The BECQUEREL Project: Progress Report for Years 2006-8 and Plans for 2009-11

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INTRODUCTORY REMARKS

The BECQUEREL Project (Beryllium (Boron) Clustering Quest in Relativistic Multifragmentation) at the JINR Nuclotron is devoted systematic exploration of clustering features of light stable and radioactive nuclei (fig. 1). A nuclear track emulsion is used to explore the fragmentation of the relativistic nuclei down to the most peripheral interactions - nuclear "white" stars. This technique provides a record spatial resolution and allows one to observe the 3D images of peripheral collisions. The analysis of the relativistic fragmentation of neutron-deficient isotopes has special advantages owing to a larger fraction of observable nucleons.

In general, nuclear beams of energy higher than *1A* GeV are recognized as a novel opportunity for the nuclear structure explorations. Among all variety of the nuclear interactions the peripheral dissociation bears uniquely complete information about the excited nucleus states above particle decay thresholds.

A peripheral dissociation is revealed as a narrow jet of relativistic fragments the total charge of which is close to the charge of the primary nucleus. In spite of the relativistic velocity of fragments the relative velocities inside the jet are non-relativistic ones. In principle, information about the generation of such fragment ensembles can be used in nuclear astrophysics in development of nucleosynthesis scenarios on the basis of few-particle fusion. The challenging task for a detection technique is to provide the completeness in the observation of relativistic fragments.

The difficulty of the principle is the following. An increase in the dissociation degree of a relativistic nucleus leads to a decrease in the fragment detector response. This circumstance makes the wholesome analysis, which is necessary up to the *He* and *H* isotopes, hardly accessible.

Then, the excited state of the produced fragment system is defined by the invariant mass of the relativistic fragment jet. Therefore the most accurate measurements of the emission angles of fragments are needed. The accuracy of momentum measurements isn't so demanding. It is enough to assume that the fragments conserve the primary momentum per nucleus. In addition, the selection of most peripheral collisions requires the detection threshold to be as low as possible for the target fragments.

