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THE BECQUEREL-2020 PROJECT

Experiment BECQUEREL-2020 at Accelerator Complex NUCLOTRON/NICA

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

D.A. Artemenkov[a)], V. Bradnova[a)], E. Firu[b)], M. Haiduc[b)], N.V. Kondratieva[a)], N.K. Kornegrutsa[a)], E. Mitsova[a,c)], A. Neagu[b)], K.B. Nomozova [a)], V.V. Rusakova[a)], R. Stanoeva[c)], A.A. Zaitsev[a)], I.G. Zarubina[a)], P.I. Zarubin[a)]

[a)]*Joint Institute for Nuclear Research, Dubna, Russia*
[b)]*Institute of Space Research, Magurele, Romania*
[c)]*Southwestern University, Blagoevgrad, Bulgaria*

NAME OF PROJECT LEADER — PZarubin — ZARUBIN P.I.

NAME OF PROJECT DEPUTY LEADER — A. Zaitsev — ZAITSEV A.A.

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	SIGNATURE	DATE
APPROVED BY JINR DIRECTOR		
ENDORSED BY JINR VICE-DIRECTOR		
CHIEF SCIENTIFIC SECRETARY		
CHIEF ENGINEER		
HEAD OF SCIENCE ORGANIZATION DEPARTMENT		
LABORATORY DIRECTOR	[signature]	22.10.2020
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JOINT INSTITUTE FOR NUCLEAR RESEARCH

Proposal for Experiment BECQUEREL-2020 at Accelerator Complex NUCLOTRON/NICA

(theme 02-1-1087-2009/2023)

Leader from JINR:
Pavel Zarubin (zarubin@lhe.jinr.ru)
Deputy leader from JINR:
Andrei Zaitsev (zaicev@lhe.jinr.ru)

Participants:
D.A. Artemenkov, V. Bradnova, N.V. Kondratieva, N.K. Kornegrutsa, K.B. Nomozova, V.V. Rusakova, V. Vartic, A.A. Zaitsev, I.G. Zarubina, P.I. Zarubin
(Joint Institute for Nuclear Research (JINR), Dubna, Russia)
M.M. Chernyavsky, N.G. Peresadko, N.G. Polukhina, T.V. Shchedrina
(P.N. Lebedev Physical Institute of Russian Academy of Sciences, Moscow, Russia)
R. Stanoeva, E. Mitsova,
(Southwestern University, Blagoevgrad, Bulgaria)
E. Firu, M. Haiduc, A. Neagu
(Institute of Space Research, Magurele, Romania)
O. Ploc, I. Ambrožová, M. Kakona, M. Lužova, K. Turek
(Nuclear Physics Institute of Academy of Sciences, Řžež, Czech Republic)
K. Olimov, Kh.K. Olimov, V.V. Lugovoi, A.R. Kurbonov, A.K. Olimov, K.I. Umarov, U.U. Abdurakhmanov
(Physical-Technical Institute of Academy of Sciences, Tashkent Uzbekistan)
S.S. Alikulov, R, Bekmirzoev
(Dzizak State Pedagogical University, Dzizak, Uzbekistan)
T. Hussein, M. Ghoneim
(Cairo University, Egypt)
H. El-Samman, A. Marey
(Minoufia University, Egypt)

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 Experiment BECQUEREL-2020 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 among key aspects 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 cluster states just 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 the nuclear clustering 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. Nuclear clustering is traditionally regarded as the prerogative of the physics of nuclear reactions at low energies. The mission of the Project BECQUEREL-2020 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 generation of ensembles consisting of He and H nuclei is possible in the peripheral dissociation of relativistic nuclei. In-depth studies of their features can shed light on topical issues in few-body nuclear physics. The focus of theoretical developments is the possibility of the existence of states with a pronounced α-condensate and nuclear-molecular structure. In turn, the findings of the corresponding laboratory searches could be involved in the development of multi-body scenarios of nuclear astrophysics.

Being flexible and inexpensive, the method of nuclear track emulsion (NTE) meets the corresponding experimental challenges at least at the search stage. In the NTE layers longitudinally exposed to relativistic nuclei tracks of fragments can be observed exhaustively, and their direction determined with the best resolution. Determination of the invariant mass of the relativistic fragment groups in the approximation of conservation of the velocity of the initial nucleus makes it possible to project the angular correlations of fragments on the energy scale of nuclear physics. Thus, on the basis of the relativistic-invariant approach, a new and at the same time visual paradigm appears for the experimental study of ensembles of the lightest nuclei just above the coupling threshold. It is possible both to use the results obtained within the framework of the NTE method when planning experiments of high complexity and a variety of the adanced detectors, as well as to apply in a large-scale the method itself leaning on the achievements of computerized microscopy. In this context, based on the experience of NTE application with respect to decays of the unstable ^{8}Be and ^{9}B nuclei, proposals are formulated to search for associated heavier states.

Technological and analytical foundations of the NTE method as applied to relativistic particles were developed in the initial period when fundamental discoveries in high-energy physics were made in the study of cosmic rays. These achievements are fully presented in the classic book by C.H. Powell, P.H. Fowler and D.H. Perkins [1] along with photographs of characteristic events. Its last chapter is devoted to discovery of relativistic nuclei in cosmic radiation.

Tracks of relativistic nuclei of cosmic origin and nuclear stars created by them were found in NTE stacks exposed in stratosphere at the end of the 40s [2]. To describe the cross section for interaction of these nuclei with nuclei of the NTE composition, a geometric overlap formula was proposed, later called the Bradt-Peters formula. Among others, stars were observed containing few relativistic α particle tracks near directions of parent nucleus tracks. Defined as peripheral, such interactions clearly indicated the α-partial clustering of the final state. This aspect of the nuclear structure is studied in depth in low energy nuclear reactions by precision spectroscopic methods.

In the 70s, NTE stack exposures to relativistic light nuclei started at the JINR Synchrophasotron and Bevalac LBL, and in the 90s, medium and heavy ones on AGS (BNL) and SPS (CERN) at significantly higher energy values. With a resolution of about 0.5 μm the NTE method provided exclusive observations of tracks from the heaviest relativistic nuclei down to singly charged particles and slow fragments of target nuclei. A search for stars along primary tracks made it possible to make an overview of types of interaction without sampling. The results obtained from 70s to the present by this method, as well as the corresponding data files, remain unique in terms of the composition of relativistic fragmentation, and the exposed NTE layers can be used for targeted studies.

Features of light nuclei appeared in the relativistic fragmentation cone. These include the universal formation of pairs of α particles with extremely small opening angles, of the order of few mrad (for example, [3]). Such narrow "forks" correspond to decays of the unstable ^{8}Be nucleus. They indicate the principal possibility of studying α-clustering in relativistic approach starting from the ^{8}Be decay energy.

Until now, the complete detection of ensembles of the lightest relativistic fragments has been demonstrated only by the NTE method. However, it does not provide the momentum analysis. This limitation can be compensated for by using information on the fragmentation of relativistic nuclei obtained from magnetic spectrometers (for example, [4,5]). It is worth noting the availability of data obtained in 90s on an exclusive study of the fragmentation of relativistic oxygen nuclei on protons using the JINR hydrogen bubble chamber placed in a magnetic field [6].

