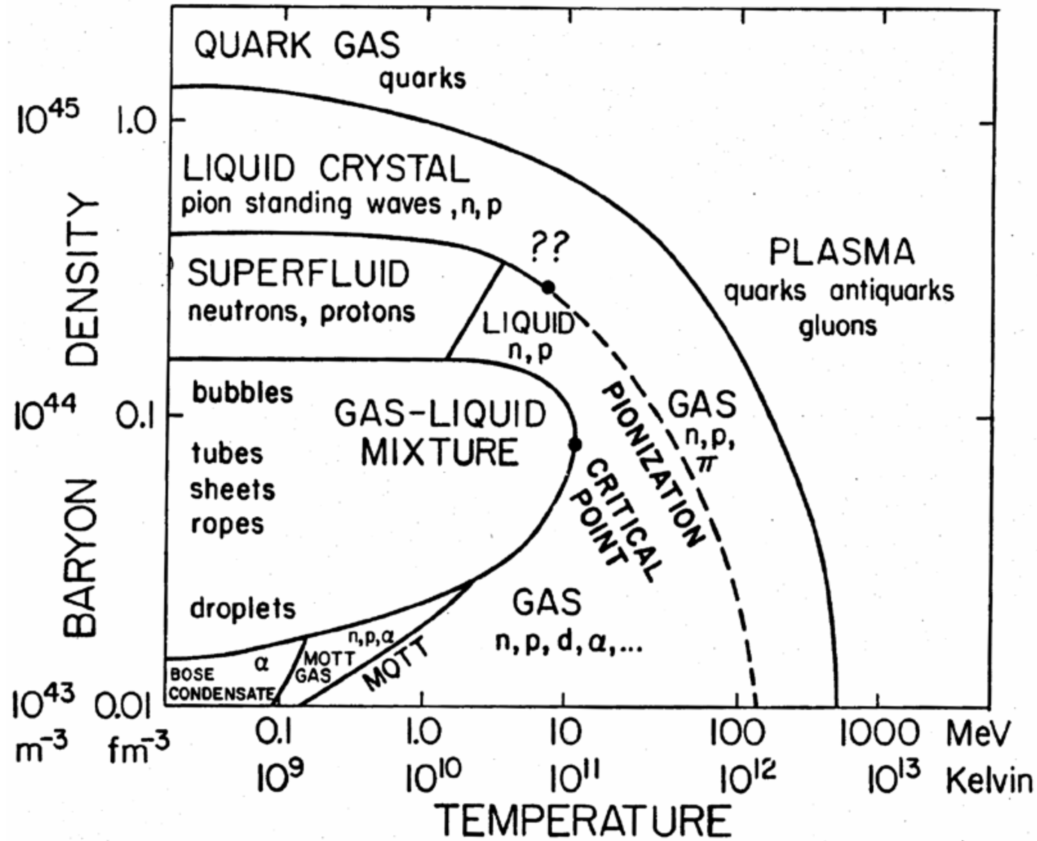
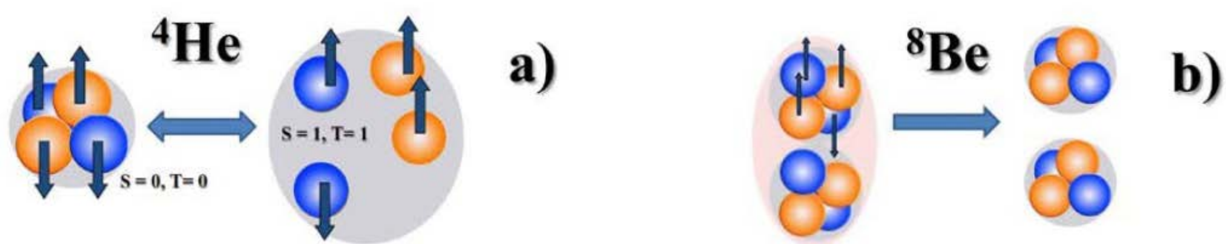
Searches for alpha condensate states in relativistic nuclear fragmentation

Andrey Zaitsev and Pavel Zarubin*

**presenter*

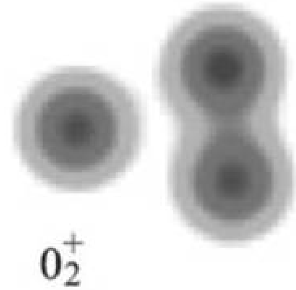
Joint Institute for Nuclear Research, Dubna, Russia



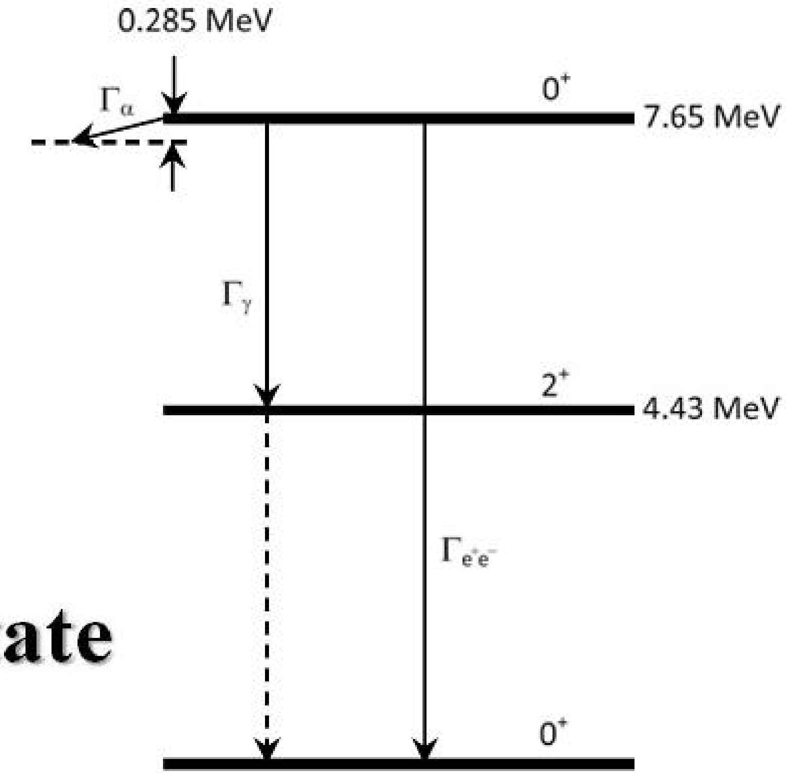


One of key aspects of nuclear structure is presence of degrees of freedom in which quartets of spin-paired protons and neutrons behave as constituent clusters, manifested in intensive formation of α-particles in a wide variety reactions and decays. Transition to study of ensembles of α-particles just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

A decay energy $^8Be \rightarrow 2\alpha$ is only $E_{th}(^8Be) = 91.8$ keV, and width $\Gamma(^8Be) = 5.57 \pm 0.25$ eV. The ^8Be nucleus is an indispensable decay product of HS. The HS state is a second ^{12}C excitation and a first at $E_{th}(HS) = 378$ keV above the 3α threshold. A value $\Gamma(HS) = 9.3 \pm 0.9$ eV corresponds in order of magnitude to a width of the decay $\pi^0 \rightarrow 2\gamma$.



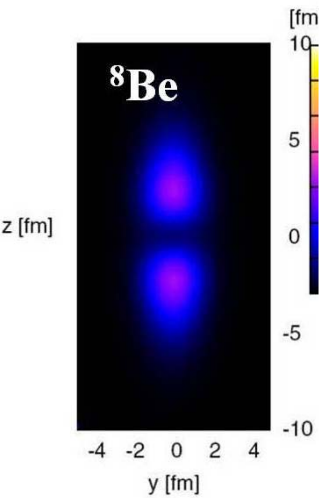
The Hoyle state

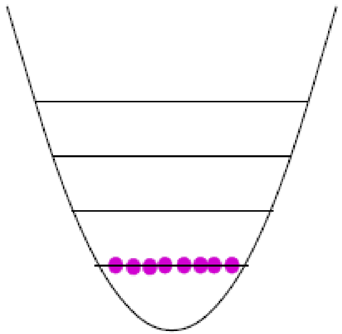


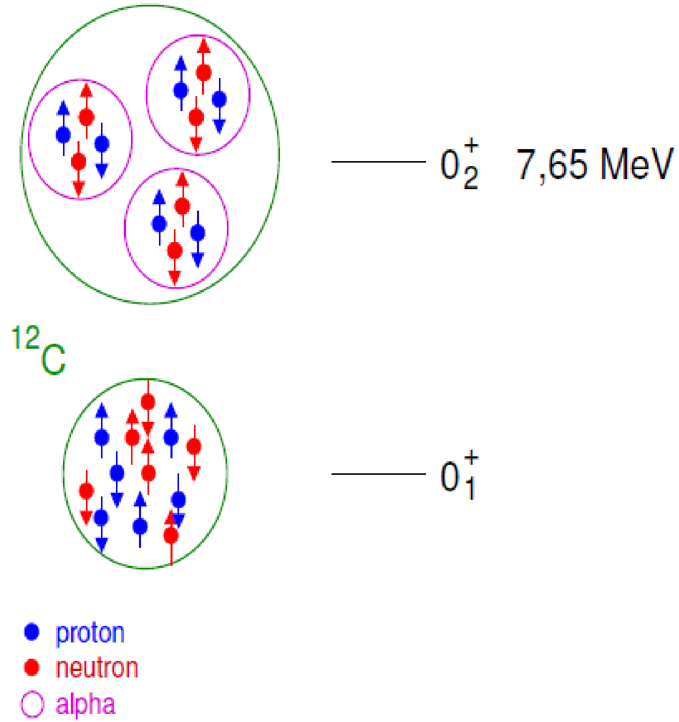
An isolation of HS from higher ^{12}C excitations points to it as a ^8Be 3α-analogue. Synthesis of ^{12}C is possible through the fusion $3\alpha \rightarrow \alpha^8Be \rightarrow {}^{12}C(0^+_2) \rightarrow {}^{12}C$ (+2γ or e^+e- with a probability of the order of 10^{-4}). Further synthesis is possible in the sequence $^{12}C^{12}C \rightarrow {}^{12}C^{12}C(0^+_2) \rightarrow {}^{16}O^8Be$ determining the ^{12}C and ^{16}O abundances. These facts assume importance of heavier analogs.

Bosons

Back to nuclei

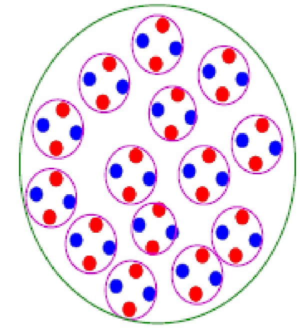






many α's

$\rightarrow$ condensate



Alpha-Clusters in Nuclear Systems

P. Schuck

strong cluster phenomena in lighter nuclei

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

Modern interest is motivated by the concept of an α-particle Bose–Einstein condensate (αBEC). A manifestation of αBEC can be α-particle excitations of nuclei immediately above the binding thresholds of α-particles. Coexisting with fermionic excitations, they are considered on the basis of the mean field of the bosonic type, formed by a gas of almost ideal bosons in the S state at an average density four times lower than usual. The ^{8}Be(0^+) ground state is described as 2αBEC, and HS as 3αBEC. The ^{8}Be → 2α and HS → ^{8}Beα decays can serve as signatures for cascade decays of more complex αBEC forms. The 0^+_6 excitation of the ^{16}O nucleus at 660 keV above the 4α threshold, considered as 4αBEC, can sequentially decay ^{16}O(0^+_6) → αHS or ^{16}O(0^+_6) → 2^{8}Be(0^+).

