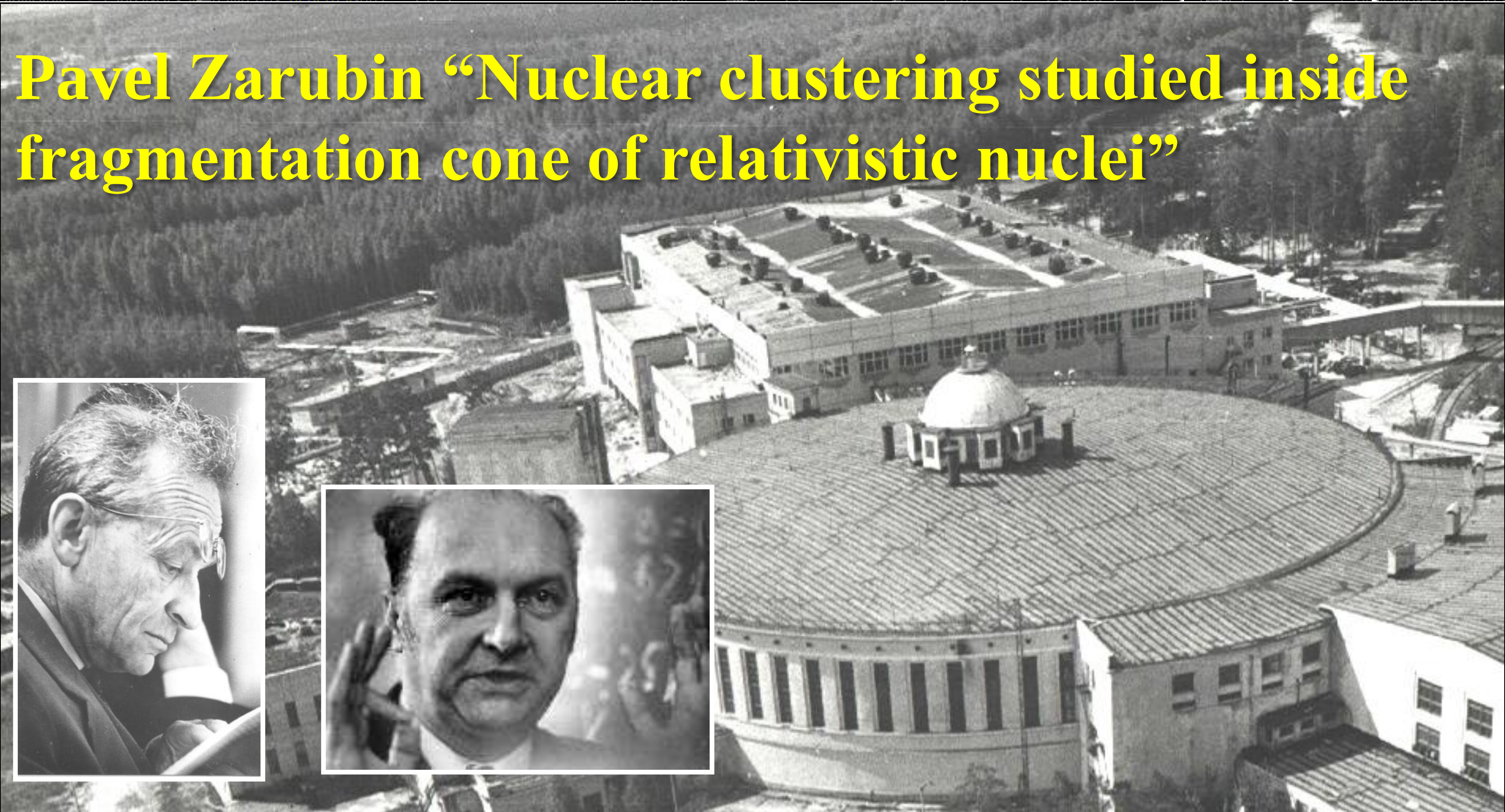
BECQUEREL PROJECT

Проект БЕККЕРЕЛЬ

Beryllium (Boron) Clustering Quest in Relativistic Multifragmentation

http://becquerel.jinr.ru

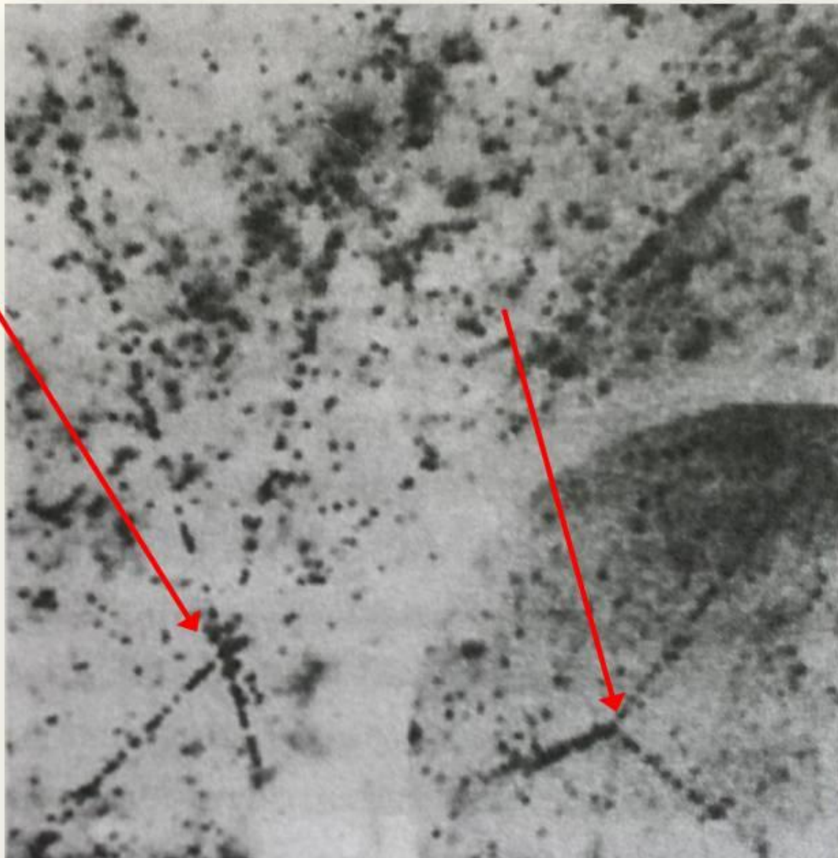
Pavel Zarubin "Nuclear clustering studied inside fragmentation cone of relativistic nuclei"

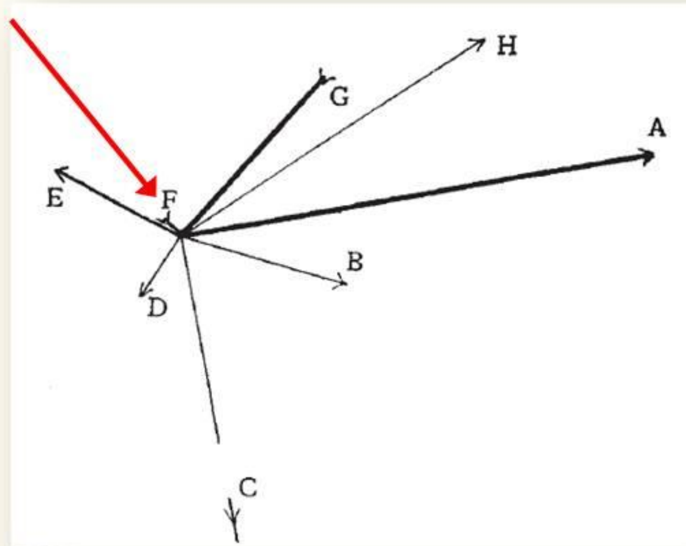


V. I. Veksler and A. M. Baldin Laboratory of High Energy Physics

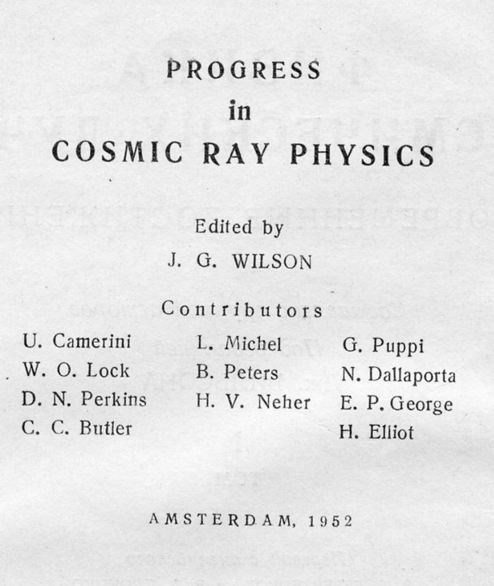
Joint Institute for Nuclear Research, Dubna, Russia

Marietta Blau (links; um 1927) und Hertha Wambacher (rechts, nach 1928) im Labor am Wiener Radiuminstitut





On photographic plates which had been exposed to cosmic radiation on the Hafelekar (2,300 m. above sea-level) near Innsbruck for five months, we found, apart from the very long tracks (up to 1,200 cm.) ......from a single point within the emulsion several tracks, some of them having a considerable length, take their departure. We observed four cases with three particles, four with four and 'stars' with six, seven, eight and nine particles, one of each kind.



PROGRESS
in
COSMIC RAY PHYSICS

Edited by
J. G. WILSON

Contributors

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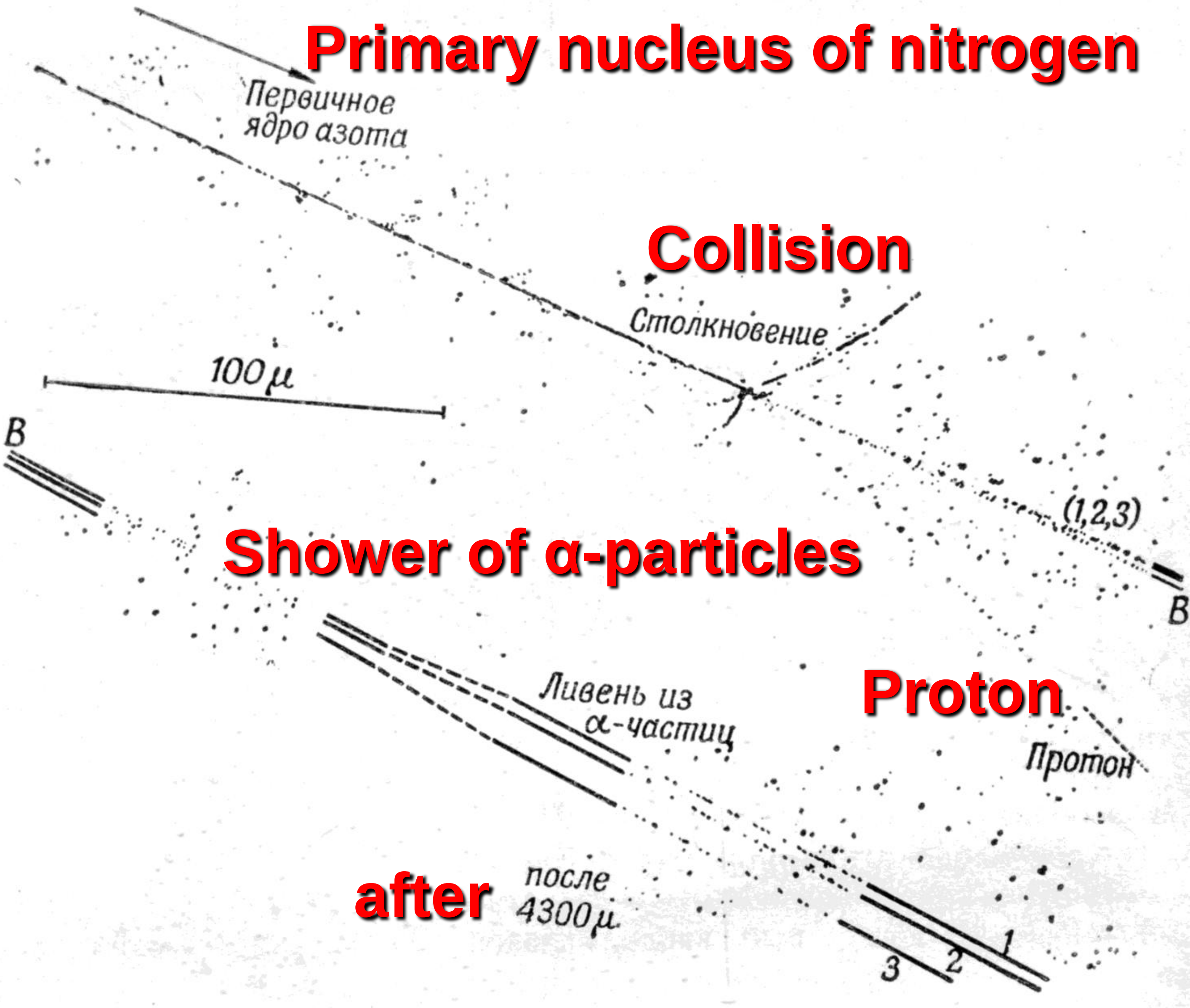
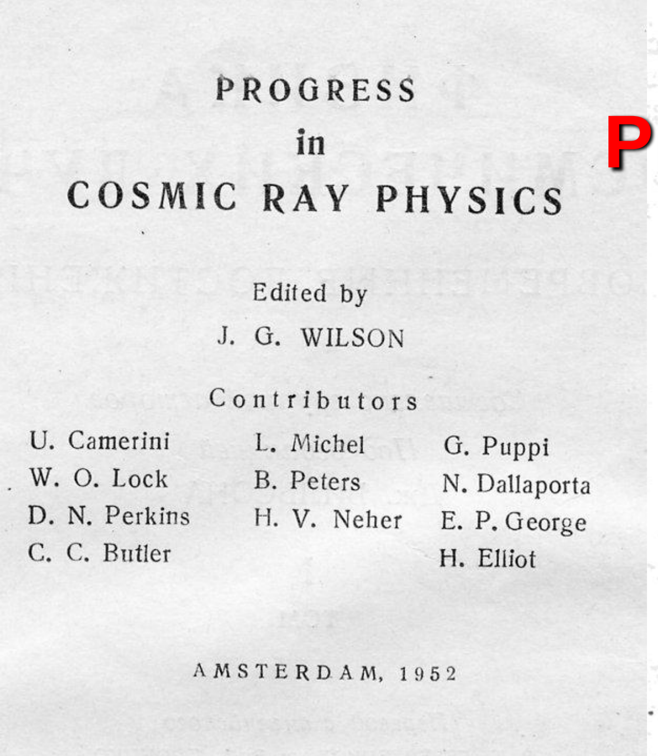
W. O. Lock
D. N. Perkins
C. C. Butler
L. Michel
B. Peters
H. V. Neher
G. Puppi
N. Dallaporta
E. P. George
H. Elliot

AMSTERDAM, 1952



Фиг. 7. Ядро азота столкнулось с ядром эмульсии. Повидимому, произошло скользящее столкновение, при котором заряд первичного ядра уменьшается на единицу. Остаток, представляющий собой возбужденное ядро углерода, распадается затем на 3 α-частицы, которые в лабораторной системе испускаются в узком конусе в направлении движения первичной частицы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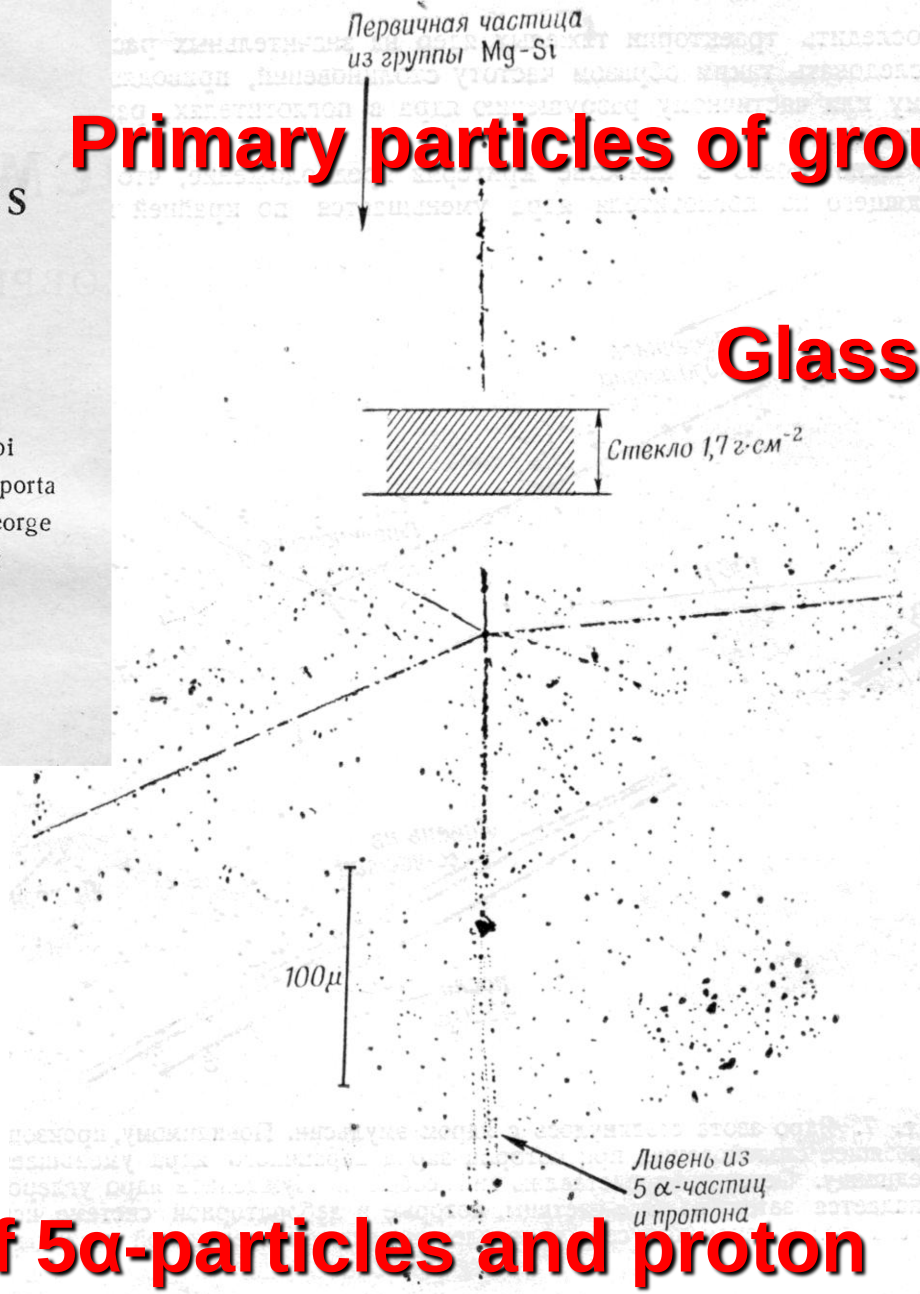
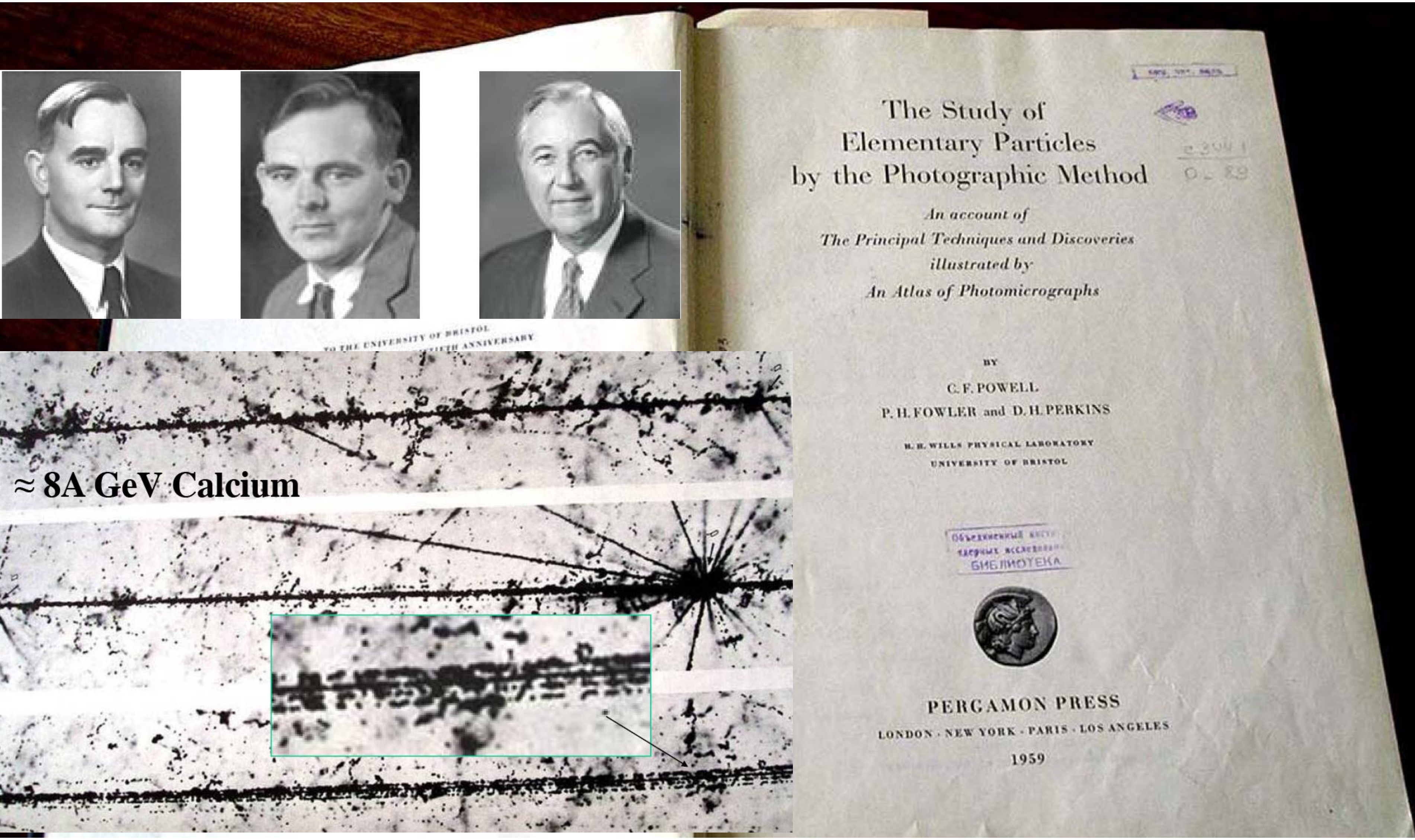
Primary particles of group Mg-Si

Glass 1.7 g cm^{-2}



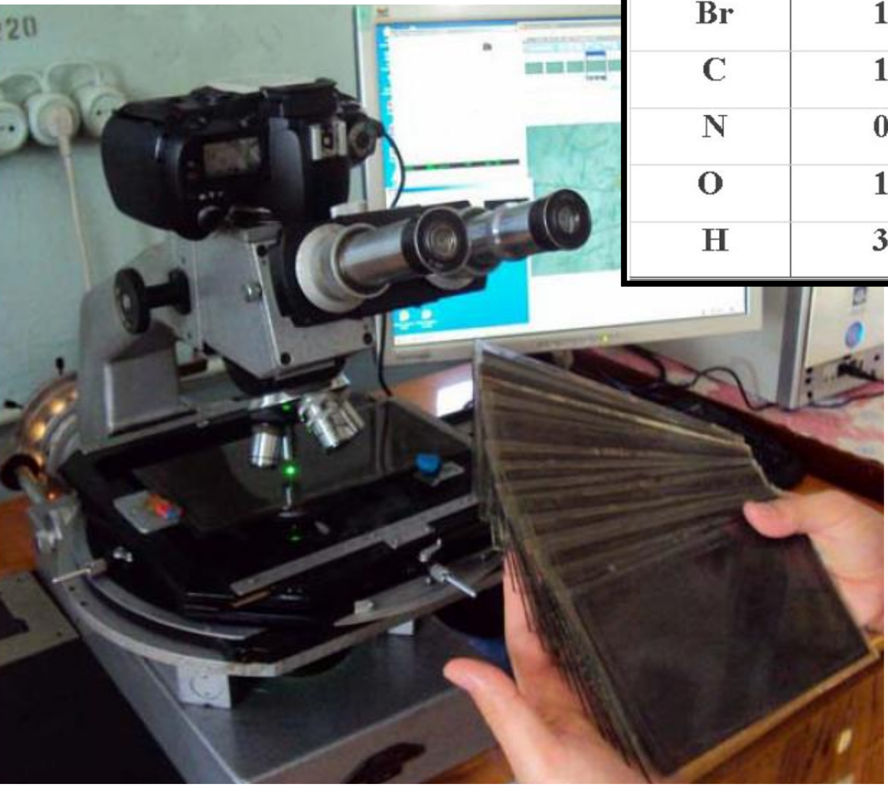
Shower of 5α-particles and proton

Фиг. 6. Ядро из группы Mg — Si столкнулось с ядром эмульсии. Предполагают, что узкий ливень, состоящий из протона и 5 α-частиц, возник в результате испарения первичного ядра, возбуждённого столкновением. Остальные частицы, испущенные в звезде, являются, повидимому, осколками ядра мишени.



