Form #24

**THE BECQUEREL PROJECT**

# Experiment BECQUEREL at Accelerator Complex NUCLOTRON/NICA

## The BECQUEREL2022 project

CODE OF THEME: 02-1-1087-2009/2023

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 ENDORSEMENT LIST

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**Contents**

**Abstract**

The BECQUEREL experiment is aimed at solving topical problems in nuclear clustering physics. The used method of nuclear track emulsion (NTE) makes it possible, due to its unique sensitivity and spatial resolution, to study in a unified approach multiple final states arising in dissociation of relativistic nuclei. Progress in this direction relies on computerized microscopy.

Currently, a research focus is on the theoretical concept of α-particle Bose-Einstein condensate (αBEC) - the ultra cold state of several S-wave α-particles near coupling thresholds. The unstable $^{8}$Be nucleus is described as 2αBEC, and the $^{12}$C($0^+_2$) excitation or Hoyle state (HS) as 3αBEC. Decays $^{8}$Be → 2α and $^{12}$C($0^+_2$) → $^{8}$Beα can serve as signatures for more complex αBEC decays. Thus, the $0^+_6$ state of the $^{16}$O nucleus at 660 keV above the 4α threshold, considered as 4αBEC, can sequentially decay $^{16}$O($0^+_6$) → α$^{12}$C($0^+_2$) or $^{16}$O($0^+_6$) → 2$^{8}$Be($0^+$). Its search is being carried out in several experiments on fragmentation of light nuclei at low energies. Confirmation of the existence of this and more complex forms of αBEC could provide a basis for expanding scenarios for the synthesis of medium and heavy nuclei in nuclear astrophysics.

The consideration of αBEC as an invariant phenomenon indicates possibility of its search in the relativistic fragmentation. A practical alternative is provided by NTE layers longitudinally exposed to relativistic nuclei. In them, the invariant mass of ensembles of He and H fragments can be determined from emission angles in the approximation of conservation of momentum per nucleon of a parent nucleus. Owing to extremely small energies and widths, the $^{8}$Be and HS decays, as well as $^{9}$B → $^{8}$Be*p*, are identified in fragmentation of light nuclei by an upper constraint on the invariant mass.

Having been tested, this approach has been used to identify $^{8}$Be and HS and search for more complex states of αBEC in fragmentation of medium and heavy nuclei. Recently, based on the statistics of dozens of $^{8}$Be decays, an enhancement in probability of detecting $^{8}$Be in an event with an increase in a number of relativistic α-particles was found. A preliminary conclusion is drawn that contributions of $^{9}$B and HS decays also increase. The exotically large sizes and lifetimes of $^{8}$Be and HS allowing suggesting possibility of synthesizing αBEC by successively connecting the emerging α-particles 2α → $^{8}$Be, $^{8}$Beα → $^{12}$C($0^+_2$), $^{12}$C($0^+_2$)α → $^{16}$O($0^+_6$), 2$^{8}$Be → $^{16}$O($0^+_6$) and further with decreasing probability at each step, when γ-quanta or recoil particles are emitted.

The main task of the forthcoming stage of the project is to clarify the relation between the appearance of $^{8}$Be and HS and α-ensemble multiplicities and search on this basis for decays of the $^{16}$O($0^+_6$) state. In this regard, the BECQUEREL experiment aims to measure multiple channels of $^{84}$Kr fragmentation below 1 GeV per nucleon. There are a sufficient number of NTE layers, transverse scanning of which on the motorized microscope Olympus BX63 makes it possible to achieve required statistics.

In continuation of the study of the fragmentation of light nuclei, the search for decays of isobar-analogue states (IAS) has begun. Manifesting at high excitation energy, but also having very small widths, IASs serve as “beacons” for structural rearrangement in the direction of similarity with their less stable isobars. In the context of nαBEC and IAS, the analysis of NTE exposed to $^{9}$Be, $^{14}$N, $^{22}$Ne, $^{24}$Mg, and $^{28}$Si nuclei will continue.

Searches for αBEC and IAS lead to the study of nuclear matter with temperature and density ranging from red giants to supernovae. In this respect NTE layers exposed to heavy nuclei at several GeV per nucleon of the NICA accelerator complex will make it possible to

study relativistic ensembles of H and He isotopes of unprecedented multiplicity under optimal conditions.

## INTRODUCTION

One of key aspects of nuclear structure is presence of degrees of freedom in which quartets of spin-paired protons and neutrons behave as constituent clusters, manifested in formation of α-particles in nuclear reactions and decays [1]. A study of ensembles of α-particles just above binding thresholds makes it possible to reveal a role of the unstable $^{8}$Be and $^{9}$B nuclei and the Hoyle 3α-state (HS) and search for their analogues.

The decay energy $^{8}Be \rightarrow 2\alpha$ is only $E_{th}(^{8}Be)$ = 91.8 keV, and width $\Gamma(^{8}Be) = 5.57 \pm 0.25$ eV. The $^{8}$Be nucleus is an indispensable decay product of $^{9}$B and HS. The $^{9}$B ground state is above a $^{8}$Be*p* threshold by $E_{th}(^{9}B)$ = 185.1 keV at $\Gamma(^{9}B) = 0.54 \pm 0.21$ keV [1]. The HS state is a second excitation (and a first α-unbound one) of the $^{12}$C nucleus (review [2]) at $E_{th}$(HS) = 378 keV above the 3α threshold. A value Γ(HS) = 9.3 ± 0.9 eV corresponds in order of magnitude to a width of the decay $\pi^0 \rightarrow 2\gamma$.

An isolation of HS from higher $^{12}$C excitations points to it as a $^{8}$Be 3α-analogue. Synthesis of $^{12}$C is possible through the fusion $3\alpha \rightarrow \alpha^{8}Be \rightarrow {}^{12}C(0^{+}{}_{2}) \rightarrow {}^{12}C$ (+2γ or $e^{+}$e- with a probability of the order of $10^{-4}$). Further synthesis of $\alpha^{1}2C \rightarrow {}^{16}O\gamma$ via a$^{16}$O level of an appropriate energy is parity forbidden. However, synthesis is possible in the sequence $^{12}C^{12}C \rightarrow {}^{12}C^{12}C(0^{+}{}_{2}) \rightarrow {}^{16}O^{8}Be$. As noted in [2], these circumstances determine the ratio of the $^{12}$C and $^{16}$O abundances in Universe. All these facts allow one to assume importance of heavier unstable states to nuclear astrophysics processes.

The significance of HS is not limited to a role of the $^{12}$C excitation, albeit a very unusual one. HS can occur in reactions with other nuclei. This circumstance unites HS, as well as $^{8}$Be and $^{9}$B, with other fragments. $^{8}$Be, $^{9}$B, and HS can serve as progenitors of branches of excited states both with the same composition and with increasingly heavier ones. Exotically large sizes of $^{8}$Be, $^{9}$B, and HS predicted theoretically (Fig. 1) are critical for understanding a fragmentation pattern in general and generation mechanisms of these objects in particular.

Current interest in nuclear clustering is largely motivated by the α-particle Bose-Einstein condensate concept (αBEC), put forward after discovery of ultra cold quantum gases (review [3]). Figure 2 shows an αBEC position on a theoretical "landscape" in a lowest nuclear density and temperature region. Some excitations of *n*α-fold nuclei immediately above α-particle binding thresholds can serve as an αBEC manifestation. Coexisting with fermionic excitations, such states are considered on a basis of a mean field of a bosonic type, formed by a gas of almost ideal bosons in the S state. They could appear at an average density of $^{8}$Be, which is 4 times lower than usual. $^{8}$Be and HS are described as 2- and 3αBEC states, and their decays can serve as signatures for more complex *n*αBEC decays. The existence of developed forms of αBEC could expand nucleosynthesis scenarios toward heavy nuclei.

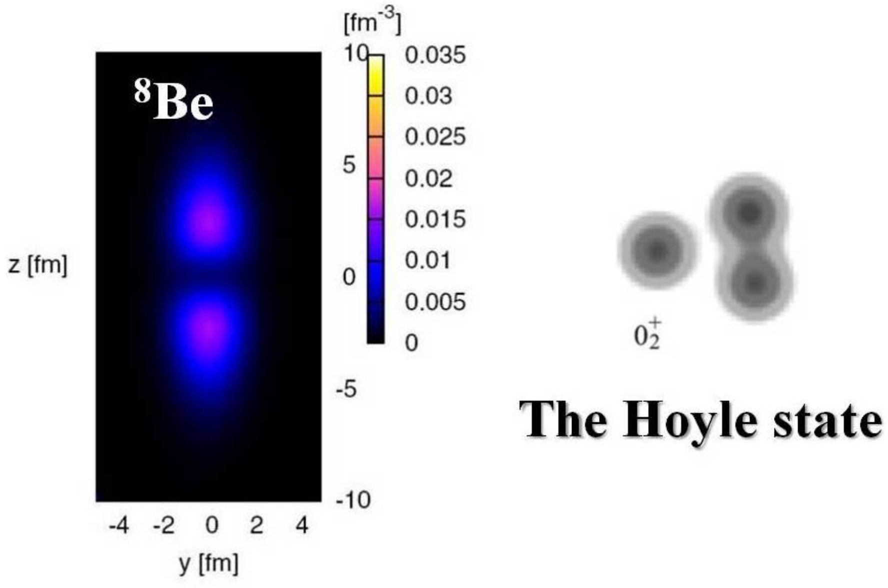


*Fig. 1. Calculated nuclear density distributions in $^{8}$Be ground state and Hoyle state [2, 3].*

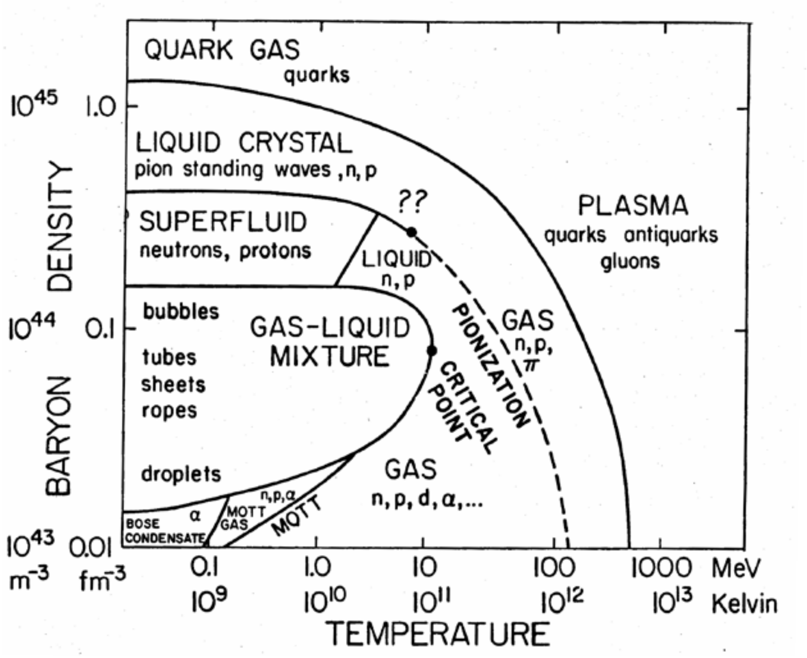


*Fig. 2. Theoretical "landscape" of phase states of nuclear matter.*

Experimental approaches to αBEC have been proposed, including the one presented here (review [8]). A search for HS similar states, but heavier, is carried out in experiments on fragmentation of light nuclei at low energies [5–10]. A focus is on the 4α analogue of HS, which is considered to be the $0^{+}_{6}$ state of the $^{16}$O nucleus at 660 keV above the 4α threshold, which can decay into αHS or 2$^{8}$Be. Consideration of *n*αBEC as weakly bound unstable states points to new possibilities for their search with increasing energy and mass numbers of generating nuclei. It is very valuable to demonstrate similarity of conclusions based on relativistic invariance.