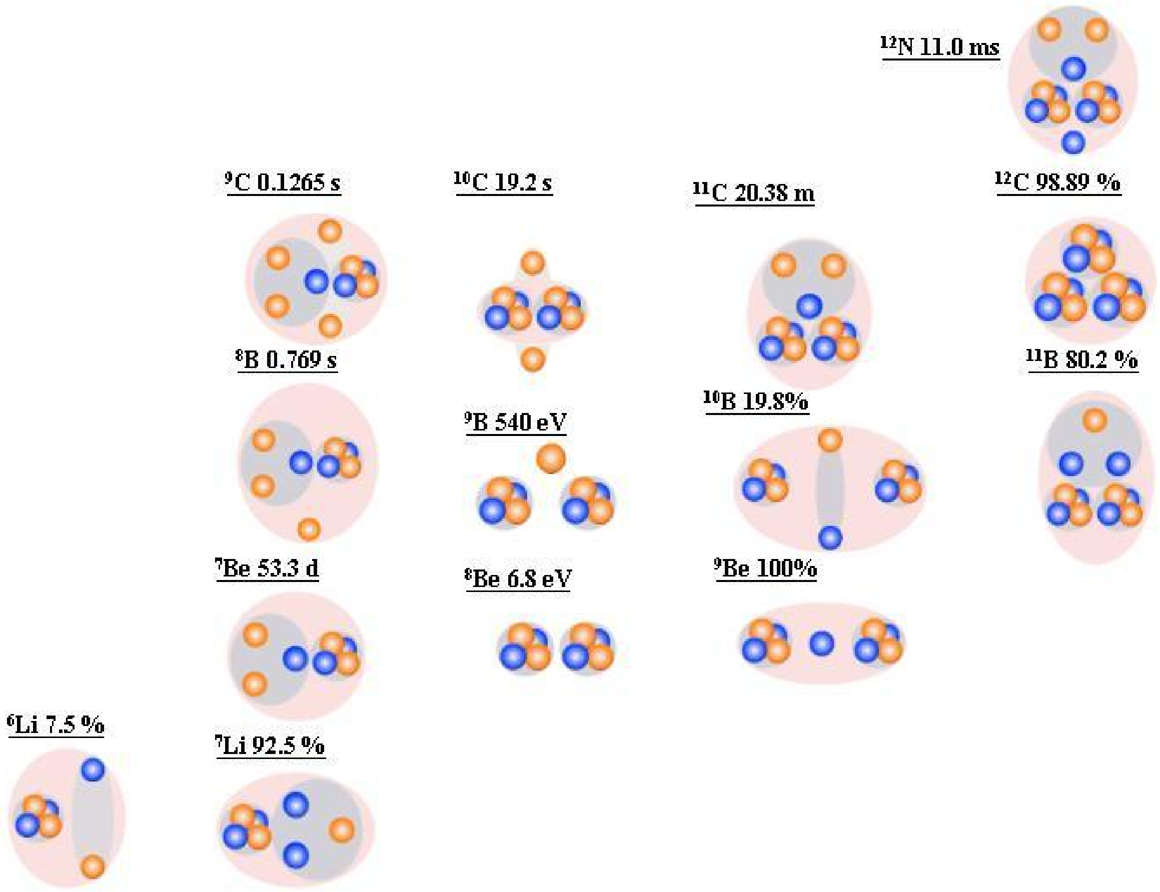

Fig. 1. Diagram of the cluster excitations of light nuclei.

The nuclear emulsion technique, which underlies the BECQUEREL Project, solves these problems and makes it possible to perform effectively survey investigations on newly produced beams. Unique information about the structure of peripheral dissociation of many nuclei has already been obtained. Limitations imposed to statistics are compensated by the fact that the fragment jets are inaccessible for observation in any other techniques.

The emulsion composition provides a special convenience to explore just peripheral interactions. It includes the *Br*, *Ag* and *H* nuclei in comparable concentrations and allows one to compare fragmentation patterns of various origins. Under the same conditions it is possible to observe the very peripheral break-up in the electromagnetic field on a heavy target nucleus (EM dissociation; fig. 2) as well as in collisions with target protons. Microphotographs and movies of typical events can be found http://becquerel.lhe.jinr.ru/movies/movies.html .

The emulsion response is described by the multiplicities of heavily ionizing fragments n_b including α particles and slow protons and n_g corresponding to non-relativistic protons. Besides, the reactions are characterized by the multiplicity of produced mesons n_s. The events in which there are no tracks of target nucleus fragmentation belong to electromagnetic or diffractive dissociation and are named "white" stars ($n_b = 0$, $n_g = 0$, $n_s = 0$). Dissociation on a proton must lead to the appearance of its track, that is, $n_b = 0$, $n_g = 1$, and $n_s = 0$. The structure of the events of these types, i. e. EM, and diffractive and free proton induced ones, is just the central subject of the Project.

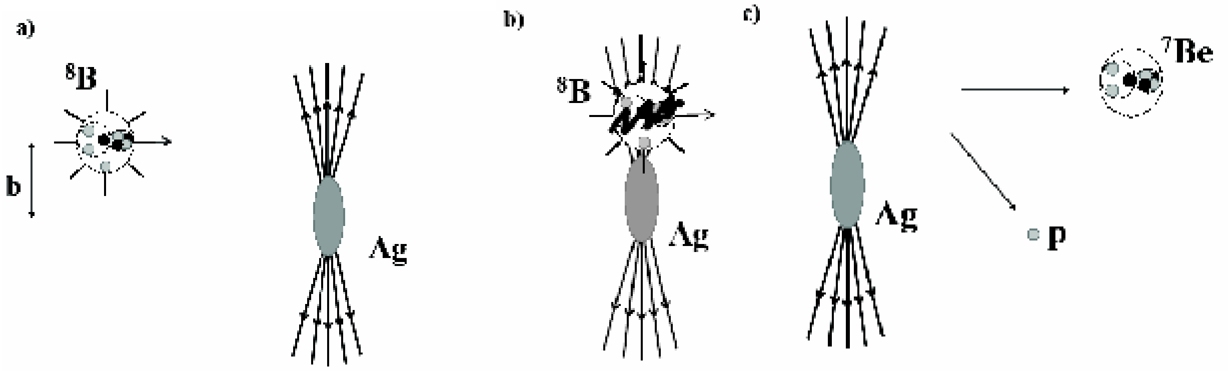

Fig. 2. Diagram of peripheral dissociation of relativistic ^8B nucleus in EM field of *Ag* nucleus: nearer approach of the nuclei with an impact parameter (a), absorption of quasireal photon by ^8B nucleus (b), ^8B dissociation on fragment pair - *p* and ^7Be (c).