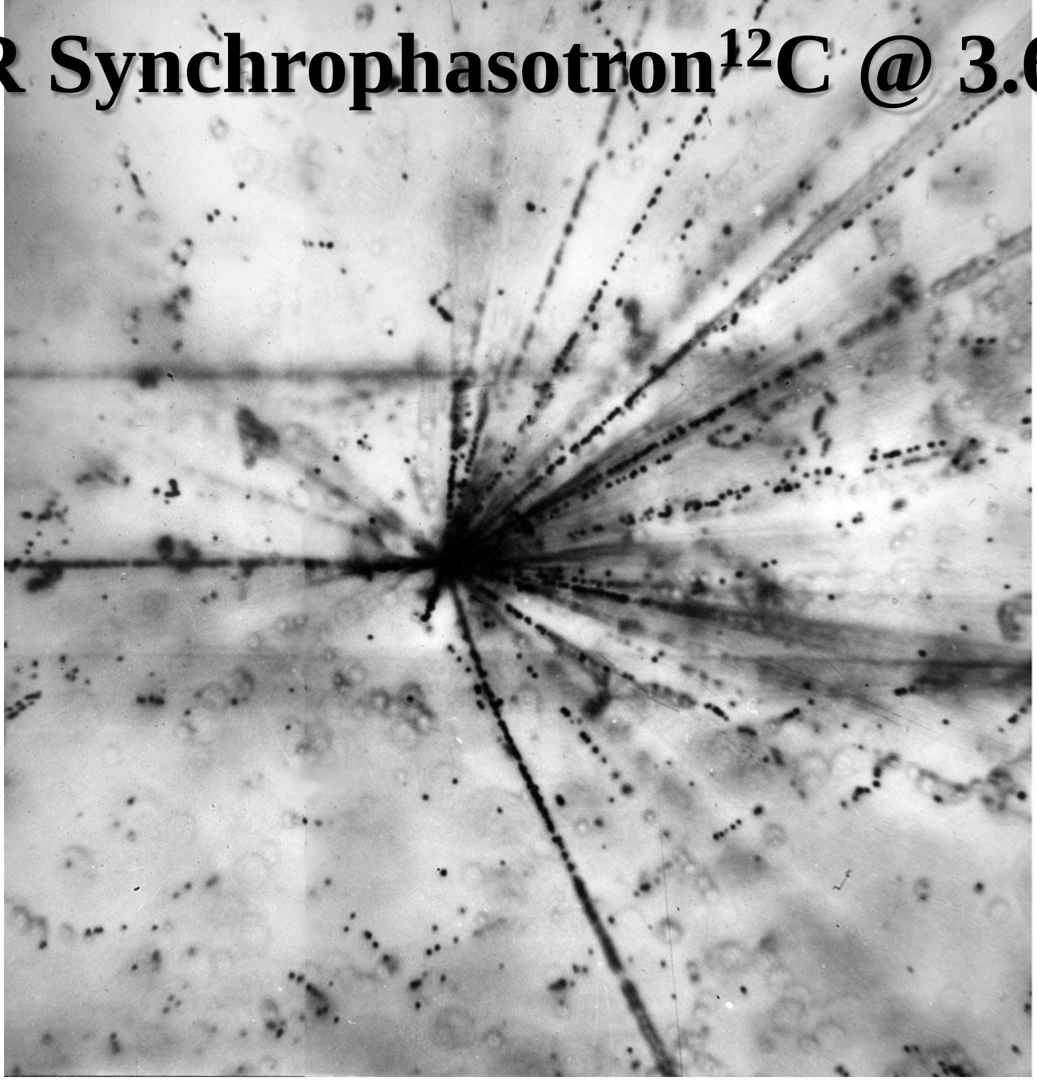
Events of multiple fragmentation of relativistic nuclei were observed as early as the 40s in the NTE exposed to cosmic rays in the stratosphere. Their photographs presented in the classic book by C. H. Powell, P. H. Fowler and D. H. Perkins, among other fundamental observations can serve as a model of clarity in our time. Our research is implemented in keeping with this tradition.

BR-2	10^{22} cm^{-3}
Ag	1.0
Br	1.0
C	1.4
N	0.4
O	1.1
H	3.0

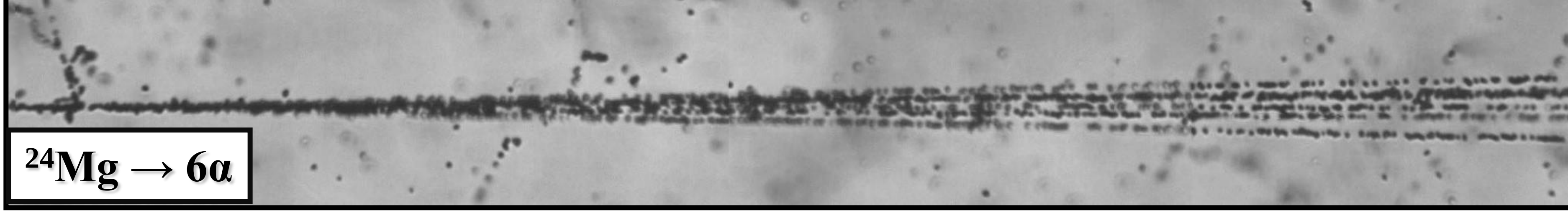


The foundations of required methods of measurements on microscopes in exposure NTE layers were laid at the beginning of studies on the physics of cosmic rays and, then, used widely when beams of relativistic nuclei became available. For these purposes three microscopes KSM-1 manufactured by Carl Zeiss (Jena) about half of century ago and still functioning well are applied in JINR. Each microscope is equipped with apochromatic and achromatic lenses providing an increase of 15 and 50x, two eyepieces 12.5x and a tube lens 2x which together give an image magnification 375-1250x. The maximum error due to manufacturing tolerances does not exceed 0.05 μm.

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



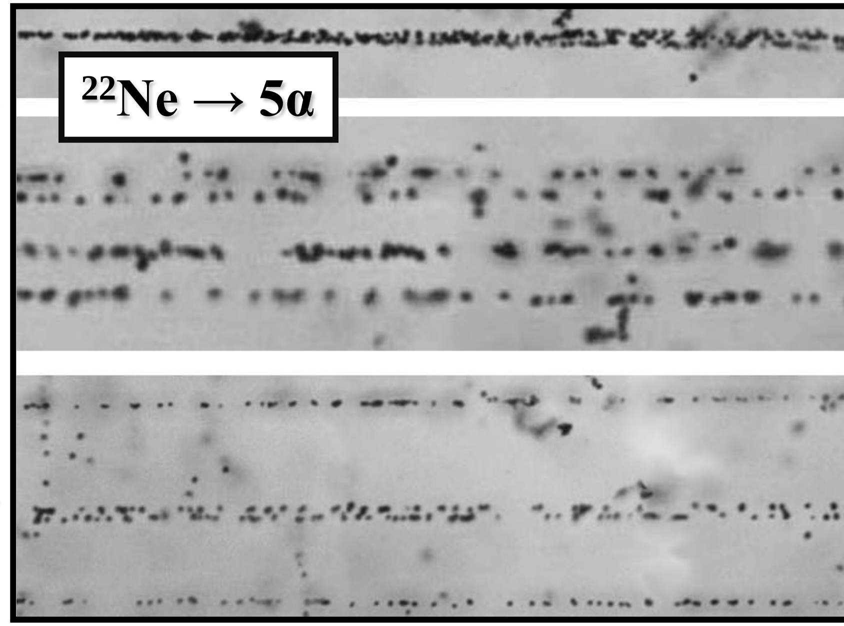
Exposures of stacks of nuclear track emulsion (NTE) to light nuclei were performed in the 70-80s at the JINR Synchrophasotron and Bevalac (LBL, USA). The use of NTE to study the interactions of the gold and lead nuclei continued in the 80-90s at the AGS (BNL, USA) and SPS (CERN) accelerators. Observations in NTE of tracks of charged particles in a full solid angle and practically without a threshold made it possible to determine the contours of a complex picture of the collision of relativistic nuclei. Special attention was paid to central nuclear collisions. The subsequent development of this area on the basis of large-scale electronic experiments is widely known. At the same time, the results obtained by the NTE method as well as the irradiated layers themselves and the files with measurement results retain their uniqueness with respect to the structure of nuclear fragmentation.

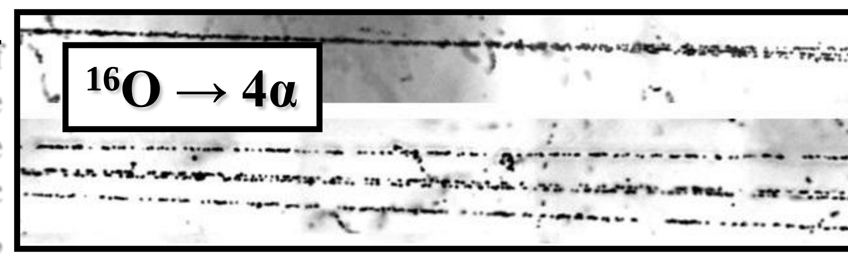


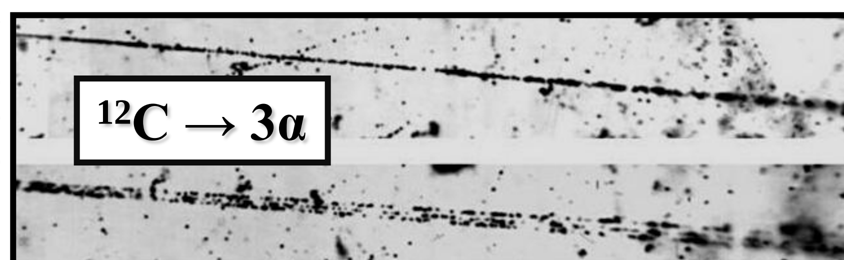
In peripheral interactions of nuclei, in which the charge of the incident nucleus is distributed between its fragments, the individual features of the incident nuclei are reflected. They are observed in NTE as often and completely as central collisions, so there is a fundamental possibility in the cone of relativistic fragmentation to study the nuclear structure.

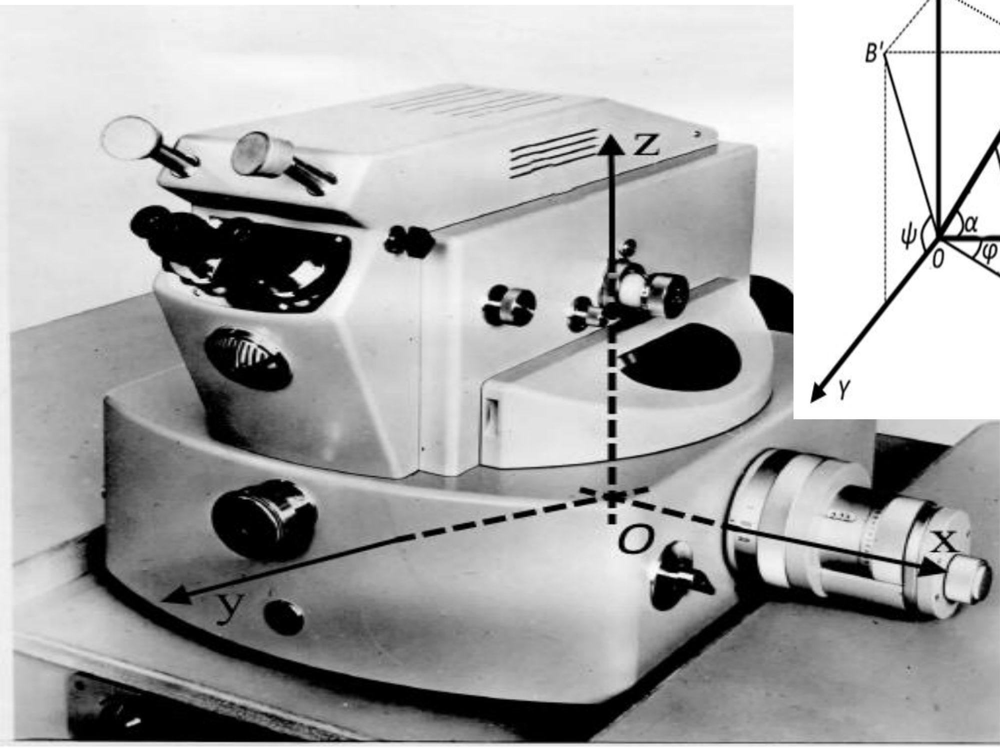
The intense “tracks” in the photos splits into the He track pairs with the opening angles of about $2{\cdot}10^{-3}$ rad corresponding to decays of the unstable ^{8}Be nucleus. Their observation testify to the completeness of observations across the spectrum of cluster excitations.

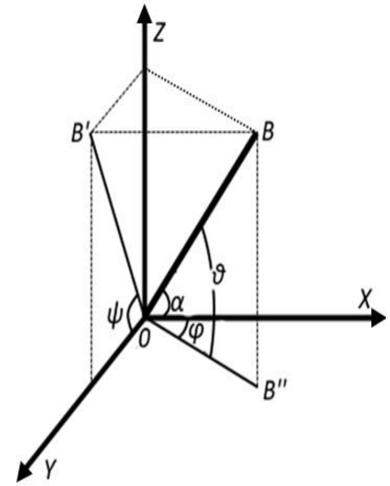
In the aspect of relativistic fragmentation, the use of traditional spectrometers was extremely limited. The difficulties encountered are of fundamental nature. They are caused by a dramatic decrease in the ionization of relativistic fragments in an extremely narrow fragmentation cone, and, often, by an approximate coincidence in the magnetic rigidity of fragments and beam nuclei. For these reasons, measurements were carried out with the registration of single relativistic fragments with charges close to the charge of the studied nucleus.











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

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

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

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

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

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

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

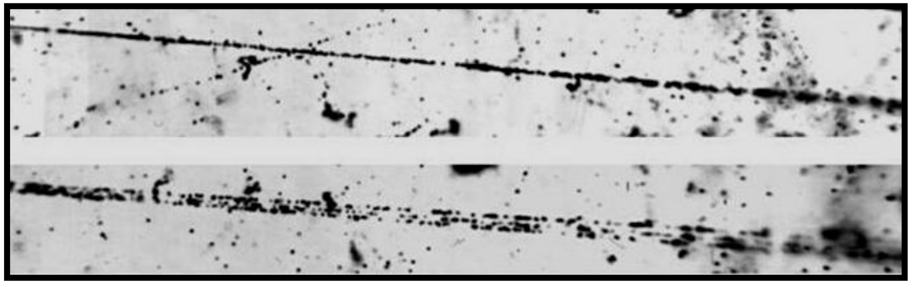
$$Q_{2\alpha} = \sqrt{2 \cdot [m_\alpha^2 + E_\alpha^2 - \vec{P}_{\alpha 1} \cdot \vec{P}_{\alpha 2}]} - 2 \cdot m_\alpha$$

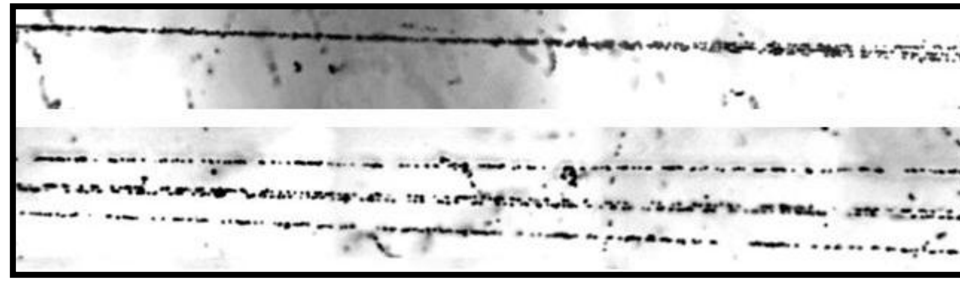
$$Q_{3\alpha} = \sqrt{3 \cdot m_\alpha^2 + 2 \cdot \sum_{i \neq j} (E_{\alpha i} \cdot E_{\alpha j} - \vec{P}_{\alpha i} \cdot \vec{P}_{\alpha j})} - 3 \cdot m_\alpha$$

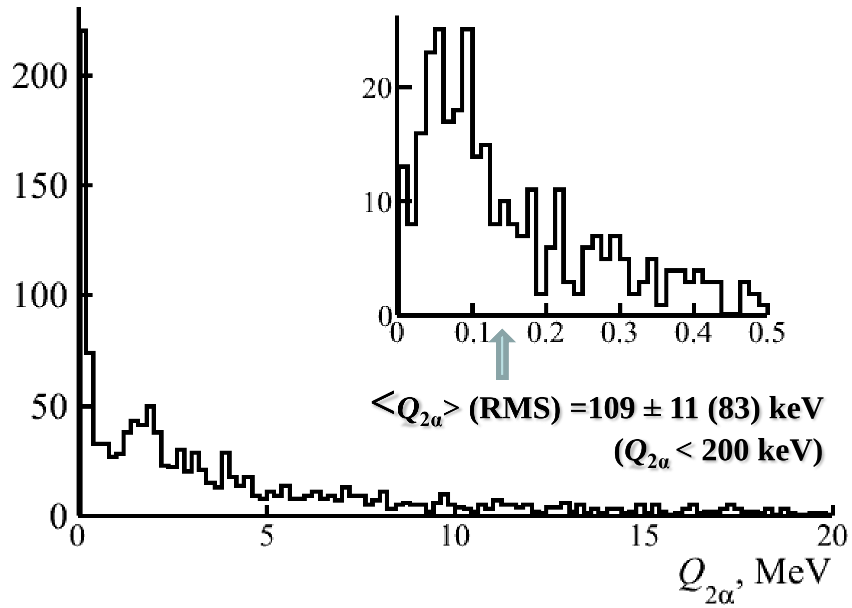
Relativistic fragments are concentrated in the cone $\sin\theta_{fr} = p_{fr}/p_0$, where p_{fr} = 0.2 GeV/c is the measure of the nucleon Fermi momentum in the projectile nucleus, and p_0 is its momentum per nucleon. The invariant mass of the system of relativistic fragments is defined as the sum of all products of 4-momenta $P_{i,k}$ of the fragments $M^{*2} = \sum(P_i \cdot P_k)$. Subtracting the mass of the initial nucleus or the sum of the fragments $Q = M^* - M$ is a matter of convenience of presentation. The components $P_{i,k}$ are determined in the approximation of the p_0 conservation.