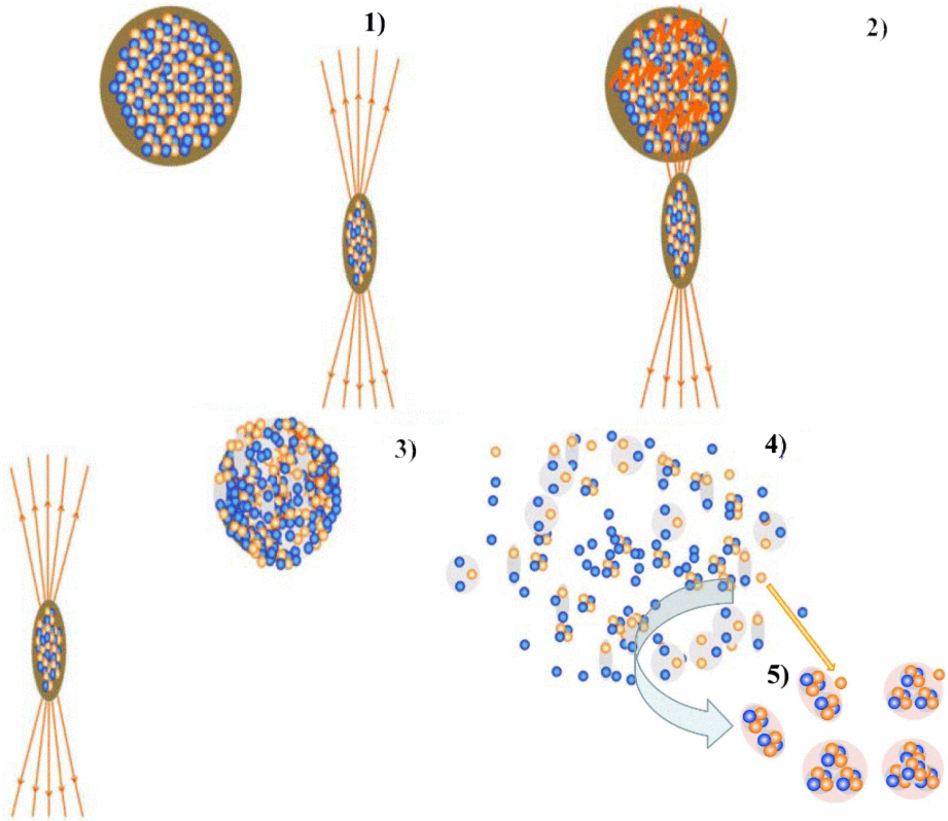


*Fig. 3. Scenario of multiple production of fragments: approach of nuclei (1), transfer of excitation to nucleus under study (2), transition to system containing real lightest nuclei and nucleons (3), its decay (4), sticking and pickup of some fragments into unstable states (5).*

The use of a technically simple and inexpensive method of NTE in beams of relativistic nuclei provides flexibility and uniformity at a search stage, and in a theoretical aspect, transparency of interpretation. During the dissociation of relativistic nuclei in a narrow solid angle of fragmentation, ensembles of He and H nuclei are intensively generated. When they are detected, there are no thresholds, and energy losses are minimal. Due to minimum energy, the decays of $^{8}$Be, $^{9}$B, and HS should appear as pairs and triplets of relativistic fragments He and H with the smallest opening angles. According to the widths, decays of $^{8}$Be, $^{9}$B, and HS occur at ranges from several thousand ($^{8}$Be and HS) to several tens ($^{9}$B) atomic sizes and must be identified by a minimum invariant mass.

The answer to this challenge was provided by the NTE method used in the BECQUEREL experiment. In NTE layers longitudinally exposed to relativistic nuclei, fragment tracks are observed completely, and their directions are measured with the best resolution. Determination of invariant masses of ensembles of relativistic He and H fragments in an initial velocity approximation makes it possible to project their angular correlations onto an energy scale, starting from $^{8}$Be decays. Possibilities and status of these studies are presented in review publications [11-13]. Achievements include $^{8}$Be and $^{9}$B identification, as well as the Hoyle state in fragmentation of light nuclei, including radioactive ones [12].

This approach began to be applied in the BECQUEREL experiment to search for αBEC in fragmentation of medium and heavy nuclei. A rapid increase in $^{8}$Be, $^{9}$B, and HS contribution with an increase in an accompanying α-particle number was found. Its cause may be the α-particle fusion with their density increase [13]. It is possible that αBEC do not arise as a result of conjugated excitation of a parent nucleus, but are formed in a sequential fragment pickup. In such a scenario (Fig. 3), αBEC unbinds from a parent nucleus and becomes an independent state of nuclear matter at extremely low density and temperature. Then selection of events with a high multiplicity of α-particles can be used as an amplifying factor. Thus, the αBEC search in fragmentation of medium and heavy nuclei becomes the main task of the BECQUEREL experiment for the coming years. The proposal focuses on this topic.

At the same time, a study of formation of unstable states by light nuclei is being developed with the respect to isobar-analogue states (IAS). Due to much higher energy and very small widths, IAS serve as "beacons" for rearrangement of studied nuclei in direction of similarity with their less stable isobars. Therefore, during the reconstruction of IAS decays, it is possible to reveal nuclear-molecular structure. Currently, a search for IAS $^{13}N^*$(15.065) is underway in fragmentation$^{14}N \rightarrow 3\alpha p$, IAS $^{8}$Be(16.6 + 16.9) in $^{9}$Be → 2α, and IAS 9B(14.7) in $^{10}C \rightarrow 2\alpha 2p$. In this aspect, available exposures to relativistic nuclei $^{22}$Ne, $^{24}$Mg, $^{28}$Si deserves analysis. Its level of difficulty is accessible to beginners.

To understand a mechanism of dissociation of nuclei, it is proposed to analyze fragmentation of NTE nuclei up to their complete destruction by relativistic muons. It is proposed to carry out transverse exposure of NTE layers nuclear to muons at CERN.

## 1. STATUS OF THE STUDY

An unstable nuclei study is possible in beams of stable and radioactive nuclei in the energy range from several to tens of MeV per nucleon. For this purpose, compact spectrometers with a significant coverage of the solid angle are being developed. They use silicon detectors with the best energy resolution placed in vacuum volumes near ultrathin targets. Decays are identified by reaction product energy correlations. In the context of this project, it is important to take into account their recent results on the αBEC search.

An experiment with full registration of projectile α-particle fragments of reaction $^{40}$Ca(25 MeV/nucleon) + $^{12}$C indicated growing contribution of $^{8}$Be up to 6α-multiplicity [14]. This fact contradicts a model predicting decrease (Table 2 in [9]). A search was carried out for the state $^{16}O(0^+_6$,15.1 MeV) in reactions $^{20}$Ne(12 MeV/nucleon) + $^{4}$He [5] and $^{16}$O(160, 280, 400 MeV) + $^{12}$C [7]. Recently, data on $^{16}$O(45 MeV) + $^{12}C \rightarrow 4\alpha$ in full kinematics [9] were analyzed for all possible configurations and the excitation function was reconstructed, as well as decays $^{12}C(0^+_2)\alpha$, $^{12}C(3^-_1)$ α and 2$^{8}$Be. However, search for the 15.1 MeV state remains unsuccessful in all cases [8]. Coincidences were measured for α-particles (386 MeV) scattered at 0$^{\circ}$ in $^{20}$Ne(α,α')5α [10]. It is stated that the newly observed states at 23.6, 21.8 and 21.2 MeV in $^{20}$Ne are strongly associated with the 4αBEC $^{16}$O candidate and are themselves αBEC candidates.

Although the status of observations αBEC candidates remains uncertain [8], HS is formed in all cases during fragmentation not only of $^{12}$C. This fact indicates that HS, like $^{8}$Be, is independent of a parent nucleus. A similar versatility should be shown by αBEC candidates. In general, it seems that in terms of statistics, the αBEC experiments have reached a practical limit. In them, studies with heavier nuclei are impossible and other approaches are required.

Such a perspective is opened in application of NTE in beams of relativistic nuclei. In the 70s, exposures of NTE stacks to light nuclei of energy of several GeV per nucleon started at the JINR Synchrophasotron and LBL Bevalac, and. in the 90s, medium and heavy nuclei at BNL AGS and CERN SPS at significantly higher energy values. Results obtained, as well as data files, retain their uniqueness with respect to relativistic fragmentation. These include α-pairs with opening angles corresponding to $^{8}$Be decays. They testify to the observation of final states down to the minimum energy..

Until now, electronic experiments have not been able to overcome difficulties caused by the quadratic decrease in ionization *vs*. charges, extremely small divergence, and coincidence of a magnetic rigidity of relativistic fragments and a beam. It is required to involve an adequate technique, as well as change representation to a relativistic invariant form. This important fact motivated a study of clustering by the NTE method.

