Progress Report on the BECQUEREL Project for Years 2002-5

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

[a]Insitutute of Physics and Technology, Almaty, Kazakhstan
[b]V. I. Veksler and A. M. Baldin Laboratory of High Energies,
Joint Institute for Nuclear Research, Dubna, Russia
[c]P. N. Lebedev Physical Institute RAS, Moscow, Russia
[d]Institute of Space Sciences, Bucharest-Magurele, Romania
[e]Petersburg Institute of Nuclear Physics RAS, Gatchina, Russia
[f]Erevan Physical Institute, Erevan, Armenia
[j]Istitute for Nuclera Research and Nuclear Energy BAS, Sofia, Bulgaria
[h]K. Safarik University, Kosice, Slovakia

INTRODUCTORY REMARKS

The BECQUEREL Project (Beryllium (Boron) Clustering Quest in Relativistic Multifragmentation) is oriented toward emulsion exposures by light stable and radioactive nuclei with an energy of the order of few GeV per nucleon in the JINR Nuclotron beams (**http://becquerel.lhe.jinr.ru/**).

Fragmentation of relativistic nuclei provides an excellent "laboratory" to explore the transition of nuclei from the ground state to a gas-like phase composed of nucleons and few-nucleon clusters having no excited states, i. e. d, t, ^{3}He, and α. The research challenge is to find indications for the formation of quasi-stable or loosely bound systems significantly exceeding the sizes of the fragments. Search for such states on the nuclear scale is of undoubted interest since they can play a role of intermediate states ("waiting stations") for a stellar nuclear fusion due to dramatically reduced Coulomb repulsion. The fragmentation features might assist one to disclose the scenarios of few-body fusions as processes inverse to fragmentation.

The charge topology of fragments in peripheral interactions of light nuclei above 1 A GeV is an basic characteristic of the multifragmentation. In this energy range, a regime of limiting fragmentation of nuclei sets in, that is, scaled fragment spectra are invariable with respect to the collision energy and the target-nucleus composition. The possibility of observing the final states consisting of charged fragments and their spectroscopy are defined by the accuracy of angular measurements. Owing to the best spatial resolution (0.5 μm), the nuclear emulsion ensures the angular resolution of the tracks of relativistic fragments of about 10^{-5} rad. This enables one to observe completely all the possible decays of nuclear excited states to fragments. For example, over a track length of 1 mm, one can surely distinguish a process ^{8}Be$\rightarrow 2\alpha$, which is revealed for a momentum of 2 A GeV/c per nucleon as a pair of tracks within an angular cone of about $4\cdot10^{-3}$ rad.

When accumulating data on nuclear multifragmentation, events without tracks from charged particles between the areas of the fragmentation of a projectile and the target-nucleus are selected. In such events the primary nucleus charge is mostly transferred into a narrow angular cone of fragmentation. The most obvious interpretation is provided for the events, which contain no tracks also from the target-nucleus fragments. They are produced with a minimal energy transfer to the fragmenting nucleus. Events of such a type are called "white" stars because of their appearance. Their fraction constitutes few percent of the total number of inelastic events. Their name reflects not only the outward look of the event, but also a sharp decrease of ionization losses (in a limiting case, by a factor of Z) in the transition from the primary nucleus track to the narrow cone of secondary tracks.