Experiments in beams of fast-moving nuclei devoted to the nuclear structure provide both advantages of detection and make it possible to include radioactive isotopes, including exotic ones, among the studied ones. Information about the structure of ground states and peripheral interactions of nuclei is extracted from momentum distributions of relativistic fragments with charges close to the initial nucleus (for example, [7-9]). The formation of the relativistic ^{7}Be* fragment (^{8}B → ^{7}Be + γ) [10] in an only bound excitation has been proved [11]. Investigations of nuclear excitations with registration together with a fragment of one or a pair of protons or neutrons require a transition to the region of hundreds of MeV per nucleon (for example, [12] and recent [13]). Then the primary beam and charged fragments, which are quite different in magnetic rigidity, can be separated.

In the case of light nuclei, the role of channels with only He and H fragments is a key one, at least due to the fact that the ^{8}Be and ^{9}B isotopes whose presence in the cone of fragmentation is very likely are unstable ones. For example, according to the NTE data ^{11}C dissociation channels containing only He and H make up 80% of events with the primary charge remaining in the fragmentation cone. Being part of the fragmentation pattern reconstruction of ^{8}Be and ^{9}B is necessary for the subsequent searches of unstable states decaying with their participation.

Collimation of relativistic fragments produced in a peripheral collision allows detecting all of them all at once in a small solid angle that is an obvious value. However, electronic experiments in this direction have encountered difficulties due to the quadratic dependence of ionization on charges, the extremely small angular divergence of relativistic fragments, and, often, an approximate coincidence in magnetic rigidity with beam nuclei. For instance, in the experiment devoted to dissociation ^{12}C → 3α at 2.1 *A* GeV, it was not possible to identify ^{8}Be decays and the bulk of the energy spectrum of α triples was reconstructed by simulation [14]. It seems that the main problem is that an increase in the degree of dissociation of the projectile leads to a rapid decrease in the ionization signal in the detectors and, apparently, unacceptably increasing requirements for their operating range. A magnetic spectrometer with a time-projection ~~camera~~ chamber with a wide sensitivity range is being developed at the GSI [15]. The experiment is aimed at studying the isotopic composition and fragmentation mechanisms of 1 *A* GeV heavy nuclei. In case of interest in the topic of clustering, the possibility of reconstructing the dissociation ^{12}C → ^{8}Be + α is worth considering.

Next, the problems of unstable states and the results of their searches in the relativistic dissociation of several light nuclei in NTE will be summarized. Being interesting with respect to the structure of the studied nuclei these observations allow one to address the question of their universality, including their manifestation in the dissociation of medium and heavy nuclei, where it becomes possible to search for increasingly complex unstable states. As a first step, an analysis of NTE exposed in BNL to 14.5 *A* GeV ^{28}Si and 10.7 *A* GeV Au nuclei is presented.

Being considered in a longer-term perspective the phenomenon of peripheral dissociation of relativistic nuclei has the latent potential of a “laboratory” for testing most 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 NTE method. 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.

1. Status and prospects of studies of unstable states

Since the early 2000s the NTE method is applied in the BECQUEREL experiment at the JINR Nuclotron to study, in the relativistic approach, the composition of fragmentation of light nuclei, including radioactive ones (reviewed in [16-18]). For this experiment the Slavich Company (Pereslavl Zalessky, Russia) has resumed production of NTE layers with a thickness from 50 to 200 μm on a glass base. NTE samples were tested with a whole variety of ionization tracks. At present, the production of layers with a thickness of 500 μm without a substrate is being mastered, which will allow continuing the application of the technique, which was considered almost lost.

So, known and previously unobserved structural features revealed of the isotopes $^{7.9}$Be, ^{8,10,11}B, ^{10,11}C, and ^{12,14}N are revealed in the dissociation channel probabilities. Decays ^{9}B → ^{8}Be + *p* are identified in the dissociation ^{10}B, ^{10}C, and ^{11}C. Earlier, dozens of ^{9}B decays were identified in fragmentation of 200–400 *A* MeV ^{12}C nuclei in a water target, when tracks were reconstructed in transversely placed NTE films [19].

Apparently, the absence of a stable state of the ^{9}B nucleus does not prevent its virtual presence in the structure of these nuclei. Their synthesis could occur through the $^{9}B + p$ resonance along the chain $^{7}Be(^{3}He,p)^{9}B(p,\gamma)^{10}C(e^{+},\nu)^{10}B(p,\gamma)^{11}C(e^{+},\nu)^{11}B$. As a result, ^{9}B is "imprinted" in the formed nuclei, which is manifested in relativistic dissociation. In the ^{7}Be fragmentation, $^{6}Be \rightarrow \alpha + 2p$ decays are identified. However, the ^{6}Be signal was not detected in the ^{10}C dissociation.

The identification of the relativistic ^{8}Be and ^{9}B decays in NTE pointed out s the possibility of identifying the unstable state of the triple of α particles, called the Hoyle state (HS) in the relativistic dissociation $^{12}C \rightarrow 3\alpha$ [20] and, then, $^{16}O \rightarrow 4\alpha$ [21]. The solution to this problem allows HS to be used as a "tool" for searching for exotic components in the nuclear structure and complex unstable states decaying with its participation. It is worth studying the possibility of extracting information about the size of HS based on the distributions of the total transverse momentum of α-triples.

Recall that HS is the second (and first α-unbound) 0^{+}_{2} excitation of the ^{12}C nucleus [11]. The discovery history and research status of this short-lived state of three real α particles are discussed in a review [22]. ^{12}C synthesis is possible through two unstable states $3\alpha \rightarrow \alpha^{8}Be \rightarrow {}^{12}C\ (0^{+}_{2}$ or HS) $\rightarrow {}^{12}C$. In the 3α-process, HS manifests itself as an unstable nucleus, albeit of an unusual nuclear molecular structure.

The nucleus ^{8}Be is an indispensable product of the decay of HS and ^{9}B. The decay energy of ^{8}Be is 91.8 keV, and the width is 5.57 ± 0.25 eV [11]. The isolation of HS among ^{12}C excitations, the extremely small values of the energy above the 3α threshold (378 keV) and the decay width (9.3 ± 0.9 eV) indicate similarity with the ^{8}Be nucleus [11]. The ^{9}B ground state is 185.1 keV higher than the threshold $^{8}Be + p$ and its width is 0.54 ± 0.21 keV [11]. A comparison of these parameters suggests that the significance of HS to nuclear physics is not limited to the role of the unusual excitation of the ^{12}C nucleus. HS is manifested in nuclear reactions as the universal object similar to ^{8}Be and ^{9}B [23-25].

According to their widths, ^{8}Be, ^{9}B, and HS can be full participants of relativistic fragmentation. The products of their decay are formed during runs from several thousand (^{8}Be and HS) to several tens (^{9}B) of atomic sizes, i.e., over a time many orders of magnitude longer than the time of the appearance of other fragments. Due to the lowest decay energy, ^{8}Be, ^{9}B, and HS should manifest themselves as pairs and triples of relativistic fragments of He and H with the smallest opening angles which distinguishes the latter from other fragmentation products.