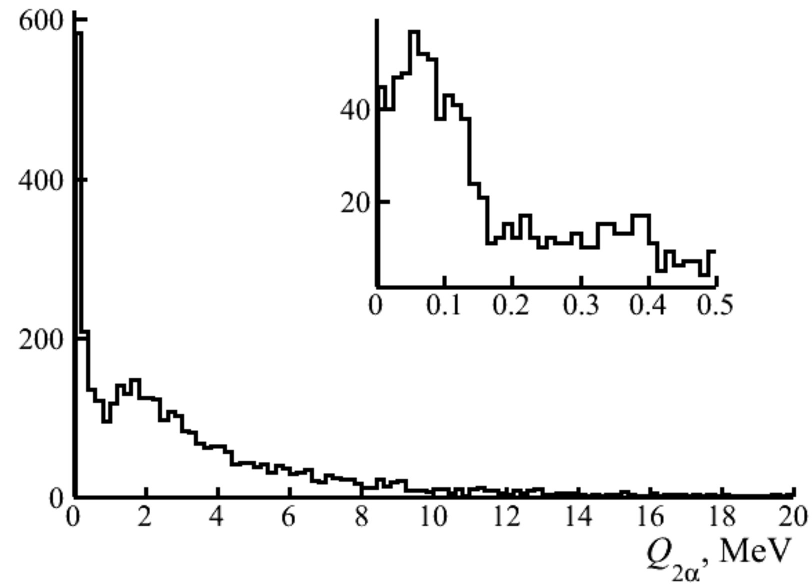
186 "white" stars $^{12}C \rightarrow 3\alpha$

641 "white" stars $^{16}O \rightarrow 4\alpha$



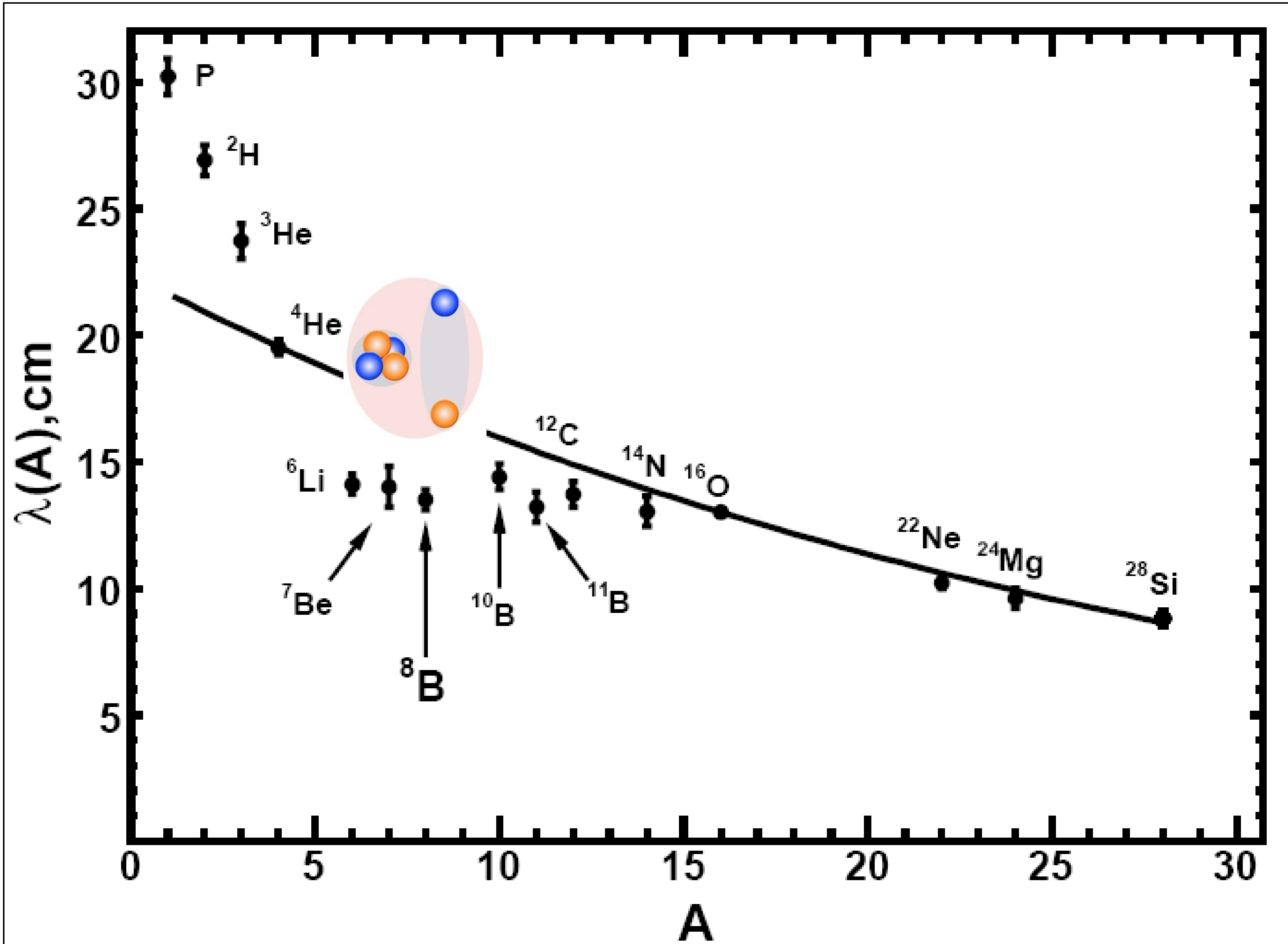






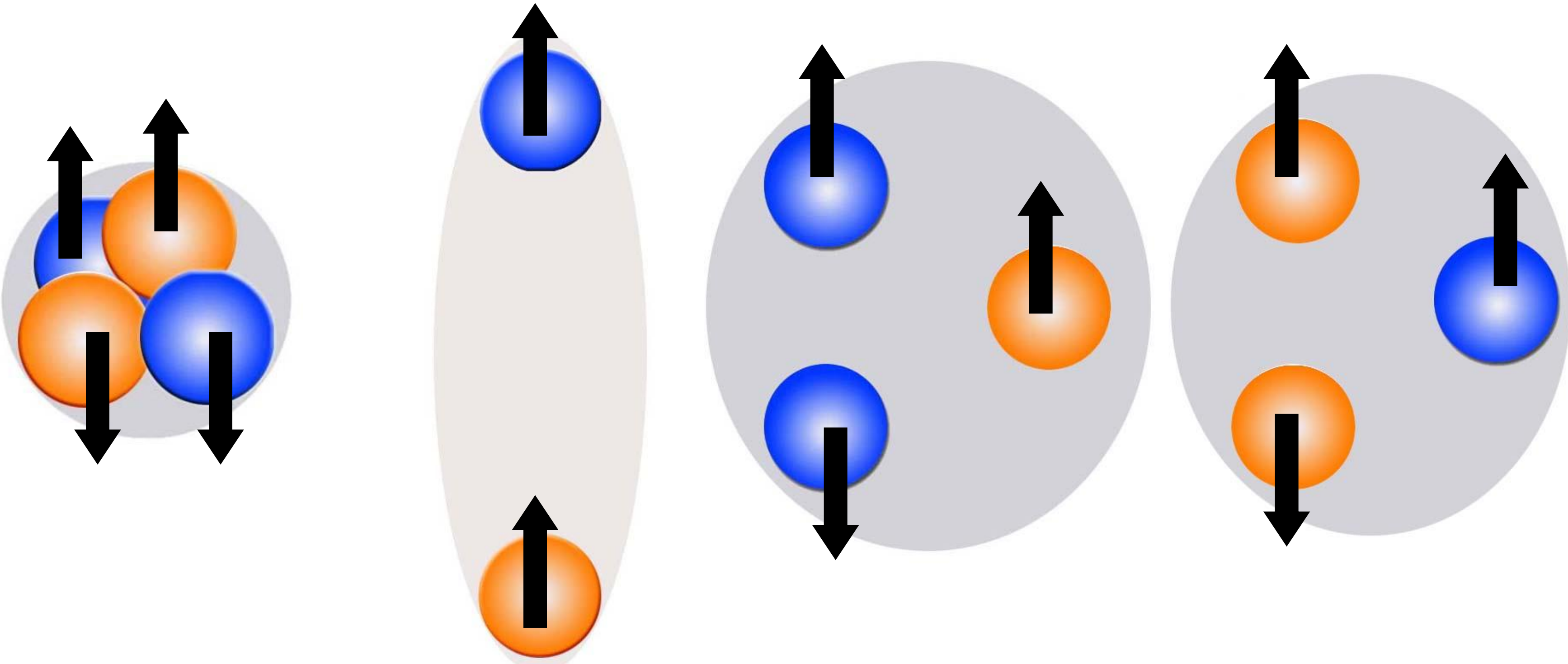
For the ^{12}C nucleus at an energy of 3.65 A GeV there are measurements of emission angles of α-particles made in the groups of G. M. Chernov (Tashkent) at 72 and A. Sh. Gaitinov (Alma-Ata) in 114 "white" stars $^{12}C \rightarrow 3\alpha$. The left figure shows the distribution over the invariant mass of α-pairs $Q_{2\alpha}$. In the $Q_{2\alpha} < 0.2$ MeV region, the contribution of the ^{8}Be decays is 17 ± 1%.

The distribution $Q_{2\alpha}$ for all 2α combinations in 641 "white" stars $^{16}O \rightarrow 4\alpha$ presented in the right figure. As in the case $^{12}C \rightarrow 3\alpha$, for $Q_{2\alpha} < 0.2$ MeV there is a contribution of ^{8}Be decays which manifests itself in 15 ± 1% of events.

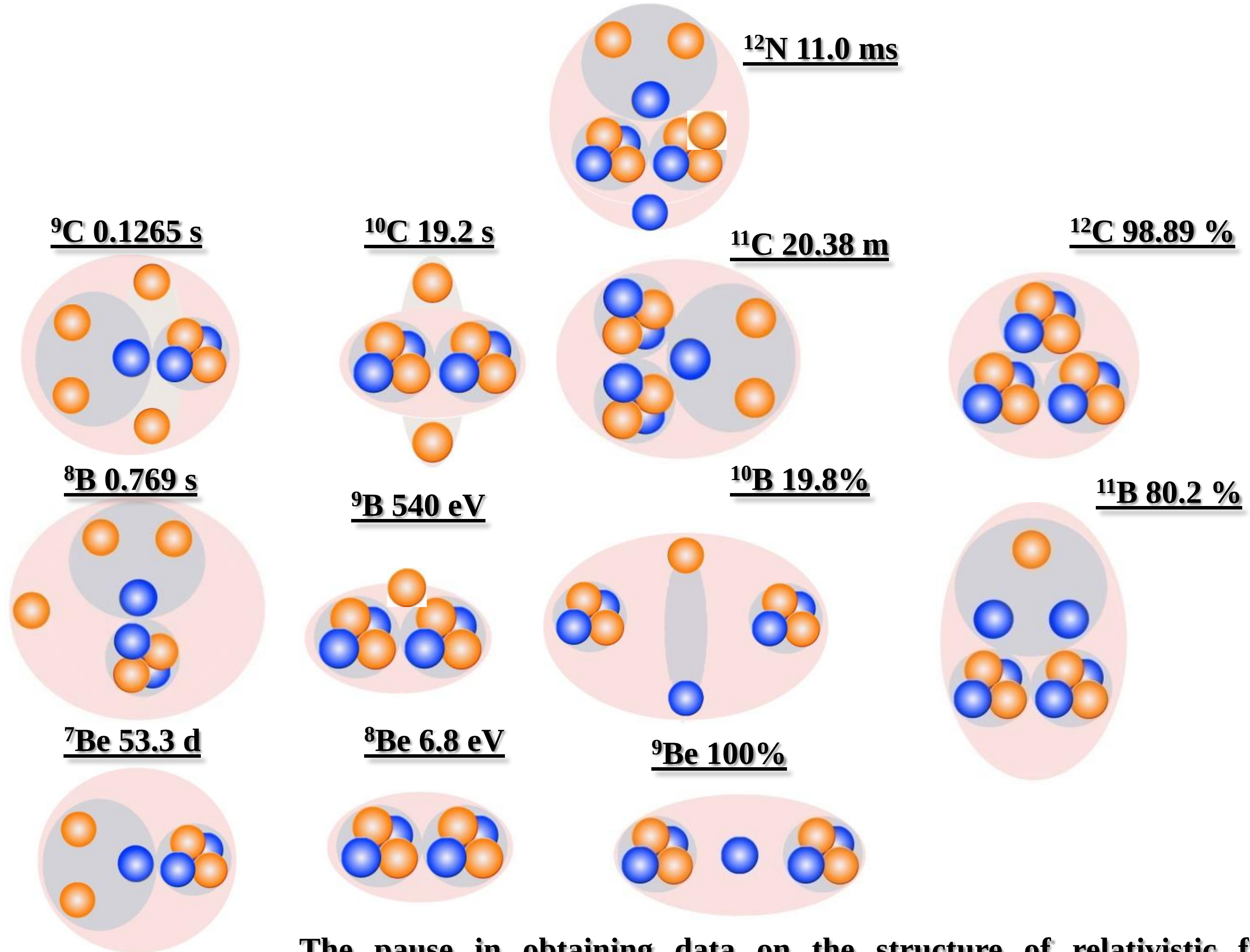


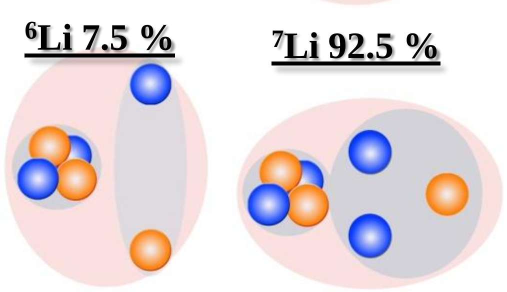
λ(A),cm
A
P
2H
3He
4He
6Li
7Be
8B
10B
11B
12C
14N
16O
22Ne
24Mg
28Si
0
5
10
15
20
25
30

Collective degrees of freedom, in which groups of few nucleons behave as composing clusters, are a key aspect of nuclear structure. The fundamental "building blocks" of clustering are the lightest nuclei having no excited states – first of all, the ^{4}He nucleus (α-particles) as well as the deuteron (d), the triton (t) and the ^{3}He nucleus (h, helion). This feature is clearly seen in light nuclei, where the number of possible cluster configurations is small.



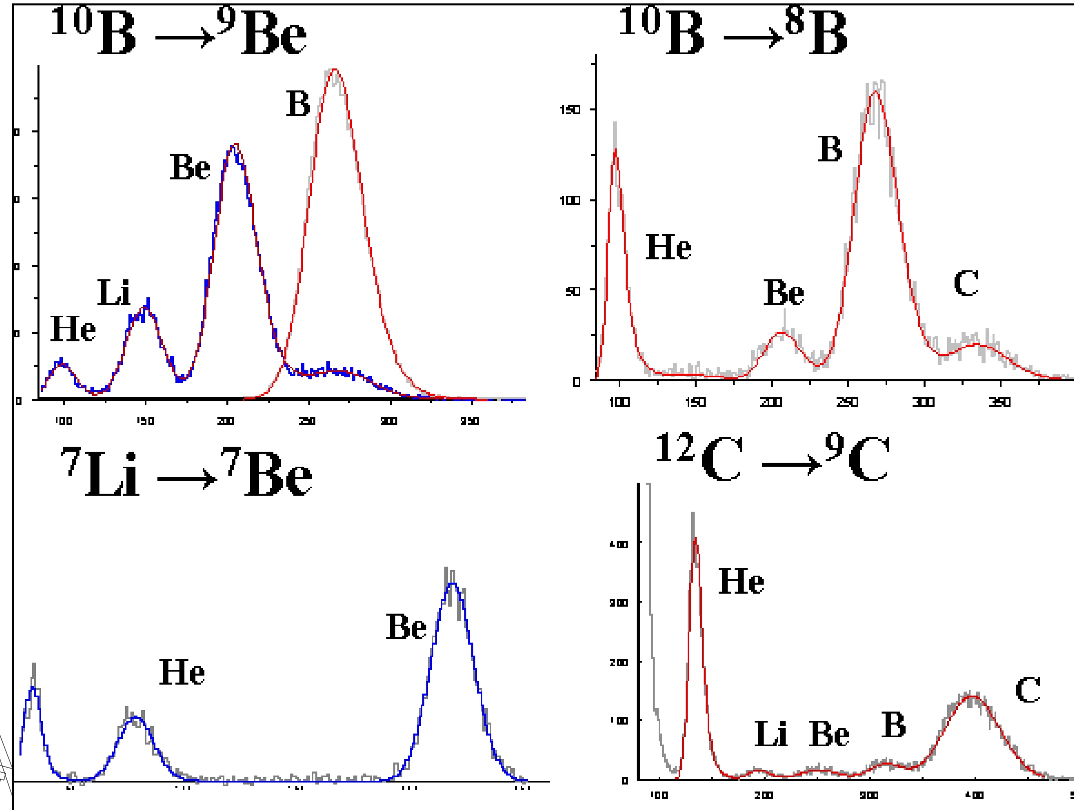
The study of the cluster structure by relativistic dissociation has both fundamental and practical importance. First of all, the probabilities with which the cluster states are shown in dissociation are related to the fundamental parameters of the ground and excited states of light nuclei. The knowledge of probabilities allows one to determine possible initial configurations of nuclear clusters, which is important for the analysis of the whole variety of nuclear reactions. Clustering is the basis of the processes accompanying the phenomenon of the physics of nuclear isobars, hyper nuclei and quark degrees of freedom. The ideas about nuclear clustering obtained in high-energy physics, are important for applications in nuclear astrophysics, cosmic ray physics, nuclear medicine, and perhaps even nuclear geology.

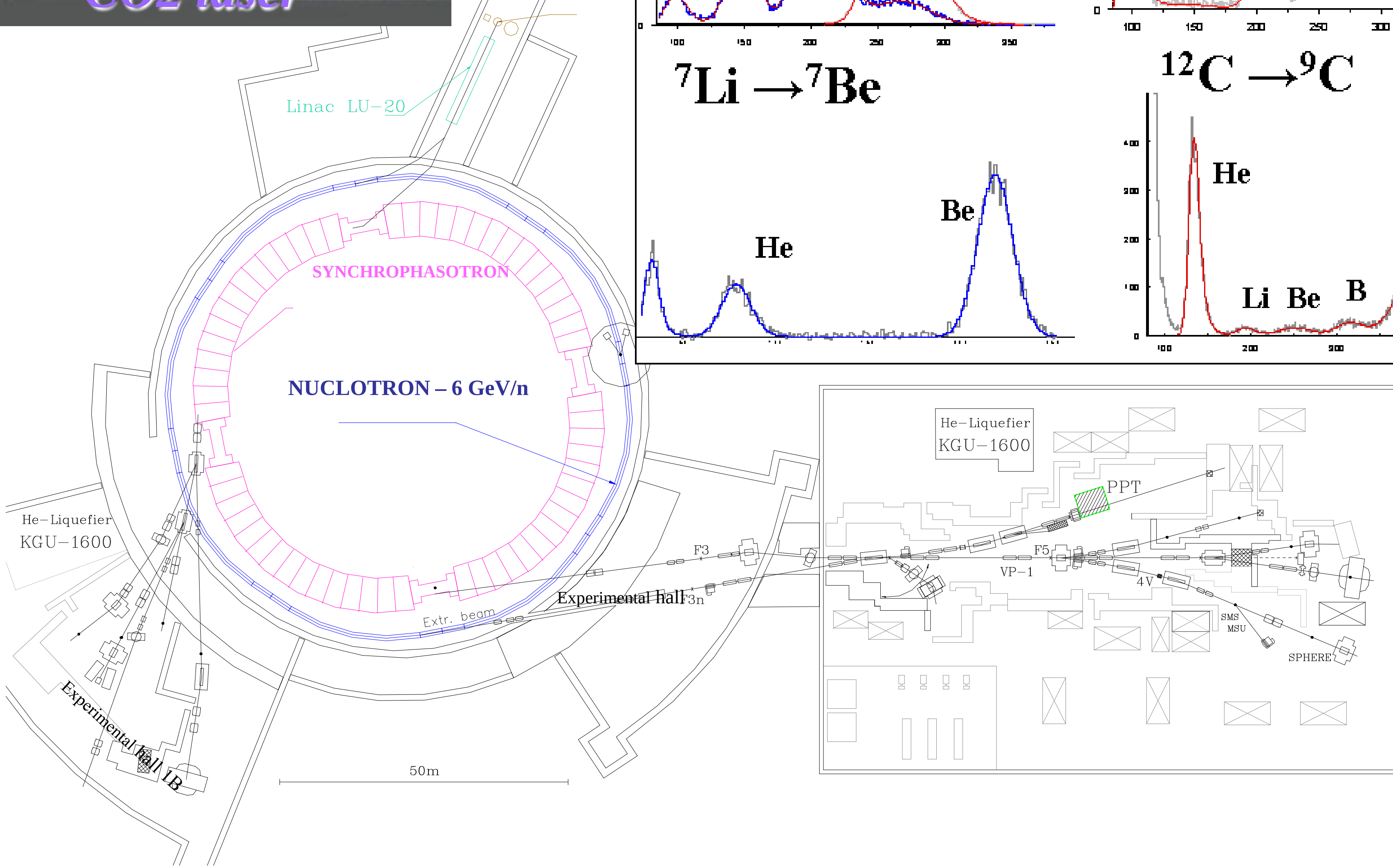


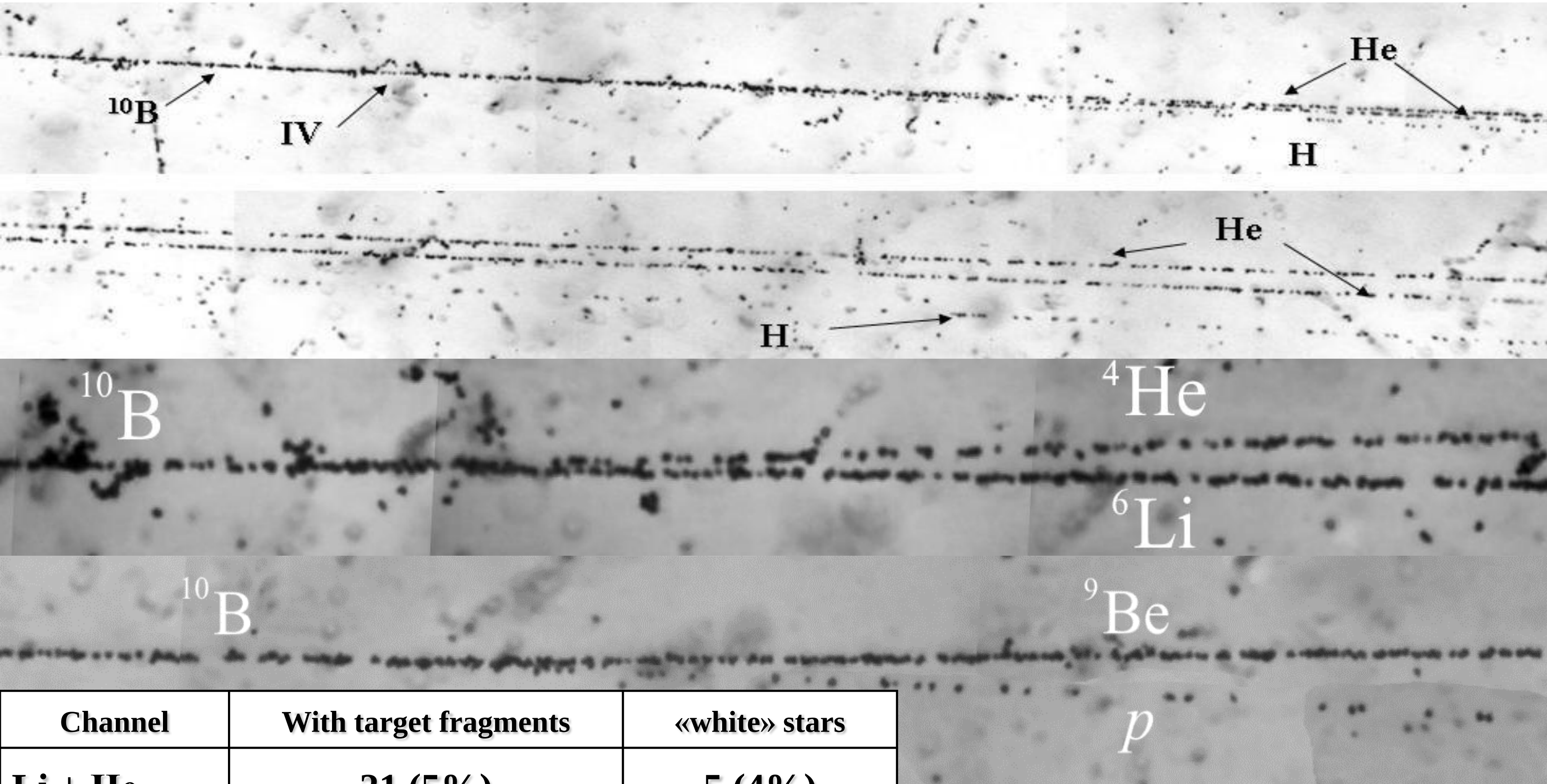


The pause in obtaining data on the structure of relativistic fragmentation motivated further exposures at the JINR Nuclotron to the light nuclei including radioactive ones. In the early 2000s, the BECQUEREL experiment aimed at systematic study of peripheral interactions of relativistic nuclei by the NTE method has been started. The analysis of peripheral interactions in longitudinally irradiated NTE layers allowed one to study cluster features of a whole family of light nuclei, including neutron-deficient ones, in the unified approach.

