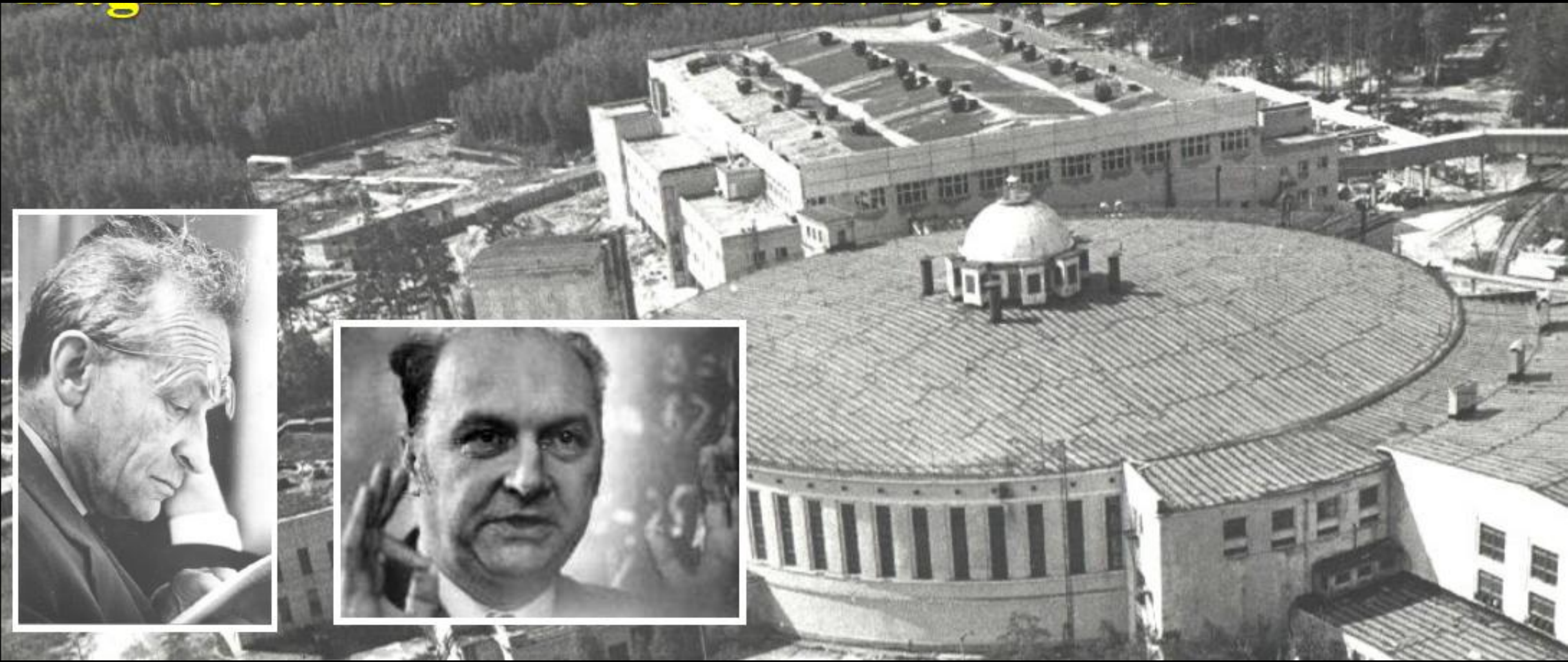
BECQUEREL
PROJECT

Проект
БЕККЕРЕЛЬ

Beryllium (Boron)
Clustering
Quest in
Relativistic Multifragmentation

http://becquerel.jinr.ru

Pavel Zarubin ”Unstable nuclei ^{8}Be and ^{9}B and the Hoyle state in relativistic nuclear fragmentation”



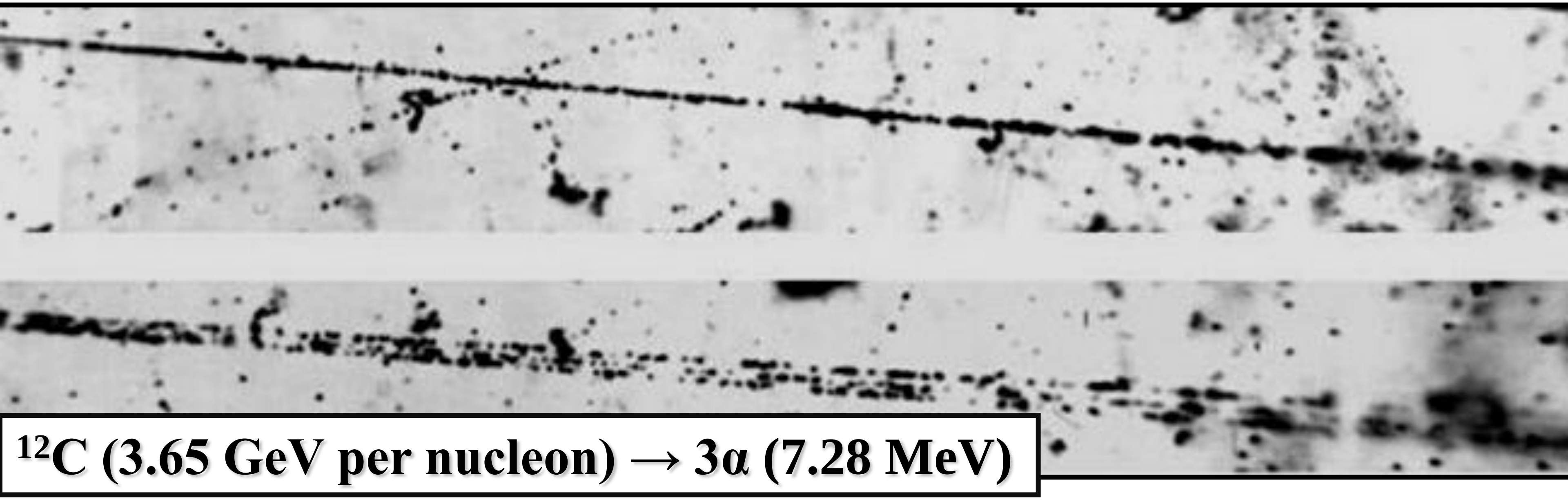
V.I. Veksler and A.M. Baldin Laboratory of High Energy Physics
Joint Institute for Nuclear Research, Dubna

Hair - 60 μm

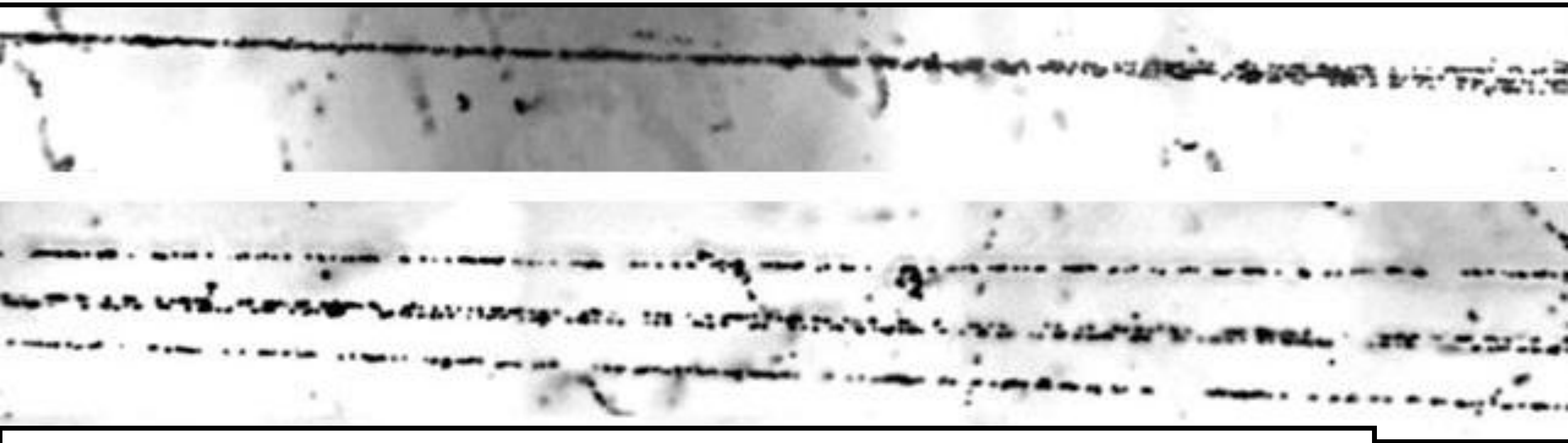
AgBr Crystal - 0.2 μm

Atom - 10^{-4} μm

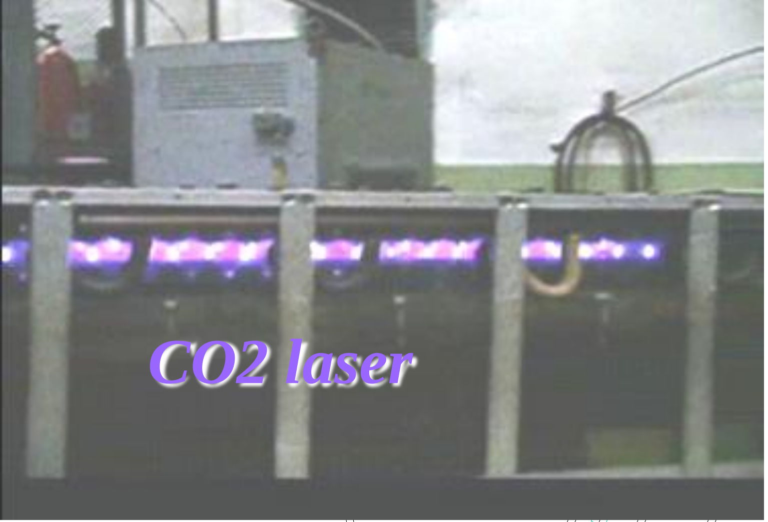
Proton - 10^{-9} μm

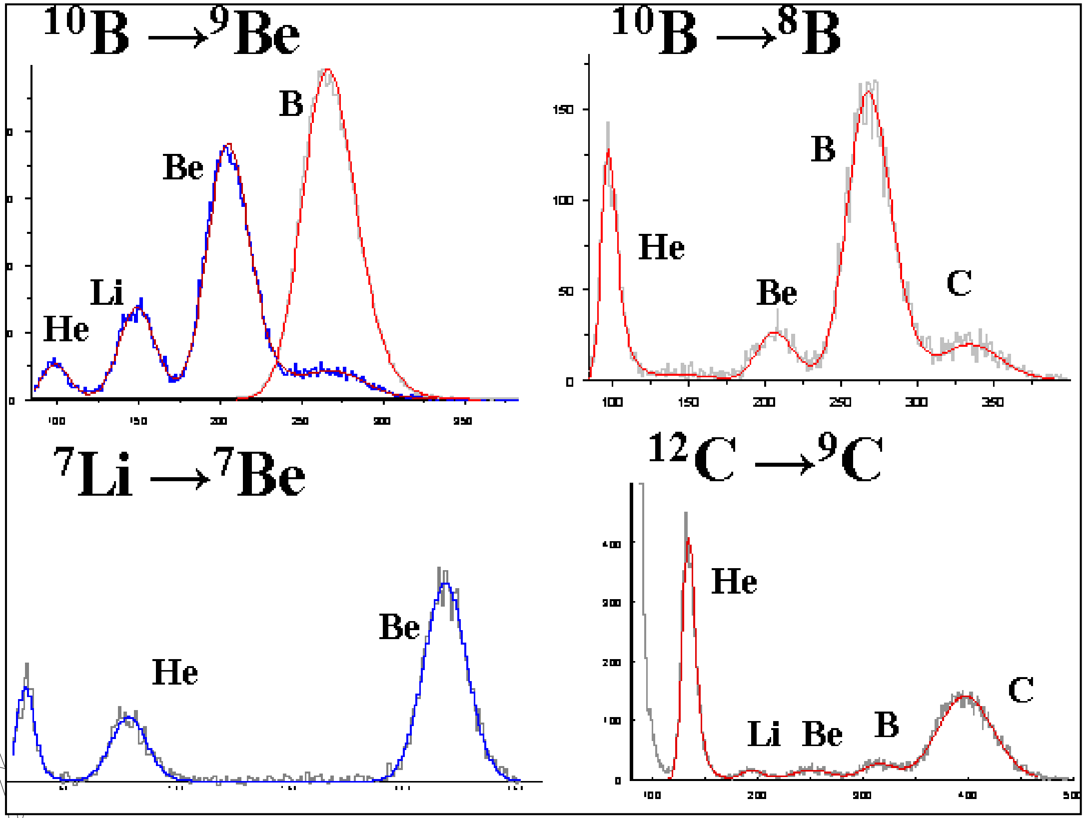


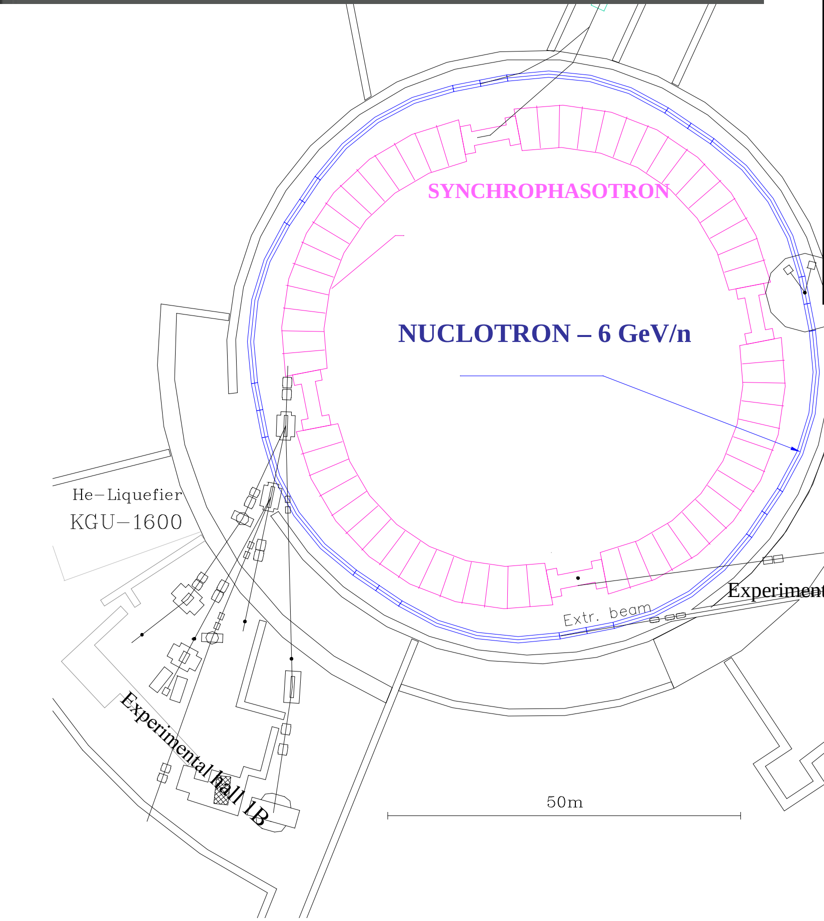
^{12}C (3.65 GeV per nucleon) → 3α (7.28 MeV)

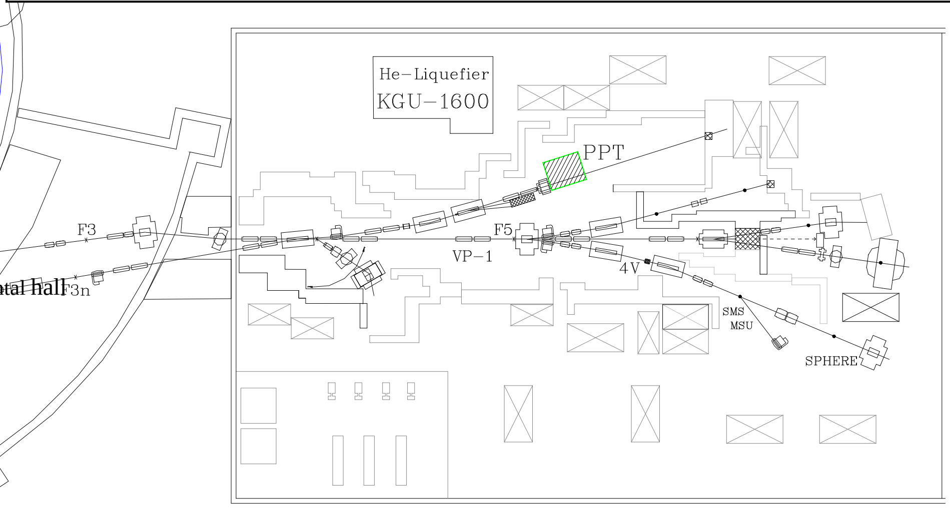


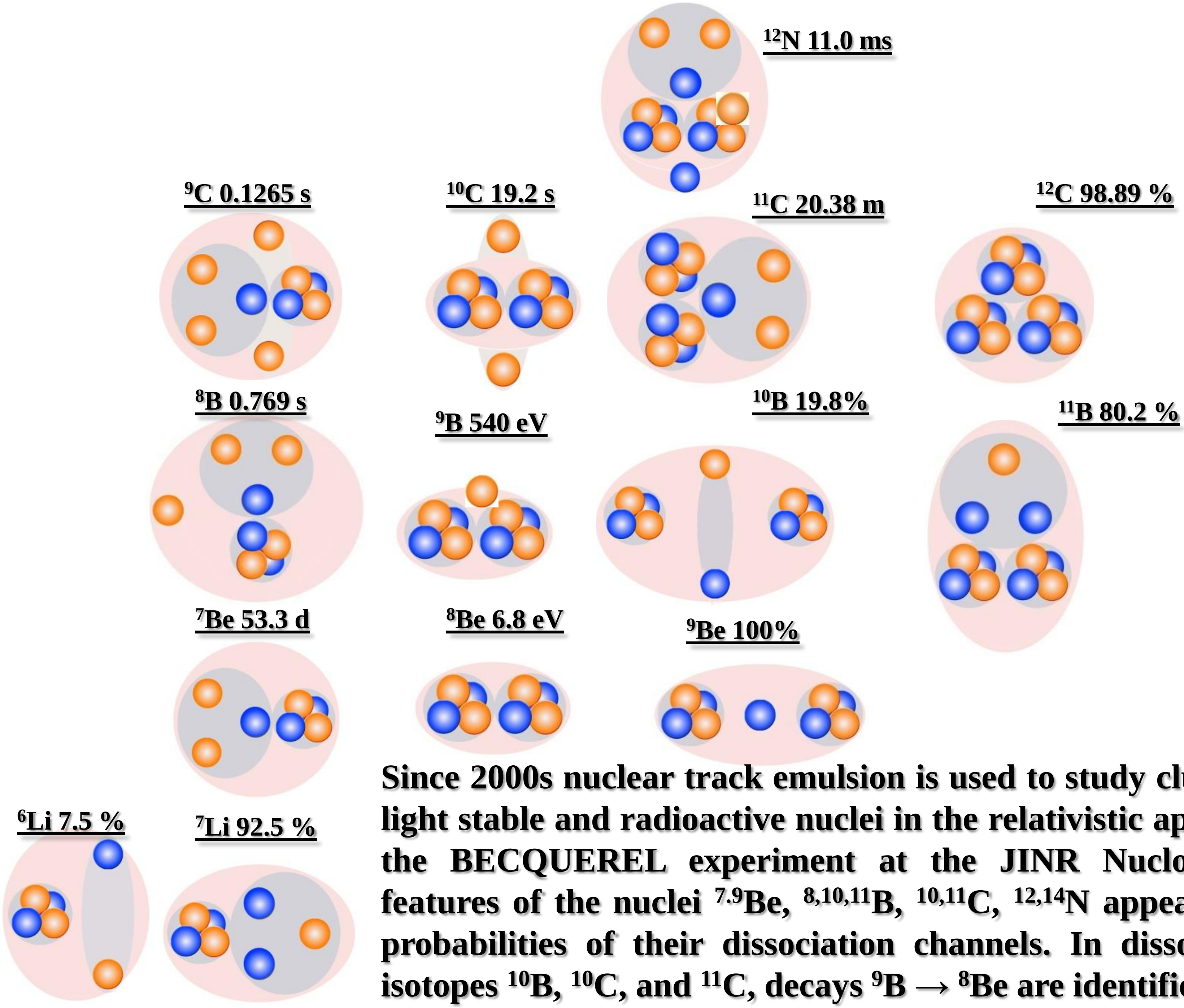
^{16}O (3.65 GeV per nucleon) → 2α^{8}Be(2α, 92 keV, Γ = 5.6 eV)


CO2 laser

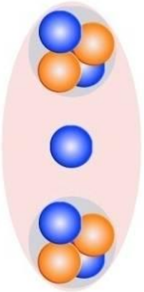

$^{10}B \rightarrow {}^{9}Be$
He
Li
Be
B
100
150
200
250
300
350
$^{10}B \rightarrow {}^{8}B$
He
Be
B
C
0
50
100
150
100
150
200
250
300
350
$^{7}Li \rightarrow {}^{7}Be$
He
Be
$^{12}C \rightarrow {}^{9}C$
He
Li
Be
B
C
0
100
200
300
400
100
200
300
400
500

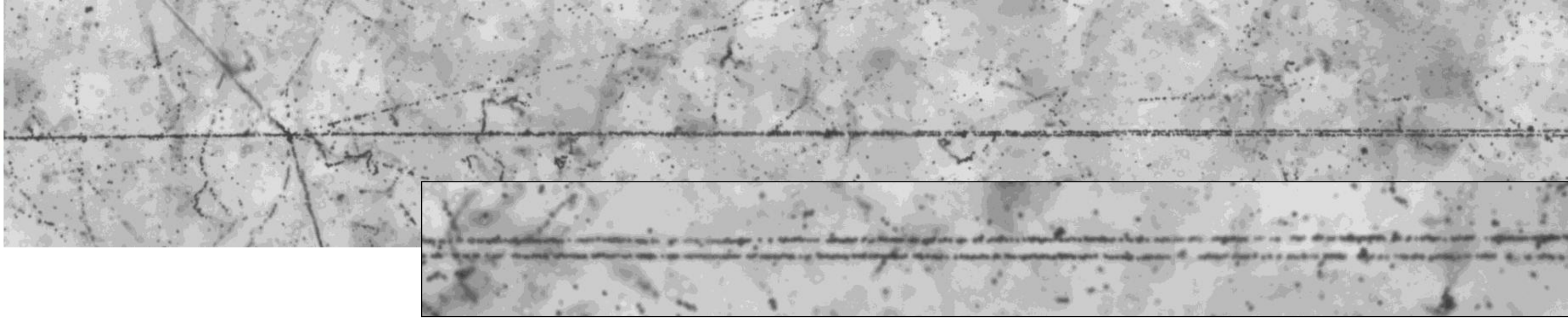

SYNCHROPHASOTRON
NUCLOTRON – 6 GeV/n
He–Liquefier
KGU–1600
Extr. beam
Experimental hall 1B
50m


