SCIENTIFIC AND TECHNICAL REASONING FOR THE RENEWAL OF PROJECT IN RESEARCH AREA WITHIN THE TOPICAL PLAN FOR JINR RESEARCH

1. General information on the project

1.1. Project code 02-1-1087-2009

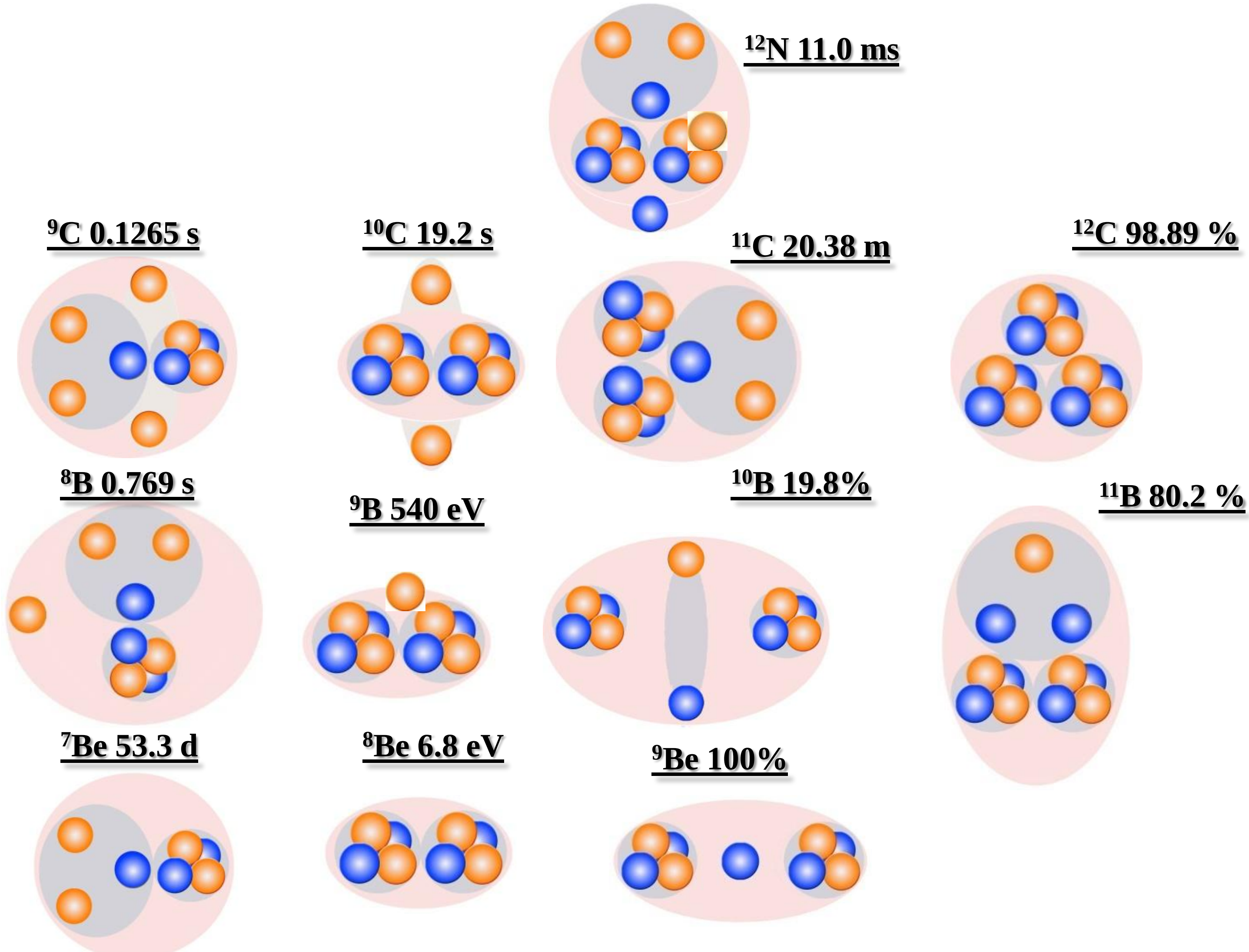
1.2. Veksler and Baldin Laboratory of High Energy Physics

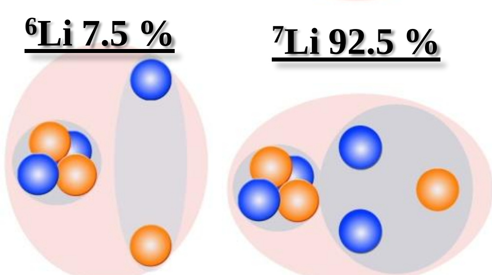
1.3. Scientific field "Physics of elementary particles and relativistic nuclear physics (02)"

1.4. The name of the Project "Experiment BECQUEREL2023 at the NUCLOTRON/NICA accelerator complex"

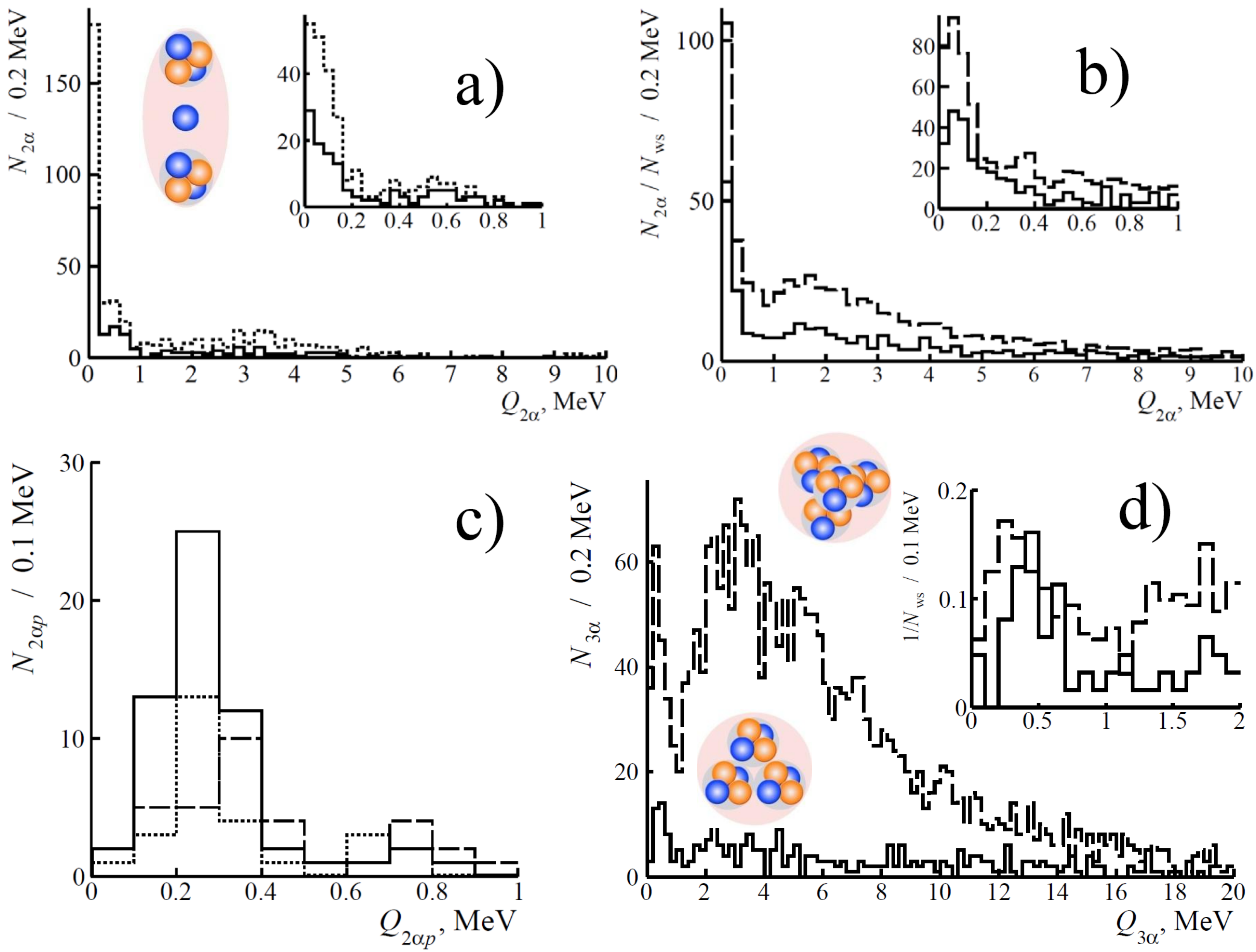
1.5. Project Leader Zarubin P.I.

1.6. Project Deputy Leader Zaitsev A.A.

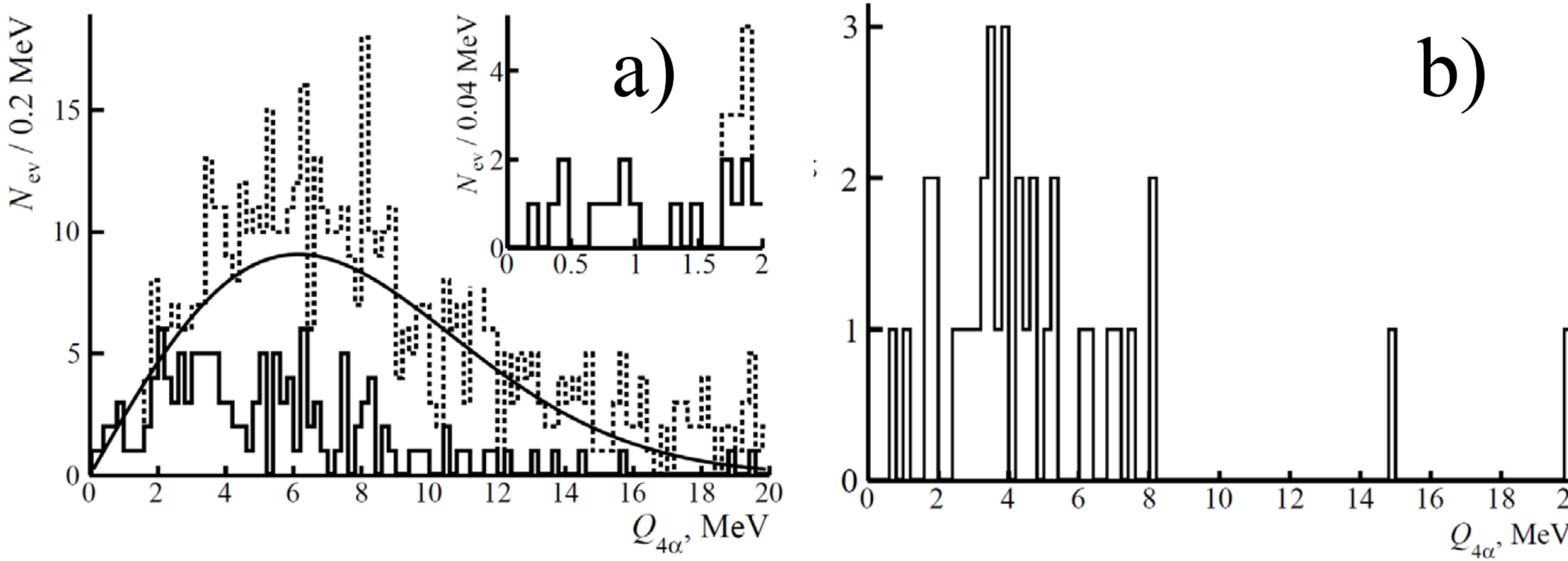




The BECQUEREL experiment is aimed at solving topical problems in nuclear clustering physics. The used method of nuclear track emulsion (NTE) makes it possible, due to its unique sensitivity and spatial resolution, to study in a unified approach multiple final states arising in dissociation of relativistic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