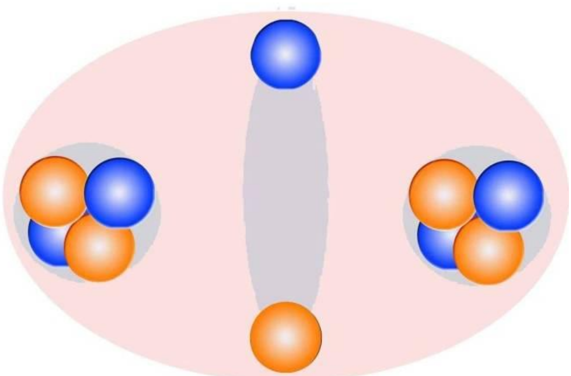

CO2 laser

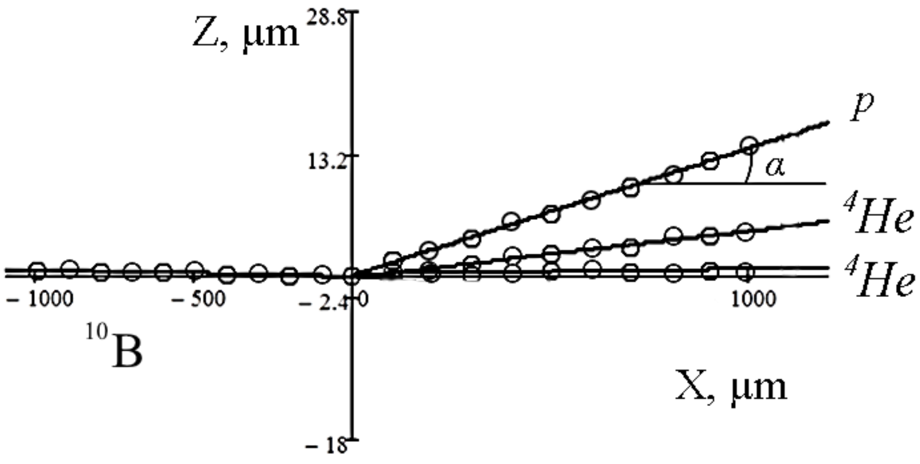

$^{10}B \rightarrow ^{9}Be$
He
Li
Be
B
$^{10}B \rightarrow ^{8}B$
He
Be
B
C
$^{7}Li \rightarrow ^{7}Be$
He
Be
$^{12}C \rightarrow ^{9}C$
He
Li
Be
B
C

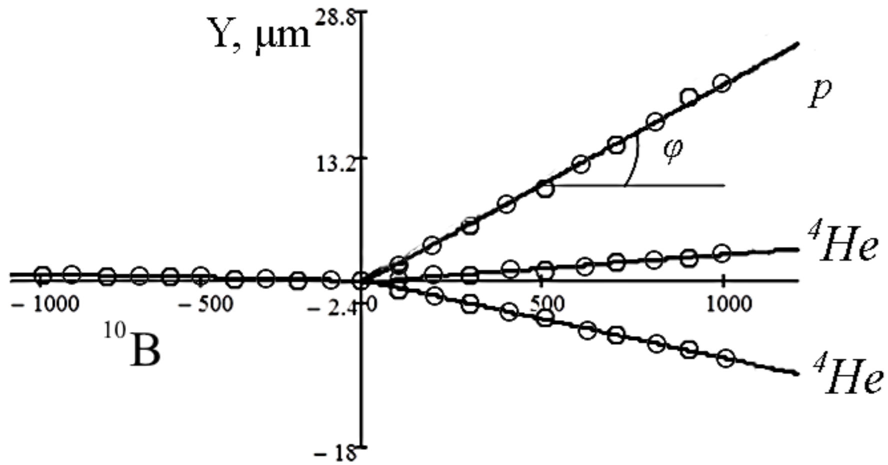

Linac LU−20
SYNCHROPHASOTRON
NUCLOTRON – 6 GeV/n
He−Liquefier
KGU−1600
Extr. beam
F3
F3n
Experimental hall
Experimental hall IB
50m
He−Liquefier
KGU−1600
PPT
F5
VP−1
4V
SMS
MSU
SPHERE



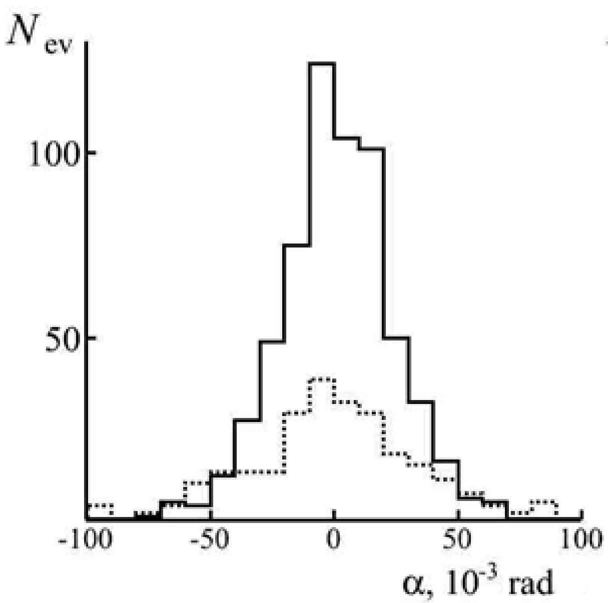
Channel	With target fragments	«white» stars
Li + He	21 (5%)	5 (4%)
Li + 2H	32 (8%)	5 (4%)
He + 3H	120 (32%)	18 (13%)
2He + H	182 (48%)	103 (76%)
5H	24 (6%)	2 (1%)
Be + H	1(< 1%)	2 (1%)

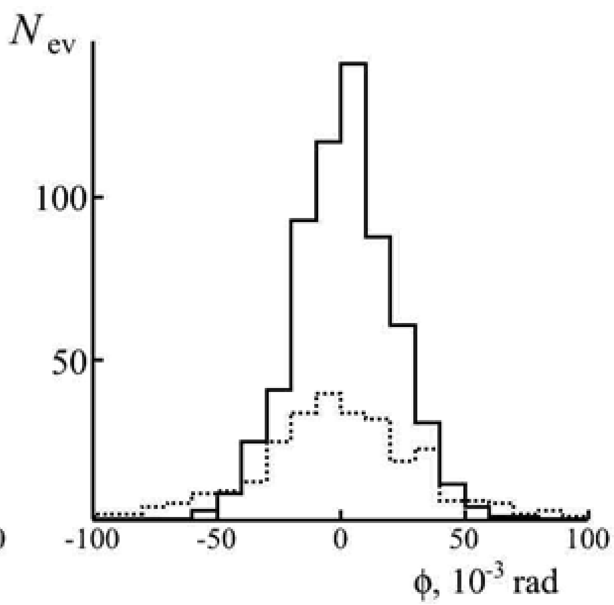




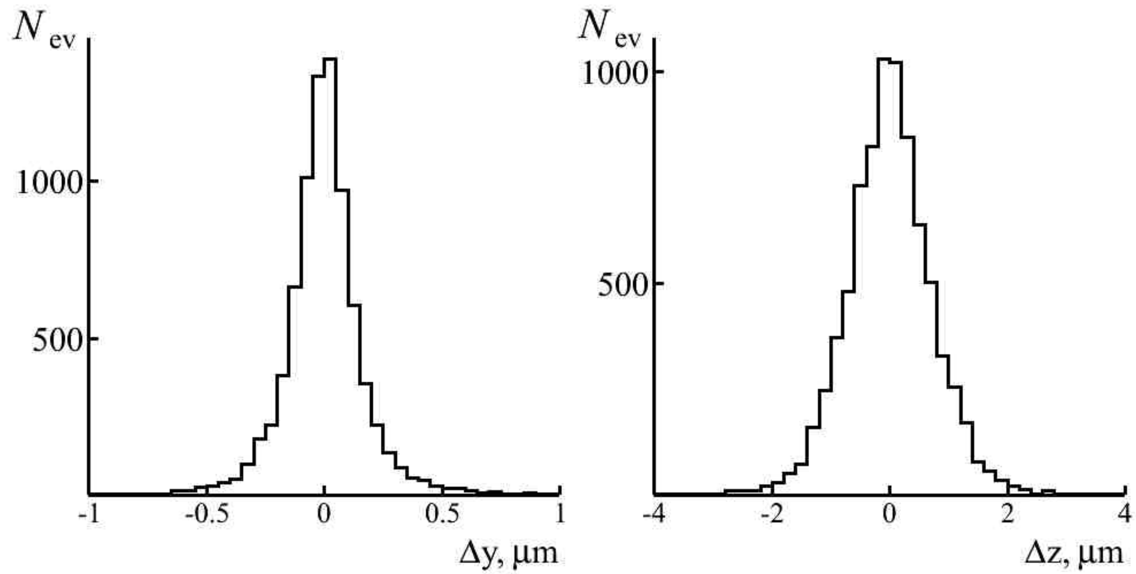


Example of restored directions in event ^{10}B → 2He + H @ 1.2 *A* GeV over vertical and planar planes.





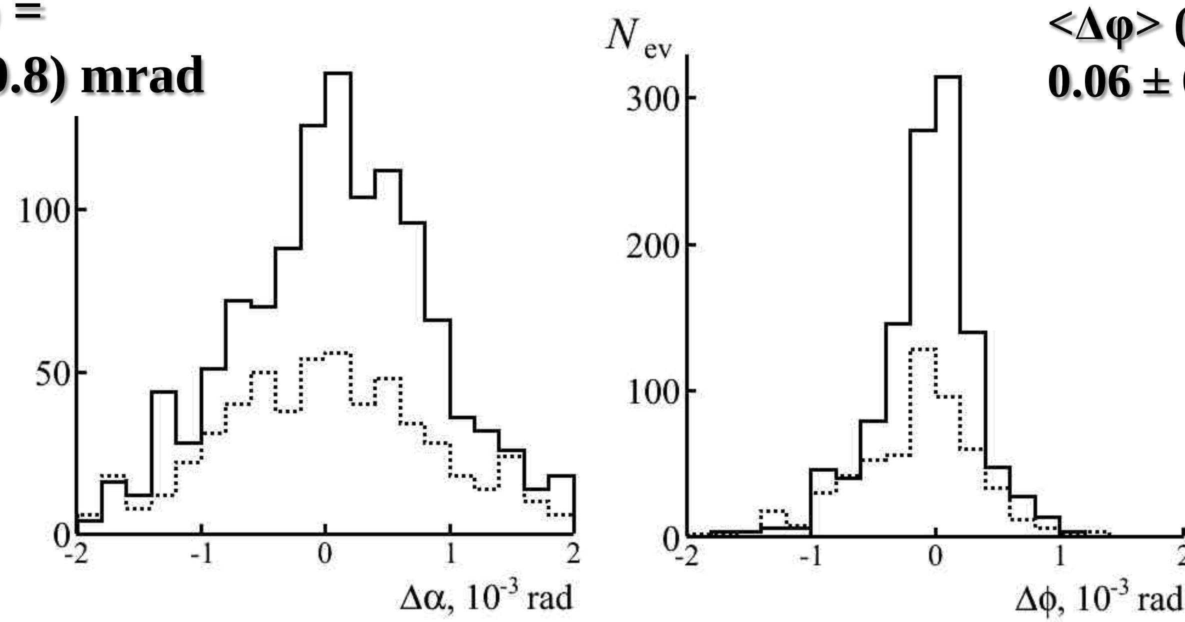
Distributions of fragments He (solid) and H (dotted) over dip and planar angles α and φ in events ^{10}B → 2He + H @ 1.2 *A* GeV.



Distributions of residuals Δ*y* and Δ*z* of fitting of coordinates of H and He tracks in events $^{10}B \rightarrow 2He + H$.

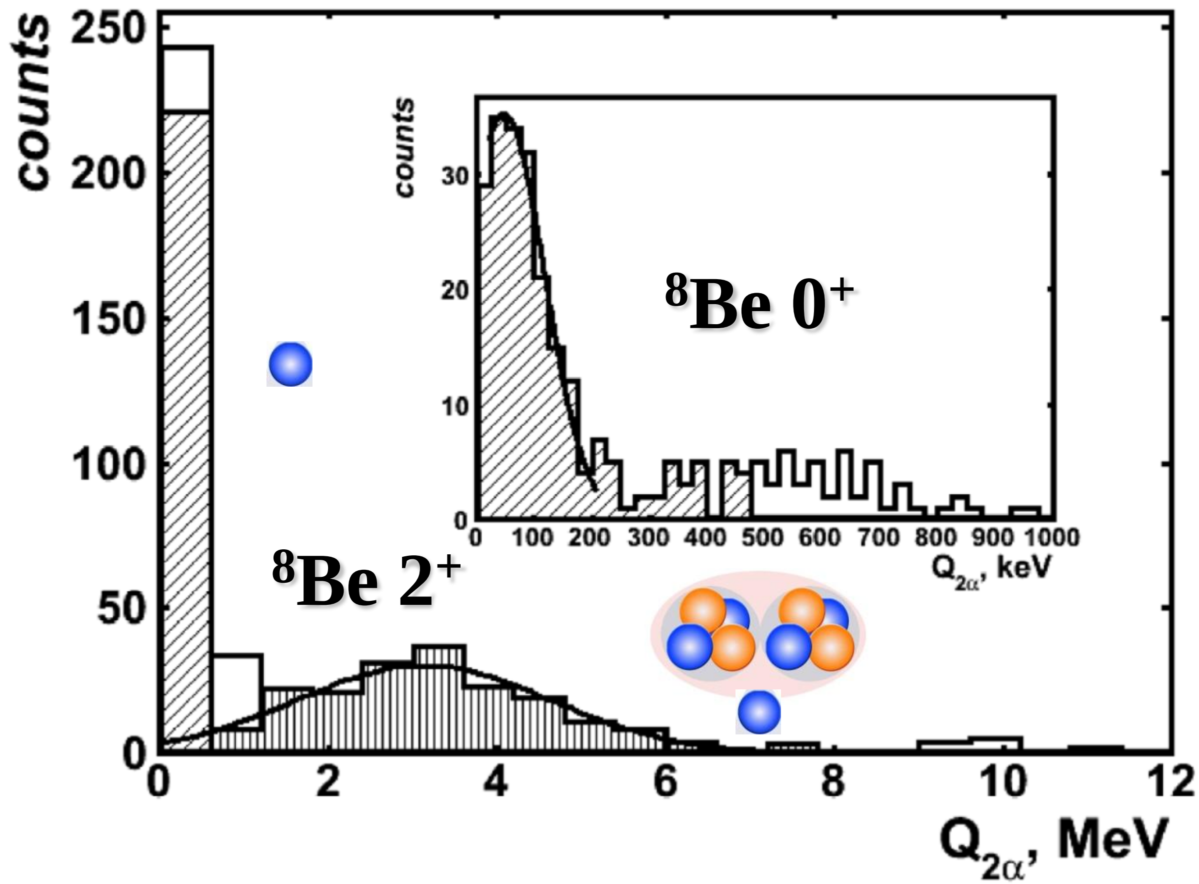
<Δα> (RMS) =
0.08 ± 0.02 (0.8) mrad

<Δφ> (RMS) =
0.06 ± 0.01 (0.4) mrad



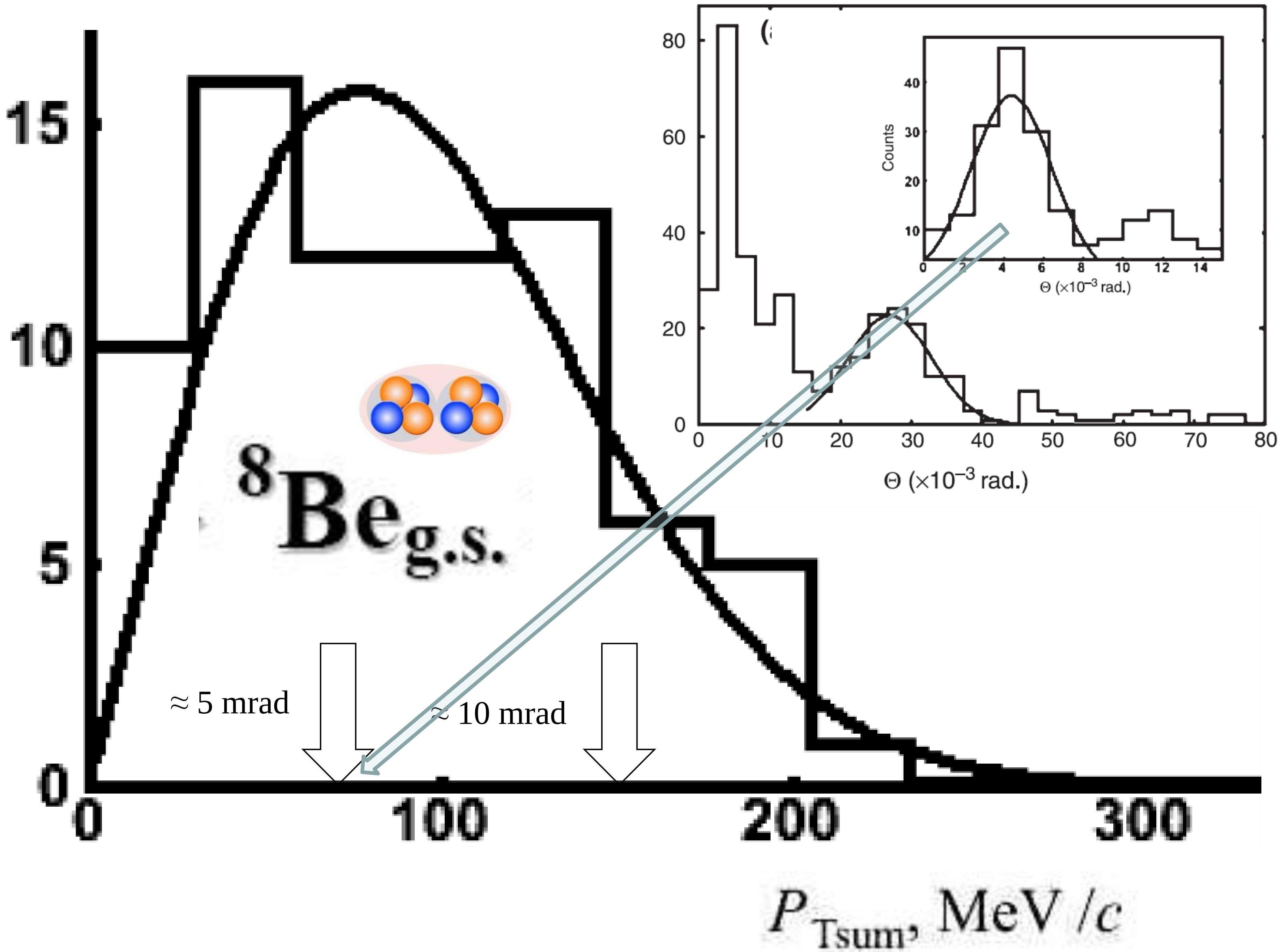
Distribution of errors in determining dip (α) and planar (φ) angles for fragments He (solid) and H (dotted) in events $^{10}B \rightarrow 2He + H$.

The secondary ^{9}Be beam was obtained by fragmentation of accelerated ^{10}B nuclei. When scanning the exposed emulsion 500 events $^{9}Be \rightarrow 2\alpha$ in a fragmentation cone of 0.1 rad have been found. About 81% α-pairs form roughly equal groups on $\Theta_{2\alpha}$: "narrow" ($0 < \Theta_n < 10.5$ mrad) and "wide" ($15.0 < \Theta_w < 45.0$ mrad) ones. The Θ_n pairs are consistent with ^{8}Be decays from the ground state 0^+, and pairs Θ_w - from the first excited state 2^+. The Θ_n and Θ_w fractions are equal to 0.56 ± 0.04 and 0.44 ± 0.04. These values are well corresponding to the weights of the ^{8}Be 0^+ and 2^+ states $\omega_{0+} = 0.54$ and $\omega_{2+} = 0.47$ in the two-body model n - ^{8}Be, used to calculate the magnetic moment of the ^{9}Be nucleus.

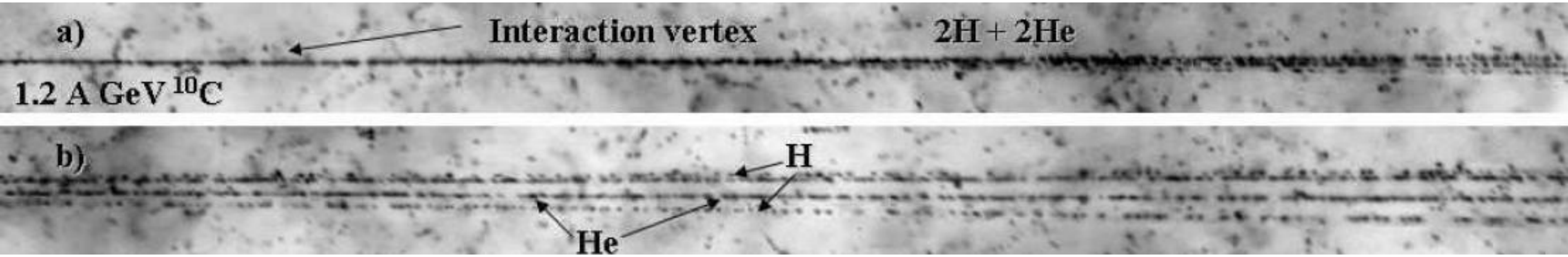


^{9}Be

$J^{\pi} = 3/2^-$

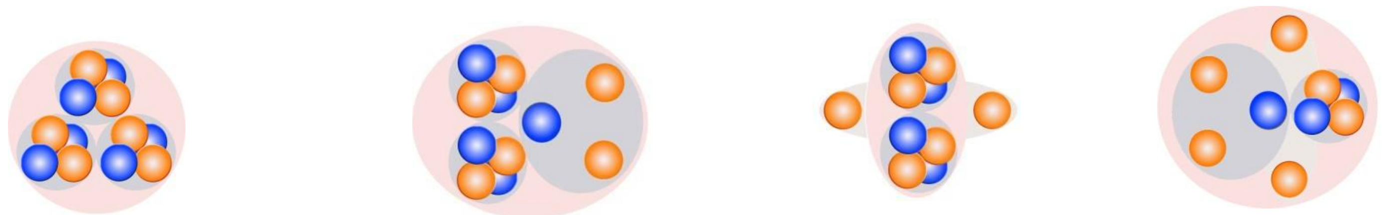


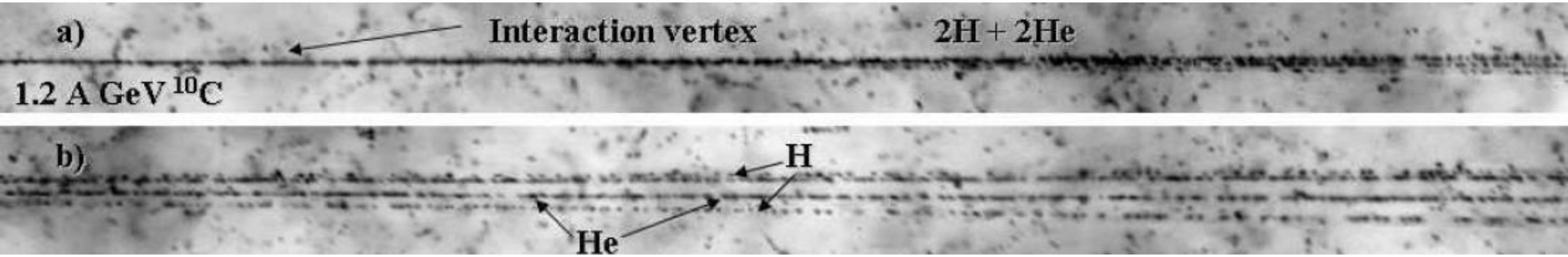
15
10
5
0
0
100
200
300
8Be g.s.
≈ 5 mrad
≈ 10 mrad
P Tsum, MeV /c
80
60
40
20
0
0
10
20
30
40
50
60
70
80
Θ (×10−3 rad.)
Counts
40
30
20
10
0
2
4
6
8
10
12
14
Θ (×10−3 rad.)