^{8}Be and HS are considered as the simplest states of the α-particle Bose – Einstein condensate [26, 27]. The 6th excited state 0^{+}_{6} of the ^{16}O nucleus at 15.1 MeV (or 660 keV over the 4α threshold) is considered as a 4α-condensate. Its decay could go in the sequence $^{16}O(0^{+}_{6})$

→ $^{12}C(0^+{}_2)$ → $^{8}Be(0^+{}_2)$ → 2α. Research in this direction is actively underway [22-24]. However, the contribution of 4α ensembles above 1 MeV is dominant. The possibility of more complex α-condensate states up to 10α-particle one with the decay energy of about 4.5 MeV above the 10α-threshold is assumed which leads to unprecedented experimental requirements including parent nucleus energy growth.

It is of interest to establish the ratio of the probabilities of ^{13}N decays to the ^{9}Bα and HS*p* channels. In addition, the ^{9}B and HS can serve as bases in the nuclear molecules ^{9}Bp, ^{9}Bα, and HS*p*. Like α-condensate states, unstable states involving protons can correspond to excitations having electromagnetic decay widths. Excitation of the $^{13}N^*$ at 15.1 MeV having a width of 0.86 ± 0.12 keV [11] can serve as a candidate for this state. An effective source for such studies is the 14N core. In this regard, the analysis of ^{14}N dissociation in nuclear reactors via the 3He + H channel is resumed.

Several isotopes have excited states with widths of the order of feweV or lifetimes of several fsec located above the separation thresholds of the α particle and the stable residue heavier than He no higher than about 1 MeV [11]. When such states are formed in the fragmentation, their decay products will also have minimal opening angles. They will be an even more convenient subject of research than α*p* states. In this regard, it is planned to analyze the mirror channels ^{11}C (B) → ^{7}Be (Li) + α. There is sufficient material for such an analysis for ^{10}B, ^{16}O, ^{22}Ne, ^{24}Mg, ^{28}Si nuclei.

On the whole, the topic of studying unstable states seems unusually intriguing, and the NTE method is an adequate way to search for them in the peripheral interactions of relativistic nuclei. Questions may be raised about the contribution to the fragmentation of decays from more highly excited states with widths up to 100 keV which would also have ranges significantly exceeding the characteristic sizes of nuclei. However, the answers are outside the resolution of the NTE method.

2. Description of the proposed research

2.1.1 Research method

Stacks to be exposed are assembled from NTE layers of size up to 10x20 cm^2 of a thickness of 200 μm on a glass base and 550 μm without it. 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 base 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.

Searching nuclear interactions in NTE without sampling (or the "following the track" method) provides a fairly uniform detection efficiency of all possible types of interactions and allows one to determine the mean free path for a certain type of interaction. This method is implemented in tracking the beam tracks of the nuclei under study from the point of entry into the NTE layer to the interaction or to the exit of the track from the layer. Time consuming, it provides the best viewing quality and consistency. Statistics of several hundreds of peripheral interactions with certain configurations of relativistic fragments is achievable with transverse scanning.

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 ones in the unstable state problem 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, $Z_{pr} = \sum Z_{fr}$. These interactions are a few per cent of the inelastic ones.

With a measuring base of 1 mm, the resolution for tracks 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 most peripheral interactions, called coherent dissociation or "white" stars, are not accompanied by fragmentation of target nuclei and the production of mesons. Photos and videos of characteristic interactions are available [16,28].

The mass numbers A_{fr} of the relativistic fragments H and He are defined as $A_{fr} = P_{fr}\beta_{fr}c/(P_0\beta_0 c)$, 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 He fragments.

The mass number assignment to H and He fragment tracks is possible by total momentum values derived from the average angle of Coulomb scattering. The use of this laborious method is justified in special cases for a limited number of tracks. In the case of dissociation of stable nuclei, it is often sufficient to assume the correspondence of He - ^{4}He and H - ^{1}H since the established ^{3}He and ^{2}H contributions do not exceed 20%. This simplification is especially true in extremely narrow ^{8}Be and ^{9}B decays [6].

The invariant mass of a system of relativistic fragments is defined as the sum of all products of 4-momenta $P_{i,k}$ fragments $M^{*2} = \sum(P_i \cdot P_k)$. Subtracting the mass of the initial nucleus or the sum of masses of fragments $Q = M^* - M$ is a matter of convenience. The components $P_{i,k}$ are determined in the approximation of conservation of the initial momentum per nucleon by fragments. Reconstruction by 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.

The most accurate measurements of the angles are provided with KSM-1 microscopes (Carl Zeiss, Jena) when using the coordinate method. Measurements are carried out in a Cartesian coordinate system. The NTE layer unfolds in such a way that the direction of the analyzed primary trace coincides with the microscope stage axis OX with a deviation not worse 0.1–0.2 μm per 1 mm of track length. Then the axis OX coincides with the primary track projection on the layer plane, and the axis OY on it is perpendicular to the primary track. The axis OZ is perpendicular to the layer plane. The measurements along OX and OY are made with horizontal micro-screws, and along the OZ, the depth of field micro-screw is used. Three coordinates are measured on the primary and secondary tracks at lengths from 1 to 4 mm in increments of 100 μm, according to a linear approximation of which the planar and dip angles are calculated. Details and illustrations of measurements on the plane of the layer and its depth have recently been published [20].

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 **[29].** 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.

2.1.2 Identification of ^{8}Be

In the fragmentation of relativistic nuclei in NTE intense tracks are observed often that branch into pairs of He tracks with minimal opening angles which are attributed ^{8}Be decays. Obviously, such a definition is inconvenient when comparing data obtained at different values of the primary energy. Universal ^{8}Be identification by the 2α-pair invariant mass $Q_{2\alpha}$ is the first “key” to the problem of the unstable nuclear states.

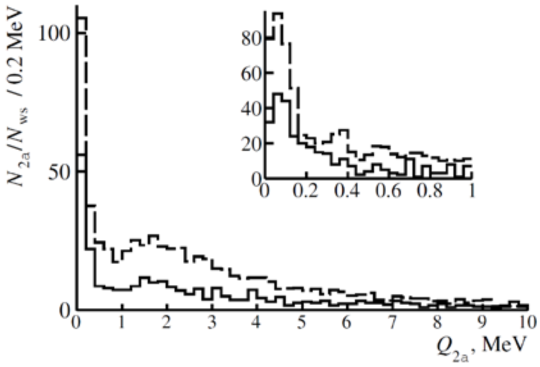

Fig. 1. Distribution of number of 2α-pairs $N_{2\alpha}$ over invariant mass $Q_{2\alpha}$ in coherent dissociation $^{12}C \to 3\alpha$ (solid line) and $^{16}O \to 4\alpha$ (dashed line) at 3.65 A GeV; the inset, enlarged part $Q_{2\alpha}$ < 1 MeV (step 40 keV); histograms are normalized to the number of “white” stars N_{ws}.

