# DISSOCIATION OF RELATIVISTIC NUCLEI IN PERIPHERAL INTERACTIONS IN NUCLEAR TRACK EMULSION *

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**Abstract.** Possibilities of the nuclear emulsion technique for the study of the systems of several relativistic fragments produced in the peripheral interactions of relativistic nuclei are discussed. The interactions of the $^{10}$B and $^{9}$Be nuclei in emulsion are taken as an example to show the manifestation of the cluster degrees of freedom in relativistic fragmentation. For the case of the relativistic $^{9}$Be nucleus dissociation it is shown that exact angular measurements play a crucial role in the restoration of the excitation spectrum of the alpha particle fragments. The energy calibration of the angular measurements by the $^{9}$Be nucleus enables one to conclude reliably about the features of internal velocity distributions in more complicated systems of relativistic $\alpha$ particles.

**Key words:** nucleus, relativistic, peripheral, fragmentation, emulsion, clustering

## 1. Introduction

The peripheral collisions of nuclei proceeding at energy above 1 A GeV are collisions of a special type in which the breakup of the primary nuclei is provoked by electromagnetic and diffraction interactions, as well as by nucleon collisions for a minimal overlap of nuclear densities. Nuclear track emulsions exposed to beams of relativistic nuclei make it possible to obtain information about the charged products of such collisions which is unique as concerns details of observation of particle tracks and the accuracy of their spatial metrology (E. M. Friedlander et al., 1983; G. Baroni et al., 1990; G. Baroni et al., 1992).

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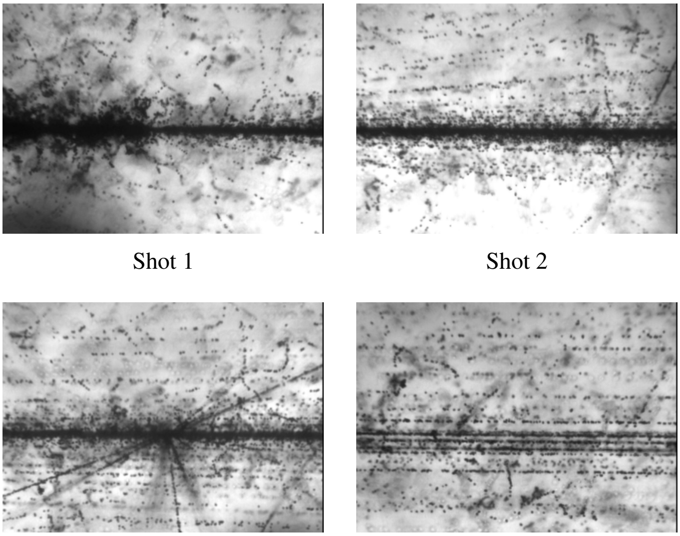


Shot 1

Shot 2

Shot 3

Shot 4

*Figure 1.* Subsequently photoed event of peripheral interaction of a 158 A GeV $^{207}$Pb nucleus in a nuclear track emulsion in $\approx 100\times 100$ $\mu$m$^2$ viewing fields: primary nucleus track and interaction vertex followed by projectile fragment jet (Shot 1); jet core with apparent tracks of singly and doubly charged particles (Shot 2); jet core with a secondary interaction star (Shot 3); completely recognizable jet core (Shot 4, 3 cm distance from the vertex).

## 2. Relativistic fragmentation

In peripheral interactions, nuclei are given an excitation spectrum near the energy dissociation thresholds. In the kinematical region of fragmentation of a relativistic nucleus, there arise systems consisting of nuclear fragments whose total charge is close to the parent nucleus charge. The opening angle of the relativistic fragmentation cone is defined by the Fermi nucleon motion. Thus, the fragments find themselves on the periphery of the particle rapidity distribution which is obtained by summing over all the channels of the reaction in question.

