Experimental studies of nuclear clusters via the dissociation of relativistic nuclei

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(on behalf of the BECQUEREL Experiment)

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India-JINR workshop on elementary particle and nuclear physics, and condensed matter research

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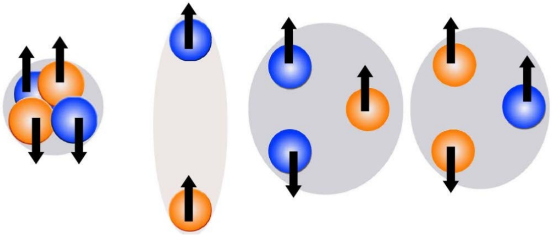
Outline

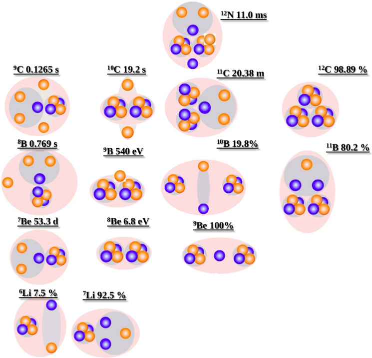
Nuclear Clusters

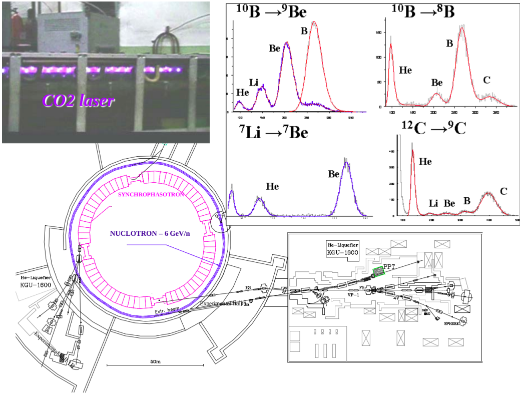
- Clusterization is a key aspect of nuclear structure, in which groups of a few nucleons behave as composite units.
- The fundamental "building blocks" of clustering are the lightest nuclei that have no excited states.
- The presence of spin-paired proton and neutron quartets in the structure of light nuclei manifests itself in the intense formation of particles in various nuclear reactions and decays.



Nuclear Track Emulsion

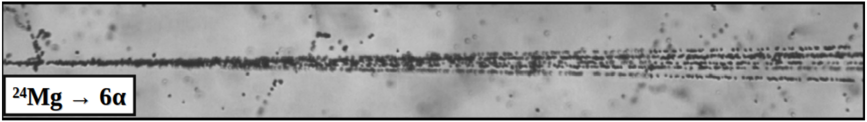
BECQUEREL Experiment



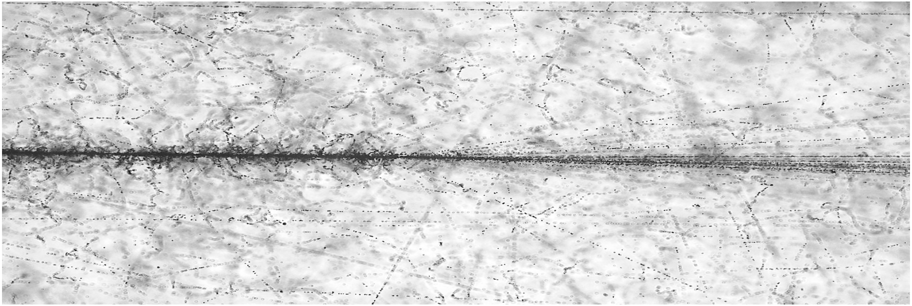


- NTE method is used in the BECQUEREL experiment at the JINR Nuclotron to study fragmentation of light stable nuclei and including radioactive nuclei.
- The features of the nuclei ^{7,9}Be, ^{8,10,11}B, ^{10,11,12}C and ^{12,14}N appeared in the probabilities of their dissociation channels.
- In dissociation of isotopes ^{10}B, ^{10}C, and ^{11}C, decays ^{9}B $\rightarrow ^{8}$Be are identified.