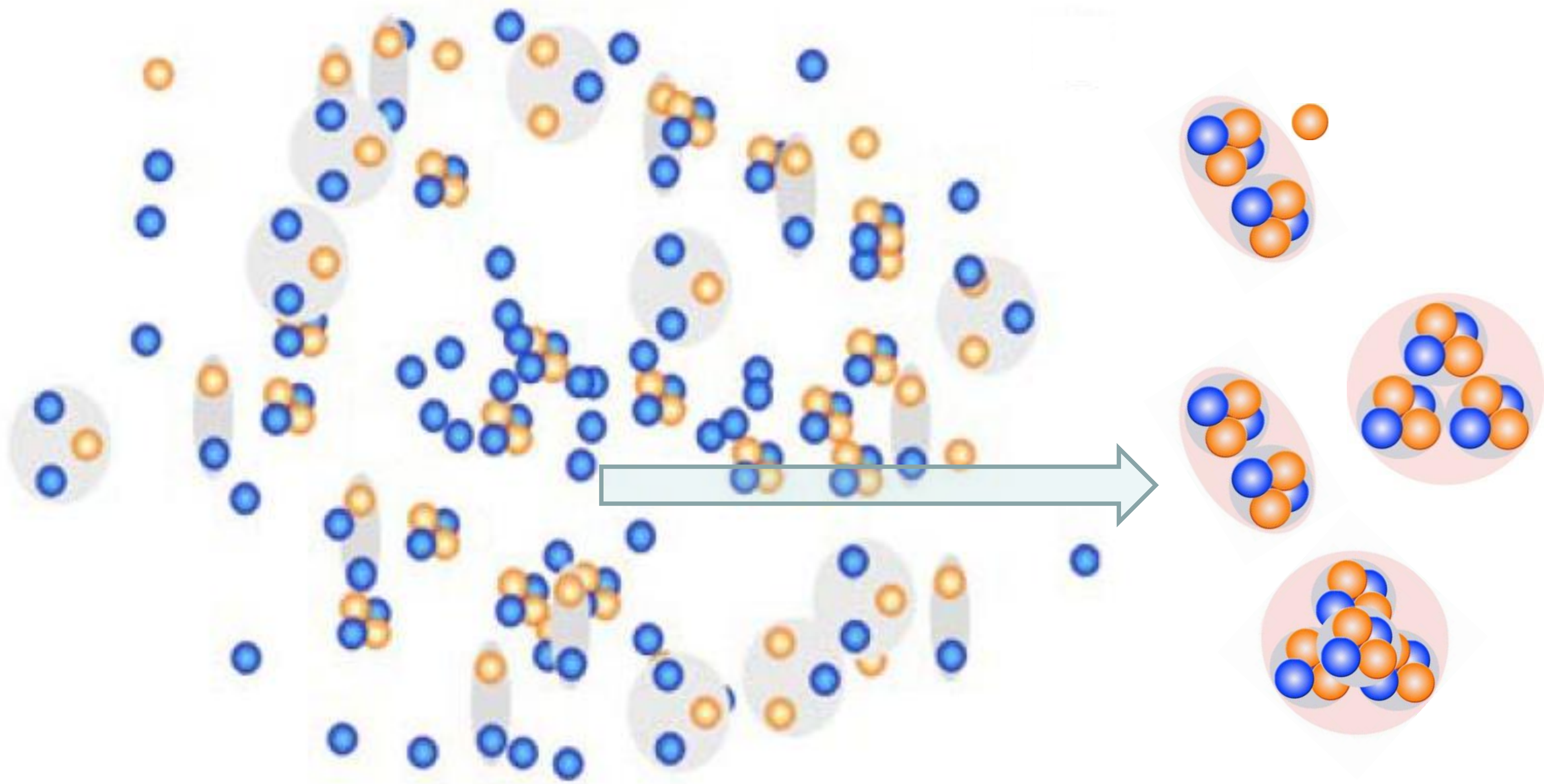


Invariant mass distributions: a) $Q_{2\alpha}$ in ^{9}Be(1.2 *A* GeV) → 2α (dotted line, solid line – "white" stars; b) $Q_{2\alpha}$ in ^{12}C(3.65 *A* GeV) → 3α (solid line) and ^{16}O(3.65 *A* GeV) → 4α (dotted line); c) $Q_{2\alpha p}$ (< 1 MeV) in ^{10}C(1.2 *A* GeV) → 2α2*p* (solid line) and ^{11}C(1.2 *A* GeV) → 2α2*p* (dots) and ^{10}B(1 *A* GeV) → 2α*p* (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).



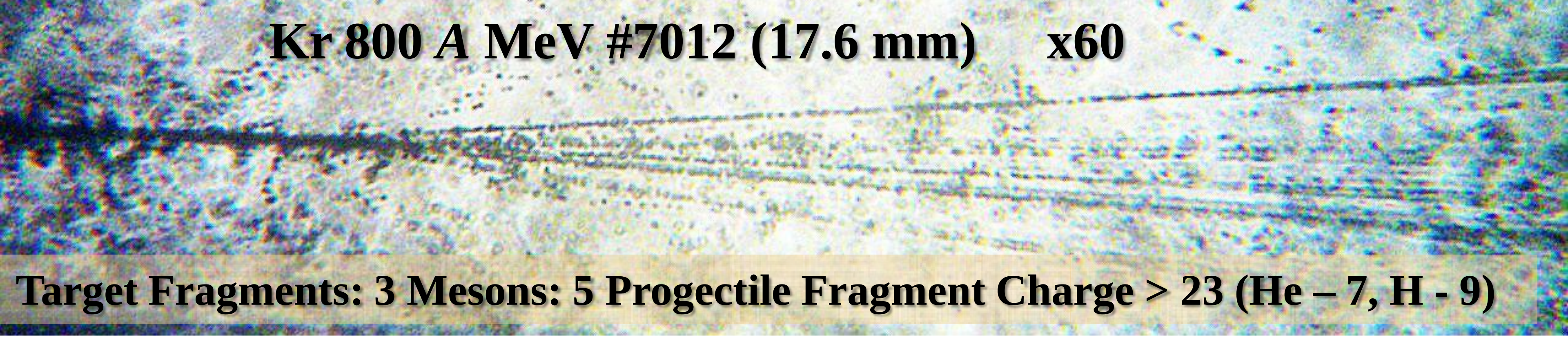
Invariant mass distributions $Q_{4\alpha}$ in 641 "white" stars $^{16}O \rightarrow 4\alpha$ at 3.65 *A* GeV of all 4α-quartets (a, dots). events αHS (a, solid) and $^{16}O \rightarrow 2^8Be$ (b); smooth line - Rayleigh distribution; the inset shows an enlarged part of $Q_{3\alpha}$ < 2 MeV.

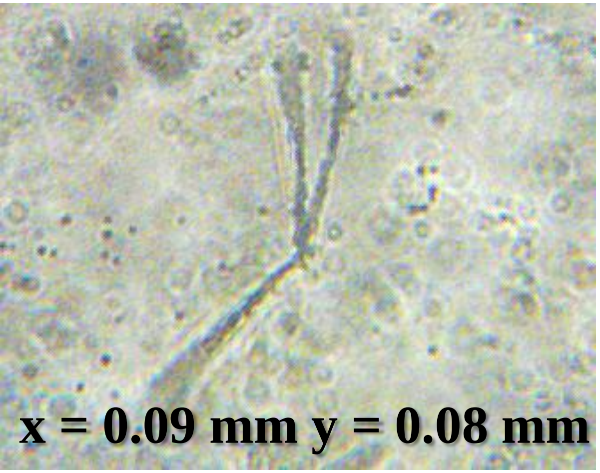
Currently, a research focus is on the theoretical concept of α-particle Bose-Einstein condensate (αBEC) - the ultra cold state of several S-wave α-particles near coupling thresholds. The unstable ^8Be nucleus is described as 2αBEC, and the $^{12}C(0^+_2)$ excitation or Hoyle state (HS) as 3αBEC. Decays $^8Be \rightarrow 2\alpha$ and $^{12}C(0^+_2) \rightarrow {}^8Be\alpha$ 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 $^{16}O(0^+_6) \rightarrow \alpha^{12}C(0^+_2)$ or $^{16}O(0^+_6) \rightarrow 2^8Be(0^+)$. Its search is being carried out in several low energy experiments on fragmentation of light nuclei. 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.

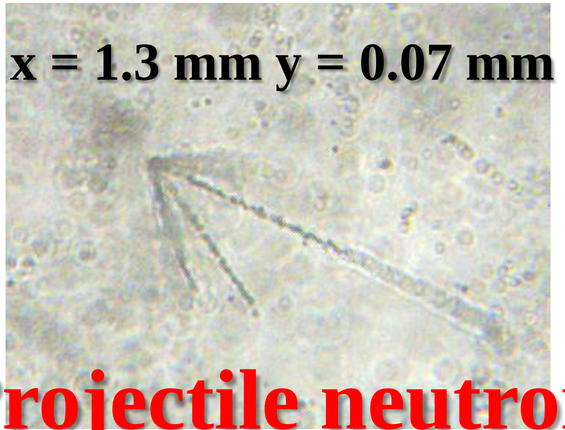


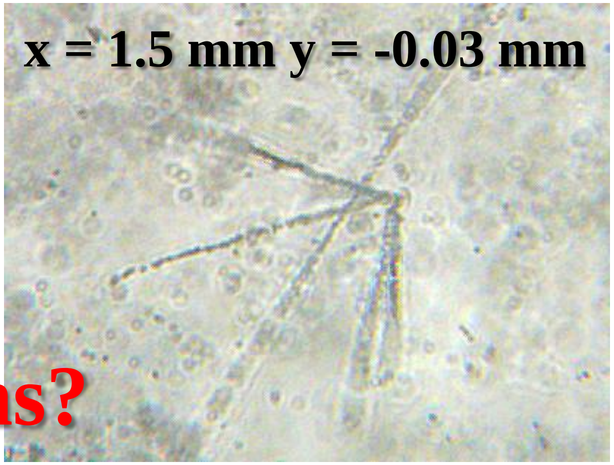
Having been tested, this approach has been used to identify ^{8}Be and HS and search for more complex states of αBEC in fragmentation of medium and heavy nuclei. Recently, based on the statistics of dozens of ^{8}Be decays, an enhancement in probability of detecting ^{8}Be in an event with an increase in 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.

Kr 800 *A* MeV #7012 (17.6 mm) x60

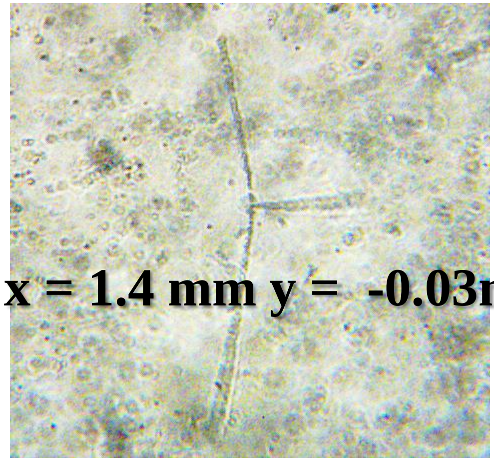


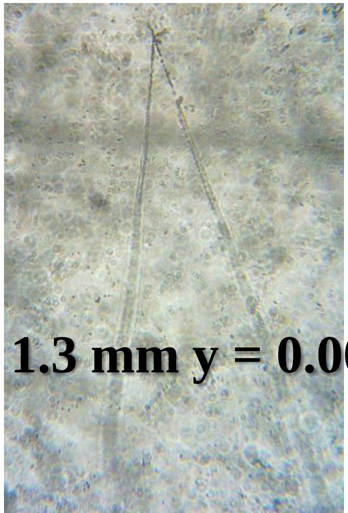


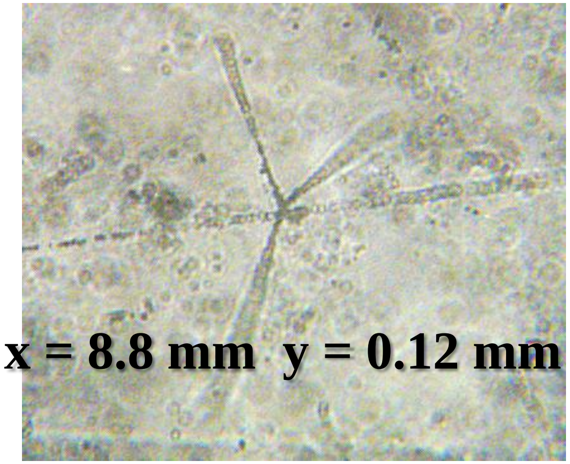


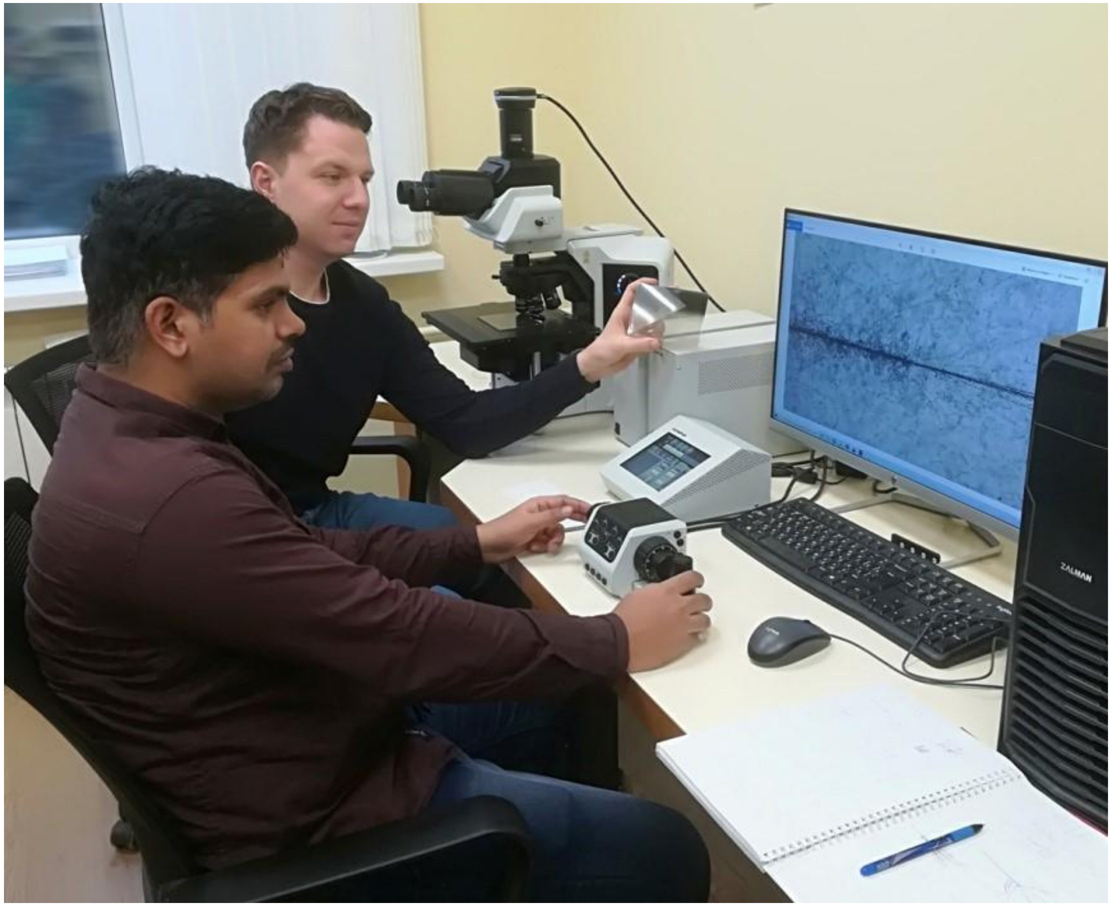


Projectile neutrons?