The values of the fragment momenta normalized to the mass numbers are distributed about the normalized momentum of the primary nucleus with a few-percent dispersion. Therefore the distribution of the velocities of fragments in their c.m.s. must be a non-relativistic one. In accordance with the established pattern of the nuclear limiting fragmentation the probabilities of population of the fragment final states reveal a very high degree of universality. They are found to be weakly dependent on the initial energy and target-nucleus properties.

The interactions of the above-mentioned type can serve as a “laboratory” for the generation of non-relativistic ensembles of several lighter nuclei. The term “peripheral” does not reflect in full measure dramatic changes which occur at the microscopic level. The dissociation degree of a nucleus can reach its total destruction into separate nucleons and lightest nuclei having no excited states, that is, $^{2,3}$H and $^{3,4}$He nuclei. A relative intensity of their production permits one to reveal the importance of different cluster degrees of freedom.

For the experimental study of multi-particle systems, the choice of those of them which result from the dissociation of a relativistic projectile and not from the dissociation of the target-nucleus has special methodical advantages. Owing to the kinematical collimation and absence of the detection threshold, relativistic fragments can completely be observed in a small solid angle and the distortions due to energy ionization losses in the detector material are minimal.

When selecting events with the dissociation of a projectile into the fragmentation cone, the non-relativistic fragments are either absent (“white”stars), or their number is insignificantly small. These fragments are emitted over all the solid angle, therefore, their fraction in the relativistic fragmentation angular cone is negligible. The target-fragments have non-relativistic momenta which allow one to distinguish them from the projectile fragments in this cone.

Of course, in the relativistic approach to the fragmentation study, there also arise its own methodical troubles. For a primary nucleus with charge Z, it is very desirable to provide the detection up to singly-charged particles. The ionization produced by all fragments can be reduced down to a factor Z, while the ionization per one track - to a factor $Z^2$ as compared with that from the primary nucleus. Therefore the experimental method should provide the widest detection range taking the $Z^2$ value into account.

## 3. Capabilities of nuclear track emulsion

The full kinematical information about the secondary particles in the relativistic fragmentation cone is needed to reconstruct an invariant mass of a fragment system. The accuracy of invariant mass estimation drastically depends on the accuracy of the track angular resolution. Hence, to provide the best angular resolution the detection of fragments with the best spatial resolution is needed.

At the initial stage of investigations, the nuclear emulsion method well satisfies these requirements. The major task of it is to search for reliable proofs of the existence of different fragmentation channels for a statistical provision at the level of dozens of events. Emulsions provide a record spatial resolution (about 0.5 $\mu$m) which makes it possible to separate the charged particle tracks in the three-dimensional image of an event within one layer thickness (600 $\mu$m), as well as ensure a high accuracy of measurement of the angles. The emulsion technique allows one to measure the particle charges, starting with the single-charged particles up to the highest-charged ones, by combining the ionization means (counting the number of breaks and the number of $\delta$ electrons per track length unit). The tracks of relativistic H and He nuclei are distinguished by vision. In the peripheral fragmentation of a light nucleus its charge can often be established by the charge topology of the relativistic fragments. A collection of appropriate reaction images can be found in (V. Bradnova et al., 2004) and in the BECQUEREL project web site (BECQUEREL, 2005). Multiple scattering measurements on the light fragment tracks enable one to separate the $^{2,3}$H and $^{3,4}$He isotopes.

