INVARIANT ANALYSIS OF THE FRAGMENTATION OF RELATIVISTIC NUCLEI IN EMULSION

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The pattern of the fragmentation of relativistic nuclei of energy above 1 A GeV in emulsion is represented in invariant variables. New data extracted from emulsions exposed to 2.1 A GeV ^{14}N and 1.2 A GeV ^{9}Be nuclei suggest the advantages of the emulsion technique in obtaining unique information on the decay of light nuclei to a few fragments with charges 1 and 2.

INTRODUCTION

A detailed study of relativistic fragment systems formed in the dissociation of nuclei of energy above 1 A GeV provides a qualitatively better understanding of the structure of nuclear excitations above the decay thresholds. In accordance with the classification developed in papers [1-6], fragmentation results in the production of fragment jets which are determined by the invariant variable region concentrated within $10^{-4} < b_{ik} < 10^{-2}$, where $b_{ik} = -(P_i/m_i - P_k/m_k)^2$, P and m are the four-momenta and the masses of the *i* and *k* fragments.

The lower limit corresponds to the decay $^{8}Be \rightarrow 2\alpha$ (decay energy 92 KeV), while the upper one - to the upper limit of non-relativistic nuclear processes as suggested by A. M. Baldin. The latter go at the level of nucleon-nucleon interactions without inclusion of the meson degrees of freedom. For the sake of illustration of the events of this class, fig. 1 gives as an example an event of relativistic ^{14}N dissociation without visual target-nucleus excitation or meson production.

The expression of the data via the relativistic invariant variable b_{ik} makes it possible to associate in a common form data on multiple target-nucleus and relativistic projectile fragmentation. There is a close connection between the b_{ik} variables and the invariant mass of the system of fragments $M^{*2} = (\Sigma P_j)^2 = \Sigma(P_i \cdot P_k)$ and the excitation energy $Q = M^{*} - M$, where M is the mass of the ground state of the nucleus corresponding to the charge and the weight of the system being analyzed.

Within the invariant approach, an optimal strategy which would take into account the formulation of the problem, the properties of the nucleus studied and limitations on real measurements is chosen by experiment. In the present talk, the advantages of this approach are discussed using the available data on nuclear fragmentation in emulsion (see [7-8] and references herein). New data for 2.1 A GeV ^{14}N and 1.2 A GeV ^{9}Be nuclei are extracted from a minor portion of the processed material. They enable one only to outline promising approaches to future analysis. A significant difference in the energy of the nuclei studied was due to practical circumstances in emulsion exposure. The presentation of the data in the invariant form makes it possible to overcome this obstacle when comparing them.

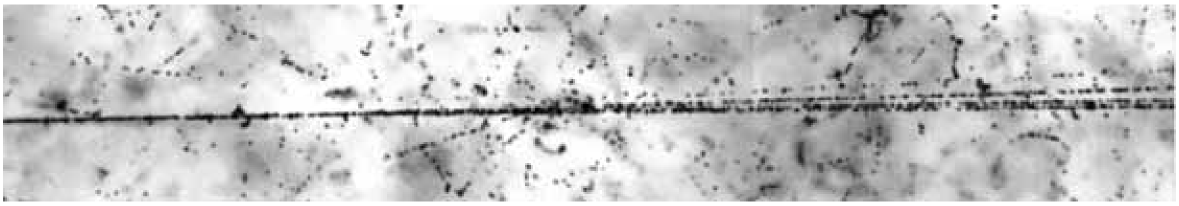

Fig. 1. Fragmentation of ^{14}N nucleus at 1.2 A GeV in emulsion. The interaction vertex and a fragment jet in a narrow angle cone are seen on the photograph. Following the direction of the fragment jet it is possible to make out 3 fragments with Z = 2 and 1 fragment with Z = 1.