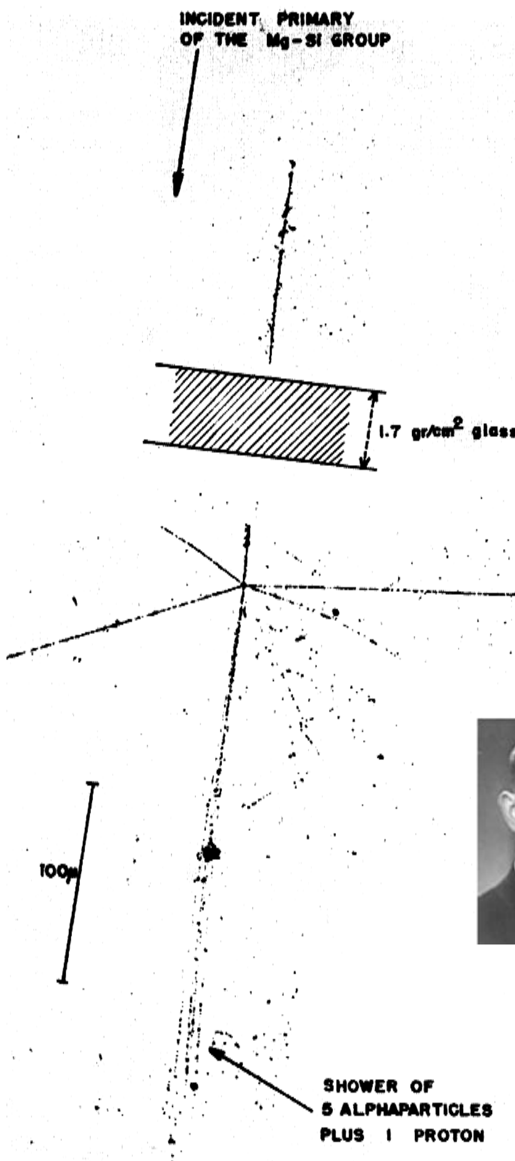

Trento 2019


Hair - 60 μm
AgBr Crystal - 0.2 μm
Atom - 10^{-4} μm
Proton - 10^{-9} μm

PHYSICAL REVIEW VOLUME 77, NUMBER 1

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

C. F. POWELL

P. H. FOWLER and D. H. PERKINS

H. H. WILLS PHYSICAL LABORATORY

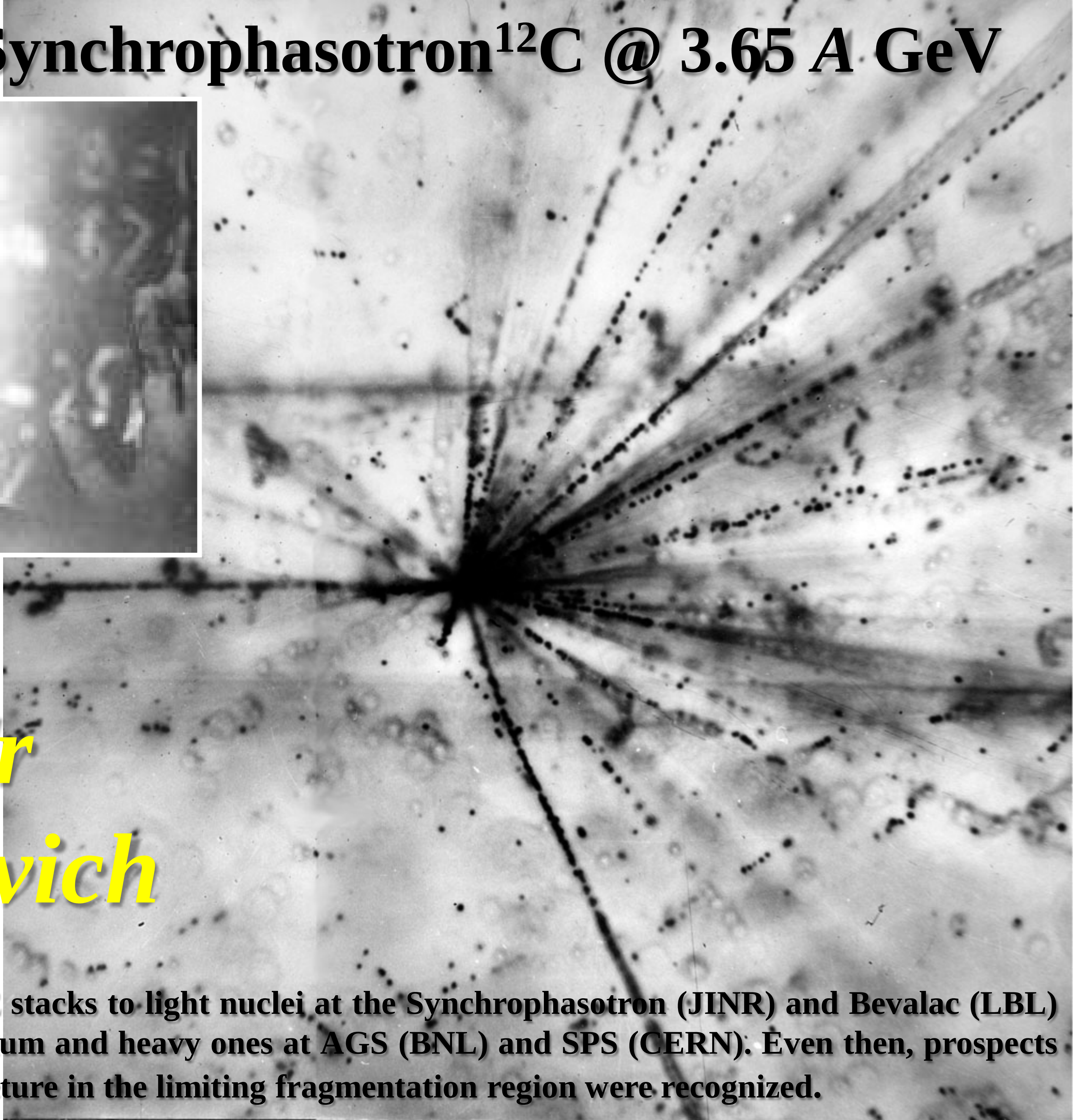
UNIVERSITY OF BRISTOL

PERGAMON PRESS

LONDON · NEW YORK · PARIS · LOS ANGELES

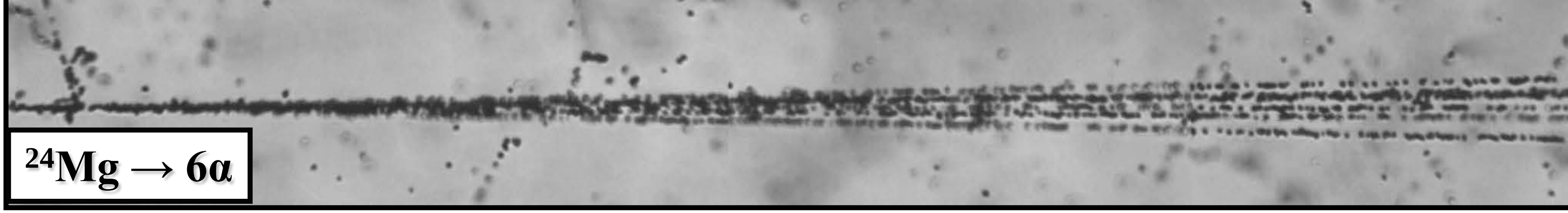
1959

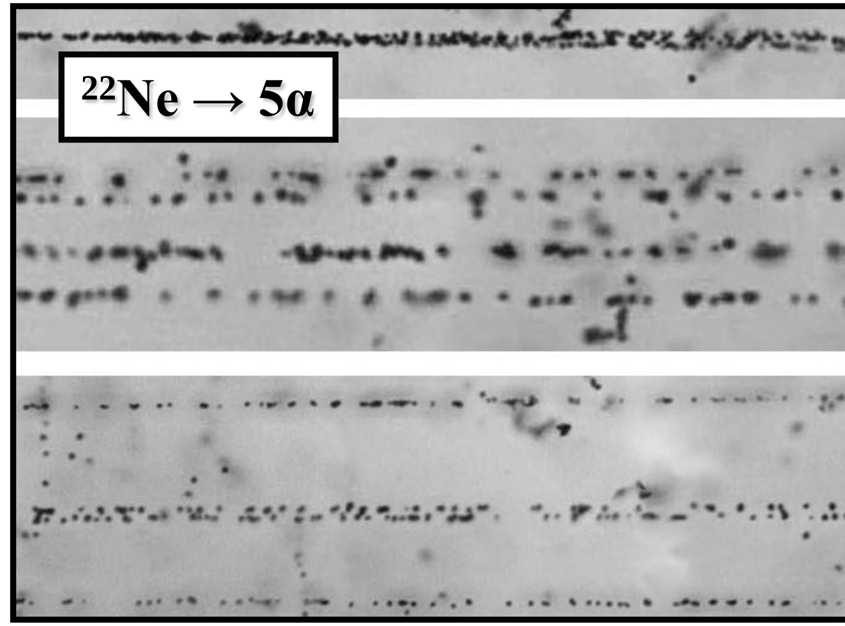
1974 JINR Synchrophasotron ^{12}C @ 3.65 *A* GeV

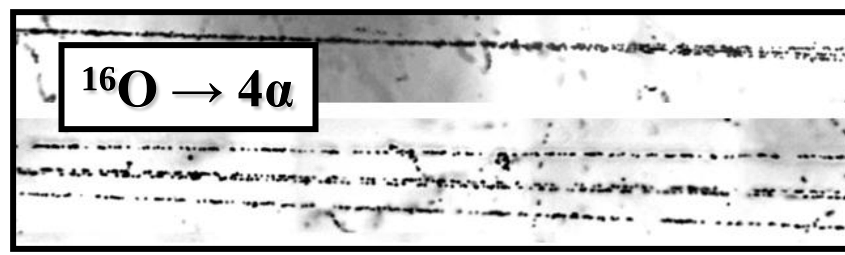


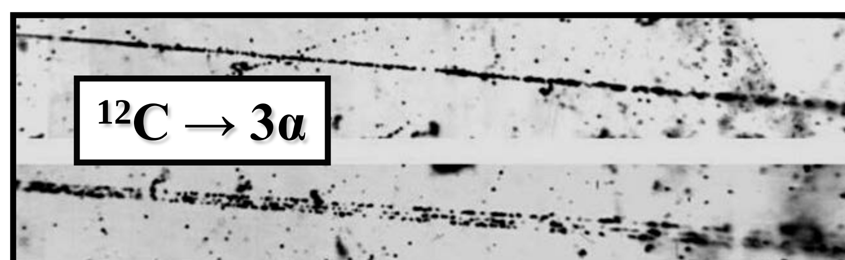
Baldin Aleksandr Mikhailovich

In the 70s exposures of NTE stacks to light nuclei at the Synchrophasotron (JINR) and Bevalac (LBL) began, and in the 90s - medium and heavy ones at AGS (BNL) and SPS (CERN). Even then, prospects of studying the nuclear structure in the limiting fragmentation region were recognized.