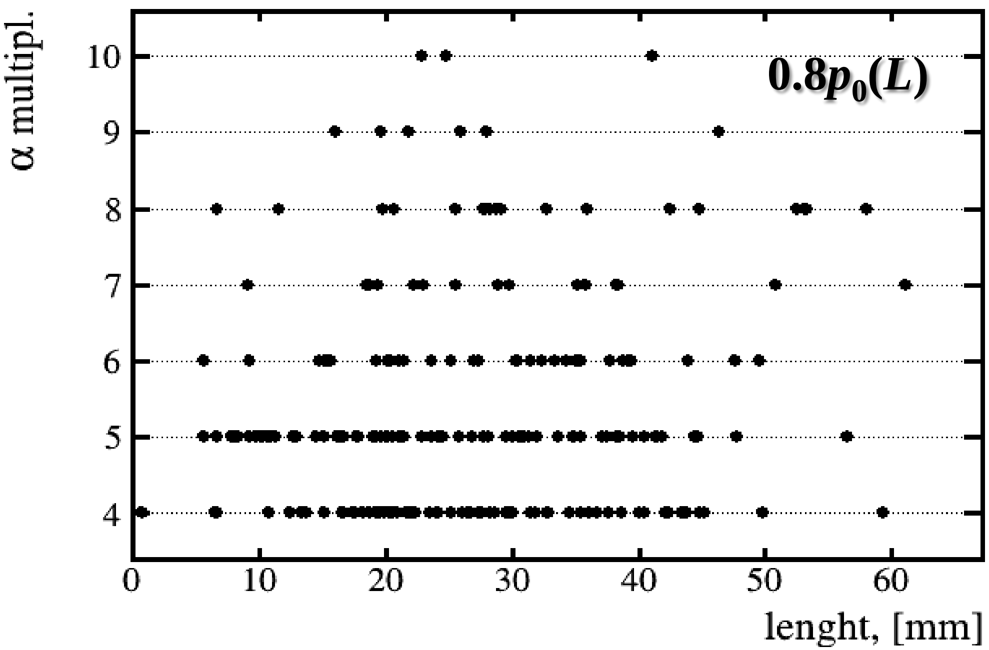


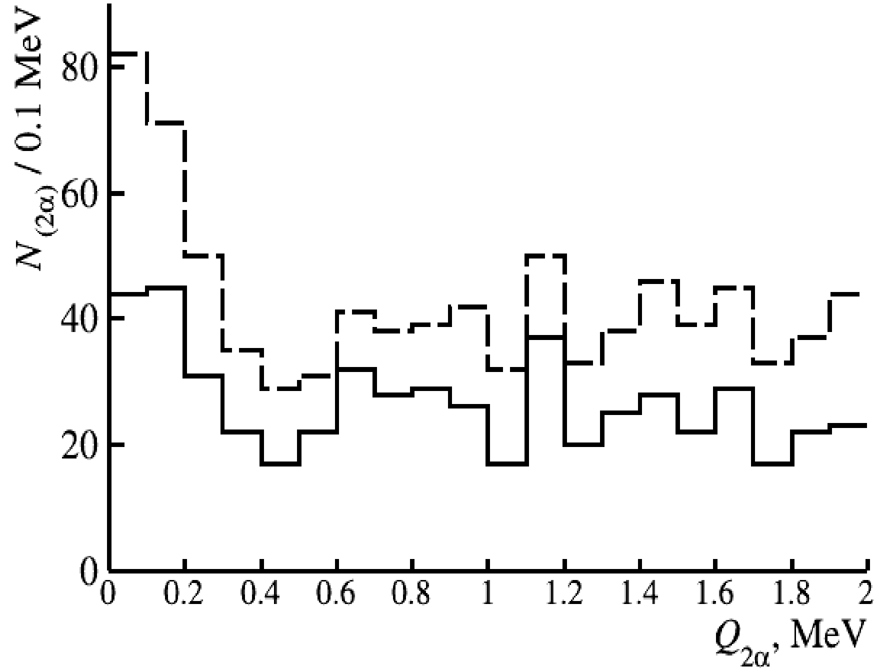


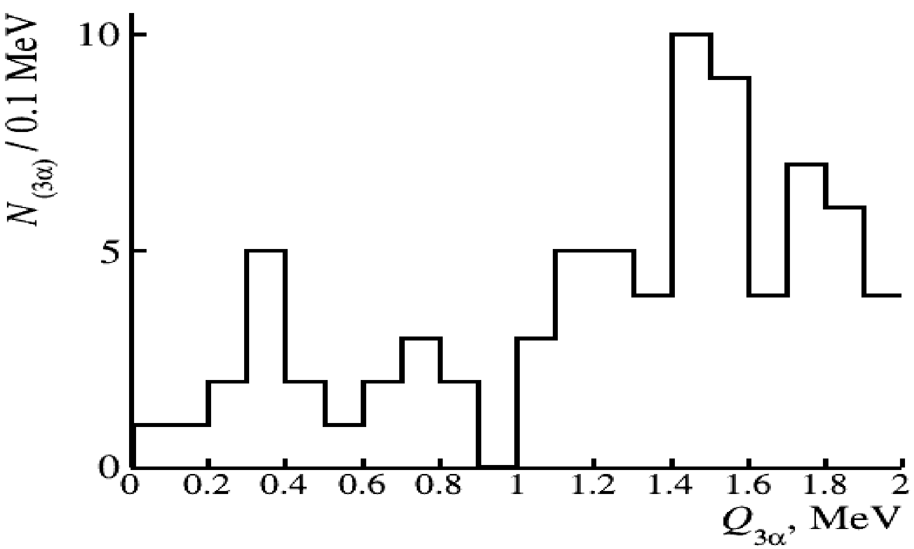


The main task of the forthcoming stage of the project is to clarify the relation between the appearance of ^{8}Be and HS and α-ensemble multiplicities and search on this basis for decays of the $^{16}O(0^{+}_{6})$ state. In this regard, the BECQUEREL experiment aims to measure multiple channels of ^{84}Kr 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. At the same time, the existing MBI-9, KSM, and MPE-11 microscopes need to be upgraded to continue precision measurements according to proven procedures.