Experimental hall
F3
F3n
He–Liquefier
KGU–1600
PPT
F5
VP–1
4V
SMS
MSU
SPHERE

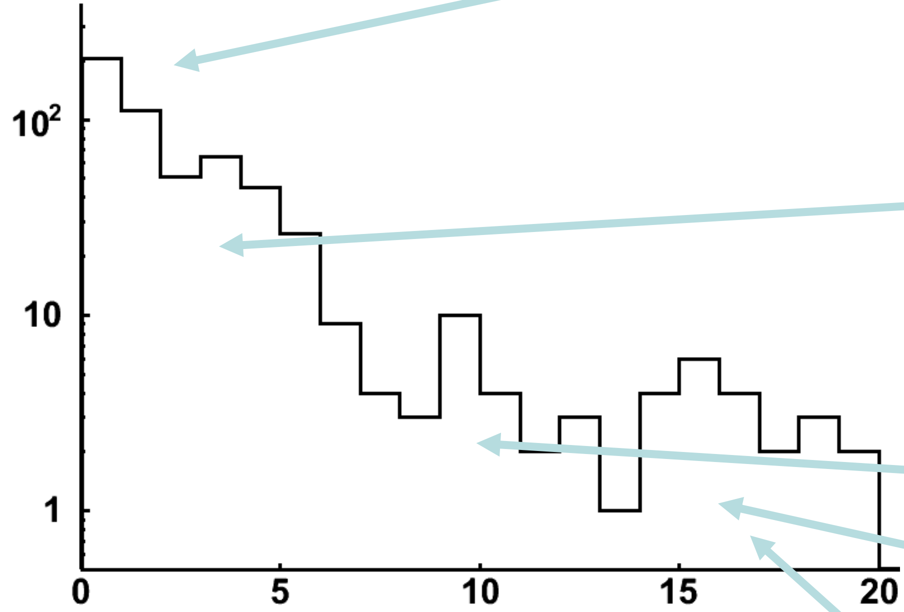


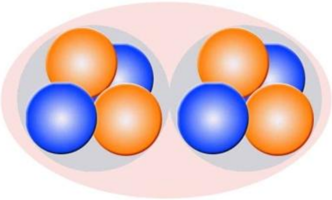
Since 2000s nuclear track emulsion is used to study clustering of light stable and radioactive nuclei in the relativistic approach in the BECQUEREL experiment at the JINR Nuclotron. The features of the nuclei $^{7.9}$Be, ^{8,10,11}B, ^{10,11}C, ^{12,14}N appeared in the probabilities of their dissociation channels. In dissociation of isotopes ^{10}B, ^{10}C, and ^{11}C, decays $^{9}B \rightarrow {}^{8}Be$ are identified

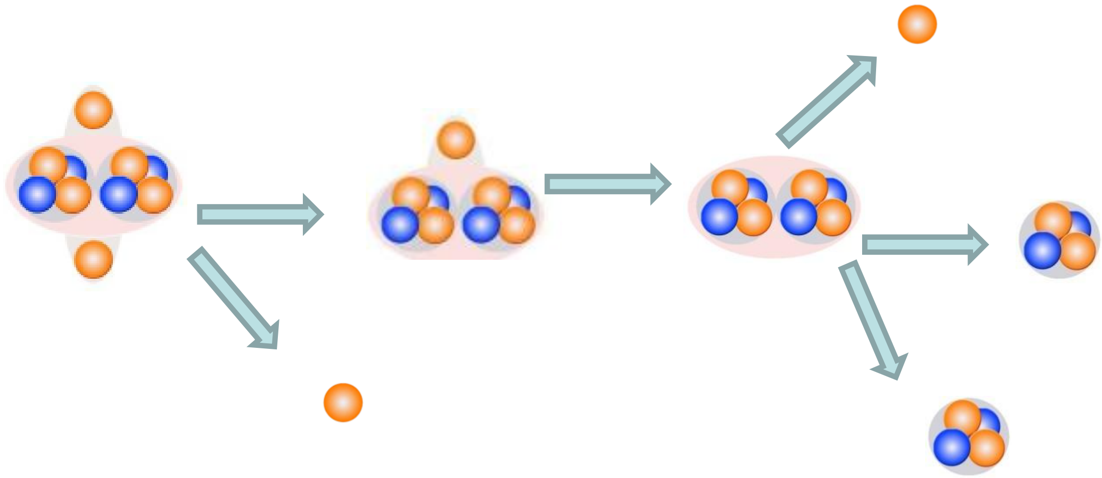




573 ^{9}Be (1.2 *A* GeV) → 2α

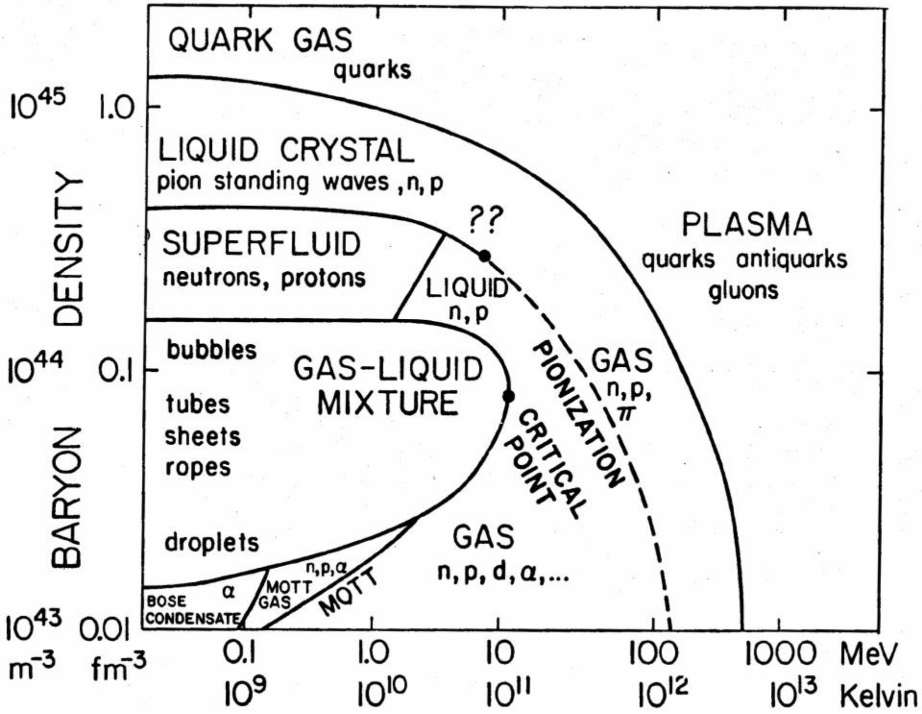


E_x (MeV ± keV)	$J^\pi; T$	Γ_{cm} (keV)	Decay
g.s.	$0^+; 0$	5.57 ± 0.25 eV [i]	α
			
3.03 ± 10 [i]	$2^+; 0$	1513 ± 15 [i]	α
i,j	2^+		
11.35 ± 150 [i]	$4^+; 0$	≈ 3500[b]	α
16.626 ± 3	$2^+; 0+1$	108.1 ± 0.5	γ, α
16.922 ± 3	$2^+; 0+1$	74.0 ± 0.4	γ, α
17.640 ± 1.0 [f]	$1^+; 1$	10.7 ± 0.5	γ, p



Channel	N_{ws}, %	N_{tf}, %
2He + 2H	186 (81.9)	361 (57.6)
He + 4H	12 (5.3)	160 (25.5)
3He	12 (5.3)	15 (2.4)
6H	9 (4.0)	30 (4.8)
Be + He	6 (2.6)	17 (2.7)
B + H	1 (0.4)	12 (1.9)
Li + 3H	1 (0.4)	2 (0.3)
$^9\mathrm{C} + n$	–	30 (4.8)

E_x [a] (MeV ± keV)	$J^\pi; T$	$\Gamma_{\mathrm{c.m.}}$ (keV)
g.s.	$\frac{3}{2}^-; \frac{1}{2}$	0.54 ± 0.21
≈ 1.6 [b]		
2.361 ± 5	$\frac{5}{2}^-; \frac{1}{2}$	81 ± 5
2.75 ± 300 [c]	$\frac{1}{2}^-; \frac{1}{2}$	3130 ± 200
2.788 ± 30	$\frac{5}{2}^+; \frac{1}{2}$	550 ± 40
4.3 ± 200 [d]		1600 ± 200
6.97 ± 60	$\frac{7}{2}^-; \frac{1}{2}$	2000 ± 200
11.65 ± 60 [e]	$(\frac{7}{2})^-; \frac{1}{2}$	800 ± 50
12.19 ± 40 [f]	$\frac{5}{2}^-; \frac{1}{2}$	450 ± 20
14.01 ± 70	$\pi = -; \frac{1}{2}$	390 ± 110
14.6550 ± 2.5	$\frac{3}{2}^-; \frac{3}{2}$	0.395 ± 0.042
14.7 ± 200 [g]	$(\frac{5}{2})^-; \frac{1}{2}$	1350 ± 200
15.29 ± 40	$T = \frac{1}{2}$	
15.58 ± 40	$T = \frac{1}{2}$	
16.024 ± 25	$T = (\frac{1}{2})$	180 ± 16
16.71 ± 100 [h]	$(\frac{5}{2}^+); (\frac{1}{2})$	
17.076 ± 4	$\frac{1}{2}^-; \frac{3}{2}$	22 ± 5
17.190 ± 25		120 ± 40
17.54 ± 100 [h,i]	$(\frac{7}{2}^+); (\frac{1}{2})$	

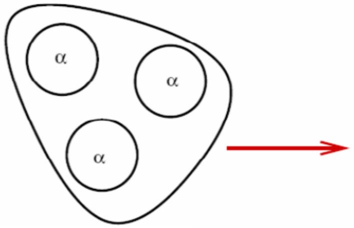


Alpha-Clusters in Nuclear Systems

P. Schuck

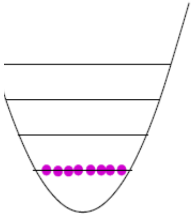
Y. Funaki, H. Horiuchi, G. Röpke,
A. Tohsaki , W. von Oertzen and T. Yamada

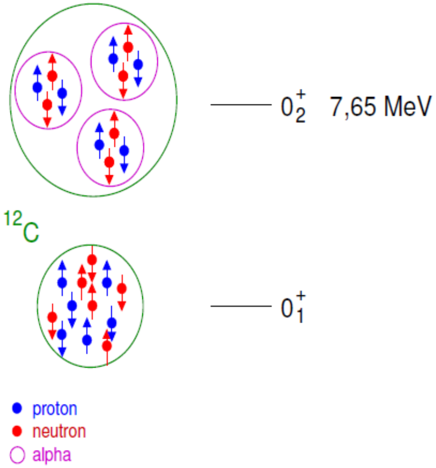
If 0_2^+ in ^{12}C dilute $\alpha-$state



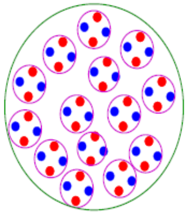
then α-condensate

infinite matter $\rho_{crit} \sim \frac{\rho_0}{3}$





many α's
→ condensate



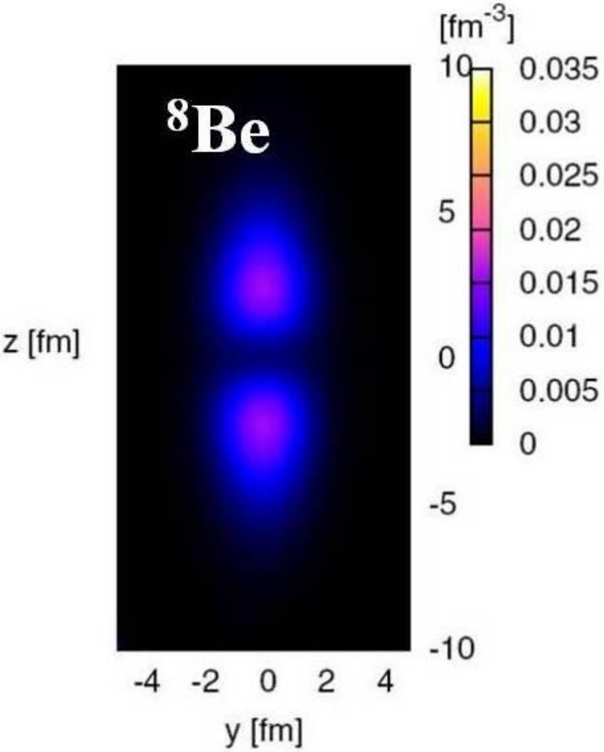
strong cluster
phenomena in
lighter nuclei

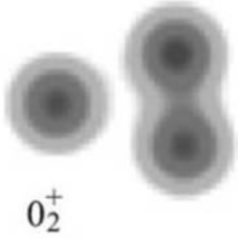
Currently, a research focus is on the theoretical concept of α-particle Bose-Einstein condensate (αBEC) - the ultra cold state of several S-wave α-particles near coupling thresholds. The unstable ^{8}Be nucleus is described as 2αBEC, and the $^{12}C(0^+_2)$ excitation or Hoyle state (HS) as 3αBEC. Decays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

Light clusters in nuclei and nuclear matter: Nuclear structure and decay, heavy ion collisions, and astrophysics

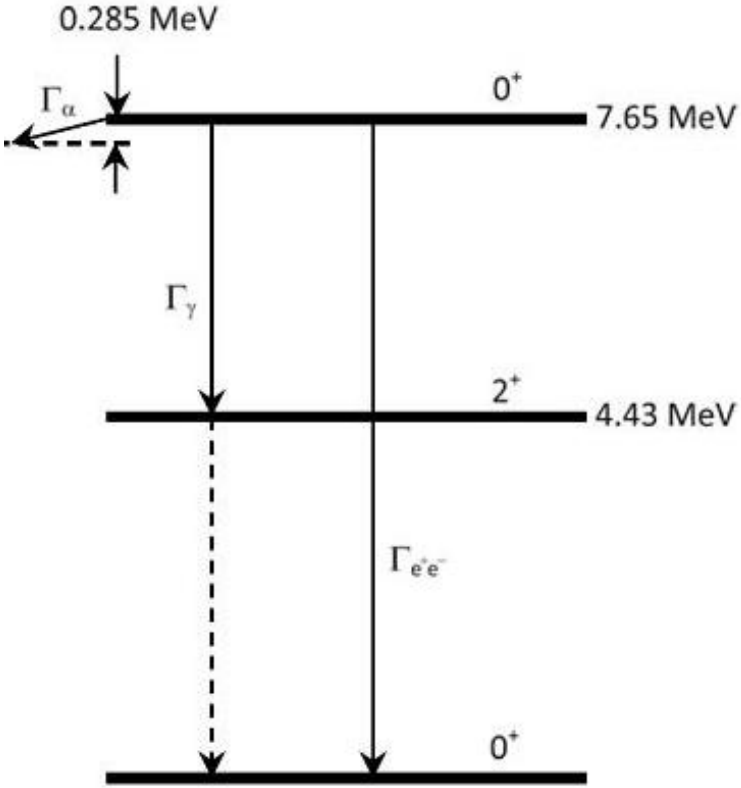
2-6 September 2019
ECT* - Villa Tambosi

The Hoyle state is the second excited state of ^{12}C at 378 keV above the 3α threshold. The ^{8}Be nucleus inevitably appears among products of ^{9}B and Hoyle state decays.

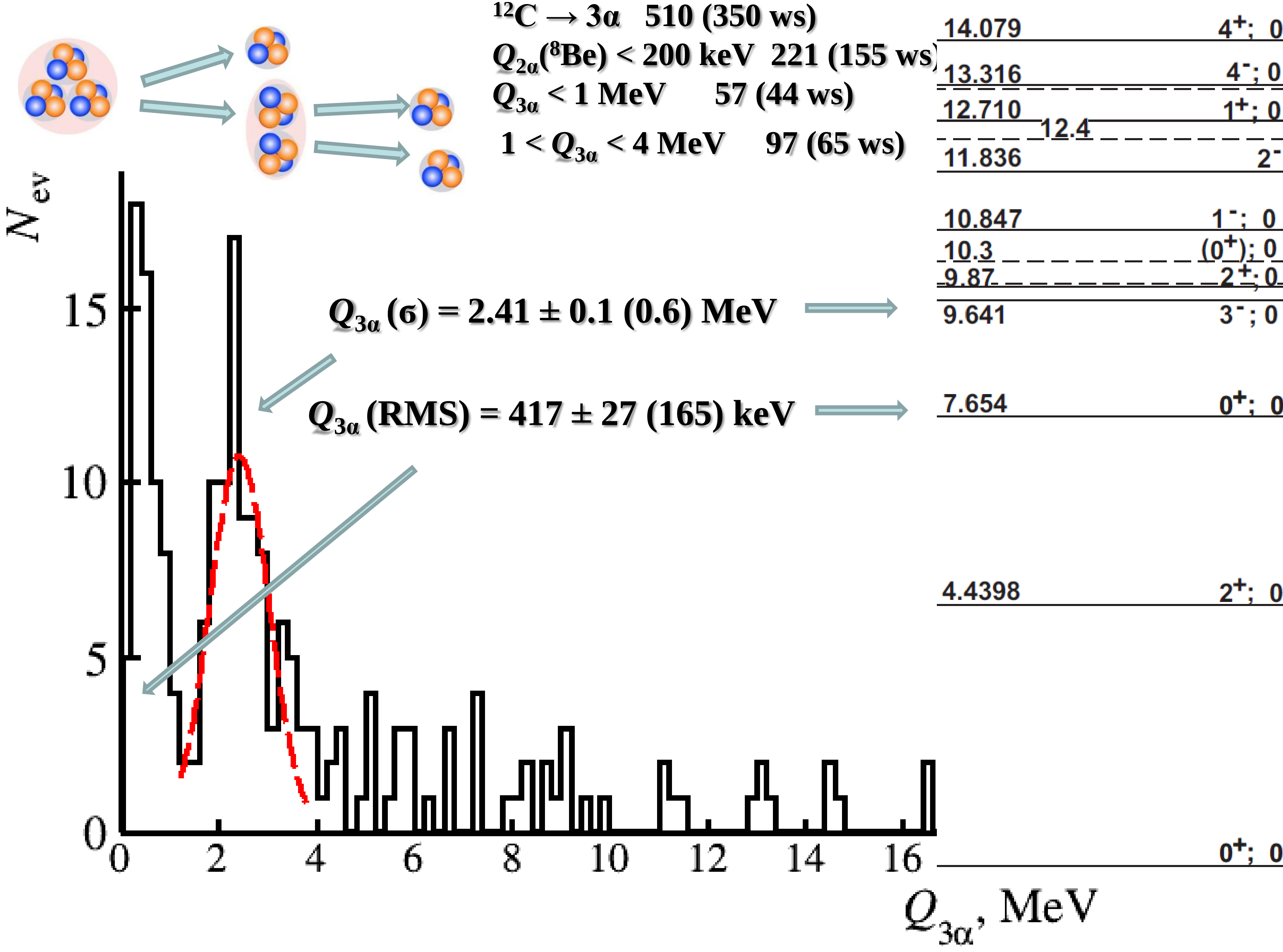




The Hoyle state



An isolated position of the Hoyle state. at the beginning of the ^{12}C excitation spectrum and its width 9.3 eV render ita 3α analog of ^{8}Be. The synthesis of ^{12}C in the red-giant medium is possible via the fusion reaction 3α → α^{8}Be →12C(0^+_2) →^{12}C (+2γ or e^+e^- with a probability of about 10^{-4}). A further synthesis via the fusion reaction α^{12}C →^{16}Oγ through a ^{16}O level at an appropriate energy is forbidden in parity. This is the circumstance that determines the relative abundances of ^{12}C and ^{16}O, as well as the survival of ^{12}C under the astrophysical conditions of helium burning. However, the synthesis of ^{16}O is possible through the sequence ^{12}C^{12}C →^{12}C^{12}C(0^+_2) →^{16}O^{8}Be.



$^{12}C \to 3\alpha$ 510 (350 ws)

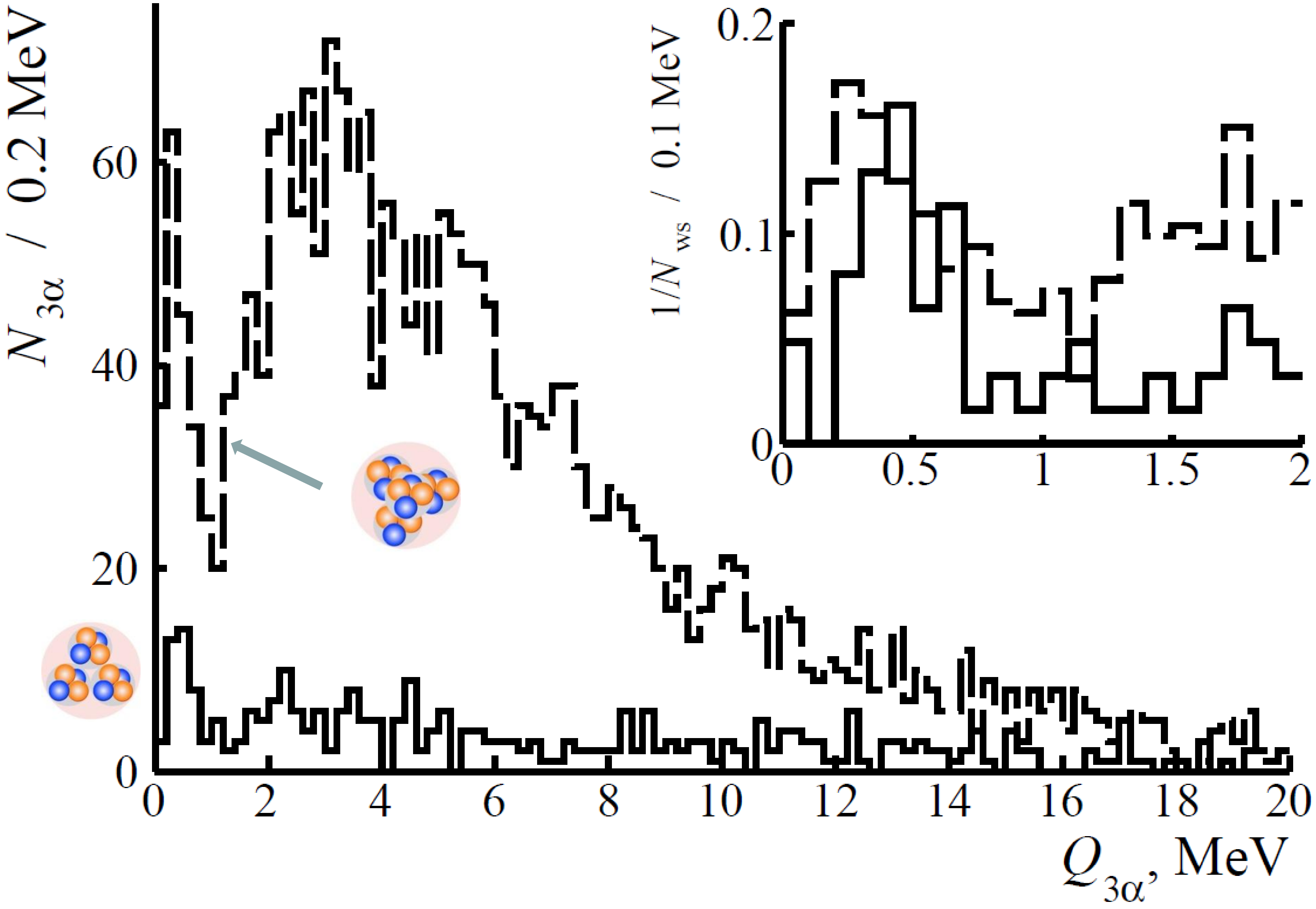
$Q_{2\alpha}(^{8}Be) < 200$ keV 221 (155 ws)