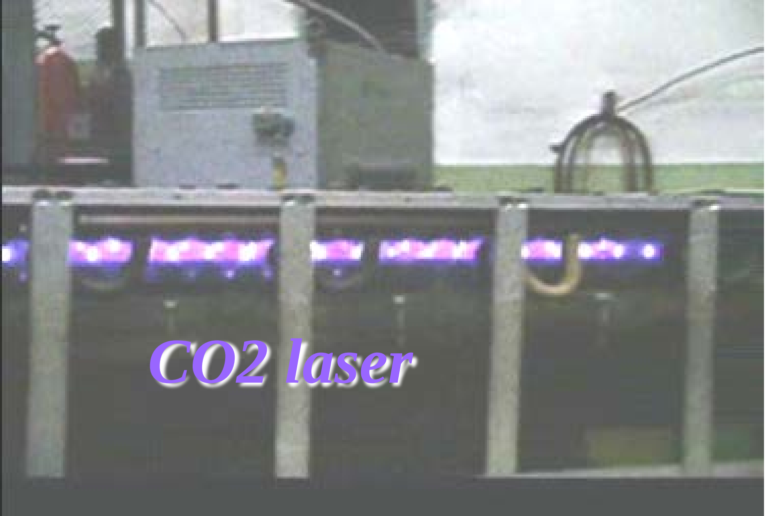


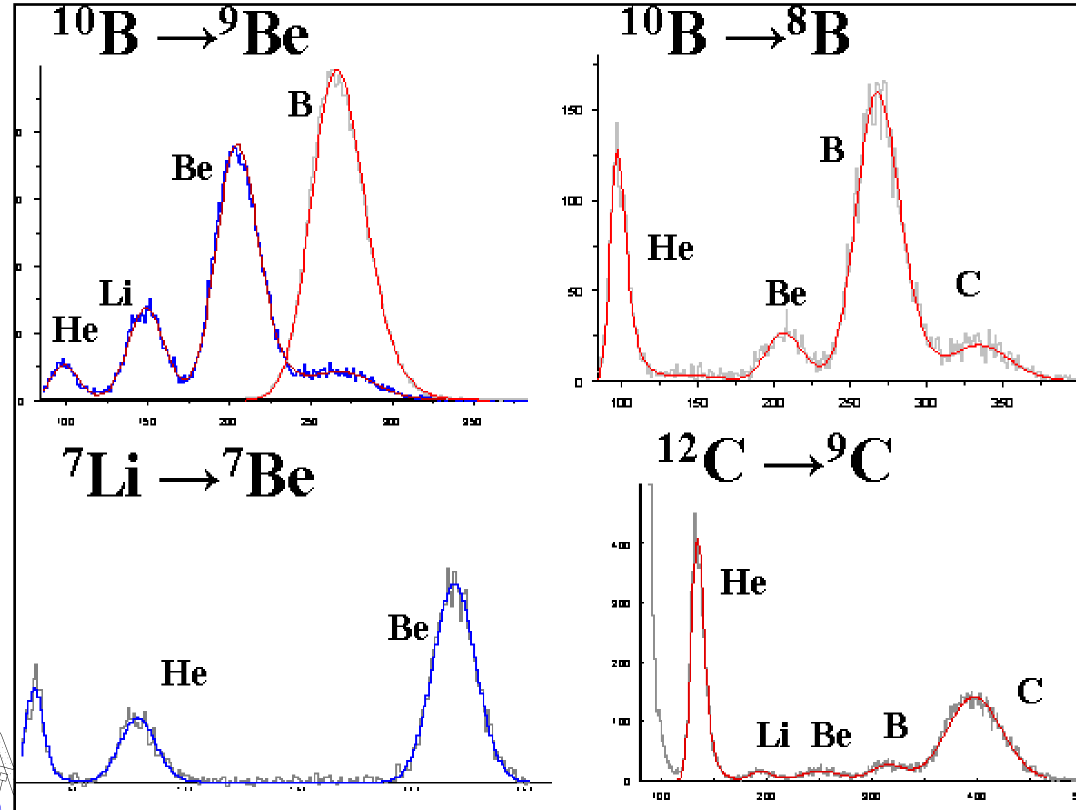


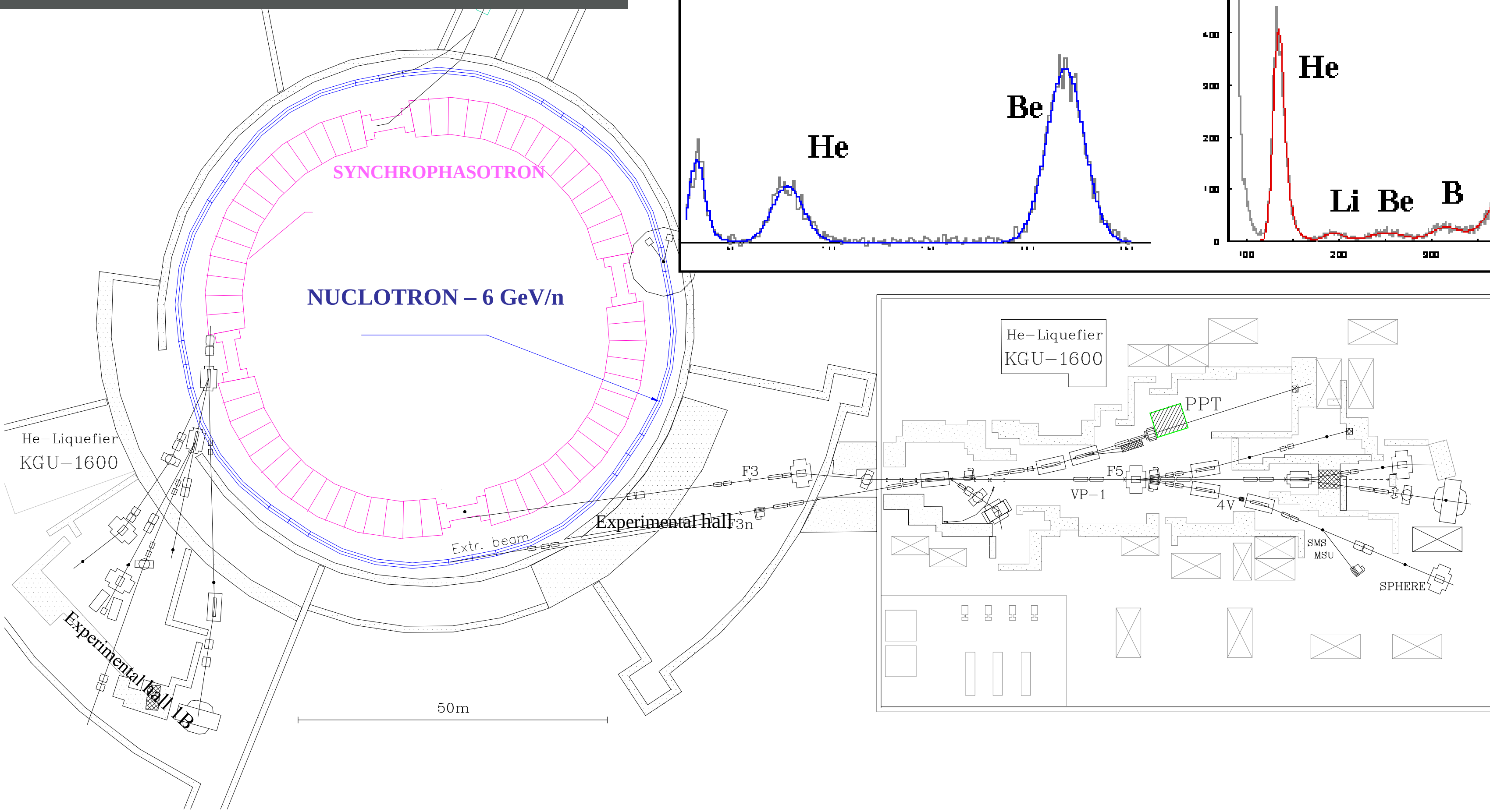
The use of a technically simple and inexpensive method of NTE in beams of relativistic nuclei provides flexibility and uniformity at a search stage, and in a theoretical aspect, transparency of interpretation. It is very valuable to demonstrate similarity of conclusions based on relativistic invariance.

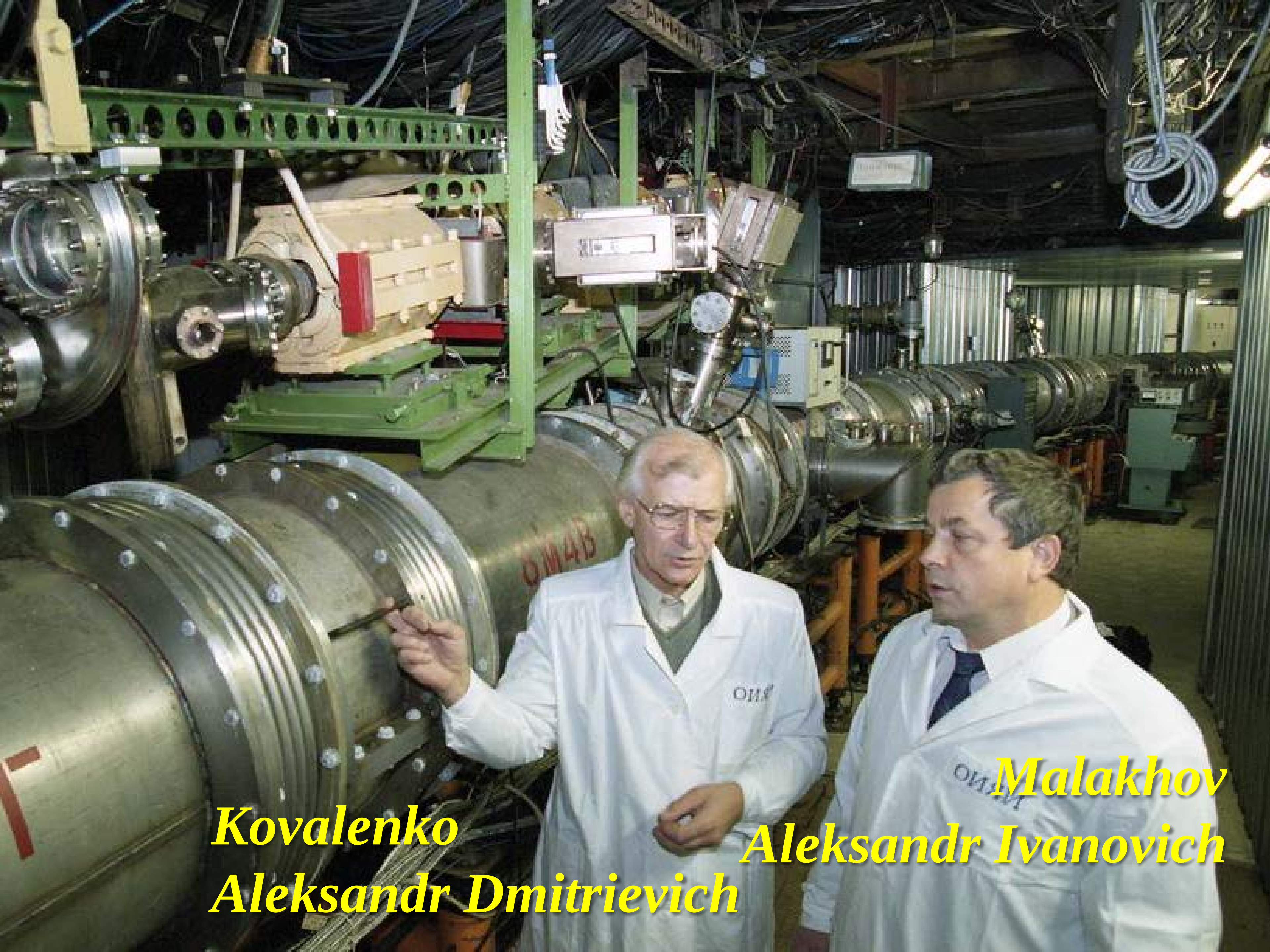
During the dissociation of relativistic nuclei in a narrow solid angle of fragmentation, ensembles of He and H nuclei are intensively generated. When they are detected, there are no thresholds, and energy losses are minimal.