The nuclear emulsion technique seems to be most suitable for the study of fragmentation of relativistic nuclei up to a total breakup to single-charged fragments. More images reflecting capabilities of emulsion technique can be found via the Web [10]. It should be noted that this method imposes some restrictions on the determination of the four-momentum components of fragments. Firstly, the possibility of obtaining the value of the spatial momentum per nucleon of a fragment is limited. As a rule, it is suggested to be equal within a few percent to the primary nucleus value which is a quite reasonable approximation. Secondly, the mass identification is possible only for relativistic hydrogen isotopes and hardly for helium isotopes. Therefore the alpha particle mass is taken for the mass of two-charged fragments which also is a good approximation when selecting stable nuclear fragments in a narrow fragmentation cone. The scalar product of unit vectors which determine the direction of fragment emission plays the decisive role in b_{ik}, M and Q estimates. Thus, owing to a record spatial resolution the nuclear emulsion method can yield unique evidence about the characteristics of narrow jets of Z = 1, 2 fragments with a total nuclear dissociation.

^{22}Ne NUCLEUS FRAGMENTATION

The formation of a nuclear state analogous to a dilute Bose gas at the atomic level can be revealed in narrow jets of doubly charged relativistic fragments near the threshold of production of an ensemble consisting of few alpha particles [11]. Such ensembles are inwardly non-relativistic systems and can possess quantum coherence. It can be predicted that these systems would have similar characteristics when they are produced under various conditions. Another property of these systems is a very narrow distribution in velocities in the c.m.s. [11]. The determination of the system c.m.s. for each event is rather complicated and not efficient. It is just in this case that the analysis of jets in the b_{ik} four-velocity space enables one to formulate the properties of few body systems in the most universal manner.

We have at our disposal data on 4100 events from 3.3 A GeV ^{22}Ne interactions which contain classification of secondly tracks by ionization and angles. Tracks classified as relativistic alpha particles were in a 6° cone with respect to the primary nucleus track. The helium isotopes can play a more significant role as compared to the symmetric nuclei due to the presence of a pair of external neutrons. This fact can be used for more effective generation and detection of five alpha particle systems in stimulating dissociation by a neutron knockout process.

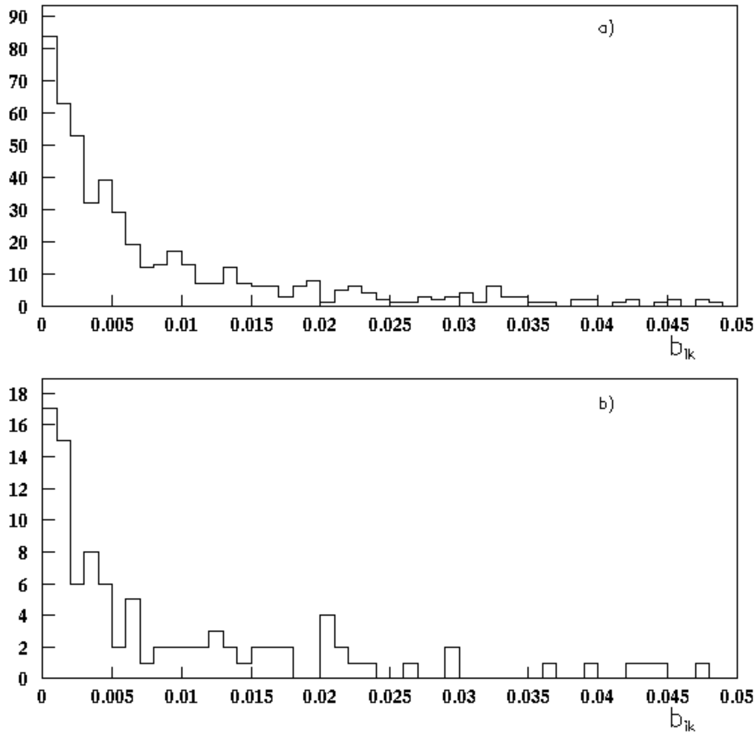

Fig. 2. The b_{ik} distribution for the fragmentation channels $^{22}Ne\rightarrow 2\alpha$ (a) and $^{22}Ne\rightarrow 5\alpha$ (b).