A vivid illustration of these assertions is the microphotograph of the event of a total disintegration of Pb nucleus of energy 158 A GeV in its peripheral interaction with an emulsion nucleus (see Fig.1). The exposure was performed in beams from the SPS accelerator (CERN) in the framework of the EMU collaboration. Experiment details can be found in (EMU01 Coolaboration, 1997; M. I. Adamovich et al., 1999). Shot 1 shows the primary nucleus track which is surrounded by a dense cloud of $\delta$ electrons. On Shot 1 the interaction vertex looks like a stepped lowering of the ionization density in which there are no tracks from the target-nucleus fragmentation. Shots 2-4 show a gradual separation of the tracks of singly and doubly charged particles from the shower trunk. At a given energy the He nucleus emission angles are restricted to a $0.1^\circ$ value. A total separation of tracks is seen on Shot 4 corresponding to a distance of about 3 cm from the vertex. The observer does not see in this event an intense flux of dozens of relativistic neutrons that have not to be able to bind the lightest nuclei. The image of an event in emulsion is created by microscopic crystals about 1 $\mu$m in thick, i.e. the latter are larger than the real sizes of nuclear fragments by about 9 orders of magnitude. Nevertheless this image reproduces rather well details of a "catastrophe" occurred at the micro-world scale.

The events of a total disintegration make up a small fraction of all the variety of the final states of heavy nuclei which embraces pairing fission, formation of single fragments accompanied by a great number of the lightest nuclei, formation of groups of light nuclei (E. M. Friedlander et al., 1983; P. L. Jain et al., 1984; EMU-01/012 Collaboration, 1997; M. I. Adamovich et al., 1998; M. L. Cherry et al., 1998). The excitation transferred to the nucleus is, to a large extent, defined by the energy threshold of the final-state mass. It grows with increasing fragment multiplicity. In this sense, the charge topology of the final state already defines the excitation. In a complicated process of the energy distribution over the multiplicity of the degrees of freedom, nuclear fragments go onto the mass surface and get some possibility to realize the Coulomb energy of mutual repulsion into the kinetic energy of each fragment. Some kind of a Coulomb "explosion"of a nucleus occurs.

The example of a total disintegration of a Pb nucleus may be interpreted as an event of the phase transition of nuclear matter from the state of quantum liquid to the state of quantum dilute gas of nucleons and the lightest nuclei. The metrology of such events is laborious and requires a high level of skill. Nevertheless such events are of an undoubted scientific interest, therefore their accumulation continues by the BECQUEREL collaboration (BECQUEREL, 2005). The light nucleus fragmentation can be considered as a component of the heavy nucleus fragmentation picture. In what follows, some examples are given to consider the role of the cluster degrees of freedom in the light nucleus fragmentation, as well as the energy scale of inter-cluster interactions.

## 4. Clustering in light nuclei

The charge topology of the relativistic fragmentation of N, O, Ne, Mg and Si nuclei in peripheral interactions in emulsion is presented in (A. El-Naghy et al., 1988; G. Baroni et al., 1990; G. Baroni et al., 1992; M. A. Jilany, 2004; N. P. Andreeva et al., 2005). A special feature of the excitation increase in this group of nuclei consists in the growth of the multiplicity of the He and H nuclei with decreasing charge of the only fragment with Z>3. In light nuclei the pairing splitting channel is practically suppressed.

More specific correlation studies were performed for the leading fragmentation channels like $^{12}$C→3$\alpha$ (V. V. Belaga et al., 1995), $^{16}$O→4$\alpha$ (N. P. Andreeva et al., 1996; V. V. Glagolev et al., 2001), $^{6}$Li→d$\alpha$ (F. G. Lepekhin et al., 1998; M. I. Adamovich et al., 1999), $^{7}$Li→t$\alpha$ (M. I. Adamovich et al., 2004), $^{10}$B→d$\alpha\alpha$ (M. I. Adamovich et al., 2004), and $^{7}$Be→$^{3}$He$\alpha$ (V. Bradnova et al., 2004). 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 (V. Bradnova et al., 2004; N. P. Andreeva et al., 2005). The next round of research, as to whether this kind of nuclear clustering is revealed in light neutron-deficient nuclei like $^{8}$B and $^{9,10,11}$C is in progress now at the JINR Nuclotron (A. I. Malakhov, 2004).

The decay of the excited states in the Be, B and C isotopes is of a clearly expressed $\alpha$ cluster character. In overcoming the mass threshold of a reaction their dissociation proceeds through the formation of an unstable $^{8}$Be nucleus in the ground and excited states. Among the reaction channels, 3-particle decays into He and H nuclei are dominant. Fragments with Z>3 do not play a crucial role.