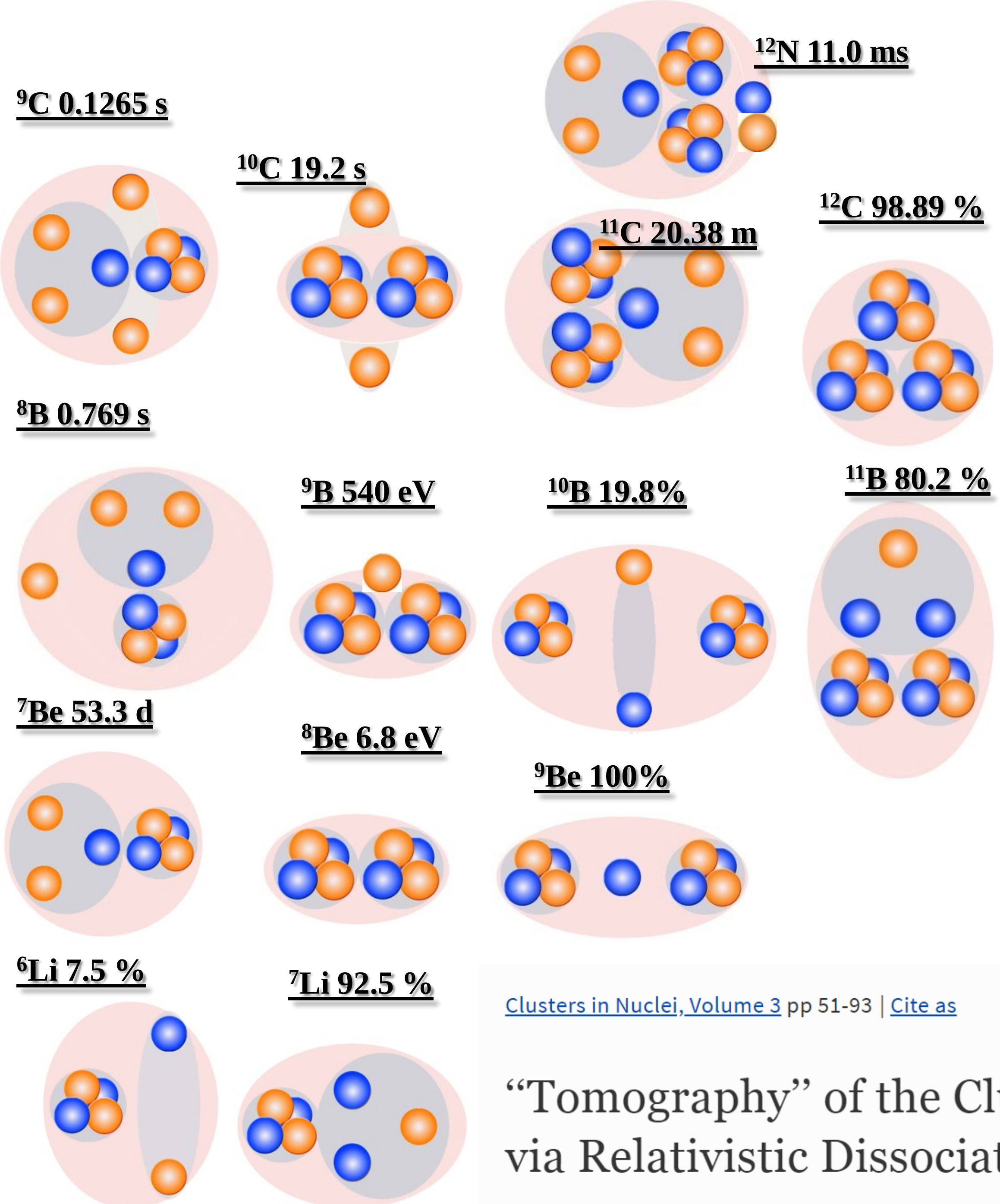
According to the widths, decays of ^{8}Be and HS occur at ranges several thousand atomic sizes and must be identified by a minimum invariant mass. Due to minimum energy, their decays of should appear as pairs and triplets of relativistic He fragments with the smallest opening angles. The same collimation along the interaction axis should be exhibited by more complex states of αBEC.

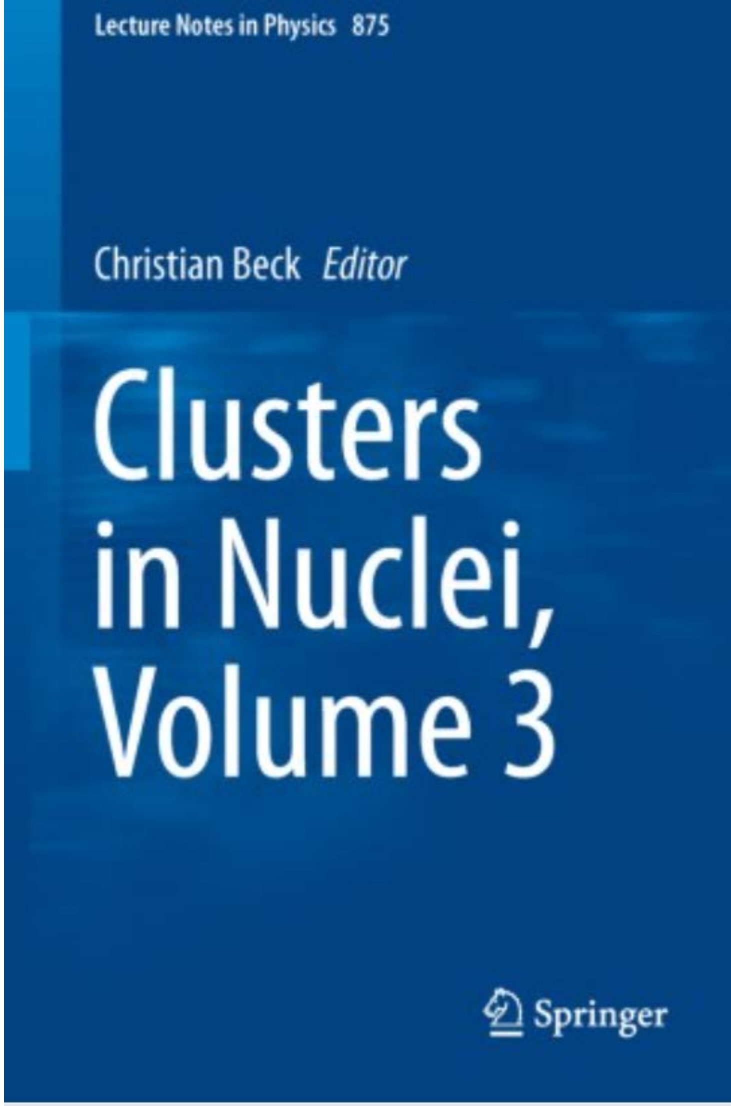

CO2 laser


$^{10}B \rightarrow {}^{9}Be$
He
Li
Be
B
$^{10}B \rightarrow {}^{8}B$
He
Be
B
C
$^{7}Li \rightarrow {}^{7}Be$
He
Be
$^{12}C \rightarrow {}^{9}C$
He
Li
Be
B
C


SYNCHROPHASOTRON
NUCLOTRON – 6 GeV/n
He–Liquefier
KGU–1600
Extr. beam
Experimental hall
F3
F3n
Experimental hall 1B
50m
He–Liquefier
KGU–1600
PPT
F5
VP–1
4V
SMS
MSU
SPHERE

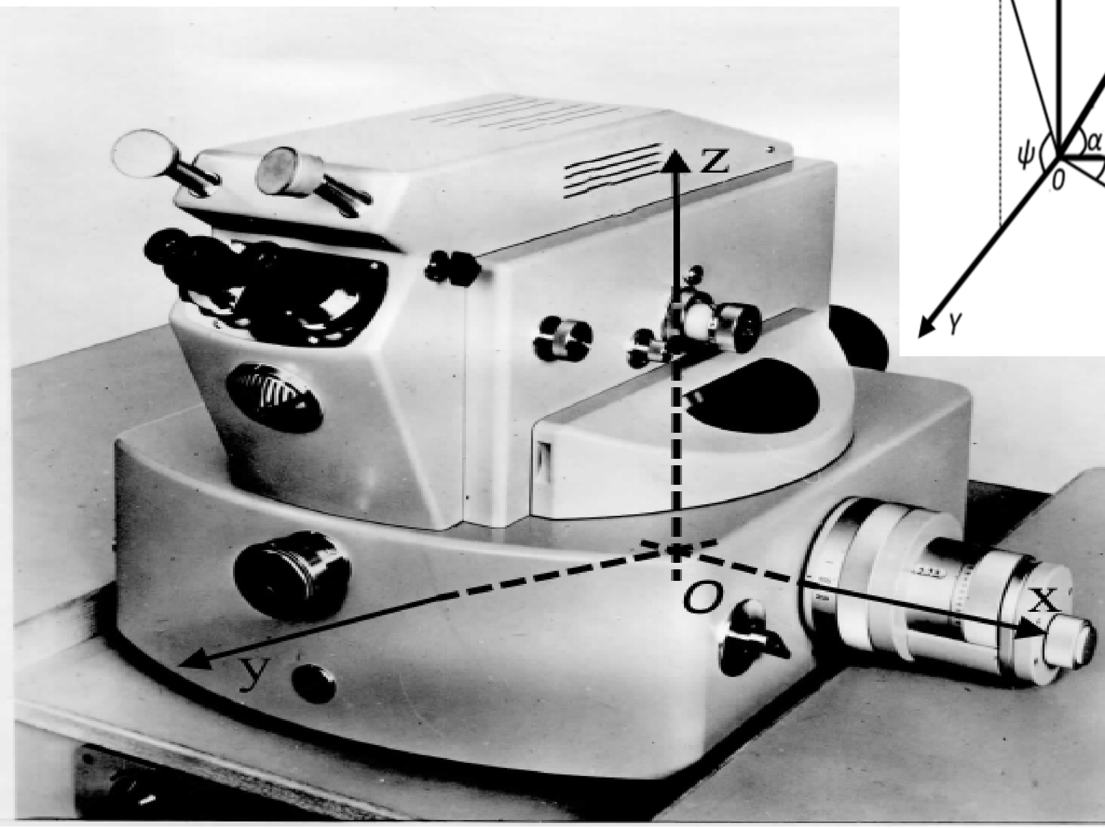

Malakhov
Aleksandr Ivanovich
Kovalenko
Aleksandr Dmitrievich

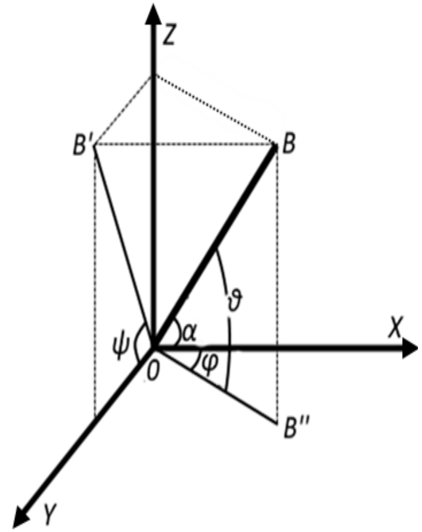




Clusters in Nuclei, Volume 3 pp 51-93 | Cite as

"Tomography" of the Cluster Structure of Light Nuclei via Relativistic Dissociation