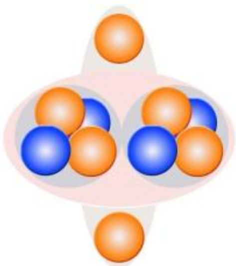


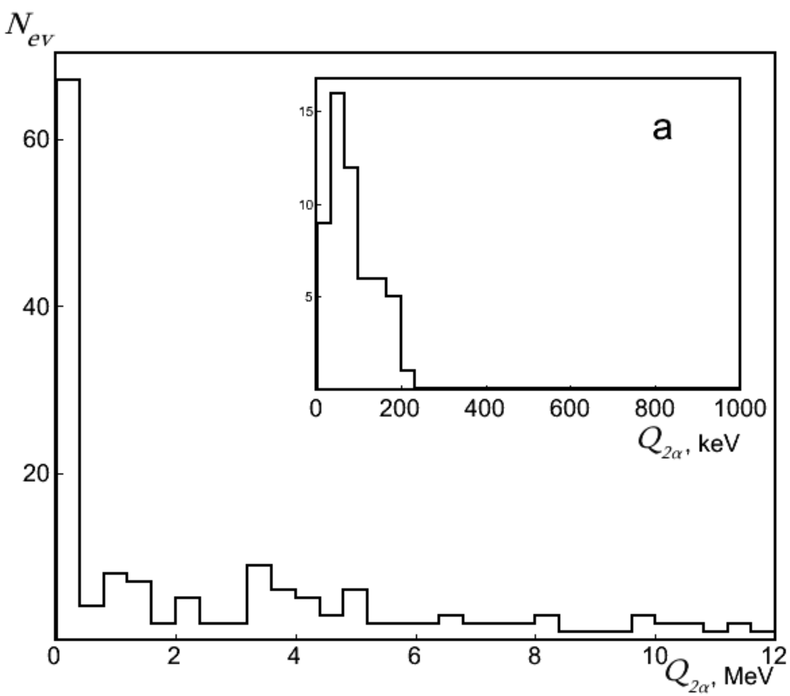
Charge topology of "white" stars

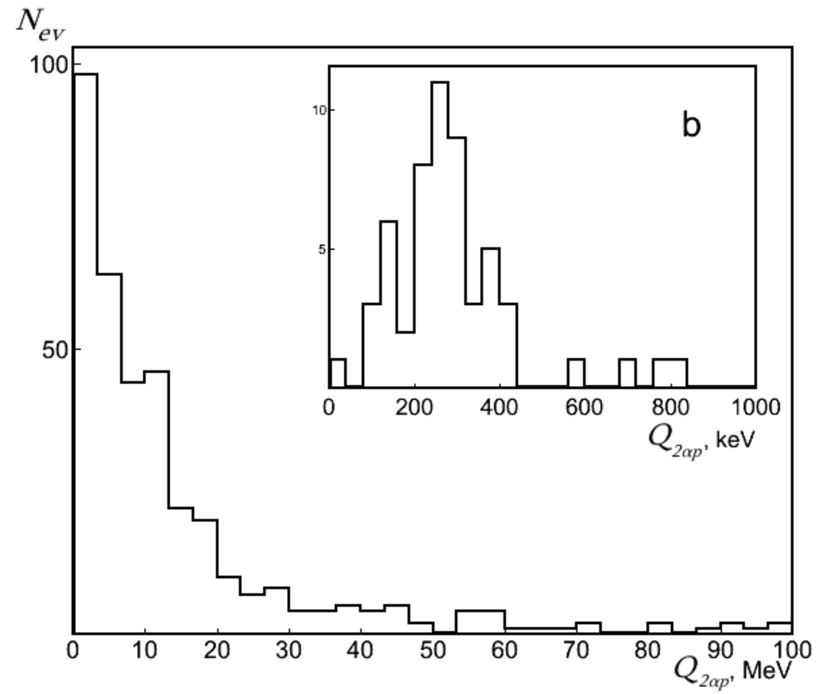
Channel	^{12}C	^{11}C	^{10}C	^{9}C
B + H		6 (5 %)	1 (0.4 %)	15 (14 %)
Be + He		18 (13 %)	6 (2.6 %)	
Be + 2H				16 (15 %)
3He	100 (100 %)	25 (17 %)	12 (5.3 %)	16 (15 %)
2He + 2H		72 (50 %)	186 (82 %)	24 (23 %)
He + 4H		15 (11 %)	12 (5.3 %)	28 (27 %)
Li + He + H		5 (3 %)		
Li + 3H			1 (0.4 %)	2 (2 %)
6H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





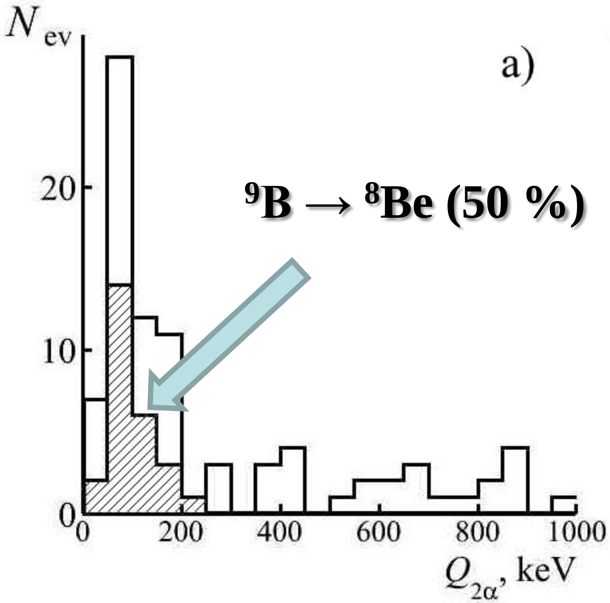


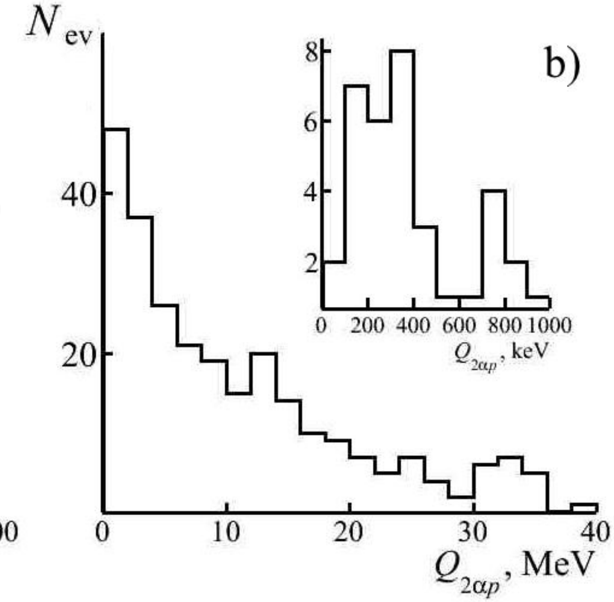




The distribution of 68 "white" stars $^{10}C \rightarrow 2\alpha + 2p$ over $Q_{2\alpha}$ and $Q_{2\alpha p}$ is shown in Figures *a* and *b*. The distribution $Q_{2\alpha}$ with an average $<Q_{2\alpha}>$ = (63 ± 30) keV allows concluding that the ^{8}Be formation is observed. In turn, the distribution $Q_{2\alpha p}$ indicates that the dissociation $^{10}C \rightarrow 2\alpha + 2p$ is accompanied by the ^{9}B formation. The average value $<Q_{2\alpha p}>$ = (254 ± 18) keV corresponds to decay $^{9}B \rightarrow {}^{8}Be + p$. A complete correspondence $Q_{2\alpha}$ to $Q_{2\alpha p}$ points to the cascade $^{10}C \rightarrow {}^{9}B \rightarrow {}^{8}Be$. The ^{9}B nucleus manifests itself with a probability of 30 ± 4 % in the ^{10}C structure.

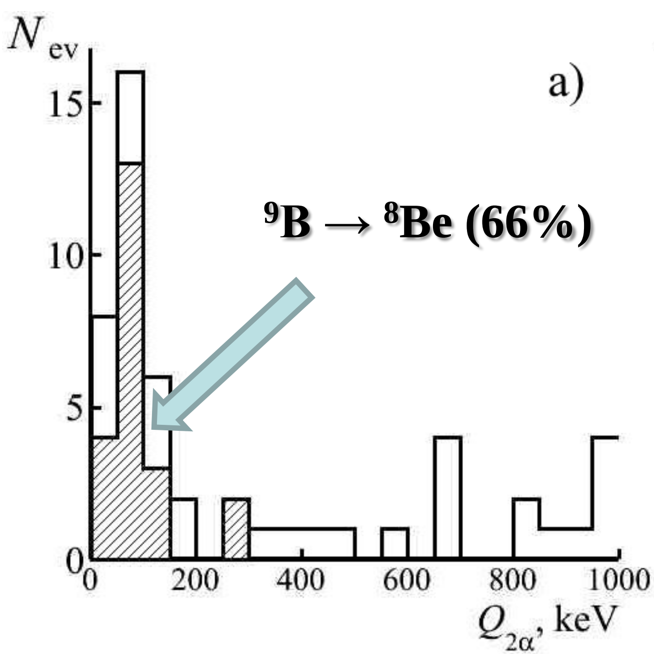
“White" stars $^{10}B \rightarrow 2He + H$ @ 1.6 *A* GeV/*c*

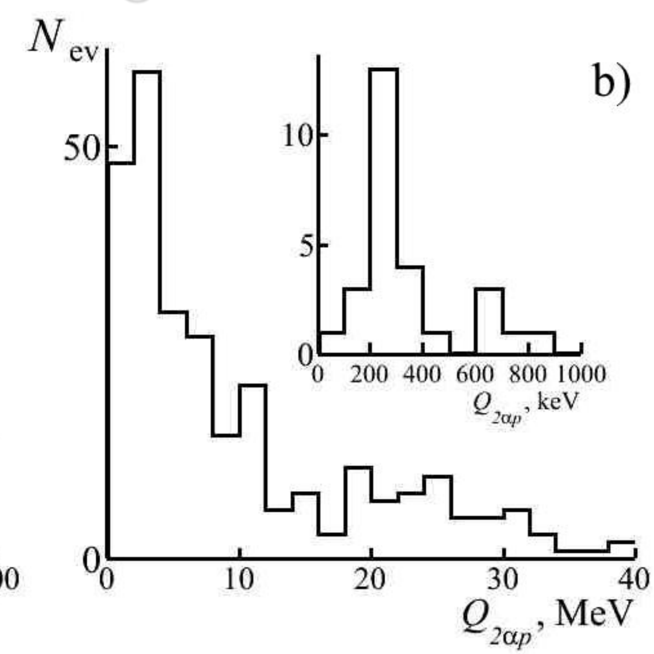


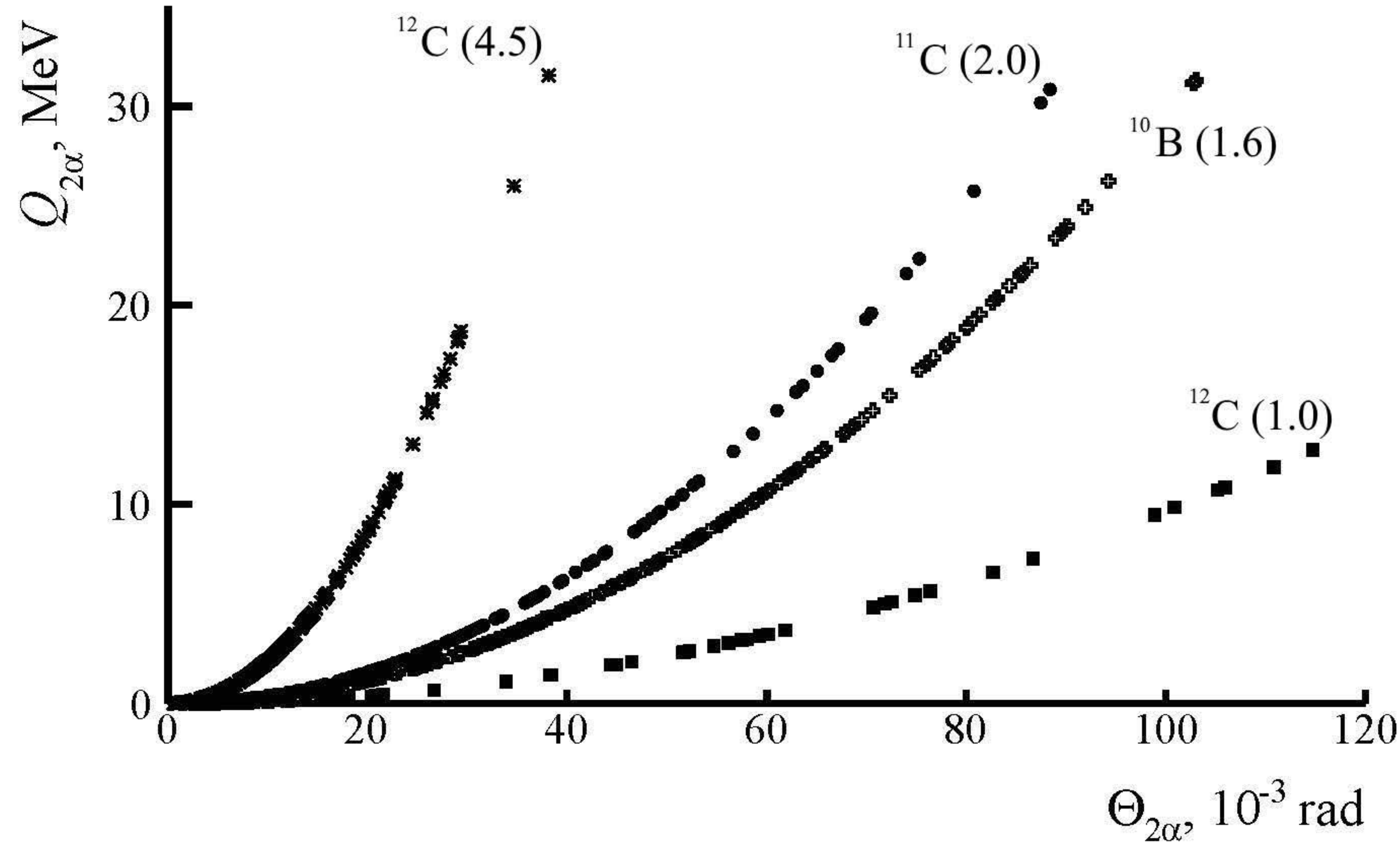


$$\frac{^{9}B + n}{^{9}Be + p} \approx 6$$

“White" stars $^{11}C \rightarrow 2He + 2H$ @ 2.0 *A* GeV/*c*







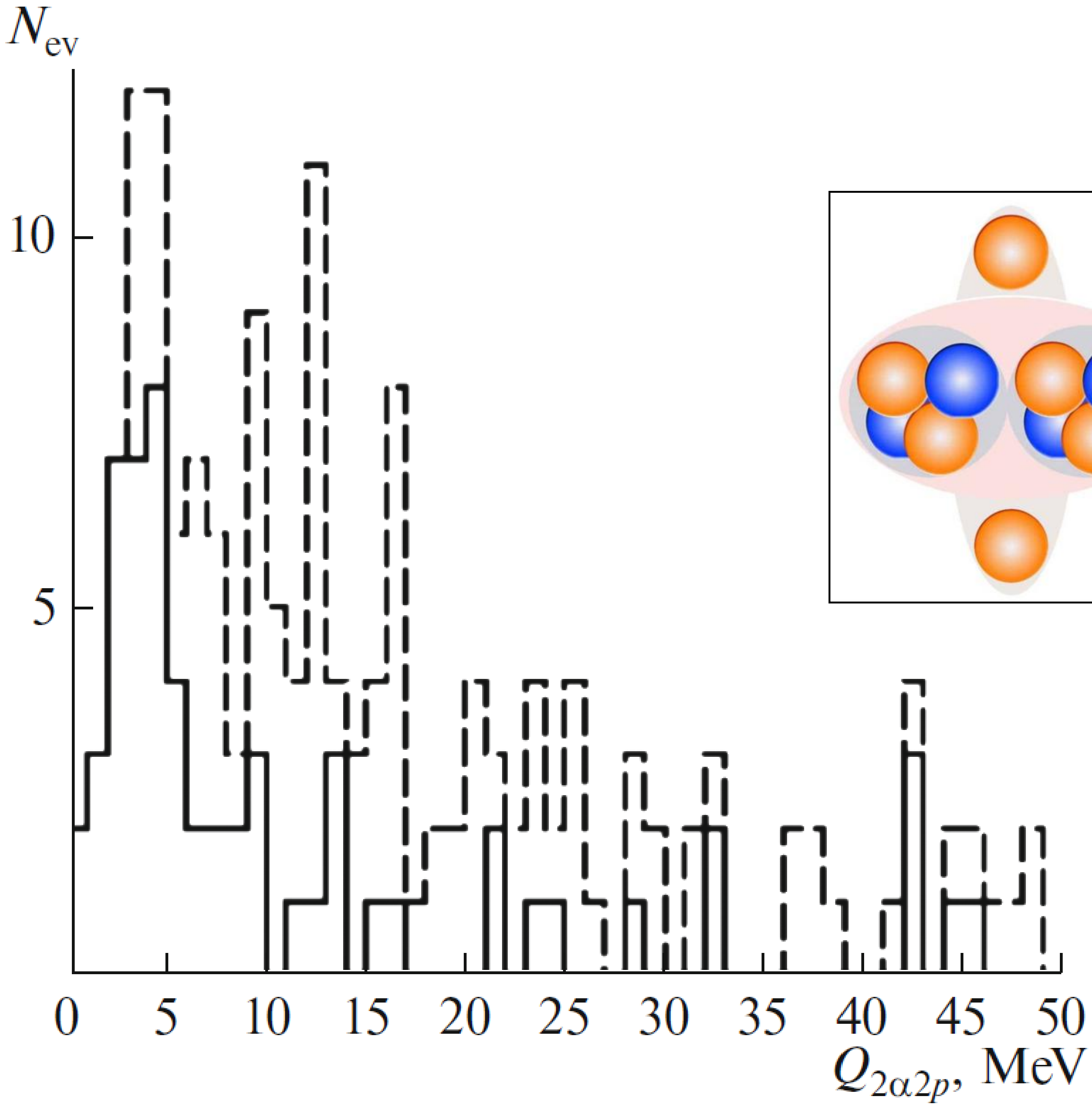
Dependence of calculated invariant masses of α-pairs $Q_{2\alpha}$ over opening angles in them $\Theta_{2\alpha}$ in events of dissociation of ^{12}C, ^{11}C and ^{10}B nuclei; momentum values are indicated in parentheses (*A* GeV/*c*).