As an important application, this conclusion can affect the problems of cosmic-ray physics related to the element abundance in the region of a Li-Be “gap”. The fundamental problem of Li-Be-B abundance in galactical cosmic rays as compared with their abundance in the matter of the Solar system has not been solved yet. This pattern points out that the main chain of subsequent splitting of nuclei, when they are propagate in interstellar H and He gases, passes over the production of the Li, Be and B nuclei. This fact greatly stimulates the interest in the search for the sources of origin of the mentioned group of nuclei, especially the $^{6,7}$Li isotopes.

Shot 1

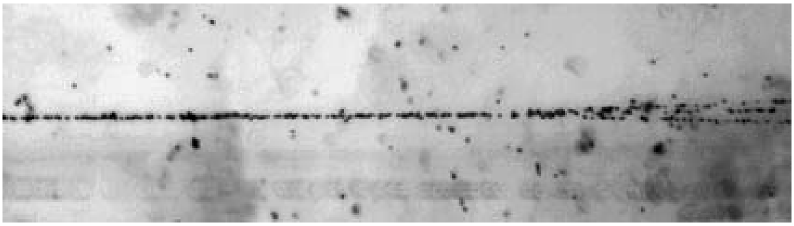
Shot 2

*Figure 2.* Subsequently reconstructed photo of dissociation of a 1 A GeV $^{10}$B nucleus into 1 doubly and 2 singly charged fragments without production of target nucleus fragments and mesons ("white"star): interaction vertex (Shot 1); apparent tracks of 1 H and 2 He nuclei (from top to bottom, Shot 2).

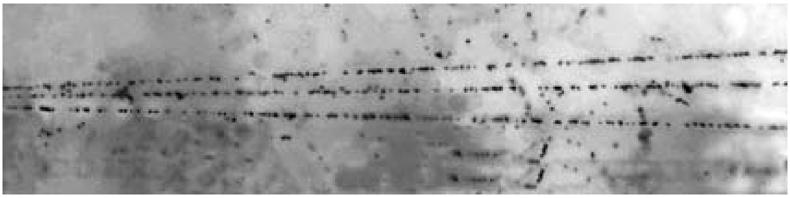
The dissociation of the $^{10}$B nucleus at an energy of 1 A GeV, studied in (M. I. Adamovich et al., 2004), may be an example which shows the dominance of the decay cluster channels. The microphotograph (see Fig.2) gives an event corresponding to the decay $^{10}$B→2$^{4}$He+H. The fraction of these events is about 80% of the total number of the events of the peripheral type. By measuring the multiple particle scattering, it is established that the deuterons participate in 40% of the decay of such a type, in just the same way as in the $^{6}$Li nucleus with a pronounced $\alpha$-d structure. The decay $^{10}$B→$^{6}$Li+$^{4}$He amounts to 15% for a lower 4.5 MeV threshold. The decay $^{10}$B→$^{9}$Be+p is only 3% for a 6 MeV threshold. Thus, for a giving type of the interaction of the $^{10}$B nucleus one has revealed the role of the 3-particle excitations as well as the role of the deuteron as a cluster element of the structure of this nucleus.

The next microphotograph (see Fig.3) shows the event of a three-particle decay of the $^{10}$B nucleus in the charge-exchange reaction without the production of a charged meson. Its charge topology may unambiguously be interpreted as $^{10}$B→2$^{3}$He+$^{4}$He. Because of a deep rearrangement of nucleons which results in the formation of a $^{3}$He cluster, an essentially higher (18 MeV) threshold should have been overcome in this event. Thus, there proceeds the population of a strongly excited state in a mirror $^{10}$C nucleus. This event points to the fact that in stellar media consisting of the $^{3,4}$He mixture there can occur an inverse process which is similar to the 3$\alpha$ process 3$^{4}$He→ $^{12}$C. The fusion process 2$^{3}$He+$^{4}$He→ $^{10}$C results in a larger energy yield which is followed in the world of stable nuclei by the production of the $^{10}$B nucleus as a final product.