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

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

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

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

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

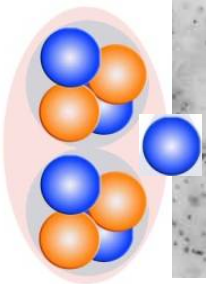
$$\Theta_{2\alpha} = \frac{P_{x1} \cdot P_{x2} + P_{y1} \cdot P_{y2} + P_{z1} \cdot P_{z2}}{P_{tot1} \cdot P_{tot2}}$$

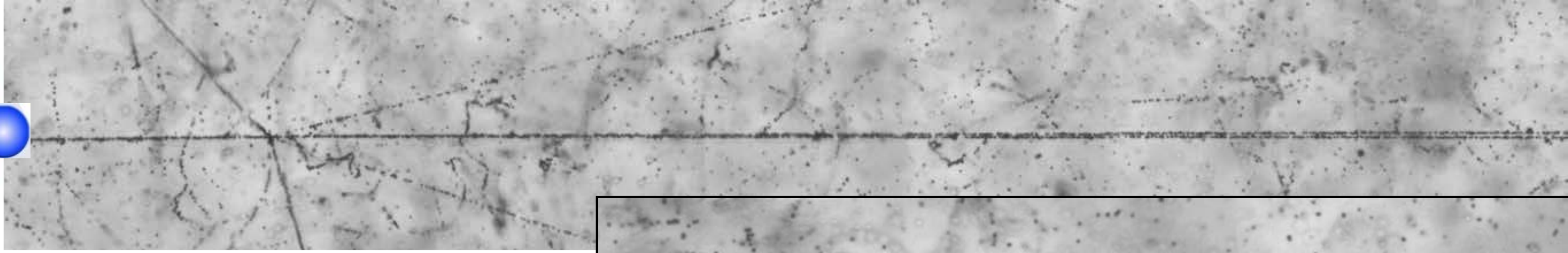
$$\mathrm{Q}_{2\alpha} = \mathrm{M}_{2\alpha} - 2 \cdot \mathrm{m}_\alpha$$

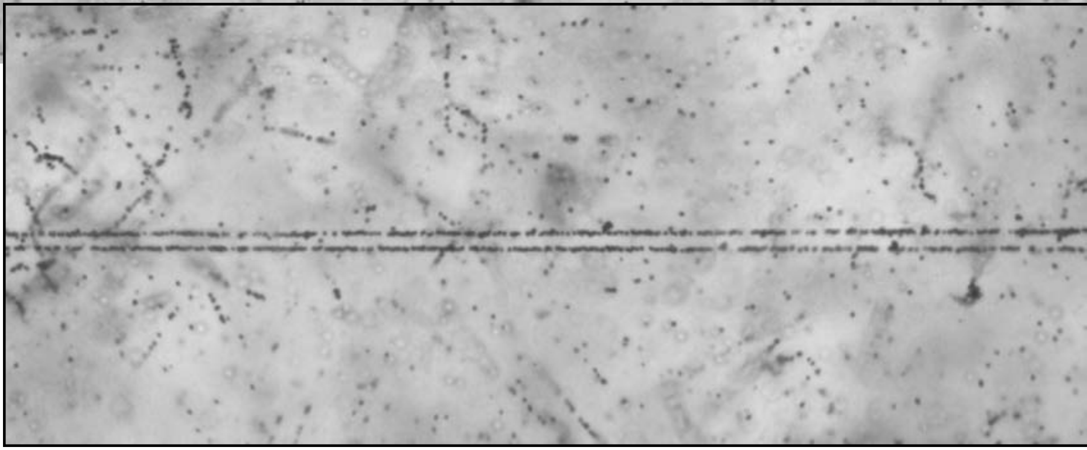
$$Q_{2\alpha} = \sqrt{2 \cdot [m_\alpha^2 + E_\alpha^2 - \vec{P}_{\alpha 1} \cdot \vec{P}_{\alpha 2}]} - 2 \cdot m_\alpha$$

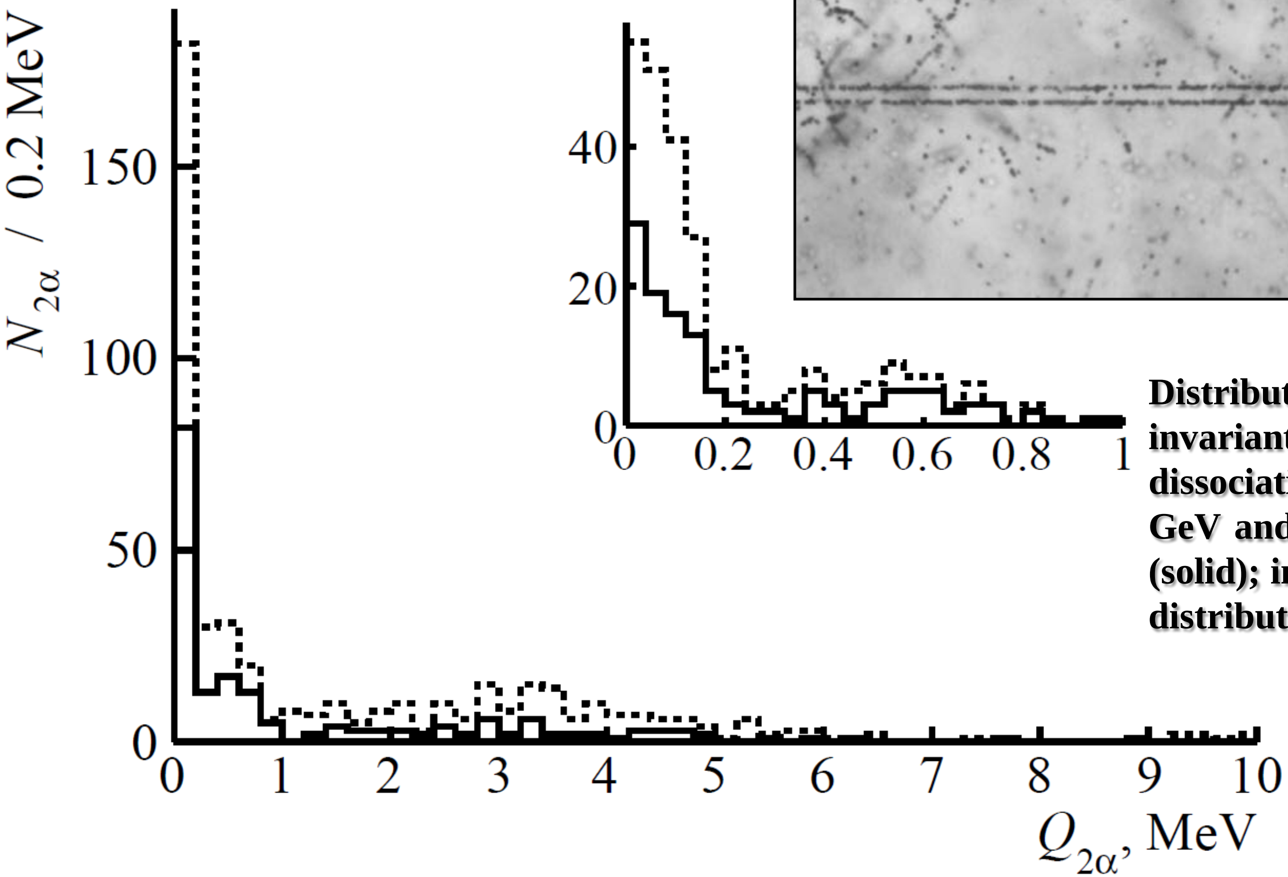
$$Q_{3\alpha} = \sqrt{3 \cdot m_\alpha^2 + 2 \cdot \sum_{i \neq j} (E_{\alpha i} \cdot E_{\alpha j} - \vec{P}_{\alpha i} \cdot \vec{P}_{\alpha j})} - 3 \cdot m_\alpha$$

In general, energy of a few-particle system *Q* is $Q = M^* - M$. M^* is the invariant mass defined by the sum of all products of *4*-momenta $P_{i,k}$ fragments $M^{*2} = \sum(P_i \cdot P_k)$. 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. Then, the definition of *Q* comes down to determining the angles between the fragment emission directions.



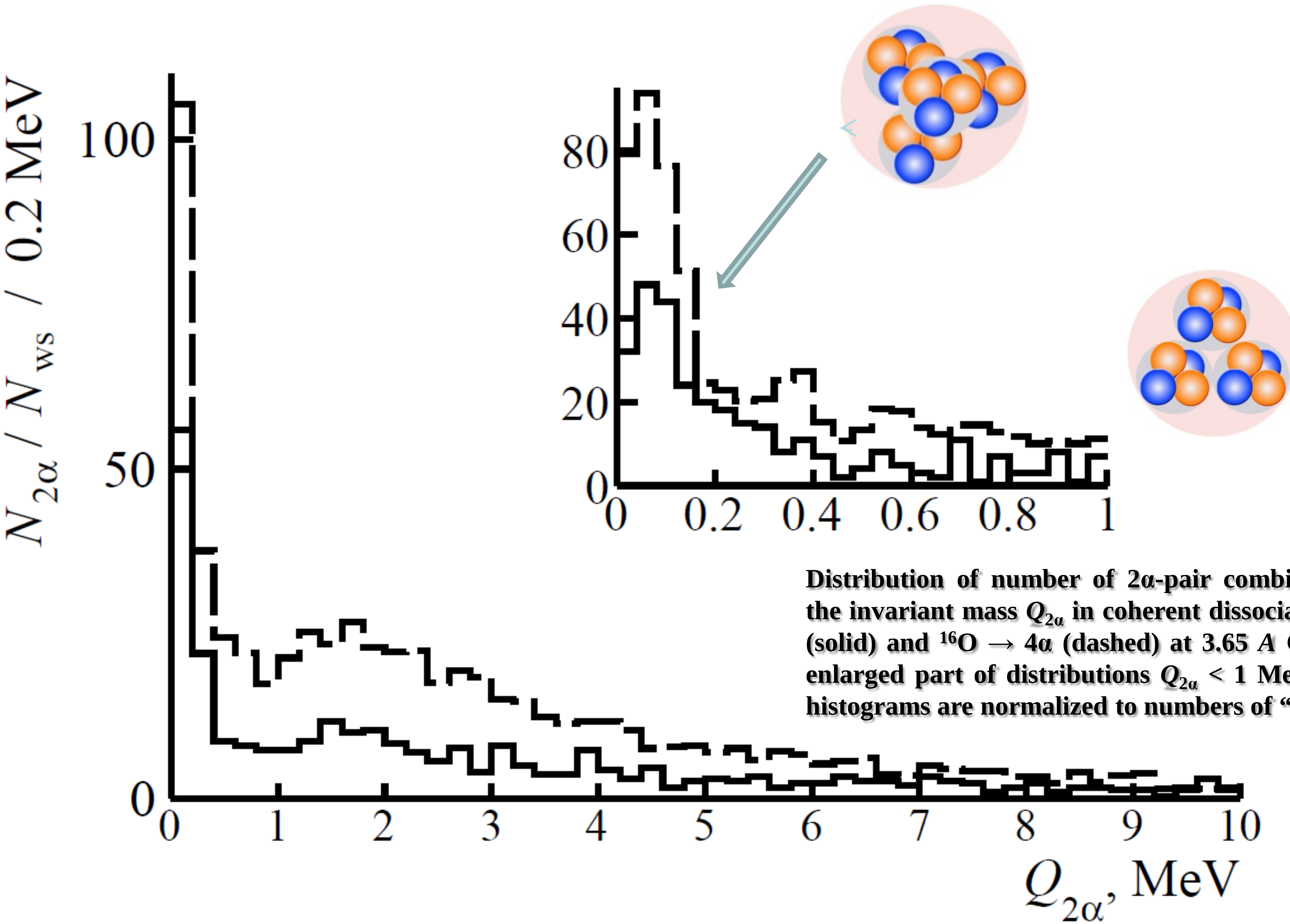






Distribution of number of 2α-pairs $N_{2\alpha}$ over invariant mass $Q_{2\alpha}$ in all 500 events of dissociation $^{9}Be \to 2\alpha$ (dotted line) at 1.2 *A* GeV and in 198 "white" stars out of them (solid); in the inset, the enlarged part of the distributions $Q_{2\alpha}$ < 1 MeV.