In what follows, the physics conclusions are presented for the ^{14}N, ^9Be, ^7Be and ^8B nucleus exposures, which are performed in 2004. The ^9C and ^{12}N exposures in 2006 are suggested as central tasks of analysis for 2009 – 11. The ^{10}C and ^{11}C enriched exposures are suggested to be performed at the Nuclotron in the forthcoming years.

SUMMARY OF PHYSICS RESULTS in 2005-8

<u>Fragmentation of ^{14}N nuclei.</u> The charge topology distribution of *2A* GeV ^{14}N peripheral interactions indicates the leading role of the multi-body channel *3He + H*. To estimate the energy scale of *3α* particle systems, the invariant mass distribution $Q_{3\alpha}$ has been obtained (fig. 3) for the 150 events in the $^{14}N \rightarrow 3\alpha + X$ channel. The major fraction of the events is concentrated in the $Q_{3\alpha}$ area from *10* to *14* MeV, covering the known ^{12}C levels. The fraction of the *α* particles originating from the ^8Be decay is ≈ *25%*. Thus, the problems of a few-body nuclear physics near the α emission threshold can be explored using detection advantages of the relativistic collisions.

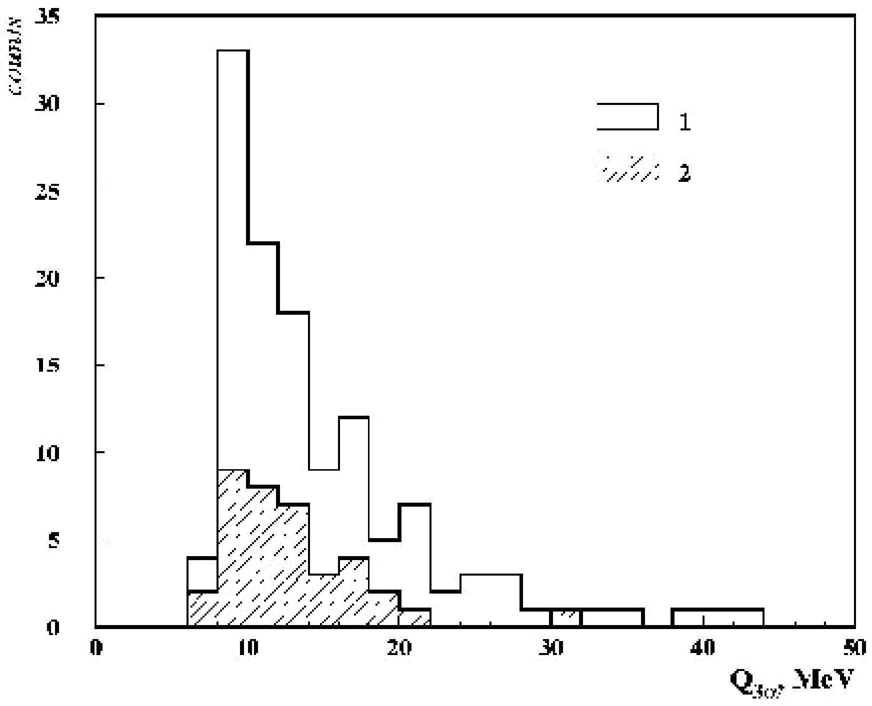

Fig. 3. The invariant mass distribution of 3α particles with respect to the ^{12}C ground state $Q_{3\alpha}$ for the process $^{14}N \rightarrow 3\alpha + X$ (1 - all the events of the given dissociation, 2 - «white» stars).

