Exploring Nuclear Clusters Through Relativistic Nucleus Fragmentation

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(BECQUEREL Experiment)

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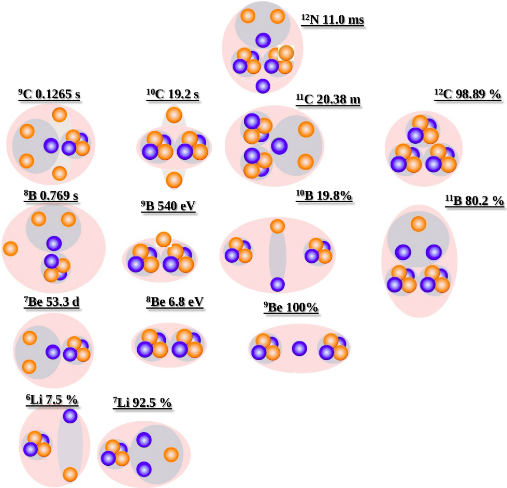
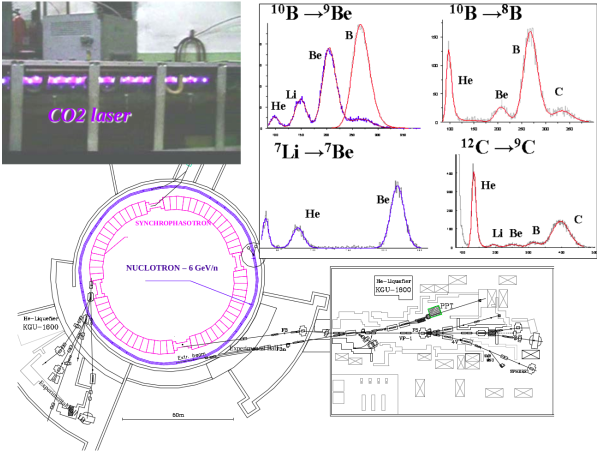
Outline

Nuclear Clusters

- The structure of light nuclei, characterized by spin-paired proton and neutron quartets, leads to the prominent formation of α particles in various nuclear reactions and decays.



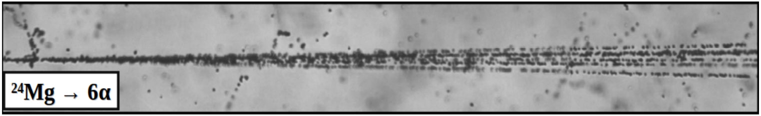
BECQUEREL Experiment

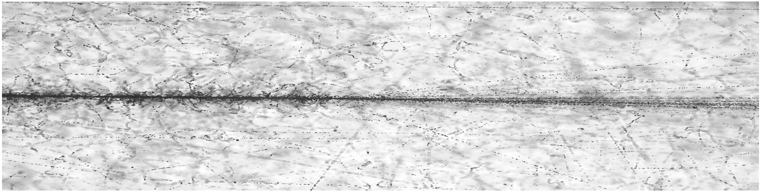


- Nuclear Track Emulsion (NTE) method is used in the BECQUEREL experiment at the JINR Nuclotron to study fragmentation of light stable nuclei and including radioactive nuclei.
- The features of the nuclei ^{7,9}Be, ^{8,10,11}B, ^{10,11,12}C and ^{12,14}N appeared in the probabilities of their dissociation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