The distribution over $Q_{2\alpha}$ of 2α-pairs ($N_{2\alpha}$ = 500), including "white" 2α-stars (N_{ws} = 198), indicates the condition $Q_{2\alpha}(^{8}Be) < 0.2$ MeV. Then the fraction of decays ^{8}Be 36 ± 3 and 41 ± 5%, respectively. Two "influxes" deserve to be noted around 0.6 and 3 MeV. The first of them corresponds to decay through the ^{9}Be 2.43 MeV excitation, and the second corresponds to decay from the first excited state $^{8}Be_{2+}$.

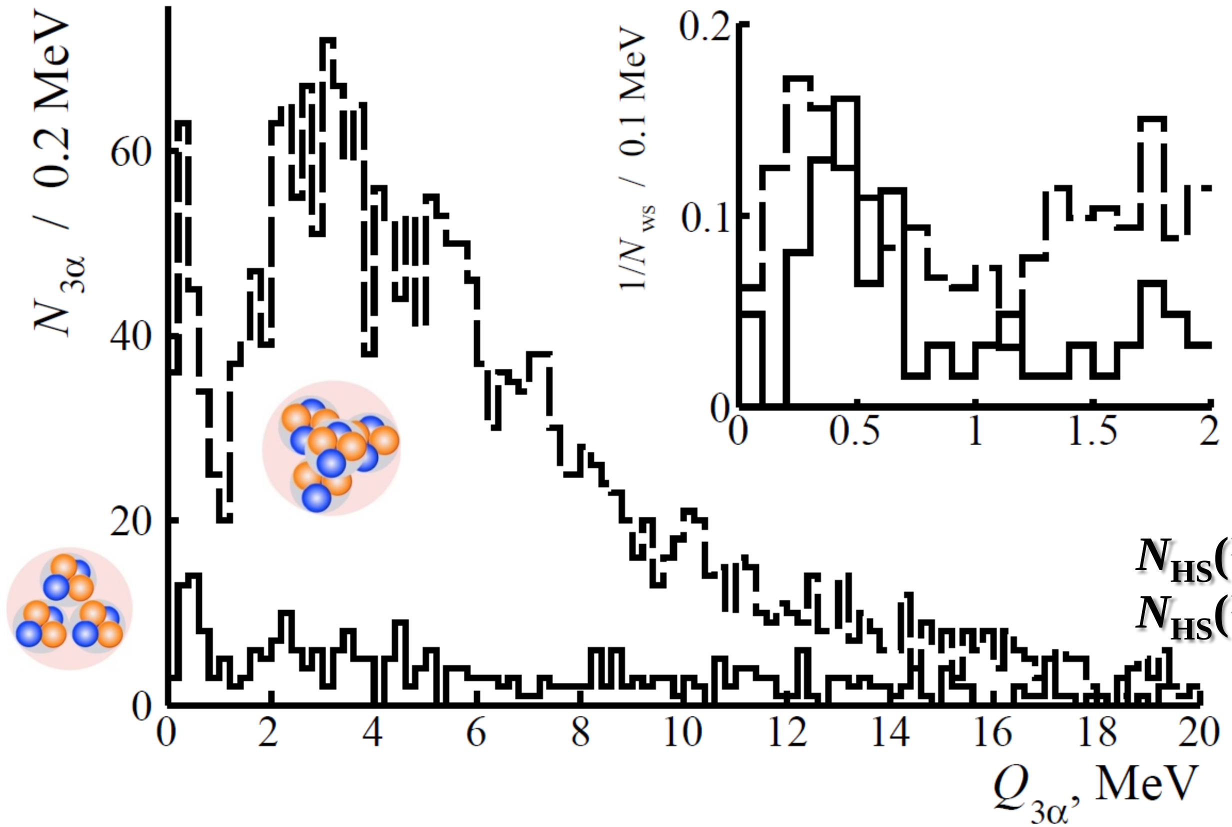


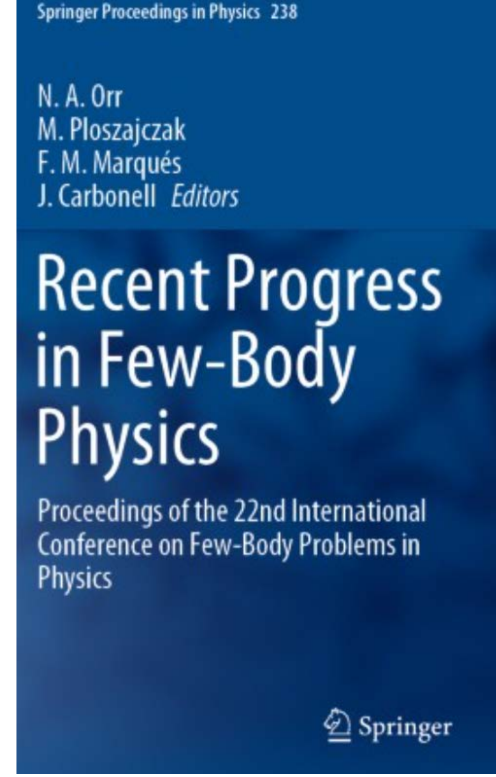
Distribution of number of 2α-pair combinations $N_{2\alpha}$ over the invariant mass $Q_{2\alpha}$ in coherent dissociation of $^{12}C \rightarrow 3\alpha$ (solid) and $^{16}O \rightarrow 4\alpha$ (dashed) at 3.65 *A* GeV; inset shows enlarged part of distributions $Q_{2\alpha}$ < 1 MeV (step 40 keV);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

Selected under the cleanest conditions, the criterion $Q_{2\alpha}(^{8}Be) < 0.2$ 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 ± 4% for $^{12}C \rightarrow 3\alpha$ and 62 ± 3% for $^{16}O \rightarrow 4\alpha$

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



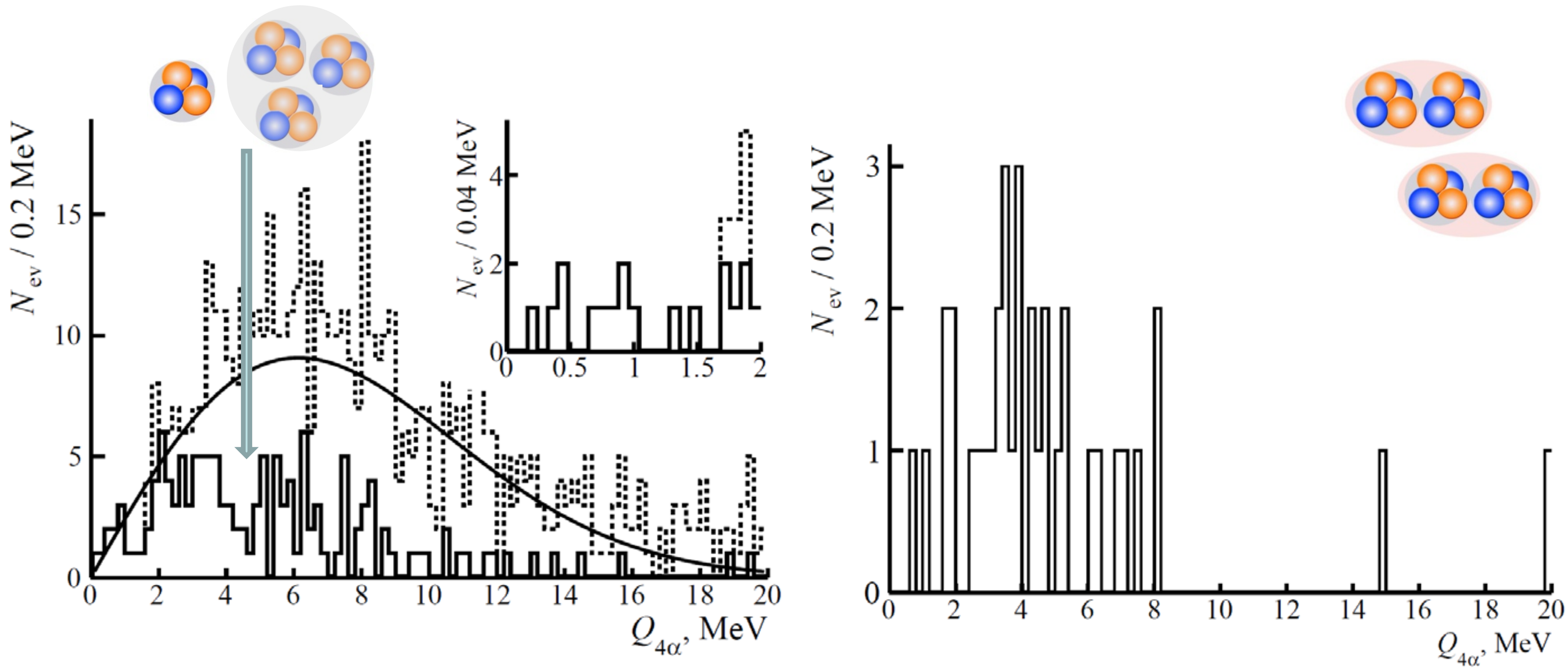


$N_{HS}(^{12}C)/N_{8Be}(^{12}C) = 0.36 \pm 0.06$

$N_{HS}(^{16}O)/N_{8Be}(^{16}O) = 0.35 \pm 0.04$.

Distribution of 3α-triples 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.

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. The growth of 2α- and 3α-combinations enhances the contribution of ^{8}Be and HS.



HS can occur as a result of α decay of the 0^+_6 excitation of the ^{16}O nucleus. The distribution of “white” $^{16}O \to 4\alpha$ stars over the invariant mass of 4α-quartets $Q_{4\alpha}$ (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 $Q4\alpha$ distribution and indicates 9 events $Q_{4\alpha}$ < 1 MeV with 〈Q4α〉 (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 $^{16}O \to 2^8Be$, which is 5 ± 1% of the “white” stars $^{16}O \to 4\alpha$. Then, the statistics of coherent dissociation for the $^{16}O \to 2^8Be$ 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 $^{16}O \to 2^8Be$ (Right) indicates two candidates ^{16}O (0^+_6). Thus, the estimate of the probability ratio of the ^{16}O (0^+_6) → 2^8Be and α + HS channels is 0.22 ± 0.17, which is unsatisfactory. At the same time, the increase in the statistics of events $^{16}O \to 4\alpha$ can be considered exhausted. There remains the possibility of studying (3-4)α-ensembles in the fragmentation of heavier nuclei.

