Form #24

THE BECQUEREL PROJECT

Experiment BECQUEREL at Accelerator Complex NUCLOTRON/NICA

CODE OF THEME: 02-1-1087-2009/2020

Theme: Research on Relativistic Heavy and Light Ion Physics. Experiments at the Accelerator Complex Nuclotron/NICA at JINR and CERN SPS

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DATE OF SUBMISSION OF PROPOSAL TO SOD

DATA OF THE LABORATORY STC

DOCUMENT NUMBER: 19.11.19 LHEP STC No. 10

DATE OF PROJECT FIRST APPROVAL

Form #25

PROJECT ENDORSEMENT LIST

Experiment BECQUEREL at Accelerator Complex NUCLOTRON/NICA

CODE OF THEME: 02-1-1087-2009/2020

Theme: Research on Relativistic Heavy and Light Ion Physics.
Experiments at the Accelerator Complex
Nuclotron/NICA at JINR and CERN SPS

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PROJECT LEADER	[signature]	20.11.19
PROJECT DEPUTY LEADER	[signature]	20.11.2019
ENDORSED PAC		

JOINT INSTITUTE FOR NUCLEAR RESEARCH

Proposal for Experiment BECQUEREL at Accelerator Complex NUCLOTRON/NICA

(theme 02-1-1087-2009/2020)

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2019

Contents

Abstract

The phenomenon of dissociation of relativistic nuclei observed with a unique completeness in the nuclear track emulsion (NTE) makes it possible to study ensembles of nucleons and lightest nuclei of interest to nuclear physics and nuclear astrophysics. Individual features of the nuclei under study are manifested in probabilities of dissociation channels. Advantages of the NTE technique include unsurpassed resolution in determining emission angles of relativistic fragments and possibility of identification of He and H isotopes among them by multiple scattering measurements.

On this basis the cluster structure of the light stable and radioactive isotopes is examined in the BECQUEREL experiment at the JINR Nuclotron. In solving these problems young researchers are trained, methods of analysis modernized and production of NTE recovered. In particular, by the invariant mass of relativistic He and H pairs and triples in the dissociation of the isotopes ^{9}Be, ^{10}B, ^{10}C and ^{11}C the unstable ^{8}Be and ^{9}B nuclei are identified, and in the ^{12}C and ^{16}O dissociation — the Hoyle state. According to the results of the experiment, a doctoral and six PhD's theses are prepared and few reviews published. The next problem is searching in the dissociation of the nuclei ^{14}N, ^{22}Ne and ^{28}Si the Hoyle state and more complex nuclear-molecular states.

The main task of the proposed BECQUEREL Experiment will be application of the NTE technique to study the low-density baryonic matter arising in the heavy nucleus dissociation. The temperature and density of this short-lived state are determined by the ratio of relativistic isotopes H and He and neutrons and their emission angles. NTE layers exposed to the NICA beams will serve as the research material allowing investigating nuclear ensembles of unprecedented multiplicity and diversity. To understand the mechanism of multiple dissociations of nuclei it is proposed to analyze fragmentation of the NTE down to their complete destruction of composing nuclei by relativistic muons. NTE irradiation by muons will be performed at CERN.

Effective solution of the assigned tasks requires investments in automated and computerized microscopes as well as improvement of the NTE technology. The project will serve as the basis for updating the traditional cooperation on the NTE use.

Introduction

Collective degrees of freedom, in which groups of few nucleons behave as composing clusters, are a key aspect of nuclear structure. The fundamental "building blocks" of clustering are the lightest nuclei having no excited states – first of all, the ^{4}He nucleus (α-particles) and then the deuteron (*d*), the triton (*t*) and the ^{3}He nucleus or *helion* (*h*). This feature is clearly seen in the light nuclei, where the number of possible cluster configurations is small. In the cluster pattern the light nuclei are represented as a superposition of different cluster and nucleon configurations. The interest in such states above binding thresholds is associated with the prediction of their properties as molecular-like ones. Being considered in a macroscopic scale, coherent ensembles of clusters may play an intermediate role in nucleosynthesis which makes the study of nuclear clustering more important and going beyond the scope of the problems of nuclear structure. At first glance, the studies of nuclear many-body systems seem to be impossible in laboratory conditions. Nevertheless, they can be studied indirectly in nuclear disintegration processes when the excitation is slightly above the appropriate thresholds.

Theory of the low-density baryonic matter arising due to clustering of nucleons into the lightest nuclei under conditions of extremely low nuclear density and temperature is under development during the last two decades (Fig. 1). An α-particle Bose–Einstein condensate (αBEC) is considered as an analogue of atomic quantum gases . The active development of the theory in this direction over the past two decades can be traced back to the works of C.J. Horowitz, G. Röpke, P. Schuck, A. S. Botvina, I. N. Mishustin and their co-authors. These developments put forward the problem of studying a variety of cluster ensembles and unbound nuclei as fundamental components of novel quantum matter. Nuclear clustering is traditionally regarded as the prerogative of the physics of nuclear reactions at low energies. The mission of the BECQUEREL Project is to use the potential of one of the sections of high-energy physics – relativistic nuclear physics – for the development of the concepts of nuclear clustering.

The phenomenon of peripheral dissociation of relativistic nuclei has the latent potential of a "laboratory" for testing advanced concepts of nuclear physics and nuclear astrophysics. The nuclear matter similar in thermodynamics and isotopic composition with a supernova can be re-created in dissociation of heavy nuclei. At the astrophysical scale this short lived state can serve as a necessary stage on the way toward synthesis of the heaviest nuclei. Beams of nuclei generated for the NICA collider will open up the prospect of systematic research in this direction using the method of the nuclear track emulsion (NTE). The project aims to identify the composition of the fragment ensembles, as well as the contribution of neutrons in the fragmentation of heavy nuclei. Due to the unique resolution and sensitivity of the NTE method the most accurate measurements of the emission angles of the relativistic isotopes H and He identified by the multiple scattering method as well as neutrons, identified by secondary vertices will be provided. Being obtained in inverse kinematics data on neutron yields available will serve as a guideline when designing hybrid "reactor + accelerator" systems.

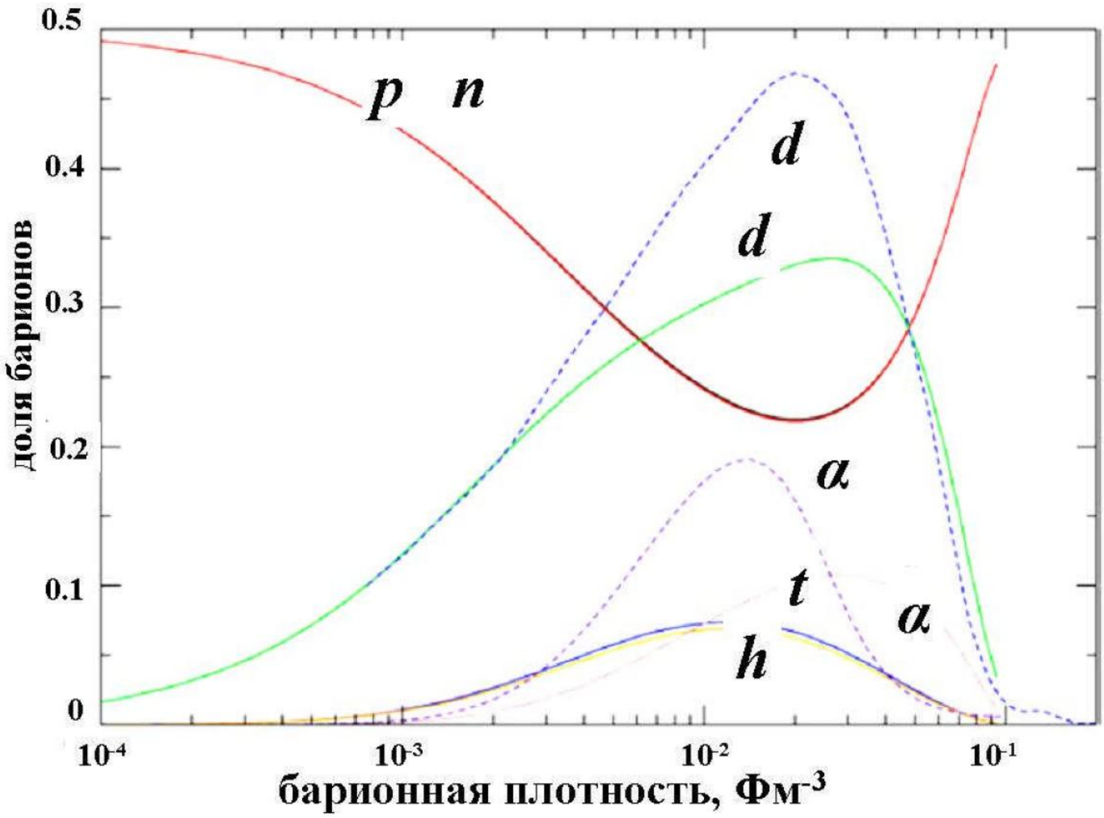

Fig. 1. Ratio of shares of nucleons and lightest nuclei depending on baryon density of symmetric nuclear matter (from report by G. Röpke).

The proposal to use dissociation of relativistic nuclei as a source of coherent ensembles of the lightest nuclei is based on the known observations. When energy above 1 *A* GeV, projectile and target fragmentation regions are clearly separated, and fragment momentum spectra enter the scale-invariant behavior. Thus, the regime of the limiting fragmentation is achieved which also means that the fragment isotopic composition remains unchanged with an increase in the collision energy. The isotopic composition of charged fragments determines the number of unbound neutrons. The detection thresholds of relativistic fragments are absent, and the energy losses in the substance are minimal.

The configuration overlap of the ground state of a fragmented nucleus with final states is most fully manifested in peripheral interactions with preservation of the baryon number in the fragmentation region. Determination of interactions as peripheral ones is simplified with the growth of energy due to the increasing collimation of fragments. The most peripheral of them called coherent dissociation or "white stars" are not accompanied by fragmentation of target nuclei. The probability of such a dissociation channel reaches several percent at energy above 1 *A* GeV. The structure of dissociation of nuclei constitutes object of this study.

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1. Status of research

The BECQUEREL experiment is based on the culture of using NTE in high-energy physics problems which has been developing since the early 1950s and has not lost value today. Exposures of NTE in the newly created beams of relativistic nuclei started in the 70s at the JINR Synchrophasotron of and LBL Bevalac. In the 90s similar exposures continued at BNL AGS and CERN SPS. In the spirit of traditions dating back to the pioneering period of cosmic ray studies NTE stacks developed in LHEP of JINR were transferred to many research centers and universities promoting the new research direction. The completeness of observation in NTE of tracks of charged particles formed the basis for the classification of nucleus-nucleus collisions. Special attention was attracted by the most destructive collisions, as meeting the highest concentration of matter and energy. The subsequent development in this direction is widely known. However, the results obtained in the 70–90s by the NTE method as well as the exposed layers themselves and the corresponding data files retain their uniqueness in terms of the fragmentation of the incident nuclei. To the maximum extent possible, this scientific heritage is preserved and available in the LHEP. The BECQUEREL project website accumulates a collection of macro-video recordings of the studied peripheral interactions of relativistic nuclei http://becquerel.jinr.ru/movies/movies.html.

