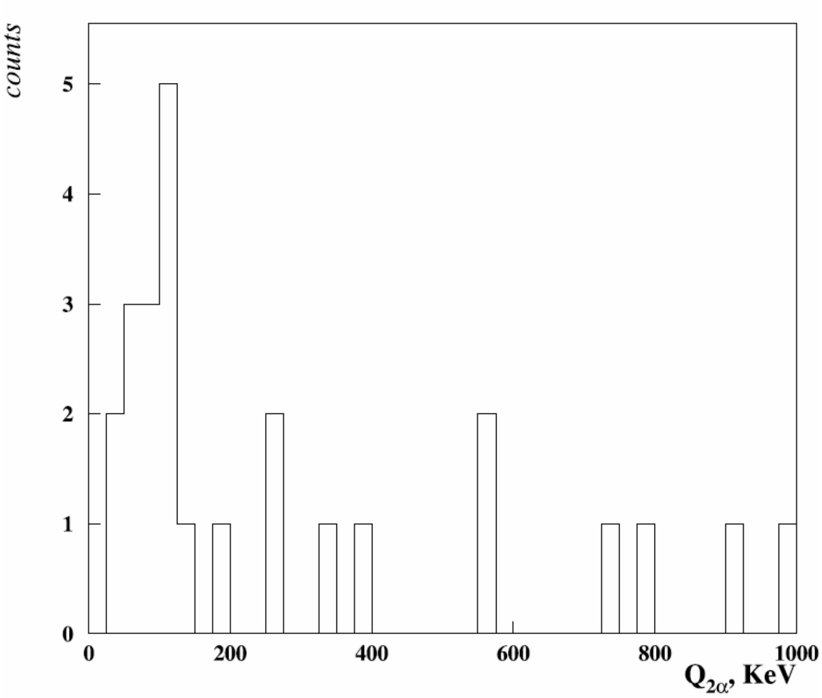

Fig. 6. The $Q_{2\alpha}$ distribution for the fragmentation channels $^{9}Be \rightarrow 2\alpha$ zoomed between 0-1000 KeV.

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