Fragmentation of ^{7}Be nuclei. **Nuclei of ^{7}Li were accelerated at the JINR Nuclotron. In the charge-exchange reaction a secondary ^{7}Be beam of energy *1.2A* GeV was formed to expose an emulsion. About *10%* of the found ^{7}Be events are associated with the peripheral interactions in which the total charge of the relativistic fragments is equal to the charge of the ^{7}Be and no mesons are produced (149 events). An unusual ratio is revealed in the composition of the doubly charged ^{7}Be fragments: the number of ^{3}He fragments is twice as large as that of ^{4}He fragments. In *50%* of peripheral interactions, a ^{7}Be nucleus breaks up to He pairs. In *50%* of events, the ^{7}Be fragmentation proceeds only to charged fragments involving no emission of neutrons. Of them, the $^{3}He + {}^{4}He$ channel dominates, while the $^{4}He + d + p$ and $^{6}Li + p$ channels constitute *10%* each. Two events involving no emission of neutrons are registered in the *3*-body $^{3}He + t + p$ and $^{3}He + d + d$ channels. The features of the relativistic ^{7}Be fragmentation in such peripheral interactions are explained by the $^{3}He + {}^{4}He$ cluster structure of the ^{7}Be nucleus.**

Fragmentation $^{9}Be \rightarrow 2He$. **The ^{9}Be nucleus is the best source of a α pair without the presence of the combinatory background. It can provide better understanding of more complicated $N\alpha$ systems. The present-day interest in such systems is inspired by the search for the α particle Bose-Einstein condensate in which the ground 0^{+} and the first excited 2^{+} states of the ^{8}Be nucleus must play the role of its basic ingredients. The peripheral dissociation to relativistic $N\alpha$ jets may turn out to be the most convenient option for its searching. The proof of the existence of such a state of dilute nuclear matter may have consequences in the development of nucleosynthesis concepts.**

In an emulsion exposed to relativistic ^{9}Be nuclei *371* events of fragmentation to a narrow pair of relativistic *He* nuclei were analyzed under the assumption of their correspondence to α particle. The clear appearance of two peaks in the distribution over the invariant mass above the α particle pair mass threshold $Q_{2\alpha}$ was observed (fig. 4). It was concluded that the 0^{+} and 2^{+} states of ^{8}Be are dominated in the spectra over $Q_{2\alpha}$.

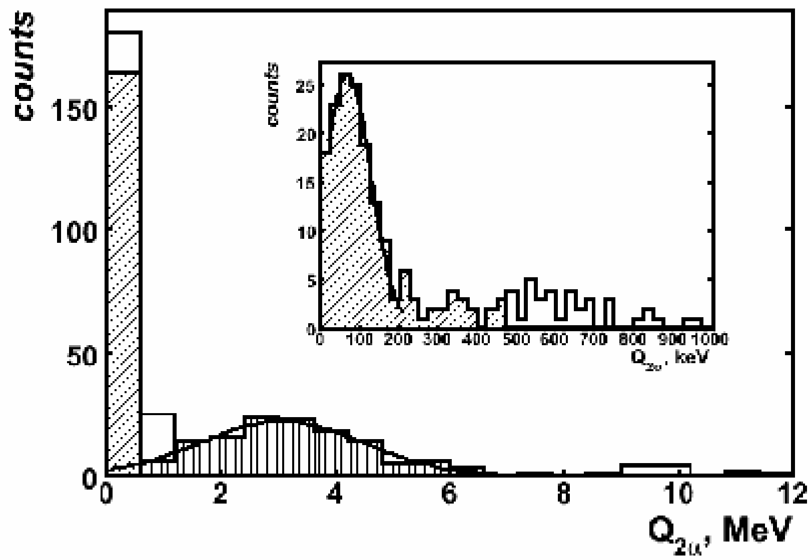

Fig. 4. The invariant energy $Q_{2\alpha}$ distribution for the $^{9}Be \rightarrow 2\alpha$ fragmentation reaction at *1.2A* GeV energy. On the intersection: the $Q_{2\alpha}$ range from *0* to *1* MeV.