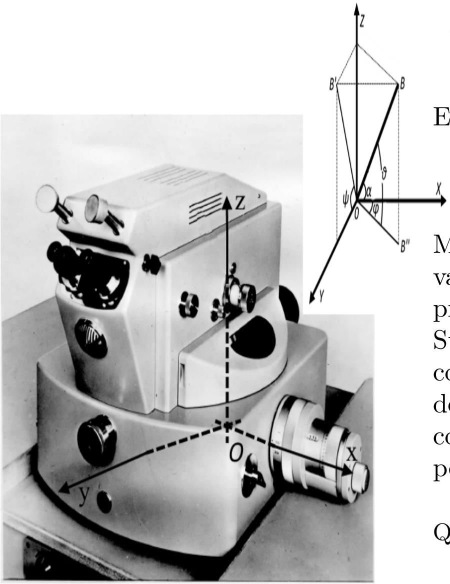
α-fragmentation of relativistic nuclei



- ✓ The study of nuclear structure in the relativistic approach under conditions of very small energy-momentum transfers has significant advantages, as the structure of the initial states of nuclei is most fully reflected in the final states of the fragments.
- ✓ Electronic experiments in this field face fundamental challenges due to the quadratic dependence of ionization on the charges of the nuclei, the extremely small angular divergence of relativistic fragments, and the frequent approximate coincidence in magnetic rigidity with the beam nuclei. Therefore, the NTE method remains unique in the relativistic fragmentation cone.



- ✓ In the nuclear emulsion, relativistic nuclei, even the heaviest ones, can fragment into nucleons and nucleon clusters, such as H and He isotopes (^{1,2,3}H and ^{3,4}He), as well as relativistic neutrons. NTE enables the study of such ensembles with record angular resolution and identification of He and H isotopes.

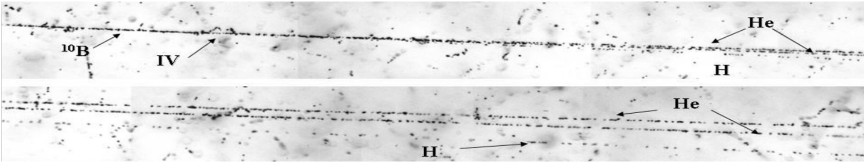


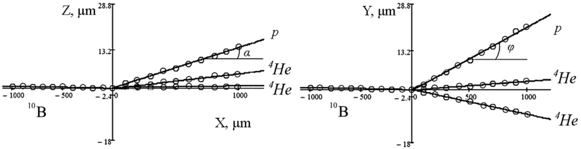
Energy of a few-particle system

$$\mathbf{Q = M^{*}\text{-}\ M}$$

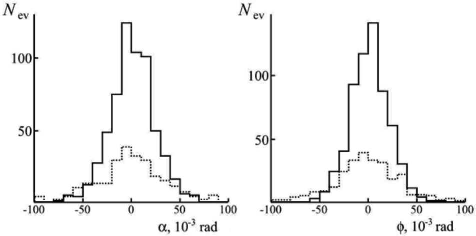
$M^{*2} = \sum(P_j)^2 = \sum(P_i.P_k)$, is the invariant mass defined by the sum of all products of 4-momenta $P_{i,k}$ fragments. Subtraction of mass M is a matter of convenience. The 4-momenta $P_{i,k}$ are determined in the approximation of conservation of the initial momentum per nucleon.

$$Q_{3\alpha} = \sqrt{\sum_{i \neq j} E_{\alpha_i} E_{\alpha_j} - P_{\alpha_i} P_{\alpha_j} \cos\theta_{2\alpha}} - 3m_\alpha$$