Events of peripheral dissociation reflecting individual features of the incident nuclei are observed in NTE as often and fully as central collisions. They point out the principal possibility of studying the nuclear structure in the cone of relativistic fragmentation. However, in this aspect, the use of traditional magnetic spectrometers with coordinate and scintillation detectors turned out to be very limited. The difficulties that have arisen are due to the dramatic difference in the ionization of the nuclei of beam nuclei and relativistic fragments sophisticated by their extremely small angular divergence, and, often, an approximate coincidence in magnetic rigidity. For these reasons, measurements were made with the registration of relativistic fragments as close as possible in charge to the nucleus under study.

The discovery in the mid 80s exotic nuclei made at BEVALAC stimulated new experiments in beams of radioactive nuclei in many accelerator centers. Studies of light nuclei along the neutron stability border formed an area of research – the physics of nuclei with exotic structure. However, the relativistic energy range turned out to be inconvenient for deeper investigations of these nuclei and their studies shifted to low-energy accelerators. Some pause of using of the relativistic approach advantages to studies of light stable and neutron-deficient nuclei motivated exposures of NTE stacks to them. Since the beginning of 2000-ies the BECQUEREL experiment at the JINR Nuclotron aimed at the systematic application of the NTE method in the physics of peripheral interactions of light nuclei including radioactive ones.

An analysis of peripheral interactions in the NTE layers irradiated at the JINR Nuclotron made it possible to study in a unified approach the cluster features of the nuclei ^{7,9}Be, ^{8,10,11}B, ^{10,11}C, ^{12,14}N and establish the contribution of unstable ^{6}Be, ^{8}Be and ^{9}B nuclei to their dissociation (reviews [1,2]). The important conclusion is that the absence of stable ground states of ^{8}Be and ^{9}B does not prevent their participation in the nuclear structure. In nucleosynthesis chains, they can serve as necessary “transfer stations”, the passage of which is “imprinted” in the nuclei formed. Until now, such participants are recognized only in the famous chain 3α → α^{8}Be → (Hoyle state) → ^{12}C.

Our observations suggest the possibility of expanding the scenarios of light isotope synthesis involving the unstable states. It is possible to consider the role of more complex nuclear molecular systems. In particular, in the coherent dissociation of the ^{10}C nucleus, an indication is obtained of the resonance in the ^{9}B*p* channel at 4 MeV [2]. Its study continues on a 4-fold increase in statistics. Sustained interest in the topic can be traced by the number of downloads of the review [1], summarizing the results of the first stage of the experiment (Fig. 2). In essence, the BECQUEREL experiment based on the fragmentation of relativistic nuclei in NTE holds the "world monopoly" in terms of detailed information about multi-particle nuclear ensembles. Since 2016, the possibility of observing the Hoyle state (HS) in the relativistic dissociation of the light nuclei is under scrutiny [3].

The main difficulty, largely overcome already, that production of NTE layers in Moscow lasted four decades was interrupted in mid-2000. Thereby, the history of the NTE method seemed complete at that time. Nevertheless, responding to the request of the BECQUEREL experiment the company "Slavich" (Pereslavl Zalessky, Russia) resumed in 2012 the production of NTE layers of thickness of 50 to 200 μm on a glass base. NTE samples were used in experiments in which there was a whole variety of tracks of ionization — from slow heavy ions to relativistic particles [4-6]. At present, production of substrateless layers of a 500 μm thickness is being restored.

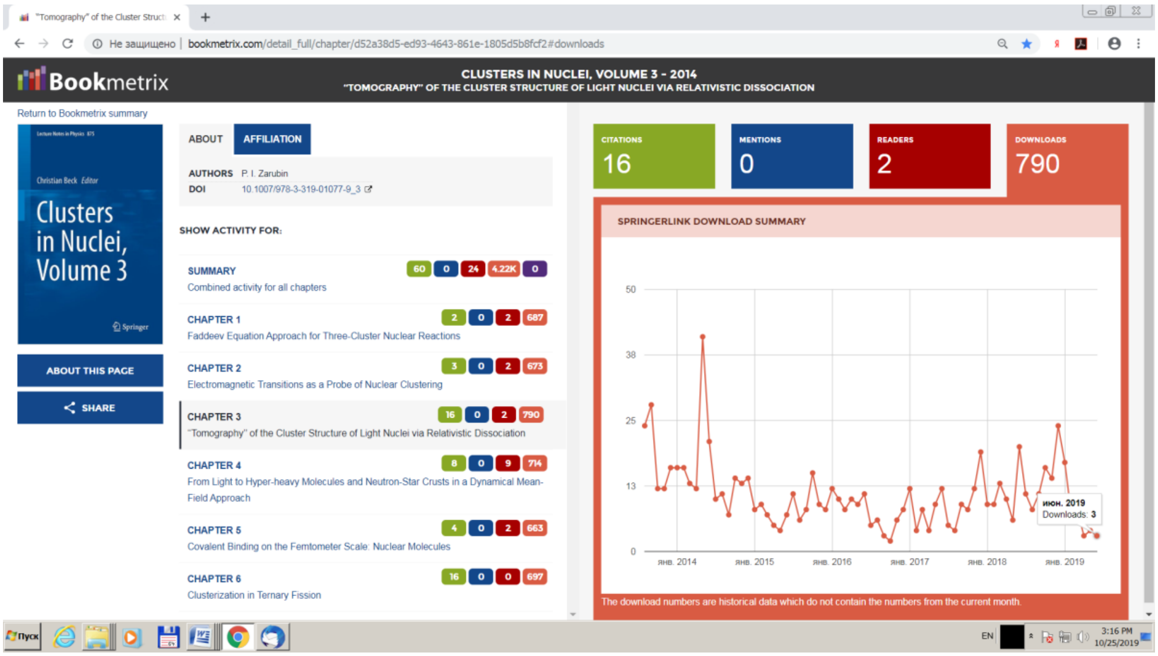

Fig. 2. Frequency of downloads of review [1].

Thus, the use of NTE has not stopped. On the contrary, a research cycle on the structure of a whole family of light nuclei was conducted; the technology, measurement methods were updated, and young researchers were trained. The developed approach to the study of multiple nuclear ensembles has a research perspective for light and medium nuclei. The special advantages of the NTE method will manifest themselves for nuclei at the proton stability boundary, which will require the formation of secondary beams (for example, ^{31}Ar in the GSI).

2. Description of the proposed research

2.1.1 The subject of the research and methods

Irradiated stacks are collected from layers of size up to 10x20 cm^2 with a thickness of 200 μm NTE on a glass substrate and 550 μm without it (Fig. 3). If a beam is directed parallel to a layer plane, then tracks of all relativistic fragments remain long enough in one layer for the 3-dimensional reconstruction of their emission angles. The substrate provides "stiffness" of the tracks, and its absence allows for longer tracking, including transitions to adjacent layers. Factors for obtaining significant event statistics are the stack thickness and the total solid angle of detection. NTE contains in similar concentrations of atoms AgBr and CNO and 3 times more H ones. In terms of hydrogen density, the NTE material is close to the liquid hydrogen target. This feature makes it possible to compare under the same conditions break-ups of projectile nuclei, both as a result of diffraction or electromagnetic dissociation on a heavy target nucleus, and as a result of collisions with protons.

Fig. 3. Developed 500 μm NTE pellicles glued on glass support. Beam nuclei entered through edge along long side.

Relativistic fragments are concentrated in the cone $\sin\theta_{fr} = p_{fr}/p_0$, where $p_{fr} = 0.2$ GeV/c is the measure of the nucleon Fermi momentum in the projectile nucleus, and p_0 is its momentum per nucleon. The charges of relativistic fragments $Z_{fr} = 1$ and 2 (the most important in the project) are determined visually due to the apparent difference in ionization. The charges $Z_{fr} \geq 3$ are determined from the density of discontinuities or the electron track density. The condition for selection of peripheral interactions is the preservation by relativistic fragments of the projectile nucleus charge Z_{pr}, that is, $Z_{pr} = \sum Z_{fr}$. With a measuring base of 1 mm, the resolution for traces of relativistic fragments is no worse than 10^{-3} rad. The transverse momentum P_T of a fragment with a mass number A_{fr} is defined as $P_T \approx A_{fr}p_0\sin\theta$ in the approximation of conservation of the velocity of the primary nucleus (or p_0). In the fragmentation of nuclei constituting NTE tracks of *b*-particles (α-particles and protons with energy below 26 MeV), *g*-particles (protons with energy above 26 MeV), and also *s*-particles (produced mesons) can be observed.

The mass numbers A_{fr} of the relativistic fragments H and He are defined as $A_{fr} = P_{fr}\beta_{fr}c/(P_0\beta_0c)$, where P is the total momentum, and βc is the velocity. The $P\beta c$ value is extracted from the average Coulomb scattering angle in NTE estimated from the track displacements at 2–5 cm lengths. To achieve the required accuracy it is necessary to measure the displacements in at least 100 points. The total momentum can be measured up to 2 to 50 GeV/c. Energy of 10 A GeV is the limit for identifying ^{4}He. The optimal value of $P\beta c$ = 5 A GeV corresponds to the NICA beam energy.

The invariant mass of the system of relativistic fragments is defined as the sum of all products of 4-momenta $P_{i,k}$ of the fragments $M^{*2} = \sum(P_i{\cdot}P_k)$. Subtracting the mass of the initial nucleus or the sum of the fragments $Q = M^* - M$ is a matter of convenience of presentation. The components $P_{i,k}$ are determined in the approximation of the p_0 conservation. Reconstruction of the invariant mass of decays of relativistic unstable nuclei ^{8}Be and ^{9}B mastered in the BECQUEREL experiment confirmed the validity of this approximation. Details and illustrations of recent measurements by the NTE method are published [3].

It is worth noting the value of NTE in educational and practical terms based on the visibility and reliability of observation. In a transversely irradiated layer, a computer calculation of a profile of an ion beam and determination of its charge composition by the spot sizes is possible. The ImageJ program (https://imagej.nih.gov/) which is widely used for recognizing objects in digitalized images was used to massively determine ion entry directions and their ranges in NTE [4]. The analyzed irradiations were carried out on the cyclotrons IC-100 and U-400M at the Flerov Laboratory of Nuclear Reactions. A similar experiment was obtained at the JINR Nuclotron when irradiated with Xe relativistic nuclei at 1 A GeV [5]. In December 2018, the NTE layers were longitudinally irradiated in the NA61 experiment in a beam of secondary nuclei with a weight to charge ratio of 2. This beam was formed by fragmentation of Pb nuclei accelerated by CERN SPS to 13 A GeV. In addition, the NTE layers were irradiated over a large transverse area behind the NA61 setup, which made it possible to determine the beam exit region, as well as the concentration region of relativistic neutrons generated by nuclear fragmentation on the target.

Thus, longitudinally and transversely irradiated NTE layers can be used for offline diagnostics of NICA beams starting with the injector.