This example illustrates the suggestion that the proof of the existence of the nuclear-physical process may become the basis for developing the ideas about the nucleosynthesis. However, in order to relate the relativistic fragmentation to thermonuclear synthesis it is necessary to establish an internal scale of kinetic



Shot 1



Shot 2

*Figure 3.* Subsequently reconstructed photo of dissociation of a 1 A GeV $^{10}$B nucleus into 3 doubly charged fragments without production of target nucleus fragments and mesons (“white”star): interaction vertex (Shot 1); apparent tracks of 3 He nuclei (Shot 2).

energies in the c.m.s. of relativistic fragments.

## 5. The energy and velocity scales in N$\alpha$-particle systems

The study of the $^9$Be nucleus dissociation into two $\alpha$ particles allows one to restore their resonance states without a combinatorial background. Owing to a low-energy threshold (1.7 MeV) this process dominates the channel $^3$He+$^4$He+2n (22 MeV threshold) which is similar to the latter by the image of the tracks. The separation of a neutron from the $^9$Be nucleus can lead to the production of an unstable $^8$Be nucleus with a decay through the ground state $0^+$ (the decay energy is 92 keV, the width is 5.6 eV), as well as through the 1st $2^+$ (3 MeV, 1.5 MeV width) and the 2nd $4^+$ (11.4 MeV, 3.5 MeV width) excited states. On the basis of a reliable observation of theses states in the excitation spectrum Q, i. e. of the invariant mass of a pair of relativistic $\alpha$ particles minus their masses, it is possible to verify the validity of the excitation estimate using only the angular measurements.

Emulsions are exposed to the secondary beam of $^9$Be nuclei of energy 1.2 GeV which is formed on the basis of the fragmentation of the $^{10}$B nuclei. At present, a total of 160 stars with a pair of relativistic He nuclei have been found in the exposed material. The directions of their tracks are within the forward cone with about a 3° opening angle. The emission angles have already been measured for 70

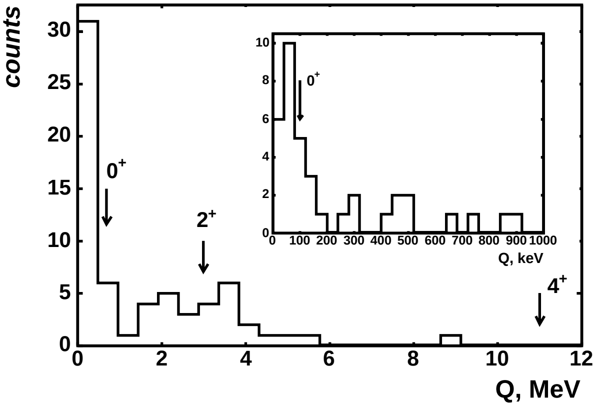


*Figure 4.* Distribution of $\alpha$ particle pairs *vs* Q for the fragmentation mode $^9$Be→2$\alpha$. Insertion: the distribution zoomed between 0-1000 keV.

events which allow one to present the spectrum Q of their excitation energies (see Fig.4).

The peaks correspond to the $^8$Be decay from the $0^+$ and $2^+$. The scale of the spectrum part 0–1 MeV, given on the insertion of Fig.4, is increased by a factor of 10. On it one can see a good coincidence of the distribution center with the decay energy of the $^8$Be ground state. The width of the peak makes it possible to define also the resolution of the method in this region of the spectrum. It is about 30 keV. On the right border of the distribution there are no events which would correspond to the second excited state $4^+$ at 11.35 MeV energy. This spectrum area needs some additional statistics. Thus, in the system of two relativistic $\alpha$ particles there are reflections of two known resonances.