Fig.2 shows the b_{ik} distribution for the fragmentation channel $^{22}Ne\rightarrow 2\alpha$ (a) and $^{22}Ne\rightarrow 5\alpha$ (b) channel (10 events). The dominant fraction of the relative velocities defining the dispersion of relativistic jets satisfies a non-relativistic criterion $b_{ik}<10^{-2}$. It appears that the distribution "tails" are due to the ^3He nucleus formation proceeding at a higher momentum transfer. In spite of a significant difference in the composition of the systems, both distributions look rather similar. Fig. 3 give the ratios of the distributions in the channels $^{22}Ne\rightarrow 3\alpha$ (a) and $^{22}Ne\rightarrow 4\alpha$ (b) to the one in the $^{22}Ne\rightarrow 2\alpha$ channel. The narrow "helium" jet production process is seen to be universal with high statistical provision.

3 events of a decay $^{22}Ne\rightarrow 5\alpha$ are found with the secondary tracks are within a 3° cone and are accompanied by neither target fragments nor produced mesons ("white" stars). Of them, in 2 events all tracks are within no more than 1°. For these two events the invariant excitation energy normalized to the nucleon number $(M^*_{5\alpha}-5m_\alpha)/4n_\alpha$ is estimated to be 400 and 600 KeV. These values are essentially lower than the Coulomb barrier. The detection of such events in emulsion and their preliminary metrology are serious arguments in favor of systematic studies of the phase transition of nuclei to a dilute Bose gas of alpha particles on the basis of much larger statistics and for a great variety of nuclei.

^{14}N NUCLEUS FRAGMENTATION

We are presently engaged in accumulating statistics on the interactions of ^{14}N nuclei of an energy of 2.1 A GeV in emulsion for the study of "white" stars $^{14}N^*\rightarrow d(p)\alpha\alpha\alpha$ in a forward cone to 8° degrees. The major task is a rapid search for "white" stars the cross section for which constitutes a few percent of the inelastic cross section. By viewing over primary tracks 540 events of interactions of ^{14}N nuclei with emulsion nuclei, including 25 "white" stars, were already found. There is an indication of an important role of the charge configuration 2+2+2+1 - 12 such events were found. An example of such star is given in fig. 1.

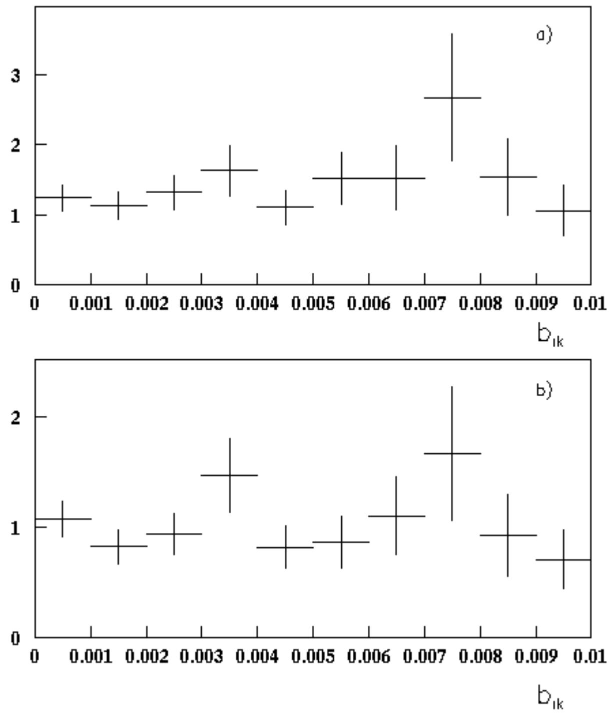

Fig. 3. The ratio of the b_{ik} distributions for the fragmentation channels $^{22}Ne\to3\alpha$ (a) and $^{22}Ne\to4\alpha$ (b).