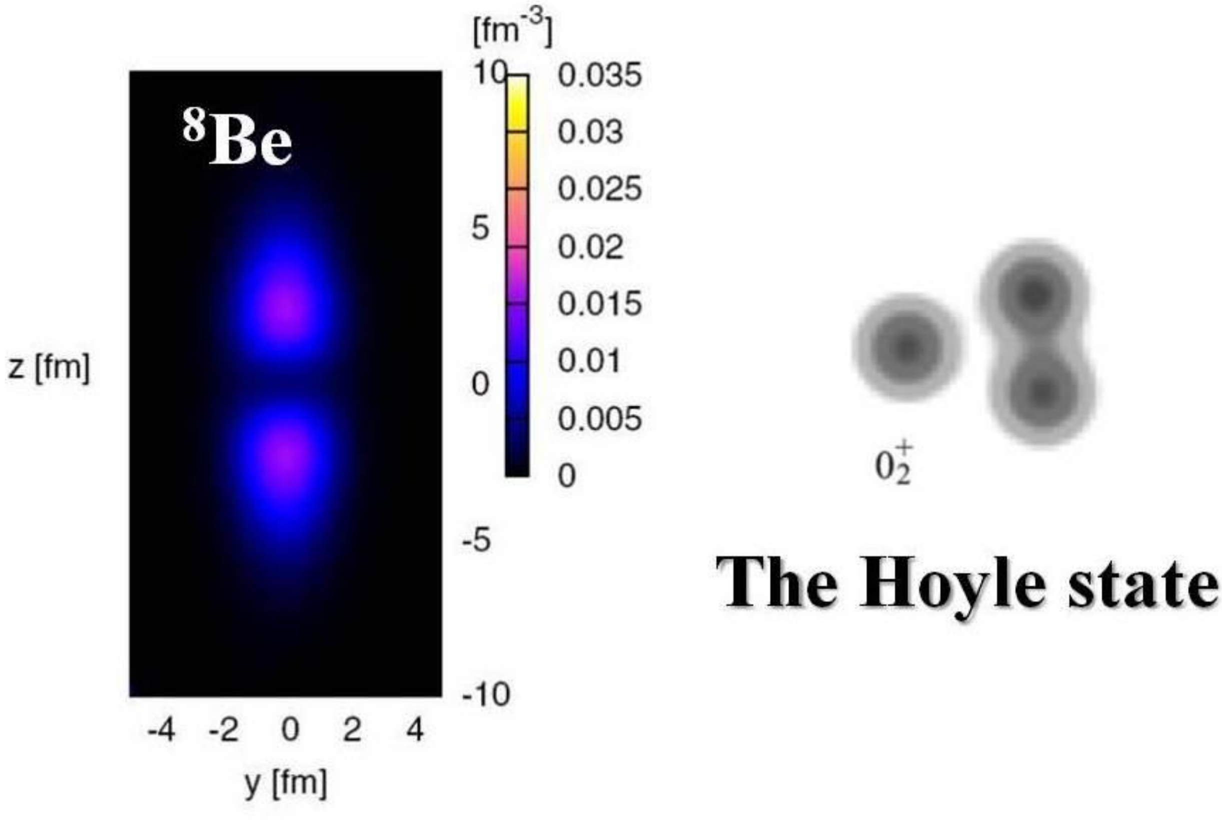

Fig. 4. Calculated distributions of nuclear density in ^{8}Be ground state and Hoyle state [7,8].

2.1.2 Hoyle state in the dissociation of light nuclei

The successful reconstruction of the ^{8}Be and ^{9}B decays allows one to take the next step — to search in relativistic dissociation ^{12}C → 3α for triples of α-particles in the Hoyle state (HS). This state is the second and first unbound excitation 0^{+}_{2} of the ^{12}C nucleus. The significance of this short-lived state of three real α-particles and the status of its research are presented in the review [7]. The ^{8}Be nucleus is an indispensable product of HS decays. The HS features such as isolation in the initial part of the ^{12}C excitation spectrum, extremely small values of decay energy and width (378 keV and 8.5 eV) indicate its similarity with ^{8}Be (91 keV and 5.6 eV). Both of them can be attributed to quasi-stable states of the nuclear-molecular type. In relativistic case the smallest energy values of ^{8}Be and HS decays are projected to narrowest flying α-particle pairs and triples, respectively. On the basis of decays ^{9}B → p^{8}Be identified in ^{10}C coherent dissociation the condition $Q_{2\alpha}$ < 200 keV of ^{8}Be fragment selection is established. Selected under the cleanest conditions this criterion takes into account practical resolution and accepted approximations,

The lowest decay energy is associated with the largest size of the super-deformed ^{8}Be nucleus (Fig. 4). Its calculated value approximately corresponds to the diameter of the Fe nucleus [8]. It is assumed that the ^{9}B and HS sizes are of the same order. It can be assumed that

HS is not limited to ^{12}C excitation but it can also appear as a 3α-partial analog of ^{8}Be in relativistic fragmentation of heavier nuclei.

The current interest is motivated by the concept of α-partial Bose-Einstein condensate (review [8]). Its status is presented in [9]. As the simplest forms of such a condensate the ground state of the unstable ^{8}Be nucleus and, after it, HS are suggested. Continuing the ^{8}Be and HS branches, it is assumed that the condensate 4α state is the 6th excited state 0^{+}_{6} of the ^{16}O nucleus, located 700 keV above the 4α threshold. Then, the condensate decomposition could go in the sequence $^{16}O\ (0^{+}_{6}) \to {}^{12}C(0^{+}_{2}) \to {}^{8}Be\ (0^{+}_{2}) \to 2\alpha$. The question arises: is it possible the existence of more complex nuclear-molecular systems?

The fact of HS generation may reflect both the presence of three weakly bound α-particles in the 0S-state in the parent nucleus as well as arise through the excited fragment $^{12}C^{*}(\to 3\alpha)$ or be a product of the interaction of α-particles in the final state. These options require theoretical consideration. Experimentally, the general question is as follows. Can the fragmentation of relativistic nuclei serve as a "factory" for the generation of ensembles of α-particles of increasing multiplicity at the lower limit of nuclear temperature? Further, in the context of the HS problem, analysis findings of distributions over invariant mass $Q_{(2\text{-}4)\alpha}$ of α-partial pairs, triples and quartets born in the dissociation of nuclei ^{12}C, ^{16}O and ^{22}Ne will be presented. Based on the data obtained in the 1980s – 1990s on dissociation of relativistic nuclei ^{12}C [10], ^{16}O [11], ^{22}Ne [12] as well as of their modern complement in the case of ^{12}C [3] a search for triples of relativistic α-particles in the Hoyle state was performed.

Determining the invariant mass of the α-particle triples $Q_{3\alpha}$ by their emission angles in the approximation of preserving the parent nucleus velocity ensures sufficient accuracy in identifying the HS against the background of higher 3α excitations of the ^{12}C nucleus (fig. 5). The contribution of HS decays to $^{12}C \to 3\alpha$ dissociation $Q_{3\alpha} < 700$ keV is 10 ± 2%. In the case of the coherent dissociation of $^{16}O \to 4\alpha$ it reaches 22 ± 2% when the portion of the channel $^{16}O \to 2^{8}Be$ is equal to 5%. Thereby, the hypothesis about HS as a universal nuclear 3α-molecule object similar to the unstable ^{8}Be 2α-nucleus gets the support. Attention is drawn to the fact that an increase in combinations of α-particles leads to a noticeable increase in the contribution of HS to the dissociation of $^{16}O \to 4\alpha$. An analysis of the invariant masses of α-quartets gives an estimate of the contribution of the decays of the state $^{16}O\ 0^{+}_{6}$ to 7 ± 2%. Consequently, the direct dissociation α + HS dominates in the HS formation. Analysis of fragmentation of the ^{22}Ne nucleus revealed the HS formation only in the 4α channel for which the share of events with HS was 15 ± 4%. Having insufficient statistical security this result serves as a guideline for continuing the search for α-ensembles by accelerating scanning over the area of nuclear NTE layers.

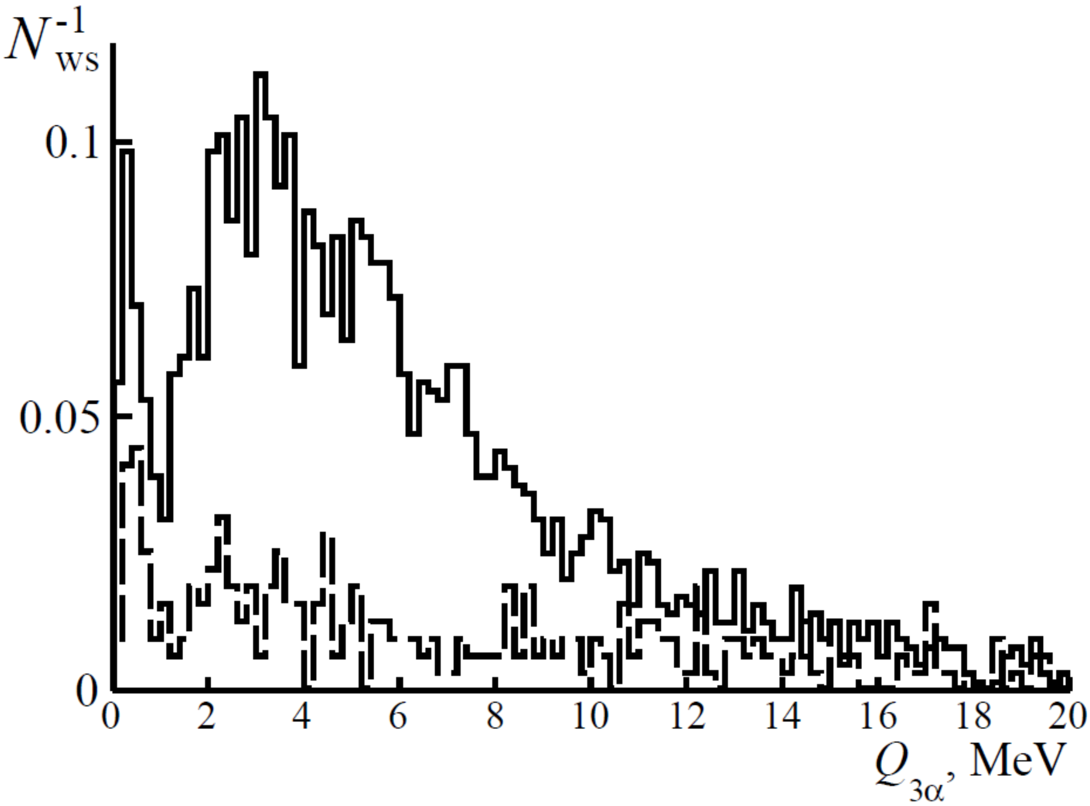

Fig. 5. Distribution of all α-triples over invariant mass $Q_{3\alpha}$ in coherent dissociation $^{12}C \to 3\alpha$ (314 events, dashed) and $^{16}O \to 4\alpha$ (641 events, solid) at 3.65 A GeV; distributions are normalized to number of "white" stars.

The application of these observations consists in testing the universality of HS and searching for heavier α-condensate states in the available NTE layers exposed to the neighboring nuclei (Fig. 6). In these cases it is possible to identify decays of ^{8}Be, and, therefore, HS. Despite the past decades, this experimental material is perfectly preserved. The closest source for verifying the HS universality is peripheral dissociation of the ^{14}N nucleus in which the channel 3He + H leads, with a contribution of ^{8}Be decays of about 25% [13]. Analysis of the NTE layers exposed to relativistic ^{14}N nuclei was resumed in the context of the HS problem as well as the role of the unstable ^{9}B nucleus. A similar analysis will be carried out in the NTE layers which exposed to relativistic nuclei ^{22}Ne, ^{24}Mg and ^{28}Si and used for overview analysis. Besides, there is sufficient amount of the NTE layers exposed at CERN SPS to ^{32}S nuclei at 200 *A* GeV. The statistics will make dozens of events in which the HS decays may be present. Potentially, the solution to the question of the universality of HS will open the horizon of a search for even more complex systems with participation ^{8}Be and HS. Earlier, the ^{8}Be formation was established upon irradiation of nuclear ions with Pb nuclei at the CERN SPS. In this regard, it is of interest to study the possibility of formation of HS in the case of dissociation of heavy nuclei.