These excitations can be compared with those of more complicated N$\alpha$ particle systems. The comparison will be made for the events of the type of "white"stars, that is, the events which contain neither target-nucleus fragments, no produced mesons. In such events, there proceeds a more "delicate"excitation of the fragmenting nucleus. The excitation of the system is defined by the mean values of the transverse momenta of $\alpha$ particles. The $\alpha$ particle transverse momenta are calculated in the laboratory system by the formula $P_T=4P_0\sin\theta$, where $P_0$ is the momentum per nucleon of a primary nucleus, $\theta$ the polar angle. As suggested in (V. V. Belaga et al., 1995), the transition to the transverse momentum vectors in the c.m.s. is possible for small angles of scattering of the primary nucleus and is described by the following equation

$$\mathbf{P}^*_{Ti} \cong \mathbf{P}_{Ti} - \frac{\sum_{i=1}^{n} \mathbf{P}_{Ti}}{N_\alpha} \qquad (1)$$

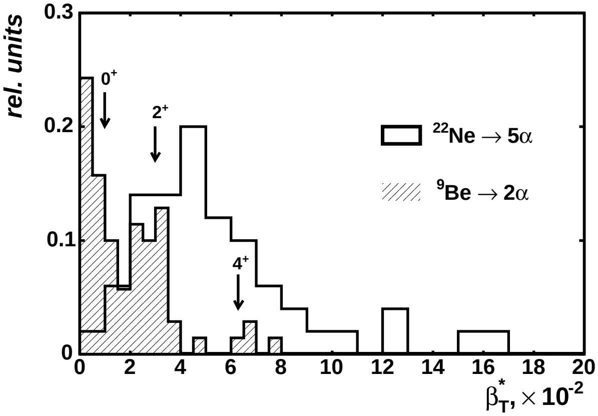


*Figure 5.* Distribution over the transverse velocities $\beta_T$ in the c.m.s. for the $\alpha$ particles produced in $^9$Be→2$\alpha$ and $^{22}$Ne→5$\alpha$ processes.

where, $\mathbf{P}_T$ is the residual vector of the $\alpha$ particle momenta.

The mean values obtained for the alpha particle transverse momenta are as follows for $^9$Be→2$\alpha$ $<P^*_T>$=103±2 MeV/c (the present paper), for $^{16}$O→4$\alpha$ $<P^*_T>$=121±2 MeV/c $^{16}$O→4$\alpha$ (N. P. Andreeva et al., 1996), and for $^{22}$Ne→5$\alpha$ $<P^*_T>$=200±2 MeV/c (processing of the available data presented in (A. El-Naghy et al., 1988)). These values clearly demonstrate the tendency to an increase of the average momentum of the $\alpha$ particles with increasing their multiplicity and consequently an increase of the total Coulomb interaction of $\alpha$ clusters.

Fig.5 shows the distribution over the transverse velocities $\beta_T$ in the c.m.s. for the $\alpha$ particles produced in $^9$Be→2$\alpha$ and $^{22}$Ne→5$\alpha$ processes. It can be concluded that the distribution over the velocities $\beta_T$, in spite of a broadening, is situated in a non-relativistic domain. In the $^9$Be case, the distribution has peaks which are due to the decay of the $0^+$ and $2^+$ states. The distribution for the $^{22}$Ne nucleus is essentially broader, its mean value reflects the growth of the $\alpha$ particle transverse momenta, and the possible contribution from the decay of the $^8$Be $0^+$ state is not significant. Thus, the energy calibration of the angular measurements by the $^9$Be nucleus enables one to conclude reliably about the features of internal velocity distributions in more complicated systems of relativistic $\alpha$ particles.

