St Petersburg University

LHEP

ЛФВЭ

HOYLE STATE AND UNSTABLE NUCLEI IN DISSOCIATION OF RELATIVISTIC NUCLEI

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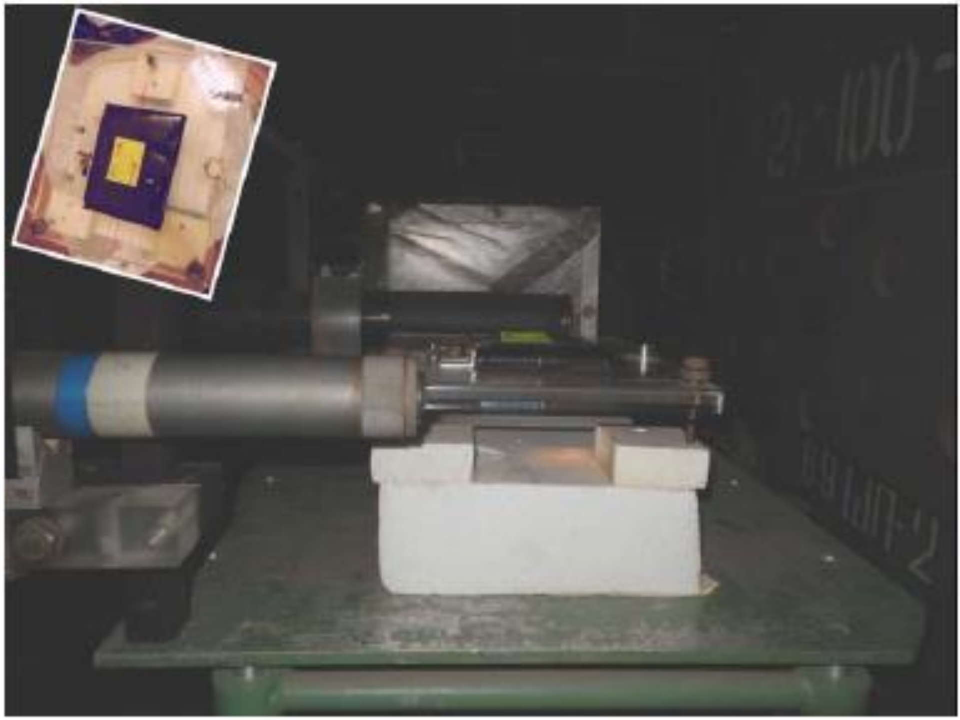
LHEP, JINR

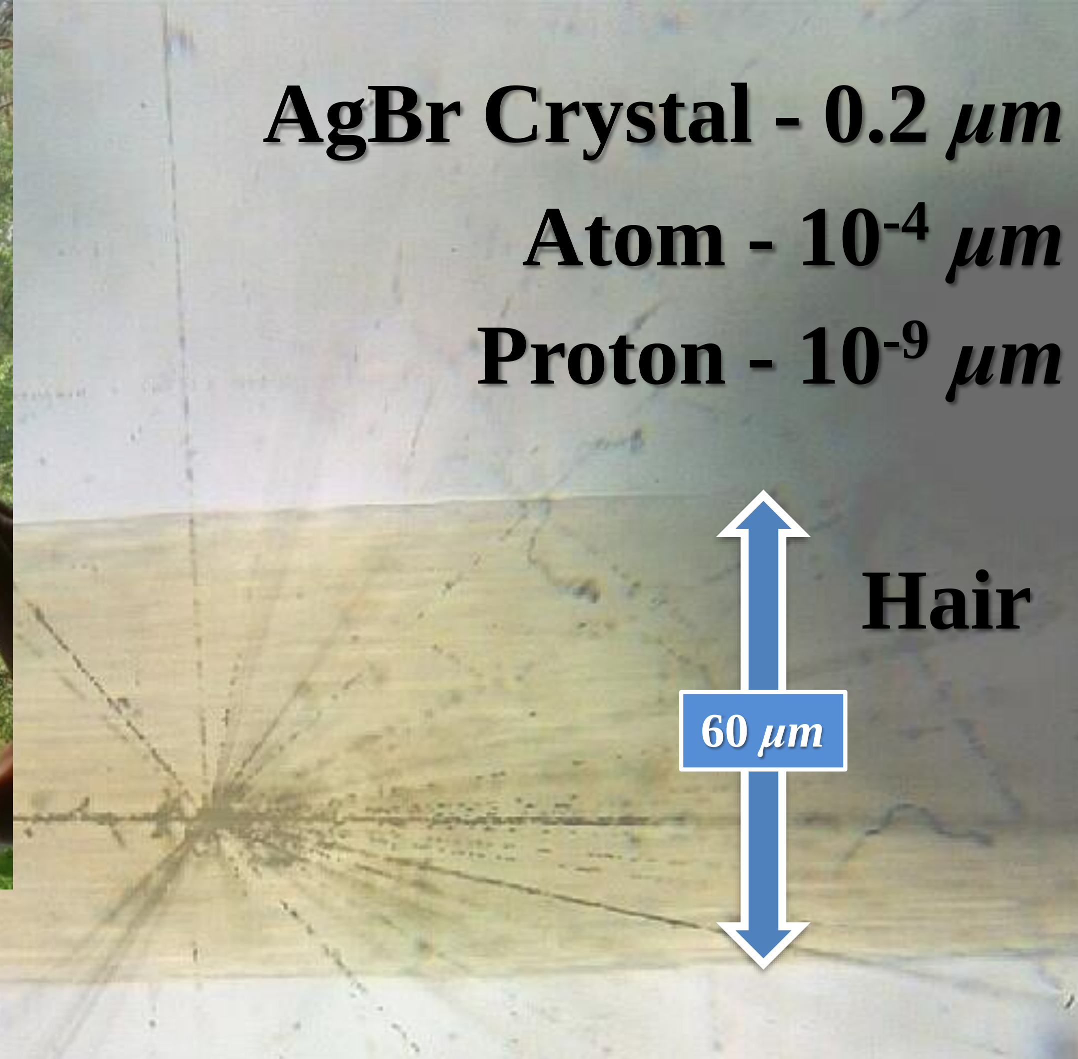
LXX International conference "NUCLEUS – 2020. Nuclear physics and elementary particle physics. Nuclear physics technologies"