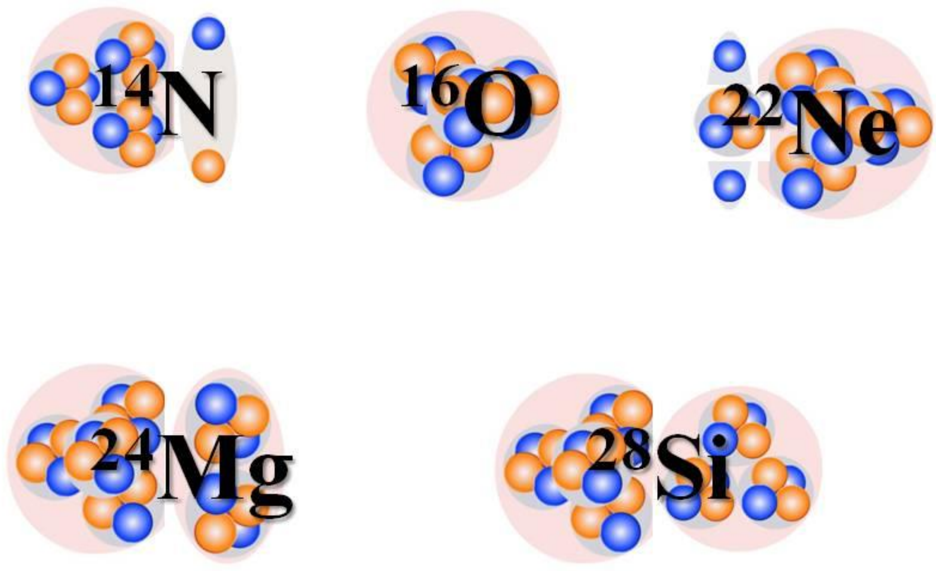

Fig. 6. Diagram of α-particle degrees of freedom in nuclei heavier than ^{12}C.

In general, the light nuclei serve as sources for generating the simplest configurations of the lightest clusters and nucleons. Being interesting in itself their research provides a basis for understanding the dynamics of fragmentation of heavy nuclei, and in practical terms it is an approbation of the analysis methods. Therefore, it is necessary to continue the ongoing studies on the basis of performed NTE exposures.

2.1.3 Composition of dissociation of heavy nuclei

The studies of light nuclei are steps toward complex ensembles He – H – *n* produced in dissociation of heavy nuclei. An example of the event of multiple coherent dissociation of a relativistic Au nucleus shown in Fig. 7 indicates a stepped “breakdown” of ionization. It is these events that are observed in NTE in the best way, and their distribution over various channels of charged fragments is interpreted most fully. The question that has to be answered is what kind of physics underlies the “catastrophic” destruction shown in Fig. 7?

Events of multiple fragmentations of relativistic nuclei down to a complete destruction into the lightest nuclei and nucleons without visible excitation of target nuclei were reliably observed in NTE for Au and Pb and even U projectile nuclei. The existence of this phenomenon is certain. It is possible that it confirms the essential role of the long-range quantum electrodynamics interaction. Charges of heavy nuclei make possible multiple photon exchanges and transitions in many-particle states (Fig. 8). An alternative scenario of coherent dissociation consists in virtual meson exchanges. Interference of electromagnetic and strong interaction is possible.

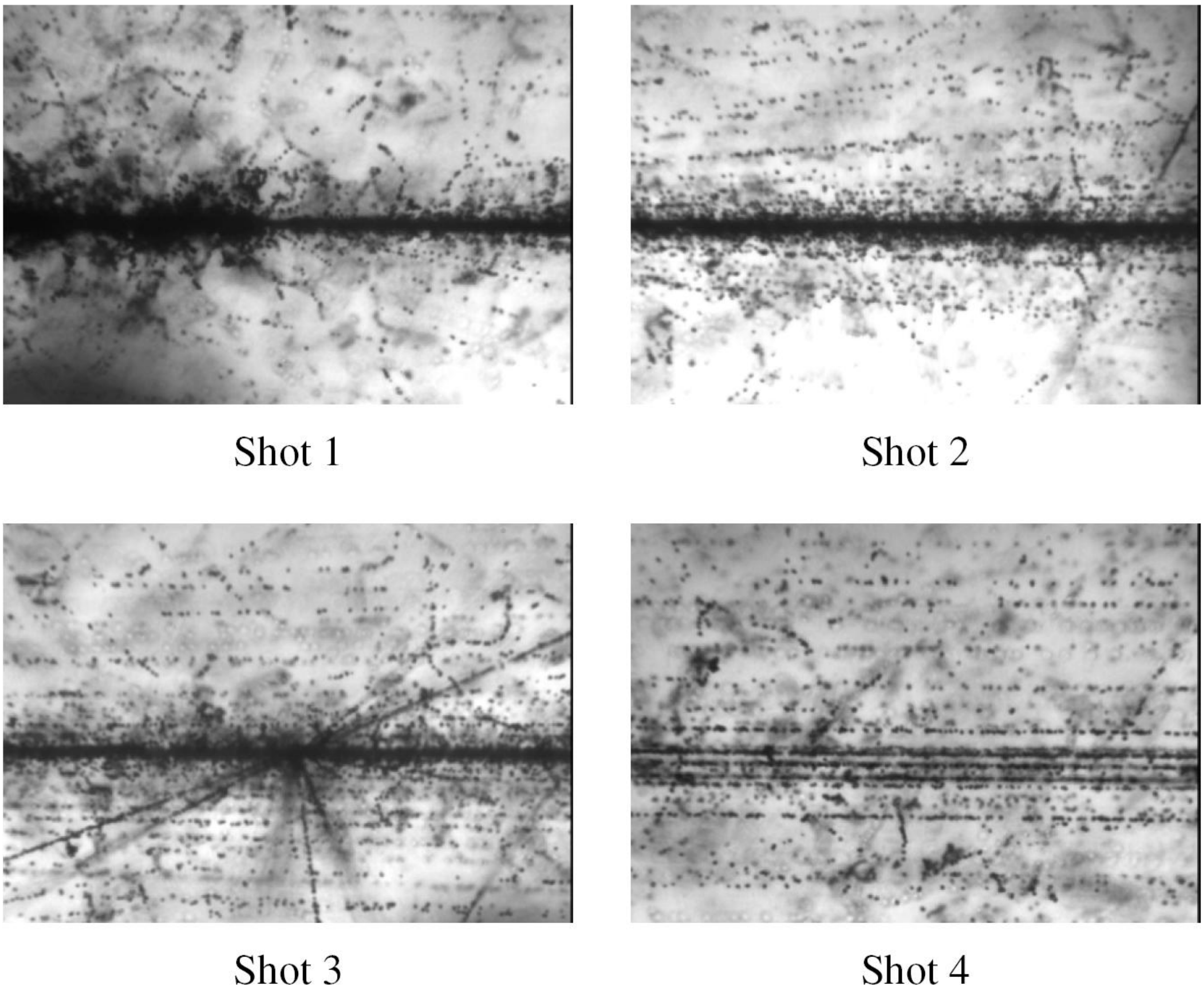

Fig. 7. Consecutively photographed event of peripheral interaction of 10.6 *A* GeV ^{197}Au nucleus in nuclear track emulsion: primary nucleus track and interaction vertex followed by projectile fragment jet (Shot 1); jet core with apparent tracks of singly and doubly charged particles (Shot 2); jet core with a secondary interaction star (Shot 3); completely resolved jet core (Shot 4, 3 cm distance from the vertex).

Dissociation of heavy nuclei leads to appearance of many-particle states with kinematic characteristics that are of nuclear astrophysical interest and which cannot be formed in other laboratory conditions. Inversion the "arrows of time" in such events suggests the idea of element synthesizing through the nucleon and lightest nucleus phase (fig. 7). The fragment energy scale in the parent nucleus system covers the temperature 10^{8-10} K from the red giant phase to supernova. The Coulomb repulsion is radically weakened in such rarefied ensembles. Being considered in a macroscopic scale, such a "nuclear packaging" can serve as a source of gravitational waves.

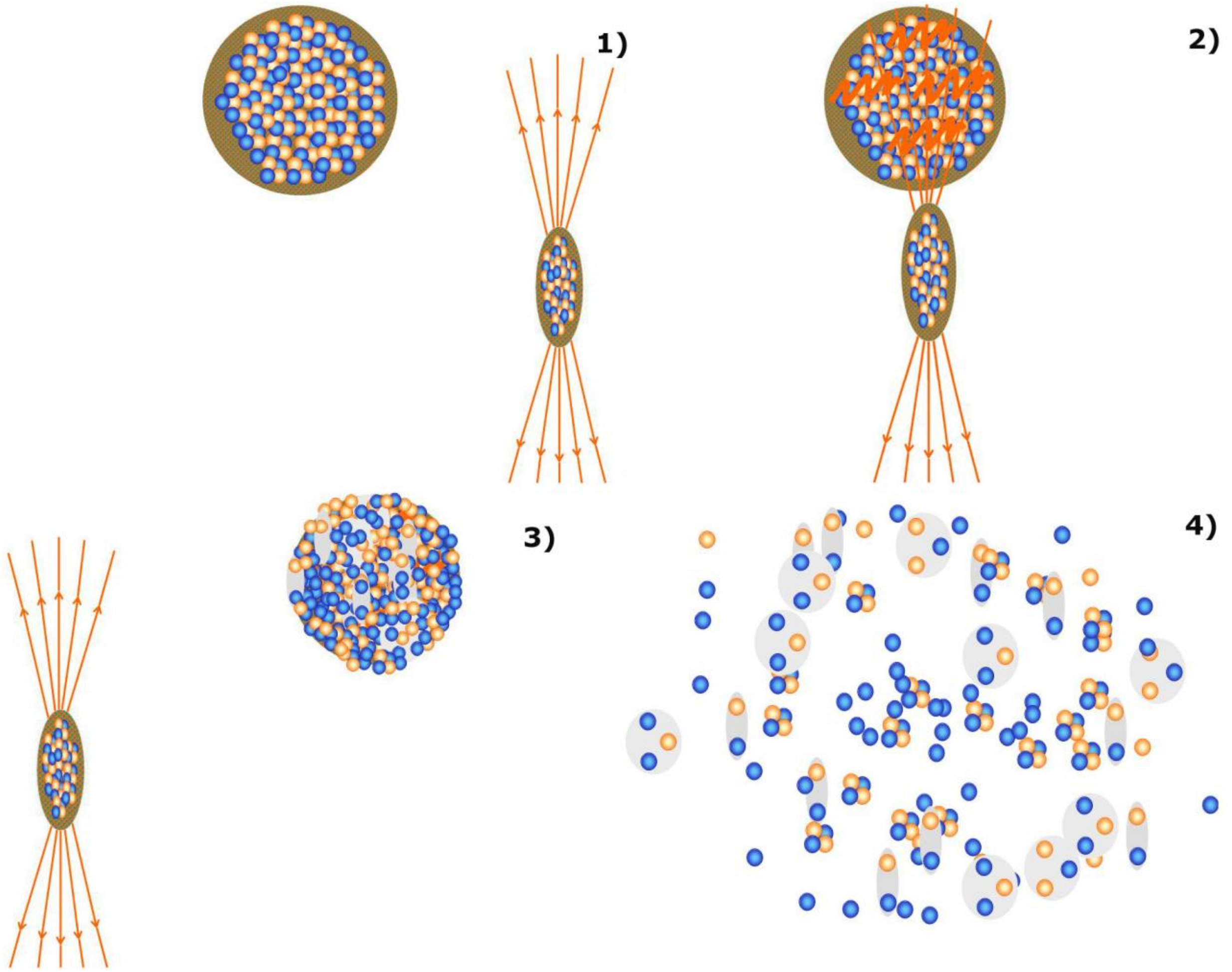

Fig. 8. Scenario of coherent dissociation of heavy nucleus in electromagnetic field of heavy target nucleus. The nuclei approach each other with an impact parameter larger than their radii (1). Intersection of electromagnetic field of the target nucleus leads to absorption of virtual photons and excitation of the projectile nucleus (2). The projectile nucleus turns into an ensemble of lightest fragments and nucleons (3). The ensemble breaks down (4).