A 6+1 configuration which is similar to the events with separation of Z=1 fragments in the dissociation of heavier symmetric nuclei (6 events) is found to be important. A multiple scattering of Z=1 tracks in emulsion is analyzed for the purpose of identifying it in mass. Preliminary data indicate that the ratio of protons to deuterons is approximately as 2:1. This implies that the fraction of fragments-deuterons noticeably decreases as compared with the cases of relativistic fragmentation of ^{6}Li and ^{10}B nuclei (2+2+1 channel) , where the proton and deuteron yields are equal. It is seen that the role of clustering in the form of deuterons becomes evidently less important which is in agreement with a large threshold of their separation as compared to protons.

A leading role of the channel 2+2+2+1 in the ^{14}N fragmentation implies that the exploration of three alpha particle systems at $b_{ik}<10^{-2}$ is prospective. For the sake of illustration, we consider several events for which angular measurements are already performed. The b_{ik} distribution (fig. 4) is of the same nature as for the above-considered $^{22}Ne\to n\alpha$ events. Further accumulation of statistics can enable one to study in more detail the question to what extent this distribution is universal.

To estimate the excitation scale fig. 5 (a) presents the distribution in an invariant excitation energy normalized to the nucleon number $(M^{*}_{3\alpha}-3m_{\alpha})/4n_{\alpha}$. In just the same way as in the case of "white" ^{22}Ne stars, it is indicated that there is a concentration of events in the region of very low energies. A distribution in which the energy is counted out from the ^{12}C nucleus mass, that is $M^{*}_{3\alpha}-m_{C}$, is given in fig. 5 (b). It is interesting that events are concentrated around ^{12}C nucleus levels of 10-14 MeV. It is possible that the detected events would give a better understanding of the nature of these excited states. These preliminary observations serve as a serious motivation for further accumulation of statistics and for detailed measurements.

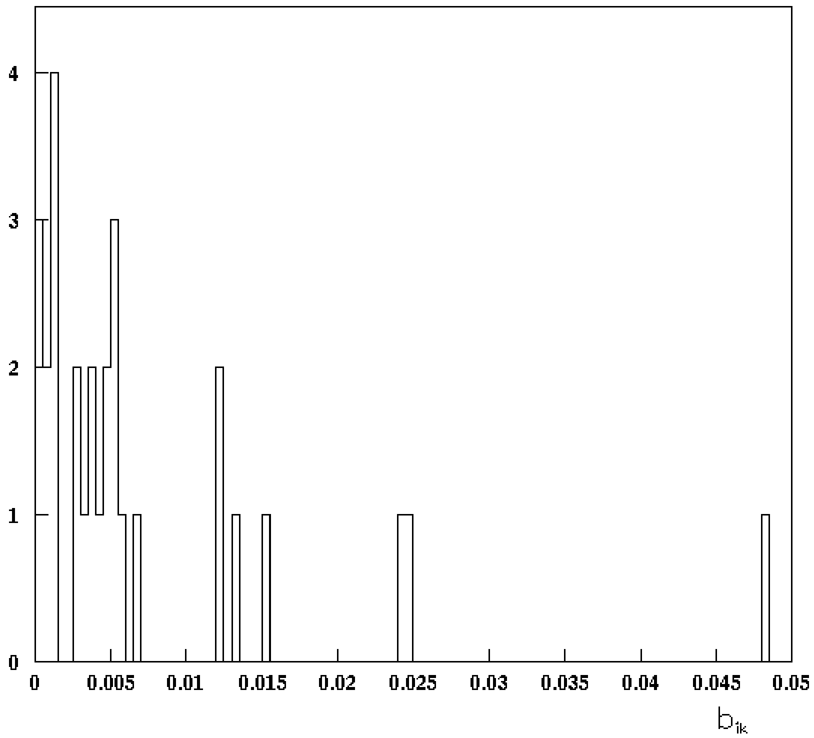

Fig. 4. The b_{ik} distribution for the fragmentation $^{14}N \to 3He$ channel.