The distribution $Q_{2\alpha}$ is shown in Fig. 1 for the coherent dissociation $^{12}C \to 3\alpha$ and $^{16}O \to 4\alpha$ at 3.65 *A* GeV. In the ^{12}C case, measurements of polar and azimuthal angles of α-particles in 316 "white" stars made in the 90s by the groups of G. M. Chernov (Tashkent) [30] and A. Sh. Gaitinov (Alma-Ata) and recently supplemented by the FIAN and JINR groups are used. In the ^{16}O case, similar data is available for 641 "white" stars [31]. For these events, Fig. 1 presents distributions of invariant mass in the region $Q_{2\alpha}$ < 10 MeV of all 2α-pair combinations $N_{2\alpha}$ normalized to the corresponding number of "white" stars N_{ws}. In the insert these data are shown in the range $Q_{2\alpha}$ < 0.5 MeV in an enlarged form. Although in both cases there are peaks corresponding to ^{8}Be, however, due to the presence of “tails” caused by reflections of (3-4)α excitations the selection condition $Q_{2\alpha}(^{8}Be)$ is not sufficiently defined.

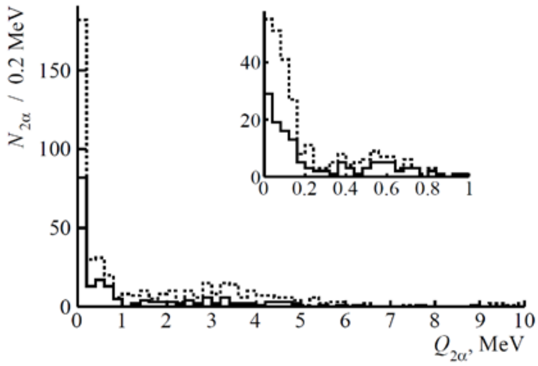

Fig. 2. Distribution of number of 2α-pairs of $N_{2\alpha}$ over the invariant mass $Q_{2\alpha}$ in 500 dissociation events ^{9}Be → 2α (dots) at 1.2 A GeV including 198 "white" stars (solid line); in inset, enlarged part $Q_{2\alpha}$ < 1 MeV.

The angular measurements of ^{9}Be → 2α at 1.2 *A* GeV (review [15]) makes it possible to possible to refine the selection condition of ^{8}Be decays by the invariant mass $Q_{2\alpha}$. The distribution over $Q_{2\alpha}$ of 500 2α-pairs including 198 "white" ones presented in Fig. 2 indicates the limit $Q_{2\alpha}$(^{8}Be) < 0.2 MeV. There are two "influxes" centered on $Q_{2\alpha}$ equal to 0.6 and 3 MeV. The first reflects the ^{9}Be excitation at 2.43 MeV [11,32], and the second one – the ^{8}Be 2^+ state [11]. The condition $Q_{2\alpha}$(^{8}Be) takes into account the accepted approximation, the kinematic ellipse of ^{8}Be decay, and the resolution of angular measurements. Its application allows us to determine the contribution of ^{8}Be decays to the statistics of "white" stars equal to 45 ± 4% for ^{12}C → 3α and 62 ± 3% for ^{16}O → 4α. A similar selection of ^{12}C → 3α at 0.42 *A* GeV gives 53 ± 11% [20]. The condition $Q_{2\alpha}$(^{8}Be) < 0.2 MeV coincides with those adopted in the electronic experiments [23–25,32].

To estimate the boundaries of assumptions in the identification of ^{8}Be associated with attributing the mass number A = 4 and the corresponding momentum to He fragments, the fragmentation ^{9}Be → 2He + *n* was modeled in Geant4 [33] in the framework of the QMD model [34] for 10^4 ^{9}Be nuclei of energy around 1.2 *A* GeV (σ = 100 MeV in the Gaussian distribution). 466 interactions ^{9}Be → 2He + *n* were obtained, including 59 pairs ^{3}He + ^{4}He and 4 - ^{3}He + ^{3}He. The value of the average momentum per nucleon of ^{4}He fragments is 1915 MeV/*c* at RMS 32 MeV/*c*. In the $Q_{2\alpha}$ distribution, approximately 2/3 of the ^{9}Be fragmentation events correspond to the formation of ^{8}Be 0^+. The average value of the relative momentum difference in the ^{4}He pars at $Q_{2\alpha}$ (^{8}Be) is 0.8%, and the contribution of pairs with the participation of ^{3}He to $Q_{2\alpha} \leq 0.2$ MeV is less than 3%. All these facts indicate the validity of the assumptions made and the sufficiency of the precision angular measurements. Moreover, modeling indicates that the inclusion of momenta to determine $Q_{2\alpha}$ would make sense if the accuracy of their measurements is of the order of tenths of a percent, while maintaining the same angular resolution. Indeed, according to the data of the hydrogen bubble chamber, there is an ^{8}Be peak in the distribution over the opening angle [6], and, therefore, in $Q_{2\alpha}$. The inclusion of momenta in the calculation of $Q_{2\alpha}$, the measurement accuracy of which is estimated at 1.5% at a length of 40 cm of liquid hydrogen, leads to the “scattering” of the peak. Undoubtedly, the use of momentum analysis also leads to an additional deterioration in the angular resolution. This conclusion is worth to be taken into account when planning electronic versions of such studies.

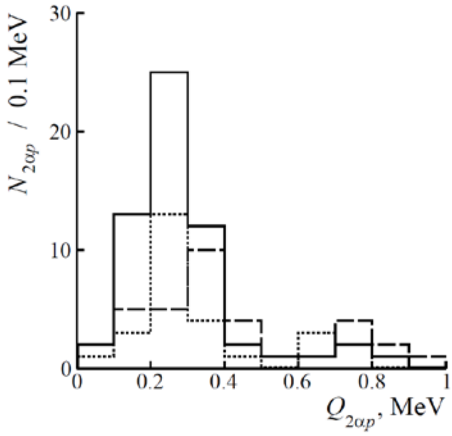

Fig. 3. Distribution of the number of 2αp triples $N_{2\alpha p}$ over invariant mass $Q_{2\alpha p}$ (< 1 MeV) in events of coherent dissociation $^{10}C \to 2He2H$ (solid line) and dissociation $^{11}C \to 2He2H$ (dots) and $^{10}B \to 2HeH$ (dashed line).

2.1.3 Relativistic decays of ^{9}B

The next “key” in the unstable state studies is the ^{9}B nucleus. When studying the coherent dissociation of the ^{10}C isotope at 1.2 *A* GeV, the 2He + 2H dissociation channel appeared as the leading one (review [15]). The statistics of the 4He + 2H quartets in it amounted to 186 or 82% of the observed “white” stars. the distribution over the invariant mass of 2α*p* triples $Q_{2\alpha p}$ presented in fig. 3 indicates the number of decays $N(^{9}B) = 54$ satisfying the condition $Q_{2\alpha p}(^{9}B) <$ 0.5 MeV which is 30 ± 4% of the events 2He + 2H. According to the condition $Q_{2\alpha}(^{8}Be) < 0.2$ MeV, ^{8}Be decays are also identified in all these 2α*p* triples and only in them. This fact indicates the dominance of the decay sequence $^{9}B \to {}^{8}Be + p$ and $^{8}Be \to 2\alpha$. The abundant formation of ^{9}B nuclei in the dissociation of ^{10}C indicates its important role as the structural basis of this isotope.