The observables of interaction vertices allow one to compare the relative population of these states for EM&Diffractive and direct nucleonic interactions. It was concluded, that in EM&D dissociation the production of α particles pair via the ground ^{8}Be 0^{+} state

proceeds more intensively than for *n - p* knockout processes. Following the concept about the ^9Be nucleus as a cluster system *α – n - α* it may be supposed that the ground state of this nucleus contains with a noticeable probability a pair of *α* particle clusters with angular momentum *L = 2*. Such a picture is worthy to be checked at the next stage of the Project in 2009 – 11 using much larger statistics of interactions with hydrogen nuclei (≈ 2000 pairs).

Fragmentation of ^8B nuclei. Nuclear emulsion was exposed to a beam of *1.2A* GeV ^8B nuclei. A leading contribution of the "white" stars $^8B \rightarrow {}^7Be + p$ (*50%* or *25* events) having the lowest energy threshold was revealed. Due to the loosely bound proton the ^8B nucleus appears to be a very sensitive probe of the EM interactions proceeding at the lowest momentum transfers even (fig. 5). Information about a relative probability of ^8B dissociation modes with larger multiplicity has been obtained. The ^7Be core dissociation in ^8B is found to be similar to that of the free ^7Be nucleus.

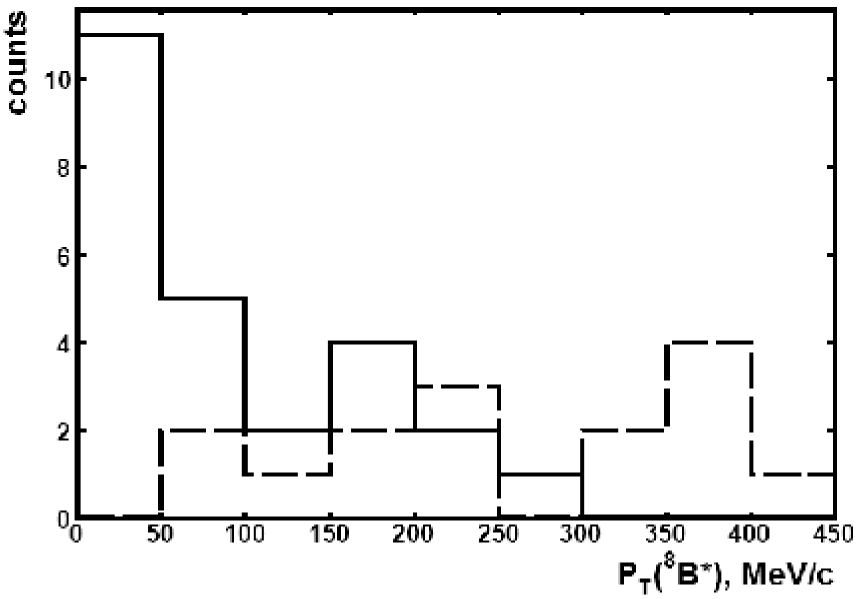

Fig. 5.The P_T ($^8B^*$) transverse momentum distribution of the pairs $^7Be + p$ produced in $^8B \rightarrow {}^7Be + p$. The solid line corresponds to "white" stars (*25* events); the dashed one – to the interactions accompanied by target fragments and produced particles (*15* events).

Multiple scattering measurements will be used to identify relativistic $^{1,2}H$ and $^{3,4}He$ isotopes. In spite of the fact that these measurements are labor demanding, the appropriate efforts can be satisfied by the identification of a 3-particle mode $^8B \rightarrow 2{}^3He + {}^2H$ (threshold of 20 MeV). This possibility is non-trivial because it is connected with a deep rearrangement of the ^8B cluster structure. The properties of this state near the threshold may turn out to be important for an inverse fusion process too. A particular feature of the $2{}^3He + {}^2H$ fusion process might consist in a larger number of vacancies for a neutron to be captured in the ^4He cluster formation.