$Q_{3\alpha} < 1$ MeV 57 (44 ws)

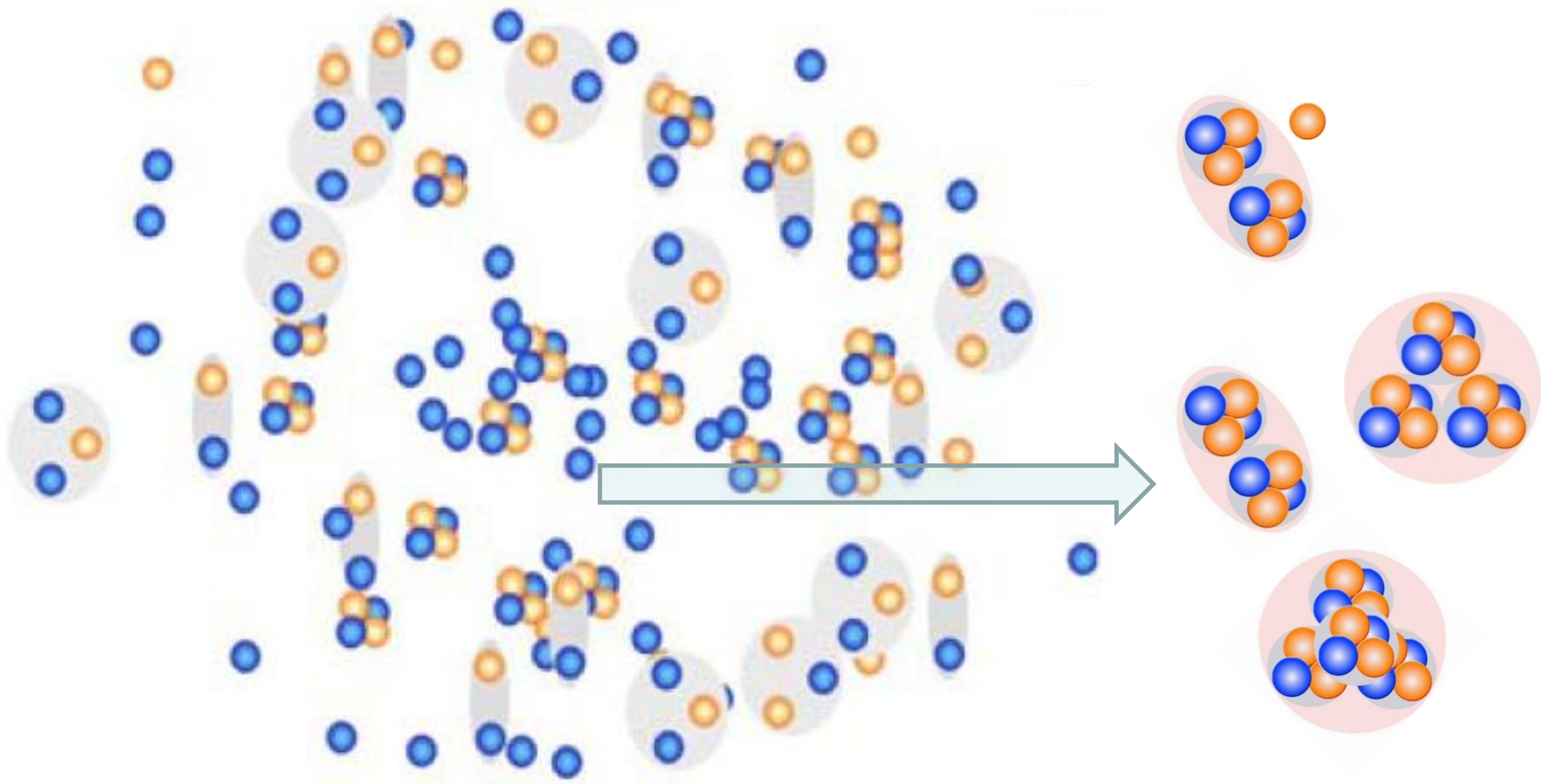
$1 < Q_{3\alpha} < 4$ MeV 97 (65 ws)

$Q_{3\alpha}$ (σ) = 2.41 ± 0.1 (0.6) MeV

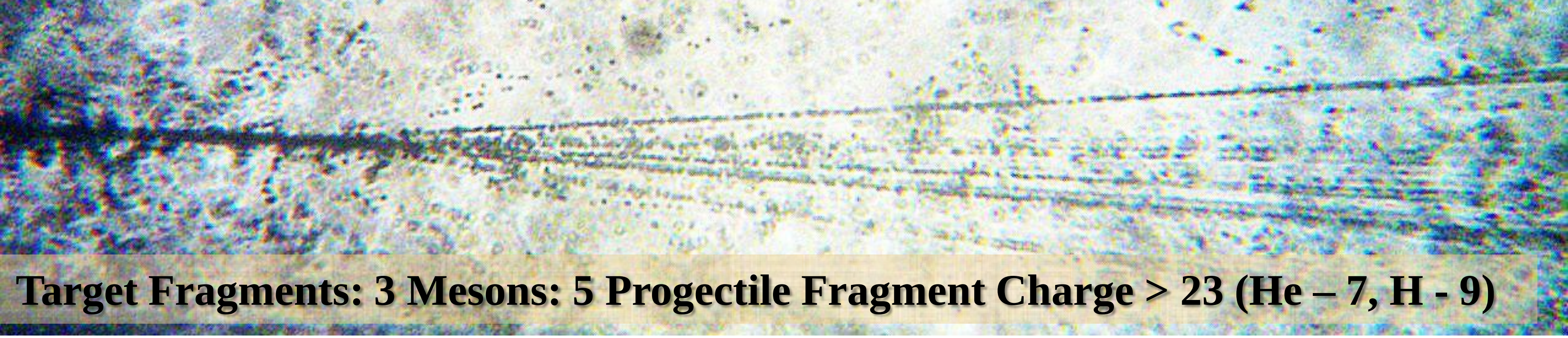
$Q_{3\alpha}$ (RMS) = 417 ± 27 (165) keV



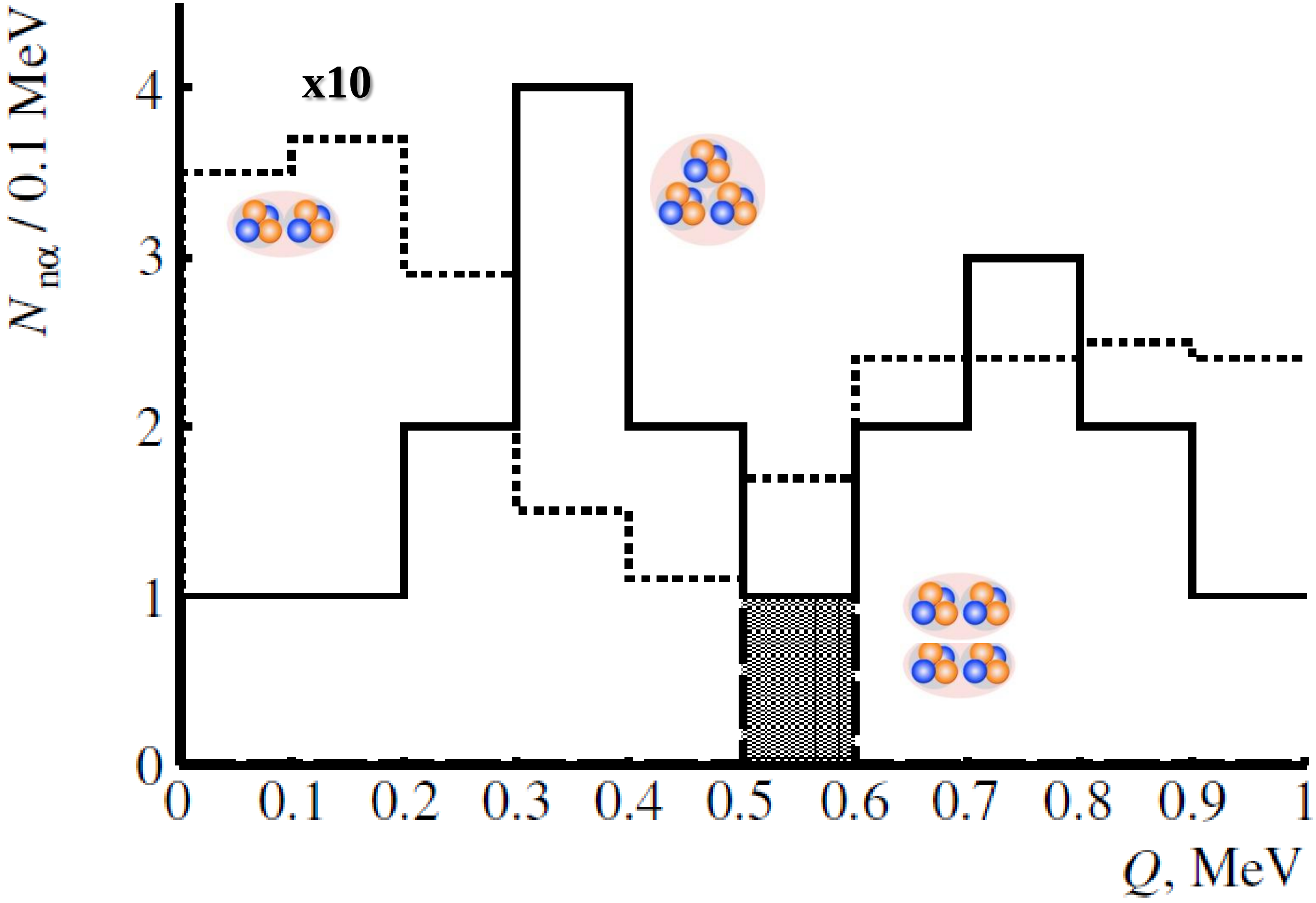
^{12}C → 3α HS 11 ± 3% ^{16}O → 4α HS 22 ± 2%



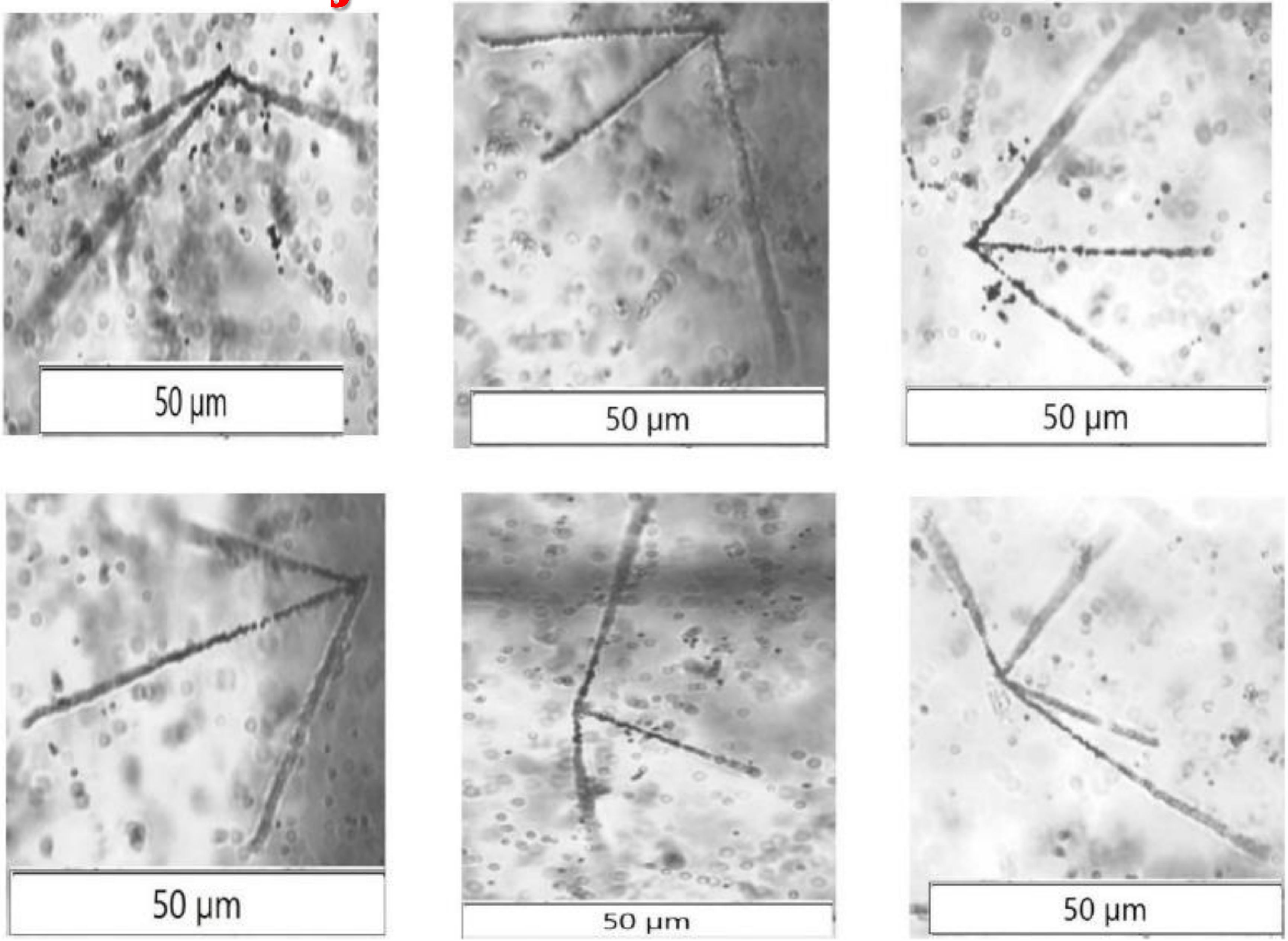
Having been tested, this approach has been used to identify ^{8}Be and HS and search for more complex states of αBEC in fragmentation of medium and heavy nuclei. Recently, based on the statistics of dozens of ^{8}Be decays, an enhancement in probability of detecting ^{8}Be in an event with an increase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



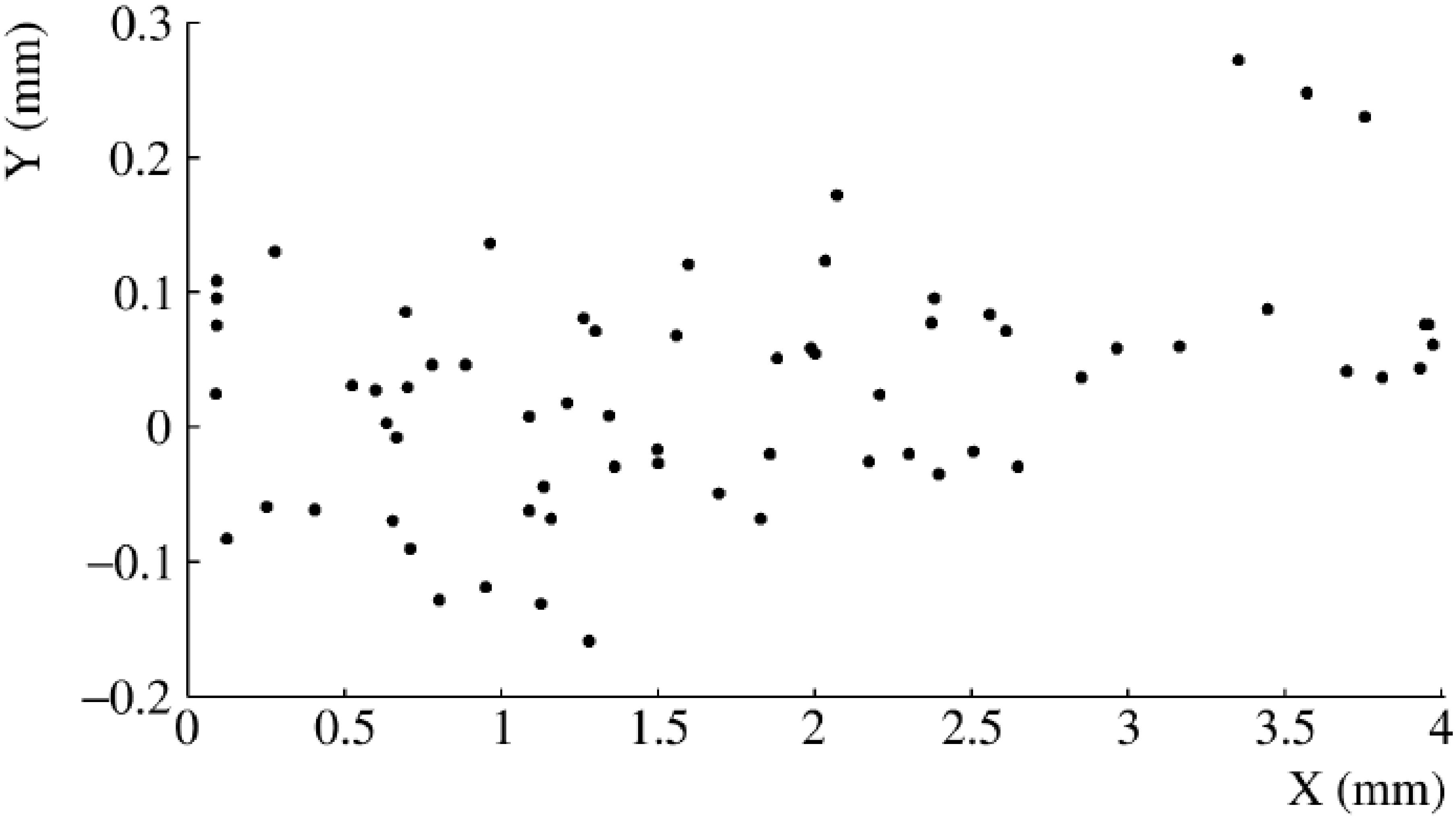
Target Fragments: 3 Mesons: 5 Progectile Fragment Charge > 23 (He – 7, H - 9)



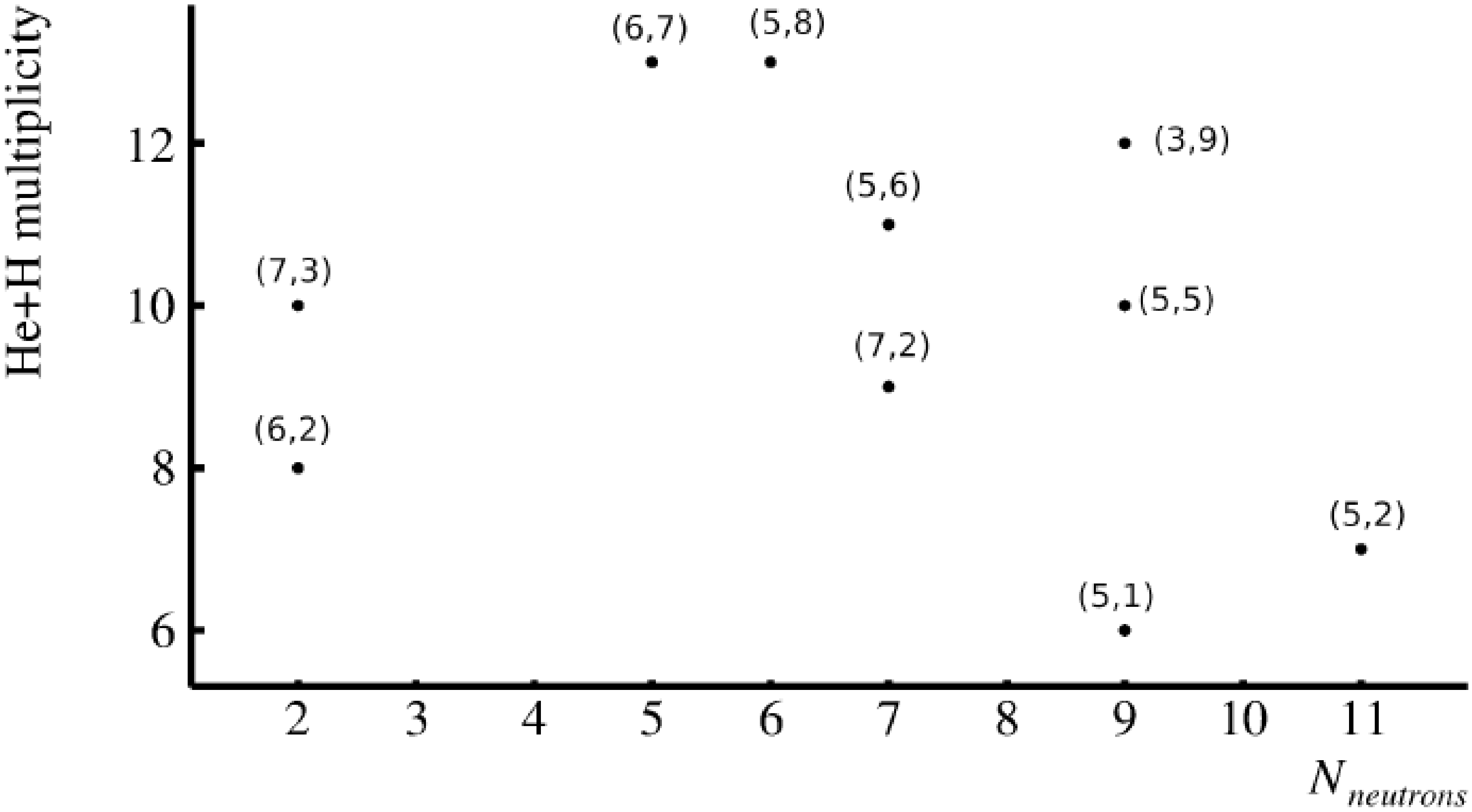
Projectile neutrons?