The confident identification of ^{8}Be and ^{9}B based on the ^{10}C nucleonic composition allows one to turn to their contribution to the ^{10}B and ^{11}C dissociation. Angular measurements are performed in 318 events $^{10}B \to 2He + H$ at 1.0 *A* GeV among which 20 decays $^{9}B \to {}^{8}Be + p$ were identified that satisfy the condition $Q_{2\alpha p}(^{9}B) < 0.5$ MэВ (Fig. 3). Similarly, in 154 events $^{11}C \to 2He + 2H$ at 1.2 *A* GeV $N(^{9}B) = 22$ (Fig. 3) are found. Thus, in the dissociation of ^{10}C, ^{10}B and ^{11}C, the universal condition $Q_{2\alpha p}(^{9}B)$ was established. In addition, when identifying $^{9}B \to {}^{8}Be + p$ decays, the criterion $Q_{2\alpha}(^{8}Be)$ is confirmed under the purest conditions.

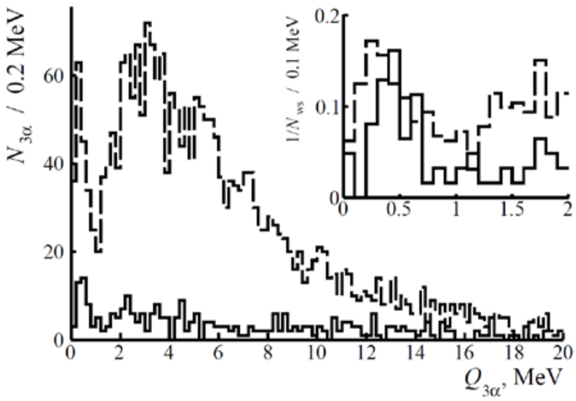

Fig. 4. Distribution of number of 3α-triples $N_{3\alpha}$ over invariant mass $Q_{3\alpha}$ in 316 "white" stars $^{12}C \rightarrow 3\alpha$ (solid) and 641 "white" stars $^{16}O \rightarrow 4\alpha$ (dashed) at 3.65 A GeV; in inset, enlarged part $Q_{3\alpha}$ < 2 MeV normalized to numbers of "white" stars N_{ws}.

2.1.4 Identification of the Hoyle state

Using the angular measurements of the "white" stars ^{12}C → 3α and ^{16}O → 4α the application of the invariant mass method can be easily extended to the identification of relativistic decays of the Hoyle state. In the latter case, HS decays can manifest themselves in the dissociation ^{16}O → ^{16}O → ^{12}C* (→ 3α) + α. Both distributions over the invariant mass of 3α-triples $Q_{3\alpha}$ presented in Fig. 4 show similarities. Their main parts in the region $Q_{3\alpha}$ < 10 MeV, covering the ^{12}C α-particle excitations up to the nucleon separation threshold are described by the Rayleigh distribution with parameters $\sigma_{Q3\alpha}(^{12}C) = 3.9 \pm 0.4$ MeV and $\sigma_{Q3\alpha}(^{16}O) = 3.8 \pm 0.2$ MeV.

In both cases, distribution peaks are observed in the region $Q_{3\alpha}$ < 0.7 MeV where the HS signal is expected. The statistics in the peaks minus the background is $N_{HS}(^{12}C) = 37$ with an average value $\langle Q_{3\alpha} \rangle$ (RMS) = 417 ± 27 (165) keV and $N_{HS}(^{16}O) = 139$ with $\langle Q_{3\alpha} \rangle$ (RMS) = 349 ± 14(174). On this basis, the contribution of HS decay to the coherent dissociation of ^{12}C → 3α is 11 ± 3%, and in the case of ^{16}O → 4α, it is 22 ± 2%. An increase in 3α combinations in ^{16}O → 4α leads to a noticeable increase in the contribution of HS decays. At the same time, the ratio of the ^{8}Be and HS yields shows an approximate constancy $N_{HS}(^{12}C)/N_{8Be}(^{12}C) = 0.26 \pm 0.06$ и and $N_{HS}(^{16}O)/N_{8Be}(^{16}O) = 0.35 \pm 0.04$.

There is a possibility of the HS emergence through the α decay of the 0^+_6 excitation of the ^{16}O nucleus. The distribution of "white" ^{16}O → 4α stars over the invariant mass of 4α-quartets $Q_{4\alpha}$ presented in Fig. 5 in the main part is described by the Rayleigh distribution with the parameter $\sigma_{Q4\alpha}$ = (6.1 ± 0.2) MeV. The condition for the presence of at least one 3α-triple with $Q_{3\alpha}$(HS) < 700 keV in a 4α-event (αHS) shifts the distribution over $Q_{4\alpha}$ to the low-energy side, and the parameter to $\sigma_{Q4\alpha}$ = 4.5 ± 0.5 MeV (Fig. 5). The enlarged view of the distribution over $Q_{4\alpha}$ presented in the inset in Fig. 5 indicates 9 events satisfying $Q_{4\alpha}$ < 1 MeV and having an average value of 〈Q4α〉 (RMS) = 624 ± 84 (252) keV. Then, the contribution of the decays $^{16}O(0^+_6) \rightarrow \alpha$ + HS is estimated to be 1.4 ± 0.5% for normalization to $N_{ws}(^{16}O)$ and 7 ± 2% for normalization to $N_{HS}(^{16}O)$.

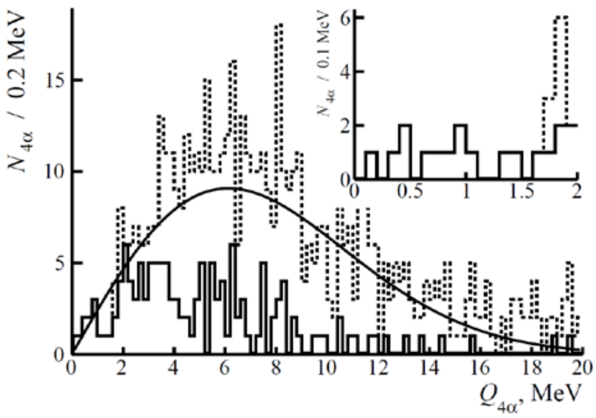

Fig. 5. Distributions over invariant mass $Q_{4\alpha}$ in 641 "white" stars $^{16}O \rightarrow 4\alpha$ at 3.65 A GeV of all 4α-quartets (dots) and αHS events (solid line); smooth line - *Rayleigh distribution; the inset, enlarged part $Q_{3\alpha}$ < 2 MeV.*

33 events $^{16}O \rightarrow 2^8Be$ are identified, which is 5 ± 1% of the "white" stars $^{16}O \rightarrow 4\alpha$. Then, the statistics of coherent dissociation for the $^{16}O \rightarrow 2^8Be$ and $^{16}O \rightarrow \alpha HS$ channels has a ratio of 0.22 ± 0.02. The distribution over the invariant mass $Q_{4\alpha}$ of the events $^{16}O \rightarrow 2^8Be$ shown in Fig. 6 indicates two candidates $^{16}O(0^+_6) \rightarrow 2^8Be$ in the region of $Q_{4\alpha}$ < 1.0 MeV. Thus, the estimate of the probability ratio of the channels $^{16}O(0^+_6) \rightarrow 2^8Be$ and $^{16}O(0^+_6) \rightarrow \alpha HS$ is 0.22 ± 0.17 which is too vague.