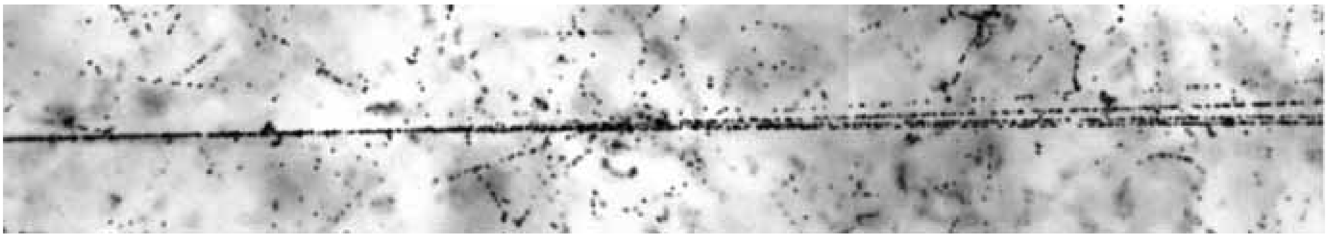

Fig. 1. Event of the 1.2 A GeV ^{14}N fragmentation in emulsion without target-nucleus excitation or meson production. The interaction vertex and a fragment jet in a narrow angle cone are seen on the photograph. Following the direction of the fragment jet (bottom part) it is possible to make out 3 fragments with Z = 2 and 1 fragment with Z = 1.

SUMMARY OF PHYSICS RESULTS in 2002-4

Clustering that involves deuterons (^{10}B and ^{14}N nuclei). The topology of "white" stars is investigated for ^{10}B nuclei at the energy of 1.0 GeV per nucleon. The fraction of the $^{10}B^*\rightarrow d\alpha\alpha$ 3-body decays is 40 % of the events with a charge topology 2+2+1. The contribution of the $^{10}B^*\rightarrow d^8Be^{(*)}\rightarrow d\alpha\alpha$ channel is estimated to be 18±3 %. The decay of an unstable ^9B nucleus is not a basic source of the events with such a topology. This is suggested by the fact that the probability of observing a 4+1 topology in the $^{10}B^*\rightarrow p^9Be$ decay is small, as well as the contribution of ^8Be to $^{10}B\rightarrow p^8Be$ is also not large. It may be concluded that the direct three-body decays with "white" stars 2+2 +1 configuration play a crucial role. Thus the decay topology $^{10}B^*\rightarrow d\alpha\alpha$ is indicative of an analogy with the 3-body decay $^{12}C^*\rightarrow 3\alpha$.

It is interesting to find out the role of the three-body decays which has been defined for $^{10}B^*\rightarrow d\alpha\alpha$, and $^{12}C^*\rightarrow 3\alpha$ as well as to develop ideas of clustering in nuclei involving deuterons. To this end, emulsion was exposed to ^{14}N nuclei of the energy of 2.1 GeV per nucleon in 2003. The major goal is the study of the "white" stars $^{14}N^*\rightarrow d\alpha\alpha\alpha$ within the forward cone to 8 ^{o}. Example is shown in fig. 1. There is an evidence for a leading role of the 2+2+2+1 charge configuration, which is related to ^{14}N decay. It is interesting that 3α excitation energy is 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.

Clustering that involves tritons (^7Li and ^{11}B nuclei). The study of the "white" stars of light odd-even stable nuclei (^7Li and ^{11}B) can provide a basis for including tritons into the general picture. It is established that in the "white" stars originating from relativistic ^7Li nuclei, the $^7Li^*\rightarrow\alpha t$ channel constitutes 50 %, $^7Li^*\rightarrow\alpha dp$ - 30 %, and $^7Li^*\rightarrow\alpha pnn$ - 20 %. As a next step, an exposure has been performed and the dissociation of ^{11}B nuclei of an the energy of 1.2 GeV is under analysis now. The major task of the experiment is the study of the "white" stars of the $^{11}B^*\rightarrow t\alpha\alpha$ channel.

Clustering in fragmentation of heavier nuclei (Ne, Mg, and Si nuclei). In-depth reanalysis of existing exposures carried out in 2002-4 have shown that the common topological feature for fragmentation of the Ne, Mg, and Si 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. In depth-analysis with impact using existing irradiations will bring qulitevly new developmenst in on nonrelativistic few body physics and nuclear astrophysics.

Clustering that involves ^3He (^7Be nuclei). The study of the ^7Be nucleus fragmentation is of interest as far as this nucleus may be a core in the ^8B nucleus. Using one and the same approach, it will be possible to compare the cluster structure of this nucleus with the ^6Li and ^7Li nuclei through the probabilities of forming "white" stars in the α^3H and p^6Li channels.