A nuclear state analogous to the dilute Bose gas can be revealed as the formation of N$\alpha$ particle ensembles possessing quantum coherence near the production threshold. Being originated from relativistic nuclei it can appear in a form of narrow n$\alpha$ particle jets in the forward cone. The predicted property of these systems is a narrow velocity distribution in the c. m. s. (P. Schuck et al., 2003). The detection of such “ultracold” N$\alpha$ states is a serious argument in favor of the reality of the phase transition of $\alpha$ clusterized nuclei to the dilute Bose gas of $\alpha$ particles. It gives a special motivation to explore lighter N$\alpha$ systems produced as potential "building blocks"of the dilute $\alpha$ particle Bose gas.

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 (A. M. Baldin and L. A. Didenko, 1990). The relativistic projectile fragmentation results in the production of a fragment jet which can be defined by invariant variables characterizing relative motion

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

with $P_{i(k)}$ and $m_{i(k)}$ being the 4-momenta and the masses of the $i$ or $k$ fragments. Following (A. M. Baldin and L. A. Didenko, 1990), 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→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.

## 6. Conclusions

The degree of the dissociation of the relativistic nuclei in peripheral interactions can reach a total destruction into nucleons and singly and doubly charged fragments. In spite of the relativistic velocity of motion of the system of fragments as a whole, the relative motion of fragments is non-relativistic one. The invariant presentation makes it possible to extract qualitatively new information about few-cluster systems from fragmentation of relativistic nuclei in peripheral interactions. The emulsion technique allows one to observe these systems to the smallest details and gives the possibility of studying them experimentally

Investigations of the relativistic fragmentation of the nuclei ranging from Be to C can serve as some kind of "bricks"in the construction of a complete picture of the phase transition of heavy nuclei to the lightest clusters. In solving such problems, the nuclear energy of the order of several GeV per nucleon is optimal as far as at these energies the relativistic fragmentation cone has the optimal value which can be measured by microscopes.

In the charge topology of the light nucleus fragments, the cluster character of their excitations is clearly manifested. The cluster degrees of freedom in nuclei are deeply associated with the process of their synthesis. The given event of the breakup with simultaneous charge-exchange of the $^{10}$B nucleus into 3 He nuclei points to a possible population of the excited states of the $^{10}$C nucleus with a deep rearrangement of the cluster structure of this nucleus. Observation of this process can point to the occurrence of an inverse fusion process 2$^{3}$He+$^{4}$He in stellar media.

For the particular case of the relativistic $^{9}$Be nucleus dissociation it is shown that precise angular measurements play a crucial role in the restoration of the excitation spectrum of the alpha particle fragments. This nucleus is dissociated practically totally through the $0^{+}$ and $2^{+}$ states of the $^{8}$Be nucleus.

A detailed study of the nuclear fragment ensembles makes it possible to go on to the search for complicated quasi-stationary states of fragments. In the nuclear scale of distances and excitations they can possess properties which make them analogous to dilute quantum gases in atomic physics at ultra-cold temperatures. The proof of the existence of such systems can find some important applications for the problems of nuclear astrophysics. In this respect, the fragment jets are a microscopic model of stellar media.

## Acknowledgements

In conclusion, we would like to remember the names of our leaders in the domain of investigations with relativistic nuclei. Unfortunately, they are no more among the living. The foundations of the research along these lines had been laid by Academician A.M.Baldin. For many years, M.I.Adamovich, V.I.Ostroumov, Z.I.Solovieva, K.D.Tolstov, M.I.Tretiakova, and G.M.Chernov had been leaders of the investigations carried out by nuclear emulsion technique at the JINR synchrophasotron. We hope that this sketch will will be a contribution to a thankful memory of the senior generation scientists in Russia.

## References

E. M. Friedlander et al.(1983) Nuclear collisions of uranium nuclei up to about 1 GeV/nucleon, *Physical Review* **C27**, 2436–2438.

G. Baroni et al.(1990) Electromagnetic dissociation of 200 GeV/nucleon $^{16}$O and $^{32}$S in emulsion, *Nuclear Physics* **A516**, 673–714.