EPJ A 2019 Impact factor 2.176
Hadrons and Nuclei

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

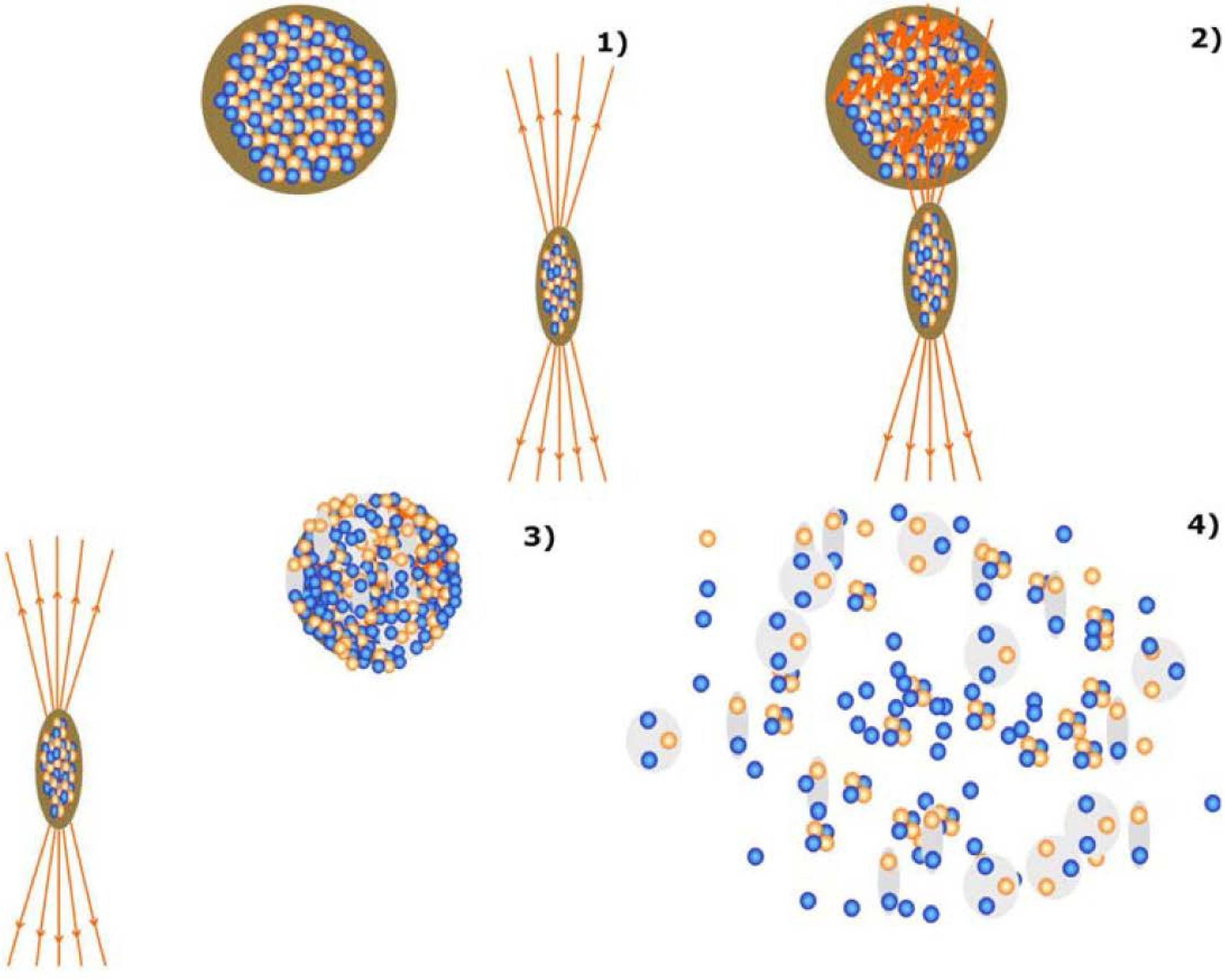
Unstable states in dissociation of relativistic nuclei

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

Au 10.7 GeV per nucleon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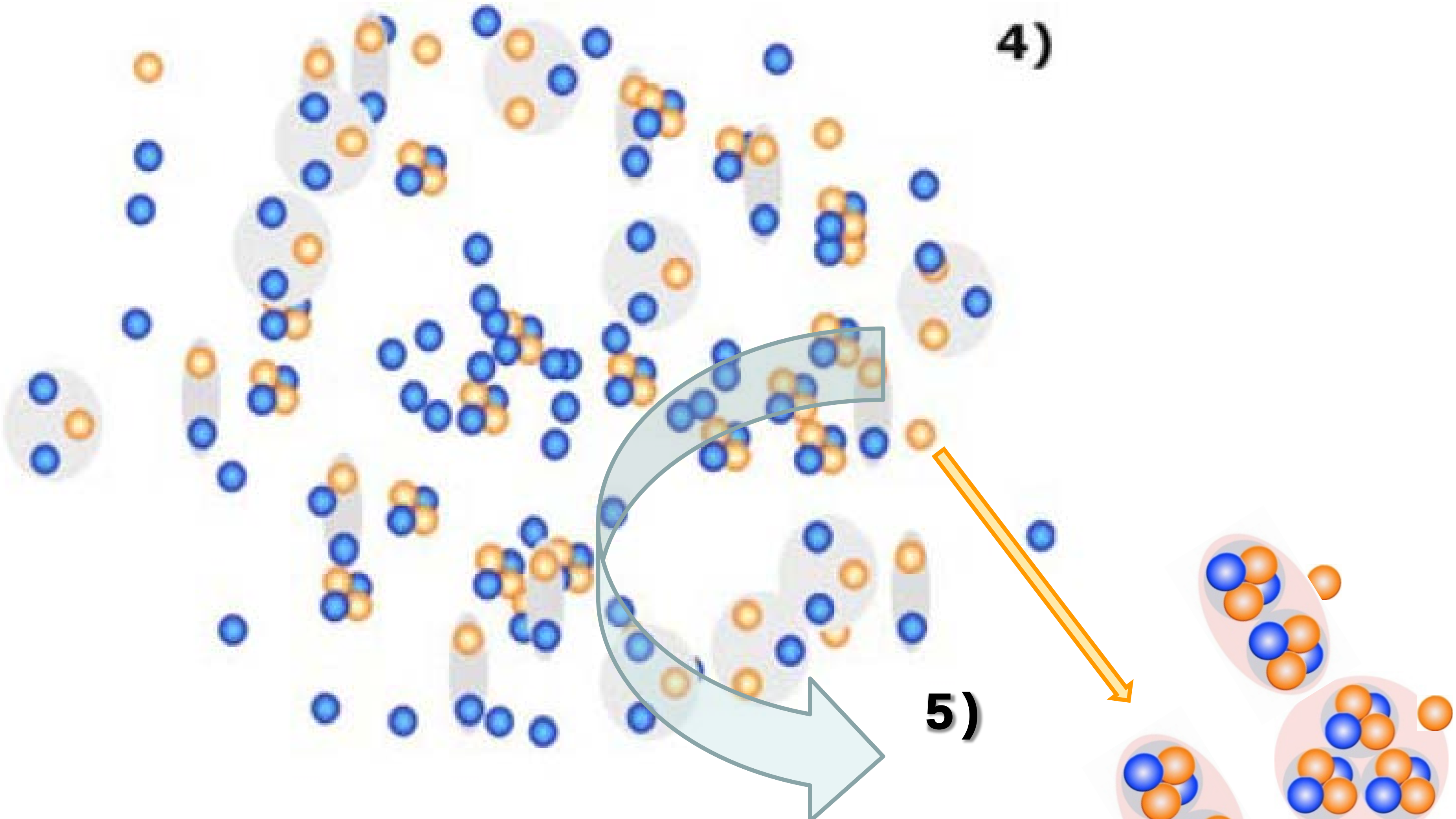
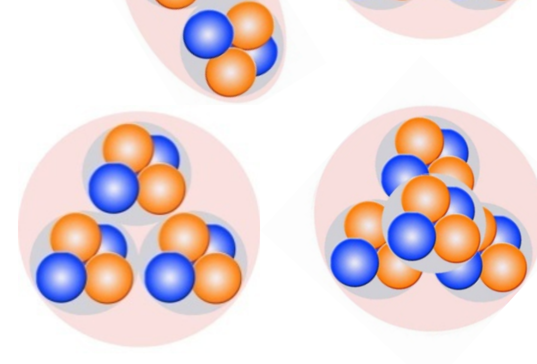




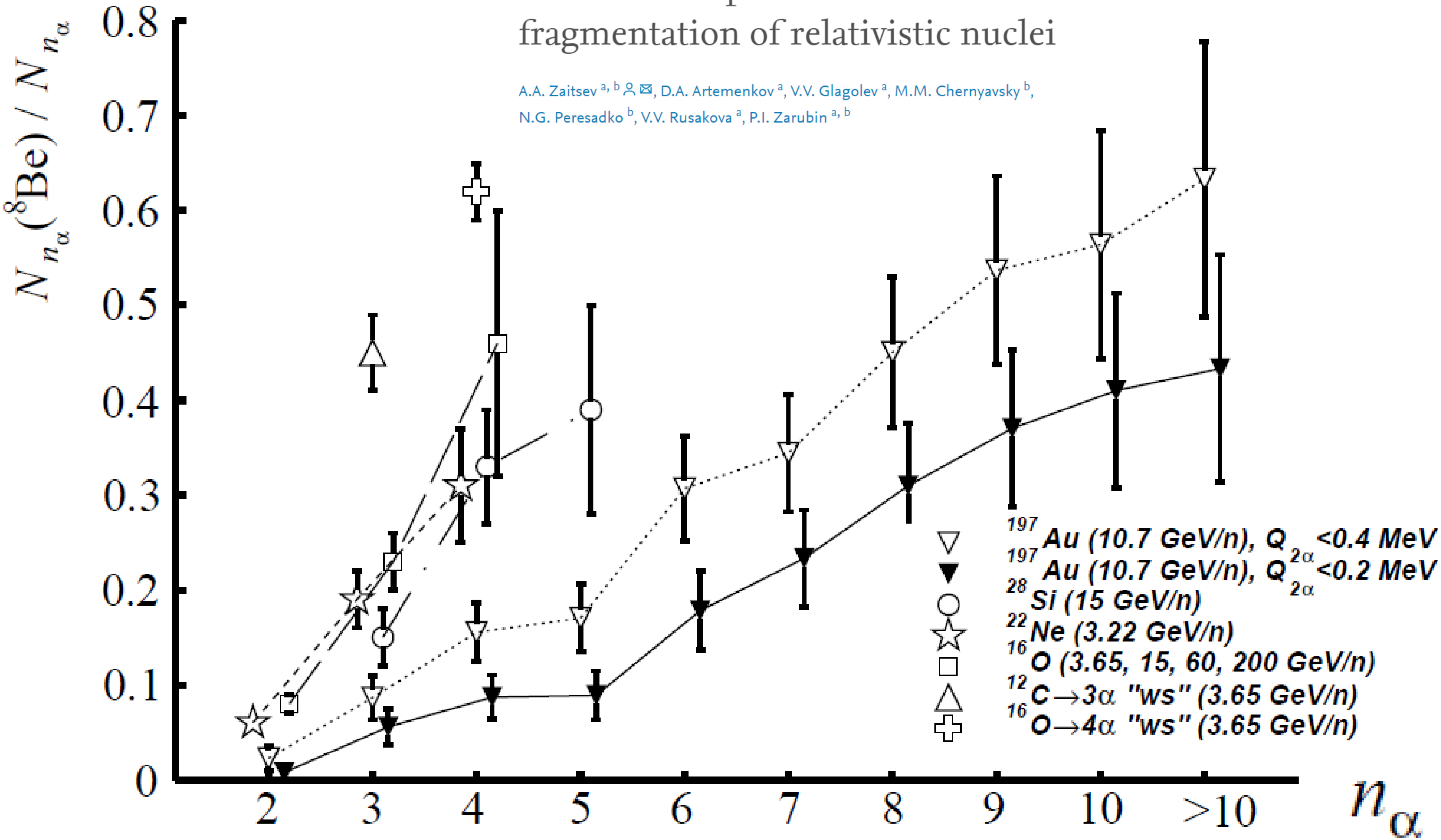
It is possible that the unstable states are part of the nuclear structure that manifests itself in fragmentation. The alternative consists in the formation of ^{8}Be in the interaction of α-pairs with the pickup of accompanying α-particles and nucleons by them. Its consequence would be an increase in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