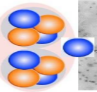


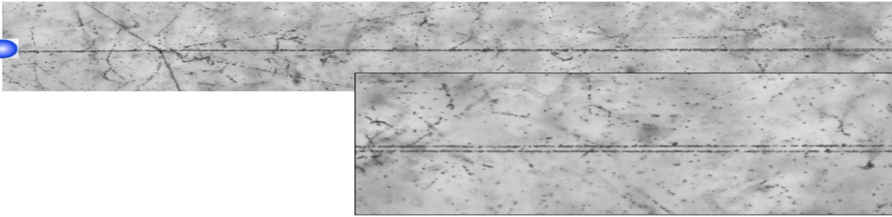


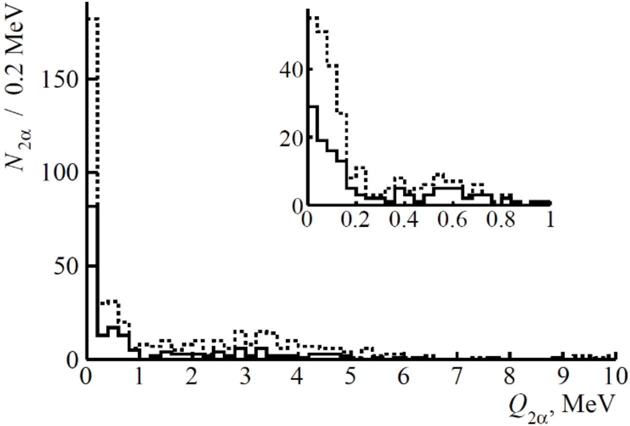
Example of restored directions in event ^{10}B $\rightarrow ^2$He + H @ 1.2 A GeV over vertical and planar planes.



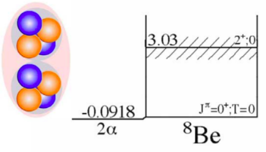
Distributions of fragments He (solid) and H (dotted) over dip and planar angles α and Φ in events ^{10}B $\rightarrow ^2$He + H @ 1.2 A GeV.



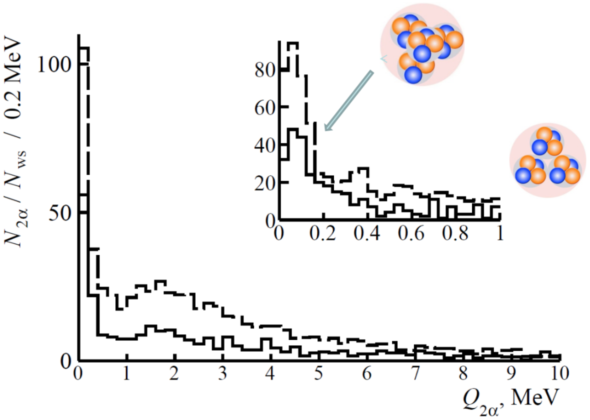




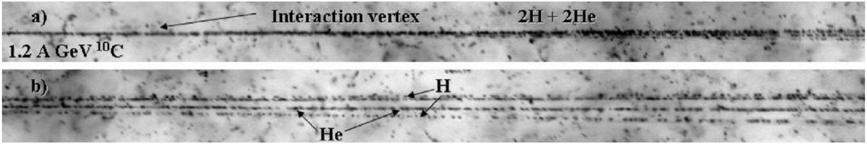
N2α / 0.2 MeV
150
100
50
0
0 1 2 3 4 5 6 7 8 9 10
Q2α, MeV
40
20
0
0 0.2 0.4 0.6 0.8 1

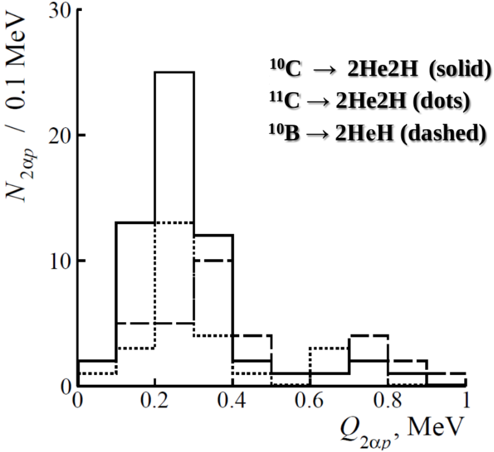


3.03
2+;0
-0.0918
2α
Jπ=0+;T=0
8Be

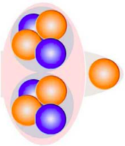


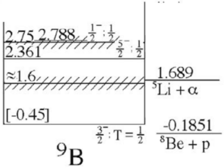
Selected under the cleanest conditions, the criterion $Q_2\alpha(^8Be) < 0.2$ MeV includes the accepted approximations, the kinematic ellipse of the ^{8}Be decay, and the resolution of angular measurements. Its application allows us to determine the ^{8}Be contribution to the statistics of "white" stars equal to $45 \pm 4\%$ for $^{12}C \rightarrow 3\alpha$ and $62 \pm 3\%$ for $^{16}O \rightarrow 4\alpha$