It is proposed to use the unique and, together with that, well-proven capabilities of the NTE method for an in-depth study of the peripheral dissociation of heavy nuclei with energy of several GeV per nucleon. To characterize the emerging state, the ratio of relativistic neutrons and isotopes of ^{1,2,3}H and ^{3,4}He is determined, and their transverse moments are determined by the emission angles. The energy value up to 5 *A* GeV of heavy nuclei allows the irradiation of NTE layers in a uniform manner in defocused beams with monitoring of a total flux of nuclei. Being possible in principle, the time-consuming analysis of the isotopic composition of relativistic fragments by the scattering method was not used in the 90s with pioneering irradiation with Au nuclei at 10 *A* GeV [14-17]. Although the formation of secondary stars by neutrons in the cone of fragmentation was observed, their research tasks were not set.

At the NICA collider, beams of heavy nuclei with energy optimal for the study of the isotopic composition of relativistic fragments by the NTE method will be created. The flexibility of NTE will allow the development of the NICA injection complex and the experiment priorities to be followed. Irradiated stacks can be quickly installed in a suitable location. The irradiation time determined mainly by the duration of the beam setup is of the order of a day per selected nucleus.

In the relativistic dissociation of heavy nuclei, light fragments are formed with a higher charge-to-mass ratio than that of the primary nucleus causing the appearance of associated neutrons. The average range of neutrons in NTE is 32 cm. These neutrons must detect themselves in the fragmentation cone by secondary stars that do not contain an incoming track. The frequency of such "neutron" stars should increase with an increase in the number of the lightest nuclei in the fragmentation cone. Reaching dozens, the multiplicity of neutrons in an event can be estimated by a proportional decrease in the mean path to the formation of "neutron" stars at lengths of the order of several centimeters. The coordinates of the interaction vertex are determined with an accuracy characteristic of NTE (not worse than 0.5 μm), which allows the angles of neutron emission to be recovered with the best accuracy Measurements of adjacent tracks can be used to compensate for possible distortion. In the case of complete dissociation of a heavy nucleus, the number of neutrons can be estimated by the isotopic composition of the relativistic fragments H and He. Is the yield of deuterons and tritons binding neutrons significant? The answer to this question may also have practical significance.

At the initial stage, the available 500 μm thick NTE layers are analyzed using statistics of dozens of peripheral interactions of Kr (2 A GeV, GSI), Au (10 A GeV, BNL) and Pb (159 A GeV, CERN) nuclei to determine the dependence of the neutron contribution on the degree dissociation of these nuclei. The first will be a detailed analysis of the "golden" events of coherent dissociation of heavy nuclei. The validity of the findings will be determined by the number of found neutron vertices, as well as the number of measured and identified tracks of H and He.

2.1.4 Multiple fragmentation induced by muons

The mechanism of dissociation of relativistic nuclei in peripheral interactions remains unclear. It is possible that there is a multiple photon exchange between the nuclei of the beam and the target. The alternative is to exchange virtual mesons. As a critical test, fragmentation of nuclei of the NTE composition under the action of relativistic muons can serve [18-20]. In this case, fragmentation may occur as a result of the transition of exchange photons into pairs of virtual mesons. This combination provides long-range action at effective destruction of nuclei and can be extended to peripheral interactions of relativistic nuclei. In this regard, it is necessary to carry out a search for the fullest possible destruction of heavy nuclei of the NTE composition (Ag and Br) under the action of relativistic muons.

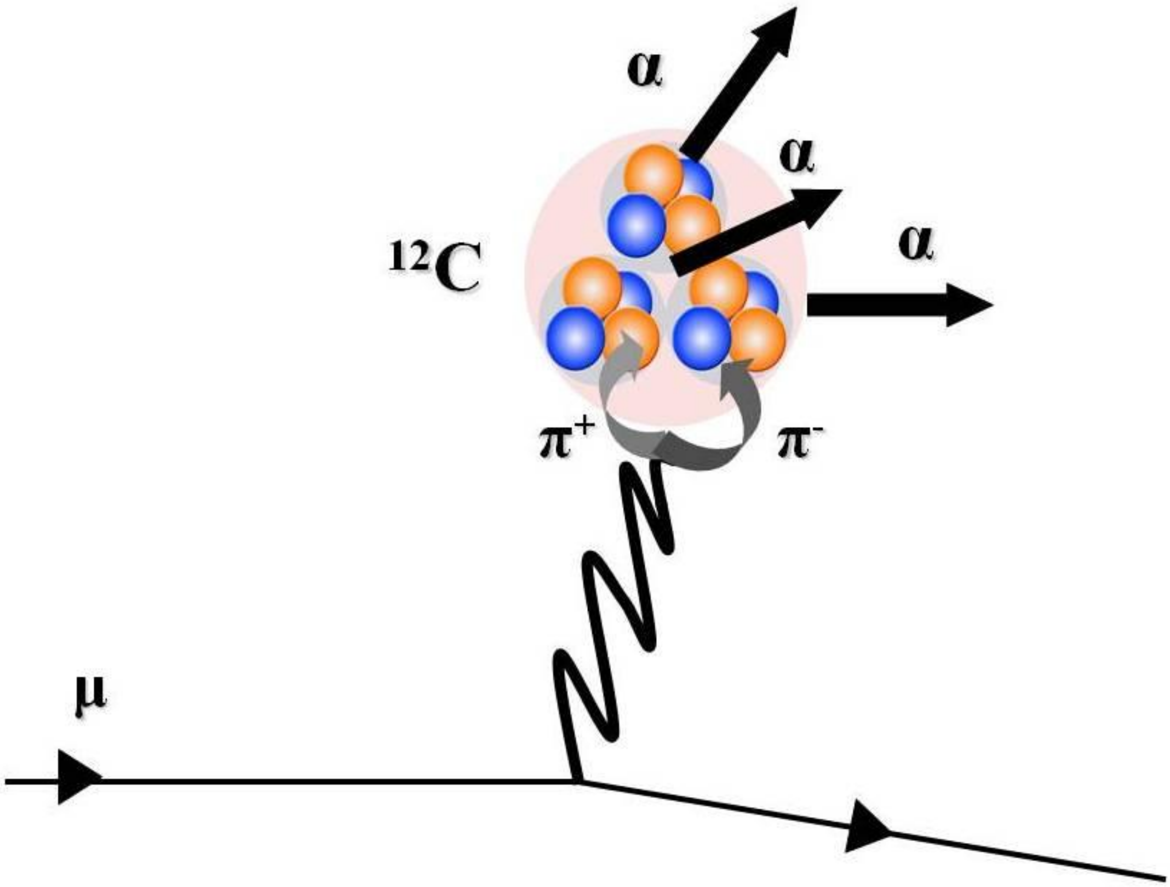

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Fig. 9. Break-up of ^{12}C nucleus into three α-particles by relativistic muon.

Cases of fragmentation of target nuclei into three *b*-particles are most probable for the breakup of $^{12}C \rightarrow 3\alpha$ (fig. 9). In these events, the ranges and angles of emission of α-particles are determined on the basis of coordinate measurements of tracks. The α-particle energy values are extracted from spline-interpolation of the energy-range calculation using the well-known SRIM model. On this basis, one can obtain the distributions over the invariant mass as well as over the total momentum of pairs and triples of α-particles. The procedure of reconstruction of the invariant mass was tested in the reconstruction of the ground state $^{8}Be_{0+}$ in the NTE exposed to 14.1 MeV neutrons and the first excited $^{8}Be_{2+}$ in the ^{8}He implantation in NTE. This experience will be applied to a relativistic muon exposure. It has been preliminarily established that the distribution over a total transverse momentum of α-particle triples produced by the splitting of ^{12}C nuclei corresponds not to electromagnetic, but to nuclear diffraction. The determination of the 3α-splitting cross section is of importance for geophysics, since it will allow testing the hypothesis of the generation of helium in the depths of the Earth’s crust by space muons.

To start studies with muons, there is also a significant reserve of NTE layers irradiated in the muon "torch" of IHEP (Protvino) for three weeks in April 2018. The average muon energy was about 2.5 GeV. Perpendicular to the beam, three stacks of 10 NTE layers with a thickness of 100 μm and three layers of 10 layers with a thickness of 200 μm were irradiated. Muon fluxes through the NTE layers were 9.3×10^6, 45×10^6, and 57×10^6. The gradations of the flux make it possible to measure the most probable 3α-splitting at low load, and then move on to rarer, but brighter, larger stars. In addition, three stacks (2 in 10 layers of 100 μm and 1 in 10 200 μm) were irradiated in the 6 GeV secondary hadron beam at an energy which allows comparing the fragmentation topologies. The approximate ratio of hadrons in the beam: pions - 60%, protons - 35% and kaons - 5%.

The transverse irradiations of NTE layers in the halo of the 160 GeV muon beam with a duration of up to a day were performed at CERN in 2017. The suitability of this material for analysis and compliance of the fragmentation topology with data at 2.5 GeV was demonstrated. An indirect estimate indicates a strong increase in the formation of nuclear stars. However, in this irradiation, both the beam monitor and the estimate of hadron admixture were absent.

In the muon beam of the COMPASS experiment, the hadron admixture does not exceed 10^{-6}, and a short exposure of acceptable density in the defocused beam is possible according to the plans of the COMPASS experiment.

2.2 Renovation of microscopes and NTE technology

The project aims to intensify application of the proven approach based on the automation of measurements provided by state-of-art microscopes. However, such microscopes are quite expensive. In this aspect is the main request of the project budget.

Coordinate measurements in NTE are carried out on three precision KSM microscopes, made half a century ago by Carl Zeiss, Jena. Thanks to qualified service, these unique devices are in working condition. Such microscopes are available in Cairo, Bucharest and Prague. There is a need for their modernization in terms of automatic reading of three measured coordinates. This development is carried out in the Radiation Dosimetry Department (Prague) under the project “Nuclear emulsion in applied problems” (The Becquerel Project) within the framework of the JINR-Czech Republic cooperation program. Its cost is about $ 5000. Replication of this product requires priority funding. Its replication requires immediate funding.