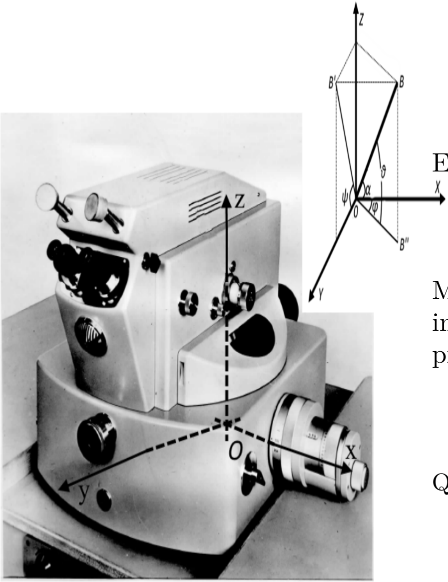
Nuclear Track Emulsion

α-fragmentation of relativistic nuclei





- Electronic experiments in this field encounter fundamental limitations: the quadratic dependence of ionization on nuclear charge, the ultra-narrow angular divergence of relativistic fragments, and their frequent magnetic rigidity overlap with beam nuclei. Thus, the NTE method remains unparalleled for studying relativistic fragmentation.
- 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.

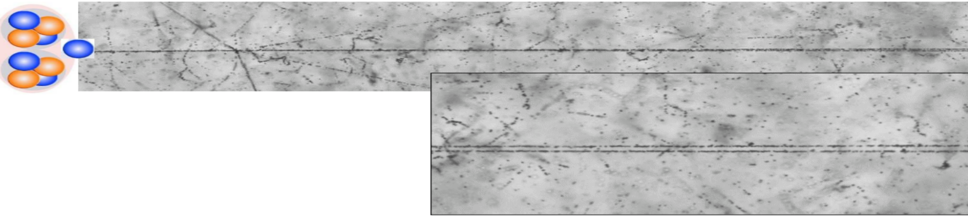


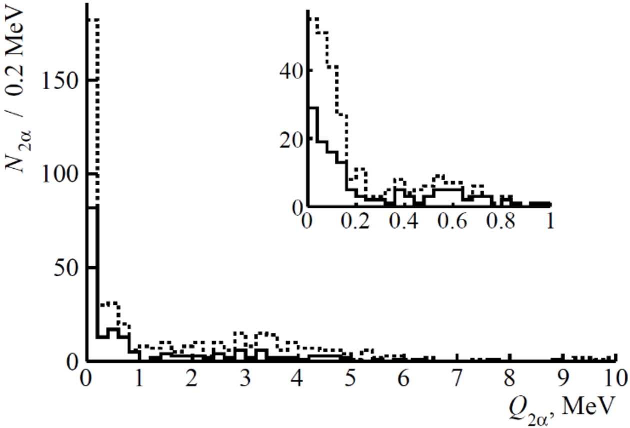
Energy of a few-particle system

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

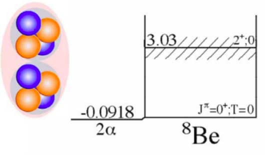
$M^{*2} = \sum(P_j)^2 = \sum(P_i.P_k)$, is the invariant mass defined by the sum of all products of 4-momenta $P_{i,k}$ fragments.

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

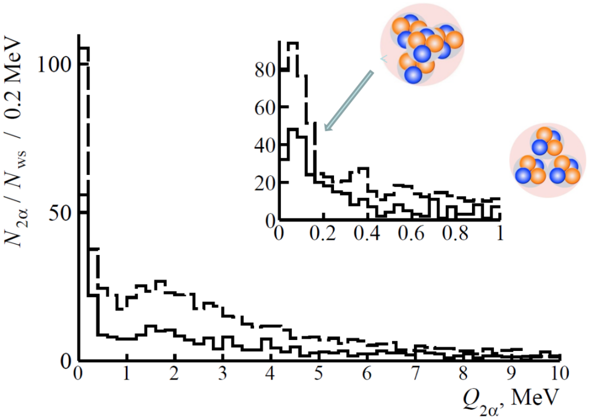




$N_{2\alpha}$ / 0.2 MeV
150
100
50
0
0 1 2 3 4 5 6 7 8 9 10
$Q_{2\alpha}$, MeV
40
20
0
0 0.2 0.4 0.6 0.8 1