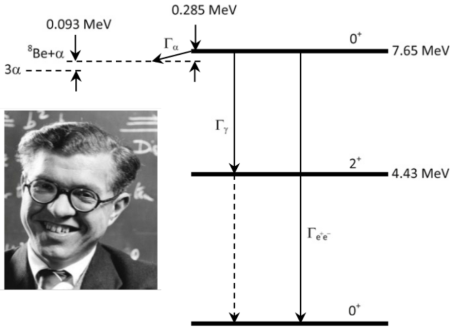
Ground state of the ^{9}B nucleus is higher than the ^{8}Bep threshold by 185 keV, and its width 0.54 keV, also indicates that it is a long-lived state

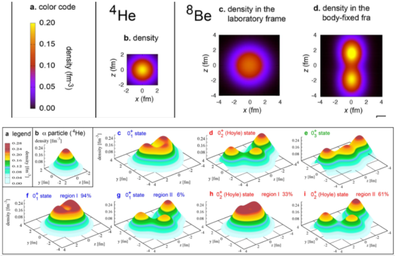




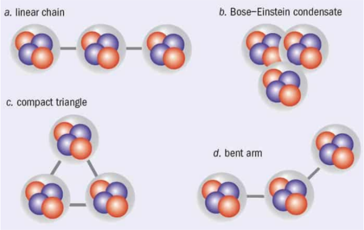
The Hoyle state of ^{12}C

The Hoyle state(HS) state is the second excited of the ^{12}C nucleus at E^{th} (HS) = 378 keV above the 3α threshold. The value τ(HS) = 9.3 $\pm$ 0.9 eV corresponds to the decay width $\pi^0 \to 2\gamma$ on the order of the magnitude.

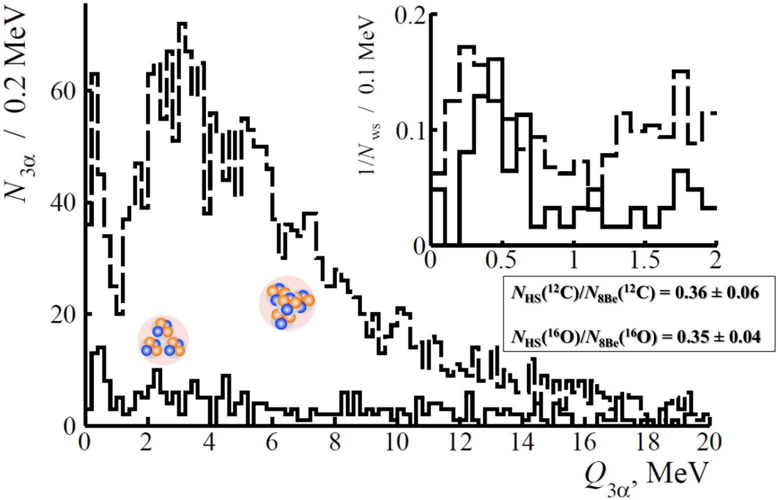




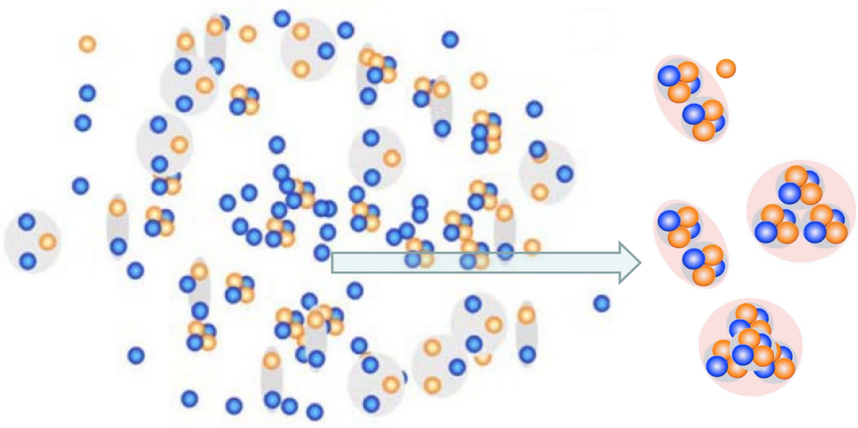
T. Otsuka et al., Nature Communication, 13, 2234, (2022)