Mean values of $<\Theta_{2\alpha}>$ and $<Q_{2\alpha}>$ ($Q_{2\alpha}$ < 300 keV)

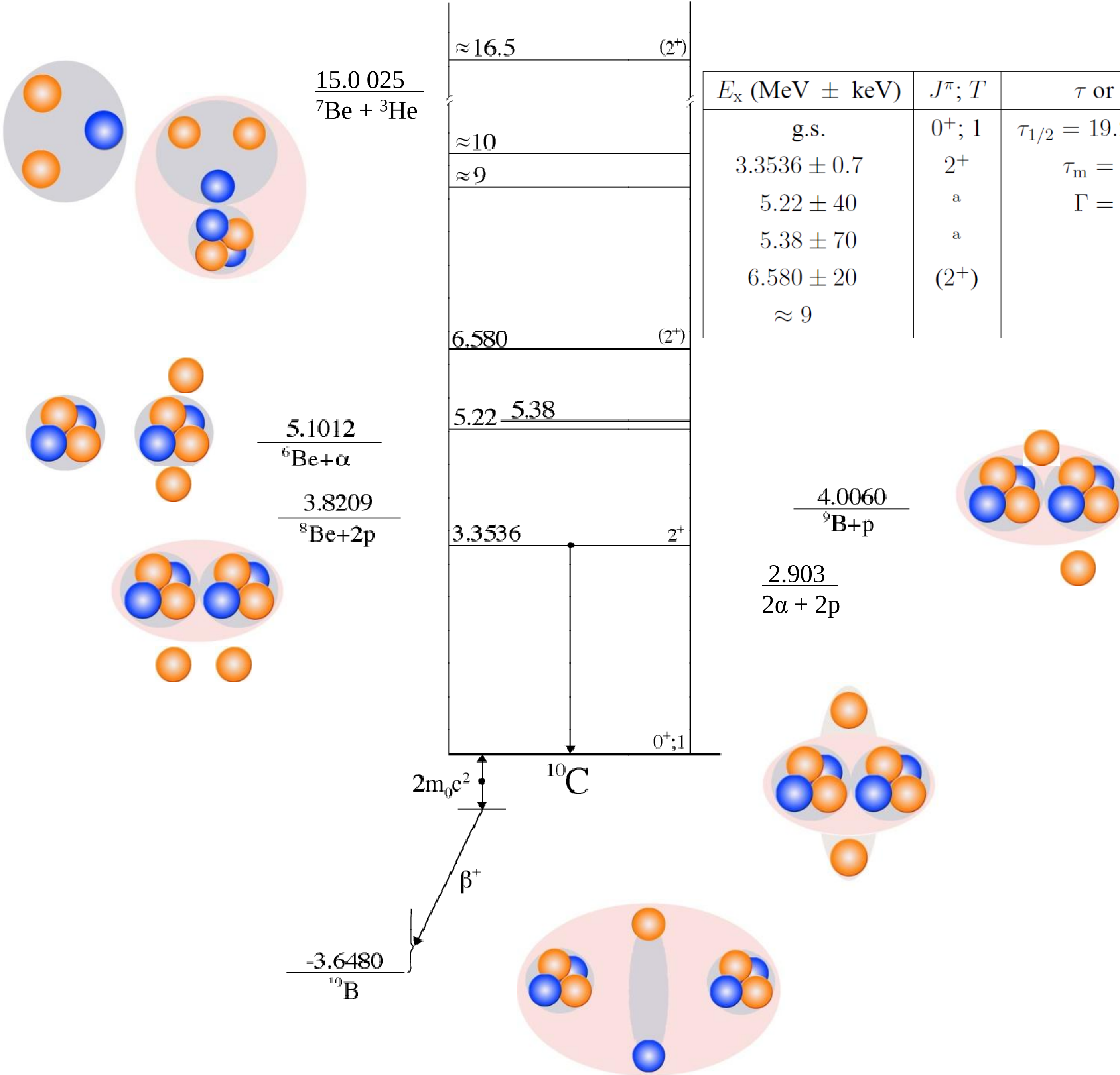
Nucleus (P_0, A GeV/c)	$<\Theta_{2\alpha}>$ (RMS), 10^{-3} rad ($Q_{2\alpha}$ < 300 keV)	$<Q_{2\alpha}>$ (RMS), keV
^{12}C (4.5)	2.1 ± 0.1 (0.8)	109 ± 11 (83)
^{14}N (2.9)	2.9 ± 0.2 (1.9)	119.6 ± 9.5 (72)
^{9}Be (2.0)	4.4 ± 0.2 (2.1)	86 ± 4 (48)
^{10}C (2.0)	4.6 ± 0.2 (1.9)	63 ± 7 (83)
^{11}C (2.0)	4.7 ± 0.3 (1.9)	77 ± 7 (40)
^{11}C(2.0) → ^{9}B → ^{8}Be		94 ± 15 (86)
^{10}B (1.6)	5.9 ± 0.2 (1.6)	101 ± 6 (46)
^{10}B(1.6) → ^{9}B → ^{8}Be		105 ± 9 (47)
^{12}C (1.0)	10.4 ± 0.5 (3.9)	107 ± 10 (79)

Mean values of $<Q_{2\alpha p}>$ ($Q_{2\alpha p}$ < 400 keV)

Nucleus	$<Q_{2\alpha p}>$, (RMS) keV
^{10}B	249 ± 19 (91)
^{10}C	254 ± 18 (96)
^{11}C	273 ± 18 (82)



Distributions over energy $Q_{2\alpha 2p}$ of all "white" stars $^{10}C \rightarrow 2He + 2H$ (dashed) and the ones with the presence of ^{9}B (solid). The distribution $Q_{2\alpha 2p}$ for the ^{10}C stars containing ^{9}B decays features the distinct peak with a maximum at 4.1 ± 0.3 MeV at RMS of 2.0 MeV. The peak statistics present 17 ± 4% of the total number of the ^{10}C "white" stars or 65 ± 14% of those containing ^{9}B decays.

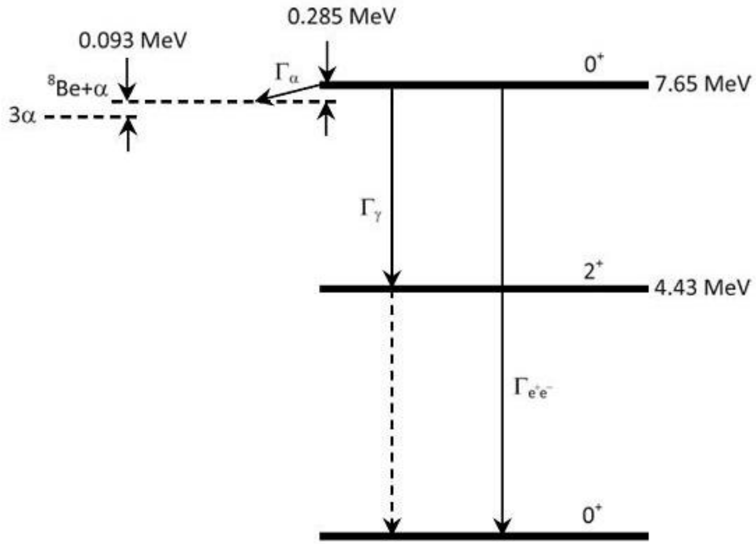


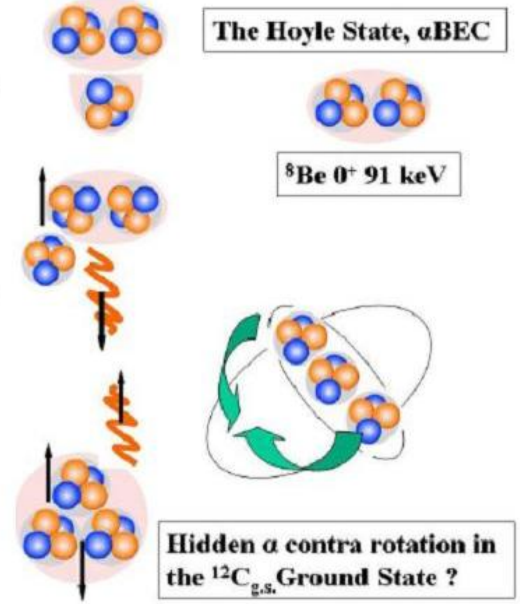
E_x (MeV $\pm$ keV)	J^π; T	τ or Γ_{cm} (keV)
g.s.	0^+; 1	$\tau_{1/2} = 19.290 \pm 0.012$ sec
3.3536 ± 0.7	2^+	$\tau_m = 155 \pm 25$ fsec
5.22 ± 40	a	$\Gamma = 225 \pm 45$ keV
5.38 ± 70	a	300 ± 60
6.580 ± 20	(2^+)	190 ± 35
≈ 9		

An analysis of peripheral interactions in the NTE layers irradiated at the JINR Nuclotron made it possible to study in a unified approach the cluster features of the nuclei ^{7,9}Be, ^{8,10,11}B, ^{10,11}C, ^{12,14}N and establish the contribution of unstable ^{6}Be, ^{8}Be and ^{9}B nuclei to their dissociation

The important conclusion is that the absence of stable ground states of ^{8}Be and ^{9}B does not prevent their participation in the nuclear structure. In nucleosynthesis chains, they can serve as necessary “transfer stations” the passage of which became “imprinted” in the nuclei formed. Until now, such participants are recognized only in the famous chain 3α → α^{8}Be → (Hoyle state) → ^{12}C.

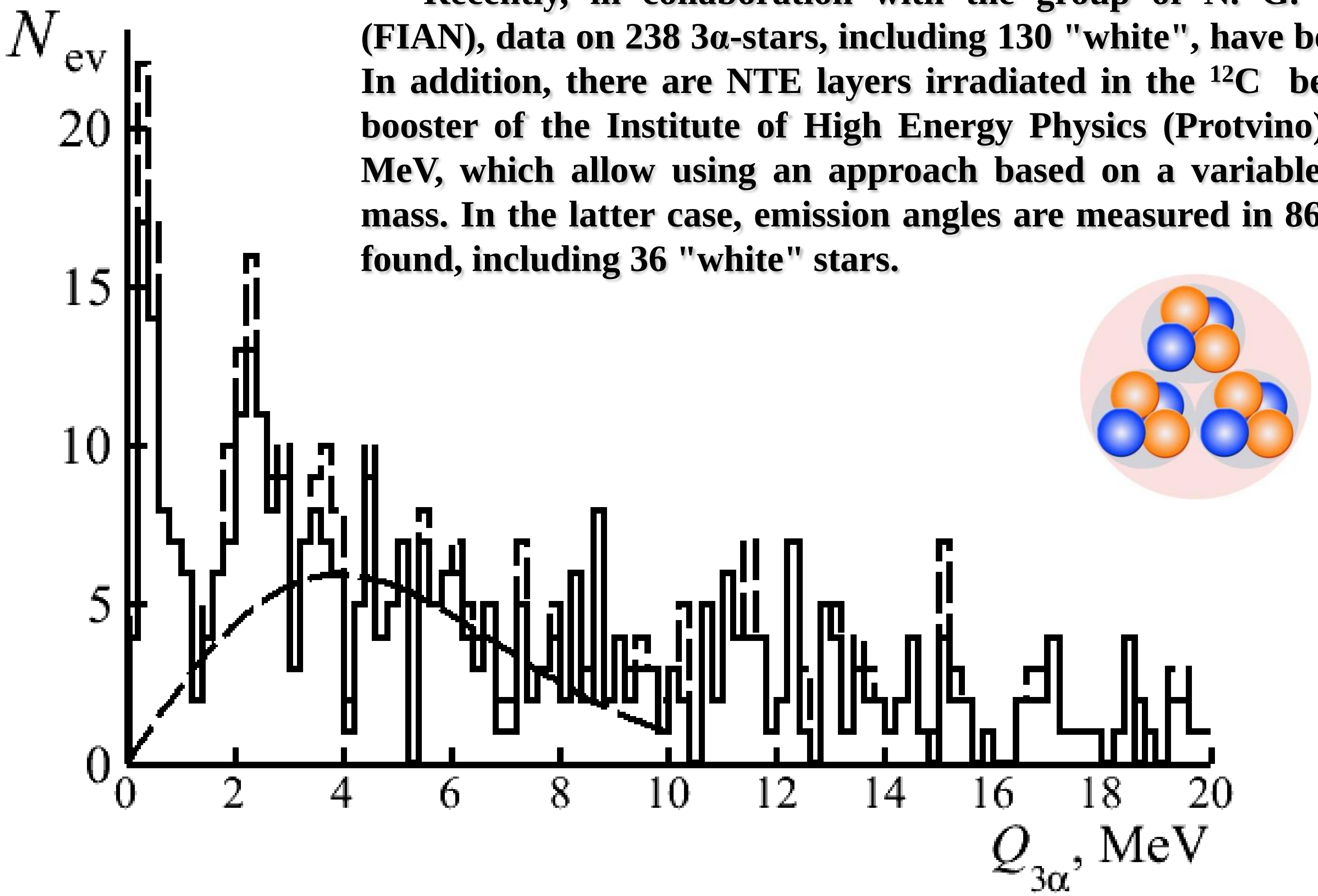
Our observations suggest the possibility of expanding the scenarios of light isotope synthesis involving the unstable states. It is possible to consider the role of more complex nuclear molecular systems. In particular, in the coherent dissociation of the ^{10}C nucleus, an indication is obtained of the resonance in the ^{9}B*p* channel at 4 MeV. Its study continues on a 4-fold increase in statistics. Since 2016, the possibility of observing the Hoyle state in the relativistic dissociation of the light nuclei is under scrutiny.





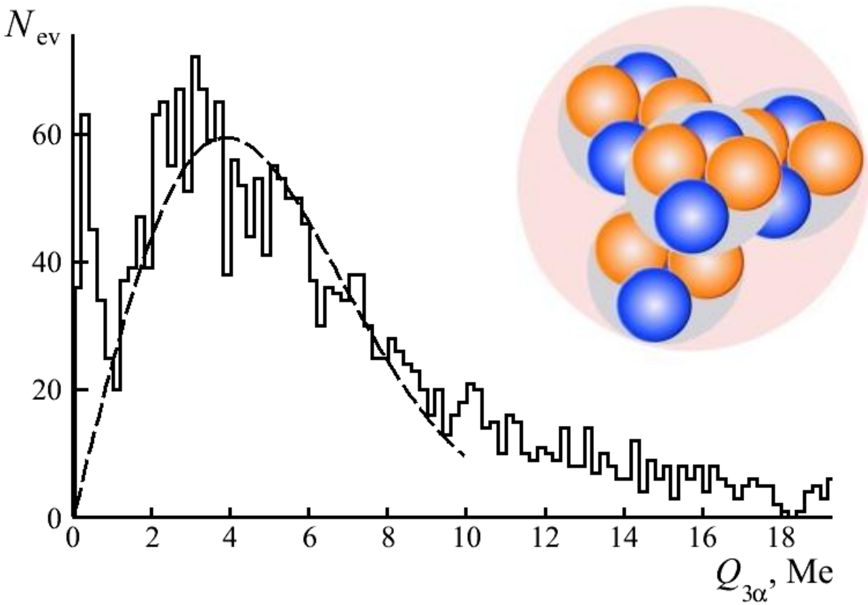
The successful reconstruction of the ^{8}Be and ^{9}B decays allows one to take the next step — to search in relativistic dissociation ^{12}C → 3α for triples of α-particles in the Hoyle state (HS). This state is the second and first unbound excitation 0^+_2 of the ^{12}C nucleus. The HS features such as isolation in the initial part of the ^{12}C excitation spectrum, lowest decay energy and its narrow width (378 keV and 8.5 eV) indicate its similarity with the 2α-particle nucleus ^{8}Be (91 keV and 5.6 eV). ^{8}Be is an indispensable product of HS decays. It can be assumed that HS is not limited to ^{12}C excitation but it can also appear as a 3α-partial analog of ^{8}Be in relativistic fragmentation of heavier nuclei.

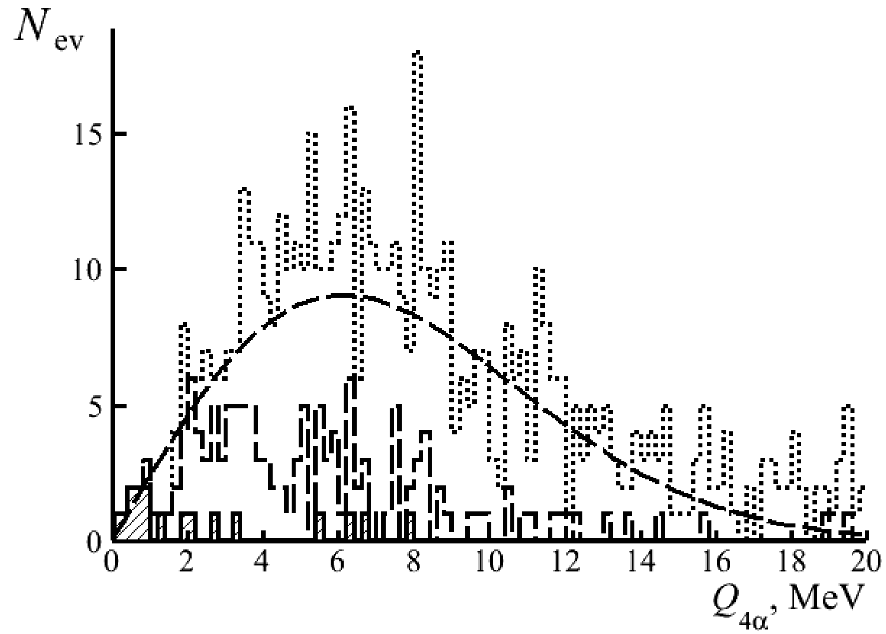
Interest in HS is motivated by the concept of α-partial Bose-Einstein condensate. As the simplest forms of such a condensate the ground state of the unstable ^{8}Be nucleus and, after it, HS are under consideration. Continuing the ^{8}Be and HS branches, it is assumed that the next condensate state of 4α's is the 6th excited state 0^+_6 of the ^{16}O nucleus, located 700 keV above the 4α threshold. Then, the condensate decomposition could go in the sequence $^{16}O(0^+_6) \rightarrow {}^{12}C(0^+_2) \rightarrow {}^{8}Be(0^+_2) \rightarrow 2\alpha$.



Recently, in collaboration with the group of N. G. Peresadko (FIAN), data on 238 3α-stars, including 130 "white", have been added. In addition, there are NTE layers irradiated in the ^{12}C beam of the booster of the Institute of High Energy Physics (Protvino) at 420 *A* MeV, which allow using an approach based on a variable invariant mass. In the latter case, emission angles are measured in 86 3α-events found, including 36 "white" stars.

The distribution $Q_{3\alpha}$ for all 510 stars is shown in Figure. The region $Q_{3\alpha}$ < 10 MeV covering the ^{12}C excitations below the nucleon separation thresholds is described by the Rayleigh distribution with the parameter $\sigma_{Q3\alpha} = (3.9 \pm 0.4)$ MeV. There is a peak in the region $Q_{3\alpha}$ < 1 MeV (51 stars) where the HS signal is expected. For events at 3.65 *A* GeV contributed to this peak the average value $\langle Q_{3\alpha} \rangle$ (RMS) is 397 ± 26 (166) keV, and at 420 *A* MeV, 346 ± 28 (85) keV, respectively. According to the condition $Q_{3\alpha}$ < 0.7 MeV 42 of 424 events at 3.65 A GeV can be attributed to HS decays, and 9 at 420 A MeV (out of 86) including 5 "white" stars (out of 36). As a result, the contribution of HS decays to $^{12}C \rightarrow 3\alpha$ dissociation is 10 ± 2%.

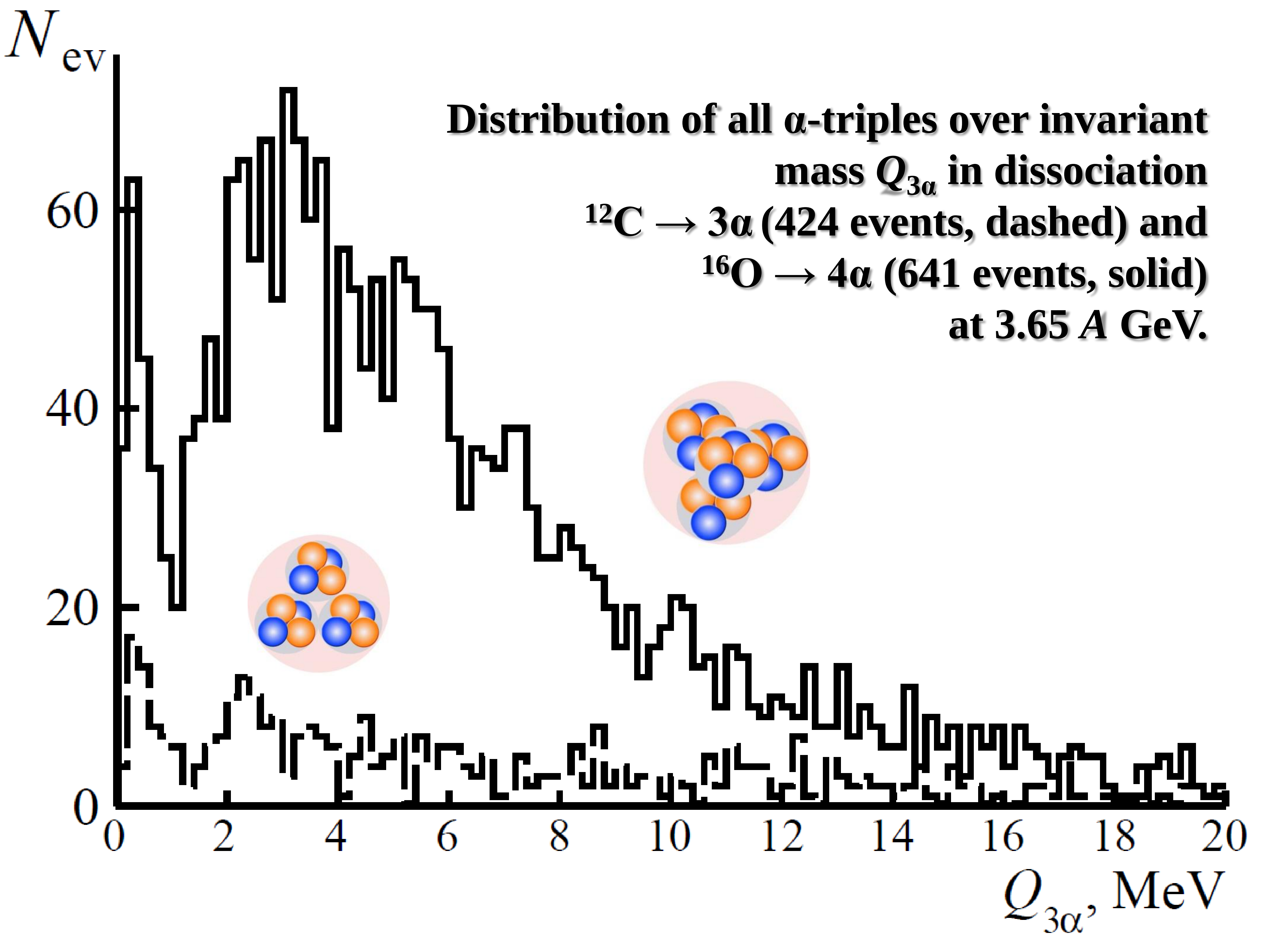




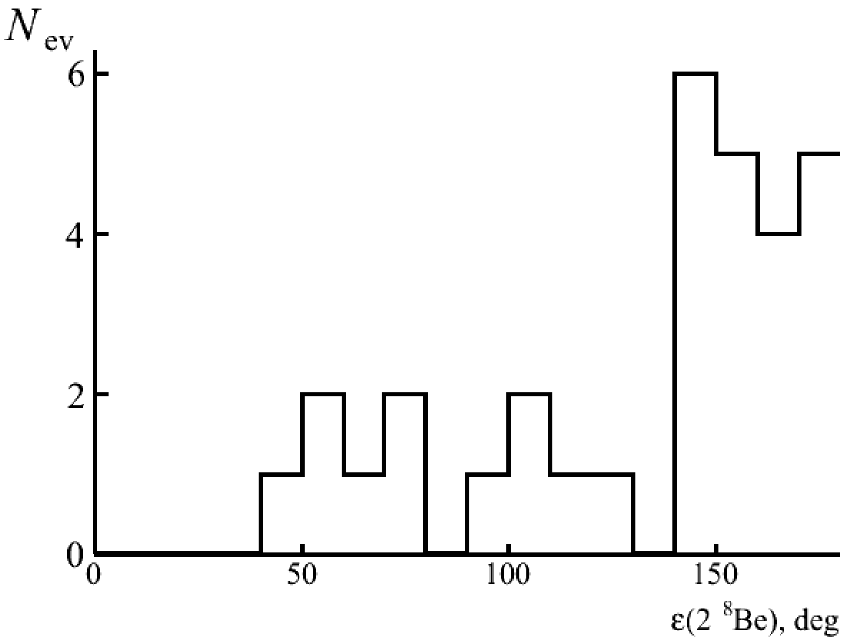
HS decays can manifest themselves in the dissociation $^{16}O \to {}^{12}C^{*}$ ($\to 3\alpha$) + α. The left figure shows the $Q_{3\alpha}$ distribution of all 3α combinations. As in the ^{12}C case, its main part with $Q_{3\alpha} < 10$ MeV is described by the Rayleigh distribution with the parameter $\sigma_{Q3\alpha}$ = (3.8 ± 0.2) MeV.