n_α	3	4	5	6	7	8	9	10	$n_\alpha>3$
N_{ev}	56	73	69	34	16	18	6	3	219

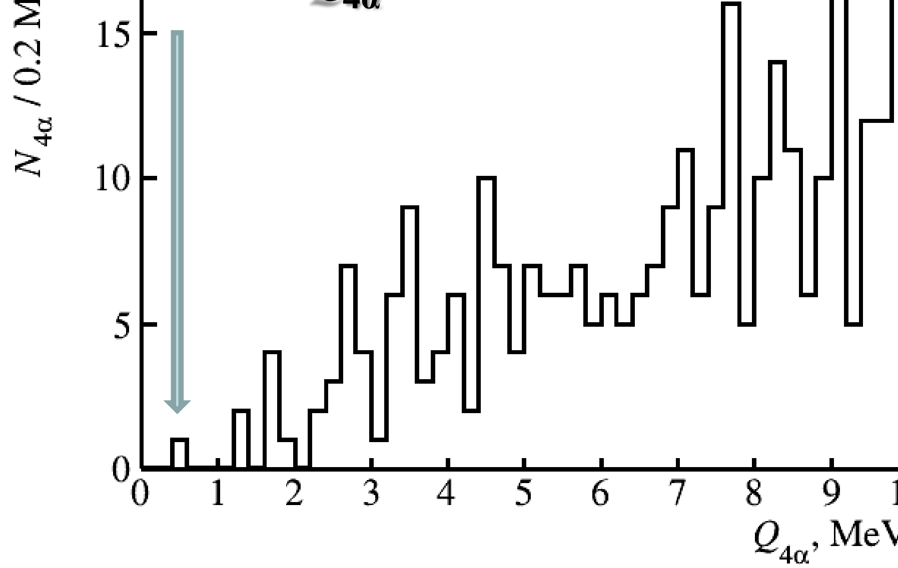


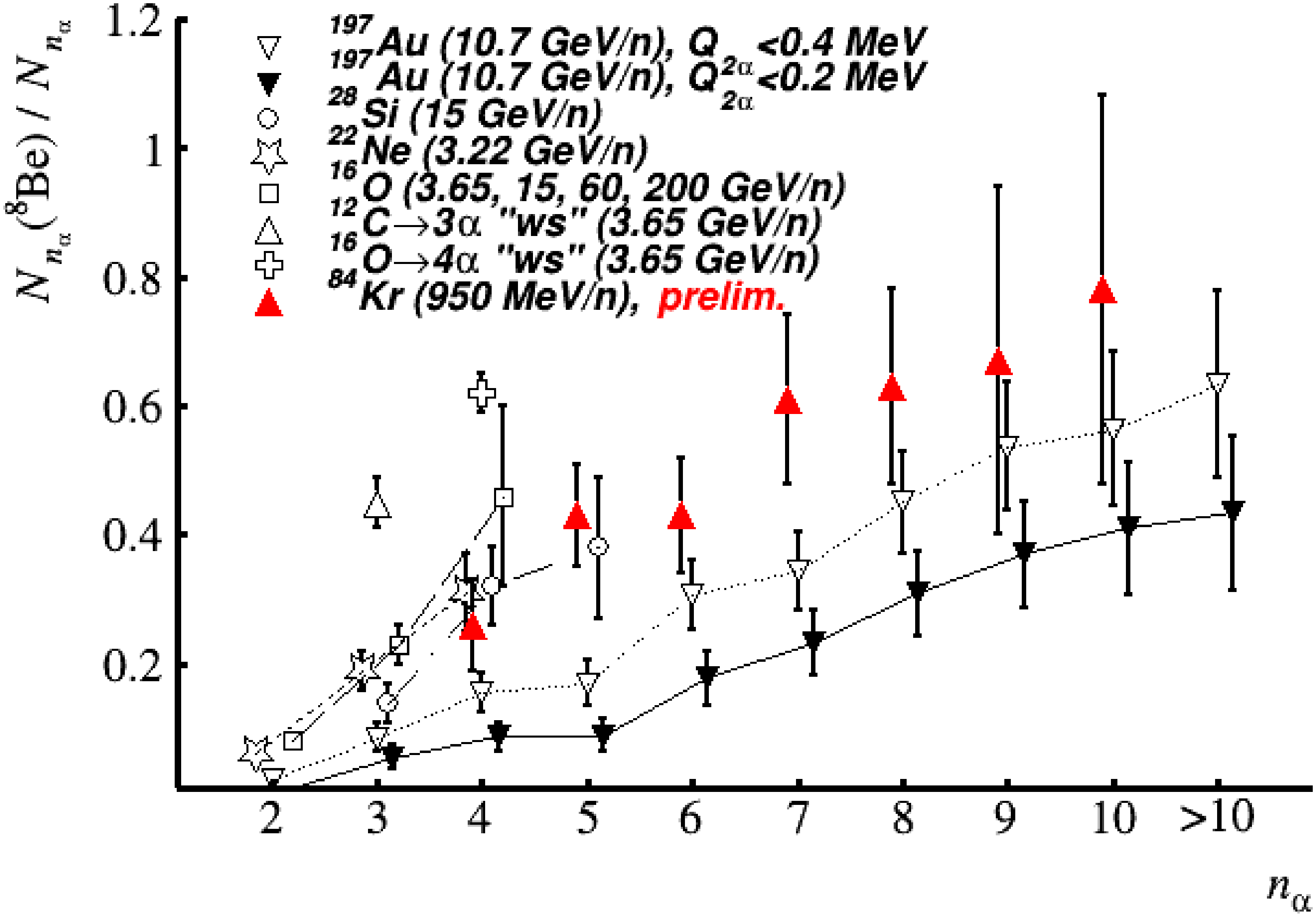




32 мм n_α = 6

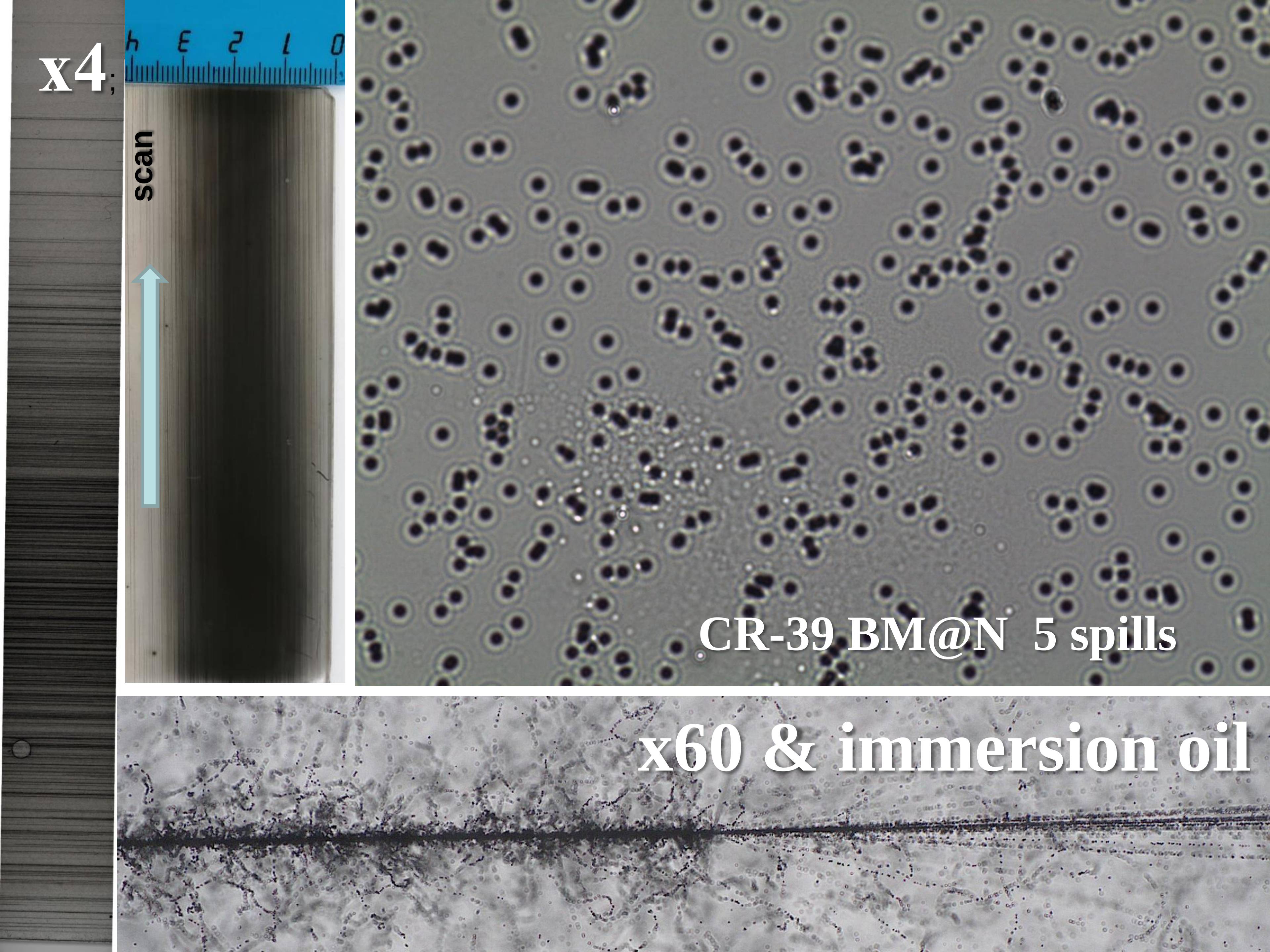
2^8Be $Q_{4\alpha}$= 0.6 МэВ

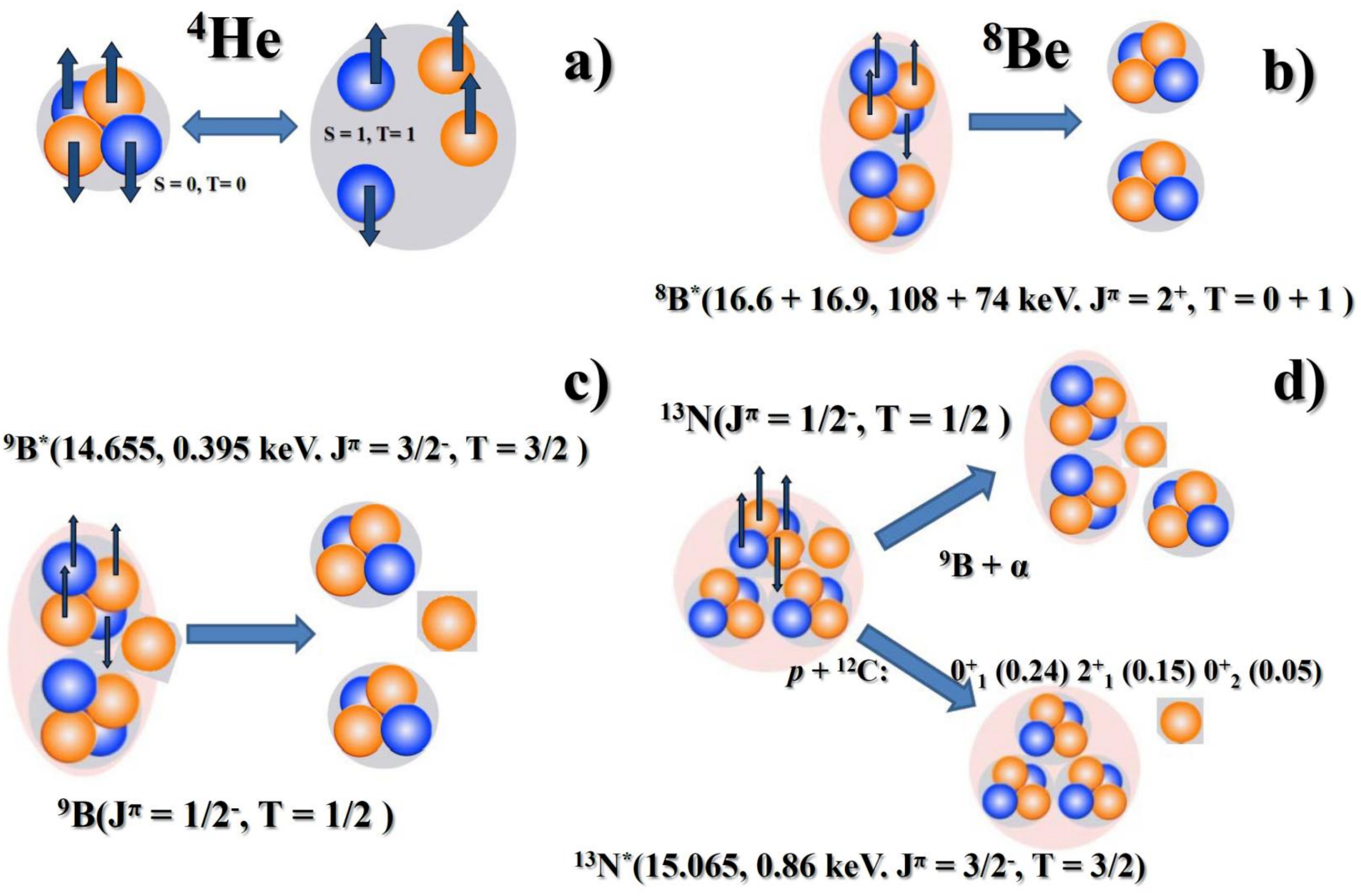




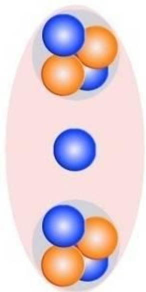
Dependence of relative contribution of $N_{n\alpha}(^8\mathrm{Be})$ decays to statistics of $N_{n\alpha}$ events with α-particle multiplicity nα in relativistic fragmentation of C, O, Ne, Si, and Au nucle; marked "white" stars $^{12}C \to 3\alpha$ and $^{16}O \to 4\alpha$ (WS); points are slightly shifted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

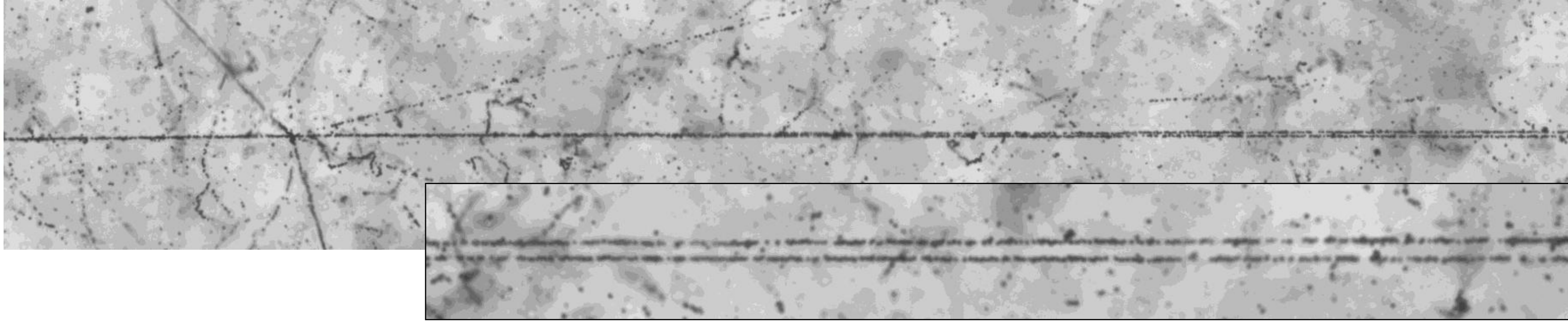
The acceleration at the Nuclotron/NICA in the last December-January of Xe nuclei up to 3.8 GeV per nucleon and the extraction of their beam made it possible to take practical steps towards nuclear emission irradiation near the accelerator and in the area of the flagship BM@N experiment. The beam was guided to the target of the setup in a magneto-optical channel along an ion guide about 70 meters long, which is necessary for working with heavy nuclei. Determination of its intensity, position and profile at ionization 2500 times higher than the ionization of protons is an extraordinary problem. Estimated irradiation of NTE stacks was carried out according to the approximate information on the flow with a duration of 1 to 25 cycles, both at the head section of the channel and behind the main BM@N equipment. In the irradiation at the BM@N setup, a CR-39 solid-state track detector (TTTD) plate was additionally used. TTTD allow determining the exact parameters of the flow of nuclei in nuclear power, where the uniformity of traces is critical. The exposed layers were developed in the VBLHEP chemical group, and TTTD were processed in FLNR.


x4;
scan
CR-39 BM@N 5 spills
x60 & immersion oil

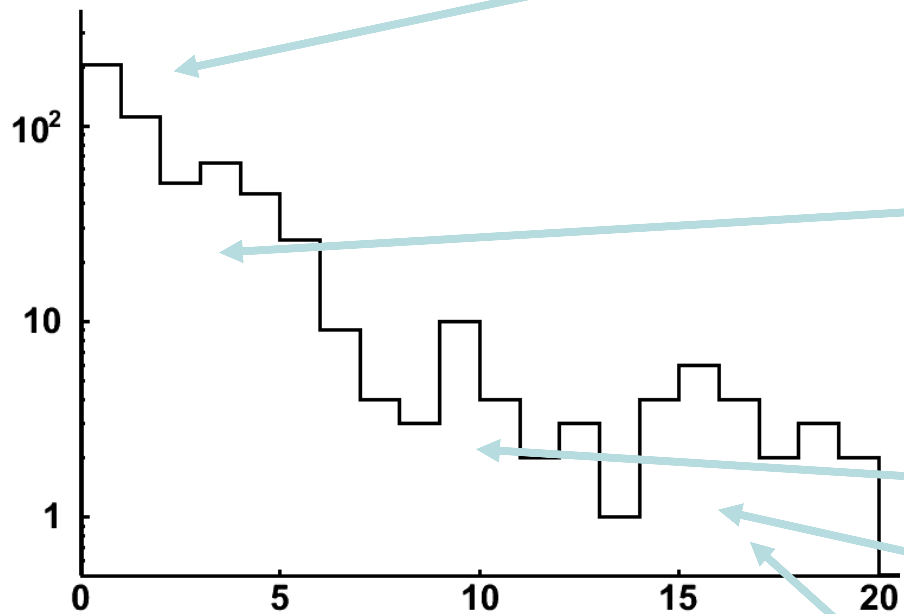


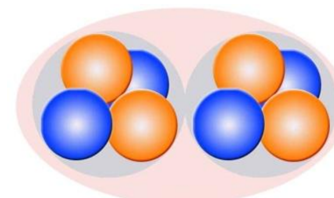
In continuation of the study of the fragmentation of light nuclei, searches for decays of isobar-analogue states (IAS) including excitations ^{8}Be* and ^{9}B* has begun. Manifesting at high excitation energy, but also having very small widths, IASs serve as “beacons” for structural rearrangement in the direction of similarity with their less stable isobars. In the context of nαBEC and IAS, the analysis of NTE exposed to ^{9}Be and ^{10}Cnuclei will continue.



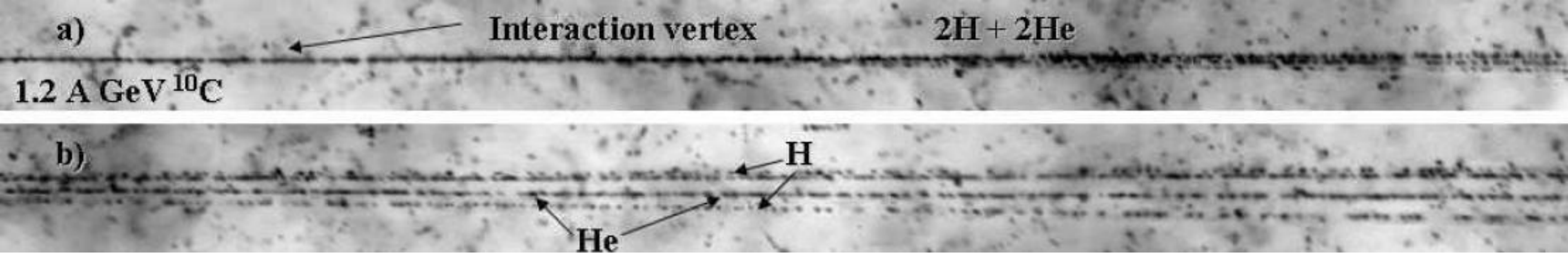


573 ^{9}Be (1.2 *A* GeV) → 2α

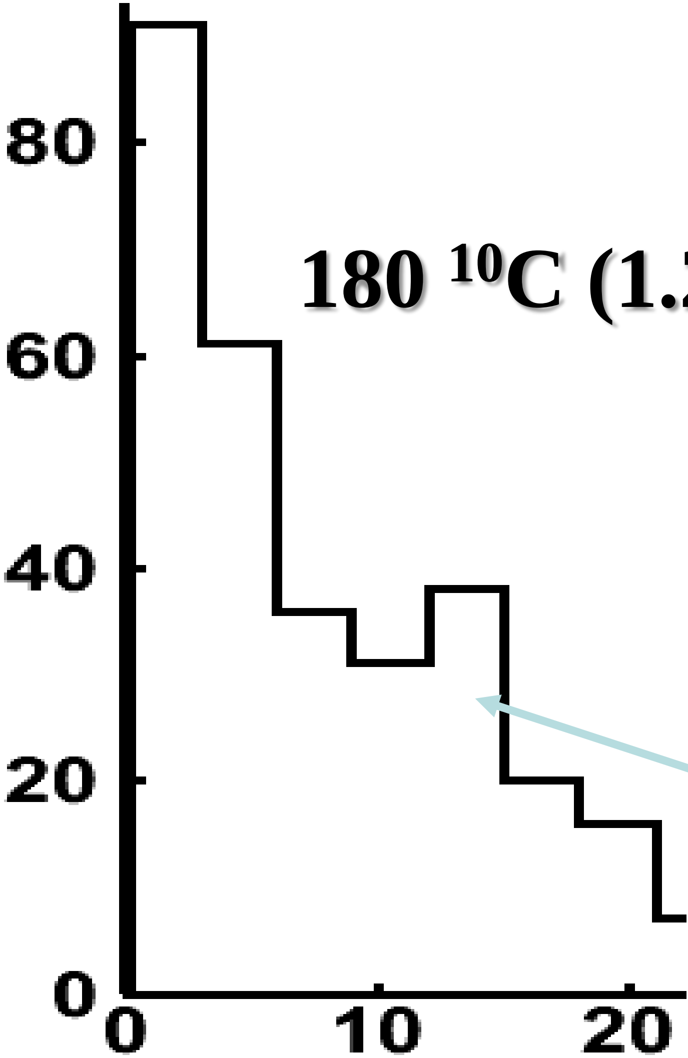


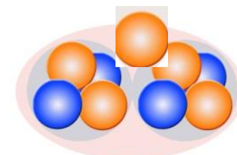


E_x (MeV ± keV)	$J^\pi; T$	Γ_{cm} (keV)	Decay
g.s.	$0^+; 0$	5.57 ± 0.25 eV [i]	α
3.03 ± 10 [i]	$2^+; 0$	1513 ± 15 [i]	α
[i,j]	2^+		
11.35 ± 150 [i]	$4^+; 0$	≈ 3500[b]	α
16.626 ± 3	$2^+; 0+1$	108.1 ± 0.5	γ, α
16.922 ± 3	$2^+; 0+1$	74.0 ± 0.4	γ, α
17.640 ± 1.0 [f]	$1^+; 1$	10.7 ± 0.5	γ, p