Emulsion stacks were exposed to ^7Be nuclei of the energy of 1.23 GeV per nucleon, the beam of which was formed at the JINR nuclotron on the basis of the charge-exchange reaction $^7Li\rightarrow{}^7Be$ in 2003. As a result, 75 "white" stars with the total secondary track charge equal to 4 were found in a cone up to 15 ^{o}.The examples of such stars for 2+2 topologies with and without target excitation, as well as for 3+1 and 1+1+1+1 topologies are given in fig.2. The $^7Be^*\rightarrow\alpha^3He$ decay, that occurs for a minimal excitation above the decay threshold, as compared with other channels, is dominant in 22 events with 2+2 topology. In the latter, 5 events are identified as the $^7Be^* \to (n)\ ^3He^3He$ decay. Thus, a clustering with ^3He formation is clearly demonstrated in the "white" stars of the ^7Be nucleus which makes it possible to put the question as to whether this clustering is revealed in neighboring neutron-deficient nuclei.

LATEST IRRADIATIONS AND PLANS FOR ANALYSIS IN 2006-8

In 2004 emulsion stacks were exposed to Nuclotron beams enriched with light 1.2 A GeV ^7Be, ^8B, ^9Be and ^9C nuclei. The primary ^7Li charge exchange reaction was chosen to form a ^7Be beam. The total irradiation flux was 40000 ^7Be nuclei for about 1.5 hour irradiation time. At present the irradiated material is being processed. One has every reason to expect that the statistics on fragmentation of this nucleus will essentially increase with the restect to early irradiation. The ^9Be and ^8B beams were formed on the basis of the primary ^{10}B stripping reaction and the ^9C beams - in ^{12}C fragmentation. About 80% of the beam consisted of these nuclei; the rest background was lighter nuclei with close charge to weight ratio.

^{9}Be nuclei. A visual scanning of emulsions exposed to ^9Be nuclei revealed by the present time about 200 interactions in which the total charge of secondary tracks in the relativistic fragmentation cone is equal to the charge of the primary one. The clear production of "white" stars with α particle pairs is initiated in the ^9Be fragmentation with removal of a loosely bound neutron. An analysis of the data going right now will allow one to conclude about clustering in the ^9Be nucleus and extent experience of ^8Be identification in n-^8Be, n-$^8Be^*$, and $\alpha n \alpha$ excitations.

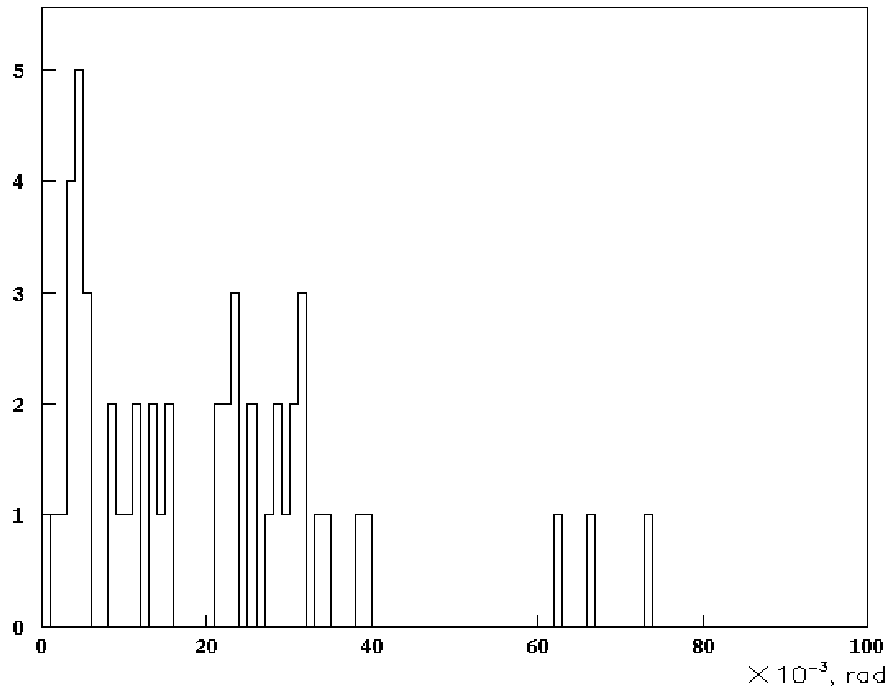

Fig. 2. Distribution in the opening angle between fragment pairs for the $^9Be \to 2\alpha$ fragmentation channel.