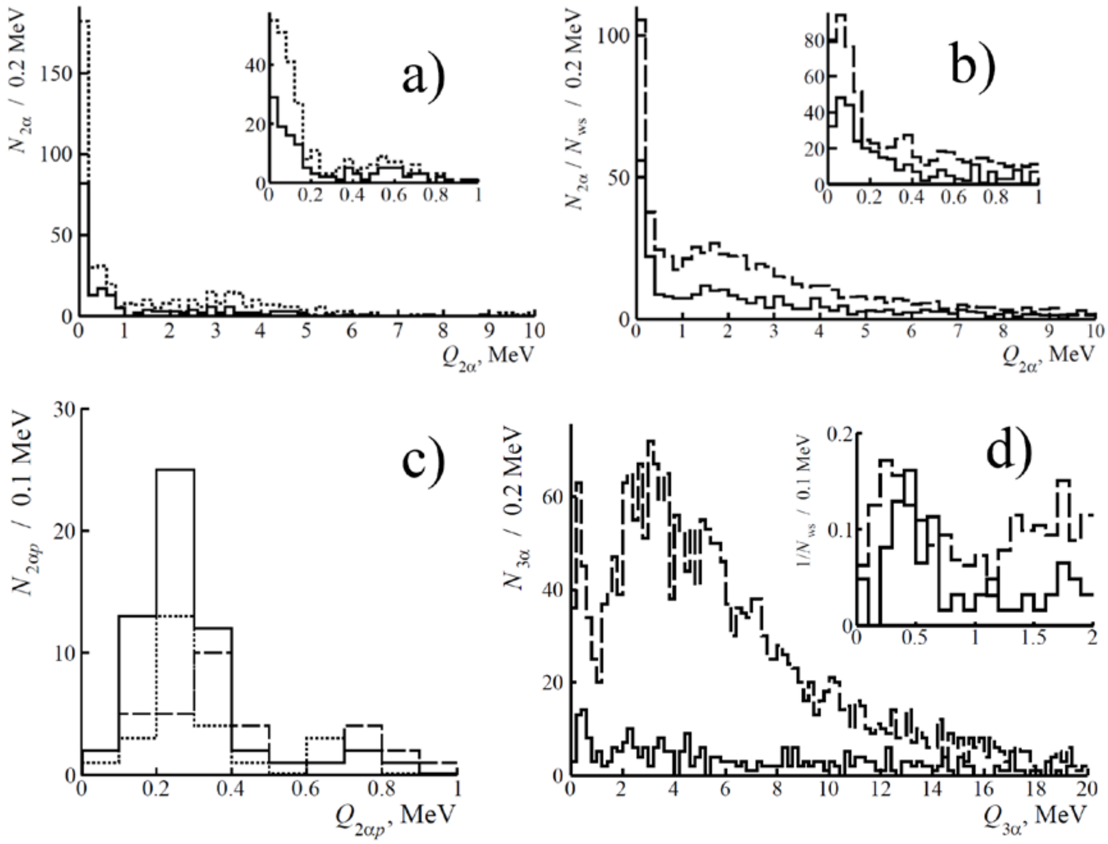


*Fig. 4. Invariant mass distributions [12]: a) $Q_{2\alpha}$ in $^{9}$Be(1.2 A GeV) → 2α (dotted line, solid line – "white" stars; b) $Q_{2\alpha}$ in $^{12}$C(3.65 A GeV) → 3α (solid line) and $^{16}$O( 3.65 A GeV) → 4α (dotted line); c) $Q_{2\alpha p}$ (< 1 MeV) in $^{10}$C(1.2 A GeV) → 2α2p (solid line) and $^{11}$C(1.2 A GeV) → 2α2p (dots) and $^{10}$B(1 A GeV) → 2αp (dotted line); $Q_{3\alpha}$ in $^{12}$C(3.65 A GeV) → 3α (solid line) and $^{16}$O(3.65 A GeV) → 4α (dashed line).*

Since early 2000s the NTE method is used in the BECQUEREL experiment at the JINR Nuclotron to study fragmentation of light nuclei (reviews [11, 12]). The features of the $^{7,9}$Be, $^{8,10,11}$B, $^{10,11}$C, and $^{12,14}$N isotopes were revealed in probabilities of dissociation channels. Decays $^{9}$B → $^{8}$Be*p* are identified via invariant masses calculated in assuming initial momentum conservation. The NTE resolution is shown to be a necessary and sufficient. The $^{8}$Be selection is determined by a cut-off to 0.2 MeV, and $^{9}$B – to 0.5 MeV (Figs. 4a and b).

The certainty in the identification of $^{8}$Be and $^{9}$B became the basis for the search for HS decays in the $^{12}$C → 3α dissociation (Fig. 4d), where the invariant mass of 3α triplets was limited to 0.7 MeV. The choice of these three conditions as "cutoffs from above" is sufficient, since the decay energies of these three states are noticeably lower than the nearest excitations with the same nucleon composition, and the reflection of more complex excitations is small for these nuclei.

An analysis of “white” stars $^{12}C \rightarrow 3\alpha$ and $^{16}O \rightarrow 4\alpha$ not accompanied by target fragments made it possible to establish that a fraction of events containing $^{8}Be$ (HS) decays is 45 ± 4% (11 ± 3%) for $^{12}C$ and 62 ± 3% (22 ± 2%) for $^{16}O$ (Fig. 4d). It can be seen that the growth of 2α- and 3α-combinations enhances the contribution of $^{8}Be$ and HS. This observation deserves verification for heavier nuclei, when the α-combinatory increases rapidly with the mass number.

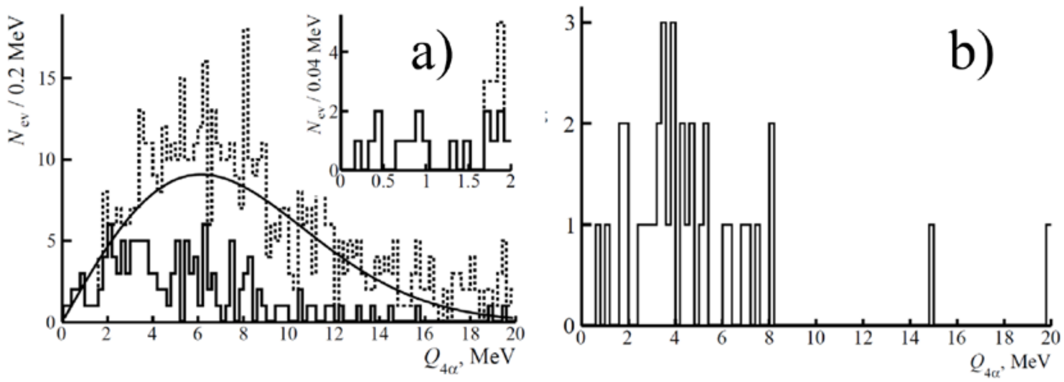


*Fig. 5. Invariant mass distributions $Q_{4\alpha}$ [12] in 641 "white" stars $^{16}O \rightarrow 4\alpha$ at 3.65 A GeV of all 4α-quartets (a, dots). events αHS (a, solid) and $^{16}O \rightarrow 2^{8}Be$ (b); smooth line - Rayleigh distribution; the inset shows an enlarged part of $Q_{3\alpha}$ < 2 MeV.*

There is possibility of HS appearance through the $^{16}O(0^{+}_{6})$ α-decay. The distribution over the 4α-quartet invariant mass of s $Q_{4\alpha}$ (Fig. 5) is mainly described by the Rayleigh distribution with the parameter $\sigma_{Q4\alpha}$ = (6.1 ± 0.2) MeV. The condition $Q_{3\alpha}$(HS) < 700 keV shifts the $Q_{4\alpha}$ distribution to the low-energy side. An enlarged view of the $Q_{4\alpha}$ distribution shown in the inset in Fig. 5a indicates 9 events satisfying $Q_{4\alpha}$ < 1 MeV and having an average value of $\langle Q_{4\alpha} \rangle$ (RMS) = 624 ± 84 (252) keV. Then the estimate of the contribution of $^{16}O(0^{+}_{6}) \rightarrow$ αHS c decays is 1.4 ± 0.5% when normalized to $N_{ws}(^{16}O)$ and 7 ± 2% when normalized to $N_{HS}(^{16}O)$.

33 events $^{16}O \rightarrow 2^{8}Be$ have been identified, which is 5 ± 1% of “white” stars $^{16}O \rightarrow 4\alpha$. Then the statistics $^{16}O \rightarrow 2^{8}Be$ and $^{16}O \rightarrow$ αHS has a ratio of 0.22 ± 0.02. Distribution over the invariant mass $Q_{4\alpha}$ of events $^{16}O \rightarrow 2^{8}Be$ shown in Figs. 5b points to two candidates $^{16}O(0^{+}_{6}) \rightarrow 2^{8}Be$ in the $Q_{4\alpha}$ < 1.0 MeV region. Thus, the estimate of the probability ratio of the channels $^{16}O(0^{+}_{6}) \rightarrow 2^{8}Be$ and $^{16}O(0^{+}_{6}) \rightarrow$ αHS is 0.22 ± 0.17.

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

## 2. DESCRIPTION OF THE PROPOSED STUDY

### 2.1.1 Possibilities of the method

The exposed stacks are assembled from layers up to 10x20 cm2 in size, 200 μm NTE on a glass substrate 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 a single layer for 3D reconstruction of angles. A substrate provides "rigidity", and its absence allows longer tracking, including transitions to neighboring layers. Factors for obtaining significant statistics are thickness and solid angle of detection. NTE contains close concentrations of Ag and Br and CNO atoms, as well as a threefold higher number of H ones. The search by tracing tracks of studied nuclei ensures the detection of about a thousand interactions without sampling. A statistics of several hundred peripheral interactions with certain configurations of relativistic fragments is achievable with transverse scanning.

The relativistic fragments are concentrated up to $\sin\theta_{fr} = p_{fr}/P_0$, where $p_{fr} = 0.2$ GeV/$c$ is a quantity characterizing the Fermi momentum of nucleons in a projectile nucleus, and $P_0$ is its momentum per nucleon. Resolution is no worse than $10^{-3}$ rad at 1 mm base. 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 that it conserves $P_0$. Tracks of relativistic fragments He and H are identified visually. Approximate conservation of a projectile charge by fragments is used to select few percent peripheral interactions.

In fragmentation of NTE nuclei, *b*-particles (α-particles and protons with energies below 26 MeV), *g*-particles (protons with energies above 26 MeV), as well as *s*-particles (produced mesons) can be observed. The most peripheral interactions, called coherent dissociation or "white" stars, are not accompanied by fragmentation of the target nuclei and the production of mesons (s-particles). Photos and videos of characteristic interactions are available on the site http://becquerel.jinr.ru/.

Assignment of mass numbers to H and He fragment is possible the mean Coulomb scattering angle. The use of this time-consuming method is justified in special cases for a limited number of tracлs. In the case of dissociation of stable nuclei, it is sufficient to assume that He - $^4$He and H - $^1$H correspond. This simplification is especially true in the case of extremely narrow $^8$Be and $^9$B decays [12].