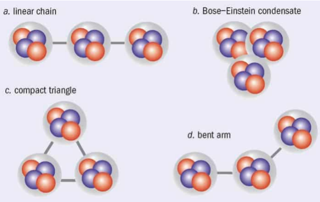
3.03
2⁺;0
-0.0918
2α
J^π=0⁺;T=0
⁸Be



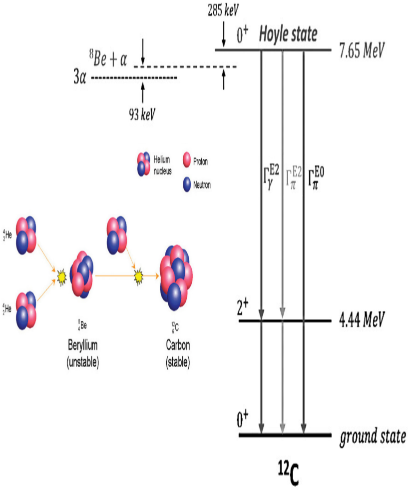
Selected under the cleanest conditions, the criterion $Q_2\alpha(^8Be) < 0.2$ MeV includes the accepted approximations, the kinematic ellipse of the ^{8}Be decay, and the resolution of angular measurements. Its application allows us to determine the ^{8}Be contribution to the statistics of "white" stars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

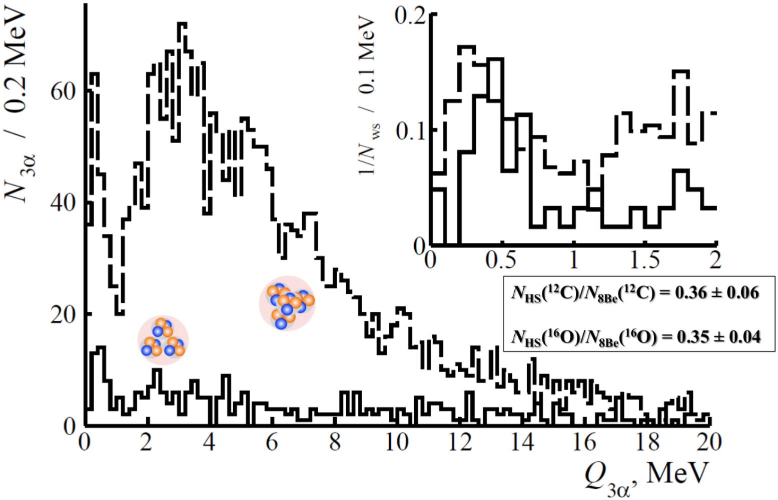
The Hoyle state of ^{12}C

The Hoyle state (HS) is the second excited state of the ^{12}C nucleus, located at an excitation energy of 378 keV above the 3α threshold. Its lifetime, $\tau(\text{HS}) = 9.3 \pm 0.9$ eV, corresponds in magnitude to the decay width of the $\pi^0 \rightarrow 2\gamma$ process.