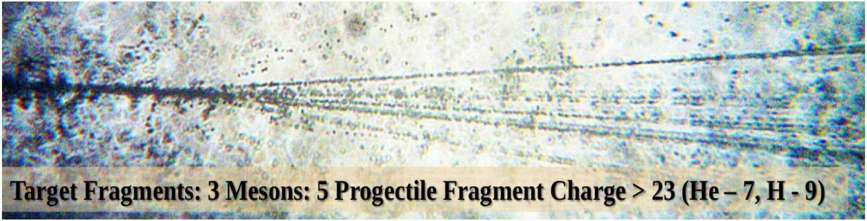
Kirsebom, The Secret of Life, Physics World, 2013

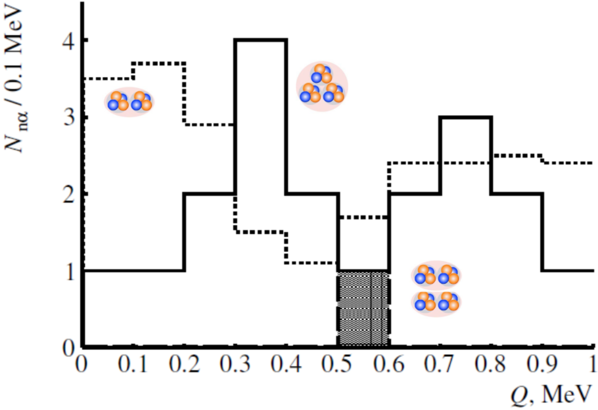


Distribution of the number of 3α-triples $N_{3\alpha}$ over the invariant mass $Q_{3\alpha}$ of 316 "white" stars $^{12}C \to 3\alpha$ (solid) and 641 "white" stars $^{16}O \to 4\alpha$ (dashed) at 3.65 A GeV.

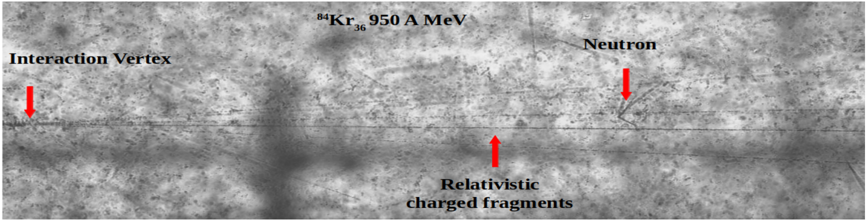


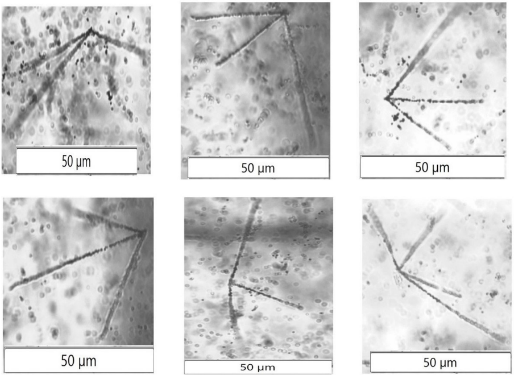
Recently, an increase in the probability of detecting ^{8}Be in an event with an increase in the number of relativistic α-particles was found, based on the statistics of dozens of ^{8}Be decays. This suggests that the contributions of ^{9}B and HS decays also increase. The exotically large sizes and lifetimes of ^{8}Be and HS allow us to suggest the possibility of synthesizing α-particle Bose-Einstein condensate (αBEC) by successively connecting the emerging α-particles.