.

Fig. 2 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 ^8Be decay from the ground state 0^+. The decay energy defined using events in the first peak is 88 ±10 KeV which is in correspondance with known data on ^8Be. The The distribution is seen to be limited by a region $b_{ik}<10^{-1}$. In spite of the fact that the statistics is rather restricted these distributions show that further accumulation of statistics is prospective.

^{8}B nuclei. It is planned to determine the relative probabilities of $^8B^* \to p^7Be$, $p^3He\alpha$, pp^6Li, and $ppd\alpha$. There arises a possibility of studying the decays $^7B \to pp p\alpha$ and p^3He^3He since a nuclear stability border gets crossed in the $^8B \to ^7B$ fragmentation. In the relativistic case such decays would be appearing as narrow jets convenient for a analysis. As a very beginning 2 "white" stars $p^3He\alpha$ are identified.

^{9}C nuclei. The priority task is to establish the probability of $^9C^*\to3^3He$ decays with respect to $^9C^*\to p^8B$, pp^7Be. The inverse processes $^3He^3He^3He\to pp^3He\alpha\to{}^9C$ are similar to 3α fusions but produce a significantly higher energy output. A decay to a ^9B nucleus that is not a bound one, results in the $^9B\to p\alpha\alpha$ decay. Thus, in a stellar medium, initially composed of the ^3He, a workout of ^4He can proceed. In fragmentation $^9C\to{}^8C$, a crossing of the stability boundary takes place once more and $^8C^*\to$ ppppα and pp^3He^3He decays can be explored. Among other interesting topologies a single candidate for $^9C^*\to3^3He$ is found already.

^{10,11}C and ^{12}N nuclei (forthcoming exposures). It is suggested years 2005-7 to form secondary beams of $^{10,11}C$ and ^{12}N nuclei using charge exchange processes ($^{10,11}B\to{}^{10,11}C$ and $^{12}C\to{}^{12}N$) and expose emulsions. This way the ^3He role in $^{10,11}C$ and ^{12}N decays might be explored to extend "3He" process ($^3He^3He\alpha$, $^3He\alpha\alpha$).

PROSPECTS FOR IN-DEPTH ANALYSIS OF FRAGMENT JETS

A detailed study of the systems of relativistic nuclear fragments formed in the dissociation of nuclei of an energy above 1 A GeV provides a qualitatively better understanding of the structure of nuclear excitations above the decay thresholds. Fragmentation results in the production of fragment jets which are determined by the invariant variable region (the squared four-velocity difference) $b_{ik}=-(P_i/m_i-P_k/m_k)^2$, where P and m are the four-momenta and the masses of the *i* and *k* fragments concentrated within $10^{-4}< b_{ik} <10^{-2}$. The lower limit corresponds to the $^8Be\to2\alpha$ decay with a record low decay energy (92 KeV), while the upper one - to the upper limit of non-relativistic nuclear processes as suggestd by A. M. Baldin. The latter go at the level of nucleon-nucleon interactions without inclusion of the meson degrees of freedom. 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 $M^{*2}=(\Sigma Pj)^2=\Sigma(P_i\cdot P_k)$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.

The nuclear emulsion technique seems to be most suitable for the study of the multiple fragmentation of relativistic nuclei up to a total breakup to single-charged fragments. 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.

The formation of a nuclear state analogous to a dilute Bose gas at the atomic level can be revealed in narrow jets involving two-charged relativistic fragments near the threshold of production of an ensemble consisting of few alpha particles. Such ensembles are inwardly non-relativistic systems and can possess quantum coherent properties. 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. 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 alpha particle systems in the most universal manner.