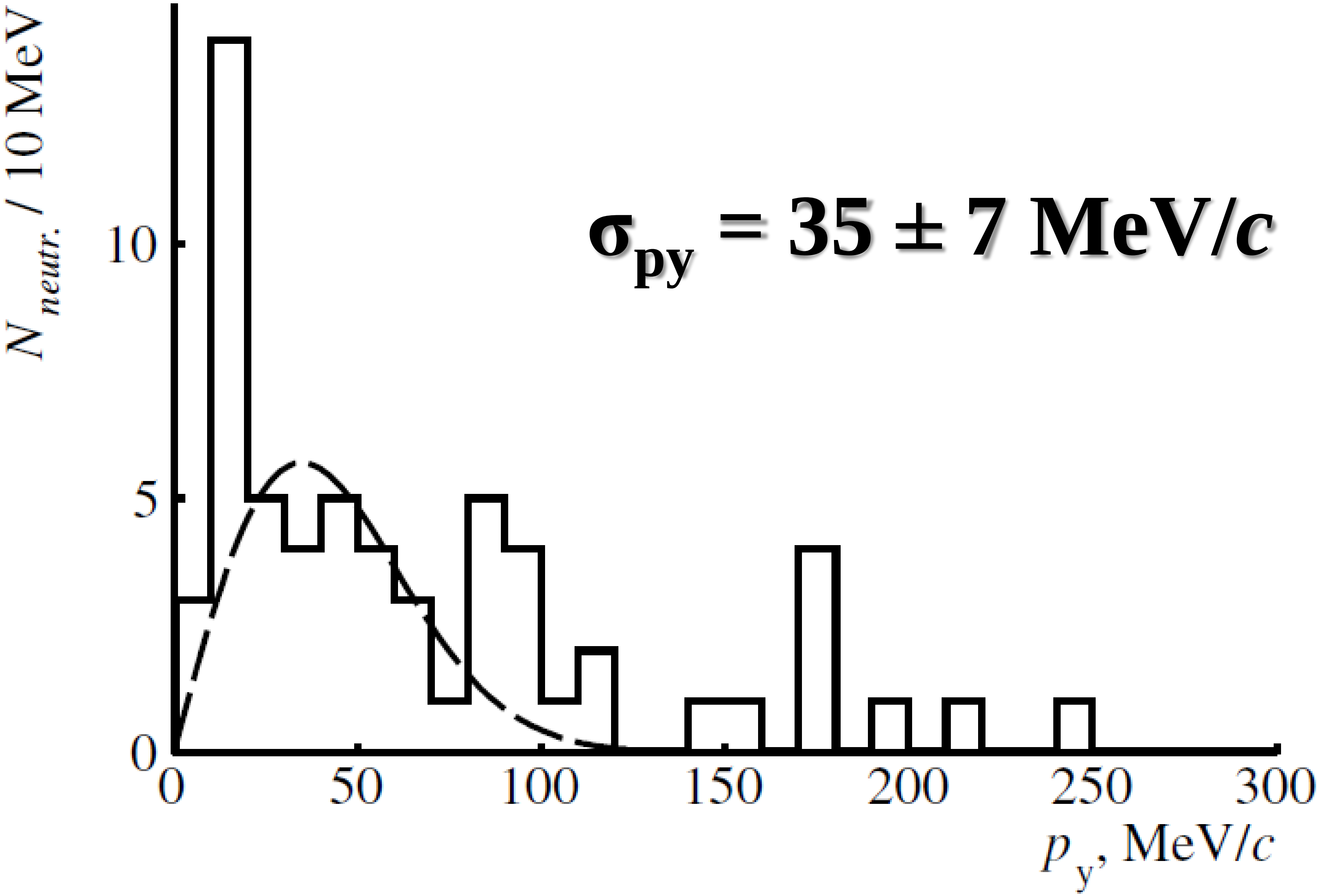
Projectile neutrons?



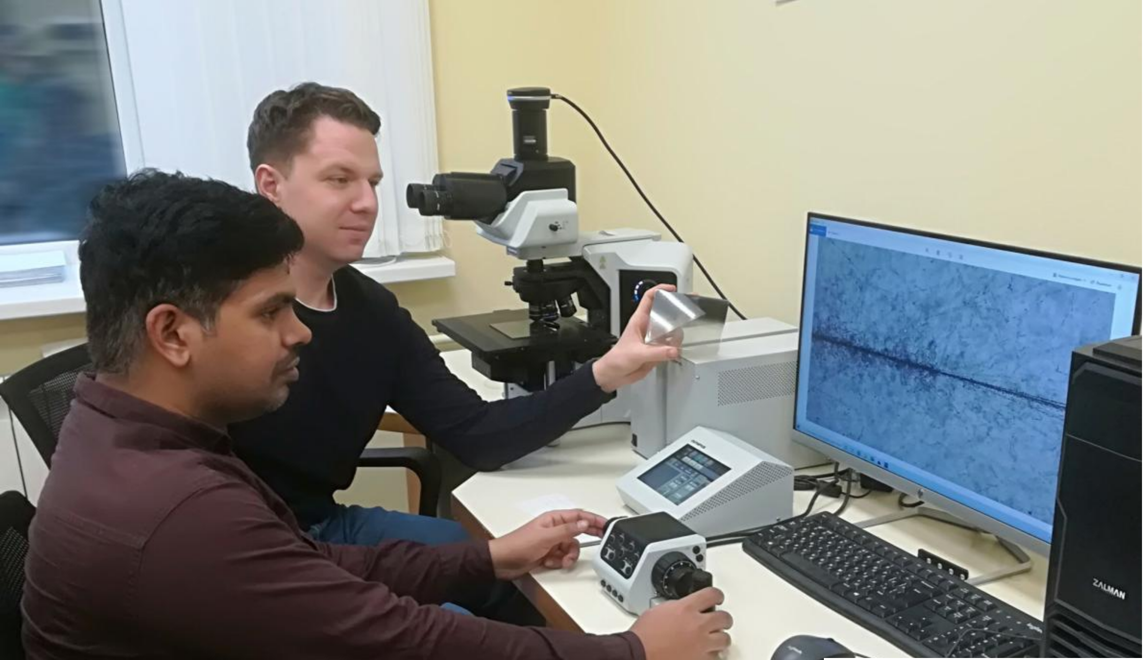
Projectile neutrons?

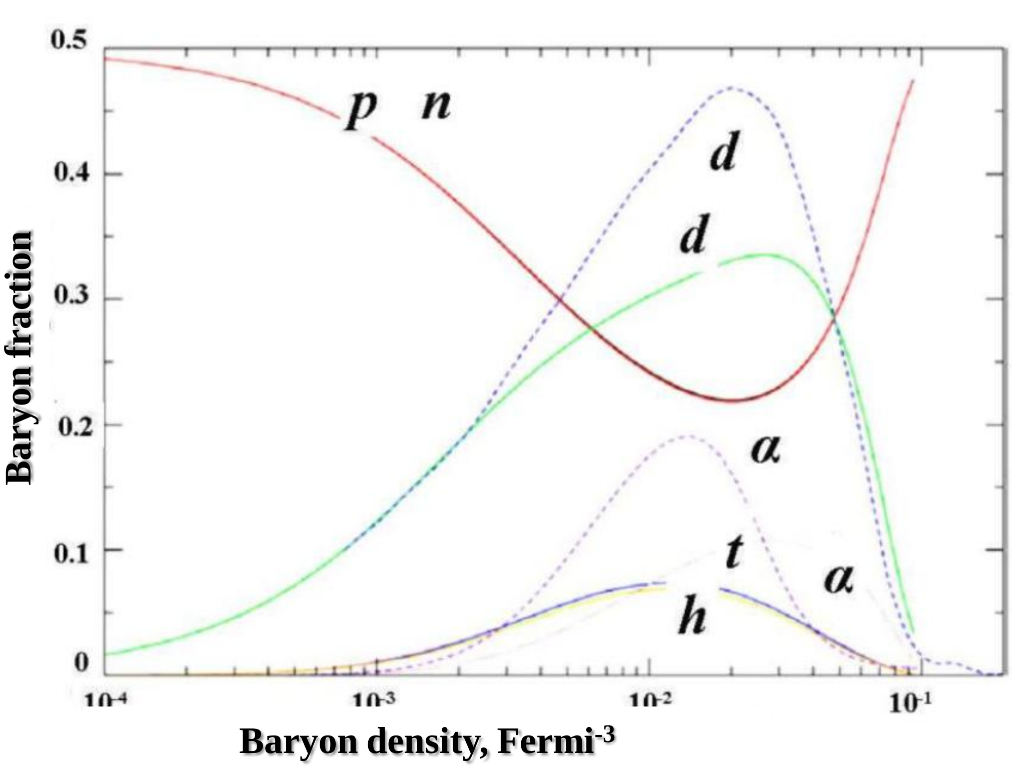


Projectile neutrons?



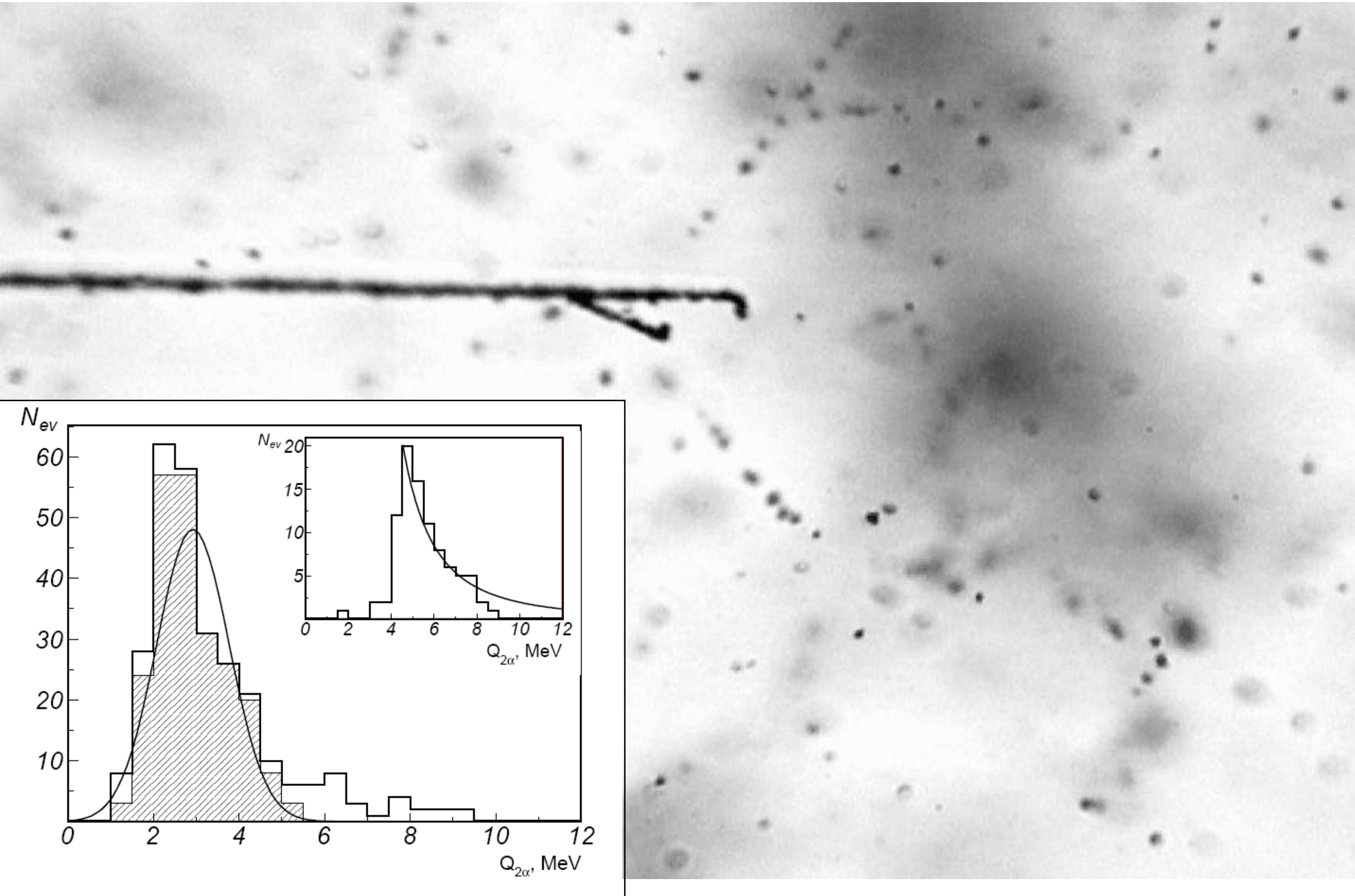
σ_{py} = 35 ± 7 MeV/c



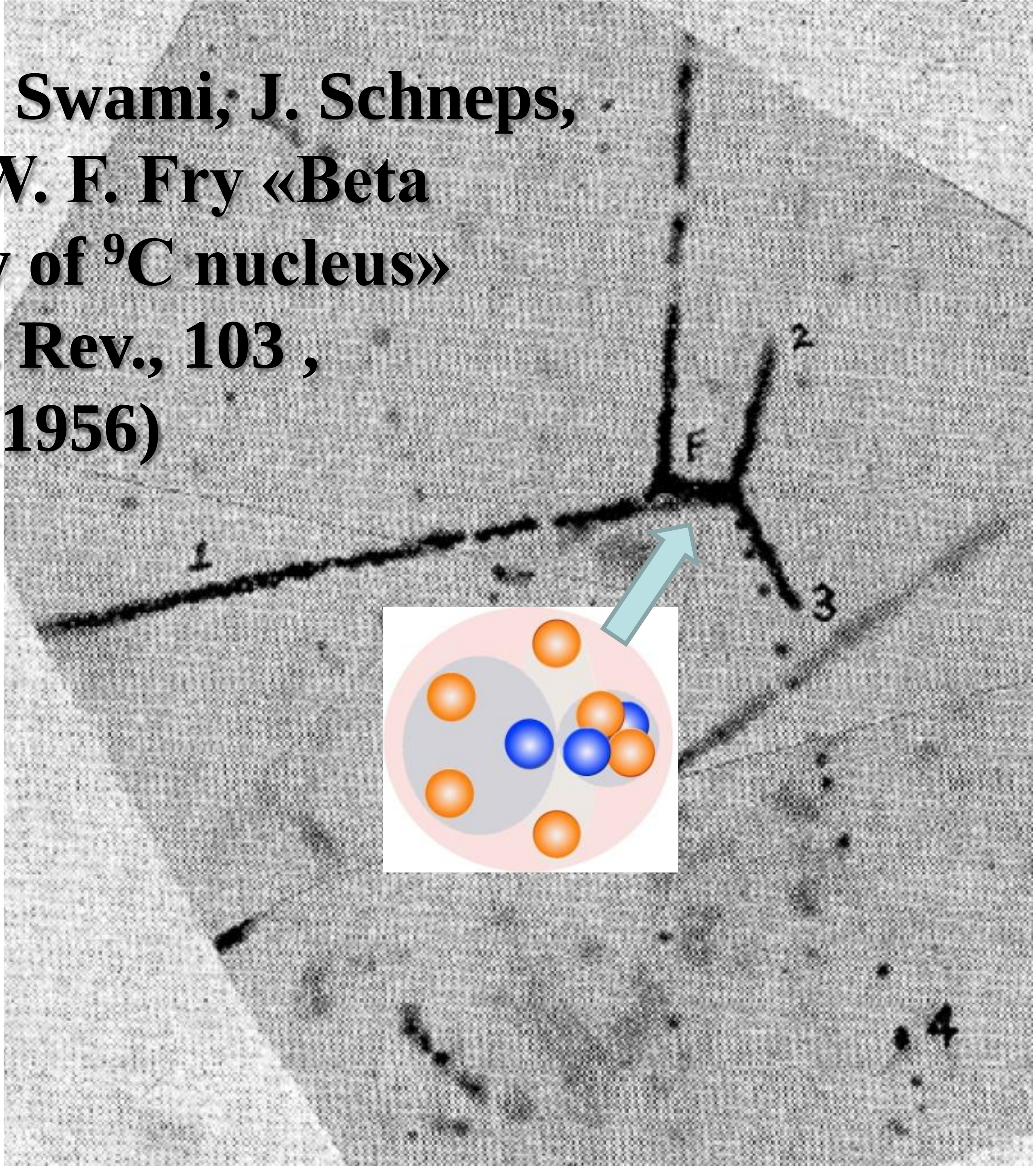


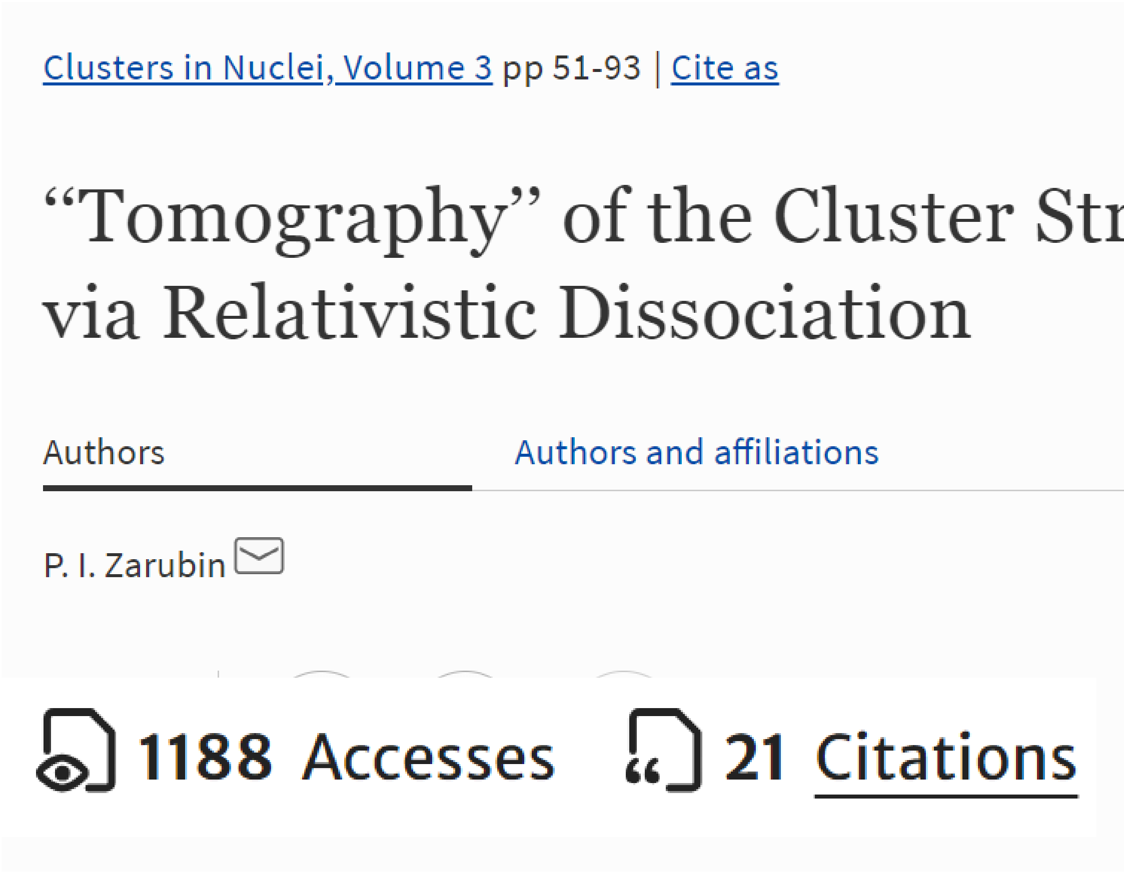
0.5
0.4
0.3
0.2
0.1
0
p
n
d
d
α
t
α
h
Baryon fraction
10^{-4}
10^{-3}
10^{-2}
10^{-1}
Baryon density, Fermi^{-3}

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



M. S. Swami, J. Schneps, and W. F. Fry «Beta decay of ^{9}C nucleus» Phys. Rev., 103 , 1134(1956)





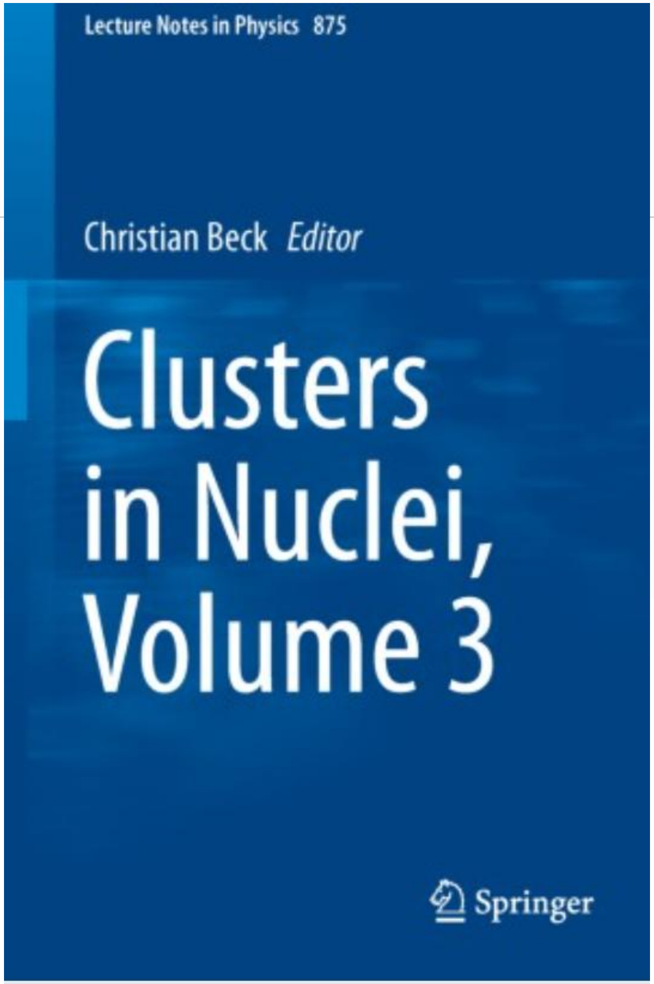
Clusters in Nuclei, Volume 3 pp 51-93 | Cite as

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

Authors Authors and affiliations

P. I. Zarubin

1188 Accesses 21 Citations



Lecture Notes in Physics 875

Christian Beck *Editor*

Clusters in Nuclei, Volume 3

Springer

International Conference on Few-Body Problems in Physics

FB22 2018: Recent Progress in Few-Body Physics pp 137-139 | Cite as

The Hoyle State in Relativistic ^{12}C Dissociation

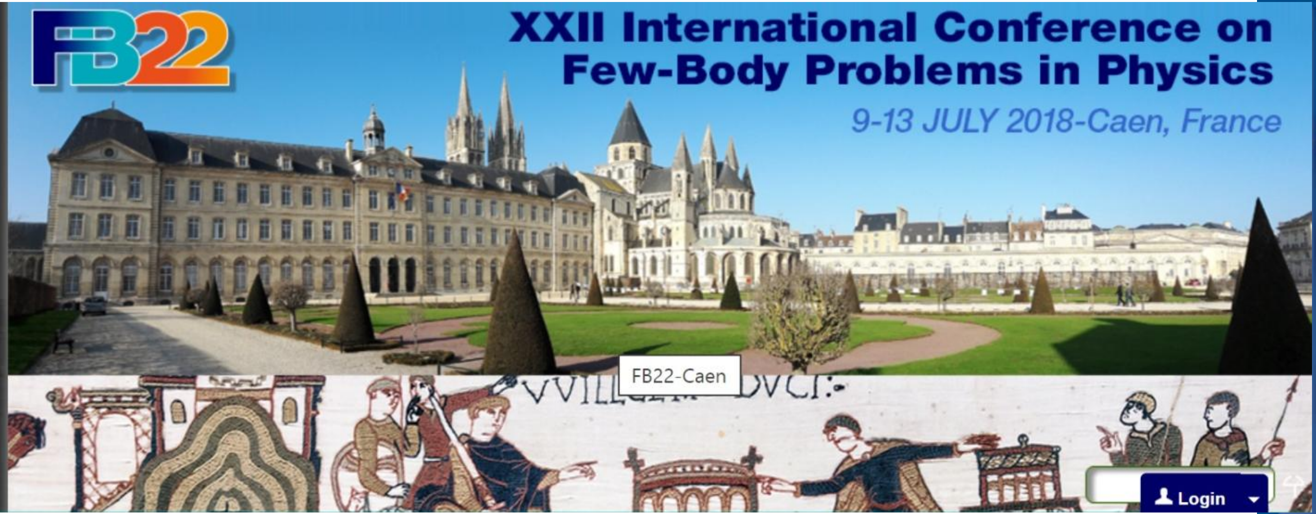
Authors | Authors and affiliations

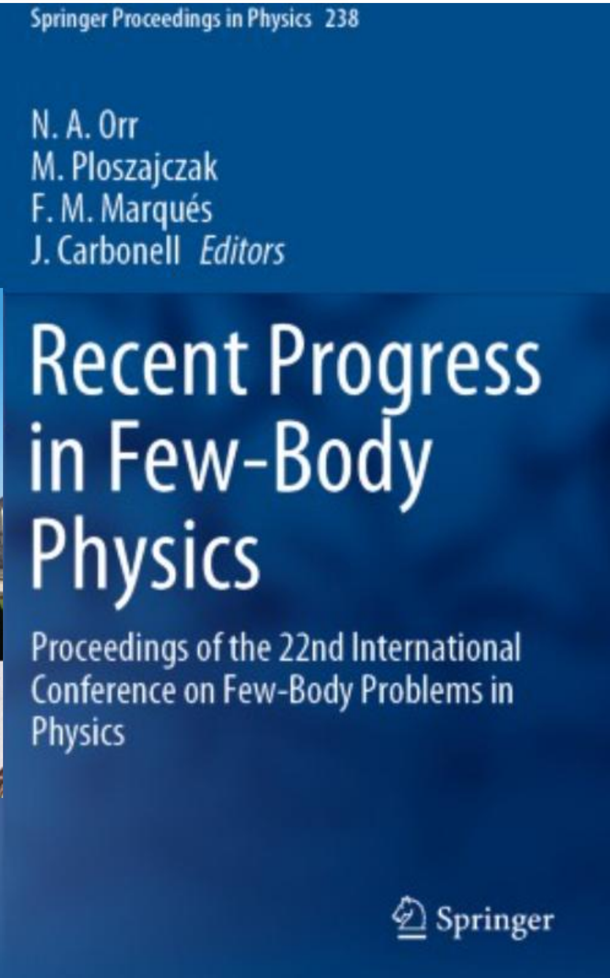
D. A. Artemenkov, M. Haiduc, N. K. Kornegrutsa, E. Mitsova, N. G. Peresadko, V. V. Rusakova, R. Stanoeva, A. A. Zaitsev, P. I. Zarubin, I. G. Zarubina