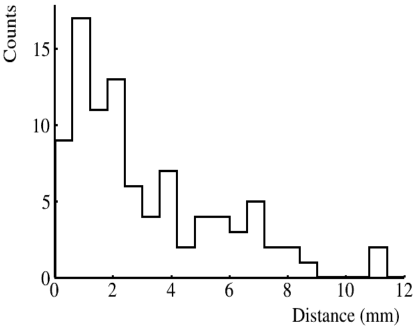

Target Fragments: 3 Mesons: 5 Progectile Fragment Charge > 23 (He – 7, H - 9)

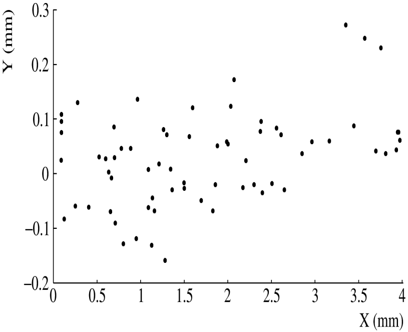

N_nα / 0.1 MeV
0
1
2
3
4
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
Q, MeV

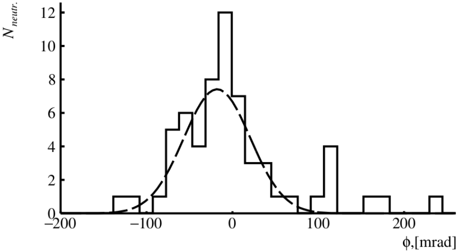
Observation of Projectile Neutrons

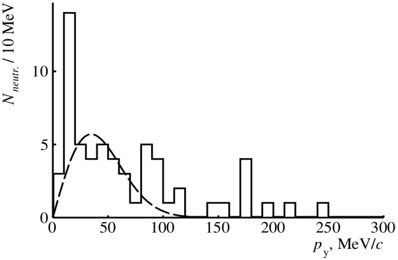


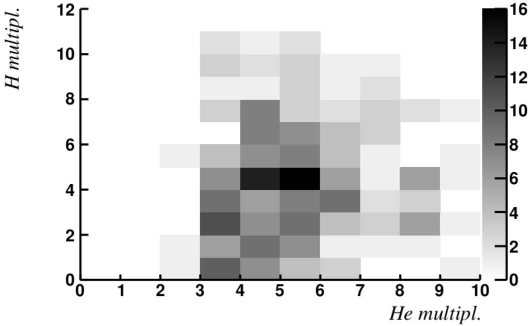


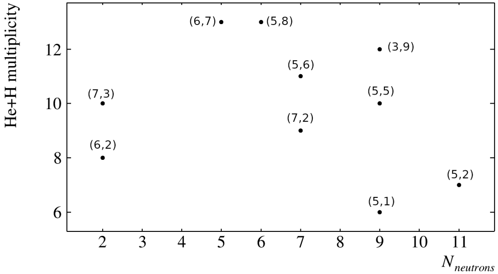

Counts
15
10
5
0
0
2
4
6
8
10
12
Distance (mm)


Y (mm)
0.3
0.2
0.1
0
−0.1
−0.2
0
0.5
1
1.5
2
2.5
3
3.5
4
X (mm)

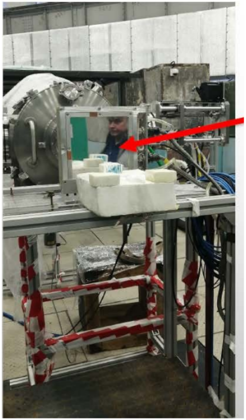

$N_{neutr.}$
12
10
8
6
4
2
0
−200
−100
0
100
200
ϕ,[mrad]

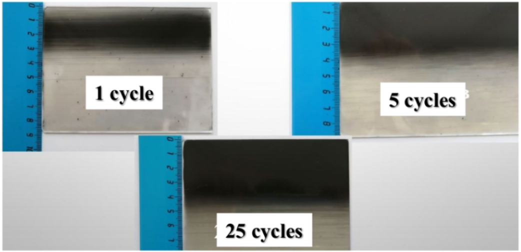

$N_{neutr.}$ / 10 MeV
10
5
0
0
50
100
150
200
250
300
p_y, MeV/c


H multipl.
He multipl.
0
2
4
6
8
10
12
0
1
2
3
4
5
6
7
8
9
10
0
2
4
6
8
10
12
14
16