MAJOR TASKS FOR 2009-11

Analysis of the ^9C and ^{12}N exposures. The conclusions about the dissociation of the ^8B and ^7Be nuclei form the solid basis for a comparative analysis of the ^9C and ^{12}N dripline nuclei chosen in the Project as the major next steps. The beam of these nuclei is created in the fragmentation and charge exchange reactions of *1.2A* GeV ^{12}C nuclei and emulsion exposures are performed in November'2006.

The fragmentation patterns established for ^8B and ^7Be nuclei are expected to be reproduced for the ^9C nucleus with the addition of one or, respectively, two protons. For

the first time the "golden" channel $^9C \rightarrow 3\ ^3He$ (threshold of *16* MeV) will become accessible for observation. The observation of 3^3He population near the threshold would allow one to put the ground for an extension of the well-known *3α* fusion process toward 3^3He one.

For ^{12}N nucleus one can expect a leading role of a "white" stars $^{12}N \rightarrow {}^{11}C + p$ reflecting its low binding (*600* keV). The new states may be accessed – $^8B + {}^4He$, $^7Be + p + {}^4He$, which are identifiable by a fragment charge composition. Their relative strengths will be defined by the interplay of Coulomb barrier, binding energy and density of final states.

The suggested $^{10,11}C$ exposures. The emulsion exposed to ^8B nuclei allowed one to observe few events with the total charge of relativistic fragments $\Sigma Z_{fr} = 6$ from the admixture of ^{10}C nuclei originated in the ^8B producing target due to the charge exchange process $^{10}B \rightarrow {}^{10}C$. Even restricted statistics points out that the *2He+2H* breakup in "white" stars is the most preferable mode. A low $^8Be + 2p$ channel threshold equal to 3.8 MeV has to be manifested in such a way.

In emulsion exposed to ^{11}B nuclei 8 "white" stars of a charge exchange type $^{11}B \rightarrow {}^{11}C^*$ has being observed in the 2-body channel $^7Be + {}^4He$ and no one in any other topology. Even on the limited statistics the obvious difference can be mentioned from the $^{10,11}B$ cases where 3-body channels *2He + H* were leading ones. This circumstance indicates on a remarkable sensitivity of relativistic peripheral dissociation to the nucleus excitation pattern.

A search for effects related with an isotopic invariance breaking in "white" star production presents a fundamental interest. In the case of ^{11}B and ^{11}C nucleus fragmentation such an analysis can be performed by comparison of a population of similar isotopic final states. Nuclear diffraction has to lead similarity while electromagnetic dissociation - to the difference in important details.

Presented observations deserve more detailed studies using much higher statistics of "white" stars. The most optimal way is to expose emulsions in secondary beams of charge exchange products $^{10}B \rightarrow {}^{10}C$ and $^{11}B \rightarrow {}^{11}C$. The charge exchange reactions $^{10}B \rightarrow {}^{10}C$ and $^{11}B \rightarrow {}^{11}C$ can be used for further exposures of emulsions with the aim not only to explore the main channels $2^4He + 2^1H$ and $^7Be + {}^4He$ but also to establish the existence of the dissociation modes $^{10}C \rightarrow {}^4He + 2^3He$ and $^{11}C \rightarrow 2^4He + {}^3He$ (threshold of *17* MeV). In just the same way as in the ^9C case its discovery can enlarge the picture of the inverse *3He* fusion process in nuclear astrophysics.

CONCLUDING REMARKS

The presented observations serve as an illustration of prospects of the Nuclotron for nuclear physics and astrophysics researches. In spite of an extraordinarily large distinction from the nuclear excitation energy the relativistic scale does not impede investigations of nuclear interactions down to energy scale typical for nuclear astrophysics, but on the contrary gives advantages. The major one of them is the possibility of principle of observing and investigating multi-particle systems.

The study of the relativistic dissociation of ^{14}N nucleus to a *3He* system confirms this prospect. The results of an exclusive study of the interactions of relativistic ^8B and ^9Be nuclei in nuclear emulsion lead to the conclusion that the known features of their structure are clearly manifested in very peripheral dissociations.