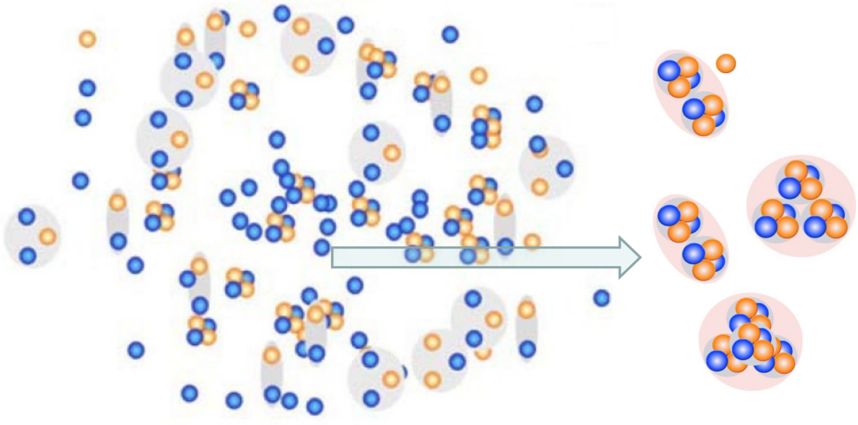


Kirsebom, The Secret of Life, Physics World, 2013





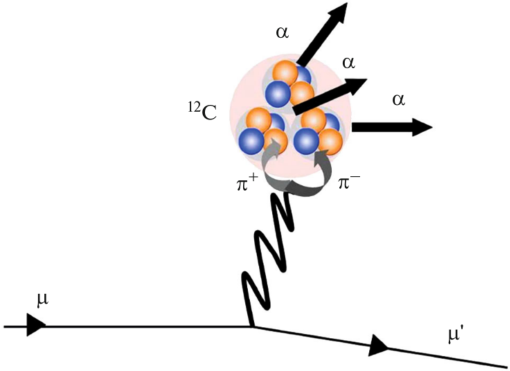
Distribution of the number of 3α-triples $N_{3\alpha}$ over the invariant mass $Q_{3\alpha}$ of 316 "white" stars $^{12}C \to 3\alpha$ (solid) and 641 "white" stars $^{16}O \to 4\alpha$ (dashed) at 3.65 A GeV.

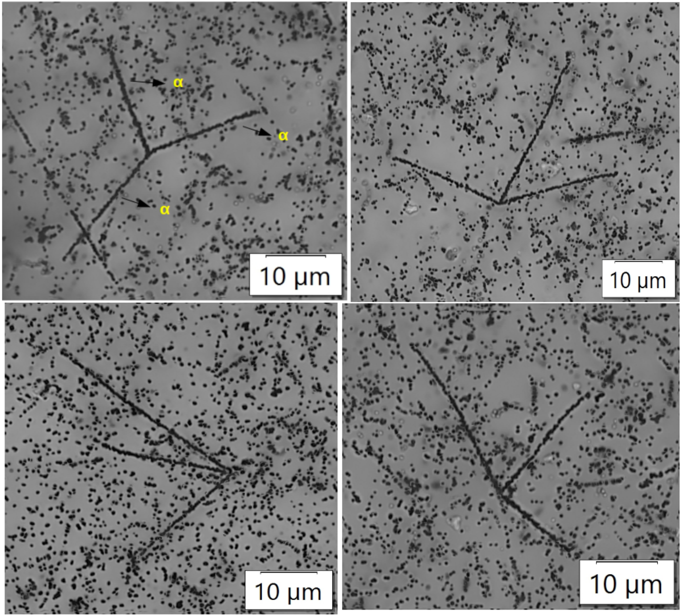


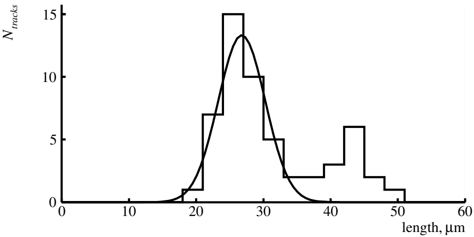
Recently, an increase in the probability of detecting ^{8}Be in an event with an increase in the number of relativistic α-particles was found, based on the statistics of dozens of ^{8}Be decays. This suggests that the contributions of ^{9}B and HS decays also increase. The exotically large sizes and 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.

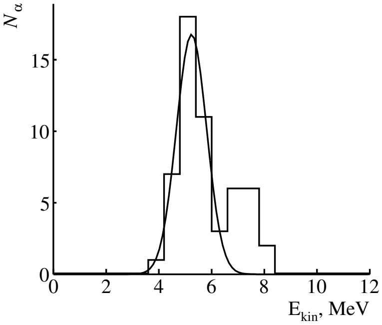
Exposure of NTE to Relativistic Muons

- NTE samples were transversely exposed to relativistic muons at 160 GeV.
- This study explores nuclear fragmentation induced by relativistic muons, focusing on the identification of short-range alpha-particle tracks resulting from the reaction $\mu + {}^{12}\mathrm{C} \to \mu' + 3\alpha$.
- SRIM simulations enabled precise energy loss and kinetic energy reconstructions, while track geometry analysis provided emission angles and invariant mass spectra.