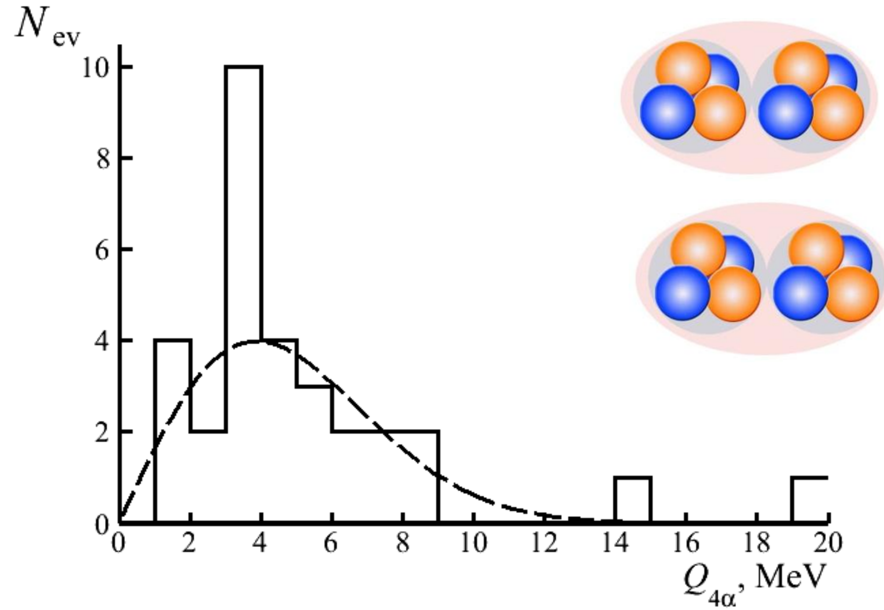
It also has a peak at $Q_{3\alpha} < 700$ keV. The condition $Q_{2\alpha} < 200$ keV meaning at least one ^{8}Be decay in a 4α event does not affect the statistics in this $Q_{3\alpha}$ range. The contribution to the peak of the combinatorial background estimated at 8% is excluded. The remaining 139 events have an average value of $\langle Q_{3\alpha} \rangle$ = (349 ± 14) keV corresponding to HS and RMS 174 keV. In 9 events of them more than one 3α-combination corresponds to the condition $Q_{3\alpha} < 700$ keV. In sum, the contribution of HS decays to the coherent dissociation of $^{16}O \to 4\alpha$ is 22 ± 2%.

HS can arise as a decay product of the excited state 0^{+}_{6} of the ^{16}O nucleus (by analogy with the decay of HS into ^{8}Be + α). In the 641 “white” star, the full distribution of α-quartets over $Q_{4\alpha}$ (right figure) is described mainly by the Rayleigh distribution with the parameter $\sigma_{Q4\alpha}$ = (6.1 ± 0.2) MeV. The condition for the presence in the 4α-event (αHS) of at least one α-triple with $Q_{3\alpha} <$ 700 keV shifts toward the low-energy direction the $Q_{4\alpha}$ distribution (Fig. 6) and the value of the parameter $\sigma_{Q4\alpha}$ = (4.5 ± 0.5) MeV. It can be assumed that in the decay of an integral object, HS and α will be correlated in directionThe condition ε(αHS) < 45^{0} identifies 9 events that satisfy $Q_{4\alpha} < 1$ MeV with an average value of $\langle Q_{4\alpha} \rangle$ = (624 ± 84) keV with RMS 252 keV . On their basis, the assessment of the contribution of the 0^{+}_{6} state is 7 ± 2%.



N_{ev}
Distribution of all α-triples over invariant
mass $Q_{3\alpha}$ in dissociation
$^{12}C \rightarrow 3\alpha$ (424 events, dashed) and
$^{16}O \rightarrow 4\alpha$ (641 events, solid)
at 3.65 *A* GeV.
0
20
40
60
0 2 4 6 8 10 12 14 16 18 20
$Q_{3\alpha}$, MeV





Among the 641 "white" stars $^{16}O \to 4\alpha$, 33 events were selected, in which two ^{8}Be fragments ($Q_{2\alpha}$ < 0.2 MeV) are present. The directions of expansion along the azimuth angle ε ($2^{8}Be$) show anti-correlation (left) which indicates the binary formation of these fragments. In 31 events $2^{8}Be$ there are no triples of α-particles that satisfy the condition HS ($Q_{3\alpha}$ < 700 keV) which gives an estimate of the contribution of the $^{16}O \to 2^{8}Be$ channel is equal to 5 ± 1%. The distribution of pairs to their full transverse momentum $P_T(2^{8}Be)$ is described by the Rayleigh distribution with the parameter σ_{PT} ($2^{8}Be$) = (161 ± 2) MeV/*c*. The right figure shows the distribution over $Q_{4\alpha}$ for $2^{8}Be$ events for which the Rayleigh parameter is (4.3 ± 1.2) MeV. The number of events in the channels $^{16}O \to \alpha HS$ and $^{16}O \to 2^{8}Be$ has a ratio 4.5 ± 0.4 which means that the first of them is clearly leading.

In general, the HS feature as a universal and sufficiently long-lived object similar to the unstable ^{8}Be nucleus is confirmed.

The closest source for verifying the HS universality is the ^{14}N dissociation in which the 3He + H channel leads, with the ^{8}Be contribution of 25%. Analysis of the NTE layers exposed in the early 2000s to relativistic ^{14}N nuclei at the JINR Nuclotron is resumed in the context of the HS problem.

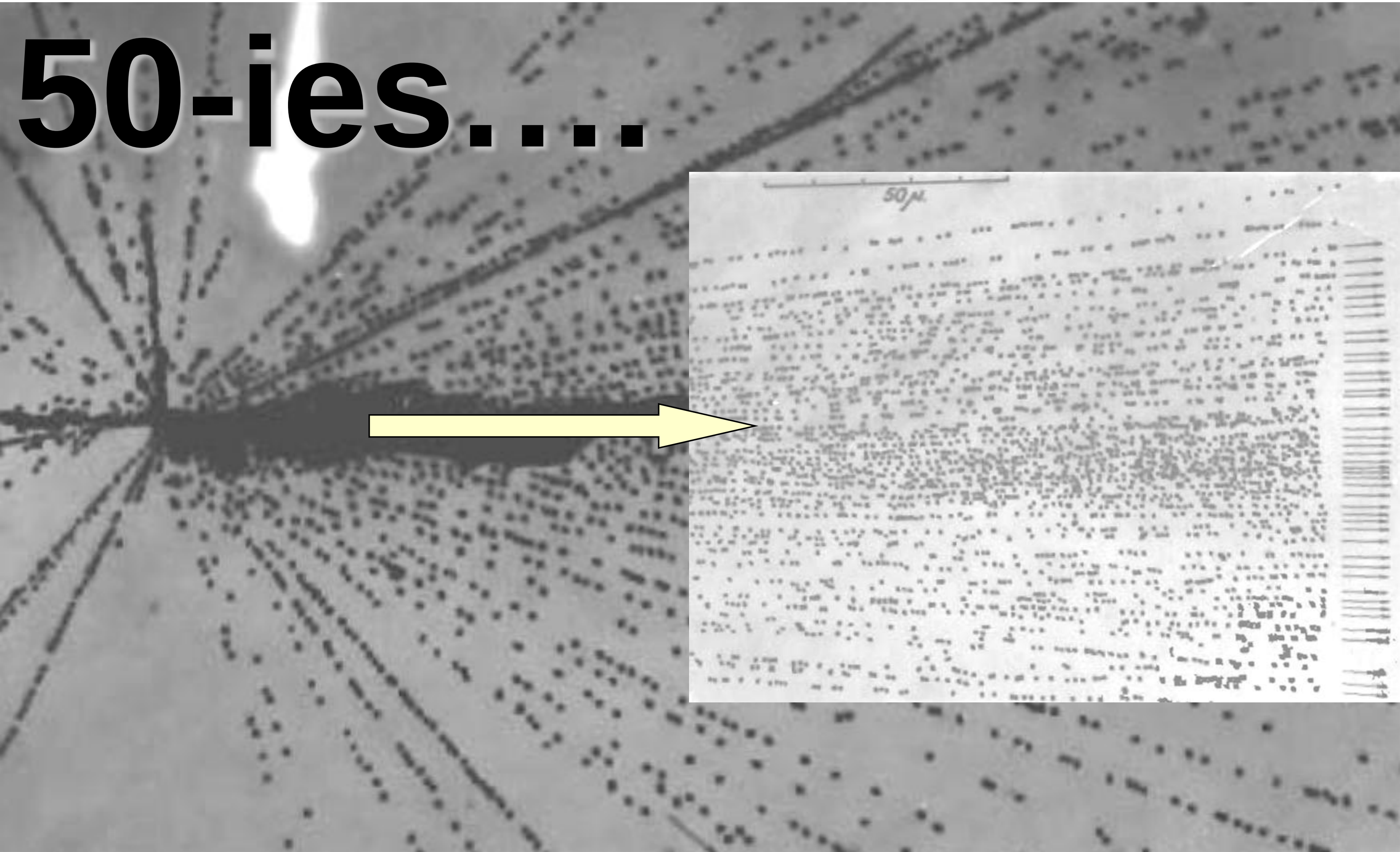
A similar analysis will be carried out in the NTE layers which were exposed relativistic nuclei ^{22}Ne and ^{28}Si at the JINR Synchrophasotron in the late 80s and used for overview analysis. Despite the past decades this experimental material has retained the necessary quality.

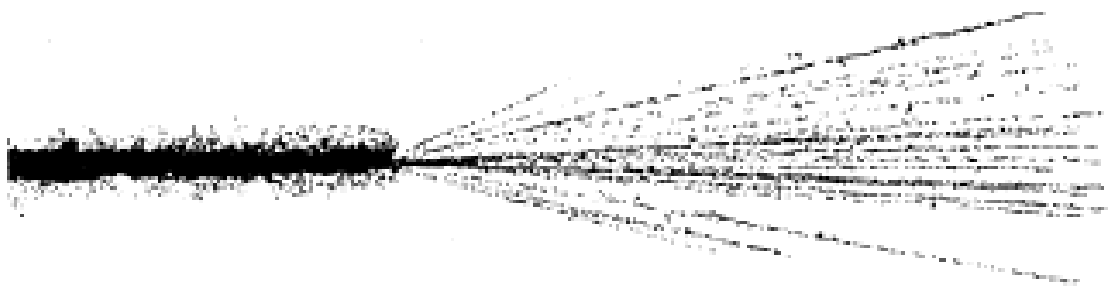
3.65 A GeV ^{28}Si along track paths 61.3 m 6252 stars

Among them 6α (12), 5α(67), 4α (170), 2 fragments (101), 14H (2)

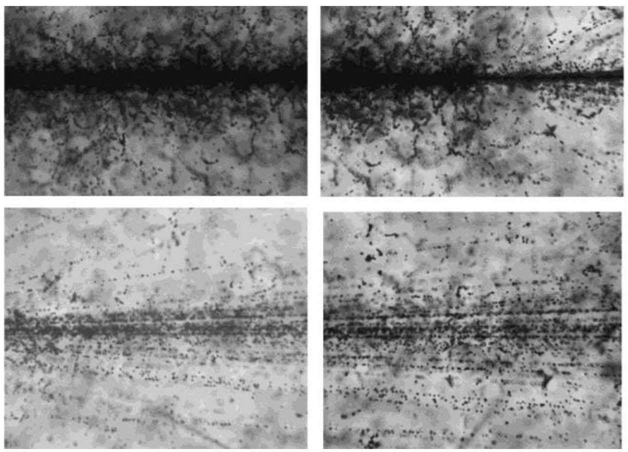
Lebedev PI (FIAN)

50-ies….

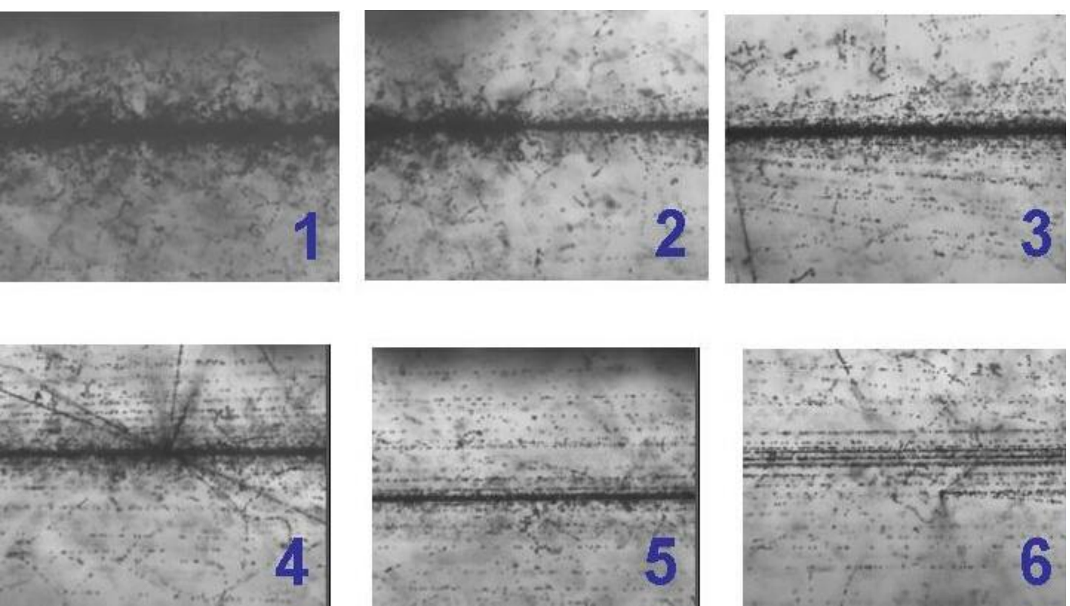




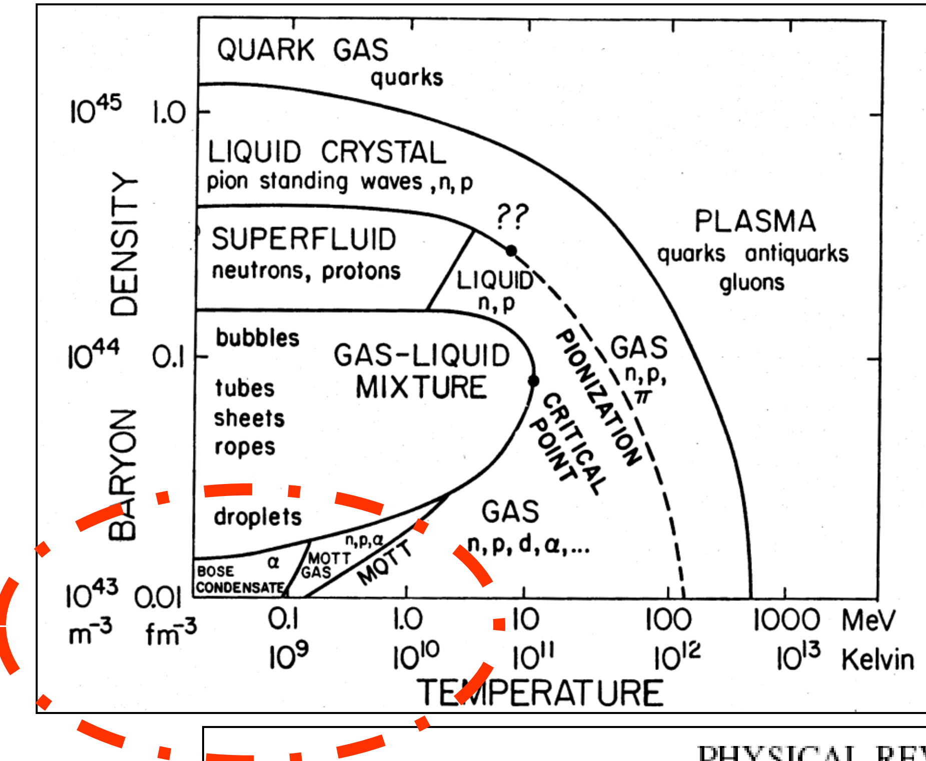
1A GeV U



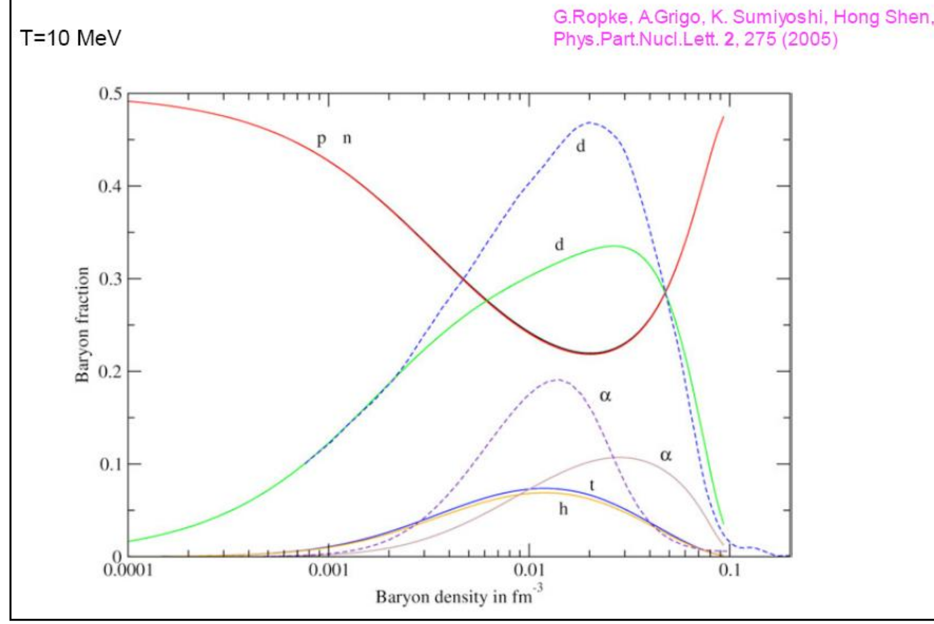
10A GeV Au



160A GeV Pb



Composition of symmetric nuclear matter



PHYSICAL REVIEW C **72**, 048801 (2005)

Multifragmentation reactions and properties of stellar matter at subnuclear densities

A. S. Botvina[1] and I. N. Mishustin[2,3]

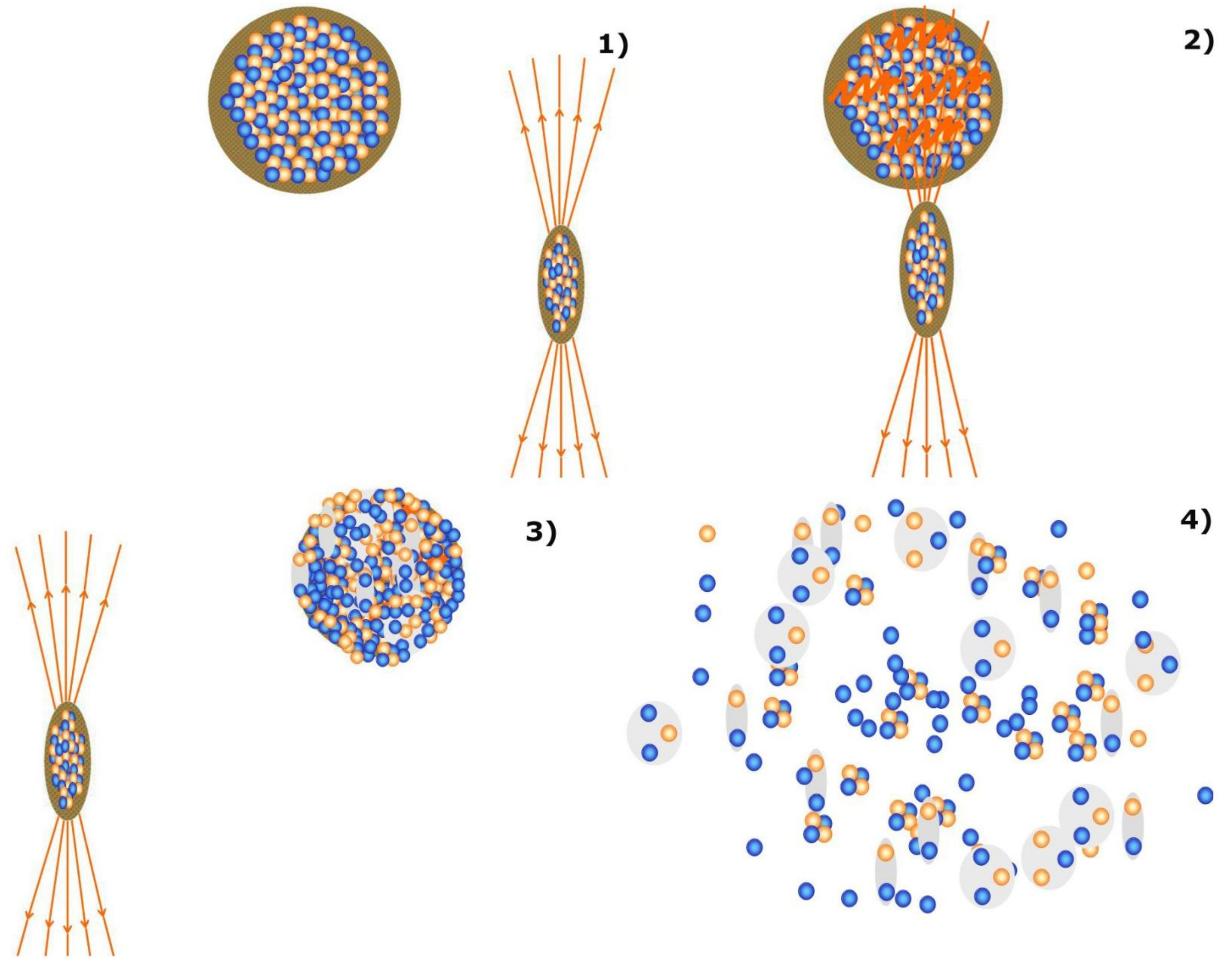
[1]*Institute for Nuclear Research, Russian Academy of Sciences, RU-117312 Moscow, Russia*

[2]*Frankfurt Institute for Advanced Studies, J.W. Goethe University, D-60438 Frankfurt am Main, Germany*