The invariant mass of a system of relativistic fragments is defined as the sum of all products of 4-momentums $P_{i,k}$ of fragments $M^{*2} = \sum(P_i \cdot P_k)$.. The subtraction of the mass of the initial nucleus or the sum of the masses of the fragments $Q = M^* - M$ is a matter of convenience of presentation. The components $P_{i,k}$ are determined in the fragment conservation approximation $P_0$. Reconstruction from the invariant mass of decays of relativistic unstable nuclei $^8$Be and $^9$B, mastered in the BECQUEREL experiment, confirmed this approximation validity [12].

The most accurate measurements of angles are provided with KSM-1 microscopes (Carl Zeiss, Jena) using the coordinate method. The measurements are carried out in the Cartesian coordinate system. An NTE layer is rotated so that direction of an analyzed primary track coincides with the OX axis of a microscope stage with deviation of up to 0.1-0.2 μm per 1 mm length. Then the OX axis of the system coincides with direction of projection of a primary track onto a layer plane, and the OY axis on it is perpendicular to a primary track. The OZ axis is perpendicular to a layer plane. For OX and OY, measurements are made by horizontal movement micro screws, and for OZ - by a depth-of-field micro screw. Coordinates are measured on primary and secondary tracks at lengths from 1 to 4 mm with a step of 100 μm, by linear approximation of which angles are calculated.

### 2.1.2 Unstable states in the dissociation of heavy nuclei

It is possible that the unstable states are part of the nuclear structure that manifests itself in fragmentation. The alternative consists in the formation of $^8$Be in the interaction of α-pairs with the pickup of accompanying α-particles and nucleons by them. Its consequence would be an increase in the $^8$Be yield with a α-particle multiplicity $n_\alpha$, and possibly $^9$B and HS. In the first case, an inverse correlation can be expected.

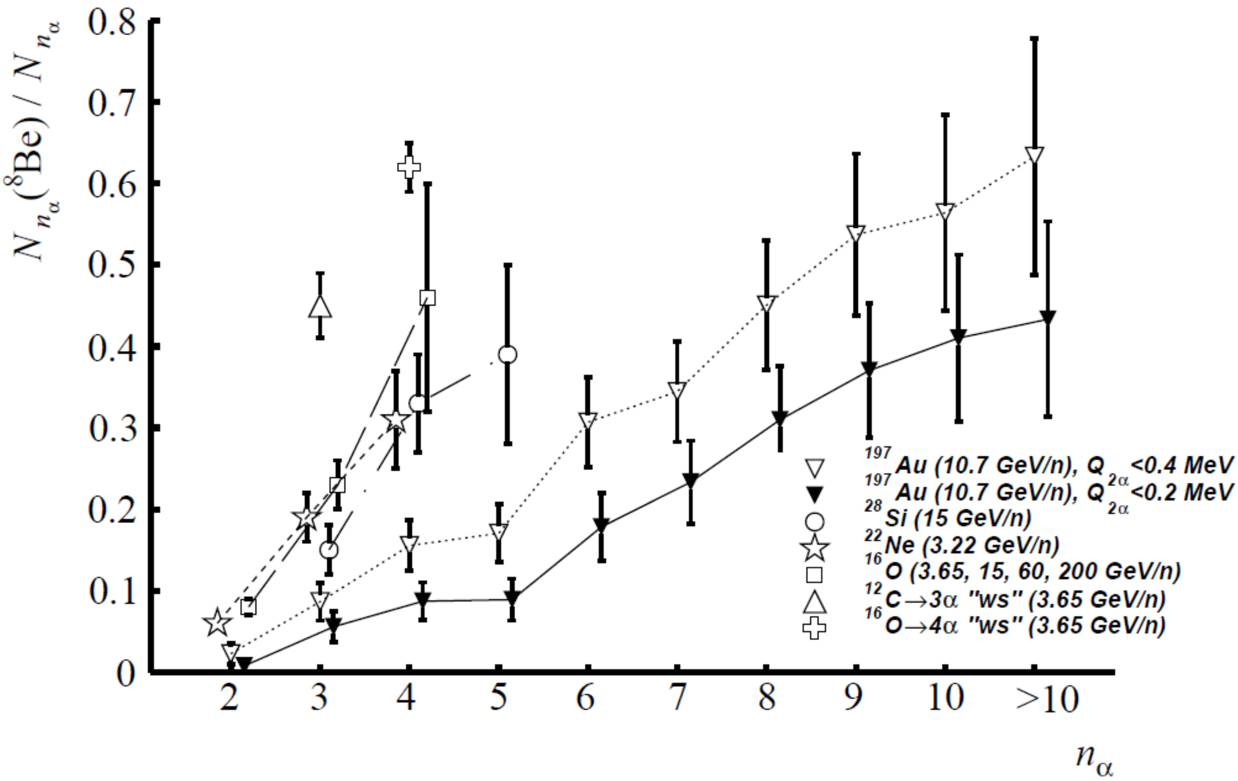


*Fig. 6. Dependence of relative contribution of $N_{n\alpha}(^8Be)$ decays to statistics of $N_{n\alpha}$ events with α-particle multiplicity nα in relativistic fragmentation of C, O, Ne, Si, and Au nuclei [13]; marked "white" stars $^{12}C \rightarrow 3\alpha$ and $^{16}O \rightarrow 4\alpha$ (WS); for convenience, points are slightly shifted from values of $n_\alpha$ and are connected by dotted line.*

Recently, measurements of interactions of $^{16}$O, $^{22}$Ne, $^{28}$Si, and $^{197}$Au nuclei performed by the Emulsion Collaboration at the JINR synchrophasotron and the EMU Collaboration were analyzed in this context (references in [13]). These data make it possible to trace contribution of the unstable states and serve as a reference for an accelerated search for events with a higher multiplicity using the cross-scanning method (Fig. 6).

In particular, $^{197}$Au 10.7 GeV/nucleon data t, where a fraction of events $n_\alpha > 3$ was 16%, indicate that the ratio continues to grow strongly towards $n_\alpha = 10$. Due to the complexity of measurements in the latter case, $Q_{2\alpha}(^8\mathrm{Be}) \leq 0.4$ MeV. $^{197}$Au interactions contain triples $Q_{2\alpha p}(^9\mathrm{B}) \leq 0.5$ MeV and $Q_{3\alpha}(\mathrm{HS}) \leq 0.7$ MeV (Table 1). The ratio of the event numbers $N_{n\alpha}(^9\mathrm{B})$, $N_{n\alpha}(\mathrm{HS})$, and $N_{n\alpha}(2^8\mathrm{Be})$ to $N_{n\alpha}(^8\mathrm{Be})$ does not show a noticeable change with $n_\alpha$, indicating an increase relative to $N_{n\alpha}$. However, small statistics make it possible to characterize only the trend. Summation of the statistics $N_{n\alpha}(^9\mathrm{B})$, $N_{n\alpha}(\mathrm{HS})$, and $N_{n\alpha}(2^8\mathrm{Be})$ over the multiplicity $n_\alpha$ and normalization to the sum $N_{n\alpha}(^8\mathrm{Be})$ leads to relative contributions of 25 ± 4%, 6 ± 2%, and 10 ± 2%, respectively. The $Q_{4\alpha}$ distribution points to near-threshold 4α-quads, in which HS and $2^8$Be decays are reconstructed with the condition $Q_{2\alpha}(^8\mathrm{Be}) \leq 0.2$ MeV, including $Q_{4\alpha}$= 1.0 (16α,HS), 1.9(11α, HS), 2.1(9α , $2^8$Be), 2.2(5α, 28Be), 2.4(9α,HS) MeV. The study of the $^{16}\mathrm{O}(0^+_6)$ problem requires a qualitatively different level of statistics for $n_\alpha$ ensembles.

Dozens of $^8$Be and $^9$B decays have been identified. At the same time, HS decays are single cases, which require increasing the statistics to the modern equivalent of $^8$Be. Then it becomes feasible to search for $^{16}\mathrm{O}(0^+_6)$. There are no fundamental problems along this path, since there are exposed NTE layers, with transverse scanning of which the required statistics of α-ensembles is achievable.

Now the statistics of $n_\alpha$ events is being increased by transverse scanning of NTE layers exposed to $^{84}$Kr nuclei at 950 MeV/nucleon (GSI, early 90s). According to the SRIM program, deceleration at lengths up to 6 cm is approximately uniform and amount to about 9 MeV/mm (total path is about 8 cm). The effect can be taken into account by positions of the vertices when calculating the invariant mass. In addition, deceleration increases fragment emission angles making measurements more convenient. The momentum of the fragments is taken with a factor of 0.8 to roughly account for the reset of the initial value in the interaction. Not being fundamental for the selection of $Q_{2\alpha}(^8\text{Be}) \leq 0.4$ MeV, this correction makes it possible to preserve the position of events in the peak $Q_{3\alpha}(\text{HS} \rightarrow {}^8\text{Be}\alpha)$.

*Table 1. Statistics of events containing at least one $^8$Be, HS, or $^9$B decay candidate or at least two $^8$Be decays under the condition $Q_{2\alpha}(^8\text{Be}) \leq 0.4$ MeV among $^{197}$Au fragmentation events $N_{n\alpha}$ with multiplicity $n_\alpha$; the total statistics of channels $n_\alpha \geq 11$ are italicized.*

| $n_\alpha$ | $N_{n\alpha}(^8\text{Be})/N_{n\alpha}$ (% $N_{n\alpha}$) | $N_{n\alpha}(^9\text{B})$ (% $N_{n\alpha}(^8\text{Be})$) | $N_{n\alpha}(\text{HS})$ (% $N_{n\alpha}(^8\text{Be})$) | $N_{n\alpha}(2^8\text{Be})$ (% $N_{n\alpha}(^8\text{Be})$) |
|---|---|---|---|---|
| 2 | 3/133 (2 ± 1) | - | - | - |
| 3 | 14/162 (9 ± 3) | 1 (7) | - | - |
| 4 | 25/161 (16 ± 4) | 7 (28 ± 12) | 2 (8 ± 6) | - |
| 5 | 23/135 (17 ± 4) | 5 (22 ± 11) | - | 1 (4) |
| 6 | 31/101 (31 ± 7) | 9 (29 ± 11) | 2 (6 ± 4) | - |
| 7 | 31/90 (34 ± 7) | 6 (19 ± 9) | 2 (6 ± 4) | 3 (10 ± 6) |
| 8 | 32/71 (45 ± 10) | 8 (25 ± 10) | 2 (6 ± 4) | 2 (7 ± 5) |
| 9 | 29/54 (54 ± 13) | 9 (31 ± 12) | 3 (10 ± 6) | 5(17 ± 8) |
| 10 | 22/39 (56 ± 15) | 4 (18 ± 10) | - | 5(23 ± 12) |
| 11 | 10/15 (67 ± 27)<br>*19/30 (63 ± 19)* | 3 (30 ± 20)<br>*7 (37 ± 16)* | 1 (10)<br>*2(11 ± 8)* | 2(20 ± 16)<br>*6 (32 ± 15)* |
| 12 | 226 2/5 | 56 1 | 13 - | 22 1 |
| 13 | 2/4 | 1 | - | 1 |
| 14 | 3/3 | 1 | - | 1 |
| 15 | 1/1 | - | - | - |
| 16 | 1/2 | 1 | 1 | 1 |