Conference paper

First Online: 07 January 2020

1157 Accesses | **3** Citations





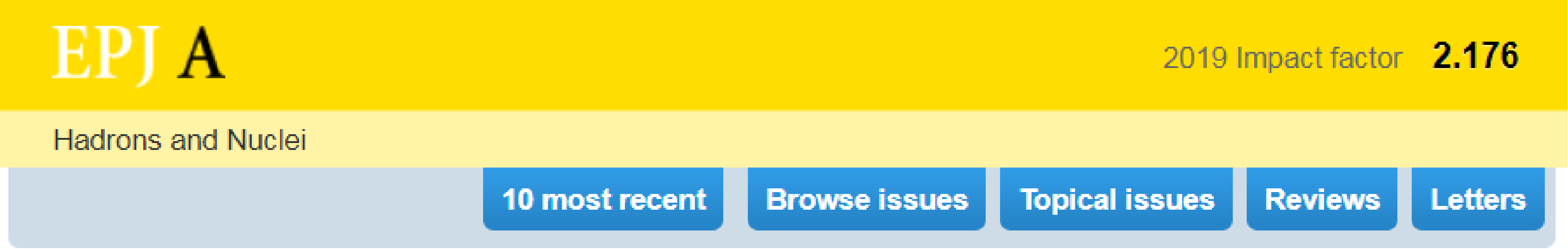
Springer Proceedings in Physics 238

N. A. Orr
M. Ploszajczak
F. M. Marqués
J. Carbonell *Editors*

Recent Progress in Few-Body Physics

Proceedings of the 22nd International Conference on Few-Body Problems in Physics

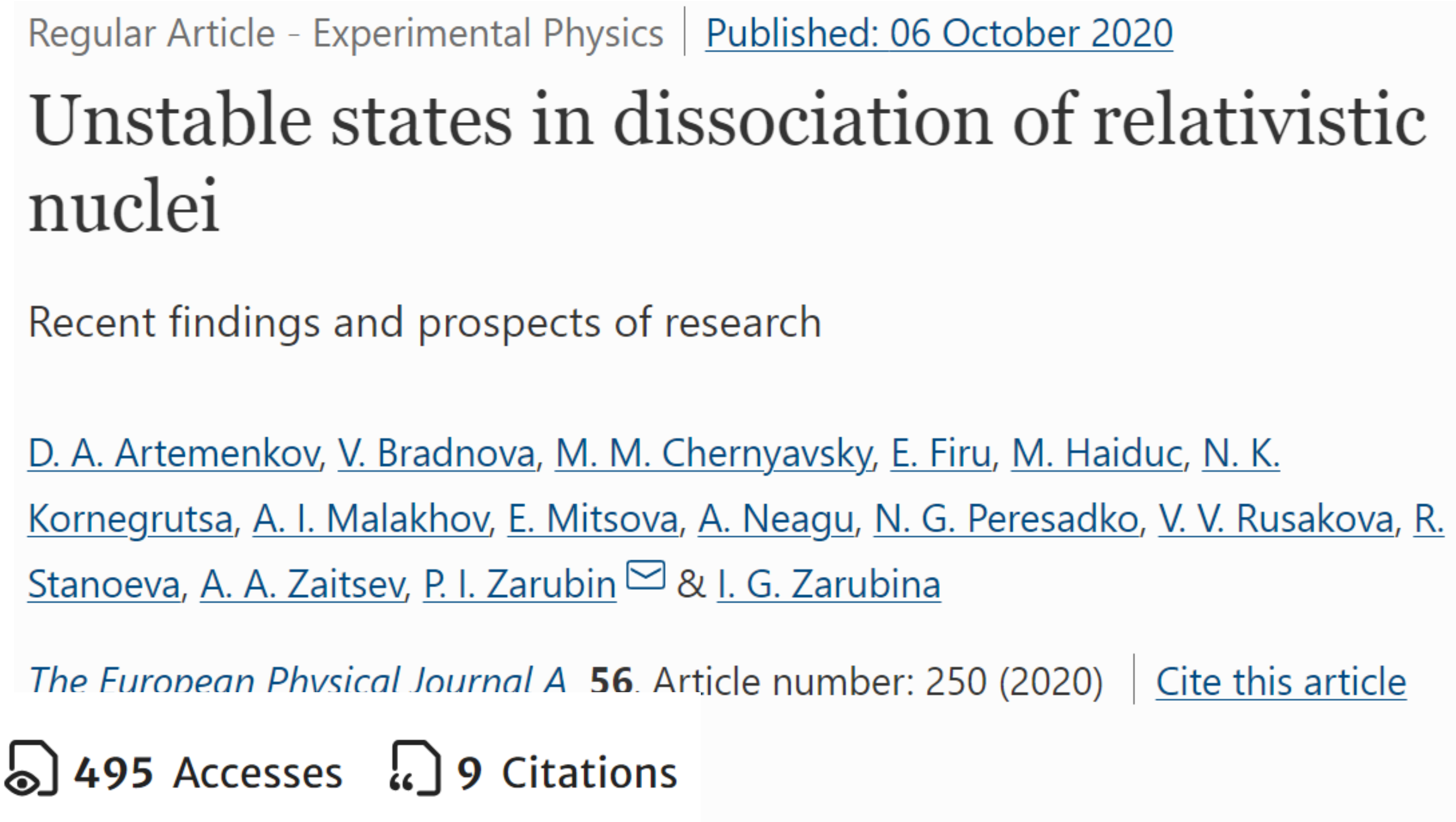
Springer



The European Physical Journal A

Light Clusters in Nuclei and Nuclear Matter: Nuclear Structure and Decay, Heavy Ion Collisions, and Astrophysics

David Blaschke, Hisashi Horiuchi, Masaaki Kimura, Gerd Roepke and Peter Schuck



Regular Article - Experimental Physics | Published: 06 October 2020

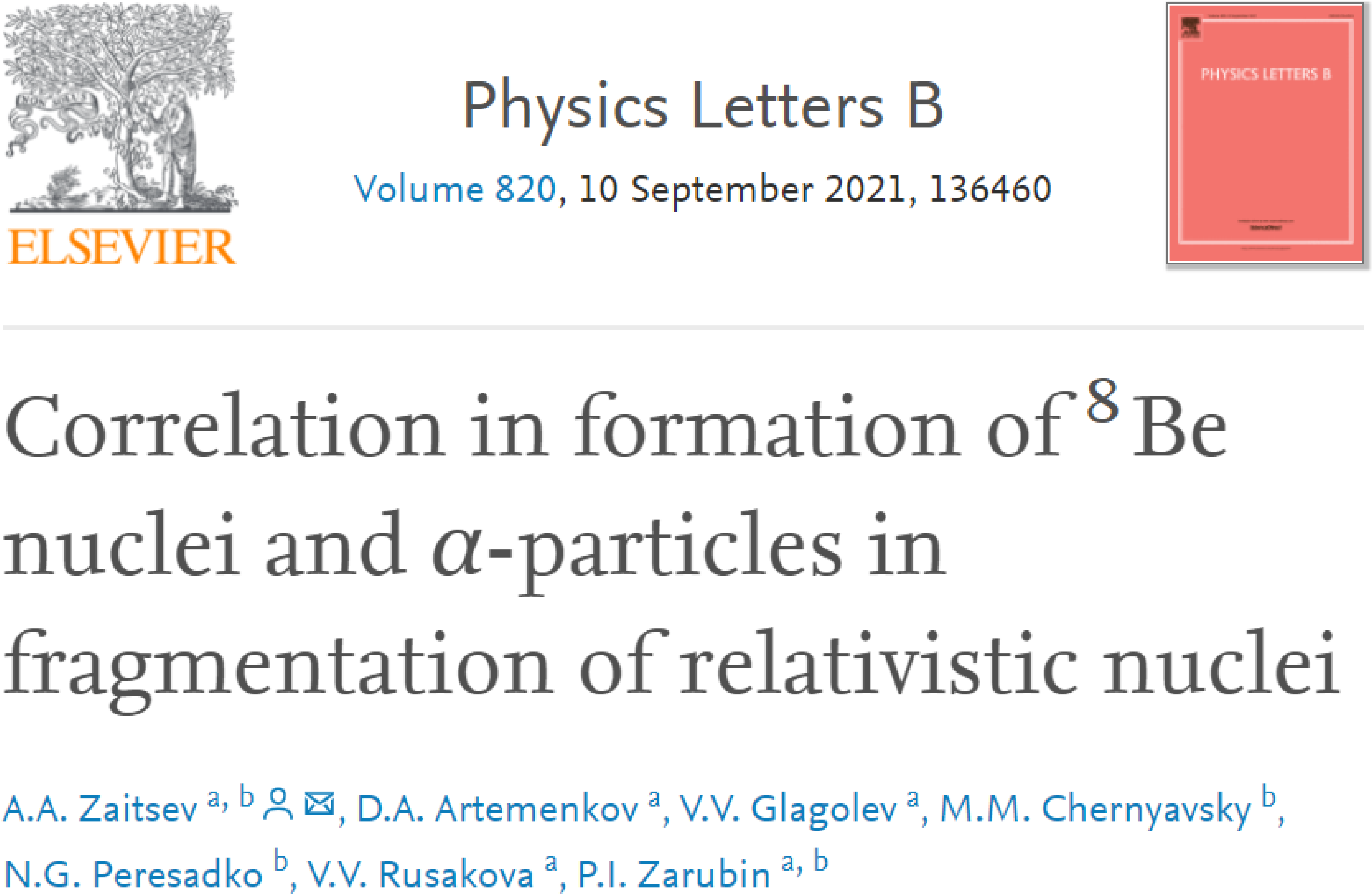
Unstable states in dissociation of relativistic nuclei

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

The European Physical Journal A **56**, Article number: 250 (2020) | Cite this article

495 Accesses 9 Citations



Physics Letters B

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]

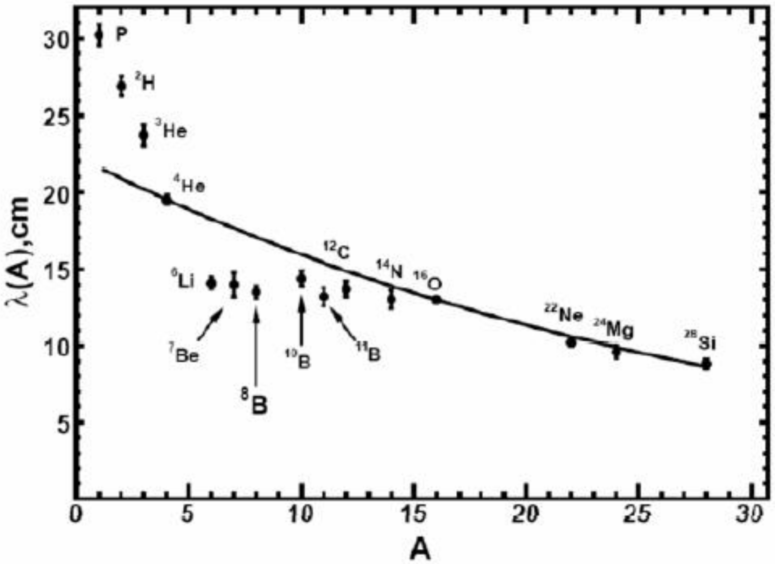
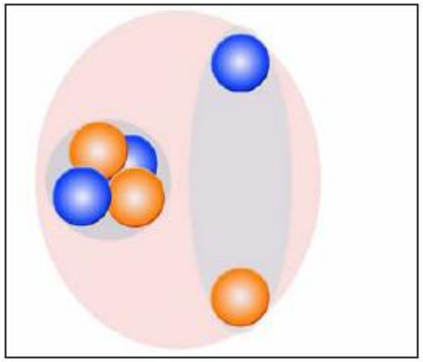


Рис. II.11 Данные по пробегам легких ядер в эмульсии, включая измерения настоящей работы (^7Be, ^8B, $^{10,11}B$, ^{14}N)



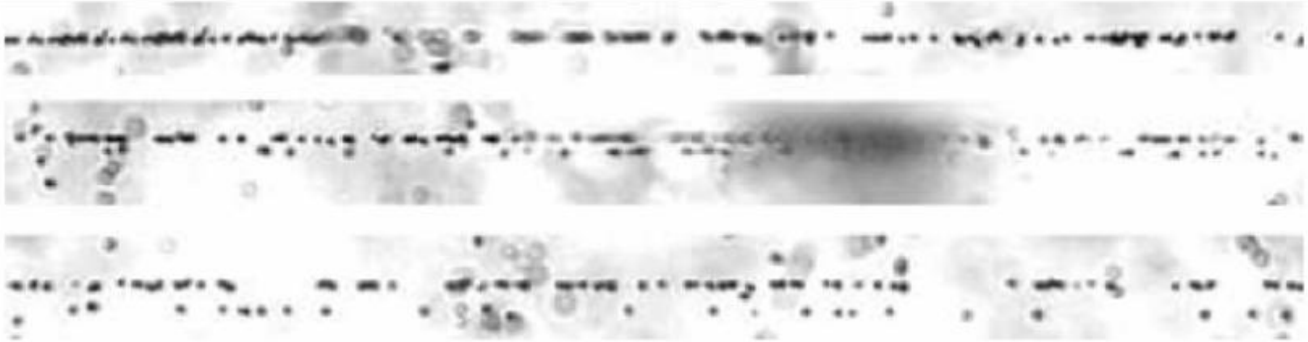
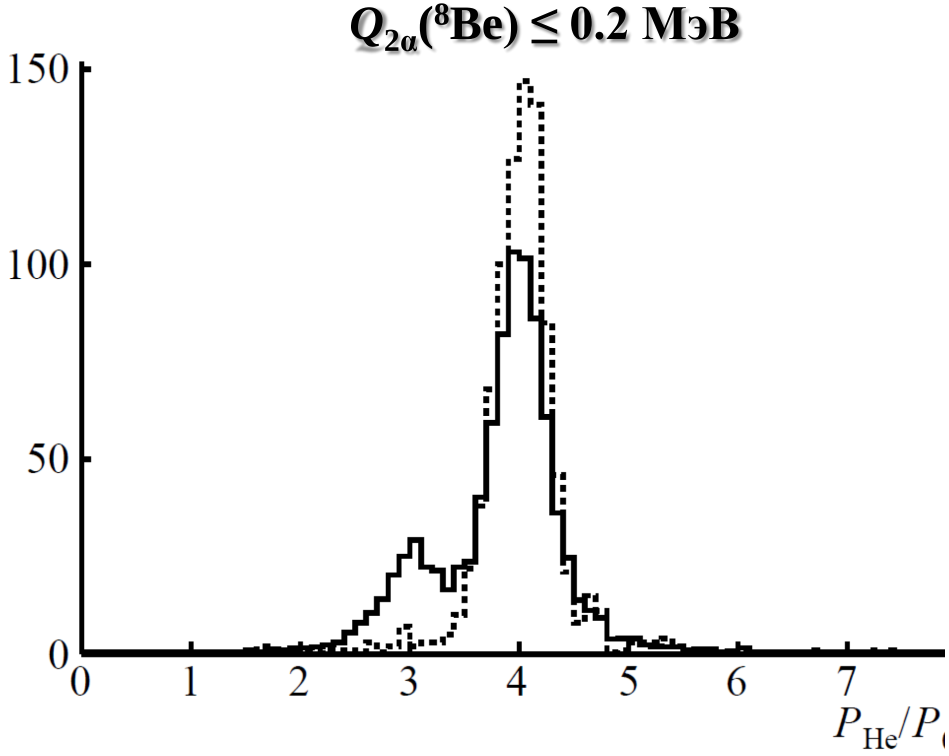
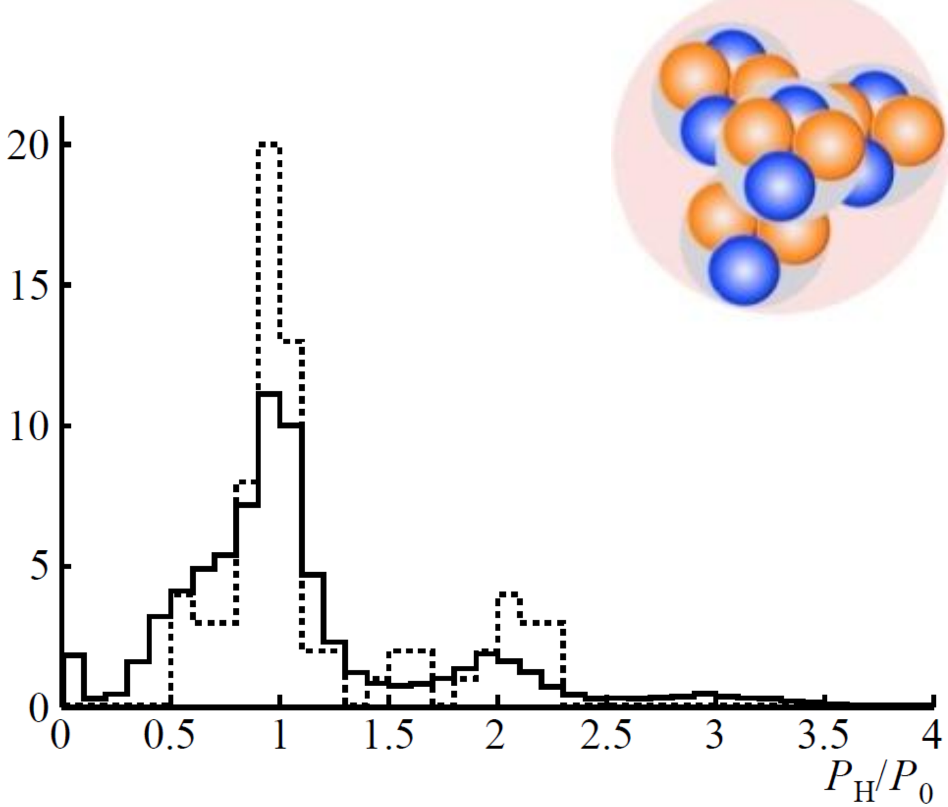


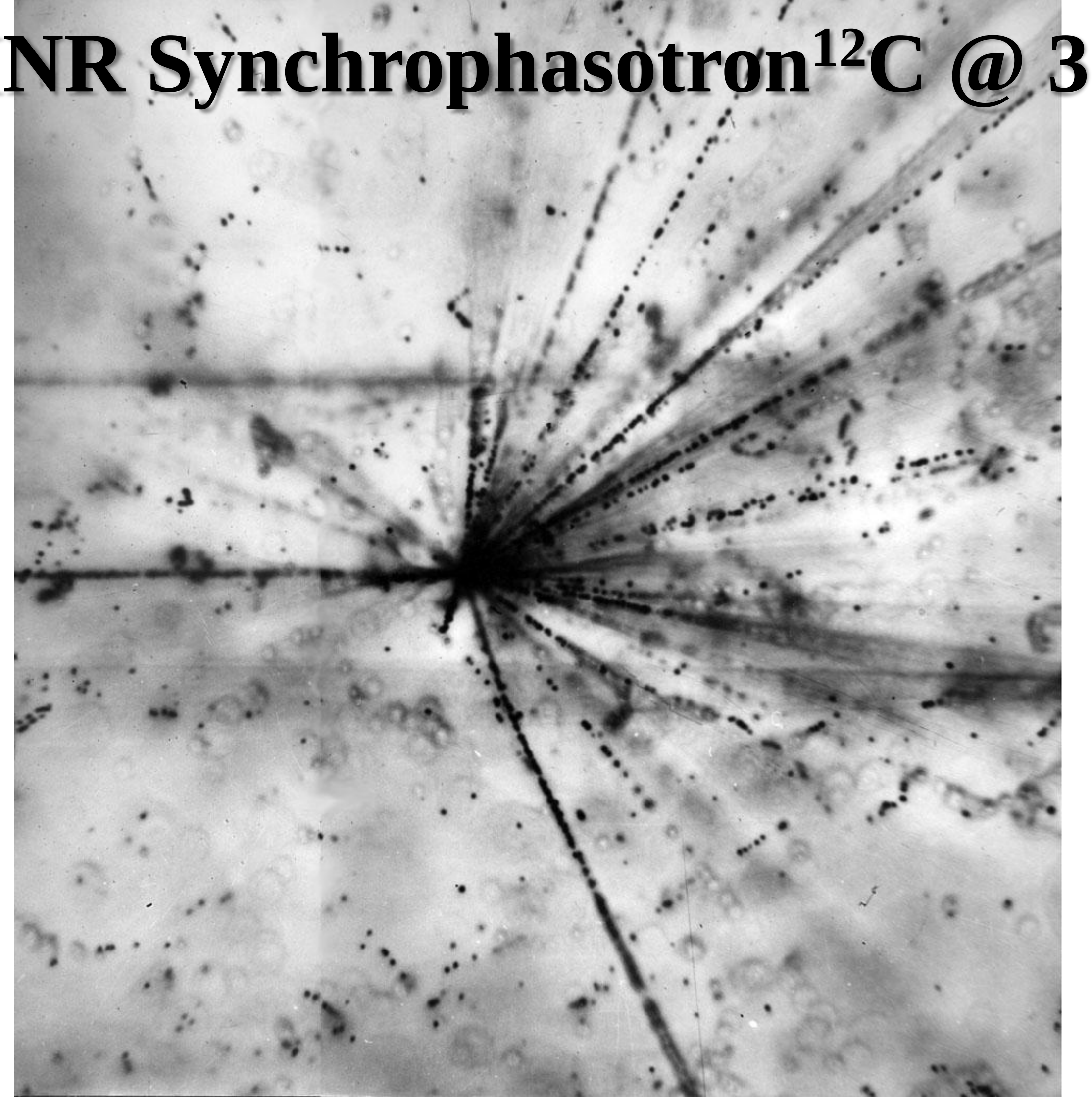
Рис II.12. Фрагментация релятивистского ядра ^6Li на одно- и двухзарядный фрагмент в эмульсии; на верхней фотографии видна вершина взаимодействия и узкая струя их двух фрагментов; при смещении вдоль струи фрагментов (нижние фотографии) отчетливо разделяются один однозарядный и один двухзарядный фрагменты



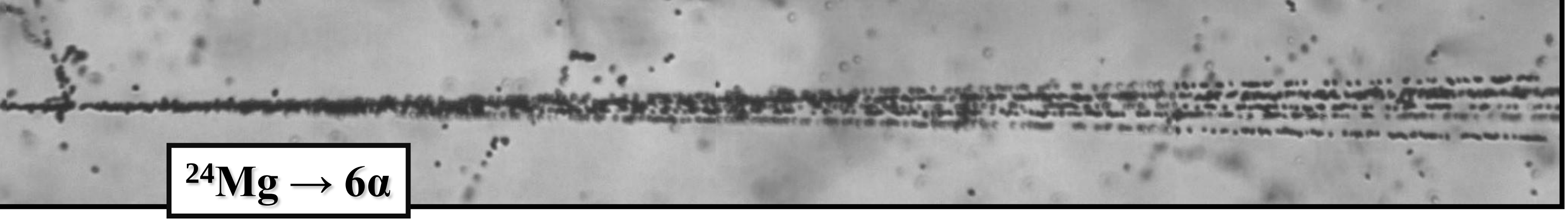


Проверить принятые приближения позволяют данные, полученные при облучении ядрами ^{16}O с энергией 2.4 ГэВ/нуклон 1-метровой водородной пузырьковой камеры ОИЯИ (ВПК-100), помещавшейся в магнитное поле. Набор данных включает измерения в полной геометрии векторов импульсов продуктов реакции $^{16}O + p$ в 11104 соударениях всех видов. В этом случае также имеется пик в начальной части распределении по углу разлета 2α-пар $\Theta_{2\alpha}$, соответствующий распадам ^8Be. Согласно измеренным импульсам фрагментов условие $Q_{2\alpha}(^8Be) \leq 0.2$ МэВ удаляет вклад ^3He, а вклад протонов составляет 90% среди фрагментов H.