An important fact is that there is no indication of a decay from lower 7.65 MeV level proceeding in the $^{12}C^{*} \to \alpha ^{8}Be$ channel. The latter should reveal itself in the formation of events with three alpha particles two of which have an extremely small $5 \cdot 10^{-3}$ rad dispersion angle at the available energy. Owing to this fact the search for a reliable method of identifying relativistic ^{8}Be decays under the simpler conditions is topical.

^{9}Be NUCLEUS FRAGMENTATION

The relativistic ^{9}Be nucleus fragmentation is an attractive source for ^{8}Be nucleus generation since the energy threshold of neutron separation of the ^{8}Be nucleus is only 1.7 MeV. The estimation of the ^{8}Be production probability will make it possible to clear up the role of this nuclear structure as a core in the ^{9}Be nucleus. In addition, the relation between $n^{8}Be$ and three-body excitation modes is expected to be established which is very important for the determination of the fragmentation scenario for heavier nuclei.

A secondary ^{9}Be nucleus was formed via fragmentation of the primary ^{10}B beam of energy of 1.2 A GeV. The beam was enriched about 80% by ^{9}Be nuclei. The background is lighter nuclei with a close charge-to-weight ratio. In viewing emulsions exposed to ^{9}Be nuclei we found by the present time 200 interactions in which the total charge of secondary tracks in the relativistic fragmentation cone is equal to the primary charge of a primary track. Fig. 6 shows a distribution for the 50 measured events over the opening angle between fragment pairs. One can resolve the peak at $4 \cdot 10^{-3}$ rad corresponding to the ^{8}Be decay from the ground state 0^{+}. The angle value $26 \cdot 10^{-3}$ rad corresponds to decay from the first excited state 2^{+}.