Fig.3 shows the b_{ik} distribution for the fragmentation channel $^{22}Ne\to2\alpha$ (a) and $^{22}Ne\to5\alpha$ (b) channel (10 events). The main part of the relative velocities defining the dispersion of relativistic jets satisfies a non-relativistic criterion $b_{ik}<10^{-2}$. In spite of a significant difference in the composition of the systems, both distributions look rather similar. 3 events of a ^{22}Ne decay to 5 He nuclei are found the tracks of which 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 energy. 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.

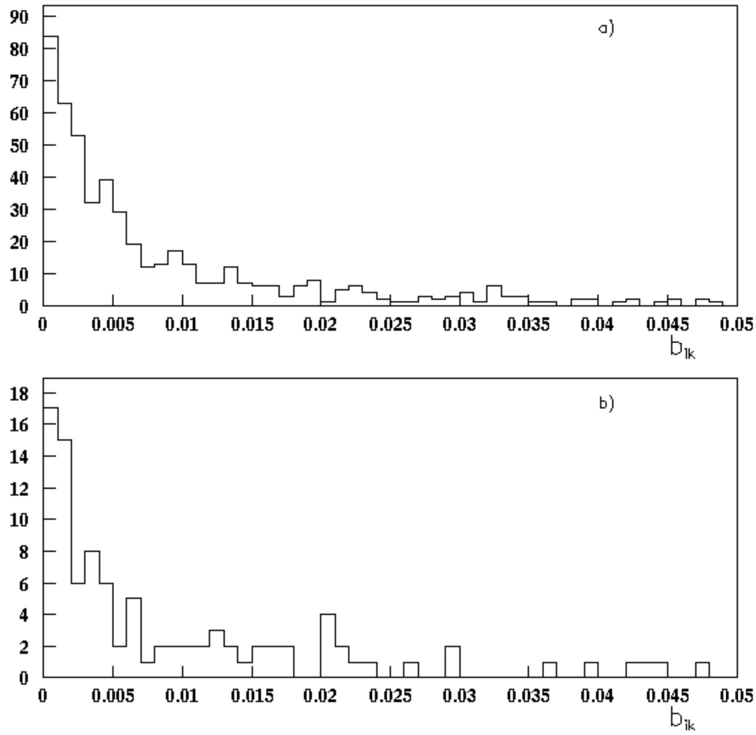

Fig. 3. The b_{ik} distribution for the fragmentation channels $^{22}Ne \to 2\alpha$ (a) and $^{22}Ne \to 5\alpha$ (b) of 3.22 A GeV.

CONCLUSIONS

The BECQUEREL project performed emulsion exposures in the Nuclotrom beams in accordance with the program. The irradiated emulsion are processed and distributed among the collaboration teams. The first physical results confirming the successful exposures are published. Thank to the best spatial resolution and the full solid angle acceptance provided by nuclear emulsions, such an approach allowed to observe poorly known nuclear structures and to identify features of their clustering. Such structures might play a role of intermediate quantum states in a fusion of more than two nuclei in stellar processes. The emulsions either newly exposed or existing emulsion heritage will provide a unique ground for studies of few body clustering in nuclear systems in forthcoming years.

The project is resumed the traditional collaboration of the VBLHE with the emulsion groups in the JINR member countries.

The project stimulated development of topical problems which are important for formulating of future nuclear physics researches in VBLHE.

The project initiated an obtaining of new primary ($^{10,11}B$ and ^{14}N) and secondary (^{6}He, ^{7}Be,^{9}Be, ^{8}B, and ^{9}C**)** beams at the Nuclotron.

The project provided 10$ from JINR PR grants as donation for the Nuclotron beam transport group for modern equipment.

The project is attracted few young researchers from JINR member countries and provided grounds for few MS and PhD works.

The project was supported by few JINR Plenary Representatives grants and the same level of support is promised in forthcoming years.