1974 JINR Synchrophasotron ^{12}C @ 3.65 *A* GeV



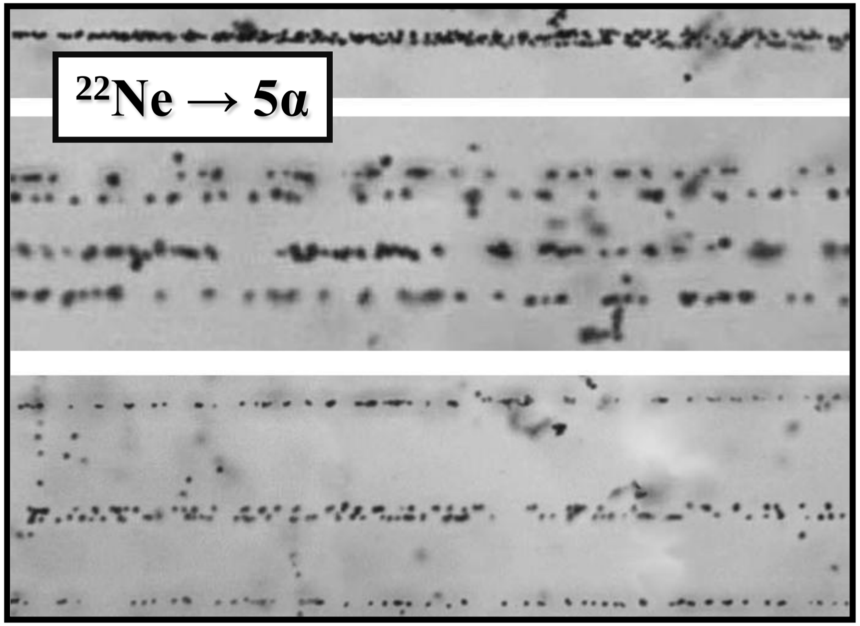
Становление в начале 70-х годов релятивистской ядерной физики было поддержано сообществами, имевшими богатый опыт применения ядерных эмульсий. Ускорители частиц открыли возможность изучения взаимодействий различных ядер определенной энергии, что позволило исследовать методом ядерной эмульсии спектры релятивистских фрагментов. Ядерная эмульсия облучалась ядрами, впервые ускорявшимися на синхрофазотроне ОИЯИ, БЕВАЛАКе, а затем, на ускорителях AGS (BNL) и SPS (CERN).

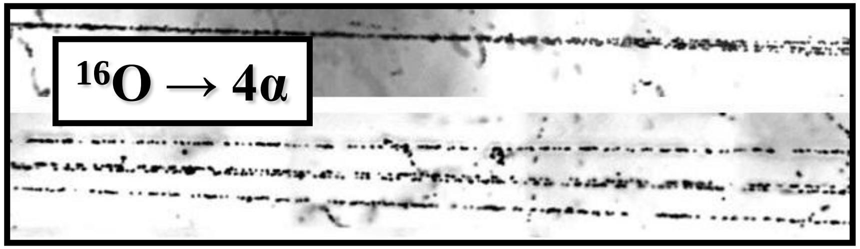


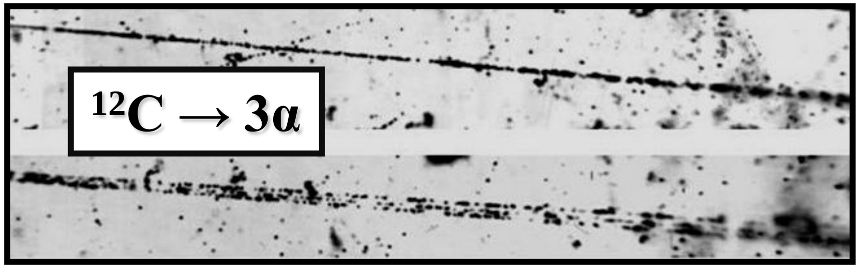
Исследование ядерной структуры в релятивистском подходе в условиях очень малых передач энергии–импульса имеет важные преимущества, поскольку в конечных состояниях фрагментов должна наиболее полно отражаться структура начальных состояний ядер.

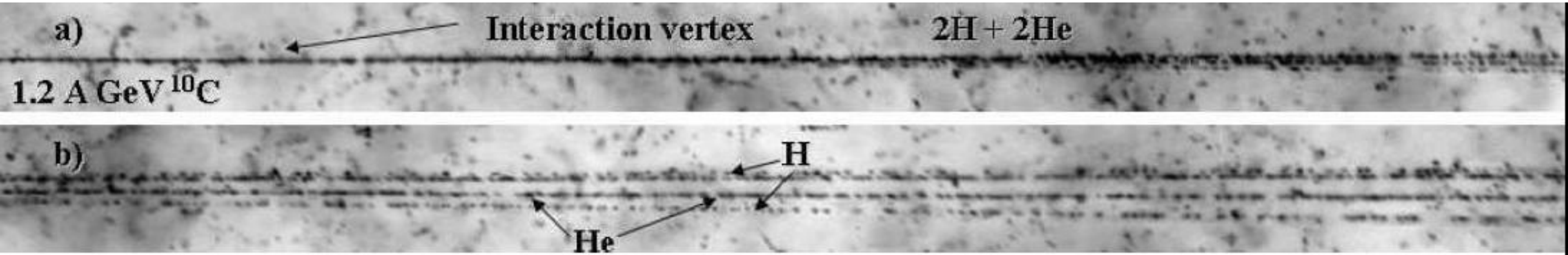
Современные эксперименты проводятся с релятивистскими радиоактивными ядрами с большим избытком нейтронов на магнитных спектрометрах. Они ориентированы на регистрацию фрагментов с начальным зарядом как у исследуемого ядра или близким к нему.

Однако в таком подходе теряются принципиально важные каналы, содержащие фрагменты *He* и *H,* и, соответственно, распады ^{8}Be и ^{9}B. Возможность разрешения этой проблемы методом ядерной эмульсии мотивирует эксперимент БЕККЕРЕЛЬ на нуклотроне ОИЯИ.



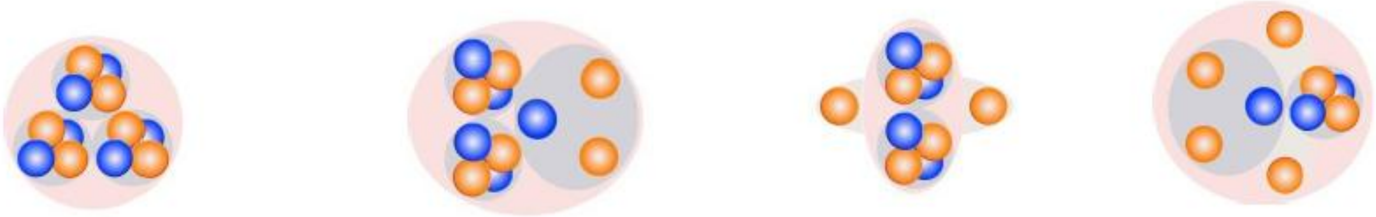


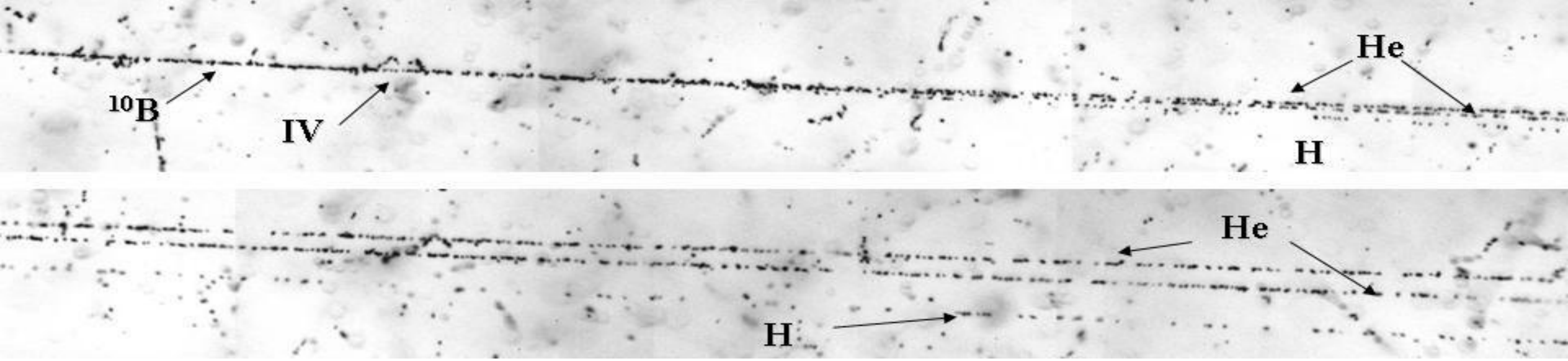


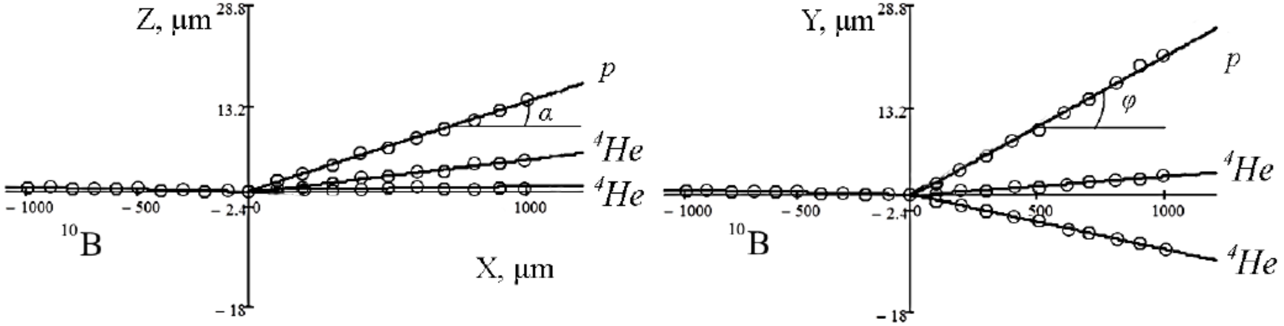


Charge topology of “white” stars

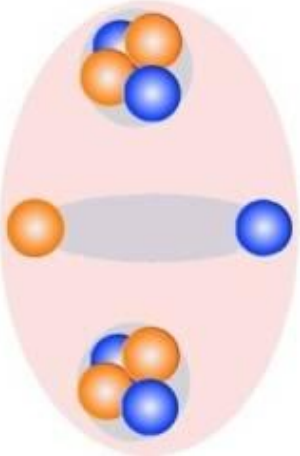
Channel	^{12}C	^{11}C	^{10}C	^{9}C
B + H		6 (5 %)	1 (0.4 %)	15 (14 %)
Be + He		18 (13 %)	6 (2.6 %)	
Be + 2H				16 (15 %)
3He	100 (100 %)	25 (17 %)	12 (5.3 %)	16 (15 %)
2He + 2H		72 (50 %)	186 (82 %)	24 (23 %)
He + 4H		15 (11 %)	12 (5.3 %)	28 (27 %)
Li + He + H		5 (3 %)		
Li + 3H			1 (0.4 %)	2 (2 %)
6H		3 (2 %)	9 (4 %)	6 (6 %)

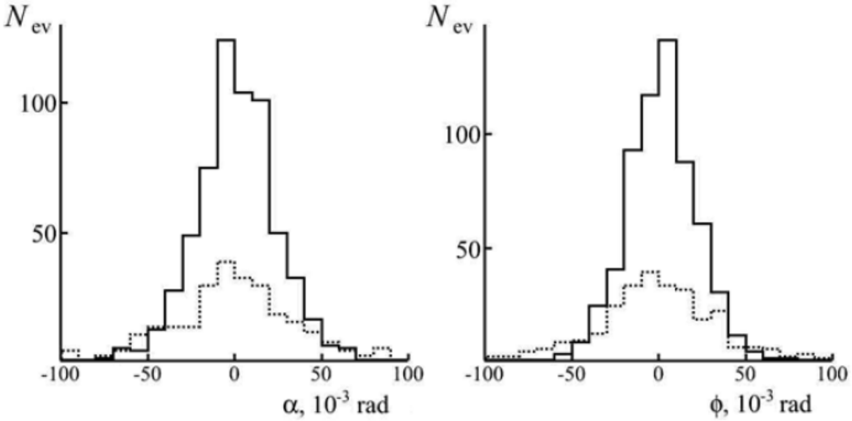




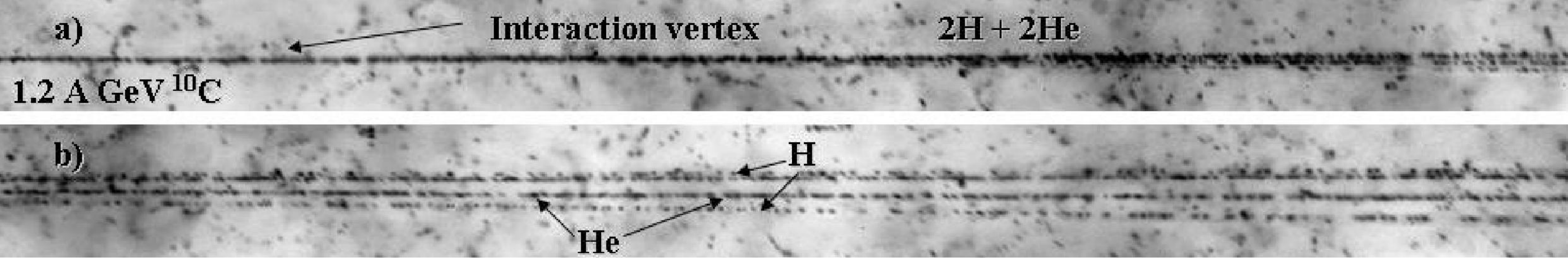


Example of restored directions in event ^{10}B → 2He + H @ 1.2 *A* GeV over vertical and planar planes.

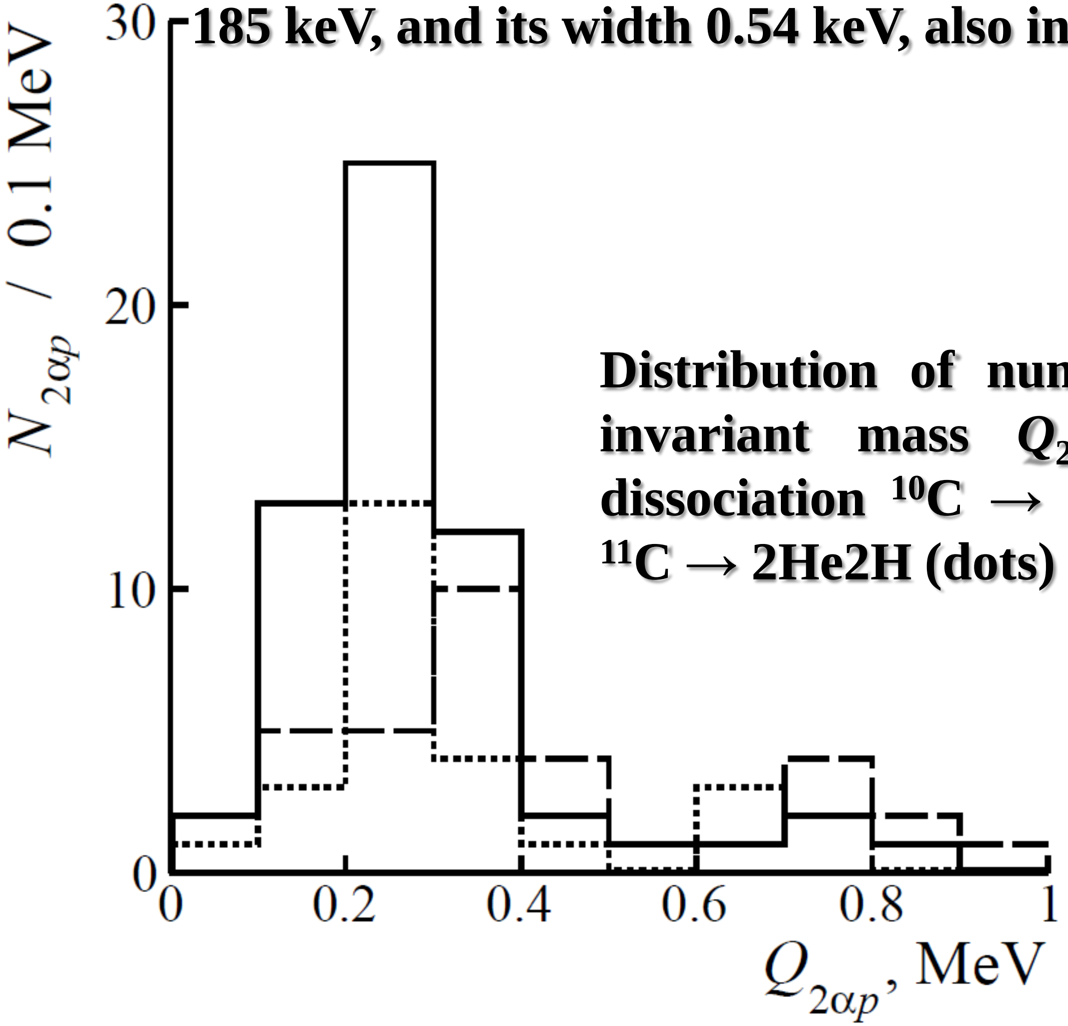




Distributions of fragments He (solid) and H (dotted) over dip and planar angles α and φ in events ^{10}B → 2He + H @ 1.2 *A* GeV.



The ground state of the ^{9}B nucleus is higher than the ^{8}Be*p* threshold by 185 keV, and its width 0.54 keV, also indicates that it is a long-lived state.



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

Статистика событий, содержащих не менее одного кандидата в распад ^{8}Be, HS или ^{9}B или не менее двух ^{8}Be при условии $Q_{2\alpha}(^8\mathrm{Be}) \leq 0.4$ МэВ среди $N_{n\alpha}$ событий фрагментации ядер ^{197}Au с множественностью n_α; курсивом выделена суммарная статистика каналов $n_\alpha \geq 11$.

n_α	$N_{n\alpha}(^8\mathrm{Be})/N_{n\alpha}$ (% $N_{n\alpha}$)	$N_{n\alpha}(^9\mathrm{B})$ (% $N_{n\alpha}(^8\mathrm{Be})$)	$N_{n\alpha}(\mathrm{HS})$ (% $N_{n\alpha}(^8\mathrm{Be})$)	$N_{n\alpha}(2^8\mathrm{Be})$ (% $N_{n\alpha}(^8\mathrm{Be})$)
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) *19/30 (63 ± 19)*	3 (30 ± 20) *7 (37 ± 16)*	1 (10) *2(11 ± 8)*	2(20 ± 16) *6 (32 ± 15)*
12	2/5	1	-	1
13	2/4	1	-	1
14	3/3	1	-	1
15	1/1	-	-	-
16	1/2	1	1	1

ЗАКЛЮЧЕНИЕ

Проект БЕККЕРЕЛЬ2023 на ускорительном комплексе НУКЛОТРОН/NICA для продолжит исследования периферических взаимодействий релятивистских ядер, в которых только метод ядерной эмульсии обеспечивает требуемое разрешение, полноту и единообразие наблюдений.

Проект сфокусирован на поиске α-частичного конденсата Бозе-Эйнштейна (αBEC). Для легких ядер, в том числе радиоактивных, апробирована идентификация по инвариантной массе распадов $^{8}\mathrm{Be} \to 2\alpha$, $^{9}\mathrm{Be} \to 2\alpha$ и $^{12}\mathrm{C}(0^{+}_{2}) \to {}^{8}\mathrm{Be}\alpha$ (состояние Хойла). Тенденция к росту ^{8}Be с числом α-частиц, а также ^{9}B и $^{12}\mathrm{C}(0^{+}_{2})$, недавно обнаруженная для средних и тяжелых ядер, указывает на возможность синтеза 4αBEC.

Проект БЕККЕРЕЛЬ2023 нацелен на анализ фрагментации ^{84}Kr при 950 МэВ на нуклон для прояснения связи ^{8}Be и состояния Хойла и множественностью α-ансамблей и поиске на этой основе распадов состояния $^{16}\mathrm{O}(0^{+}_{6}) \to {}^{12}\mathrm{C}(0^{+}_{2})\alpha$ и $2{}^{8}\mathrm{Be}$ как кандидата в 4αBEC. Попутно оценивается множественность и поперечные импульсы сопровождающих нейтронов.

В продолжение исследований с легкими ядрами в диссоциации ^{9}Be и ^{10}C ведется поиск изобар-аналоговых состояний ^{8}Be и ^{9}B. Во фрагментации ядер из состава эмульсии под действием релятивистских частиц осваивается методика идентификации по инвариантной массе ансамблей остановившихся α-частиц.

В декабре 2022 г. слои ядерной эмульсии облучены ядрами ^{124}Xe с энергией 3.8 ГэВ на нуклон. Тем самым, получен материал для анализа множественных состояний α-частиц и нуклонов при оптимальной энергии Определение среднего разворота пучковых следов указывает на возможность идентификации релятивистских изотопов. Применение CR-39 позволило полностью реконструировать профиль и интенсивность использованного пучка.