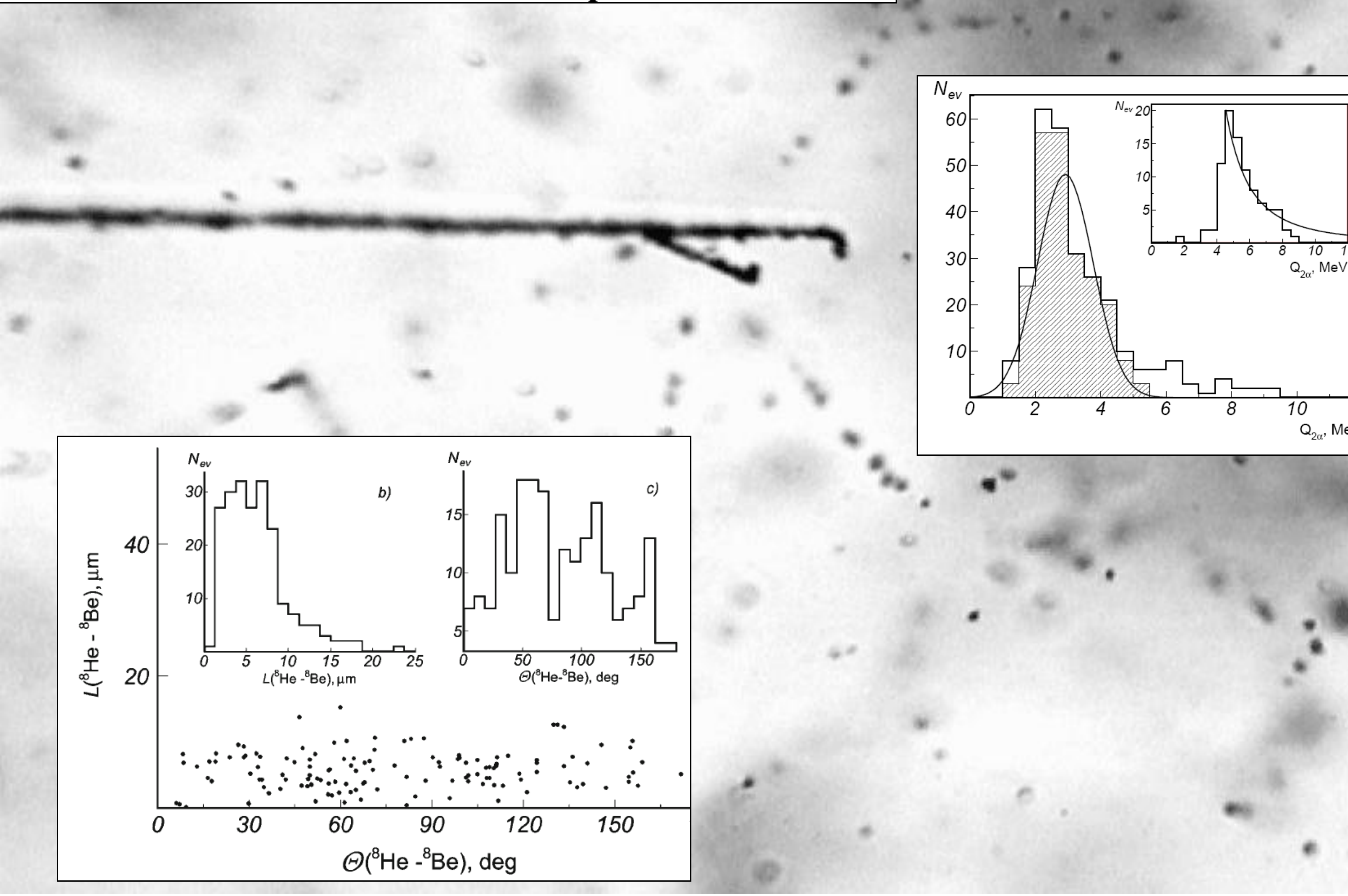
180 ^{10}C (1.2 *A* GeV) → 2α2*p*

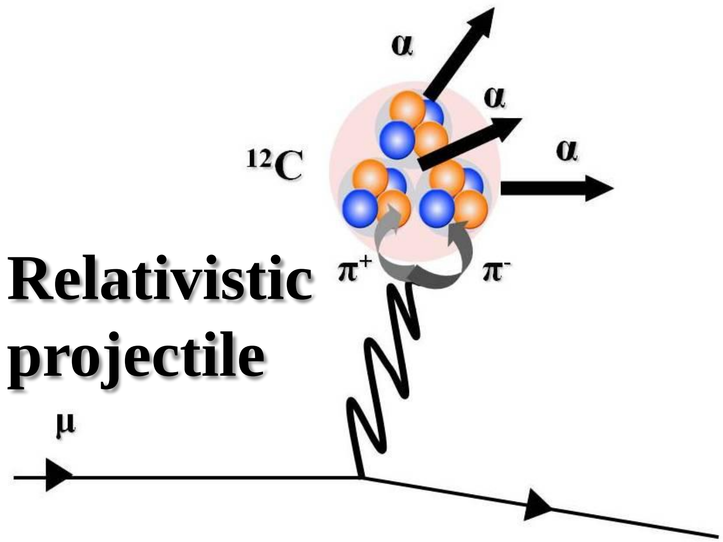


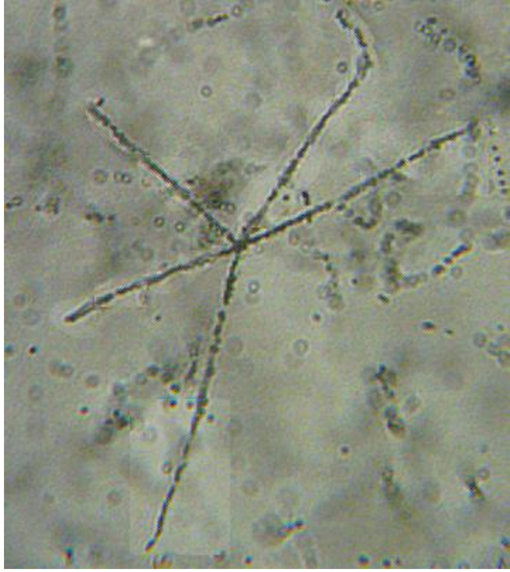


E_x [a] (MeV ± keV)	$J^\pi; T$	$\Gamma_{c.m.}$ (keV)	Decay
g.s.	$\frac{3}{2}^-; \frac{1}{2}$	0.54 ± 0.21	p
			p, (α)
2.361 ± 5	$\frac{5}{2}^-; \frac{1}{2}$	81 ± 5	p, α
2.75 ± 300 [c]	$\frac{1}{2}^-; \frac{1}{2}$	3130 ± 200	p
2.788 ± 30	$\frac{5}{2}^+; \frac{1}{2}$	550 ± 40	p, α
4.3 ± 200 [d]		1600 ± 200	
6.97 ± 60	$\frac{7}{2}^-; \frac{1}{2}$	2000 ± 200	p
11.65 ± 60 [e]	$(\frac{7}{2})^-; \frac{1}{2}$	800 ± 50	p
12.19 ± 40 [f]	$\frac{5}{2}^-; \frac{1}{2}$	450 ± 20	p, α
14.01 ± 70	$\pi = -; \frac{1}{2}$	390 ± 110	p, α
14.6550 ± 2.5	$\frac{3}{2}^-; \frac{3}{2}$	0.395 ± 0.042	γ, p
14.7 ± 200 [g]	$(\frac{5}{2})^-; \frac{1}{2}$	1350 ± 200	

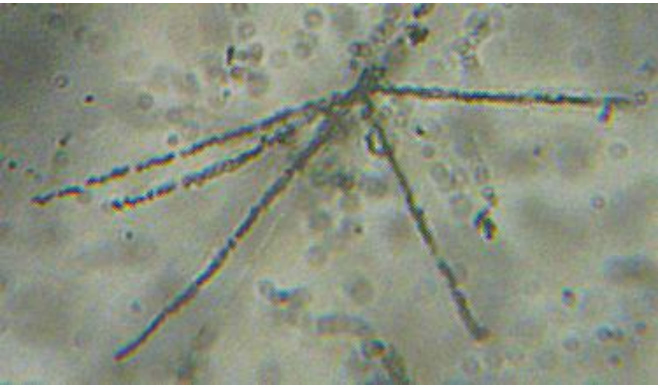
Exposure of Nuclear Track Emulsion to ^{8}He Nuclei at the ACCULINNA Separator

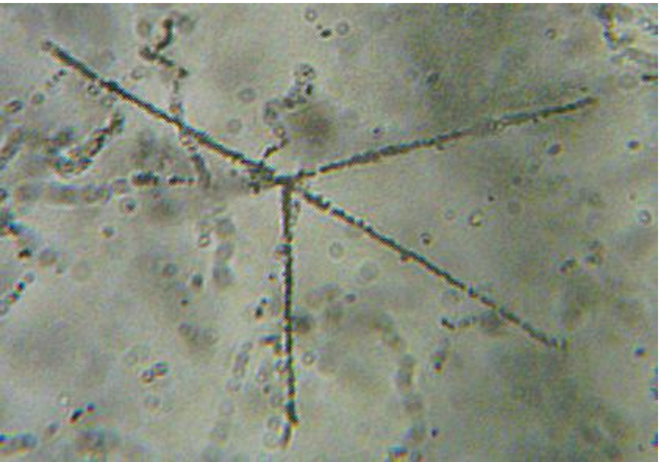


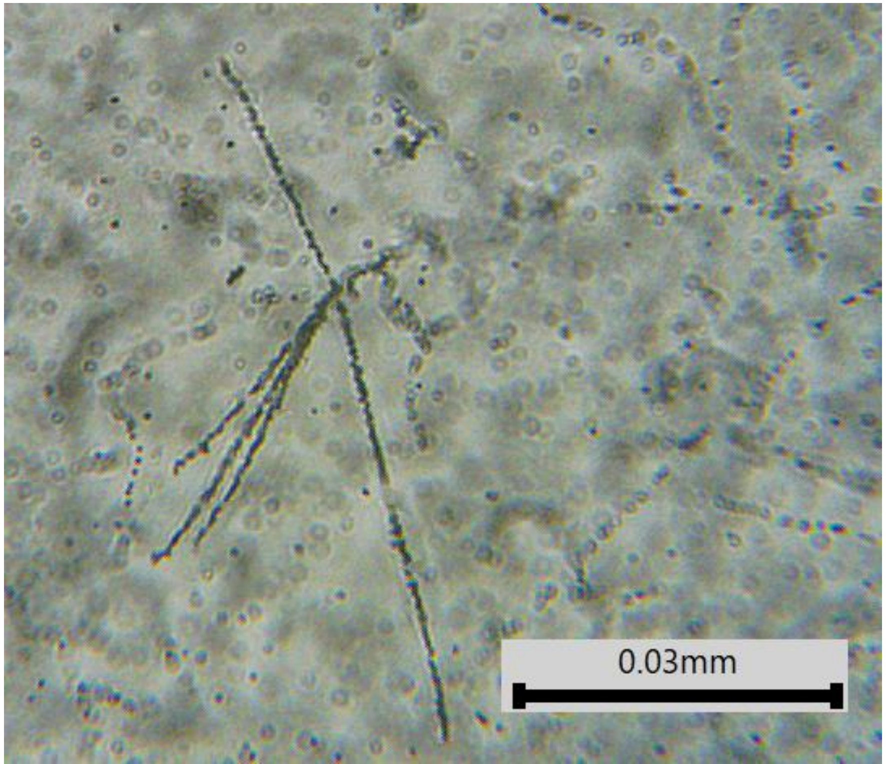




Stopped alphas in target fragmentation







SUMMARY

The BECQUEREL2023 project at the NUCLOTRON/NICA accelerator complex will continue to study peripheral interactions of relativistic nuclei, where only the nuclear emulsion method provides the required resolution, completeness, and uniformity of observations.

The project is focused on the search for α-particle Bose-Einstein condensate (αBEC). Identification of decays ^{8}Be → 2α, ^{9}Be → 2α, and ^{12}C(0^{+}_{2}) → ^{8}Beα (the Hoyle state) was tested by the invariant mass for light nuclei, including the radioactive ones.

Recently this group has discovered a trend of increasing ^{8}Be with the growing number of α-particles, as well as ^{9}B and ^{12}C(0^{+}_{2}) for medium and heavy nuclei that indicates an opportunity of 4αBEC synthesis.