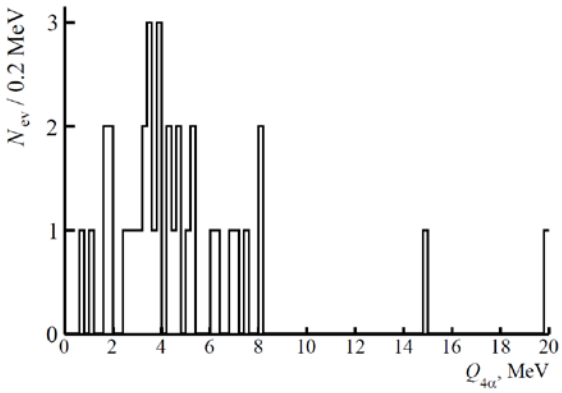

Fig. 6. Distribution of events $^{16}O \rightarrow 2^8Be$ over invariant mass $Q_{4\alpha}$.

It can be concluded that although the direct dissociation dominates in the formation of HS a search for its 4α "precursor" is possible in the relativistic dissociation of nuclei. At the same time, increasing the statistics of events $^{16}O \rightarrow 4\alpha$ in the traditional way can be considered exhausted. There remains the possibility of studying (3-4) α-ensembles in the fragmentation of heavier nuclei.

2.1.5 Search for unstable states in the fragmentation of Si and Au nuclei

EMU collaboration data are available on 1093 interactions of ^{28}Si nuclei at 14.6 *A* GeV [35] and 1316 ones of ^{197}Au at 10.7 *A* GeV [36] which contains measurements of the angles of emission of relativistic fragments. Then the search for events was conducted on the primary tracks without sampling. The number of events with the multiplicity of relativistic α particles $N_\alpha > 2$ in the Si case is 118, and Au is 843. Recently, the search for Si interactions $N_\alpha > 2$ has been resumed by scanning along the bands across the direction of entry of the primary tracks. The measurement cone is limited to 2^0. Thus, the analysis in the region of interest of small invariant masses is radically accelerated. In a relatively short time, 133 events $N_\alpha > 2$ were added to the Si statistics. The distributions over invariant masses $Q_{2\alpha}$, $Q_{2\alpha p}$, $Q_{3\alpha}$ and $Q_{4\alpha}$ in the small value regions obtained on the basis of these data are presented in Fig. 7 and 8. According to the criteria described above, the numbers of decays ^{8}Be (N_{8Be}), ^{9}B (N_{9B}) and HS (N_{HS}) are determined by them.

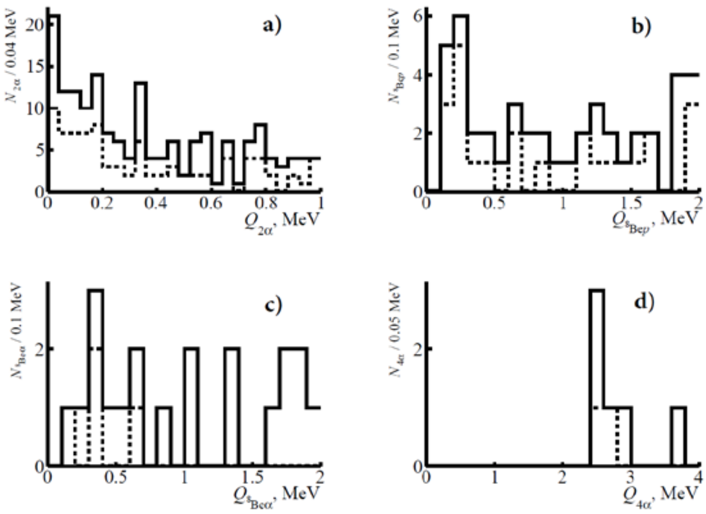

Fig. 7. Distributions of 2α, 2αp, 3α and 4α combinations from events of fragmentation of ^{28}Si nuclei at 14.6 A GeV over the invariant masses $Q_{2\alpha}$ (a), $Q_{2\alpha p}$ (b), $Q_{3\alpha}$ (c) and $Q_{4\alpha}$ (d) in the their small value regions according to data for without sampling (points) and recent measurements in accelerated search (added by solid line).

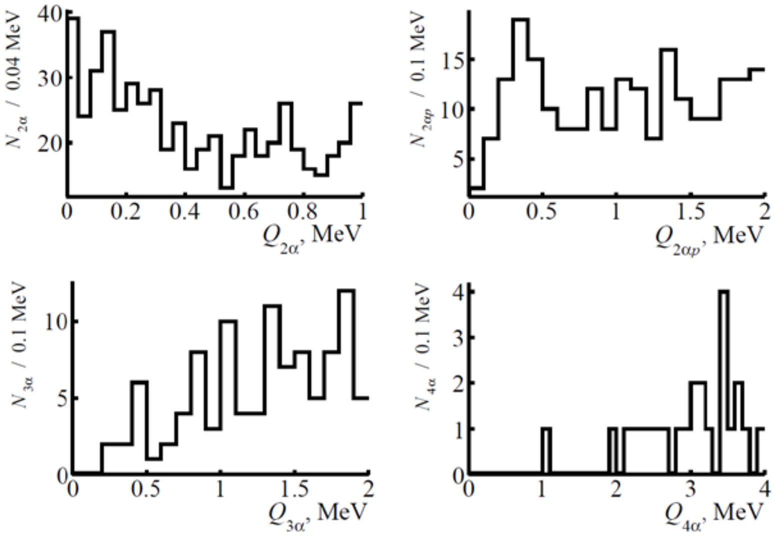

Fig. 8. Distributions of 2α, 2αp, 3α and 4α combinations from events of fragmentation of ^{197}Si nuclei at 10.7 A GeV over the invariant masses $Q_{2\alpha}$ (a), $Q_{2\alpha p}$ (b), $Q_{3\alpha}$ (c) and $Q_{4\alpha}$ (d) in the their small value regions.

A similar analysis of Au interactions yielded N_{8Be} = 143; N_{9B} = 38 with < $Q_{2\alpha p}$> (RMS) = 320 ± 16 (116) keV; N_{HS} = 12 with < $Q_{3\alpha}$> (RMS) = 435 ± 29 (106) keV at N_α = 4(2), 6(2), 7(2), 8(2), 9(1), 11(1) and 16(1). N_{HS}/N_{8Be} = 0.08 ± 0.01 at N_α > 2. There is one 4α quartet including HS with $Q_{4\alpha}$ = 1 MeV at N_α = 16. In 11 events, ^{8}Be pair formation is identified.