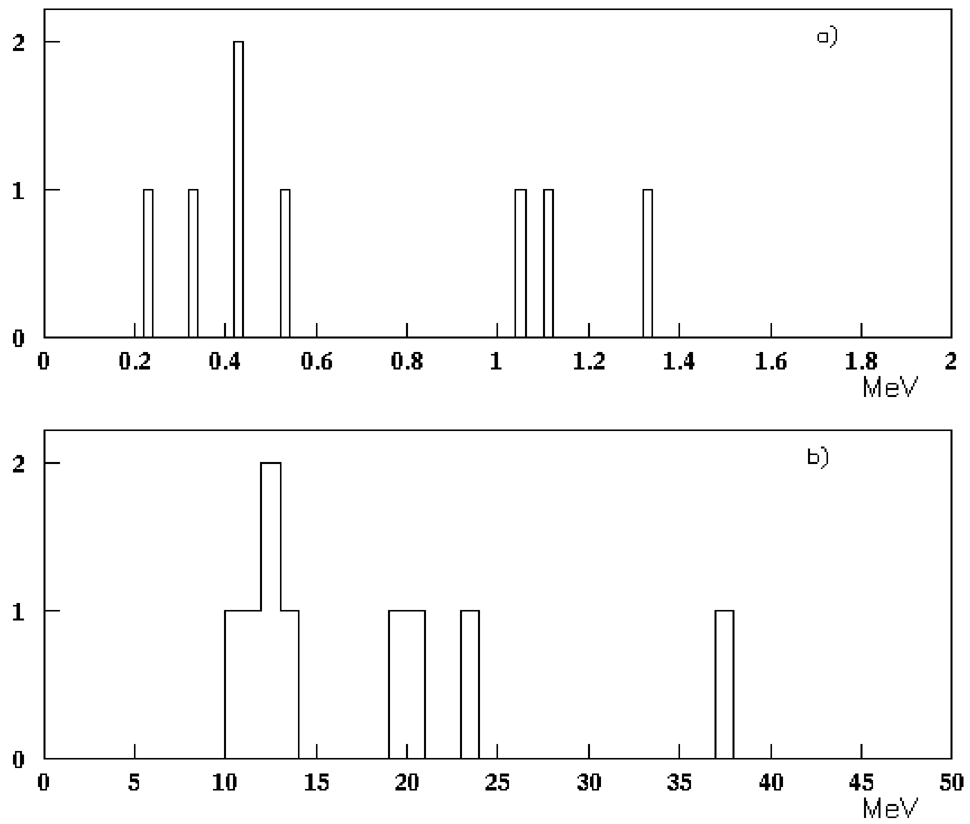

Fig. 5. Distribution in invariant excitation energy for the $^{14}N \to 3He$ channel at an energy of 2.1. A GeV normalized to the nucleon number (a) and with respect to the ground state of the nucleus ^{12}C (b).

Fig. 7 (a) shows the b_{ik} distribution for two-charged fragment pairs from 50 measured events. The distribution is seen to be limited by a region $b_{ik}<10^{-2}$ in this case as well. A part of this distribution zoomed near zero is presented in fig. 7 (b). One can see a concentration of 14 events for $b_{ik}<2\cdot10^{-4}$ corresponding to a ^8Be decay from the ground state. The decay energy defined using them is 88 ±10 KeV. In spite of the fact that the statistics is rather restricted these distributions show that further accumulation of statistics is prospective.

CONCLUSIONS

In the present talk use is made of the invariant approach to analyzing the fragmentation of a number of nuclei of energy above 1 A GeV in emulsion. New results are obtained from the exposure of emulsion to ^{14}N nuclei at 2.1 A GeV and to ^9Be at 1.2. A GeV. In spite of limited statistics it can be asserted that the use of the relativistic invariant approach to the analysis of multiple fragmentation of light nuclei in emulsion, suggested by A.M.Baldin in a rather general form, is an effective mean of obtaining sufficiently clear conclusions about the behavior of systems involving a few lightest nuclei at energies typical of quantum coherence.

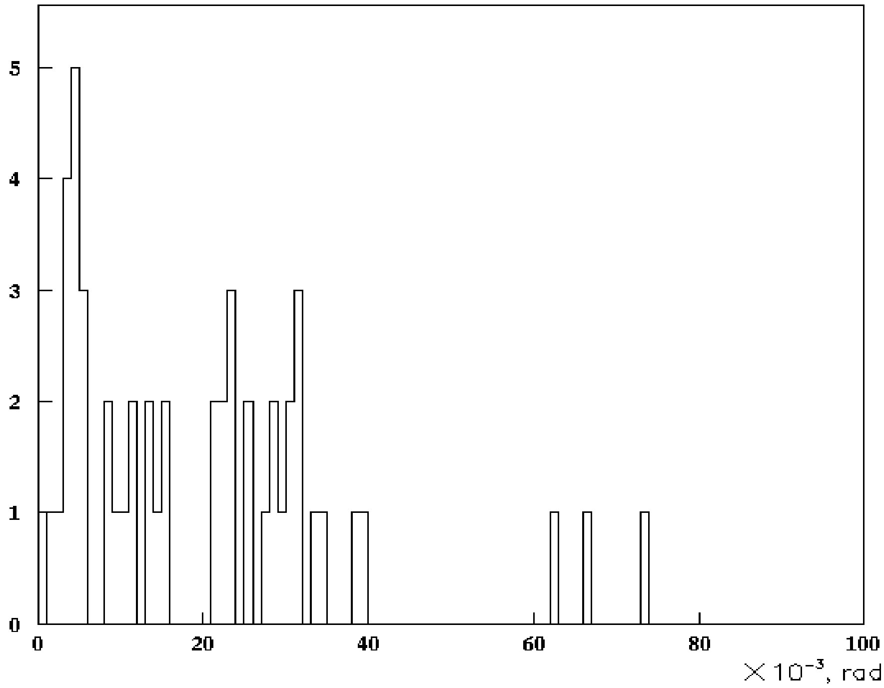

Fig. 6. Distribution in the opening angle between fragment pairs for the $^{9}Be \rightarrow 2He$ fragmentation channel.