The BECQUEREL2023 project is aimed at analyzing the ^{84}Kr fragmentation at 950 MeV per nucleon to clarify the connection between ^{8}Be and the Hoyle state and the multiplicity of α-ensembles. On this basis it is possible to search for the decays of the ^{16}O(0^{+}_{6}) → ^{12}C(0^{+}_{2})α state and 2^{8}Be as a candidate for 4αBEC. The multiplicity and transverse momenta of accompanying neutrons have been estimated along with the above tasks.

The studies with light nuclei in the dissociation of ^{9}Be and ^{10}C, the search for isobar-analogue states of ^{8}Be and ^{9}B are in progress. In the fragmentation of the emulsion caused by nuclei under the action of relativistic particles, the technique has been mastered to identify ensembles of the stopped α-particles by means of the invariant mass method.

In December 2022, the nuclear emulsion layers were exposed to the ^{124}Xe nucleus beam at 3.8 GeV per nucleon. In the result, the proper emulsion has been obtained to analyze the multiple states of α-particles and nucleons at the optimal energy. Using the CR-39 detector made it possible to completely reconstruct the profile and intensity of the applied beam.

In general, the combination of classical nuclear techniques and the successful mastering of the unique motorized microscope have provided further investigations of relativistic radioactive isotopes at JINR, attracting young researchers.

<table>
<tr><th colspan="3" rowspan="2">Names of costs, resources, funding sources</th><th colspan="5">Cost, distribution by years</th></tr>
<tr><th>1st year</th><th>2 st year</th><th>3 st year</th><th>4 st year</th><th>5 st year</th></tr>
<tr><td colspan="2" rowspan="8"></td><td>International Cooperation (IC)</td><td>40</td><td>40</td><td>40</td><td>40</td><td>40</td></tr>
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<tr><td>Services of research organisations</td><td>20</td><td>20</td><td>20</td><td>20</td><td>20</td></tr>
<tr><td>Acquisition of software</td><td>30</td><td></td><td></td><td></td><td></td></tr>
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<tr><td>Service costs (planned in case of direct belonging to the project)</td><td></td><td></td><td></td><td></td><td></td></tr>
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<tr><td>– accelerator/installation,</td><td>100</td><td>100</td><td>100</td><td>100</td><td>100</td></tr>
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<tr><td>Extrabudgetary (additional estimate)</td><td>Contributions of co-executors
Funds under contracts with customers
Other funding sources</td><td></td><td></td><td></td><td></td><td></td></tr>
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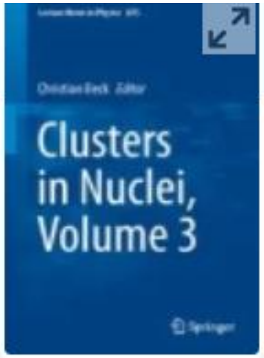
JINR core staff in the BECQUEREL 2023 Project

Zarubin P.I. Rusakova V.V. Artemenkov D.A. Zaitsev A. A. Bradnova V. Natarjan M.	Head of Sector, DSc Microscope Group Head, PhD Senior Res. PhD Senior Res. PhD Chemist Group Head Res., PhD
Zarubina I.G. Kornegrutsa N.K. Kondratieva N.V. Nomozova K.B	Software Engineer Engineer Chemist Engineer
Kashanskaya O.N.	Senior Assistant, MS student
Marin I.I. Stelmakh G.I. Shcherbakova N.S.	Microscope Technician Microscope Assistant Microscope Assistant

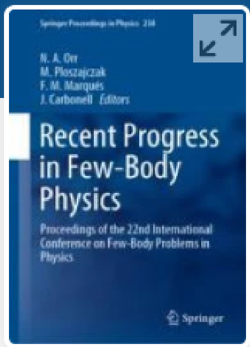


Clusters in Nuclei, Volume 3 pp 51–93 | Cite as

“Tomography” of the Cluster Structure of Light Nuclei via Relativistic Dissociation

P. I. Zarubin

Chapter



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The Hoyle State in Relativistic ^{12}C Dissociation

D. A. Artemenkov, M. Haiduc, N. K. Kornegrutsa, E. Mitsova, N. G. Peresadko, V. V. Rusakova, R. Stanoeva, A. A. Zaitsev, P. I. Zarubin & I. G. Zarubina

Conference paper | First Online: 07 January 2020

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Unstable states in dissociation of relativistic nuclei

Recent findings and prospects of research

D. A. Artemenkov, V. Bradnova, M. M. Chernyavsky, E. Firu, M. Haiduc, N. K. Kornegrutsa, A. I. Malakhov, E. Mitsova, A. Neagu, N. G. Peresadko, V. V. Rusakova, R. Stanoeva, A. A. Zaitsev, P. I. Zarubin & I. G. Zarubina

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Volume 820, 10 September 2021, 136460

Correlation in formation of ^{8}Be nuclei and α-particles in fragmentation of relativistic nuclei

A.A. Zaitsev [a, b], D.A. Artemenkov [a], V.V. Glagolev [a], M.M. Chernyavsky [b], N.G. Peresadko [b], V.V. Rusakova [a], P.I. Zarubin [a, b]

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NUCLEI
Experiment

Prospects of Searches for Unstable States in Relativistic Fragmentation of Nuclei

D. A. Artemenkov[1], V. Bradnova[1], O. N. Kashanskaya[2], N. V. Kondratieva[1], N. K. Kornegrutsa[1], E. Mitsova[1),3)], N. G. Peresadko[4], V. V. Rusakova[1], R. Stanoeva[5),3)], A. A. Zaitsev[1),4)*], I. G. Zarubina[1], and P. I. Zarubin[1),4)]

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Abstract—Prospects of the BECQUEREL experiment devoted to studying, within the relativistic approach, problems of nuclear-cluster physics are discussed. The nuclear track emulsion method used in the present study permits fully investigating relativistic final states in the fragmentation of nuclei. The present study focuses on the dynamics of the formation of a ^{8}Be nucleus and the Hoyle state, as well as on searches for the 4α condensate decaying through them. The development of analysis of exposure to ^{84}Kr nuclei at an energy of 950 MeV per nucleon is described in this context. The status of searches for the isobar analog state of the ^{13}N nucleus in the fragmentation of ^{14}N nuclei at an energy of 2 GeV per nucleon is presented as a continuation of studies of light nuclei.

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[1)]Joint Institute for Nuclear Research , Dubna, Russia.
[2)]Francisk Skorina Gomel State University , Gomel, Belarus.
[3)]Institute for Nuclear Research and Nuclear Energy, Bulgarian Academy of Sciences, Sofia, Bulgaria.
[4)]Lebedev Physical Institute of the Russian Academy of Sciences, Moscow, Russia.
[5)]Southwest University Neofit Rilski, Blagoevgrad, Bulgaria.
[*]E-mail: zaicev@jinr.ru

Prospects of searching for unstable nucleus states in relativistic nuclear fragmentation

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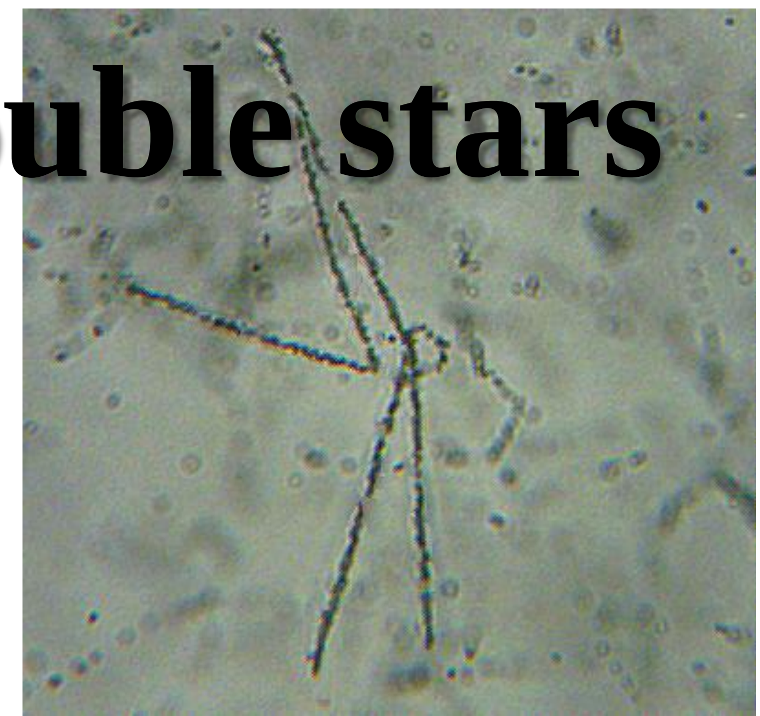
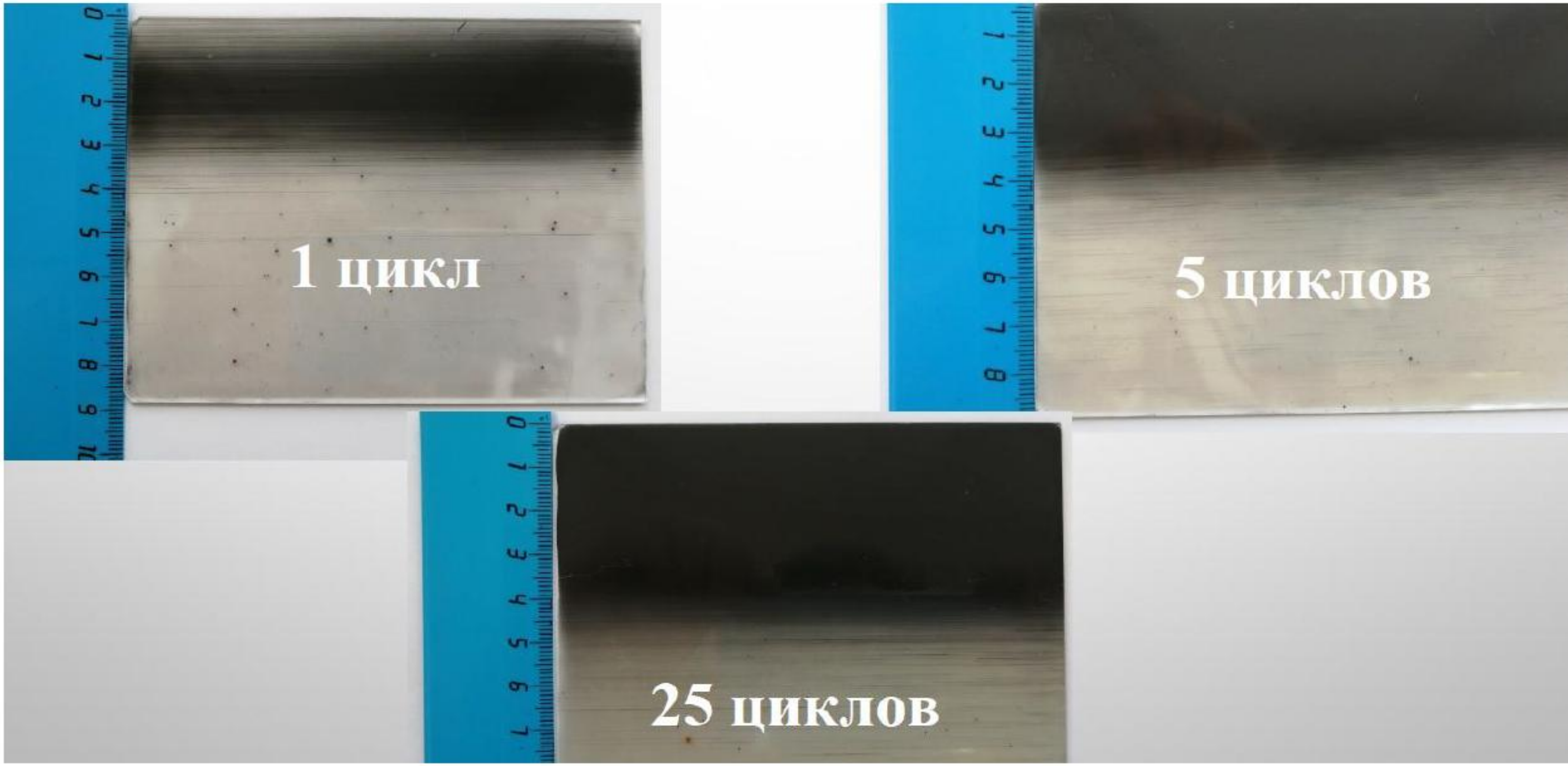
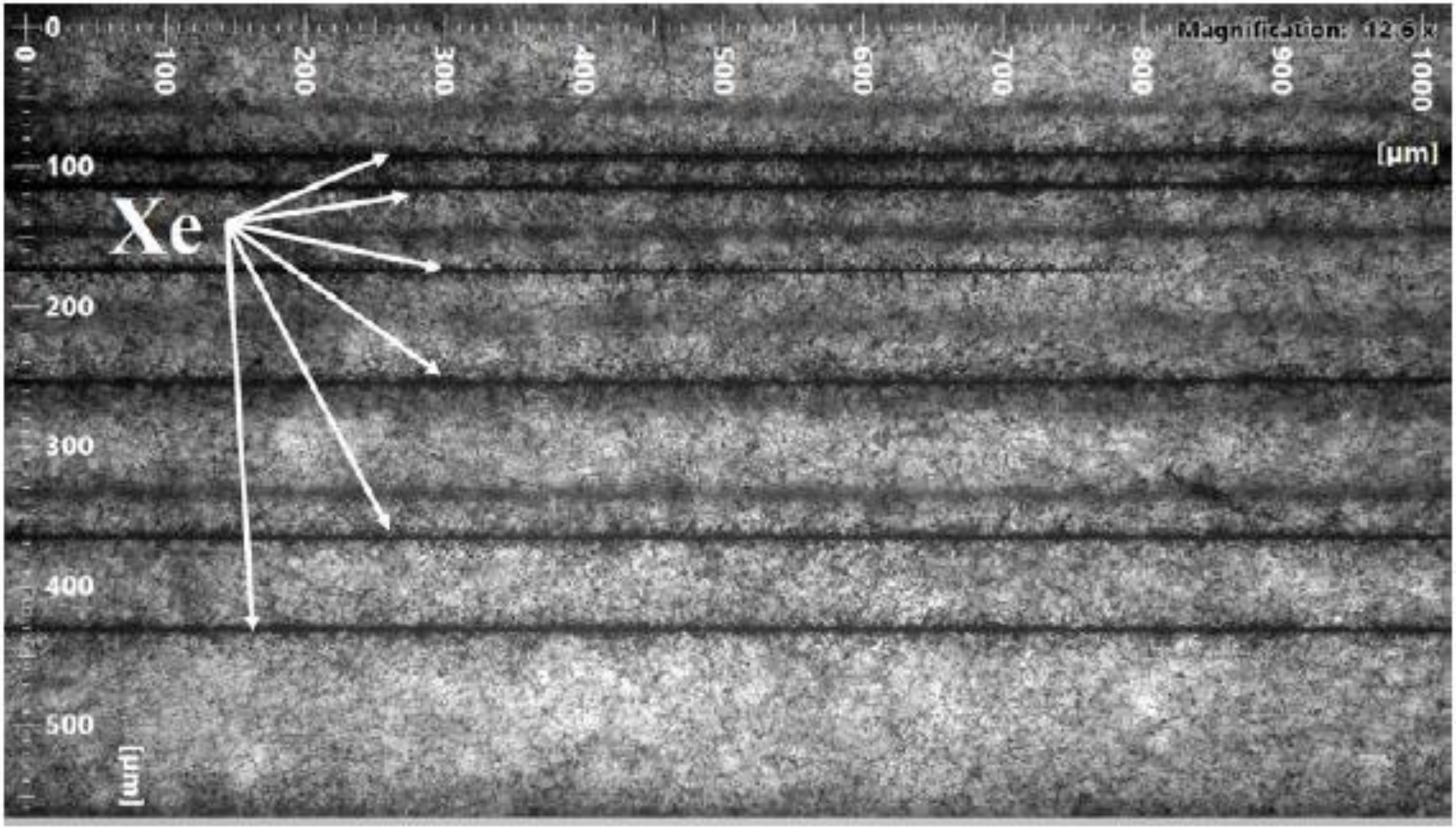
Mysterious double stars