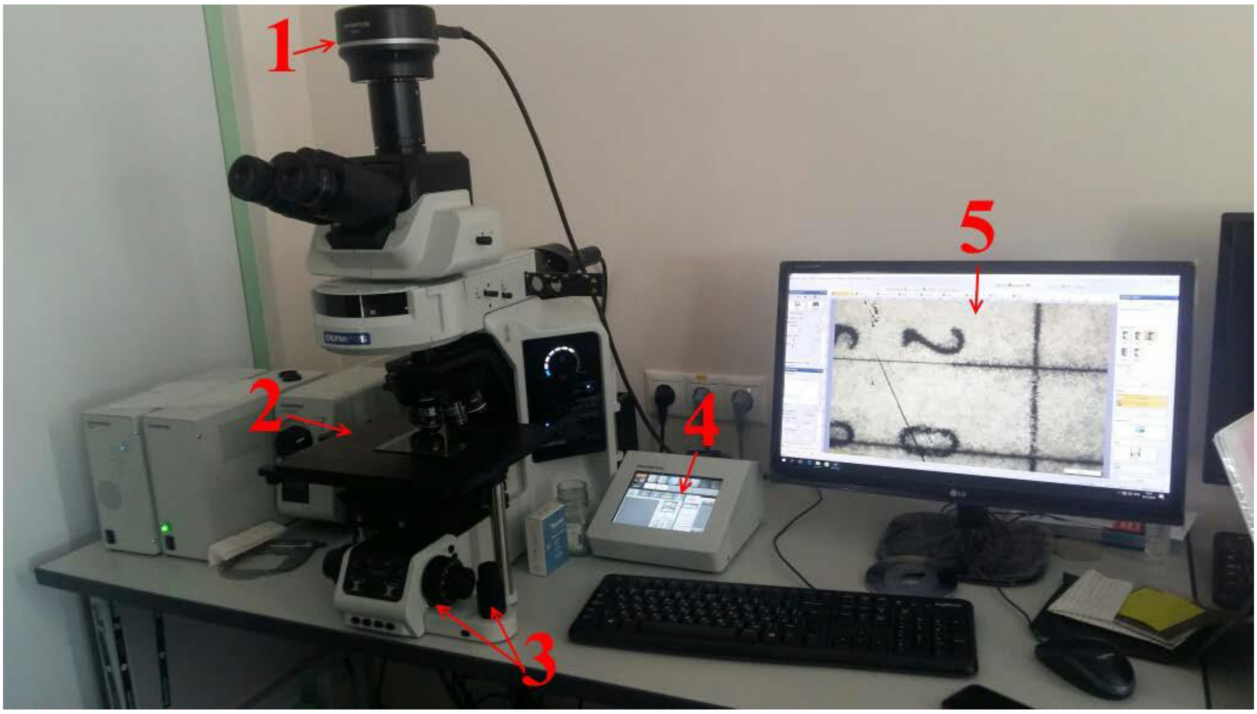

Fig. 10. Photo of BX63 microscope. Marked: 1) digital camera DP74, 2) motorized stage, 3) joysticks for controlling the focus and movement of the stage in the XOY plane, 4) microscope control unit, 5) PC for working with the received image.

At the same time, the stated fundamental tasks and the accumulated methodical culture deserve an update on the basis of the Olympus BX63 motorized microscope. Its estimated price is $ 80000. Fig. 10 shows a photograph of this microscope working at the Institute of Endocrinology (Moscow). Under the lens, a NTE layer on a glass support is placed which is irradiated longitudinally by krypton nuclei. A part of aт image of a 1 mm marking grid deposited on the NTE layer is displayed on the monitor. A horizontally oriented trace of the krypton nucleus and the fragments generated by it are visible on the screen. On the BX63 microscope, it is possible to automatically search for the vertices of peripheral dissociation by the effect of an ionization stall (“step”). Changing the lens is done by turning the revolver at the same point without operator intervention. Further measurements of the coordinates are made automatically when visually tracing the tracks of the fragments. To work on such a perfect instrument, a new generation of researchers must be trained.

New exposures involve purchasing of NTE layers and the modernization of the chemical laboratory in which they are developed. Planned expenses for materials and laboratory devices are $ 10,000 per year.

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2.3 Expected results

The recent achievements of the participants of the BECQUEREL experiment in studies with light relativistic nuclei and the preserved microscopic and chemical-technological basis give reason to expect in the future about three years the following physical and methodological results:

Light nuclei An answer will be obtained to the question of the universal nature of the formation of triples of α-particles in the Hoyle state in the dissociation of the nuclei ^{14}N and ^{28}Si. Possibility of existence of more complex states of this type will be investigated.

Heavy nuclei In the existing layers of nuclear energy irradiated with Kr, Au, and Pb nuclei, several dozen dissociation events will be selected and documented. In the selected interactions, charge topology distributions of lightest fragments accompanied by their identification will be obtained; neutron transverse momentum distributions restored, and mean number neutrons estimated.

Muons Irradiation of NTE stacks in a clean muon beam at CERN will be performed and analysis of nuclear fragmentation fin NTE will begin.

The results of the initial stage will allow one to present the structure of nuclear dissociation with unique detail, as well as to clarify the proposals for applying the NYE method in the NICA beams. On this basis, the hypothesis about the possibility of studying the dilute nuclear matter in dissociation of heavy nuclei will be tested. The results of the experiment will make it possible to conclude that the isotopic composition and temperature of the rarefied nuclear matter arising at the time of dissociation of the heavy nucleus. Measurements of neutron emission angles will make it possible to estimate their spatial distributions at the periphery of heavy nuclei (neutron “skin”). More broadly, these results are important for testing in the important sector of model representations of relativistic nuclei interactions.

The NTE method, which combines unique information content with remarkable flexibility of application, does not require significant acceleration time. An important argument in favor of the NTE method is the possibility of “physics at a distance”, i.e. analysis of irradiated and developed layers in institutions with suitable microscopes and trained personnel. The project will contribute to the preservation of the method and the training of young scientists for broad use in nuclear experiment, dosimetry, radiation medicine and ecology.

Especially important is the active use of this method in connection with the promising development of automatic microscopes and the progress of image recognition programs (artificial intelligence). With regard to the nuclear experiment, such a development is based on the classical NTE method.

2.4 Beam time schedule

The NTE method, which combines unique information content with remarkable flexibility of use, does not require significant accelerator time. The typical duration of tuning of a beam directed to a NTE stack is hours, and the time of irradiation is minutes. The choice of accelerated nuclei will be made by specialists of the Nuclotron accelerator and the priority experiment BM@N.

2.5 Share of responsibility

JINR contributions/responsibilities:

Development of the physical program, implementation of exposures and analysis of experimental data are to a decisive extent carried out by VHEP staff. The Becquerel experiment is based on own capabilities of developing NTE layers and measurements of nuclear interactions on microscopes. According to the project budget, NTE layers will be purchased, microscopes and chemical laboratory equipment will be updated. Thus, the basis for attracting external participants will be provided.

2.6 Scientific experience of authors

A proven methodology is applied, the application of which is a logical development of an approximately 15-year cycle of research on the BECQUEREL project at JINR, and much earlier work. On the subject of the project under the leadership of P. I. Zarubin, six Ph.D. theses were defended, and he defended his doctoral thesis. It is planned that the next results of the project will be included in two PhD theses. Data analysis is directly coordinated by three PhDs.There is the prospect of defending doctoral theses. Three experienced microscopist technicians are involved in the accumulation of statistics. Microscopes are maintained in working condition by a qualified technician. A group of chemists (3 people) retains an internationally recognized emulsion development experience.

2.7 Publications, theses and presentations at conferences

2.7.1 Publications of team members over the past 5 years

1. P. I. Zarubin “”Tomography” of the cluster structure of light nuclei via relativistic dissociation” Lecture Notes in Physics, **875**, Clusters in Nuclei, Volume 3. Springer Int. Publ., 51(2013); arXiv:1309.4881.
2. K.Z. Mamatkulov *et al*. “Dissociation of ^{10}C Nuclei in Nuclear Track Emulsion at Energy of 1.2 GeV per Nucleon” Phys. At. Nucl. **76** 1224(2013); arXiv:1309.4241.
3. R.R. Kattabekov *et al*. “Coherent dissociation of relativistic ^{12}N nuclei” Physics of Atomic Nuclei **76** 1219(2013); arXiv:1310.2080.
4. N.K. Kornegrutsa *et al.* «Clustering features of the ^{7}Be nucleus in relativistic fragmentation» Few Body Syst. **55** 1021(2014); arXiv:1410.5162.
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6. A.A. Zatsev *et al.* “Dissociation of Relativistic ^{10}B Nuclei in nuclear track emulsion” Phys. Part. Nucl. **48** 960(2017); DOI:10.1134/S1063779617060612.
7. D.A. Artemenkov, A. A. Zaitsev, P. I. Zarubin “Unstable nuclei in dissociation of light stable and radioactive nuclei in nuclear track emulsion” Phys. Part. Nucl. **48** 147(2017); arXiv: 1607.08020.
8. D.A. Artemenkov *et al.* “Study of the Involvement of ^{8}Be and ^{9}B Nuclei in the Dissociation of Relativistic ^{10}C, ^{10}B, and ^{12}C Nuclei” Phys. At. Nucl. **80** 1126(2017).
9. D.A. Artemenkov *et al.* “Recent findings in relativistic dissociation of ^{10}B and ^{12}C nuclei” Few Body Syst. **58** 89(2017).
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15. K.Z. Mamatkulov *et al.* ”Experimental examination of ternary fission in nuclear track emulsion” Phys. Part. Nucl. **48** 910(2017).
16. P.I. Zarubin “Recent applications of nuclear track emulsion technique” Phys. At. Nucl. **79** 1525(2016).