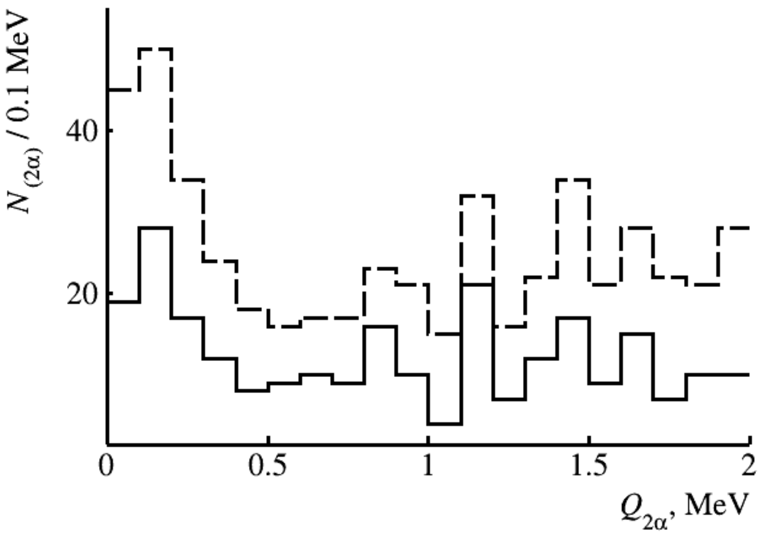


*Fig. 7. Invariant mass distribution of pairs of α-particles $Q_{2\alpha}$ in fragmentation $^{84}$Kr nuclei according to new measurements (solid line) and early data (added by a dotted line).*

Figure 7 shows distribution of 85 events $n_\alpha > 3$ over $Q_{2\alpha}$. Planar angles in this sample were measured directly with a microscope by rotating the layer relative to the primary trace. Being more productive, this method is less accurate than the coordinate method. Nevertheless, it is sufficient to select $Q_{2\alpha}(^8Be) \leq 0.4$ MeV and candidates for more complex decays. In addition, early measurements of 184 interactions $n_\alpha > 3$ of $^{84}$Kr nuclei at 950 - 800 MeV/nucleon are added to the distribution, for which there is no information about the position of the top, assuming an energy of 875 MeV per nucleon. This point is not critical for identifying $Q_{2\alpha}(^8Be) \leq$ 0.4 MeV. The ratios $N_{n\alpha}(^8Be)$ and $N_{n\alpha}$ (%)for both samples are $n_\alpha = 4$ (24 ± 6), 5 (27 ± 6), 6 (53 ± 15), and the sum $n_\alpha > 6$ (64 ± 14). The new sample contains the 2$^8$Be event at $n_\alpha = 6$, isolated in the initial part of the spectrum $Q_{4\alpha}$ at 0.6 MeV.

Thus, the universal effect of an increase in probability of detecting $^8$Be in an event with an increase in the multiplicity of α-particles in it manifests itself for one more nucleus. The presented data are the first contribution to a targeted search for 4αBEC. The 4αBEC problem requires at least a 10-fold increase in statistics, which is realistic using the Olympus BX63 motorized microscope.

For the near future, the BECQUEREL experiment focuses on the analysis of exposure $^{84}$Kr nuclei at 950 MeV per nucleon to study amplification and search for unknown unstable states. Acceleration of accumulation of statistics of events of multiple α-particle fragmentation is provided by transverse scanning of the NTE layers.. The correction for deceleration in the calculation of the invariant mass occurs according to the position of the vertices in order to use the most part of the NTE volume. As a development, it is highly desirable to expose NTE to heaviest nuclei at few GeV per nucleon.

#### 2.1.3 Isobar analog states in the dissociation of light nuclei

The results of studies of relativistic fragmentation of light stable and radioactive isotopes indicate prospects for its development. Dissociation $^9$Be → 2α appeared as an effective source of $^8$Be, and $^{10}$C → 2α2*p* – $^9$B. The discovery of HS decays in the dissociation $^{12}$C → 3α and $^{16}$O → 4α raised a question of their role in the $^{14}$N case. At present, contribution of $^8$Be, $^9$B, and HS to the relativistic fragmentation $^{14}$N → 3α is under the study. The next step will be search for decays of isobar-analogue states (IAS). Despite high excitation energy (13-18 MeV), IAS are distinguished by widths Γ, which are much smaller than those of other excited states. This circumstance is associated with a change in an isospin of an initial state $\Delta T = 1$. It indicates a rearrangement of structure of light nuclei in direction of similarity with their less stable isobars. It can be assumed that in light nuclei they arise as a result of a perturbation of the spin structure in α-like nucleon quartets nnpp with $J = 0$ (Fig. 8).

At present, attention is focused on NTE layers exposed at to 2.0 GeV per nucleon $^{14}$N nuclei at the JINR Nuclotron. Earlier, when tracing tracks of $^{14}$N, the distribution over channels with fragments of approximately charge conservation was established, and the leading one among them was the 3HeH channel. The statistics of events, increased by transverse scanning, gave 25-30% contribution of $^8$Be → 2α decays [4]. The available statistics of $^{10}$B → 2He events at 1 GeV per nucleon makes it possible to compare neighboring odd–odd $^{14}$N and $^{10}$B nuclei, including the $^8$Be and $^9$B contributions.

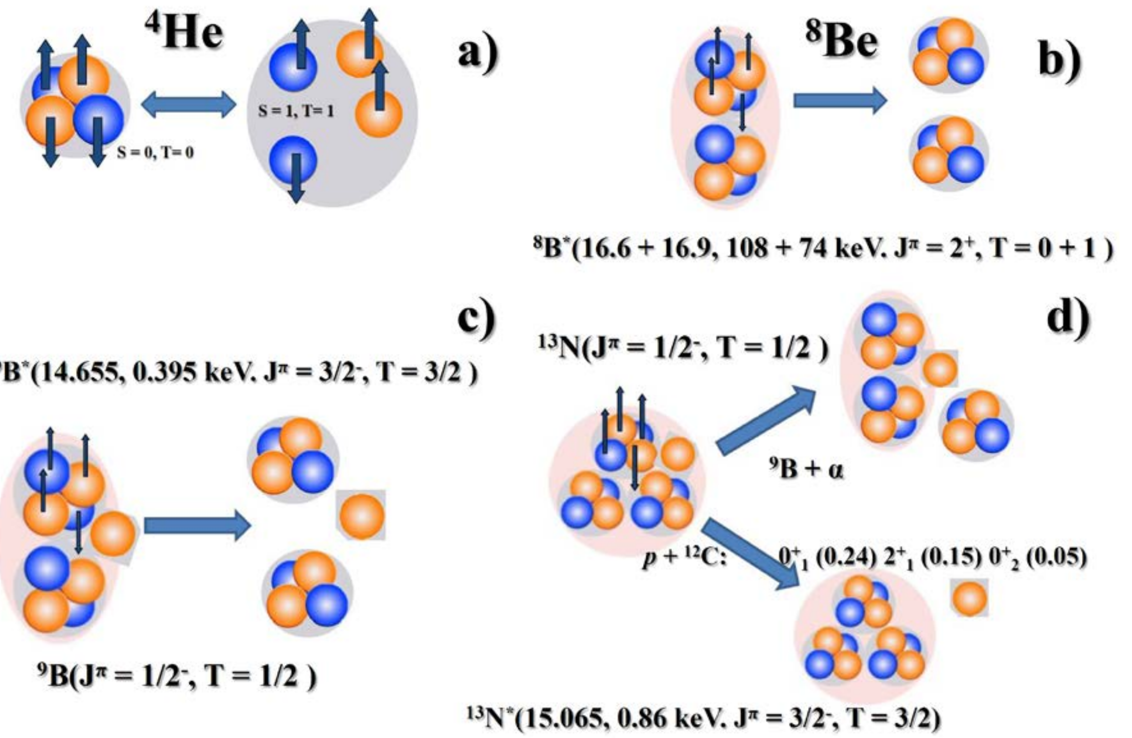


*Fig. 8. Scenario for emergence of IAS in light nuclei based on perturbation of α-particle configuration (a) in $^{8}$Be (b), $^{9}$B (c), and $^{13}$N (d).*

The IAS data in light nuclei make it possible to trace manifestation of the (*hn*-*tp*) configuration starting from $^{8}$Be (Fig. 8b). The excitation spectrum of this nucleus contains a doublet of states $^{8}$Be(16.6), Γ = 108 keV and $^{8}$Be(16.9), Γ = 74 keV, mixed in isospin T = 0 + 1. Located below the threshold $^{7}$Li + *p* (17.255) and decaying into an α-pair, they can serve as candidates for the α + (*hn/tp*) configuration. In addition, there is a $^{8}$Be IAS (17.640) with T = 1 and Γ = 10.7 keV above the threshold of $^{7}$Li + *p* isospin allowed decay. Energy levels of the $^{8}$Be(16.6 + 16.9) doublet are quite far from the nearest excitation $^{8}Be_{4+}$(11.4) with Γ = 3.5 MeV, which allows their joint identification, as described above, in the relativistic fragmentation $^{9}$Be → 2α.

The addition of a proton leads to the configuration α + (*hn/tp*) + *p* (T = 3/2 (Fig. 8c)), which could correspond to IAS $^{9}$B(14.655), which has Γ = 0.395 keV. When studying the coherent dissociation of 2 GeV per nucleon $^{10}$C nuclei, the leading position of the 2He2H channel (82%) was found to be largely due to $^{9}$B decays (30%) (review [11]). A complete coincidence of the decays of the ground states $^{9}$B → $^{8}$Be appeared. Available angular measurements in “white” stars $^{10}$C → 2α2p make it possible to check the presence of $^{9}$B(14.655) decays in them. They are supplemented by measurements of 2α2*p* stars containing target fragments or produced mesons. The statistics are incremented in this case.