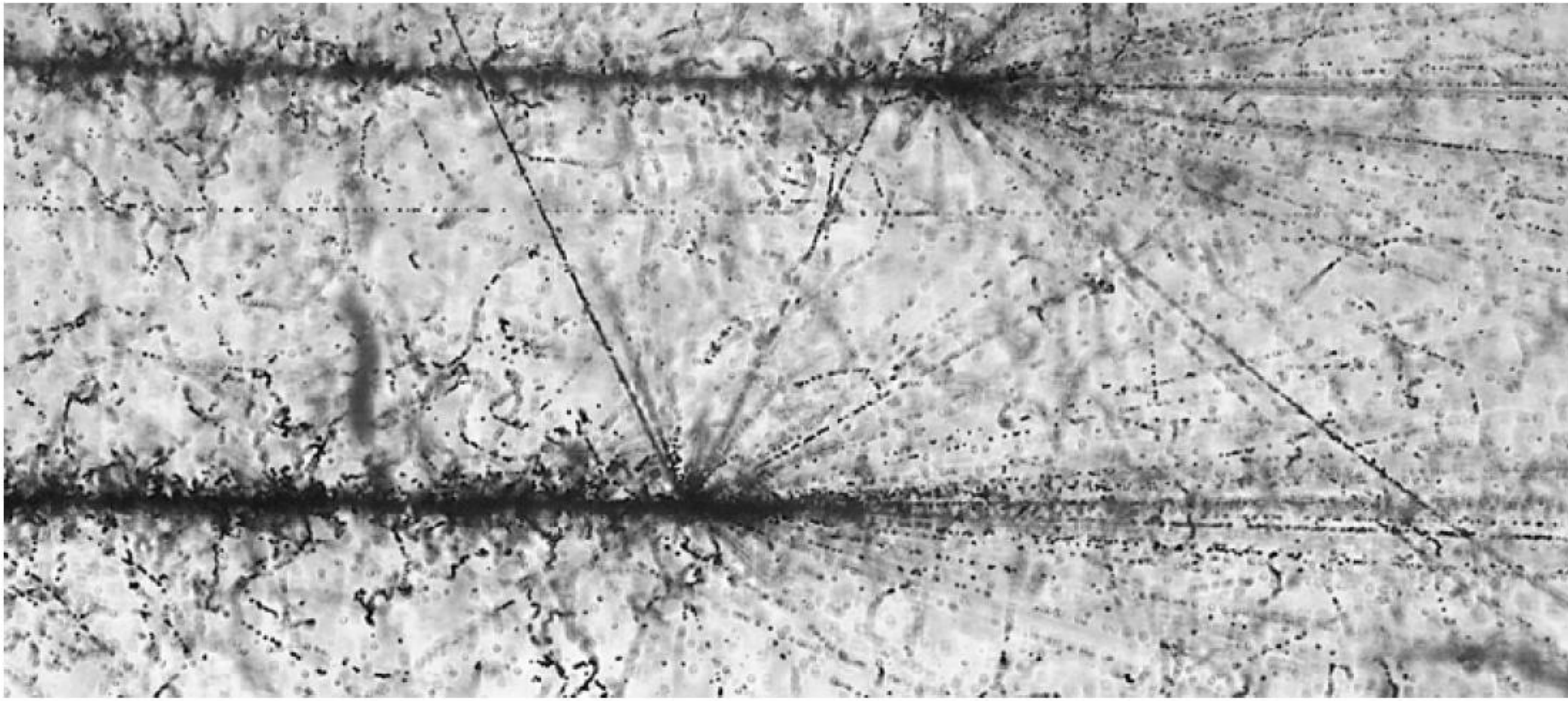




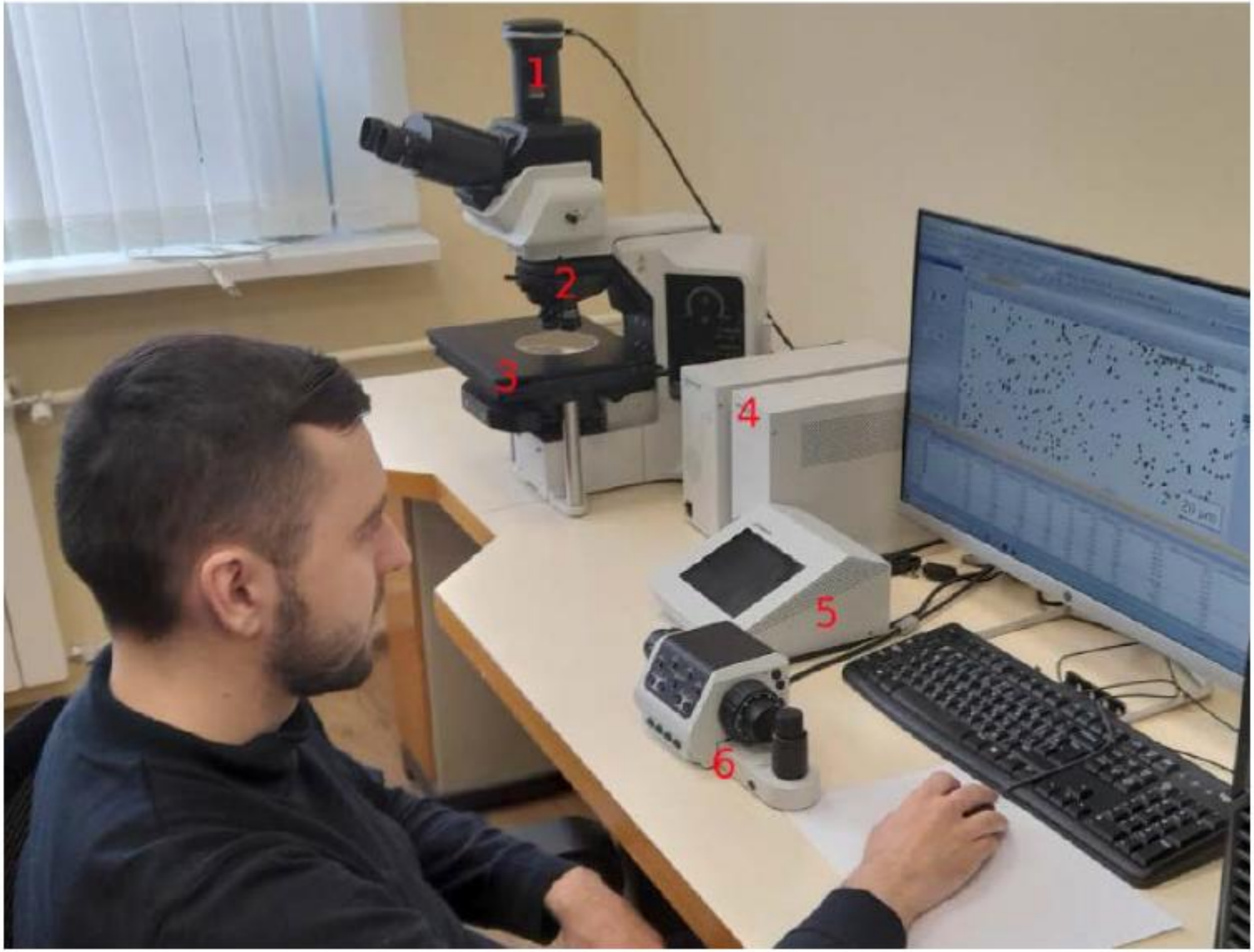
Layers of nuclear track emulsion exposed Xe nuclei for 1, 5, 25 accelerator cycles



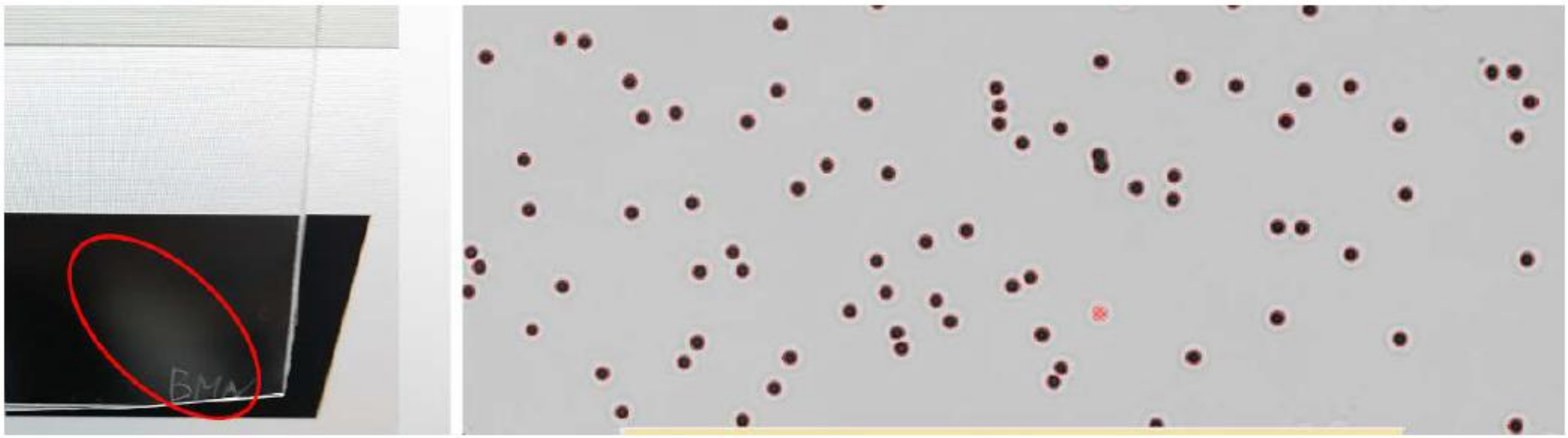
Xe exposed emulsion at 12x, single cycle



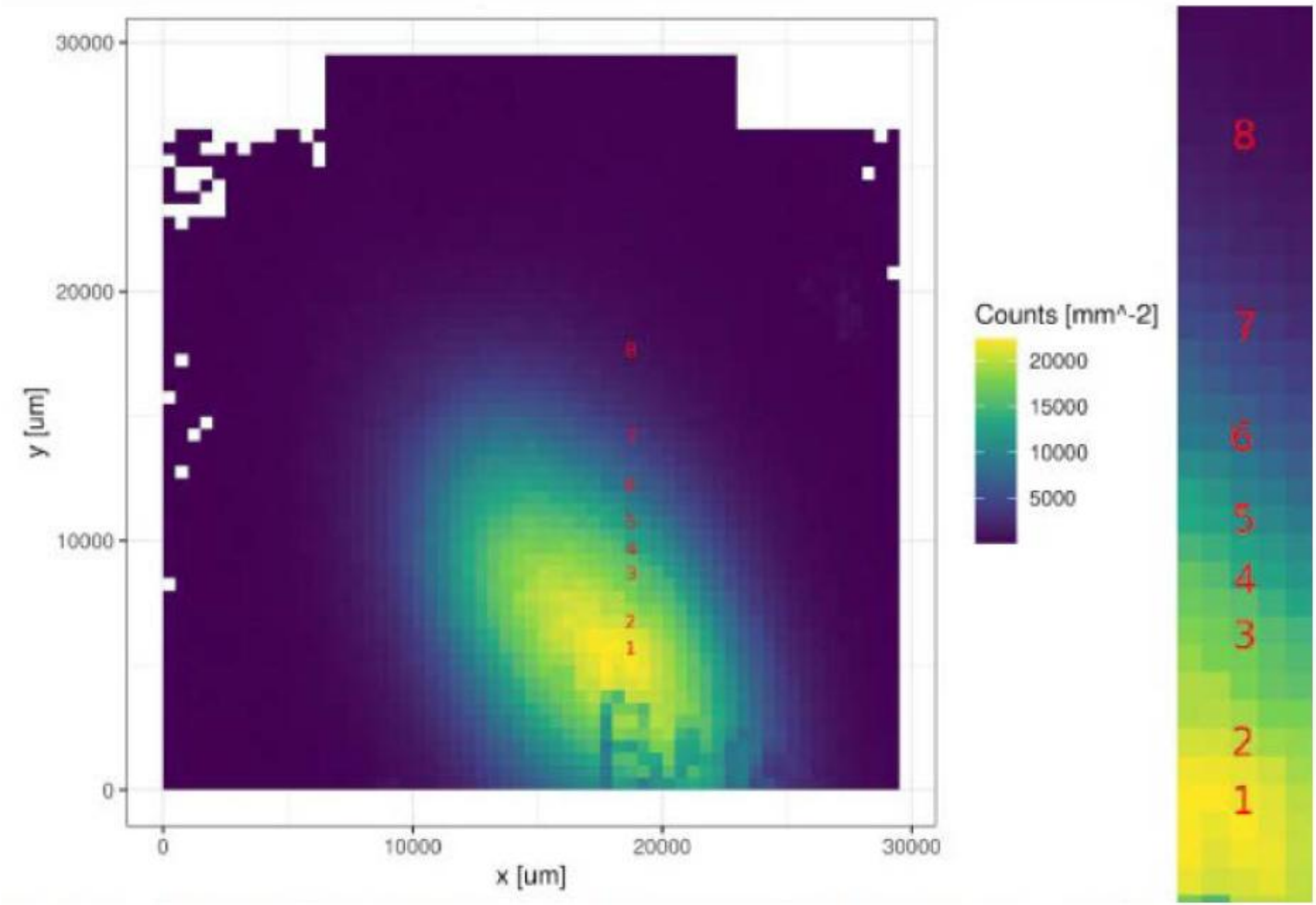
Two stars in view field at 40x, Xe beam single cycle