Under the assumption of a power-law dependence on the charge of the parent nucleus Z, which determines the production of α particles, the ^{8}Be и ^{9}B yields nuclei grows approximately as $Z^{0.8}$. Such a behavior is close to volume type dependence. The ratio of these yields is approximately the same. Statistics of 3α triples N_{HS} is small for estimates.

It can be concluded that in the both cases, ^{8}Be and ^{9}B decays are identified and indications of HS formation is obtained, and in the Au case, one candidate for 4α decay of the ^{16}O(0^+_6) state was found. Due to the fact that the measurements were made without sampling, they allow one to plan searches for the unstable states. A set of statistics of events N_α > 2 will be significantly accelerated during transverse scanning

2.1.6 Longer-term objectives

The results obtained make it possible to assess the prospects of the presented approach in modern problems of nuclear physics. Among the most important of them is the verification of theoretical ideas about matter arising from the fusion of nucleons in clusters that do not have excited states up to the coupling threshold [37]. These are the lightest ^{4}He nuclei, as well as deuterons, tritons and ^{3}He nuclei. The evolution of the composition of the lightest isotopes is predicted at a nuclear density less than normal and a temperature of several MeV. Passing through such a phase may be necessary on the way to the synthesis of heavy nuclei. A look at the dissociation of relativistic nuclei with time reversal indirectly indicates the feasibility of such a transition.

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. 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.

In the parent nucleus reference system, lightest fragment distributions over energy cover the temperature range 10^8-10^{10} K corresponding to phases from the red giant to the supernova. In the dissociation of heavy nuclei, an unprecedented variety of coherent ensembles of the lightest nuclei and nucleons is available. The observations of unstable states presented here substantiate the possibility of studying cluster matter up to the lower limit of nuclear temperature and density. Identification of ^{1,2,3}H and ^{3,4}He isotopes by multiple scattering allows expanding the analysis of cluster states in the direction of the properties of the rarefied matter. The transverse momenta of fragments are determined from the emission angles, which makes it possible to isolate the temperature components. The practical feasibility of a detailed study of relativistic cluster jets can serve as a motivation for assessing the applicability of the relativistic approach to the problem of the existence of cold and rarefied nuclear matter.

In the relativistic dissociation of heavy nuclei, the formation of light fragments occurs with a greater ratio of charge to mass number than that of the primary nucleus, causing the appearance of associated neutrons that manifest themselves in secondary stars. The frequency of such "neutron" stars should increase with an increase in the number of lightest nuclei in the fragmentation cone. The average range of neutrons in NTE is about 32 cm. Reaching dozens, the multiplicity of neutrons in an event can be estimated by proportionally decreasing the average path to the formation of the "neutron" stars at paths of the order of several centimeters. The accuracy of determining the coordinates of their vertices makes it possible to restore the angles of neutron emission, and, therefore, the transverse momenta in the approximation of the conservation of the initial velocity. Thus, it is possible to study the effects of the neutron “skin”. Estimation of the yield of neutrons, as well as deuterons and tritons binding neutrons, can be of applied value.

It remains unclear why the peripheral dissociation of the nuclei corresponds to a sufficiently large cross section and a wide distribution over the multiplicity of fragments. This phenomenon may be based on the transition of virtual photons exchanged between the beam and target nuclei into pairs of virtual mesons. A critical test can be the fragmentation of the NTE composition nuclei under the action of relativistic muons [38-40]. The combination presented in fig. 9 provides long-range interaction with effective nuclear destruction and can be extended to peripheral interactions of relativistic nuclei. It was established that fragmentation of the target nuclei under the action of muons is most likely for the breakup $^{12}C \rightarrow 3\alpha$. In these events, the α particle energy and emission angles are determined from the ranges making it possible to obtain distributions over the invariant mass, as well as over the total momentum of pairs and triples of α particles. It has been preliminary established that the distribution over the total transverse momentum of the α-particle triples corresponds not to electromagnetic, but nuclear diffraction. Note that the 3α splitting cross section is important for geophysics, since it will allow testing the hypothesis of helium generation in the earth's crust by cosmic muons.

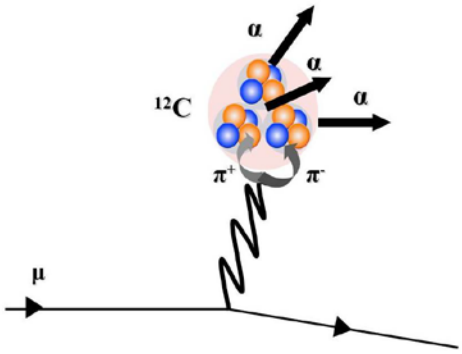

Fig. 9. Diagram of breakup of ^{12}C nucleus into three α-particles by relativistic muon.

Figure: 10. Microscopes KSM (left) and MPE-11.

2.1.7 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 (Fig. 10). Its cost is about $ 5000. Replication of this product requires priority funding. Its replication requires immediate funding.

In addition, there is a practically unexploited microscope MPE-11 (Fig. 10), designed to work on line with a computer, install a video camera and control a joystick. Its modernization will sharply increase the rate of measurements. This solution is used by colleagues in two groups of FIAN. The cost of the interface is about $ 10 thousand. It is important to emphasize that the modernization will preserve the continuity of measurements, train newcomers without the risk of serious breakdowns, and also use hardware and software innovations developed by students and graduate students.