The $^{14}$N fragmentation is the simplest source of 3α*p* states. The object of study can be an IAS $^{13}$N$^{*}$(15.065, Γ = 0.86 keV) with isospin T = 3/2 at 5.6 MeV above the $^{9}$Bα threshold (Fig. 8d). Its decay into 3α*p* (T = ½) is isospin suppressed, which determines Γ. The $^{13}$N$^{*}$(15.065) proton decays of populate $^{12}$C excited states. The probabilities of its decay are established into the ground $0^{+}_{1}$ (0.24), 1st excited and the only bound $2^{+}_{1}$ (0.15) and the 2nd excited. Although the NTE resolution does not allow one to identify higher $^{12}$C$^{*}$ excitations among the relativistic fragments, the HS and $^{9}$B decays reconstructed among the 3α*p* quads can serve as convenient signatures of $^{13}$N$^{*}$(15.065). As a signal of the IAS branch, detection of $^{14}$N → $^{13}$N$^{*}$(15.065) would motivate searches for short-lived nuclear-molecular states in fragmentation of neighboring nuclei. Another possibility is to search for the $^{13}$N$^{*}$ (> 20.4 MeV) T = 1 state from the $^{13}$N$^{*}$ → 3α*d* decays, also suppressed by isospin.

Consider $^{13}$N$^{*}$(15.065) in the α-cluster pattern (Fig. 8d). Then the values T = 3/2 and J = 3/2 are possible in the configurations 2α+(*hn*)+*p* and 2α+(*tp*)+*p* involving virtual pairs *hn* or *tp* with spin J = 1, where the $^{3}$He cluster is denoted by *h* (helion). Such a transition is possible upon spin flip of an S-wave nucleon in the 3α*p* ensemble, without overcoming the coupling threshold *hn* and tp (about 20 MeV). The decay of $^{13}$N$^{*}$(15.065) is initiated by the return of a nucleon to the α-cluster, and the released energy is realized through the emission of a proton or α-particle and the excited and ground states $^{12}$C and $^{9}$B, respectively.

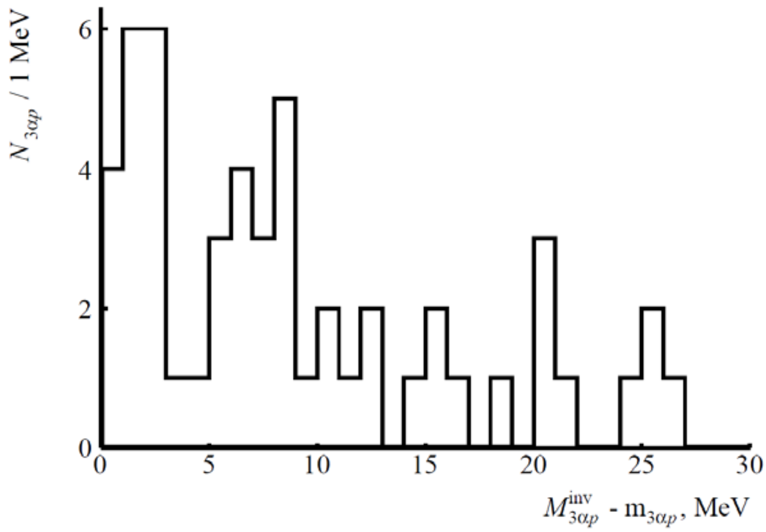


*Fig. 9. Invariant mass distributions $Q_{3\alpha p}$ in 60 events $^{14}N \to 3\alpha p$ at 2 GeV per nucleon.*

Fig. 9 represents the current state of the ongoing analysis, indicating IAS in the range of 5-9 MeV, which is satisfactory in this approach. Thus, the bound α-particle appears as an elastically deformable object underlying a whole family of sufficiently long-lived states. Its relaxation to the S-state determines the final states of IAS decays. In the direction of testing this hypothesis, the analysis of exposures to $^{9}$Be, $^{14}$N, $^{22}$Ne, $^{24}$Mg, and $^{28}$Si nuclei will be continued

### 2.1.4 Future challenges

The results obtained allow one to assess a more distant perspective. Among the most important of them is verification of theoretical ideas about the matter that arises as a result of the combination of nucleons into clusters that do not have excited states up to the bond threshold – α, *t, h, d* [15]. Evolution of the lightest isotope composition at a nuclear density less than normal and temperature of several MeV is predicted (Fig. 10). Passage through such a phase may be necessary for the synthesis of heavy nuclei. A look at dissociation of relativistic nuclei with time reversal indirectly indicates feasibility of such a transition (Fig. 11).

In a reference frame of a parent nucleus, energy distribution of lightest fragments covers the temperature range $10^{8}$–$10^{10}$ K, corresponding to phases from red giants to supernova. In the dissociation of heavy nuclei, an unprecedented variety of coherent ensembles of lightest nuclei and nucleons is available. Observations of the unstable states discussed here substantiate the possibility of studying cluster matter down to the lowest nuclear temperature and density.

Identification of the $^{1,2,3}H$ and $^{3,4}He$ isotopes by the multiple scattering method makes it possible to expand the analysis in direction of isotopic properties. Transverse momenta of fragments are determined from emission angles, which make it possible to isolate temperature components.

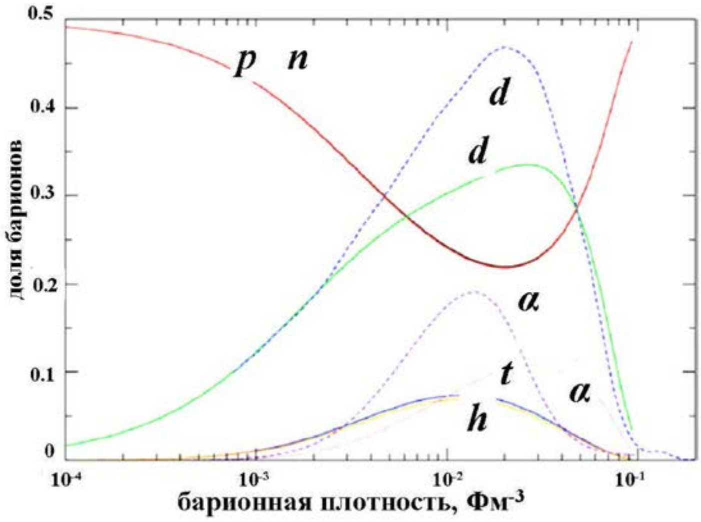


*Fig. 10. Ratio of fractions of nucleons and lightest nuclei over baryon density of symmetric nuclear matter (from the report of G. Röpke).*

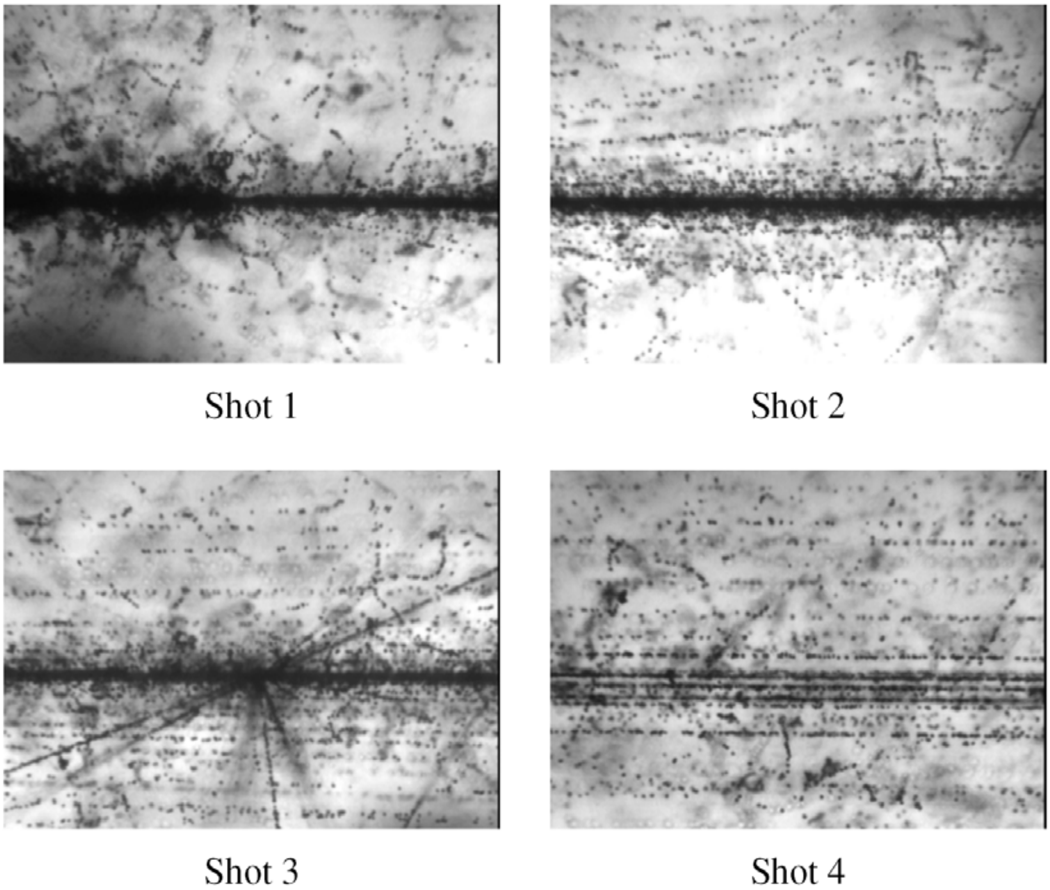


*Fig. 11. Sequentially photographed event of peripheral interaction of 10 GeV per nucleon $^{194}Au$ nucleus: primary nucleus track and interaction vertex (frame 1); shower shaft with emerging tracks of singly and doubly charged particles (frame 2); shower core with secondary star (frame 3); fully resolved core (frame 4 at 3 cm from vertex).*

In relativistic dissociation of heavy nuclei, formation of light fragments with a larger charge-to-mass number ratio than that of a primary nucleus occurs, causing appearance of associated neutrons that manifest themselves in secondary stars. A frequency of such "neutron" stars should increase with increase in number of lightest nuclei in fragmentation cone. An average range of neutrons in NTE is about 32 cm. Reaching tens, multiplicity of neutrons in an event can be estimated from a proportional decrease in the average range until formation of "neutron" stars at lengths of the order of several centimeters. An accuracy of determining coordinates of their vertices makes it possible to reconstruct neutron emission angles, and, hence, transverse momenta in approximation of maintaining an initial velocity. Thus, it is possible to study effects of neutron "fur coat". An estimate of a yield of neutrons, as well as deuterons and tritons that bind neutrons, can be of practical importance.