В целом, сочетание классических ядерных методик и успешное освоение моторизованного микроскопа позволяет развить в ОИЯИ исследования с релятивистскими радиоактивными изотопами, привлекая к ним молодых исследователей.

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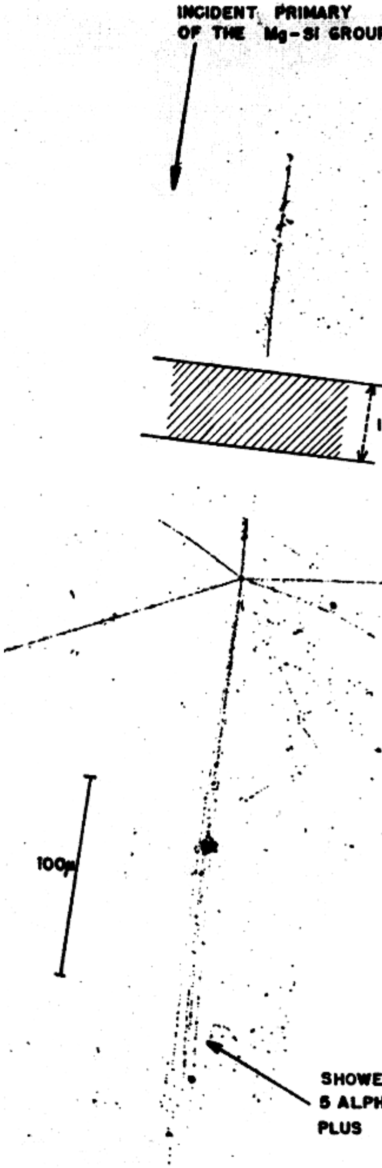
The Heavy Nuclei of the Primary Cosmic Radiation

H. L. Bradt and B. Peters
University of Rochester, Rochester, New York

(Received September 9, 1949)



The Study of Elementary Particles by the Photographic Method

An account of
The Principal Techniques and Discoveries
illustrated by
An Atlas of Photomicrographs

BY
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N.K. Kornegrutsa, D.O. Krivenkov, A.I. Malakhov, K. Olimov, N.G. Peresadko, N.G. Polukhina, P.A. Rukoyatkin, V.V. Rusakova, R. Stanoeva, S.P. Kharlamov, 2013, publishe
in Yadernaya Fizika, 2013, Vol. 76, No. 10, pp. 1286–1291.

Dissociation of ^{10}C Nuclei in a Track Nuclear Emulsion at an Energy of 1.2 GeV per Nucleon

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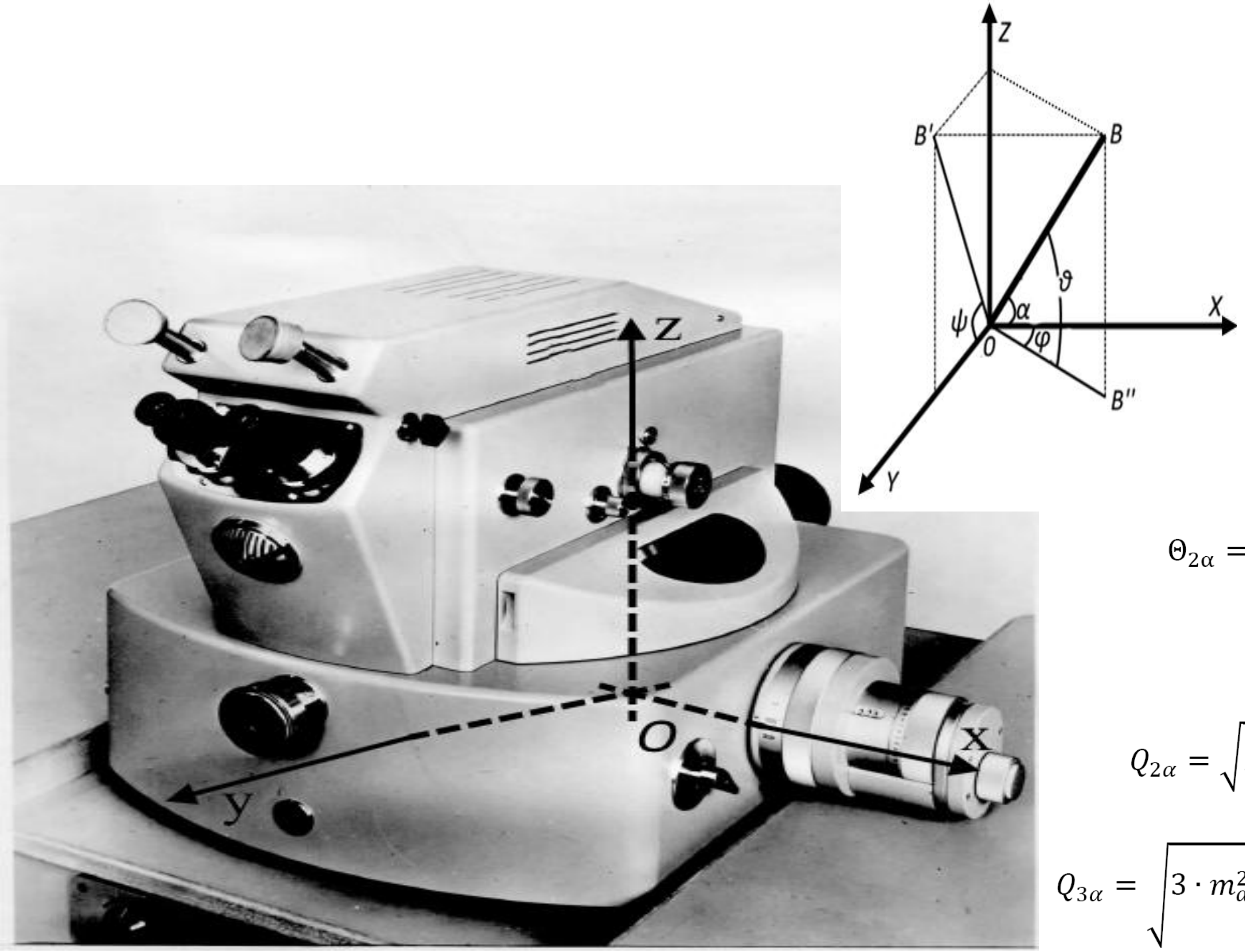
Received March 21, 2012

Abstract—The charge topology in the fragmentation of ^{10}C nuclei in a track nuclear emulsion at an energy of 1.2 GeV per nucleon is studied. In the coherent dissociation of ^{10}C nuclei, about 82% of events are associated with the channel $^{10}\mathrm{C} \to 2\alpha + 2p$. The angular distributions and correlations of product fragments are presented for this channel. It is found that among $^{10}\mathrm{C} \to 2\alpha + 2p$ events, about 30% are associated with the process in which dissociation through the ground state of the unstable $^9\mathrm{Be}_{\mathrm{g.s.}}$ nucleus is followed by $^8\mathrm{Be}_{\mathrm{g.s.}} + p$ decays.



$$P_x = P_0 \cdot A \cdot \cos\alpha \cdot \cos\varphi$$

$$P_y = P_0 \cdot A \cdot \cos\alpha \cdot \sin\varphi$$

$$P_z = P_0 \cdot A \cdot \sin\alpha$$

$$P_{tot} = \sqrt{P_x^2 + P_y^2 + P_z^2}$$

$$E_\alpha = \sqrt{P_0^2 \cdot A^2 + m_\alpha^2}$$

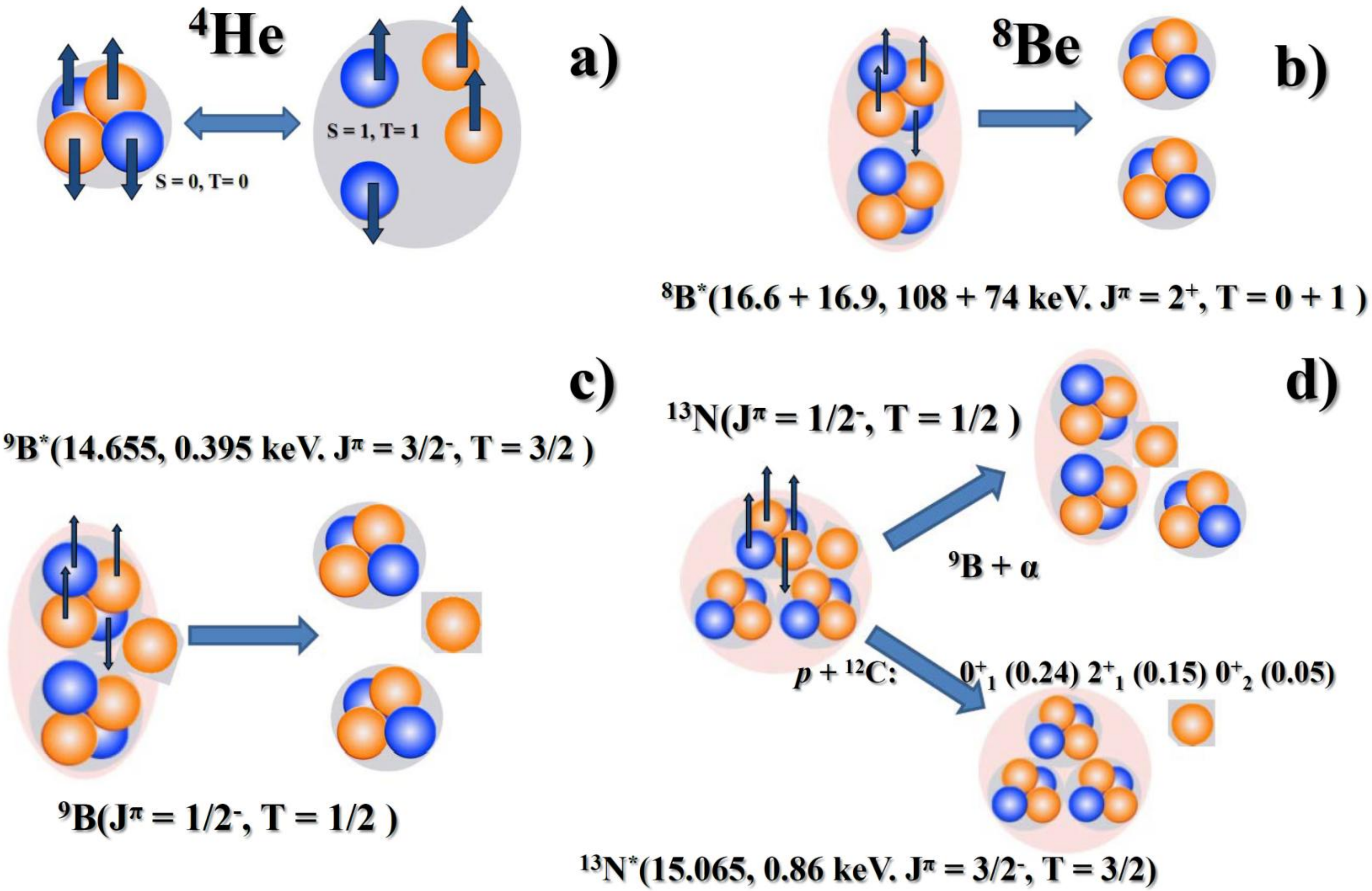
$$\Theta_{2\alpha} = \frac{P_{x1} \cdot P_{x2} + P_{y1} \cdot P_{y2} + P_{z1} \cdot P_{z2}}{P_{tot1} \cdot P_{tot2}}$$

$$\mathrm{Q}_{2\alpha} = \mathrm{M}_{2\alpha} - 2 \cdot \mathrm{m}_\alpha$$

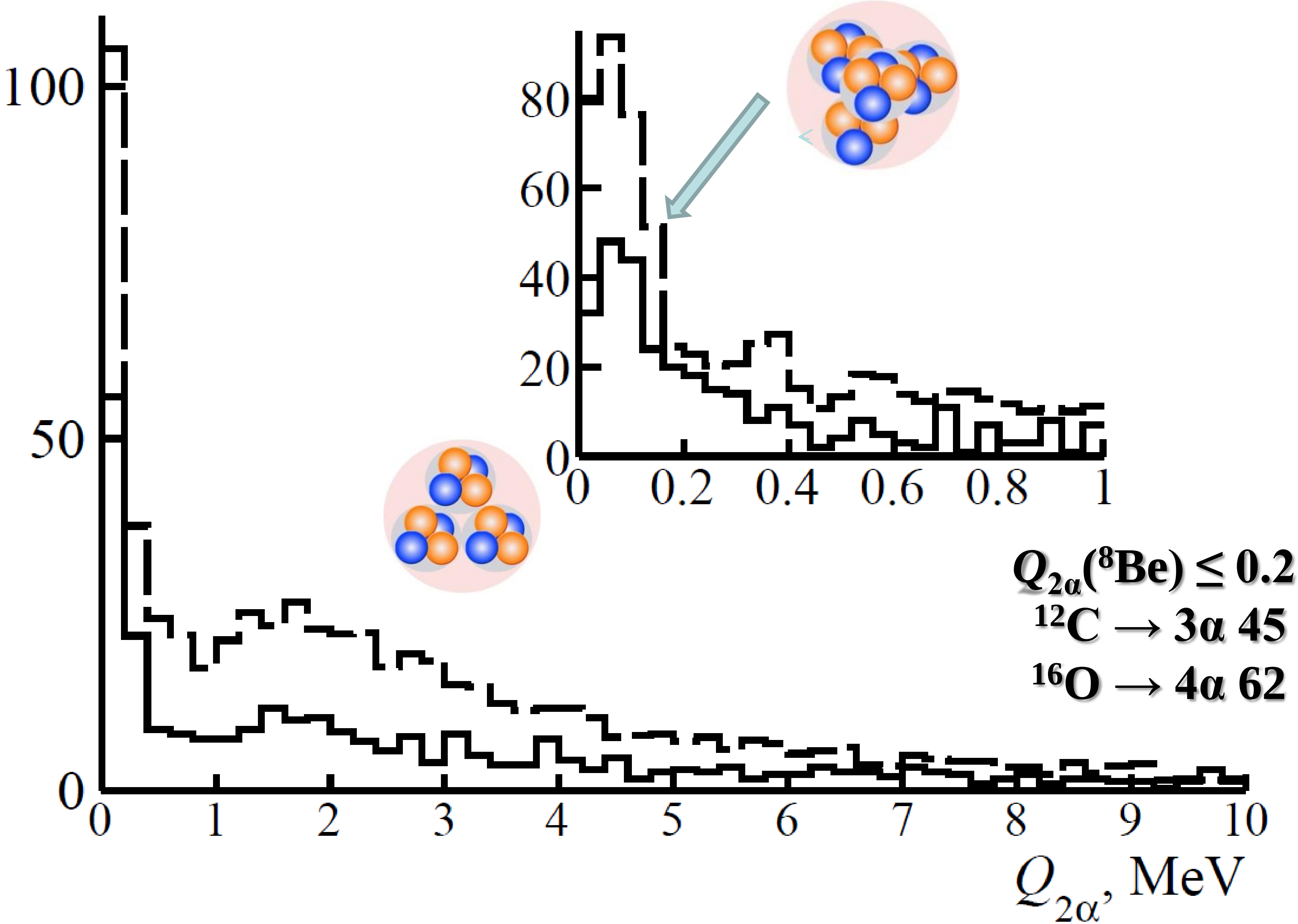
$$Q_{2\alpha} = \sqrt{2 \cdot [m_\alpha^2 + E_\alpha^2 - \vec{P}_{\alpha 1} \cdot \vec{P}_{\alpha 2}]} - 2 \cdot m_\alpha$$

$$Q_{3\alpha} = \sqrt{3 \cdot m_\alpha^2 + 2 \cdot \sum_{i \neq j} (E_{\alpha i} \cdot E_{\alpha j} - \vec{P}_{\alpha i} \cdot \vec{P}_{\alpha j})} - 3 \cdot m_\alpha$$

Инвариантная масса системы релятивистских фрагментов определяется как сумма всех произведений 4-импульсов $P_{i,k}$ фрагментов $M^{*2} = \sum(P_i \cdot P_k)$. Вычитание массы начального ядра или суммы масс фрагментов $Q = M^* - M$ является вопросом удобства представления. Компоненты $P_{i,k}$ определяются в приближении сохранения фрагментами начального импульса на нуклон. Реконструкция по инвариантной массе распадов нестабильных ядер ^{8}Be и ^{9}B, освоенная в эксперименте БЕККЕРЕЛЬ, подтвердила справедливость этого приближения.



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.



$Q_{2\alpha}(^{8}Be) \leq 0.2$ MeV
$^{12}C \rightarrow 3\alpha$ 45 ± 4%
$^{16}O \rightarrow 4\alpha$ 62 ± 3%

Distribution of number of 2α-pair combinations $N_{2\alpha}$ over the invariant mass $Q_{2\alpha}$ in coherent dissociation of $^{12}C \rightarrow 3\alpha$ (solid) and $^{16}O \rightarrow 4\alpha$ (dashed) at 3.65 *A* GeV; inset shows enlarged part of distributions $Q_{2\alpha} < 1$ MeV (step 40 keV).

SUMMARY

The BECQUEREL experiment is aimed at nuclear clustering physics. The nuclear track emulsion (NTE) makes it possible to study multiple final states arising in dissociation of relativistic nuclei. A current focus is on the theoretical concept of α-particle Bose-Einstein condensate (αBEC).

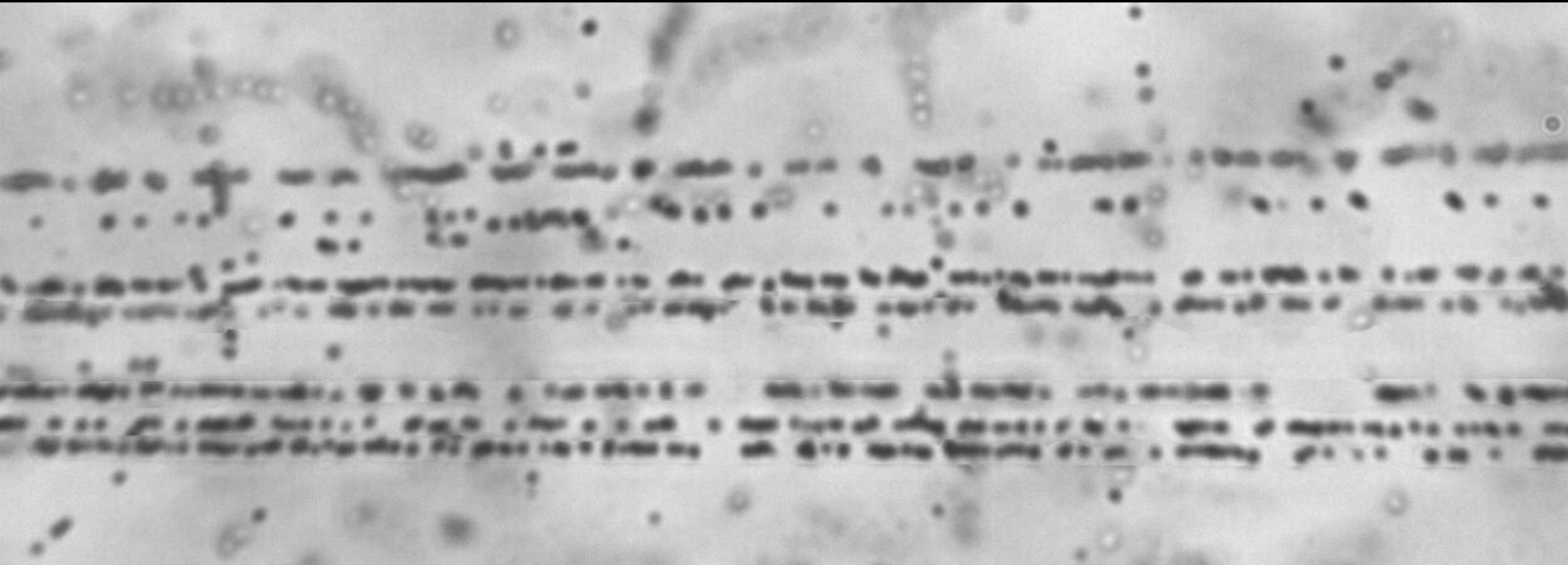
Owing to extremely small energies and widths, the ^{8}Be and HS decays, as well as $^9B \to {}^8Be\,p$, are identified in fragmentation of light nuclei by an upper constraint on the invariant mass. This approach has been used to identify ^{8}Be and HS and search for more complex states of αBEC in fragmentation of medium and heavy nuclei.

An enhancement in probability of detecting ^{8}Be in an event with an increase in number of relativistic α-particles is found. 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.

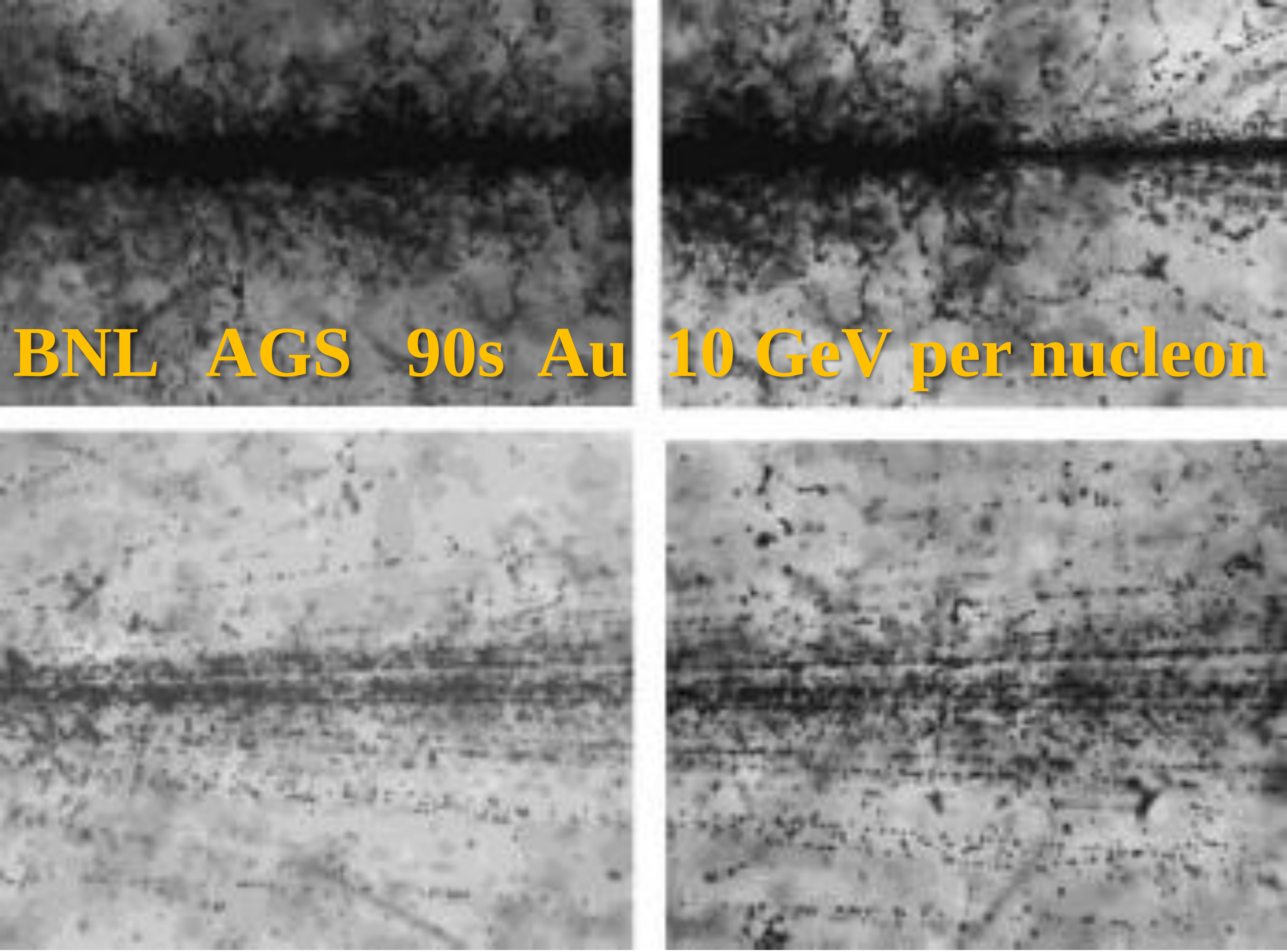
The main task of the forthcoming stage of the project is to clarify the relation between the appearance of ^{8}Be and HS and α-ensemble multiplicities and search on this basis for decays of the $^{16}O(0^+_6)$ state in ^{84}Kr fragmentation below 1 GeV per nucleon.