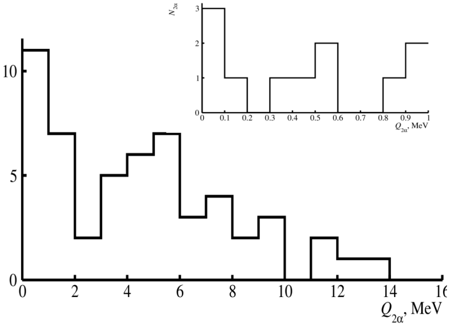



α
α
α
10 μm
10 μm
10 μm
10 μm

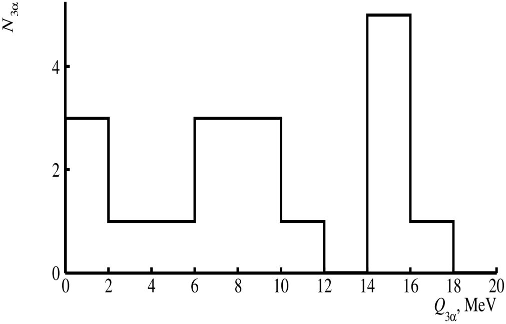




Alpha-particles ranges and emission angles were determined from track coordinate measurements, revealing a mean range of 26.78 ± 0.67 μm (RMS $= 7.7$ μm); energy was estimated using the SRIM model, with a mean value of 5.2 ± 0.09 MeV (RMS $= 1.03$ MeV).

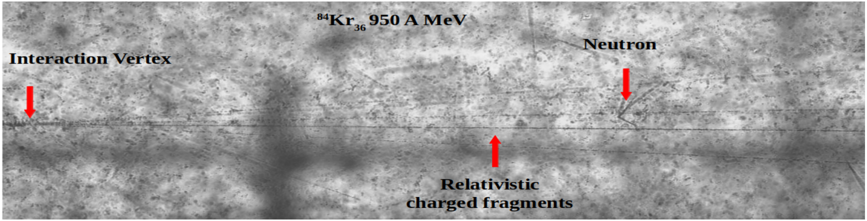


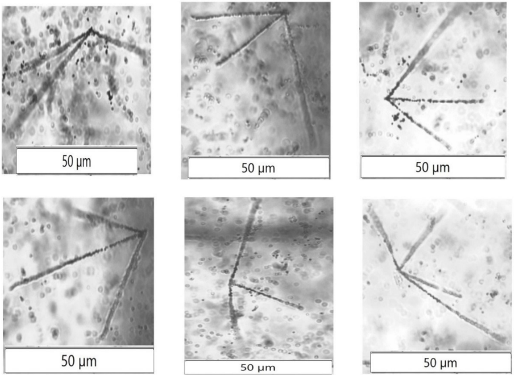
10
5
0
0
2
4
6
8
10
12
14
16
$Q_{2\alpha}$, MeV
$N_{2\alpha}$
3
2
1
0
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
$Q_{2\alpha}$, MeV