It remains unclear why peripheral dissociation of nuclei corresponds to a sufficiently large cross section and a wide distribution over a multiplicity of fragments. This phenomenon may be based on transition of virtual photons into pairs of virtual mesons which are exchanged between beam and target nuclei. A critical test can be fragmentation of nuclei of the NTE composition under an action of relativistic muons [38–40]. The combination shown in Fig. 12 provides long-range interaction with effective destruction of nuclei and can be extended to peripheral interactions of relativistic nuclei. It has been established that fragmentation of target nuclei under the action of muons is most probable for the breakup $^{12}C \rightarrow 3\alpha$. In these events, α-particle energy and emission angles are determined from ranges, making it possible to obtain distributions over invariant masses, as well as over a total momentum of pairs and triplets of α-particles. It has been preliminary established that distribution of α-triples over a total transverse momentum corresponds not to electromagnetic, but to 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.

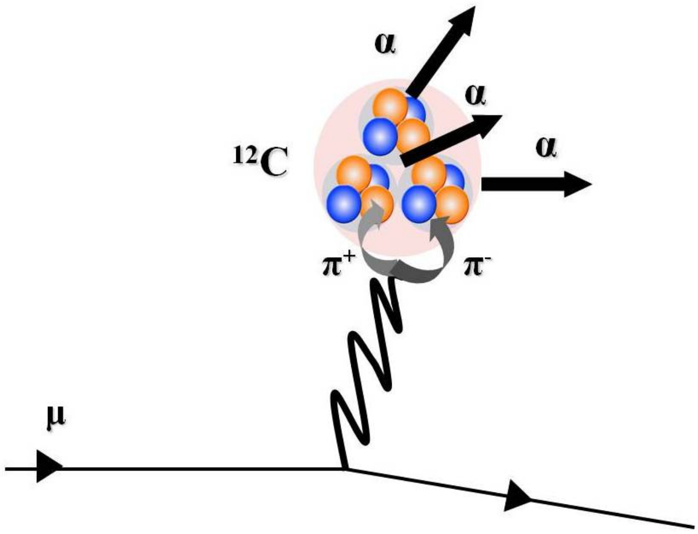


*Fig. 12. Diagram of breakup of $^{12}C$ nucleus into three α-particles by relativistic muon.*

### 2.1.5 Upgrading microscopes and NTE technology

The project aims to intensify application of a proven approach based on automation of measurements provided by state-of-the-art microscopes. However, such microscopes are quite expensive and should be tools of intensive collective use. According to a request supported by the PAC for NP, at the end of 2021, delivery of the motorized microscope Olympus BX63 for the BECQUEREL experiment took place. Thus, prerequisites arise for accelerating proven procedures for searching for and measuring interactions in NTE. Mastering work on a microscope by young participants of the BECQUEREL project becomes a key practical task. In addition to increasing productivity, remote control and analysis is feasible on this microscope, which allowing involving experts in nuclear physics and programming in the project.

The motorized microscope makes it possible to export data and images to collaborating institutes and universities. It can be used for beam diagnostics by the methods NTE and solid-state track detectors, as well as for solving applied problems. Mastering the capabilities of this microscope will allow one to move on to solving problems of automatic search with recognition of characteristic images.

A main practical difficulty, which has already been largely overcome, is that production of NE layers, which had been carried out in Moscow for four decades, was interrupted in the mid-2000s. Thus, the NTE history of seemed to be completed. However, in response to a request from the BECQUEREL experiment, the Slavich Company (Pereslavl-Zalessky) resumed production of NTE layers 50 to 200 μm thick on a glass base in 2012. NTE samples were used in experiments in which there was a whole variety of ionization traces, from slow heavy ions to relativistic particles. At present, production of 500 μm thick NTE layers without a substrate is being restored.

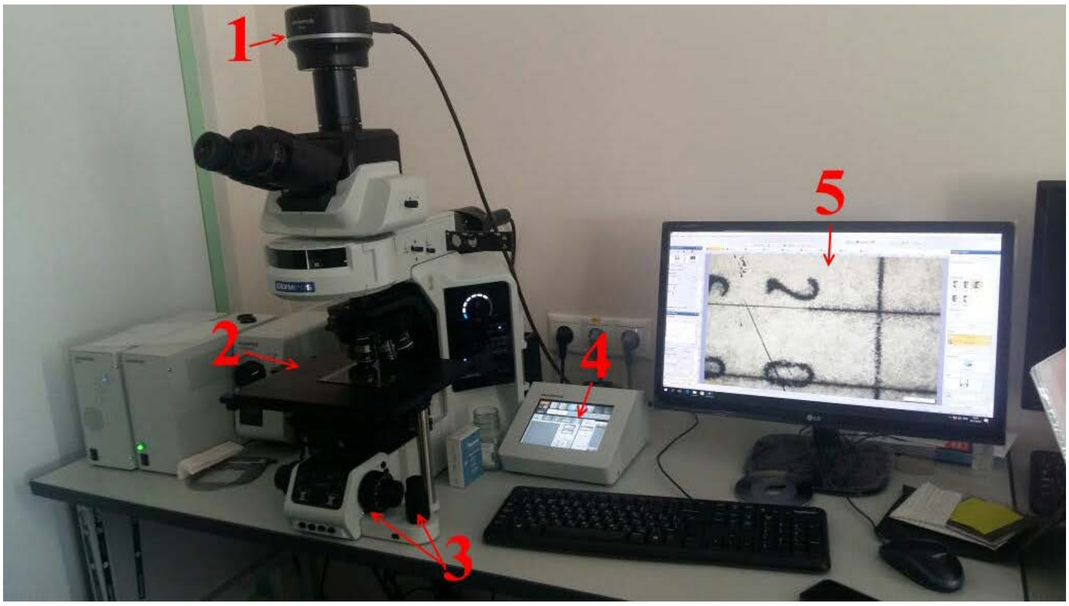


*Fig. 12. Photograph of BX63 microscope. The following are noted: 1) digital camera DP74, 2) motorized object stage, 3) joysticks for controlling focus and movement of the object stage in the XOY plane, 4) microscope control unit, 5) PC for working with resulting image.*

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

This whole complex of problems is the focus of the BECQUEREL experiment at the present time. It is to be hoped that rapid advances in image analysis will make it possible to give an entirely new dimension to the NTE use of the nuclear structure study in the relativistic approach. 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.

## 2.2 References


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## 2.3 Expected results and their significance

The recent achievements of the BECQUEREL experiment and the preserved microscopic and chemical-technological basis give grounds to expect the following physical and methodological results in the perspective of about three years:

The BECQUEREL experiment focuses on fragmentation of $^{84}$Kr nuclei at energy of up to 950 MeV per nucleon to study dynamics of occurrence of the $^{8}$Be nucleus and the Hoyle state and search for the α-particle condensate decaying through them. A basis for the conclusions will be the statistics of about 1000 measured events with more than three relativistic α-particles. A motorized microscope Olympus BX63 will be used, development of capabilities of which will be a special methodological challenge.

An answer will be obtained to a question about a universal nature of formation of the Hoyle state in dissociation of $^{14}$N and $^{28}$Si nuclei. Possibility of the occurrence of isobar-analogue states in fragmentation of light nuclei will be investigated.

### 2.4. Accelerator time request

The NTE method, which combines unique information content with remarkable flexibility of application, does not require significant expenditures of accelerating time. A typical duration of tuning a beam output to a NTE stack is hours, and irradiation time is minutes. The choice of nuclei will be made by accelerator specialists and priority experiments.

### 2.5. Definition of responsibility

JINR's contribution/responsibilities: Development of a physics program, implementation of irradiations and analysis of experimental data are to a large extent carried out by the VBLHEP staff. The BECQUEREL experiment relies on its own ability to develop NTE and their analysis on microscopes. According to a project budget, NTE layers of nuclear power will be purchased, microscopes and equipment of the chemical laboratory will be updated. This will provide a basis for attracting external participants.

### 2.6. Scientific experience of the authors

A proven methodology is applied, application of which is a logical development of the approximately 20-year research on the BECQUEREL project at JINR, and significantly earlier work. On of the project subject, under the guidance of P.I. Zarubin, six candidate dissertations were defended, and he himself defended his doctoral dissertation. It is planned that the next results of the project will be included in two candidate dissertations. There is a prospect of defending doctoral dissertations. Data analysis is directly coordinated by three PhDs. Three experienced laboratory assistants-microscopists participate in the statistics accumulation. Microscopes are maintained in working condition by a qualified technician. A group of chemists (3 people) retains internationally recognized NTE development experience.

## 2.7. Publications, dissertations and presentations at conferences

### 2.7.1 Publications of team members over the past 5 years


1. A.A. Zatsev *et al.* “Dissociation of Relativistic $^{10}$B Nuclei in nuclear track emulsion” Phys. Part. Nucl. **48** 960(2017).
2. 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.
3. 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).
4. 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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11. 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).
12. D.A. Artemenkov *et al.* “Nuclear track emulsion in search for the Hoyle-state in dissociation of relativistic $^{12}$C nuclei” Radiation Measurements **119** 199(2018); arXiv:1812.09096.
13. A.A. Zaitsev and P.I. Zarubin “Application of nuclear track emulsion in search for the Hoyle state in dissociation of relativistic $^{12}$C nuclei” Phys. At. Nucl. **81**, 1237(2018).
14. D.A. Artemenkov *et al.* ”The Hoyle State in Relativistic $^{12}$C Dissociation” Springer Proc. Phys. **238**, 137 (2020).
15. A.A. Zaitsev, P.I. Zarubin “The Hoyle State in the Relativistic Dissociation of Light Nuclei” Phys. Atom. Nucl., **82**, 1225 (2020).
16. D.A. Artemenkov *et al.* “Unstable states in dissociation of relativistic nuclei: Recent findings and prospects of research” Eur. Phys. J. A **56** 250 (2020); arXiv: 2004.10277.
17. E. Mitsova *et al.* “Search for decays of the $^{9}$B nucleus and Hoyle state in $^{14}$N nucleus dissociation”; arXiv: 2011.06265.
18. A.A. Zaitsev *et al.*, “Correlation in formation of $^{8}$Be nuclei and α-particles in fragmentation of relativistic nuclei” Phys. Lett. B 820 136460 (2021); arXiv: 2102.09541.
19. N.G. Peresadko, A.A. Zaitsev, P.I. Zarubin “Enhanced production of $^{8}$Be nuclei in relativistic nuclei fragmentation” To be published in PoS (PANIC2021); arXiv: 2111.07678.
20. E. Mitsova *et al.*,”Search for Decays of the $^{9}$B Nucleus and Hoyle State in $^{14}$N Nucleus Dissociation” Phys. Part. Nucl, **53**, 456 (2022); arXiv:2011.06265.