17. D.A. Artemenkov *et al.* “Study of nuclear multifragmentation induced by ultrarelativistic μ-mesons in nuclear track emulsion” Journal of Physics: Conference Series **675** 022022(2016).
18. D.A. Artemenkov, A.A. Zaitsev, and P.I. Zarubin “Search for the Hoyle state in dissociation of relativistic ^{12}C nuclei” Phys. Part. Nucl. **49** 530(2018).
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2.7.2 MS (3), PhD (8) and DSc (1) Theses

2019 A.A. Zaitsev “Investigation of the dissociation of relativistic ^{10}B, ^{11}C and ^{12}C nuclei by the method of nuclear photo emulsion” (PhD)

2016 K.Z. Mamatkulov “Investigation of the coherent dissociation of the ^{10}C nucleus at energy of 1.2 GeV per nucleon” (PhD)

2015 A.T. Neagu “Analysis of the fragmentation of relativistic light nuclei interactions in nuclear emulsion and the study of cluster structure” (PhD)

2014 A.A. Zaitsev “Analysis of exposure of nuclear track emulsion to thermal neutrons” (MS)

2010 E. Firu “Clustering and fragmentation in induced nuclear interactions of relativistic radioactive beams” (PhD)

2010 D. O. Krivenkov “Investigation of the coherent dissociation of relativistic ^{9}C nuclei” (PhD)

2010 P.I. Zarubin “Clustering of nucleons in the dissociation of light relativistic nuclei” (DSc)

2008 T.V. Shchedrina “Investigation of the fragmentation of relativistic nuclei ^{14}N by nuclear photographic emulsion” (PhD)

2008 A.T. Neagu “Fragmentation of relativistic nuclei ^{56}Fe in nuclear emulsions irradiated at the Dubna Nucleotron” (MS)

2008 R.Zh. Stanoeva “Study of relativistic fragmentation of ^{8}B nuclei by the method of nuclear photographic emulsion” (PhD)

2007 D.A. Artemenkov “The study of the fragmentation of ^{9}Be nuclei into alpha-particle pairs in a nuclear photo-emulsion an energy of 1.2 A GeV” (PhD)

2005 R.Zh. Stanoeva “Application of method of nuclear photoemulsion for study of multiple fragmentation of relativistic nuclei ^{14}N” (MS)

2.7.3 Recent oral presentation at conferences abroad

2019 XXXVI Mazurian Lake Conference on Physics (Piaski, Poland) A.A. Zaitsev

2019 Workshop “Light clusters in nuclei and nuclear matter: Nuclear structure and decay, heavy ion collisions, and astrophysics” (Trento, Italy) P.I. Zarubin

2018 European Nuclear Physics Conference (Bologna, Italy) A.A. Zaitsev

2017 The 27th International Conference on Nuclear Tracks and Radiation Measurements (Strasbourg, France) P.I. Zarubin, I.G. Zarubina

3. Human resources

Table. LHEP staff participants (*- 6 participants below 40)

No	Name, degree, position	Responsibilities	FTE
1.	Zarubin P.I. DSc head of emulsion sector	Project Leader	1.0
2.	Rusakova V.V. PhD head of group	Coordination of the search and measurement of events by laboratory technicians, training on microscopes	1.0
3.*	Artemenkov D. A. PhD, senior researcher	Analysis of measurements, interaction modeling, training on microscopes	1.0
4.	Zarubina I. G. engineer	Data analysis, website, video	1.0
5.*	Zaitsev A. A. PhD researcher	Measurements on microscopes, data analysis and, training on microscopes	1.0
6.*	Kornegrutsa N. K. engineer	Measurements on microscopes, data analysis	1.0
7.*	Mitsova E. junior researcher	Measurements on microscopes, data analysis	1.0
8	Bradnova V. head of group	NTE development and technology	1.0
9.	Kondratieva N. V. engineer	NTE development and technology	1.0
10.*	Vartic V. engineer	NTE development and technology	
11.	Kulikova L.I. assistant	NTE development	1.0
12.	Stelmakh G. I. assistant	Statistics collection	1.0
13.*	Nomozova K. B. engineer	Statistics collection, measurements on microscopes	1.0
14.	Shcherbakova N. S. assistant	Statistics collection	1.0
15.	Marin I.I. technician	Microscopes maintenance, NTE exposures	1.0
		Σ	14.0

4. Estimation of the project budget expenses for 3 years

Form No.26

Proposed timetable and necessary resources for the implementation
of the project "The BECQUEREL Experiment"

Expenditures, resources, financing sources			Cost (k$) Resource requirements		Proposal of the Laboratory on distribution of finances and resources					
					2021		2022		2023	
			Theme 1087		Theme 1087		Theme 1087		Theme 1087	
Expendi-ture	Main units of equipment, work towards its updating, adjustment, etc.		15		5		5		5	
	Construction /repair of premises		-		-		-		-	
	Materials		30		10		10		10	
Required resources	Stan -dart hour	LHEP design bureau	-		-		-		-	
		JINR Work-shop	-		-		-		-	
		LHEP Workshop	-		-		-		-	
		Nuclotron	-	-	-	-	-	-	-	-
Σ			45	-	15	-	15	-	15	-
Total:			45		15		15		15	
Financing sources		Budget. Theme 1087	45		15		15		15	

Theme 1087 - LHEP
Project leader [signature] P.I. Zarubin

5. Estimation of expenditures

Form No. 29

Estimated expenditures for the Project: "**Study of Multiple Fragmentation of Relativistic Nuclei in Nuclear Track Emulsion (The BECQUEREL Experiment)**"

№	Name of the items cost	full cost (k$)		2021		2022		2023	
		Theme 1087		Theme 1087		Theme 1087		Theme 1087	
1.	Accelerator (Nuclotron), hour	150		50		50		50	
2.	Computer communications	15		5		5		5	
3.	LHEP Design bureau	-		-		-		-	
4.	LHEP Workshop	-		-		-		-	
5.	Materials	30		10		10		10	
6.	Equipment	15		5		5		5	
7.	Payment research	-		-		-		-	
8.	Travel allowance, including:	120		40		40		40	
	(a) to non-rouble zone countries	60		20		20		20	
	b) in the rouble zone	60		20		20		20	
	c) protocol-based	-		-		-		-	
Σ		180		60		60		60	
Total direct expenses:		180		60		60		60	

Theme 1087 – VBLHEP
PROJECT LEADER P.I. Zarubin

VBLHEP DIRECTOR /V.D. Kekelidze

VBLHEP CHIEF ENGINEER-ECONOMIST L.M. Nozdrina

6. Strengths, weaknesses, opportunities, threats

The following aspects are the strengths of the project:

- clearly formulated research objectives on the fundamental problems of modern nuclear physics;
- reliance on the own scientific and methodological culture in application of NTE;
- combination of the unique resolution of NTE and capabilities on the state-of-art accelerators;
- the research basis in the form of the microscope and chemical laboratory;
- full knowledge by the VBLHEP staff with a well-proven methodology, including exposure and development of layers, the search for events and their measurement;
- clearly understood prospects for automation of measurements on microscopes;
- Opportunities for young researchers to master the dynamics of relativistic nuclear collisions and to independently solve the problems posed;
- the presence of initial scientific “capital” in the form of layers excellently irradiated at JINR, BNL, CERN;
- established cooperation with the manufacturer;
- low cost and flexibility in following the development of the NICA complex;
- the possibility of "physics at a distance".

The practical problem of the project is the establishment by the manufacturer of the production of thick non-substrate layers. Another problem is the departure from the widespread use of this technique. The implementation of the objectives of the project will contribute to the full restoration of the classical methodology of the nuclear experiment which was already considered lost.

Orientation of the project towards a clear and accessible methodology will allow attracting a wider circle of students of natural sciences, including pedagogical, to the NICA project. There are no particular technical and radiation safety issues.

Project Review
"BECQUEREL experiment at the NUCLOTRON / NICA accelerator complex"

The phenomenon of dissociation of relativistic nuclei observed with a unique completeness in the nuclear track emulsion (NTE) makes it possible to study ensembles of nucleons and lightest nuclei of interest to nuclear physics and nuclear astrophysics. Individual features of the nuclei under study are manifested in probabilities of dissociation channels. Advantages of the NTE technique include unsurpassed resolution in determining emission angles of relativistic fragments and possibility of identification of He and H isotopes among them by multiple scattering measurements.

The motivation of the project is the search for metastable states of multiple ensembles of the lightest nuclei and nucleons. Such states can serve as an intermediate substance in astrophysical processes of nucleosynthesis. The possibility of such a phase of baryonic matter as extremely rarefied and cold on a nuclear scale is predicted by theorists and has undoubted fundamental significance. Although at first glance, an experimental study of such a phase is impossible, a hypothesis has been put forward in the project about its reproduction in the narrow cone of dissociation of relativistic nuclei.

The project is aimed at the intensive application of this technique to study the fragmentation of medium and heavy nuclei in the unified approach. It is a logical development of the approximately 15-year cycle of research on the BECQUEREL experiment at the JINR Nuclotron, and even earlier work on relativistic nuclear physics. The project is based on the fact that, in relation to multiple fragmentation of relativistic nuclei, nuclear emulsion remains the only means of observation that provides not only observations that are unique in resolution and sensitivity, but also provide reasonable statistics and also identification of the lightest nuclei. Possession of the method by the authors in all aspects is not in doubt. In the respect of the analysis an invariant mass method based on record resolution is developed and tested widely enough in application to relativistic fragmentation, which made it possible to identify unstable ^{8}B and ^{9}B nuclei, as well as the Hoyle state. Demonstrating the resolution of the method, these results become milestones for determining the universal role of these metastable objects in the dissociation of heavier nuclei and the search for more complex states corresponding to the predicted alpha-particle condensate. The search for such states is possible in the narrowest components of fragment jets. All this is well described in the project. A clear research program has been formulated. There is material for the immediate start of research and suggestions for the future. On this path there is the prospect of unexpected discoveries in nuclear physics.

The project results will substantiate new proposals for nuclear physics research at the NICA complex. The project will contribute to the preservation of the method and the training of young scientists who own it, its use in nuclear experiments, dosimetry, radiation medicine and ecology. The active use of this method is particularly important in connection with the promising development of automatic microscopes and the progress of image recognition programs (artificial intelligence). Such a development will be at the forefront of today's time - the classic nuclear emulsion. Thus, the BECQUEREL project undoubtedly deserves full support.

Никитин В.

V.A. Nikitin
Chief Researcher, VBLHEP, JINR
Doctor of Physical and Mathematical Sciences
Professor

Comments on the draft
"BECQUEREL experiment on the Nuclotron accelerator complex/NICA»

Noting the variety and value of the proposed problems, I want to focus on the significance of the proposed project for testing the theoretical concept of The Bose-Einstein condensate as a condensate of alpha particles - the predicted counterpart of ultracold quantum gases. The status of development of the alpha-condensate concept is presented in detail in the review by Tohsaki, H. Horiuchi, P. Schuck and G. Roepke "Status of α-particle condensate structure of the Hoyle state" Review of Modern Physics 89 (2017) 01100. The review notes a proposal to search for condensate states in the dissociation of relativistic nuclei. The proposal is also noted in W. Von Oertzen's lecture review "Alpha-cluster condensations in nuclei and experimental approaches for their studies" Clusters in Nuclei, Lecture Notes in Physics 818, 109 (2010). In this concept, the degrees of freedom of alpha-multiple nuclei near collapse thresholds are predicted based on the boson-type mean field formed by the alpha particle gas. Coexisting with ordinary fermionic excitations, such states are possible because the alpha particle has the properties of an almost ideal boson. They occur at an average density similar to the core ^{8}Be, which is 4 times smaller than the usual nuclear. Being bosons, alpha particles can condense in the 0S orbit of their own cluster field. The Hoyle state with its three alpha particles is regarded as the lightest alpha condensate and as an ^{8}Be core with one additional alpha particle in 0S orbit.

It is worth noting that the ^{12}C nucleus can transition from the ground state to an unbound but very long-lived one at 7.65 MeV, named after the astrophysicist F. Hoyle, who predicted the existence of this resonance more than 60 years ago to explain the prevalence of the ^{12}C isotope. The transition to the Hoyle state in fusion reactions can serve as an "entrance gate" for the synthesis of heavier nuclei. A theoretical description of the experimental data extracted from the inelastic electron excitation of the ^{12}C nucleus indicates that the Hoyle state has a volume 3-4 times larger than the ground state. However, pointing to the exotic structure of the state these measurements do not answer questions about its internal structure. This may be possible in the proposed experiment, where an indication of the origin of the Hoyle state has already been found. The assumption that condensate decay can be detected in the decay of an alpha partial gas along the cascade chain ^{16}O $(0^+{}_6) \rightarrow$ ^{12}C $(0^+{}_2) \rightarrow$ ^{8}Be $(0^+{}_2) \rightarrow 2\alpha$ is very interesting.