G. Baroni et al.(1992) The electromagnetic and hadronic diffractive dissociation of $^{16}$O ions, *Nuclear Physics* **A540**, 646–658.

V. Bradnova et al. (2004) Studies of light nucleus clustering in relativistic multifragmentation processes, *Acta Phys. Slovaca* **54**, 351–365.

Web site of the BECQUEREL Project: http://becquerel.jinr.ru.

P. L. Jain et al.(1984) Fission of Uranium Nuclei in Flight at Relativistic Energies, *Physical Review Letters* **52**, 1763–1766.

M. I. Adamovich et al.(1997) He production in 158 A GeV/c Pb on Pb interactions, *Physics Letters* **B 390**, 445–449.

M. I. Adamovich et al.(1999) Angular distributions of light projectile fragments in deep inelastic Pb+Em interactions at 160 A GeV, *The European Physical Journal* **A 6**, 421–427.

M. I. Adamovich et al.(1997) Multifragmentation of Gold nuclei in the interactions with photoemulsion at 10.7 GeV/nucleon, *Zeitschrift für Physik* **A 359**, 277–290.

M. I. Adamovich et al.(1997) Critical behavior in Au fragmentation at 10.7A GeV, *The European Physical Journal* **A 1**, 77–83.

M. L. Cherry et al.(1998) Fragmentation and particle production in interactions of 10.6 GeV/N gold nuclei with hydrogen, light and heavy targets, *The European Physical Journal* **C 5**, 641–645.

A. El-Naghy et al.(1988) Fragmentation of $^{22}$Ne in emulsion at 4.1 A GeV/c, *Journal of Physics* **G14**, 1125–1137.

M. A. Jilany(2004) Nuclear fragmentation in interactions of 3.7A GeV $^{24}$Mg projectiles with emulsion targets, *Physical Review* **C70**, 014901-01–014901-13.

N. P. Andreeva et al.(2005) Topology of ”white stars” in relativistic fragmentation of light nuclei, *Physics of Atomic Nuclei* **68**, 455–465.

V. V. Belaga et al.(1995) Coherent dissociation $^{12}C \to 3\alpha$ in lead-enriched emulsion at 4.5 GeV/c per nucleon, *Physics of Atomic Nuclei* **58**, 1905–1910.

N. P. Andreeva et al.(1996) Coherent dissociation $^{16}O \to 4\alpha$ in photoemulsion at an incident moment of 4.5 GeV/c per nucleon, *Physics of Atomic Nuclei* **58**, 1905–1910.

V. V. Glagolev et al. (2001) Fragmentation of relativistic oxygen nuclei in interactions with a proton, *The European Physical Journal* **A11**, 285–296.

F. G. Lepekhin et al. (1998) Yields and transverse momenta of the $^{6}$Li fragments in the emulsion at 4.5 GeV/c per nucleon, *The European Physical Journal* **A1**, 137–141.

M. I. Adamovich et al.(1999) Interactions of $^{6}$Li with photoemulsion nuclei, *Physics of Atomic Nuclei* **62**, 1378–1387.

M. I. Adamovich et al. (2004) Dissociation of relativistic $^{7}$Li in emulsion and structure of $^{7}$Li nucleus, *Journal of Physics* **G30**, 1479–1485.

M. I. Adamovich et al. (2004) Investigations of clustering in light nuclei by means of relativistic-multifragmentation processes, *Physics of Atomic Nuclei* **62**, 514–517.

V. Bradnova et al. (2004)Nuclear clustering in processes of relativistic multifragmentation, *Nuclear Physics* **A734**, E92–E95.

A. I. Malakhov (2004) Research program for the Nuclotron, *Nuclear Physics* **A734**, 82–90.

P. Schuck et al.(2003) Alpha-particle condensation in nuclei, *Comptes Rendus Physique* **4**, 537–540.

A. M. Baldin and L. A. Didenko (1990) Asymptotic properties of hadron matter in relative four velocity space, *Fortschritte der Physik* **38**, 261–332.