### 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 presentations 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 | 14.0 |
| | | | |

## 4. 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 NIC project. There are no particular technical and radiation safety issues.

Form No.26

Proposed timetable and necessary resources for the implementation of the project “The BECQUEREL2022 project”

| Expenditures, resources, financing sources | | | Cost (k$) Resource requirements | | Proposal of the Laboratory on distribution of finances and resources | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | 2023 | | 2024 | | 2025 | |
| | | | Theme 1087 | | Theme 1087 | | Theme 1087 | | Theme 1087 | |
| Expenditure | Main units of equipment, work towards its updating, adjustment, microscope BX53etc. | | 55 | | 45 | | 5 | | 5 | |
| | Construction /repair of premises | | - | | - | | - | | - | |
| | Materials | | 30 | | 10 | | 10 | | 10 | |
| Required resources | Standart hour | LHEP design bureau | - | | - | | - | | - | |
| | | JINR Workshop | - | | - | | - | | - | |
| | | LHEP Workshop | - | | - | | - | | - | |
| | | Nuclotron | - | - | - | - | - | - | - | - |
| Σ | | | 5 | - | 55 | - | 15 | - | 15 | - |
| Total: | | | 5 | | 55 | | 15 | | 15 | |
| Financing sources | | Budget. Theme 1087 | 5 | | 55 | | 15 | | 15 | |

Theme 1087 - LHEP

Project leader P.I. Zarubin

Form No. 29

**Estimated expenditures for the Project** "Study of Multiple Fragmentation of Relativistic Nuclei in Nuclear Track Emulsion (The BECQUEREL2022 Project)"

(full title of Project)

| Expenditure items | Full cost | 2023 y. | 2024 y. | 2025 y. |
|---|---|---|---|---|
| Direct expenses for the Project | | | | |
| 1. Accelerator, reactor | 150 h | 50 | 50 | 50 |
| 2. Computers | h | | | |
| 3. Computer connection | k$ | | | |
| 4. Design bureau | standard hour | | | |
| 5. Experimental Workshop | standard hour | | | |
| 6. Materials | 30 k$ | 10 | 10 | 10 |
| 7. Equipment (microscope BX53) | 55 k$ | 45 | 5 | 5 |
| 8. Construction/repair of premises | k$ | | | |
| 9. Payments for agreement-based research | 60 k$ | 20 | 20 | 20 |
| 10. Travel allowance, including: | 120 k$ | 40 | 40 | 40 |
| a) non-rouble zone countries | 60 | 20 | 20 | 20 |
| b) rouble zone countries | 60 | 20 | 20 | 20 |
| c) protocol-based | | | | |
| Total direct expenses | 265 k$ | 115 | 75 | 75 |

Theme 1087 – VBLHEP

PROJECT LEADER P.Zarubin P.I. Zarubin

LABORATORY DIRECTOR R. Lednicky

LABORATORY CHIEF ENGINEER-ECONOMIST L.M. Nozdrina

## 7.1. Review by A.G. Litvinenko

**Project review**
**"The BECQUEREL experiment at the NUCLOTRON/NICA accelerator complex"**

The project is aimed at studying interactions of light nuclei at low energies and possible manifestation of the α-particle Bose-Einstein condensate in relativistic fragmentation of heavy nuclei. Particular attention is to the clarifying a role of nuclear clusters (α-particles) in these reactions. The nucleus, as a many-particle system, has a wide range of excitations, including not only single-particle excitations (nucleon), but also the collective ones. To understand the course of nuclear reactions, singularities in the continuous spectrum, including nuclear resonances and nuclear clusters, play an essential role. Ideas about the structure and properties of these states (energy, width for nuclear resonances) and a probability of their formation (sometimes as an intermediate state) are important for understanding the synthesis of nuclei in the Universe.

Let us dwell on correspondence of the research method to the tasks being solved. The project studies fragmentation products of relativistic nuclei in the region of spectators, in other words, in the small angle region, where dissociation products have a momentum per nucleon close to a momentum per nucleon in a projectile nucleus. The nuclear emulsion method is used as a basic detector. In the fragmentation region of a projectile nucleus, the characteristic angles θ are determined by the ratio of the Fermi momentum for a nucleon ($p_F \sim$ 0.2 GeV) to the momentum per nucleon in the projectile nucleus ($p_b \sim$ 4.5 per nucleon). This gives the spectator protons expansion angles $\theta_p \leq$ 0.04 rad. According to A. S. Goldhaber, Phys. Lett. B 53, 306 (1974) for nuclear fragments, the angular distributions are narrower than for protons. So for the α-particles produced during carbon fragmentation $\theta_\alpha \leq$ 0.01 rad. Without going into details, it should be noted that the assumption of conserving the momentum per nucleon used in calculating the effective mass is more accurate for α-particles than for protons. This is also one of the consequences of the work cited above.

Another feature of studies with nuclear emulsion is an opportunity of observing tracks of several nuclei in the fragmentation cone. It opens opportunities for correlation studies. Under such conditions, the relative angles between the fragments are an order of magnitude smaller than those indicated above. It is difficult to imagine an electronic experiment with such a high spatial resolution as in the emulsion and, what is related, with an angular resolution. The search for possible manifestations of α condensate makes such studies interesting and useful. It is hard to hope that the project will provide comprehensive answers about the properties of this condensate, but these studies are not only interesting as a exploratory experiment, but also necessary for a deeper understanding of the properties of hadronic matter.

I think that the project should be supported. This is justified not only by the above arguments, but also by a large number of publications based on the results of previous studies in peer-refereed journals. Only in the previous 5 years, 19 papers were published. Since 2008 till the present moment, 6 candidate and doctoral dissertations have been defended on the project subject. The project is important for young researchers to master the concepts and methods of relativistic nuclear physics.

The significance of the study is in line with the resources requested. There is research material for the proposed period, and the prospect of obtaining new material on more beams of heavy nuclei at higher energies. Recently, a motorized microscope has been obtained, which makes it possible to count on a sharp increase and completeness of the analysis. Information about this experiment is fully presented on the site.

/10.02.2022/

A.G. Litvinenko
Head of Sector VBLHEP JINR, Ph.D.

**7.2. Review by Yu.N. Uzikov**

## Review report on "The BECQUEREL-2022 experiment at the NUCLOTRON/NICA accelerator complex"

The BECQUEREL experiment is dedicated to the use of relativistic nucleus beams to study nuclear clustering phenomena. The alpha clustering of many nuclei affects nuclear level spectra, nuclear reaction dynamics and characteristics, and in recent years has been actively studied theoretically in microscopic *ab initio* approaches based on first principles (D. Lee, Front. Phys. 2020; doi: 10.3389/fphy. 2020.00174). Information about nuclear clustering is important both for understanding many phenomena in nuclear astrophysics and for practical applications in nuclear medicine and other areas related to the use of nuclear technologies.

Traditional methods of experimental study of the cluster structure of nuclei – cluster transfer reactions, photo-disintegration of nuclei, knocking out of clusters by protons, electrons, and other probes despite their detailed development and wide application, do not cover all possible aspects of multiple cluster phenomena. The method of studying the fragmentation of relativistic nuclei in nuclear emulsions used in the BECQUEREL experiment in combination with the use of a computerized microscope has important advantages and can make a significant contribution to these studies. At the previous stages of this experiment, the contribution of the unstable $^{8}$Be and $^{9}$B nuclei and the Hoyle state of the $^{12}$C nucleus to the processes of dissociation of a number of light nuclei, including radioactive ones, was identified by the invariant mass method. The approach was later extended to the fragmentation of medium and heavy nuclei.

The current stage of the project is focused on studying the predictions of the well-known in the literature concept of the alpha-particle Bose-Einstein condensate (H. Tohsaki et al. Rev. Mod. Phys. 89 (2017) 01100), the simplest manifestations of which are assumed to be the $^{8}$Be nucleus and the Hoyle state. The experiment is aimed at studying the increase in the yield of $^{8}$Be nuclei and the Hoyle state found in e fragmentation of heavy nuclei, as well as at searching for a 4-alpha analogue of the Hoyle state. To solve this problem, there are necessary prerequisites - nuclear emulsions exposed to krypton nuclei and a high-performance microscope.

Within the framework of the project, it is planned to expose nuclear emulsions with heavier nuclei and to study in detail the isotopic composition of fragmentation of heavy nuclei. The study of the fragmentation of light nuclei will also be continued in order to search for highly excited nuclear-molecular formations in decays of isobar-analogue states. It is planned to expose to relativistic muons. The results expected in this case can be applied in nuclear geology and radiobiology.

In general, the study of the phenomenon of the formation of multiple states in the dissociation of relativistic nuclei in nuclear emulsions is currently an alternative to traditional research by methods of low-energy cluster physics. The scientific significance of the project is high. The first results of the project are published in peer-reviewed publications. The requested resources correspond to the objectives of the project. The attention of the authors is drawn to the progress in the microscopic description of Hoyle's condition and the importance of close collaboration with theorists. The stylistic shortcomings of the text are noted. In general, the project deserves support.

Yu.N. Uzikov,
Leading Researcher, DSc

## 7.3. Review by V. A. Nikitin

**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

## 7.4. Review by S. N. Ershov

### 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 ($0^{+}_{6}$) → $^{12}$C ($0^{+}_{2}$) → $^{8}$Be ($0^{+}_{2}$) → 2α 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

### 7.5. Letter of support by J. Natowits

**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
TEXAS A & M UNIVERSITY

### 7.6. Decision of the STC Laboratory

**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

**Programme Advisory Committee for Nuclear Physics**

**53rd meeting, 22 January 2021**

## Recommendations

### V. New project: "BECQUEREL"

The PAC heard a report on the BECQUEREL project presented by P. Zarubin. The project is aimed at studying the dissociation of relativistic nuclei by means of nuclear track emulsion (NTE). The fragmentation of nuclei into stable and radioactive isotopes was studied in the experiment at the Nuclotron. Various isotopes and multiple direct decays were observed and associated with the ensemble of light nuclear fragments and interpreted as the decay of Hoyle states. Education of young scientists is an important part of the project. The finalized data analysis allowed several young researchers to defend their PhD theses. The realization of the plans for data processing automation is expected to result in a significant increase in the statistics. However, since the last presentation, no many new results were shown and only one new publication appeared. The report is also lacking a clear identification of the flagship experiment.

Recommendation. The PAC recognized the uniqueness of the NTE technique for the measurements of charged particles at relativistic energies, however, in comparison with other techniques is seen to be less competitive. Therefore, the BECQUEREL project is ranked by the Committee in category "C".