The results and proposals for the new Becquerel project were presented by its leader in the invited report at the workshop "Light clusters in nuclei and nuclear matter: nuclear structure and decays, heavy ion collisions and astrophysics" (2-6, September 2019, Trento, Italy). It is remarkable that the search for ever-increasing complexity can be carried out in the same experimental approach.

In general, the use of the phenomenon of dissociation of relativistic nuclei in a nuclear emulsion to generate quantum condensate states provides an alternative to the search in this direction by methods of low-energy physics. These ideas can be applied to explain phenomena in nuclear astrophysics and cosmic ray physics. For all these reasons, the project deserves support. The scientific significance of the project is high. The requested resources correspond to the project objectives.

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ANONYMOUS REVIEW
FOR PHYSICAL SECTION OF LHEP STC
BECQUEREL project

First of all, I would like to make a comment about the language in which the text is written. A secondary problem in this case comes to the fore, for the author's vocabulary extremely complicates the understanding of the essence of the matter. If in the case of "coherent ensembles of clusters that play an intermediate role in nucleosynthesis", one can still guess that we are talking about known nuclear resonances, then "quantum electrodynamic interaction", "studying the nuclear structure in the cone of relativistic fragmentation", "kinematic characteristics representing nuclear-astrophysical interest ", as well as much more remained a mystery to me.

The suggestions of the authors of the project can be described as very slurred. First, in the section "Expected Results and Their Significance", the authors report that they expect to receive an answer about the "universal nature of the formation of triples of α particles in the Hoyle state in the dissociation of ^{14}N and ^{28}Si nuclei". I strongly do not understand what expression means

"The universal nature of production", on the basis of which a conclusion can be made about universality, and also what could be the consequences of such a conclusion. Suppose "universal character" means that the cross section for population of a state is large. How large should it be to testify to universality? On the other hand, the authors say that the Hoyle state hypothesis

"As a universal object like ^{8}Be" has already received confirmation. So, ^{8}Be is an object of unconditional universality? How should this be understood? The assertion that "the Hoyle state does not boil down to ^{12}C excitation, but can arise as a 3α-partial analogue of ^{8}Be," further complicates the understanding of the authors' motives and intentions. What does it mean that one of the excited states of ^{12}C does not reduce to excitation of ^{12}C, but "arises as an analogue"?

Confirmation of the "universality" of the Hoyle state, as claimed, has already been obtained with ^{12}C, ^{16}O, and ^{22}Ne beams as a result of measuring the fraction of events corresponding to this state in the full spectrum of the invariant mass of 3 α particles. This share ranged from 10 to 20%. Taking into account other channels of fragmentation of the original nucleus, it will obviously be significantly smaller, but the question is not even that, but what information does this quantity carry? If we are talking about studying the cluster structure of the nucleus, then the relationship of this quantity with the structure exists only in the context of theoretical models that are used to describe the results of the experiment. However, the authors do not report anything about how, in the framework of which model the results can be interpreted.

The authors rightly point out that low energies are more suitable for studying the nuclear structure, but the "pause in applying the benefits of the relativistic approach" as "motivation for further irradiation of stacks of nuclear materials" looks extremely doubtful.

The section "Expected Results" does not say anything about the search for exotic resonance states decaying into 4 α particles; nevertheless, this problem is mentioned in other sections. Such a state could be an interesting find; however, to find it, it is necessary to justify the choice of reaction in which it would be populated with an acceptable cross section. The value of such a state for nucleosynthesis is extremely doubtful, even if the width of such a state turns out to be comparable with the widths of ^{8}Be and the Hoyle state and it decays with the emission of a γ-quantum, simply because the probability of interaction of two ^{8}Be is very small (equilibrium concentration of ^{8}Be at a density of 10^{5} g/m^{3} 10 orders of magnitude lower than the density of α particles).

With regard to heavy nuclei, the authors propose "to select and document several dozen events of multiple dissociation, .. to establish the distribution according to the charge topology of the lightest fragments, .. to restore the distribution of neutrons along the transverse momentum". In my opinion, the need for such "documentation" is not sufficiently substantiated. The authors speak exclusively about what they intend to measure, but never mention what the purpose of these experiments is. What should the "charge topology of the lightest fragments" tell us about, measured with very modest (several dozen events) statistics? Is it possible to speak of a "unique detail" of the representation of the "dissociation structure" by registering only the light products of fragmentation of heavy nuclei? What will serve as a criterion for confirming or refuting the "hypothesis about the possibility of studying rarefied nuclear matter in the dissociation of heavy nuclei"? How do the authors intend to establish a relationship between the angles of neutron emission and their spatial distribution at the periphery of heavy nuclei?

In certain cases, measurements of the transverse momentum distributions of neutrons and clusters are of interest, however, a lot of such experiments have been done and I would like to understand which aspects of the nuclear structure of which nuclei are of interest to the authors.

In conclusion, I am forced to note that the physical justification of the proposed program does not look very convincing, and as a demonstration of "sustained interest in the topic", it would be worth noting the number of downloads of the review [2], but the number of links to it. The undoubted advantage of the discussed technique is the simplicity of its application. Processing the information received is so time-consuming that, as I understand it, a very large amount of raw data has been accumulated over the years of measurements. If I'm not mistaken and this is true, then before continuing to increase this volume, it might be wise to spend time analyzing existing data in order to search for interesting events.

Answers to questions from an anonymous reviewer

Suppose "universal character" means that the cross section for population of a state is large. How large should it be to testify to universality? On the other hand, the authors say that the hypothesis of Hoyle's state "as a universal object like ^{8}Be" has already been confirmed. So ^{8}Be is an object of unconditional universality?

The issue of universality is not related to the size of the cross section. HS universality - the appearance in dissociation of other nuclei is heavier than ^{12}C. Heavier nuclei can serve as a "factory" of HSs as the narrowest relativistic α-triples. ^{8}Be arises in a wide variety of reactions, including the relativistic dissociation of gold and lead nuclei. In general, nuclei are universal objects of the microworld (like particles), and excitations are associated with a specific nucleus.

How should this be understood? The assertion that "the Hoyle state does not boil down to 12C excitation, but can arise as a 3α-partial analogue of 8Be," further complicates the understanding of the authors' motives and intentions. What does it mean that one of the excited states of 12C does not reduce to excitation of 12C, but "arises as an analogue"?

Yes, a long-lived analogue. ^{12}C is the simplest initial state for HS, as ^{9}Be for ^{8}Be. HS, like ^{8}Be, has a lifetime of the order of magnitude for the pi-0 meson. In the relativistic case, this means decay over a length of about 1000 atomic sizes ($_{9}B$ - about one).

Confirmation of the "universality" of the Hoyle state, as claimed, has already been obtained with ^{12}C, ^{16}O, and ^{22}Ne beams as a result of measuring the fraction of events corresponding to this state in the full spectrum of the invariant mass of 3 α particles. This share ranged from 10 to 20%. Taking into account other channels of fragmentation of the original nucleus, it will obviously be significantly smaller, but the question is not even that, but what information does this quantity carry?

Information on the contribution of the HS to the wave function of the initial state.

What should the "charge topology of the lightest fragments" tell us about, measured with very modest (several dozen events) statistics?

It is planned to establish the ratio of the lightest isotopes. This is the key to justifying the study of sparse nuclear matter in the cone of relativistic dissociation.

Is it possible to speak of a "unique detail" of the representation of the "dissociation structure" by registering only the light products of fragmentation of heavy nuclei?

All fragments are recorded. Interest is focused on peripheral dissociation events with maximum multiplicity. To search for them, an accelerated method of viewing by bands is used.

What will serve as a criterion for confirming or refuting the "hypothesis about the possibility of studying rarefied nuclear matter in the dissociation of heavy nuclei"?

To begin with, the reconstruction of the relativistic decays of ^{8}Be, then HS (they are also rarefied), more complex configurations are possible. Further isotopic analysis, then the distribution of the transverse momentum of neutrons.

How do the authors intend to establish a relationship between the angles of neutron emission and their spatial distribution at the periphery of heavy nuclei?

In the approximation of conservation of the primary momentum, it is assumed to obtain the distribution over the transverse Fermi momentum, and from it the spatial distribution.

In certain cases, measurements of the transverse momentum distributions of neutrons and clusters are of interest, however, a lot of such experiments have been done and I would like to understand which aspects of the nuclear structure of which nuclei are of interest to the authors.

We hope that the neutron "blanket" effect will manifest itself in a particularly narrow distribution along the transverse momentum.

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30 Sept. 2019

Dr. Pavel Zarubin
zarubin@lhe.jinr.ru

Dear Pavel

Thank you for sharing your proposal with me. I think it clearly demonstrates that your techniques for studying fragmentation of relativistic nuclei using nuclear emulsions offer some significant possibilities to explore a number of phenomena of current interest. Certainly, tracing the possible existence of condensed states analogous to the Hoyle state in heavier nuclei is an exciting current topic and your method would seem to be ideal for an initial survey of such alpha-clustered states. That you can compete with very highly sophisticated (and very expensive) spectrometers and/or time projection chambers is quite impressive. Given your ability to study a wide range of such light nuclei, this project appears to me to be particularly well motivated.

The multi-fragmentation problem is one with a long history. Here again systematic investigations may reveal new correlations not previously recognized. To me the most interesting possibilities reside in the studies of the peripheral collisions and the possibility to observe the multi-fragmentation in the absence of a very complex collision dynamics. For the same reasons the muon induced fragmentations appear to offer some real advantages and comparing the peripheral interaction results with the muon induced results may offer some new insights into these processes.

It is abundantly clear from your discussion that this endeavor is a labor intensive one and that the requested upgrades to your technical capabilities are well motivated. I certainly hope that you will receive a positive response to this research proposal and that we will see some stimulating new results in the near future.

With best regards,

Joseph B. Natowitz

J. B. Natowitz
University Distinguished Professor, Emeritus

ВЫПИСКА ИЗ ПРОТОКОЛА
заседания НТС ЛФВЭ
от 19 ноября 2019 года

Присутствовали на заседании 29 членов НТС из общего числа 38 членов НТС.

НТС ЛФВЭ рассмотрел предложение об открытии нового проекта **БЕККЕРЕЛЬ** темы «Исследования по физике релятивистских тяжелых и легких ионов на ускорительных комплексах Нуклотро/NICA ОИЯИ и SPS ЦЕРН» (02-1-1087-2009/2020). НТС решил рекомендовать ПКК по ядерной физике открыть новый проект до конца 2022 года с первым приоритетом.

Рецензенты: В.А.Никитин, С.Н.Ершов.

Председатель НТС ЛФВЭ Е.А.Строковский

Ученый секретарь НТС ЛФВЭ С.П.Мерц

ABSTRACT OF THE MINUTES
OF THE NOVEMBER 19, 2019
VBLHEP STC MEETING

29 STC members were present at the meeting out of a total of 38 STC members.

VBLHEP STC considered a proposal to open a new project **BECQUEREL** theme «Research on Relativistic Heavy and Light Ion Physics. Experiments at the Accelerator Complex Nuclotron/NICA at JINR and CERB SPS» (02-1-1087-2009/2020). STC has decided to recommend to the PAC for Nuclear Physics to open a new project by the end of 2022 with the first priority.

Referees: V.A.Nikitin, S.N.Ershov.

VBLHEP STC Chairman E.A.Strokovsky

VBLHEP STC Scientific Secretary S.P.Merts