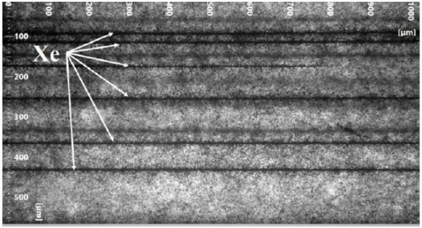

He+H multiplicity
$N_{neutrons}$
(6,7)
(5,8)
(3,9)
(5,6)
(7,3)
(5,5)
(7,2)
(6,2)
(5,2)
(5,1)
6
8
10
12
2
3
4
5
6
7
8
9
10
11

Exposure of ^{124}Xe nuclei at 3.8 GeV per nucleon (December-2022)



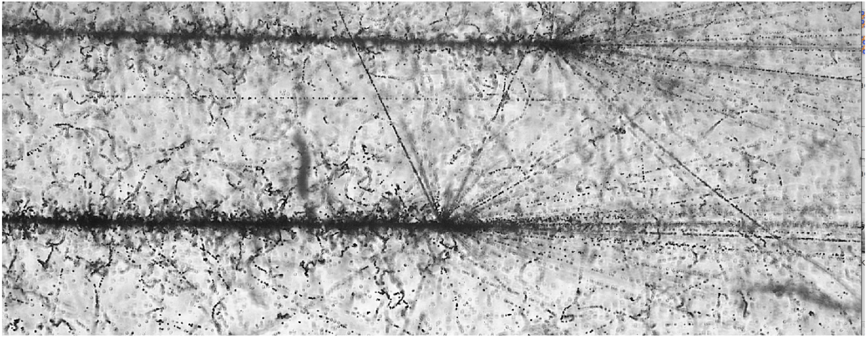


Layers of nuclear track emulsion exposed Xe nuclei for 1, 5, 25 accelerator cycles



Xe exposed emulsion at 12x, single cycle

^{124}Xe Emulsion interaction



Two Stars in View field at 40x, Xe beam single cycle

Analysis in progress

www.jinr.ru/posts/white-stars-reconstructed-at-jinr-by-nuclear-photoemulsion-method/

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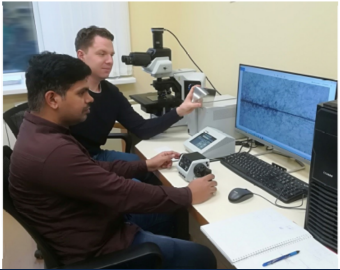
“White” stars reconstructed at JINR by nuclear photoemulsion method

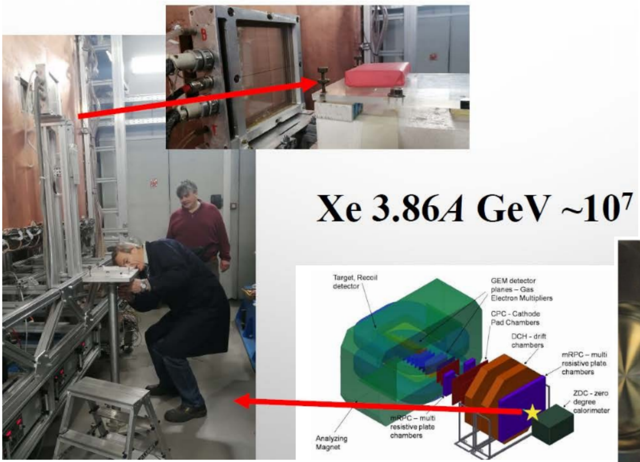
News, 30 December 2022

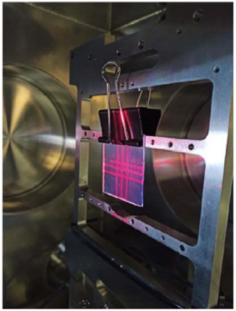
Participants of the BECQUEREL experiment (led by Pavel Zarubin) have started analysing interactions of xenon nuclei with the energy of 3 GeV/nucleon in layers of nuclear emulsion irradiated during the ongoing run at the NICA Accelerator Complex. The obtained macrophotographs of events allow scientists to see the way the interactions of the heaviest particles ever accelerated at NICA look like. It also makes it possible to reconstruct them with high accuracy.