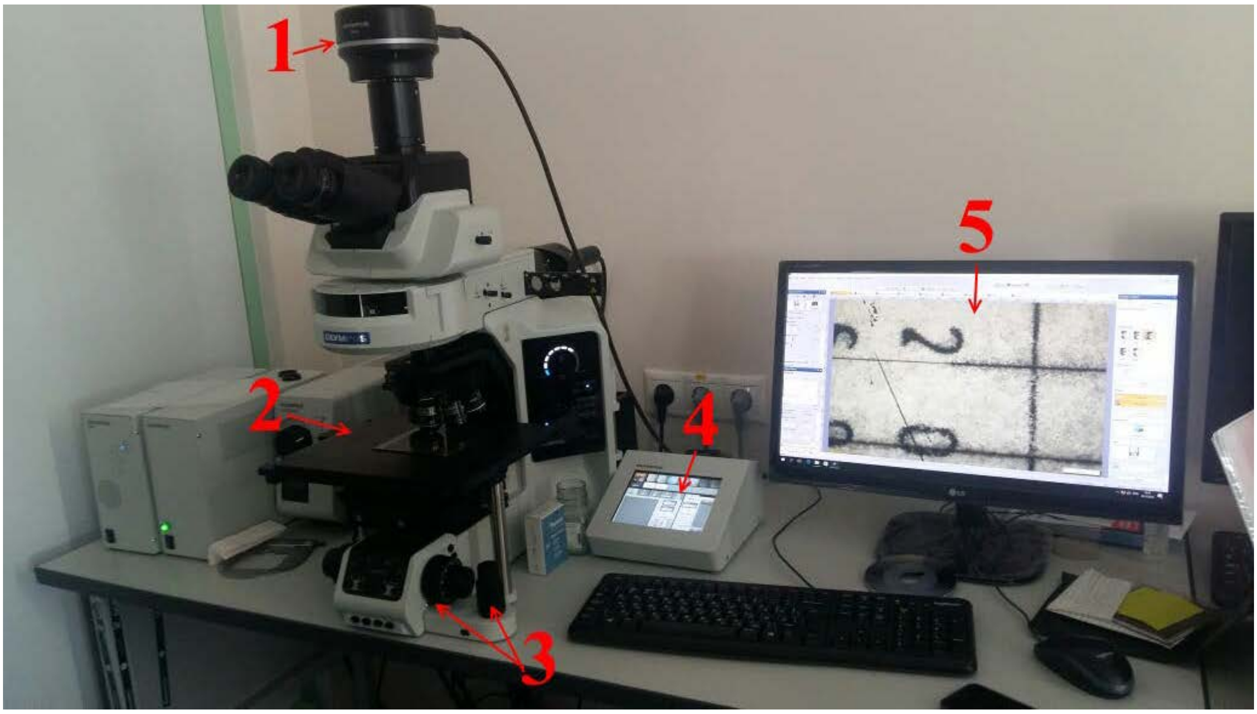

Fig. 11. Photo of BX63 microscope. Marked: 1) digital camera DP74, 2) motorized stage, 3) joysticks for controlling the focus and movement of the stage in the XOY plane, 4) microscope control unit, 5) PC for working with the received image.

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. 11 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.

2.1.8 Conclusions

Preserved and recently obtained data on interactions of light relativistic nuclei in a nuclear track emulsion allowed to establish the contribution in their dissociation of unstable nuclei ^{8}Be and ^{9}B and the Hoyle state as well as to assess the prospects of such research in relation to medium and heavy nuclei. These three states are uniformly identified by the invariant masses calculated from the measured angles of emission of He and H fragments under the assumption of conservation of the primary momentum per nucleon.

The ^{8}Be selection in dissociation of the isotopes ^{9}Be, ^{10}B, ^{10}C, and ^{11}C is determined by the restriction from above of the invariant mass of 2α-pairs up to 0.2 MeV, and the ^{9}B *2αp*-triple mass up to 0.5 MeV. The certainty in the ^{8}Be and ^{9}B identification of became the basis for the search for decays from the Hoyle state in the dissociation ^{12}C → 3α. In the latter case, the 3α triple invariant mass is set to be limited to 0.7 MeV. The choice of these three conditions as "cut-offs from above" is sufficient because the decay energy values of these three states are noticeably lower than the nearest excitations with the same nucleon compositions, and the reflections of more complex excitations is small for these nuclei.

Being tested in the studies of the light nuclei, a similar selection is applicable to the dissociation of heavier nuclei to search for more complex states. In turn, the products of α-particle or proton decay of these states could be the Hoyle state or ^{9}B, and then ^{8}Be. A possible decay variant is the occurrence of more than one state from this triple. In any case, the initial stage of searches should be the selection of events containing relativistic ^{8}Be decays.

Dozens of ^{8}Be and ^{9}B decays are identified in the relativistic fragmentation cone of Si and Au nuclei. At the same time, the small number of 3α triples attributable to the decay of the Hoyle state which requires increasing statistics to the current ^{8}Be equivalent. Then, the search for the excited state ^{16}O(0^+_6) will become feasible. There are no fundamental problems along this path since there are a sufficient number of earlier exposed NTE layers, with transverse scanning of which the required α ensemble statistics is achievable. This whole complex of problems, united by questions of identification of unstable states, is in the focus of the application in the BECQUEREL-2020 experiment in the present time.

It is hoped that the rapid progress in image analysis will give a whole new dimension to the use of the NTE method in the study of nuclear structure in the relativistic approach. The solution of the tasks set requires investment in modern automated microscopes and the reconstruction of NTE technology at a modern level. At the same time, such a development will be based on the classical NTE method, the foundations of which were laid seven decades ago in cosmic ray physics.

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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 "Recent applications of nuclear track emulsion technique" Phys. At. Nucl. **79** 1525(2016).
2. 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).

3. 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.
4. 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.
5. 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).
6. D.A. Artemenkov *et al.* "Recent findings in relativistic dissociation of ^{10}B and ^{12}C nuclei" Few Body Syst. **58** 89(2017).
7. K.Z. Mamatkulov *et al.* "Experimental examination of ternary fission in nuclear track emulsion" Phys. Part. Nucl. **48** 910(2017).
8. 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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10. Zaitsev, A. A.; Zarubin, P. I. "Application of nuclear track emulsion in search for the Hoyle state in dissociation of relativistic ^{12}C" Phys. At. Nucl. **81**, 1237(2018).
11. D.A. Artemenkov *et al.* "Unstable states in dissociation of relativistic nuclei. Recent findings and prospects of research" EPJ A 56, 250(2020); arXiv: 2004.10277.

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.	Kulikova L.I. assistant	NTE development	1.0
11.	Stelmakh G. I. assistant	Statistics collection	1.0
12*	Nomozova K. B. engineer	Statistics collection, measurements on microscopes	1.0
13.	Shcherbakova N. S. assistant	Statistics collection	1.0
14.	Marin I.I. technician	Microscopes maintenance, NTE exposures	1.0
		Σ	13.0

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-2020 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	
Expenditure	Main units of equipment, work towards its updating, adjustment, etc.		80		80		-		-	
	Construction /repair of premises		-		-		-		-	
	Materials		75		25		25		25	
Required resources	Standart hour	LHEP design bureau	-		-		-		-	
		JINR Work-shop	-		-		-		-	
		LHEP Workshop	-		-		-		-	
		Nuclotron	-	-	-	-	-	-	-	-
Σ			155	-	105	-	25	-	25	-
Total:			155		105		25		25	
Financing sources		Budget. Theme 1087	155		105		25		25	

Theme 1087 - LHEP
Project leader P.I. Zarubin

22.10.2020

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-2020 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								
3.	LHEP Design bureau	-		-		-		-	
4.	LHEP Workshop	-		-		-		-	
5.	Materials	75		25		25		25	
6.	Equipment	80		80		-		-	
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		275		145		65		65	
Total direct expenses:		275		145		65		65	

Theme 1087 – VBLHEP
PROJECT LEADER P.I. Zarubin

VBLHEP DIRECTOR V.D. Kekelidze

VBLHEP CHIEF ENGINEER-ECONOMIST L.M. Nozdrina

5. 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.

S. N. Ershov
DSc, Head of sector, Bogolyubov LTP, JINR

TEXAS A&M UNIVERSITY
Cyclotron Institute
College Station, Texas 77843-3366
(979) 845-1415 FAX (979) 845-1899
email: natowitz@comp.tamu.edu

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

ABSTRACT OF THE MINUTES
OF THE OCTOBER 19, 2020
VBLHEP STC MEETING

30 STC members were present at the meeting out of a total of 37 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» (02-1-1087-2009/2023). STC has decided to recommend to the PAC for Nuclear Physics to open a new project by the end of 2023 with the first priority.

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

VBLHEP STC Chairman E.A.Strokovsky

VBLHEP STC Scientific Secretary S.P.Merts