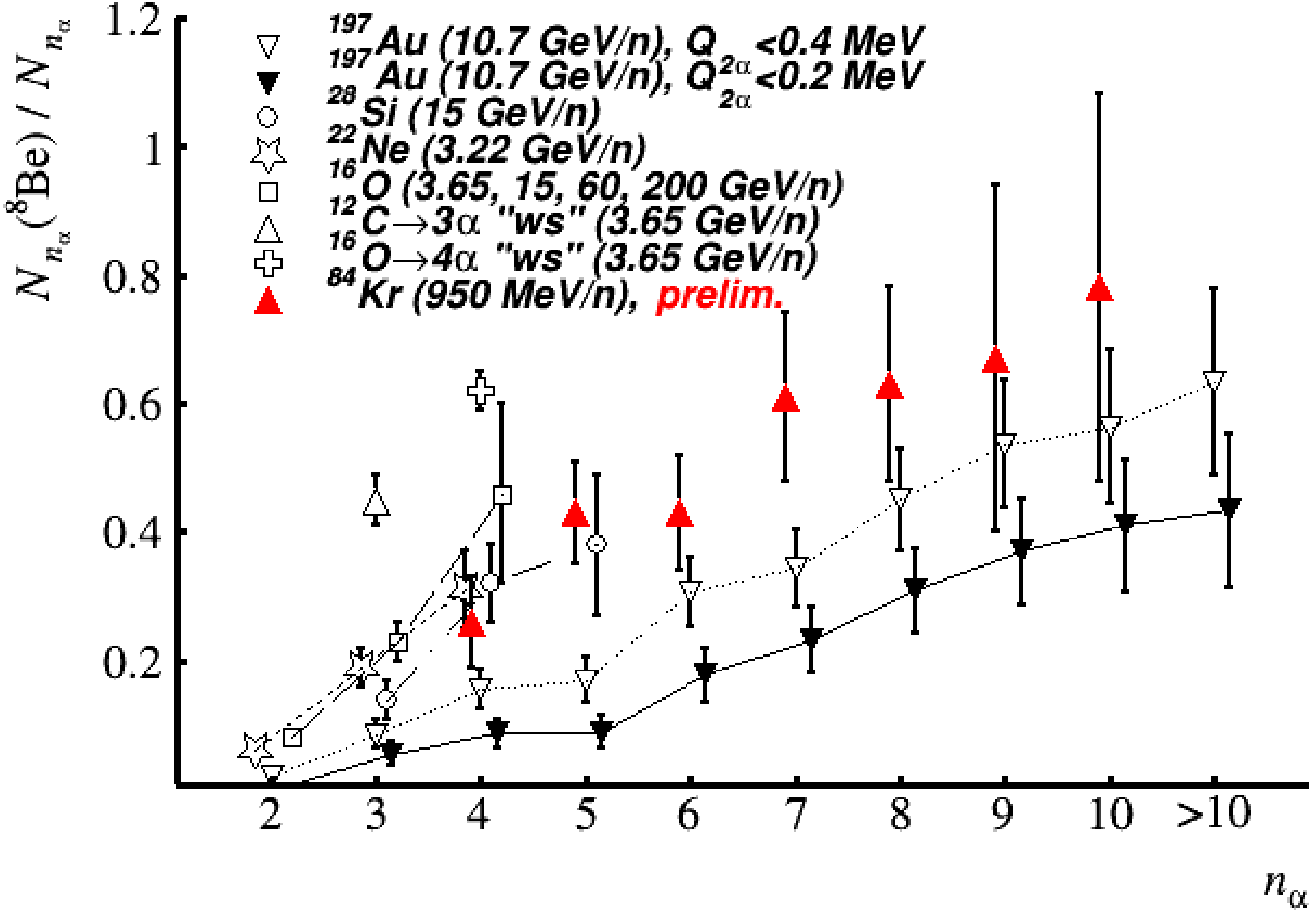
Searches for αBEC lead to the study of nuclear matter with temperature and density ranging from red giants to supernovae. In this respect NTE layers exposed to heavy nuclei at several GeV per nucleon of the NICA accelerator complex will make it possible to study relativistic ensembles of H and He isotopes of unprecedented multiplicity under optimal conditions.

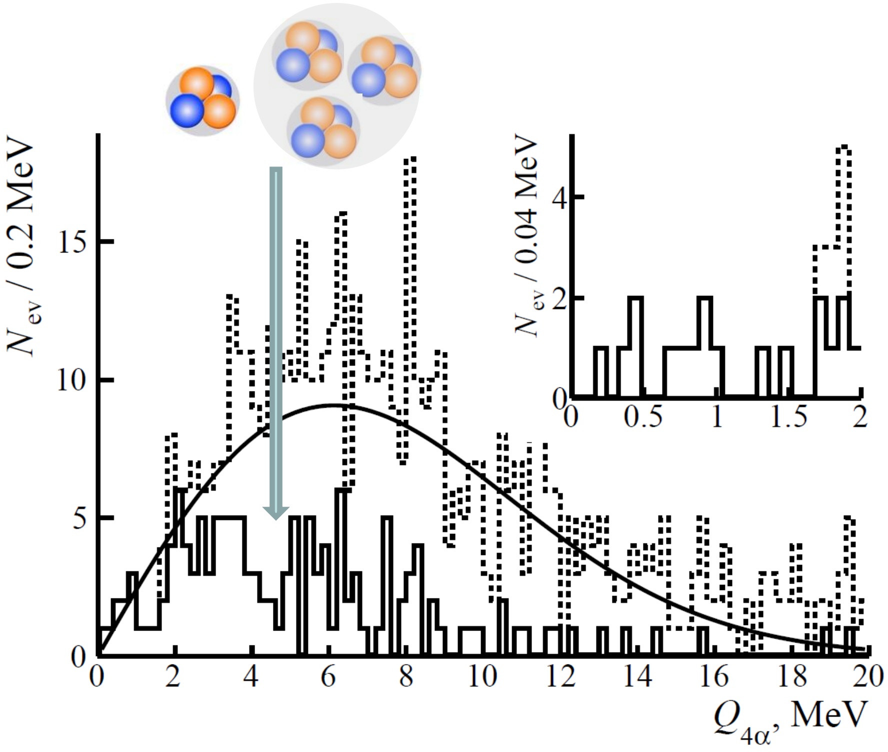
Синхрофазотрон 1986 г. ^{28}Si 3.65 ГэВ на нуклон

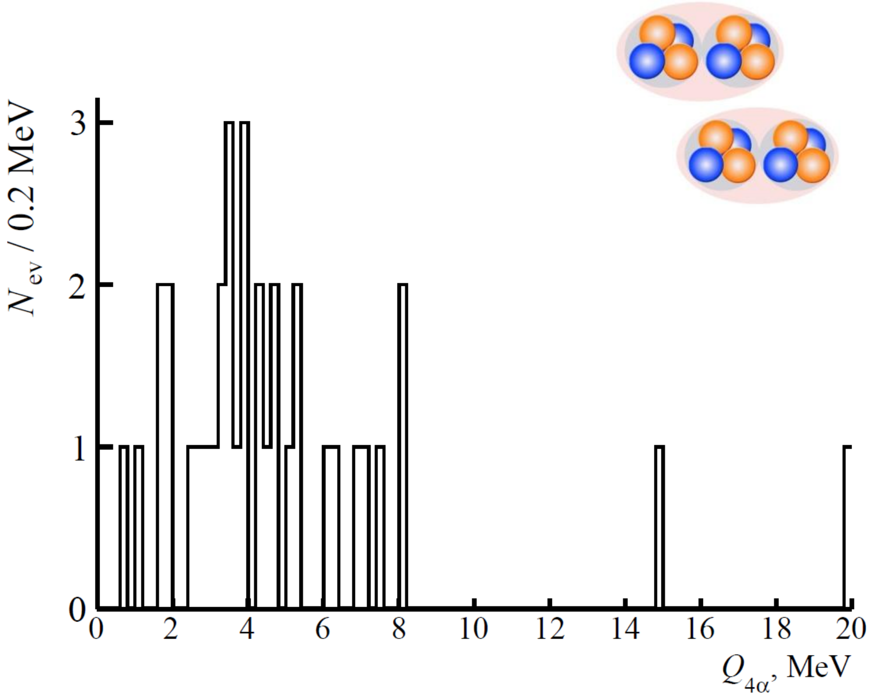


BNL AGS 90s Au 10 GeV per nucleon



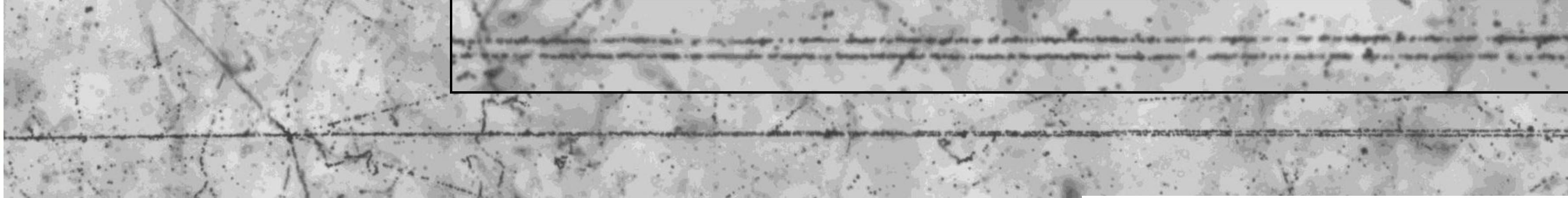

$N_{n_\alpha}(^8\mathrm{Be}) / N_{n_\alpha}$
1.2
1
0.8
0.6
0.4
0.2
▽ ^{197}Au (10.7 GeV/n), $Q_{2\alpha}$<0.4 MeV
▼ ^{197}Au (10.7 GeV/n), $Q_{2\alpha}$<0.2 MeV
○ ^{28}Si (15 GeV/n)
☆ ^{22}Ne (3.22 GeV/n)
□ ^{16}O (3.65, 15, 60, 200 GeV/n)
△ ^{12}C→3α "ws" (3.65 GeV/n)
✚ ^{16}O→4α "ws" (3.65 GeV/n)
▲ ^{84}Kr (950 MeV/n), prelim.
2
3
4
5
6
7
8
9
10
>10
n_α

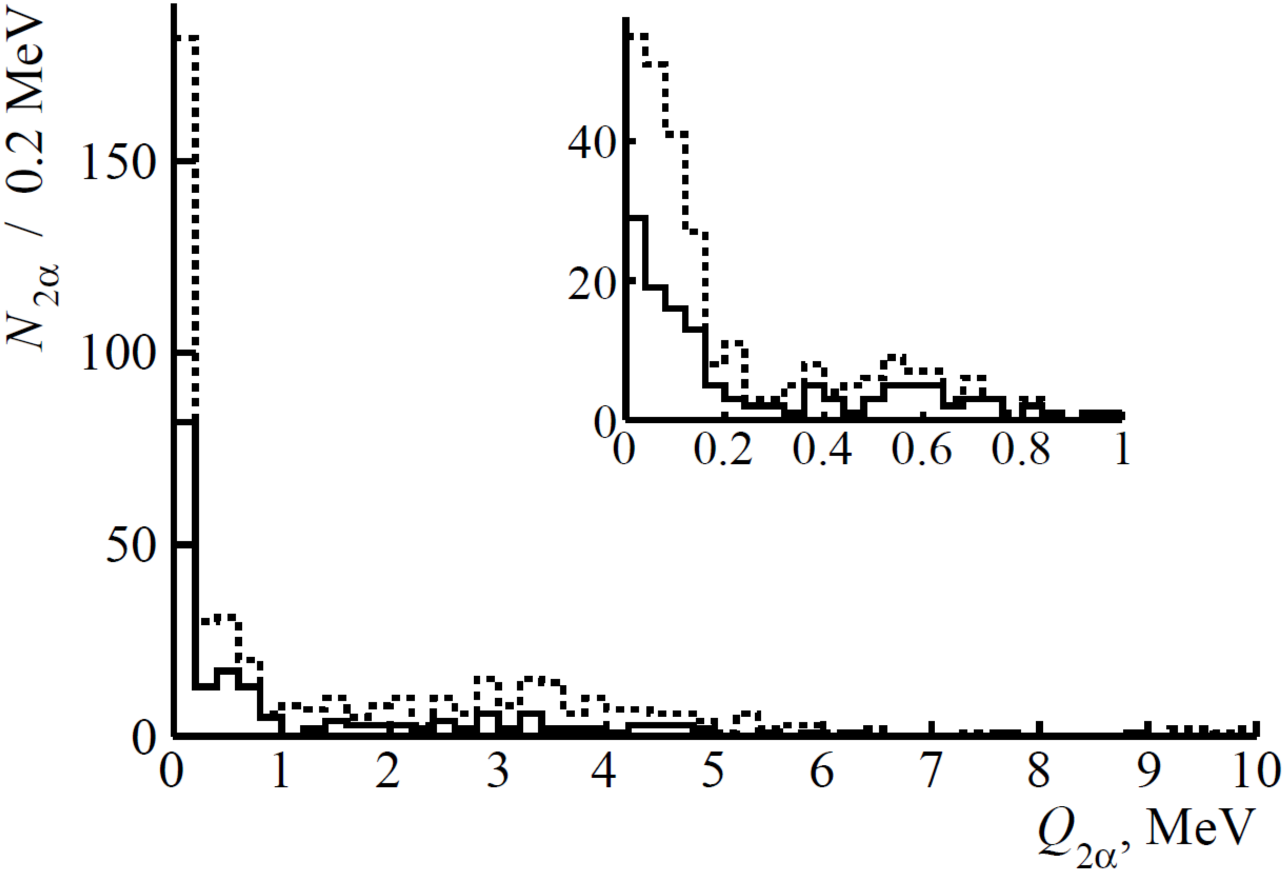


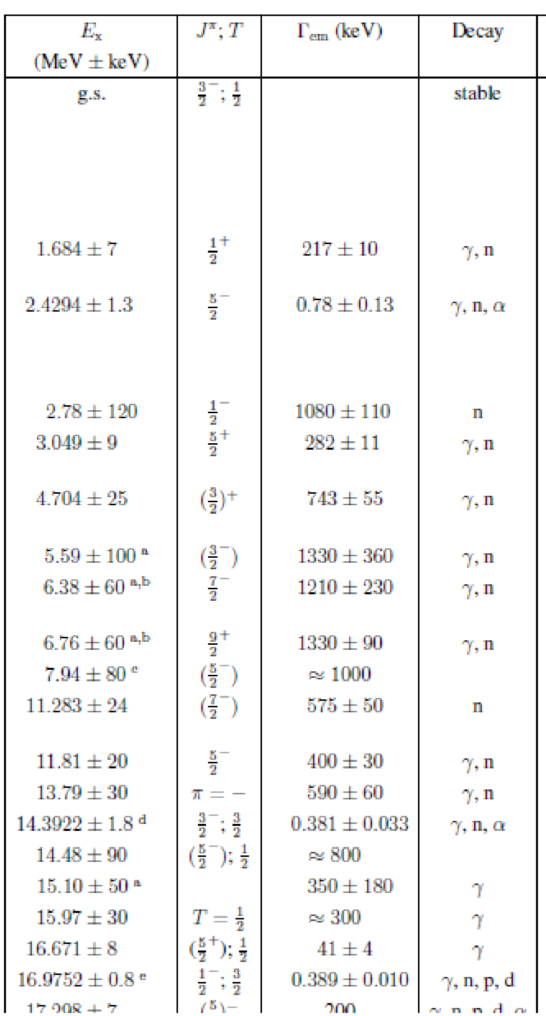


HS can occur as a result of α decay of the 0^+_6 excitation of the ^{16}O nucleus. The distribution of “white” ^{16}O → 4α stars over the invariant mass of 4α-quartettes $Q_{4\alpha}$ (Left) is described by the Rayleigh distribution with $\sigma_{Q4\alpha}$ = (6.1 ± 0.2) MeV. The condition $Q_{3\alpha}$ (HS) < 700 keV shifts the $Q_{4\alpha}$ distribution and indicates 9 events $Q_{4\alpha}$ < 1 MeV $\langle Q_{4\alpha}\rangle$ (RMS) = 624 ± 84 (252) keV. The contribution of ^{16}O (0^+_6) → α + HS decays is estimated to be 7 ± 2% for normalization to HS. It can be concluded that the direct dissociation of α + HS dominates in the formation of HS.

33 events were identified ^{16}O → 2^{8}Be, which is 5 ± 1% of the “white” stars ^{16}O → 4α. Then, the statistics of coherent dissociation for the ^{16}O → 2^{8}Be and αHS channels has a ratio of 0.22 ± 0.02. The distribution over the invariant mass $Q_{4\alpha}$ < 1.0 MeV of events ^{16}O → 2^{8}Be (Right) indicates two candidates ^{16}O (0^+_6). Thus, the estimate of the probability ratio of the ^{16}O (0^+_6) → 2^{8}Be and α + HS channels is 0.22 ± 0.17, which is unsatisfactory. At the same time, the increase in the statistics of events ^{16}O → 4α can be considered exhausted. There remains the possibility of studying (3-4)α-ensembles in the fragmentation of heavier nuclei.

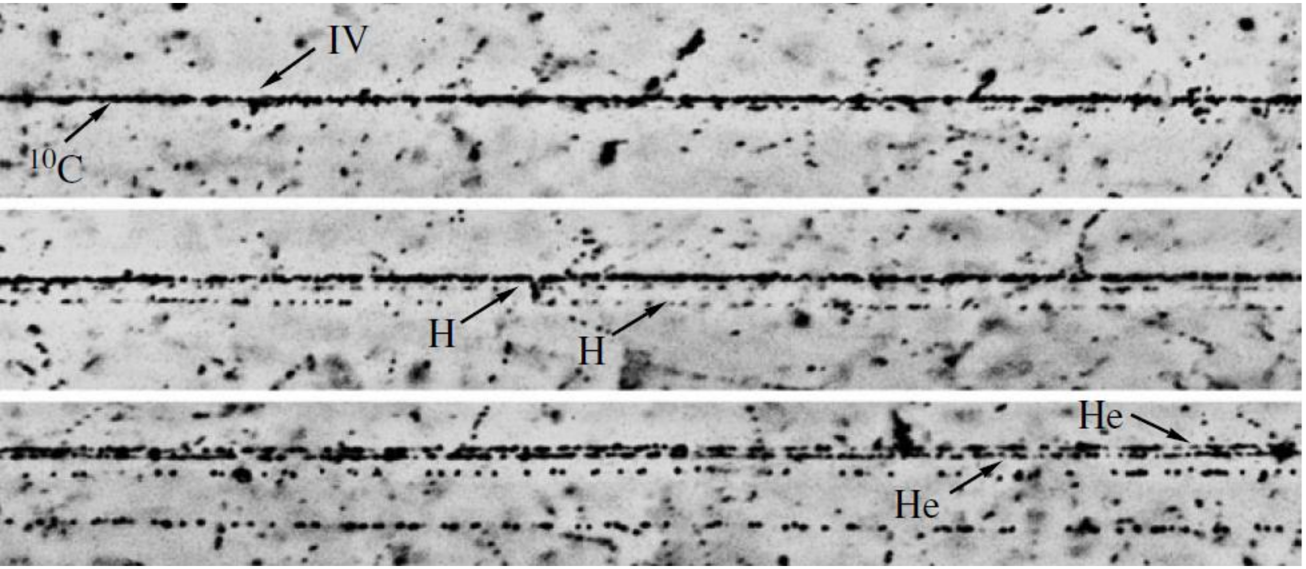






E_x (MeV ± keV)	$J^\pi; T$	Γ_{cm} (keV)	Decay
g.s.	$\frac{3}{2}^-; \frac{1}{2}$		stable
1.684 ± 7	$\frac{1}{2}^+$	217 ± 10	γ, n
2.4294 ± 1.3	$\frac{5}{2}^-$	0.78 ± 0.13	γ, n, α
2.78 ± 120	$\frac{1}{2}^-$	1080 ± 110	n
3.049 ± 9	$\frac{5}{2}^+$	282 ± 11	γ, n
4.704 ± 25	$(\frac{3}{2})^+$	743 ± 55	γ, n
5.59 ± 100 [a]	$(\frac{3}{2}^-)$	1330 ± 360	γ, n
6.38 ± 60 [a,b]	$\frac{7}{2}^-$	1210 ± 230	γ, n
6.76 ± 60 [a,b]	$\frac{9}{2}^+$	1330 ± 90	γ, n
7.94 ± 80 [c]	$(\frac{5}{2}^-)$	≈ 1000	
11.283 ± 24	$(\frac{7}{2}^-)$	575 ± 50	n
11.81 ± 20	$\frac{5}{2}^-$	400 ± 30	γ, n
13.79 ± 30	$\pi = -$	590 ± 60	γ, n
14.3922 ± 1.8 [d]	$\frac{3}{2}^-; \frac{3}{2}$	0.381 ± 0.033	γ, n, α
14.48 ± 90	$(\frac{5}{2}^-); \frac{1}{2}$	≈ 800	
15.10 ± 50 [a]		350 ± 180	γ
15.97 ± 30	$T = \frac{1}{2}$	≈ 300	γ
16.671 ± 8	$(\frac{5}{2}^+); \frac{1}{2}$	41 ± 4	γ
16.9752 ± 0.8 [e]	$\frac{1}{2}^-; \frac{3}{2}$	0.389 ± 0.010	γ, n, p, d
17.298 ± 7	$(\frac{5}{2})^-$	200	γ, n, p, d, α

The distribution over $Q_{2\alpha}$ of 500 2α-pairs (dots) including 198 "white" ones (solid) indicates the limit $Q_{2\alpha}$(^{8}Be) < 0.2 MeV. There are two "influxes" centered on $Q_{2\alpha}$ around 0.6 and 3 MeV. The first reflects the ^{9}Be excitation at 2.43MeV and the second one the ^{8}Be$_{2+}$ state.



The ground state of the ^{9}B nucleus is higher than the ^{8}Be*p* threshold by 185 keV, and its width 0.54 keV, also indicates that it is a long-lived state.