The investigations with light nuclei provide a basis for challenging studies of increasingly complicated systems *He – H - n* produced via multifragmentation of heavier relativistic nuclei in the energy scale relevant for nuclear astrophysics. In this respect, the motivated prospects are associated with a detailed analysis of the already observed fragment jets in the events of EM&Diffractive dissociation of *Au* nuclei at *10.6A* GeV and *Pb* nuclei at *160A* GeV.

Due to a record space resolution the emulsion technique provides unique entirety in studying of light nuclei, especially, neutron-deficient ones. Providing the 3D observation of narrow dissociation vertices this classical technique gives novel possibilities of moving toward more and more complicated nuclear systems. Therefore this technique deserves upgrade, without changes in its detection basics, with the aim to speed up the microscope scanning for rather rare events of peripheral dissociation.

To benefit from advances in years 2005-8, the BECQUREL Project is requested to be prolonged for years 2006-8 as a first priority topic in the 0983 theme with an annual level of funding from the JINR budget 20,000 $ (including JINR PR grants).

REQUESTED INFORMATION FOR JINR PP PAC

1. Institutions involved in the project

- **1.1** ***Laboratory of High Energies,Joint Institute for Nuclear Research, Dubna, Russia***
- **1.2** ***P. N. Lebedev Physical Institute RAS (FIAN), Moscow, Russia***
- **1.3** ***Institute of Space Sciences (ISS), Bucharest-Magurele, Romania***
- **1.4** ***Erevan Physical Institute (ErPh)I, Erevan, Armenia***
- **1.5** ***Istitute for Nuclear Research and Nuclear Energy BAS (INRNE), Sofia, Bulgaria***
- **1.6** ***K. Safarik University (SU), Kosice, Slovakia***

2. List of people involved and percentage of time devoted to the project

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Dr.V. Bradnova (JINR, 100%),
Res. Ass. D. O. Krivenkov (JINR, 100%),
Prof. A. I. Malakhov (JINR, 20%),
Dr. P. A. Rukoyatkin (JINR, 20%),
Dr. V. V. Rusakova (JINR, 100%),
Res. Ass. T. V. Shchedrina (JINR, 100%),
Dr. P. I. Zarubin (JINR, 100%),
Prog. Eng. I.G Zarubina (JINR, 100%)
Dr. M. M. Chernyavsky (FIAN, 50%),
Dr. S. P. Kharlamov (FIAN. 100%),
Dr. S. G. Gerasimov (FIAN, 50%),
Res. Ass. L. A. Goncharova (FIAN, 50%),
Dr. G. I. Orlova (FIAN, 50%),
Dr. N. G. Peresadko (FIAN, 100%),
Prof. N. G. Polukhina (FIAN, 20%),
Dr. M. Haiduc (ISS, 50%),
Res. Ass. A. Neagu (ISS, 100%),
Res. Ass. E. Stefan (ISS, 100%),
Dr. A. A. Moiseenko (ErPhI, 100%),
Dr. V. R. Sarkisyan (ErPhI, 100%),
Res. Ass. R. Stanoeva (INRNE, 100%),
Prof. S. Vokal (SU, 50%),

3. The project was approved for the first time in April 2002 for years 2003-5

4. The project was prolonged for years 2006-8 in April 2005.

5 (+ 7). PUBLICATIONS IN 2005 – 8

[1] N. P. Andreeva *et al.*, "Topology of "white" stars in relativistic fragmentation of light nuclei", Phys. At. Nucl. 68, 455 (2005); arXiv:nucl-ex/0605015v2. Prepared for Conference on Physics of Fundamental Interactions, Moscow, Russia, 1-5 Mar 2004.

[2] N. P. Andreeva *et al.*, "Clustering in light nuclei in fragmentation above *1A* GeV", Eur. Phys. J. A27, S1, 295(2006), arXiv: nucl-ex/0604003. Contributed to 2nd Conference on Nuclear Physics in Astrophysics, Debrecen, Hungary, 16-20 May 2005.

[3] T. V. Shchedrina *et al.*, "Peripheral interactions of relativistic ^{14}N nuclei with emulsion nuclei", Phys. At. Nucl., 70, 1230 (2007); arXiv:nucl-ex/0605022. Contributed to Russian Academy of Sciences Conference, Moscow, Russia, 5-9 Dec 2005.