The nuclear photographic emulsion is a suspension of silver bromide microcrystals in 180 μm (about 0.2 mm) thick gelatin layers. Such layers have great sensitivity and allow recording tracks of fragments produced during the decay of nuclei in the “analog” mode. Layers for this experiment were produced at the Micron enterprise of Slavich Company in Pereslavl-Zalessky.

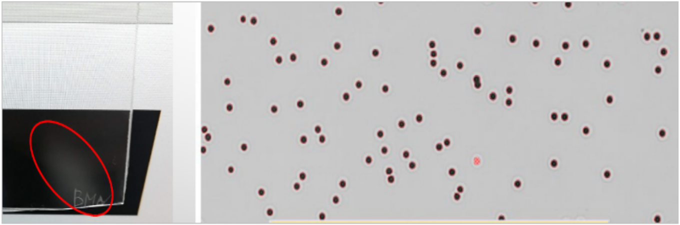


Exposure at BM@N (January-2023)

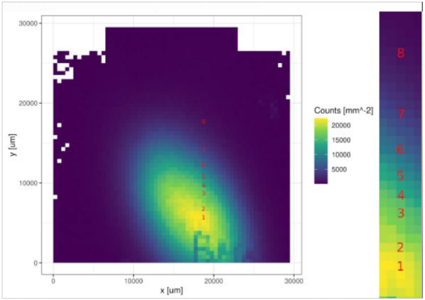




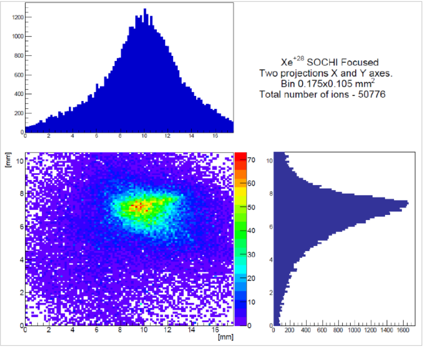
CR-39 detector in vacuum chamber of SOCHi station



Photograph of the CR-39 detector exposed Xenon nuclei (left) and its macrophotograph at 40x magnification; craters detected by the program are highlighted in red.



Nuclear beam profile at the site of irradiation of nuclear emulsion stacks after the BM@N experiment reconstructed in the CR-39 detector



Beam profile of xenon nuclei during beam focusing at the SOCHI station, reconstructed in the CR-39 detector.

Conclusions

- The BECQUEREL experiment will continue to investigate the peripheral interactions of relativistic nuclei, extending the analysis of multiple states of α-particles and nucleons to the exposures of ^{124}Xe nucleus.
- Nuclear emulsion provides the necessary resolution, completeness, and uniformity of observations for the search for αBEC. Identification of the decays $^{8}\mathrm{Be} \to 2\alpha$, $^{9}\mathrm{Be} \to 2\alpha$, and $^{12}\mathrm{C}(0_2^+) \to {}^{8}\mathrm{Be}\alpha$ (the Hoyle state) was tested by the invariant mass of light nuclei, including the radioactive ones.
- This group has recently discovered a trend of increasing ^{8}Be, ^{9}B, and $^{12}\mathrm{C}(0_2^+)$ with the growing number of α-particles for medium and heavy nuclei, suggesting the possibility of 4αBEC synthesis.
- The analysis reveals that the majority of the neutrons concentrated a region of up to 4 mm and their average transverse momentum of neutrons, including volume factor are 50 MeV/c.
- Analysis of ^{84}Kr emulsion interaction can clarify the connection between ^{8}Be, the Hoyle state, and the multiplicity of α ensembles.On this basis, it is possible to search for the decays of the $^{16}\mathrm{O}(0_6^+) \to {}^{12}\mathrm{C}(0_2^+)\alpha$ state and two ^{8}Be.

Thank you for your time !