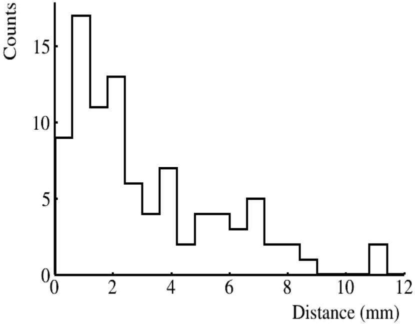


$N_{3\alpha}$
4
2
0
0
2
4
6
8
10
12
14
16
18
20
$Q_{3\alpha}$, MeV

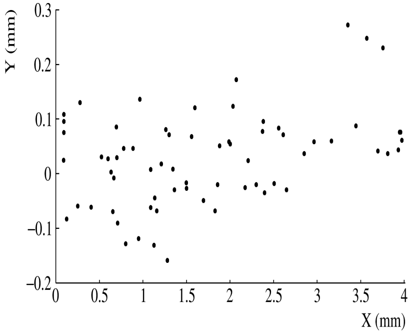
Observation of Projectile Neutrons



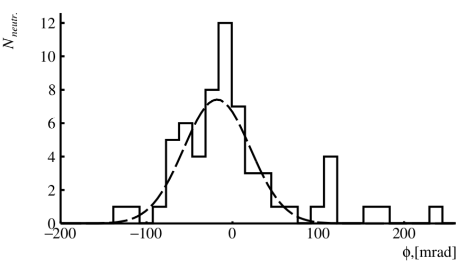




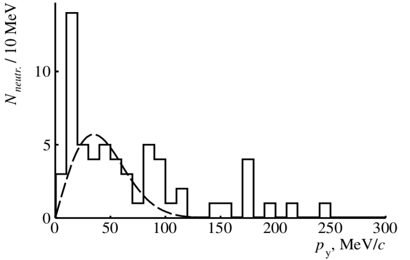
Counts
15
10
5
0
0
2
4
6
8
10
12
Distance (mm)



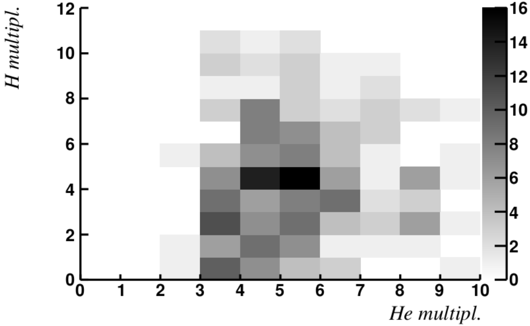
Y (mm)
0.3
0.2
0.1
0
−0.1
−0.2
0
0.5
1
1.5
2
2.5
3
3.5
4
X (mm)

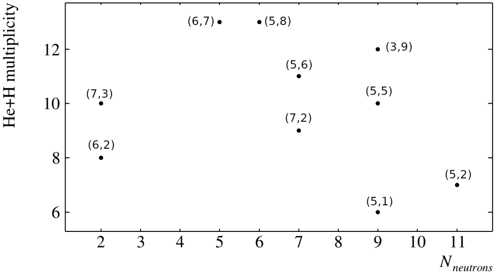


$N_{neutr.}$
12
10
8
6
4
2
0
−200
−100
0
100
200
ϕ,[mrad]



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


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


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)

Summary

- Nuclear emulsion provides the high spatial resolution, completeness, and uniformity necessary for investigating α-particle Bose-Einstein condensation (αBEC). The identification of key decay channels-^{8}Be $\rightarrow 2\alpha$, ^{9}Be $\rightarrow 2\alpha$, and ^{12}C(0_2^+) $\rightarrow$ ^{8}Be+α (Hoyle state) was performed through invariant mass analysis of light nuclei, including radioactive isotopes.
- Muon-induced alpha-particle ranges and emission angles were determined from track coordinate measurements, with energies estimated using the SRIM model. Future work will focus on calculating the reaction cross section for ^{12}C-μ interactions, which are important for analyzing natural gas fields. While helium is typically associated with U/Th decay, it can also result from muon-induced reactions with ^{12}C. Accurate cross-section data will enable better estimates of gas field age and volume.
- The group has recently identified a trend of increasing production of ^{8}Be, ^{9}B, and ^{12}C(0_2^+) with a growing number of α-particles in medium and heavy nuclei, suggesting the potential formation of a 4α Bose-Einstein condensate (BEC).


Thank you for your time !