[4] D. A. Artemenkov et al., "Special features of the $^{9}Be \rightarrow 2He$ fragmentation in emulsion at energy of *1.2A* GeV", Phys. At. Nucl., 70, 1226 (2007); arXiv:nucl-ex/0605018v1. Contributed to Russian Academy of Sciences Conference, Moscow, Russia, 5-9 Dec 2005.

[5] N. G. Peresadko *et al.*, "Fragmentation channels of relativistic ^{7}Be nuclei in peripheral interactions", Phys. At. Nucl., 70, 1266(2007); arXiv: nucl-ex/0605014. Contributed to Russian Academy of Sciences Conference, Moscow, Russia, 5-9 Dec 2005.

[6] R. Stanoeva *et al.*, "Peripheral fragmentation of the ^{8}B nuclei fragmentation at energy of *1.2A* GeV in nuclear track emulsion", Phys. At. Nucl., 70, 1216 (2007); arXiv: nucl-ex/0605013. Contributed to Russian Academy of Sciences Conference, Moscow, Russia, 5-9 Dec 2005.

[7] P. A. Rukoyatkin, L. N. Komolov, R. I. Kukushkina, V. N. Ramzhin, "Beams of relativistic nuclear fragments at the Nuclotron accelerator facility". Czechoslovak Journal of Physics, Supplement C, Vol. 56, C379 (2006).

[8] D. A. Artemenkov *et al.* "Peripheral fragmentation of relativistic B-11 nuclei in photo emulsion", e-Print: nucl-ex/0610023. Submitted to 9th International Workshop on Relativistic Nuclear Physics: From Hundreds MeV to TeV (RNP 2006), Modra, Harmonia, Slovakia, 22-27 May 2006.

6 (+ 7). List of references for additional written publications

[9] D. A. Artemenkov, T. V. Shchedrina, R. Stanoeva, and P. I. Zarubin, "Clustering features of ^{9}Be, ^{14}N, ^{7}Be, and ^{8}B nuclei in relativistic fragmentation", AIP Conf. Proc. 912, 78(2007); arXiv: 0704.0384. Contributed to International Symposium on Exotic Nuclei (EXON 2006), Khanty-Mansiysk, Russia, 17-24 Jul 2006.

[10] D.A. Artemenkov, G.I. Orlova, P.I. Zarubin, "Dissociation of relativistic nuclei in peripheral interactions in nuclear track emulsion", Nuclear Science and Safety in Europe, Springer, (2006) 189-200; arXiv: nucl-ex/0604007.

[11] N.P. Andreeva *et al.*, "Diffractive dissociation of relativistic nuclei in nuclear track emulsion", Prepared for International Conference on New Trends in High Energy Physics (Experiment, Phenomenology, Theory), Yalta, Crimea, Ukraine, 10-17 Sep 2005. Published in *Jalta 2005, New trends in high-energy physics* 93-104.

[12] P.I. Zarubin, "Clustering pattern of light nuclei in peripheral dissociation above *1A* GeV. Prepared for 19th European Few-Body Conference on Problems in Physics (EFB 19), Groningen, The Netherlands, 23-27 Aug 2004. Published in AIP Conf. Proc. 768: 404-406, 2005.

[12] Websites "The BECQUEREL Project" http://becquerel.jinr.ru/ and http://becquerel.lhe.jinr.ru.

8. Degrees

R. Stanoeva (MS Degree, Blagoevgrad Univ., BG, 2005),

T. V. Filatova (BS Degree, Tomsk Univ., RU, 2006),

O. I. Vinogradova (BS Degree, Tomsk Univ., RU, 2006),

R. Stanoeva (PhD Thesis submitted to LHE Council, 2008),

D. A. Artemenkov (PhD Thesis submitted to LHE Council, 2008)

9. Nuclotron beam time requested – approximately 60 hours per year.

10. Nuclotron beam time received – approximately 30 hours per year.

11. The year of data taking completion 2009.

12. Requested finances – 80,000 $ for years 2009-11