Relativistic fragments are concentrated in a cone defined by $b_{ik}<10^{-2}$ and their differential distributions in this domain are alike. This approach makes it possible to explore the particular features of decay of individual nuclei. The excitation energy of a system involving a few fragments over the ground state with the same baryon number can be estimated in an invariant form up to the ^{8}Be nucleus decays.

The work was supported by the Russian Foundation for Basic Research (Grants nos. 96-1596423, 02-02-164-12a, 03-02-16134, 03-02-17079, 04-02-16593 and 04-02-17151), 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 Bulgaria, Czech Republic, Slovak Republic, and Romania in 2002-2004.

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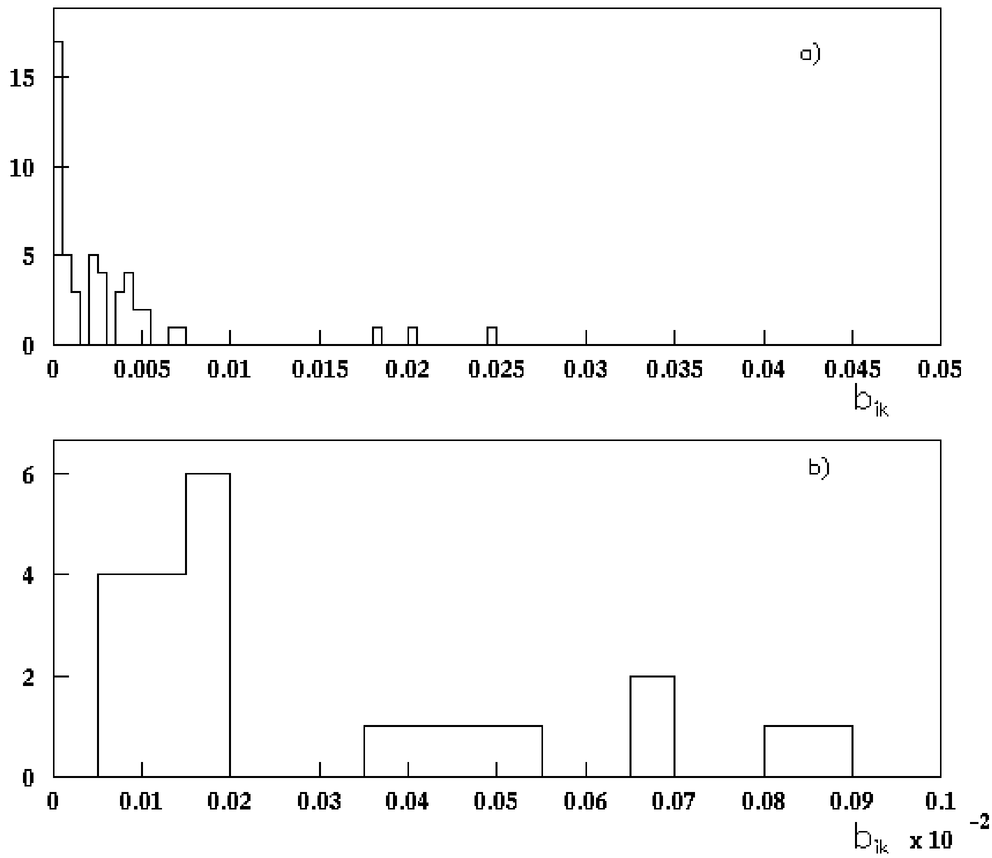

Fig. 7. Full scale distribution over b_{ik} for the $^{9}Be \to 2He$ fragmentation channel (a) and zoomed one (b).

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