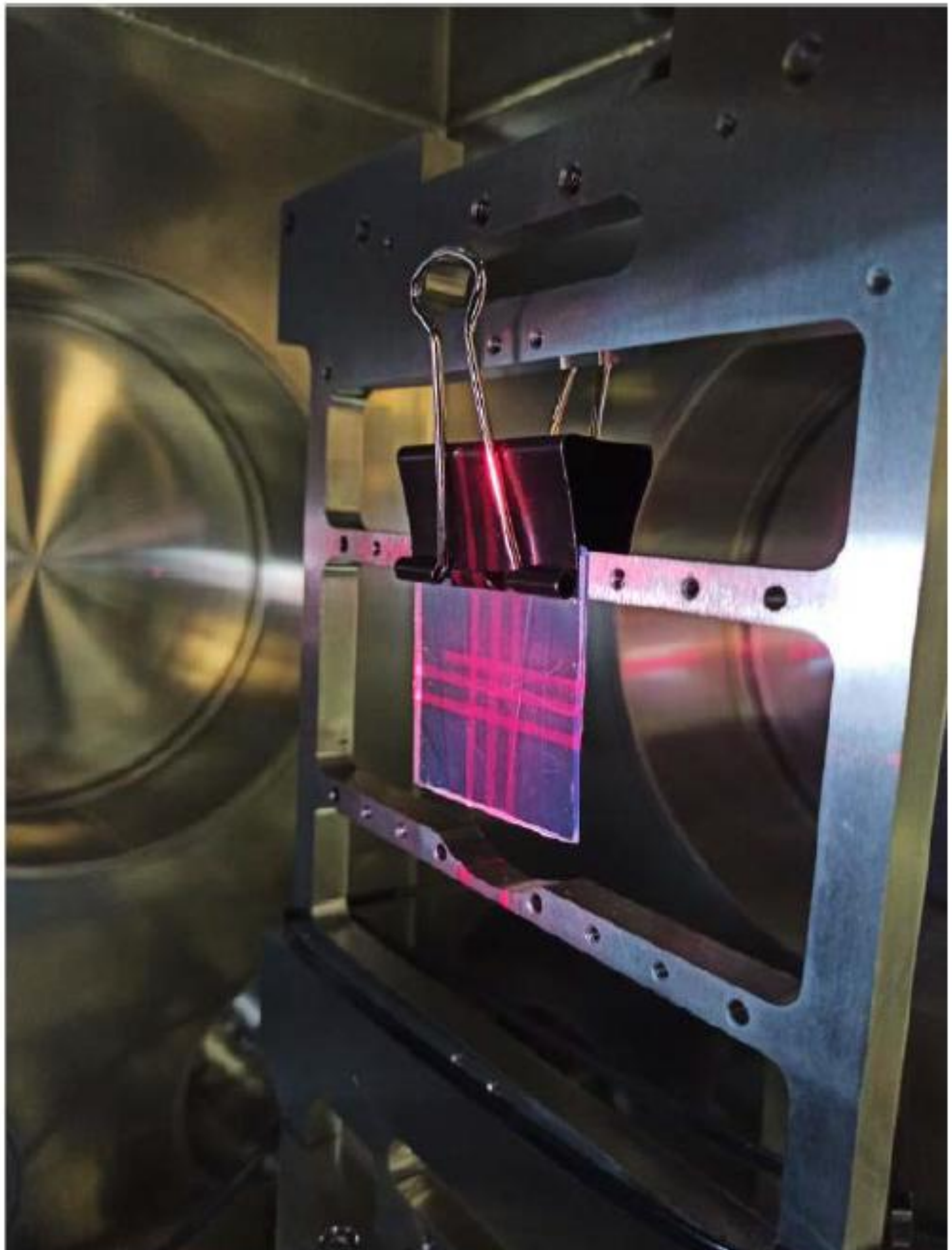
Student Stanislav Murashko of Belarusian State University in practice https://start.jinr.ru/ analyzes irradiation of CR-39 detector on Olympus BX63 microscope (1 - high-speed video camera, 2 - lens revolver, motorized table, 3. 4, 5 - controls)



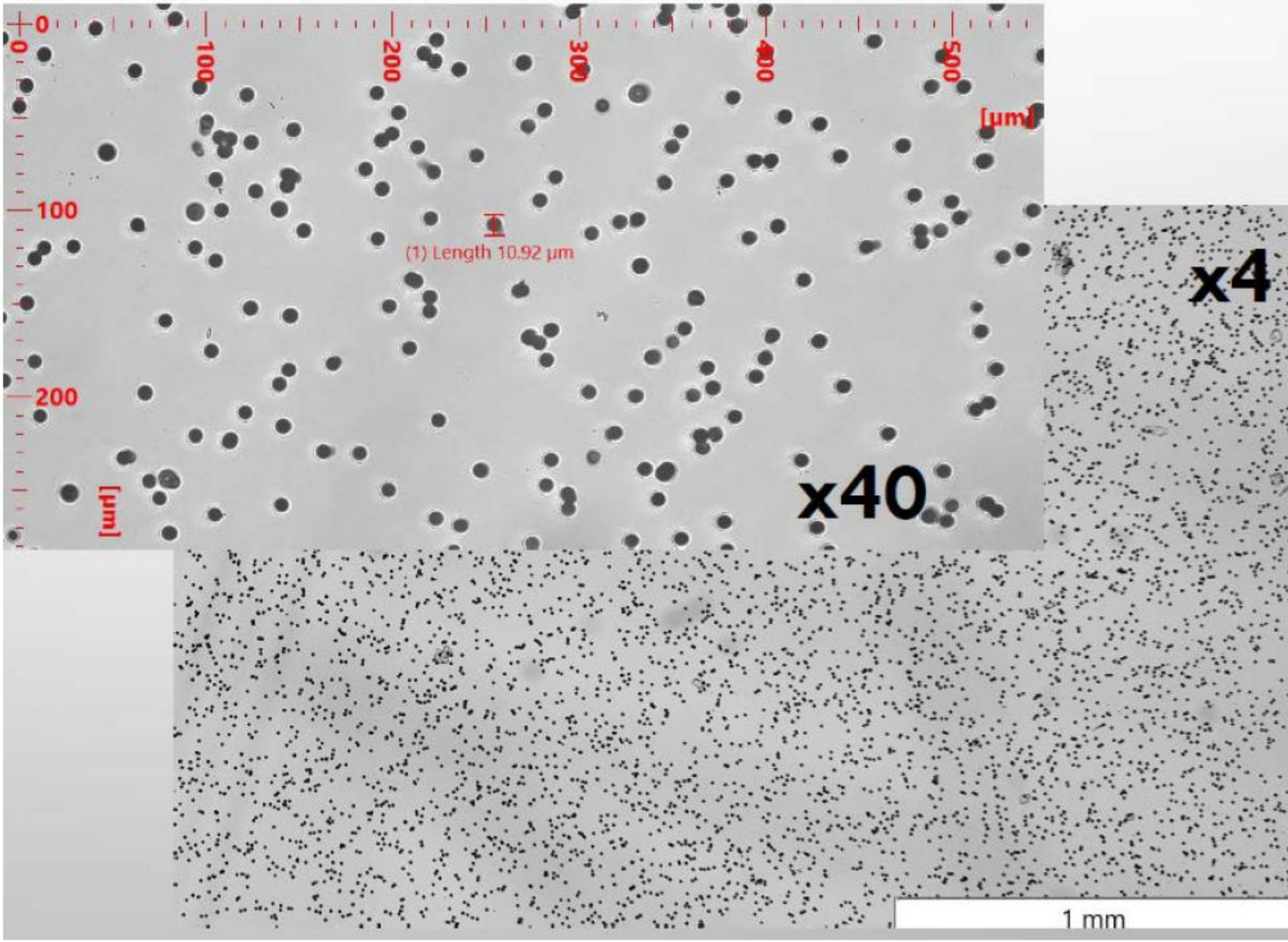
CR-39 detector exposed to 5 accelerator cycles of relativistic Xe nuclei behind the BM@N experiment (left) at 40x; program detected craters by are highlighted in red



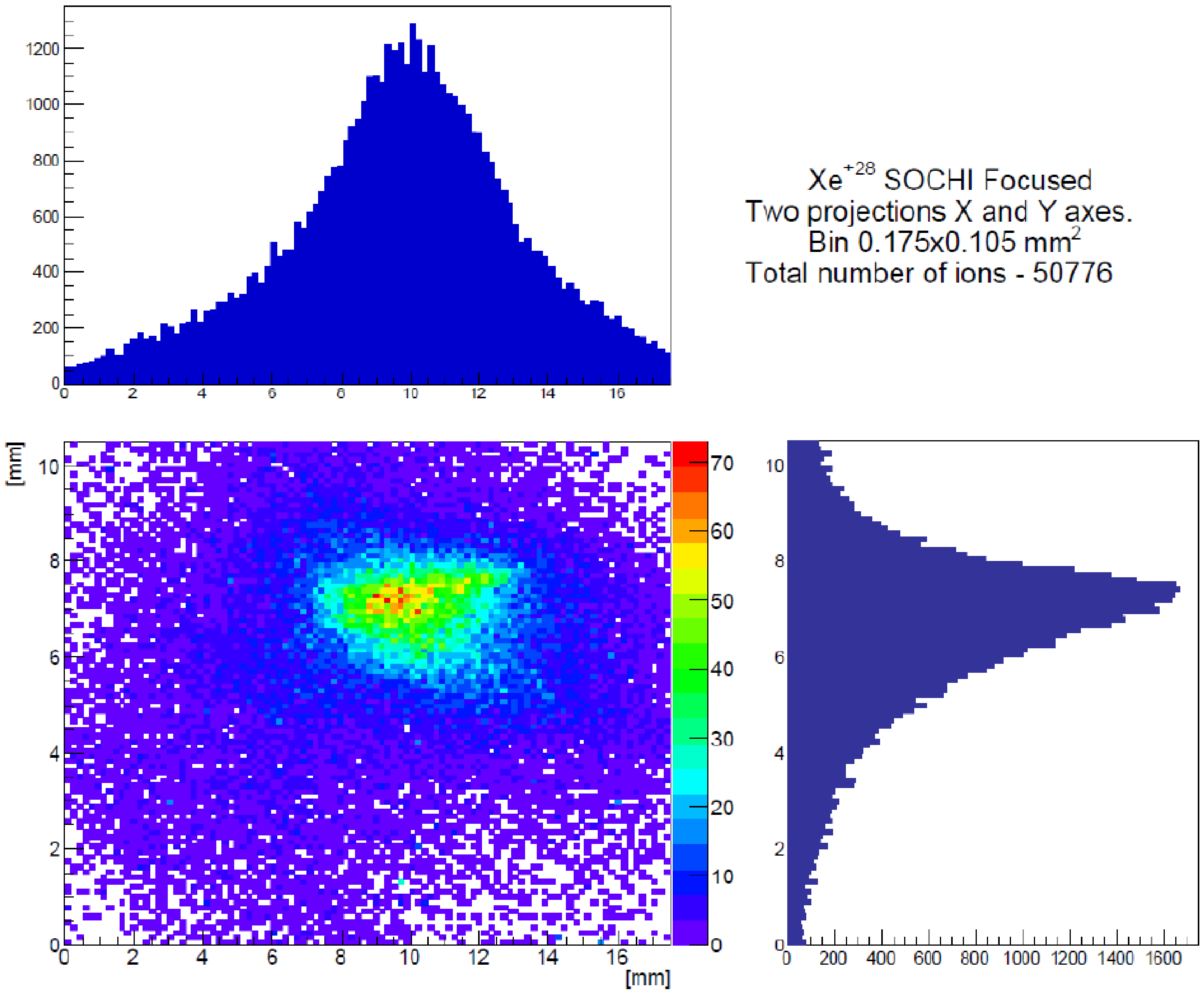
Xe beam profile reconstructed in CR-39 detector behind BM@N experiment



CR-39 detector in vacuum chamber of SOCHi station



CR-39 detector irradiated with 3.2 MeV per nucleon Xe nuclei at SOCHi station.



Profile reconstructed in CR-39 detector of focused Xe beam at SOCHi station.