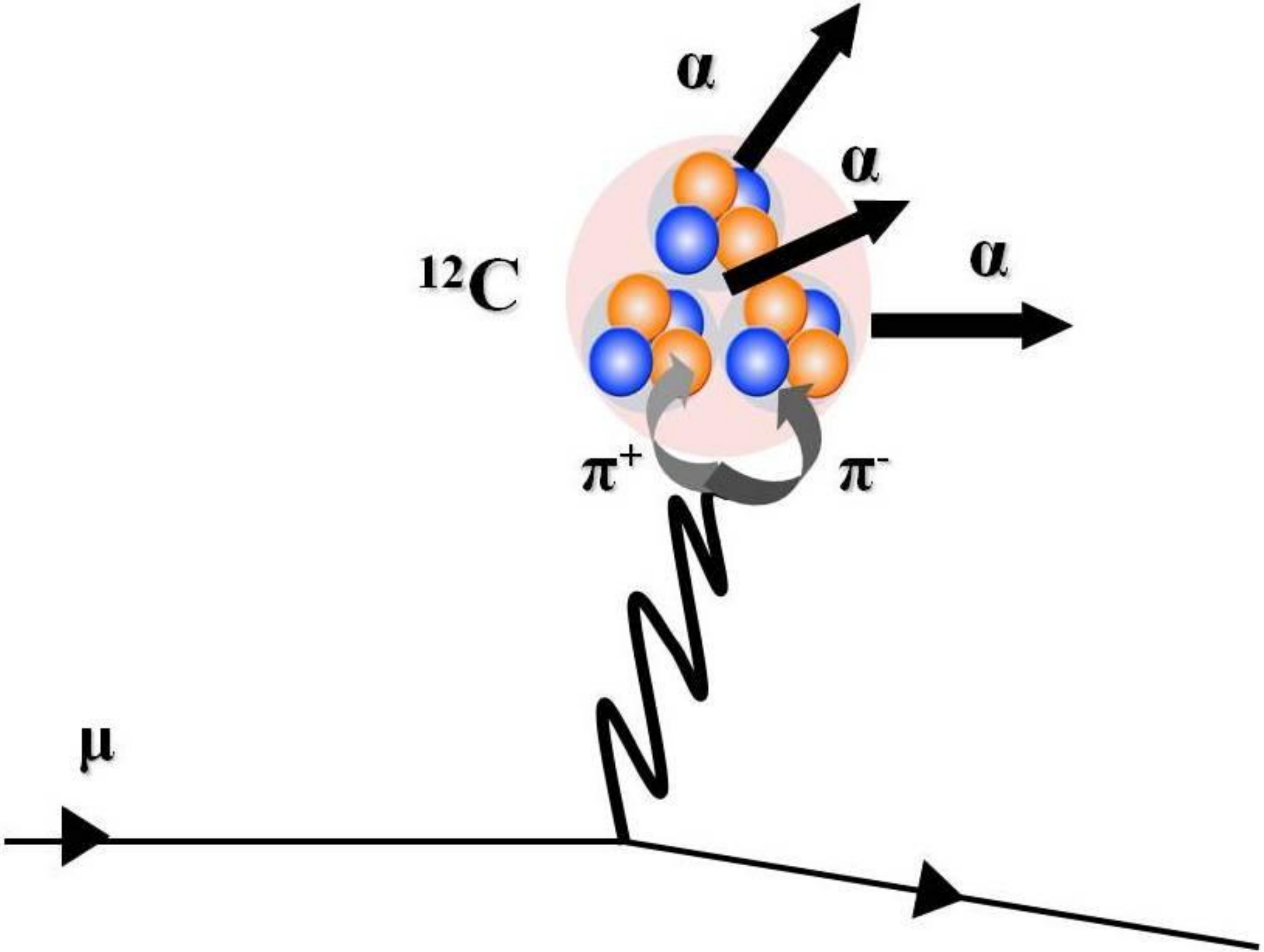
[3]*Kurchatov Institute, Russian Research Center, RU-123182 Moscow, Russia*

(Received 20 June 2005; published 24 October 2005)

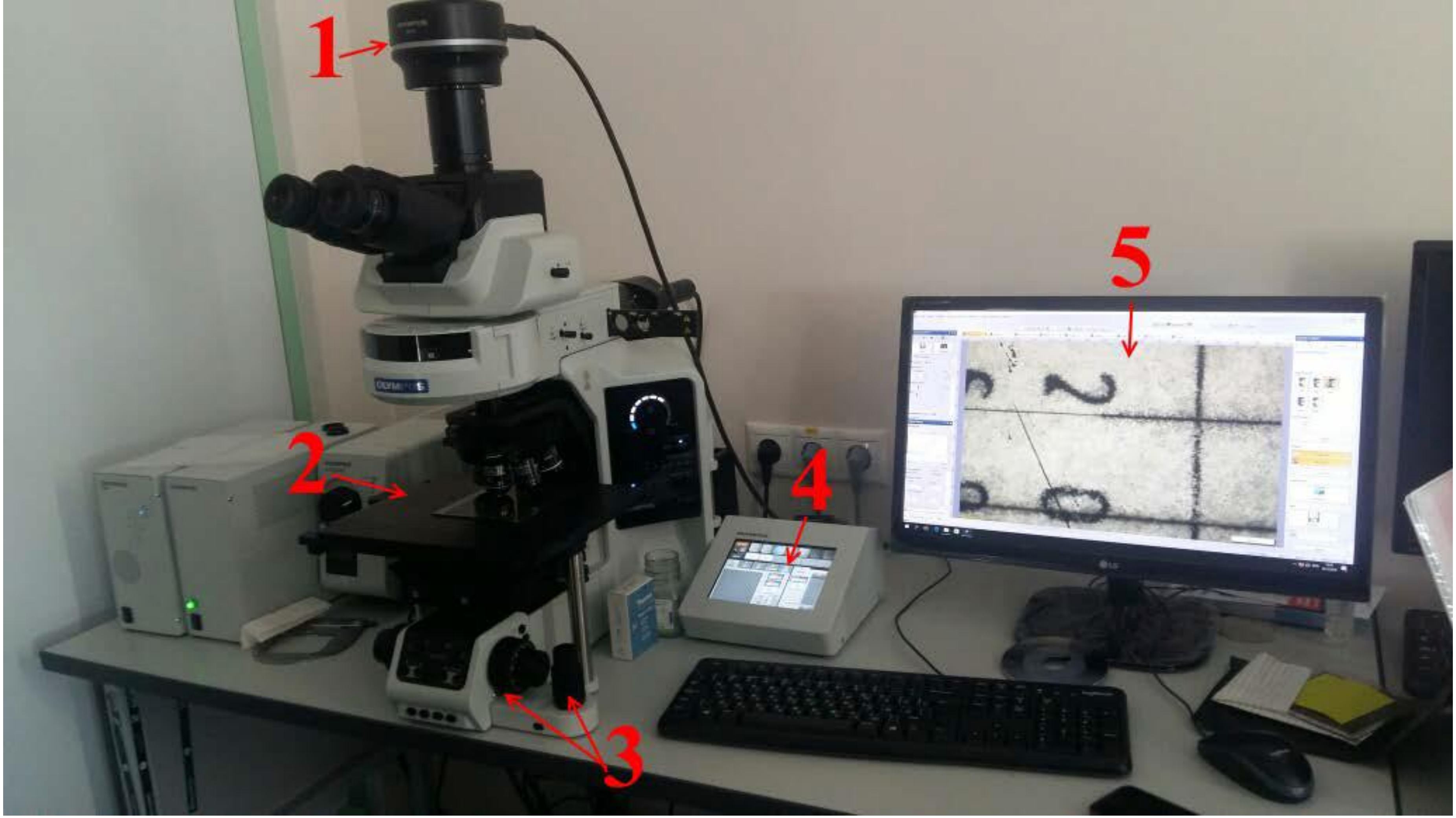
We point out the similarity of thermodynamic conditions reached in nuclear multifragmentation and in supernova explosions. We show that a statistical approach previously applied for nuclear multifragmentation reactions can also be used to describe the electroneutral stellar matter. Then properties of hot unstable nuclei extracted from the analysis of multifragmentation data can be used to determine a realistic nuclear composition of hot supernova matter.



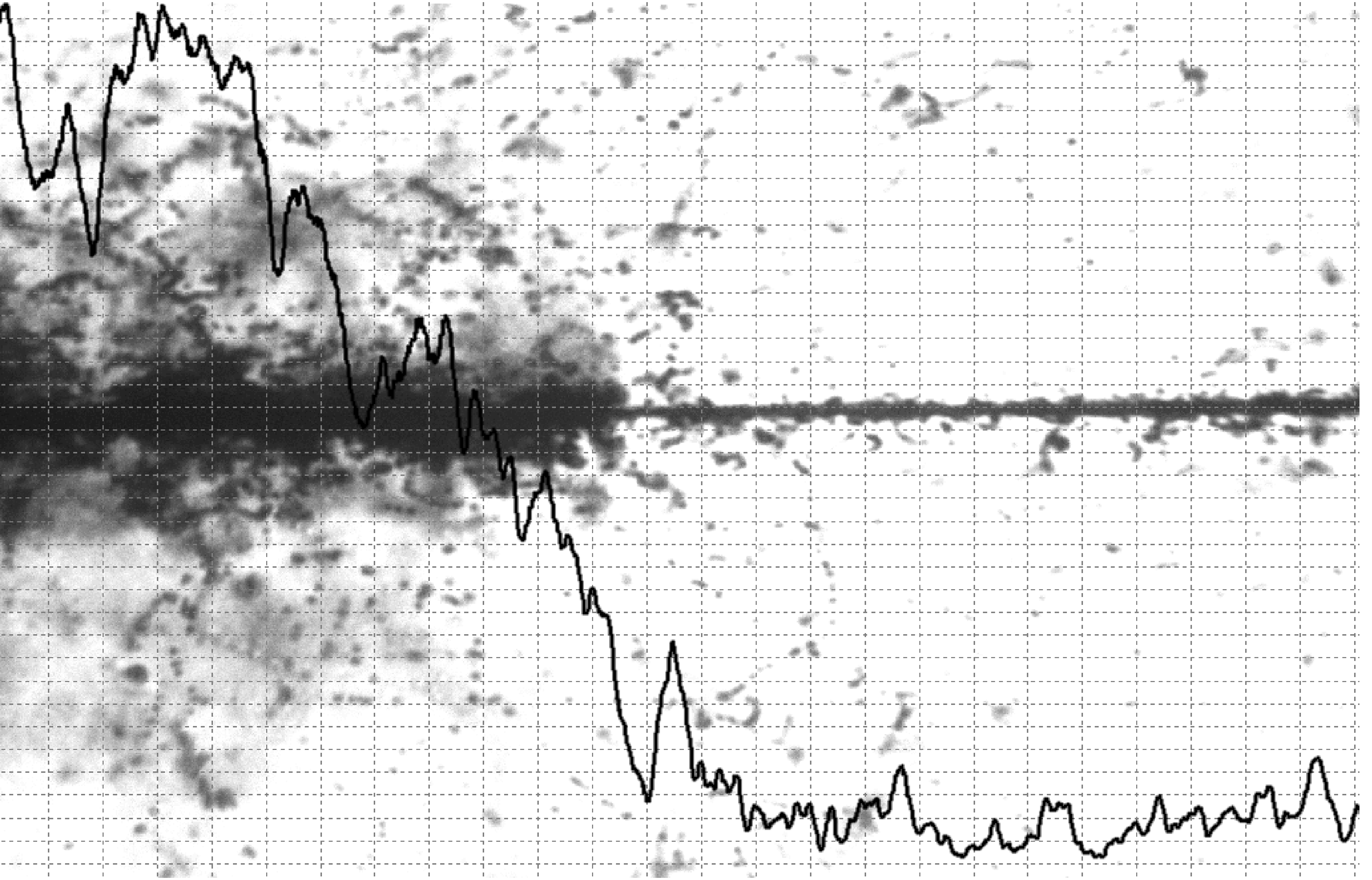
The phenomenon of peripheral dissociation of relativistic nuclei has the latent potential of a “laboratory” for testing advanced concepts of nuclear physics and nuclear astrophysics. The nuclear matter similar in thermodynamics and isotopic composition with a supernova can be re-created in dissociation of heavy nuclei.



The mechanism of dissociation of relativistic nuclei in peripheral interactions remains unclear. It is possible that there is a multiple photon exchange between the nuclei of the beam and the target. The alternative is to exchange virtual mesons. As a critical test, fragmentation of nuclei of the NTE composition under the action of relativistic muons can serve. In this case, fragmentation may occur as a result of the transition of exchange photons into pairs of virtual mesons. This combination provides long-range action at effective destruction of nuclei and can be extended to peripheral interactions of relativistic nuclei. In this regard, it is necessary to carry out a search for the fullest possible destruction of heavy nuclei of the NTE composition (Ag and Br) under the action of relativistic muons.



The stated fundamental tasks and the accumulated methodical culture deserve an update on the basis of the Olympus BX63 motorized microscope. Under the lens, a NTE layer on a glass support is placed which is irradiated longitudinally by krypton nuclei. A part of aт image of a 1 mm marking grid deposited on the NTE layer is displayed on the monitor. A horizontally oriented trace of the krypton nucleus and the fragments generated by it are visible on the screen. On the BX63 microscope, it is possible to automatically search for the vertices of peripheral dissociation by the effect of an ionization stall ("step"). Changing the lens is done by turning the revolver at the same point without operator intervention. Further measurements of the coordinates are made automatically when visually tracing the tracks of the fragments. To work on such a perfect instrument, a new generation of researchers must be trained.



The phenomenon of dissociation of relativistic nuclei observed with a unique completeness in the nuclear track emulsion (NTE) makes it possible to study ensembles of nucleons and lightest nuclei of interest to nuclear physics and nuclear astrophysics. Individual features of the nuclei under study are manifested in probabilities of dissociation channels. The advantages of the NTE technique include the unsurpassed resolution in determining emission angles of relativistic fragments and the possibility of identification of the He and H isotopes among them by multiple scattering measurements.

On this basis the cluster structure of the light stable and radioactive isotopes is examined in the BECQUEREL experiment at the JINR Nuclotron. In particular, by the invariant mass of relativistic He and H pairs and triples in the dissociation of the isotopes ^{9}Be, ^{10}B, ^{10}C and ^{11}C the unstable ^{8}Be and ^{9}B nuclei are identified, and in the ^{12}C and ^{16}O dissociation — the Hoyle state. The next problem is searching in the dissociation of the nuclei ^{14}N, ^{22}Ne and ^{28}Si the Hoyle state and more complex nuclear-molecular states.

The main perspective will be application of the NTE technique to study the low-density baryonic matter arising in the heavy nucleus dissociation. The temperature and density of this short-lived state are determined by the ratio of relativistic isotopes H and He and neutrons and their emission angles. NTE layers exposed to the NICA beams will serve as the research material allowing investigating nuclear ensembles of unprecedented multiplicity and diversity. To understand the mechanism of multiple dissociations of nuclei it is proposed to analyze fragmentation of the NTE down to their complete destruction of composing nuclei by relativistic muons. NTE irradiation by muons will be performed at CERN.

Effective solution of the assigned tasks requires investments in automated and computerized microscopes, as well as improvement of the NTE technology. The project will serve as the basis for updating the traditional cooperation on the NTE use.

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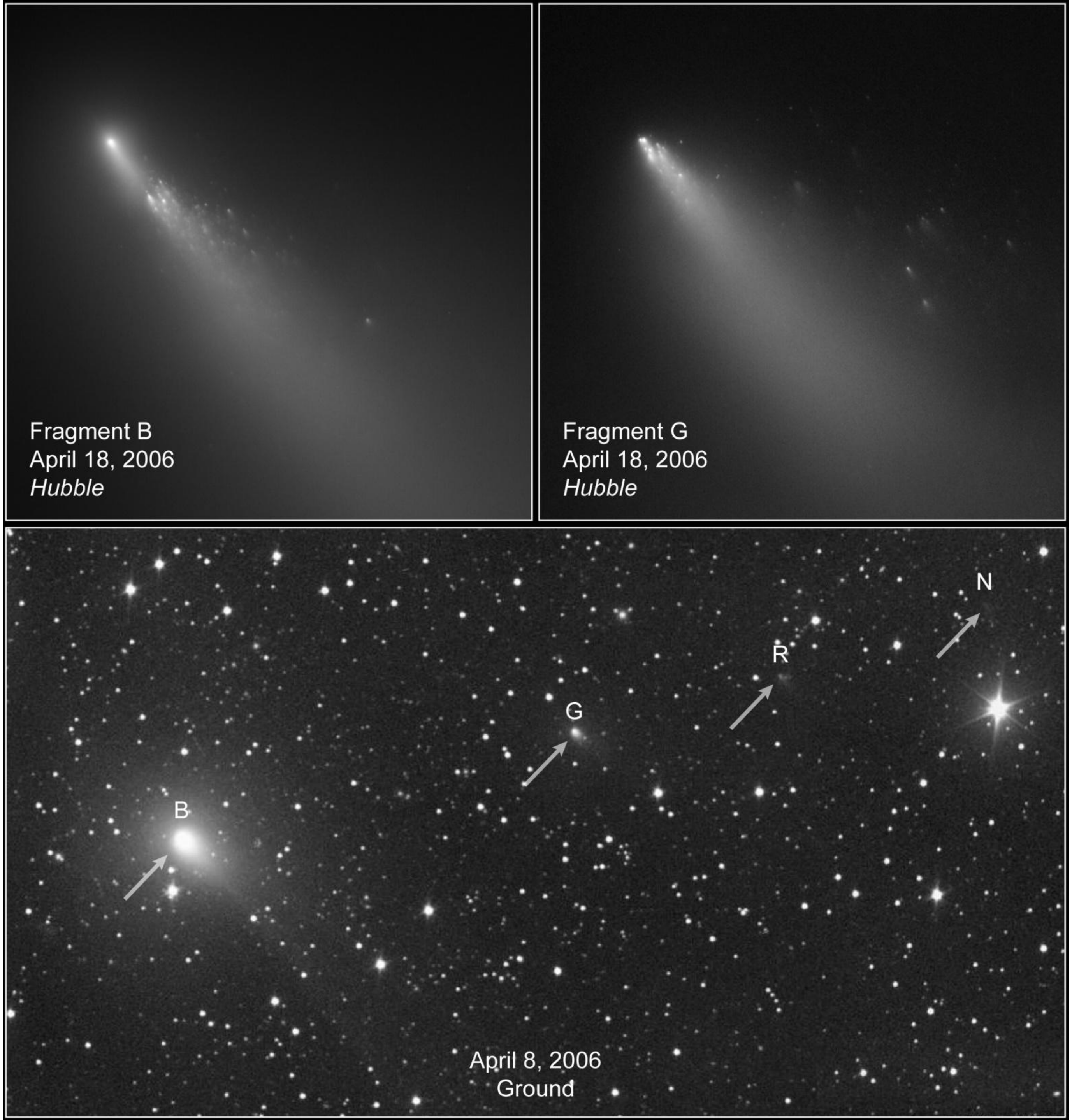
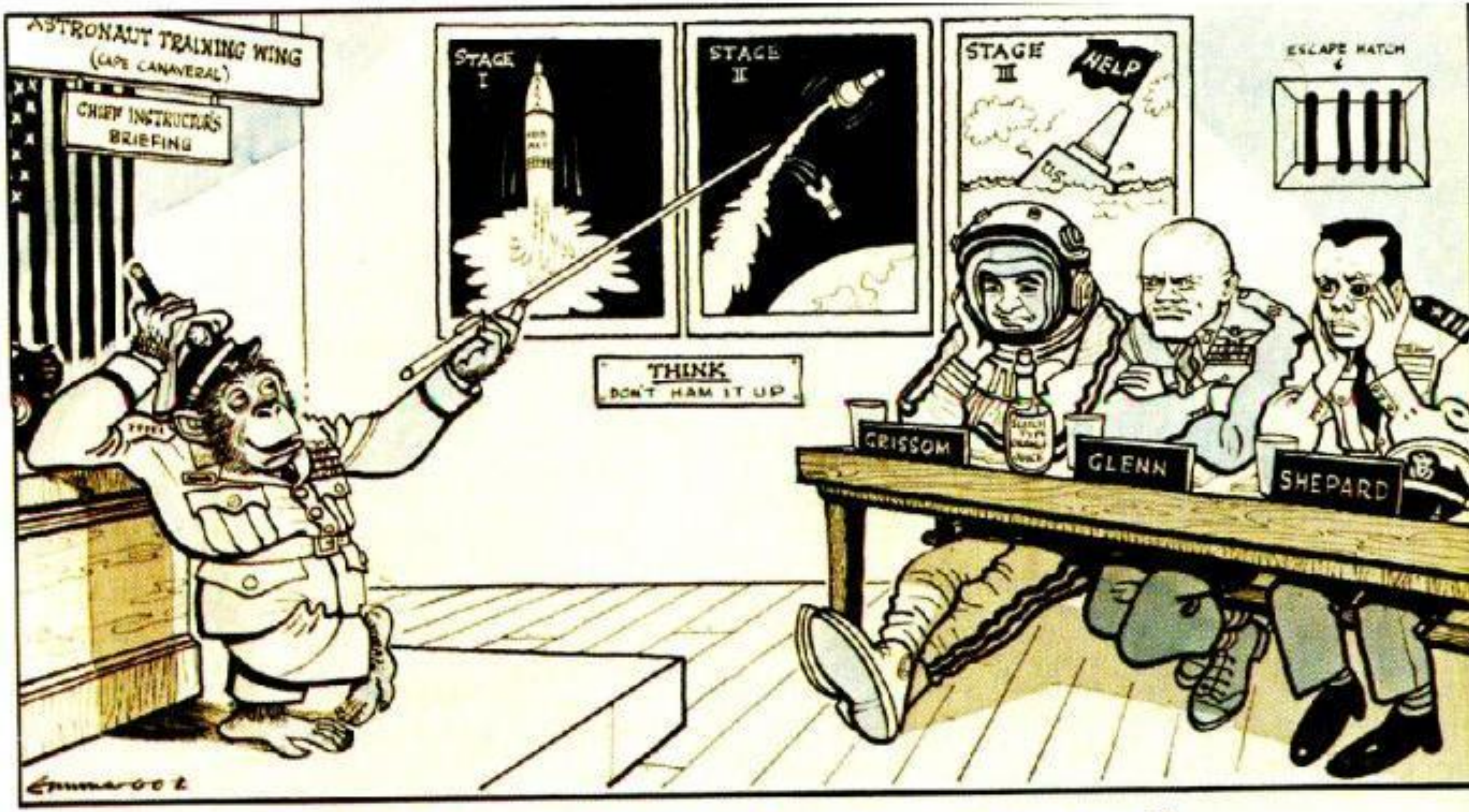

Fragment B
April 18, 2006
Hubble
Fragment G
April 18, 2006
Hubble
N
R
G
B
April 8, 2006
Ground



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