ELSEVIER

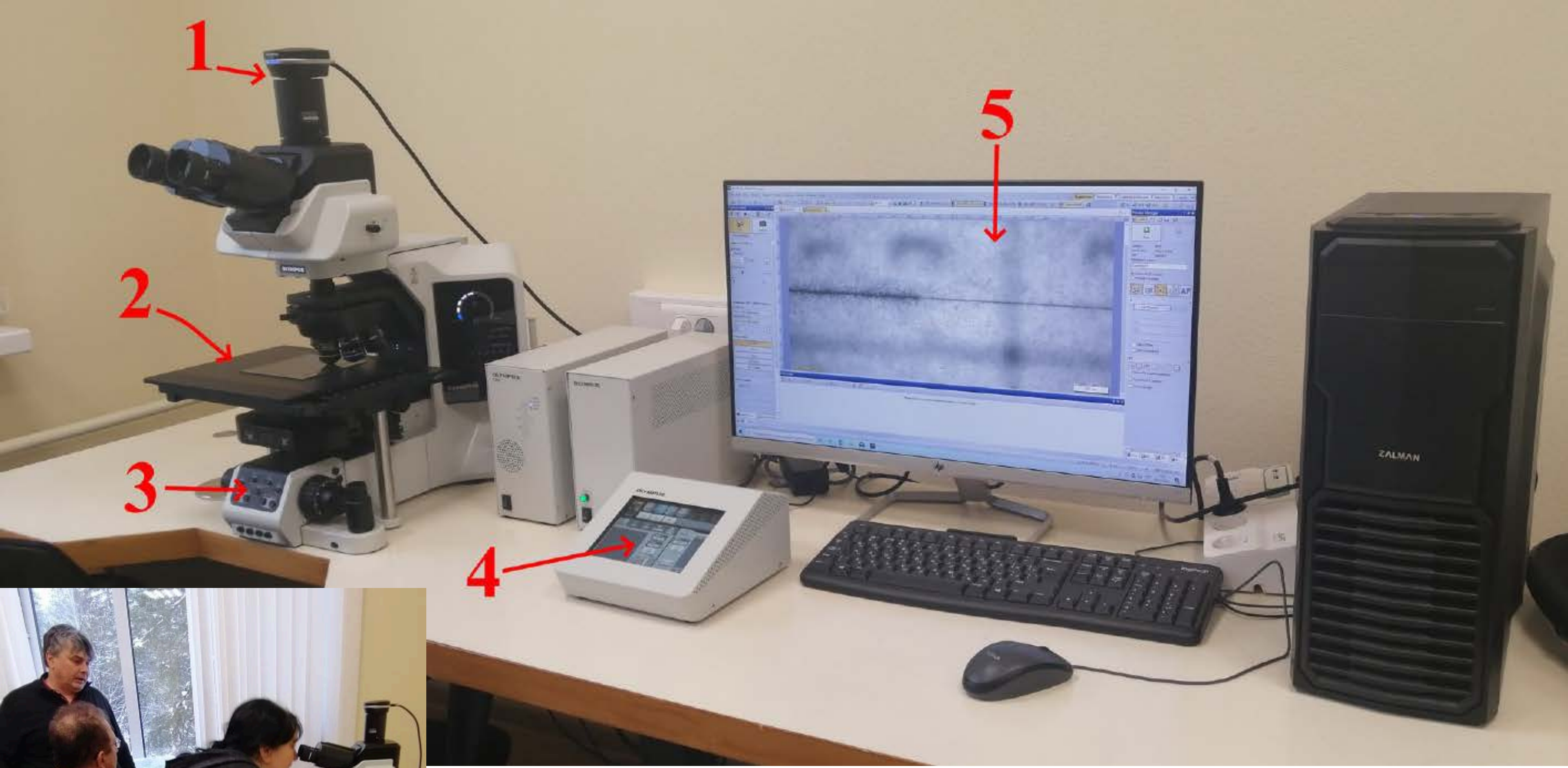
Physics Letters B
Volume 820, 10 September 2021, 136460

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]



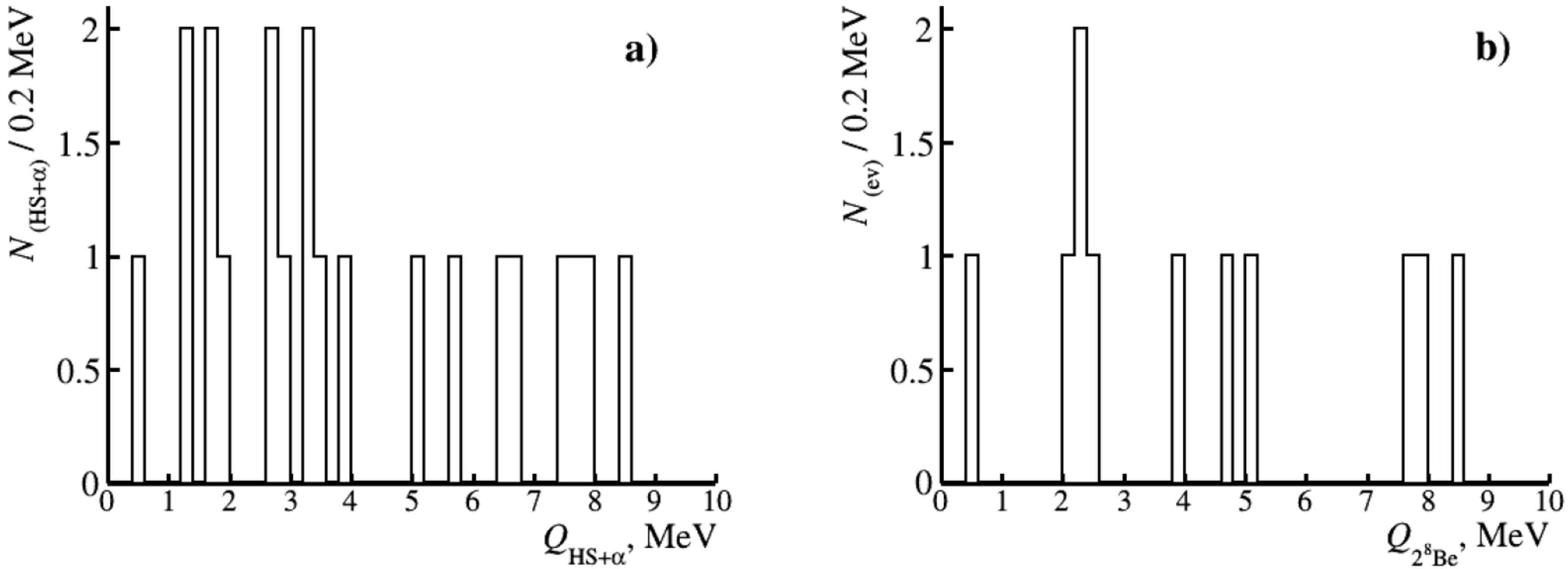
n_α	$N_{n\alpha}(^8Be)/N_{n\alpha}$ (% $N_{n\alpha}$)	$N_{n\alpha}(^9B)$ (% $N_{n\alpha}(^8Be)$)	$N_{n\alpha}$(HS) (% $N_{n\alpha}(^8Be)$)	$N_{n\alpha}(2^8Be)$ (% $N_{n\alpha}(^8Be)$)
2	3/133 (2 ± 1)	-	-	-
3	14/162 (9 ± 3)	1 (7)	-	-
4	25/161 (16 ± 4)	7 (28 ± 12)	2 (8 ± 6)	-
5	23/135 (17 ± 4)	5 (22 ± 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



Olympus BX63 microscope:

1) **digital camera DP74,**
2) **motorized object stage,**
3) **joysticks for controlling focus and movement of object stage in XOY plane,**
4) **microscope control unit,**
5) **PC for working with resulting image.**

The monitor shows an enlarged image of interaction of a Kr nucleus below 1 GeV per nucleon



$n\alpha$	4	5	6	7	8	9-13
$N_{n\alpha}$	40(69)	50(54)	21(27)	10(19)	15(12)	7(3)
$N_{n\alpha}/N_{ev}$,%	7.9± 1.0	6.2 ± 0.9	3.1 ± 0.6	2.2 ± 0.5	1.4 ± 0.4	0.4 ± 0.2
$N_{n\alpha}(\geq 1^8\mathrm{Be})$	5(15)	16(10)	12(13)	4(10)	11(8)	4(3)
$N_{n\alpha}(\geq 1^8\mathrm{Be})/N_{n\alpha}$, %	19 ± 5	25 ± 6	52 ± 13	48 ± 16	70 ± 21	70 ± 35
$N_{n\alpha}(2^8\mathrm{Be})$	0	2	2	1	5	2
N_{HS}	1	2	1	1	2	2

SUMMARY

Near threshold α-ensembles are generated in the limiting nuclear fragmentation. Only the nuclear track emulsion method answers the challenges. The ^{8}Be → 2α and HS → ^{8}Beα decays determined from the emission angles of the fragments at the very beginning of the spectrum of invariant masses.

This approach has been tested for nuclei from Ne to Au in a range from several to several tens of GeV per nucleon. The ^{8}Be probability increases in the α-particle multiplicity. The ^{9}B and HS contributions also increase, but their statistics are extremely low. The exotically large sizes and lifetimes of ^{8}Be and HS suggest the synthesis of the αBEC states by combining α-particles u 2α → ^{8}Be, ^{8}Beα → HS, HSα → ^{16}O(0^{+}_{6}), 2^{8}Be → ^{16}O(0^{+}_{6}). Then αBEC can be regarded as a short-lived state of nuclear matter, not associated with the excitation of the parent nucleus.

In development, the BECQUEREL project aims to measure ^{84}Kr fragmentation below 1 *A* GeV to clarify the relationship ^{8}Be and HS and the multiplicity and search for the 4αBEC state . To track the evolution and universality of the conclusions, the 3.65 *A* GeV ^{28}Si fragmentation is analyzed.. The search for events in them by transverse scanning on the motorized microscope Olympus BX63 makes it possible to achieve the required statistics. Track measurements in selected α-ensembles are carried out on the most precise KSM microscopes.

Searches for αBEC lead to the study of nuclear matter with temperature and density ranging from red giants to supernovae. Future exposures 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.