To benefit form advances in years 2003-5, **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 10,000 $ (including JINR PR grants).**

PUBLICATIONS & REPORTS

1. M. I. Adamovich et al. Irradiation of nuclear emulsions in relativistic beams of ^{6}He and ^{3}H nuclei. Particles and Nuclei, Letters, 1[110]29 (2002), Письма в ЭЧАЯ, 1[110]29 (2002).
2. V. Bradnova et al. Beryllium (Boron) clustering quest in relativistic multifragmentation (BECQUEREL Project). Physics of Atomic Nuclei, Vol. 66, No 9, 2003, pp 1646-1650. Ядерная физика, т. 66, №9, 2003, стр. 1694-1698. (Presented at School-Seminar on Heavy Ion Physics, Dubna, 2002).
3. V. Bradnova et al. Nuclear clustering quest in relativistic multifragmentation.Few-Body Systems Suppl. 14 (2003) 241.
4. V. Bradnova et al.. Nuclear clustering quest in relativistic multifragmentation. Few-Body Systems Suppl. 14 (2003) 241. (Presented at 18th European Conference on Few-Body Problems in Physics, Bled, Slovenia, 2002).
5. A.I. Malakhov. Reserch Program for the Nuclotron. Nucl. Phys. A734(2004)82-90 (Presented at VIII Int. Conf. on Nucleus-Nucleus Collisions, Moscow, 17-24 June 2003).
6. V. Bradnova et al. Nuclear clustering in processes of relativistic multifragmentation. Nucl. Phys. A734(2004)E92-E95 (Presented at VIII Int. Conf. on Nucleus-Nucleus Collisions, Moscow, 17-24 June 2003).
7. V. Bradnova et al. Studies of light nuclear clustering in relativistic multifragmentation processes. Acta Physica Slovaca, vol.54, №4, 351-365 (2004) (Presented at Workshop "Relativistic Nuclear Physics from MeV to TeV", Stara Lesna, Slovakia, August 2003).
8. M. I. Adamovich et al. Investigation of clustering in light nuclei by means of relativistic-multifragmentation processes. Physics of Atomic Nuclei, Vol. 67, No 3, 2004, pp 514-517. Ядерная физика, т. 67, №5, 2004, стр. 533-536 (Presented at Conference on fundamental interactions, ITEP, Moscow, 2002).
9. N. P. Andreeva et al. Topology of “white stars” in relativistic fragmentation of light nuclei. Physics of Atomic Nuclei, Vol. 68, No 3, 2005, pp. 455-465. Ядерная физика, т. 68, №3 2005, с. 484-494 (Presented at Conference on fundamental interactions, ITEP, Moscow, 2004).
10. P. I. Zarubin. Clustering pattern of light nuclei in peripheral dissociation above 1 A GeV. To be published by AIP. (Presented at 19^{9h} European Conference on Few-Body Problems in Physics, Groningen, The Netherlands, 2004).
11. F. G. Lepekhin. Yields of $^{8}Be \to 2\alpha$ in the Emulsion at 1 GeV per Nucleon. PNPI Preprint 2554 (in Russian; submitted to Physics of Atomic Nuclei).

FUNDING PROFILE

This work is supported by the Russian Foundation for Basic Research (project 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 the Slovak Republic (annually), the Czech Republic(annually), Romania (2002), and Bulgaria (2004).

2001: 3.5 k$+4 k$ (JINR Budget for travel and workshops)=7.5 k$

2002: 1 k$ (Grant of PR Slovakia) +2 k$ (Grant of PR Czech Rep.)+ 12 k$ (Grant of PR Romania)+4 k$ (JINR Budget for travel and workshops)=19 k$

Comment: 7.5 k$ of PR of Romania were provided for beam transport team.

2003: 2.5 k$ (Grant of PR Slovakia)+2 k$ (Grant of PR Czech Rep.)+8 k$ (JINR Budget for emulsion)+5 k$ (JINR Budget for travel and workshops)=17.5 k$

2004: 3.5 k$ (Grant of PR Slovakia)+2 k$ (Grant of PR Czech Rep.)+2 k$ (Grant of PR Bulgaria)+4 k$ (JINR Budget for travel and workshops)=11.5 k$

Comment: 2.5 k$ of PR of Slovakia ond Czechia were provided for beam transport team.

2005-8 (expected annually): 3.5 k$ (Grant of PR Slovakia)+2 k$ (Grant of PR Czech Rep.)+3 k$ (Grant of PR Bulgaria)+4 k$ (JINR Budget for travel and workshops)=10.5 k$