Saint Petersburg, 11-17 October 2020

BECQUEREL Experiment at Nuclotron JINR

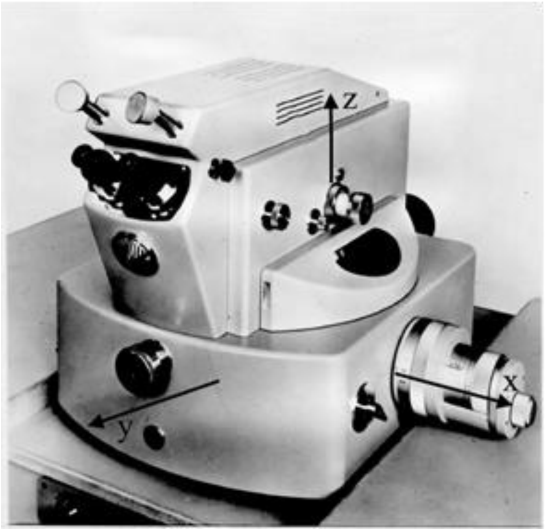


Within the framework of the project, a systematic study of the cluster structure of light nuclei is carried out. The project is based on the analysis of layers of nuclear emulsion longitudinally irradiated in primary and secondary nuclear beams with an energy of about 1 *A* GeV. The research is provided by the developing laboratory and the laboratory of viewing and measuring microscopes of the sector of thick-layer nuclear emulsion of the V. Veksler & A. M. Baldin Laboratory of High Energy Physics JINR.

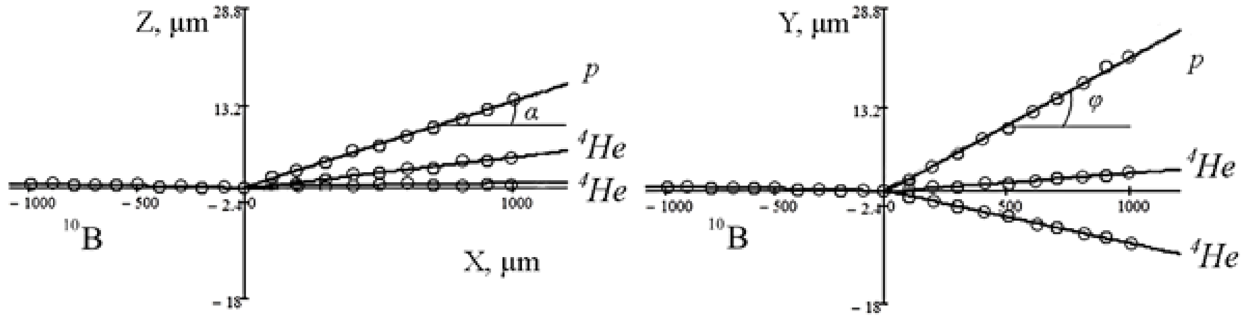


The project is based on the method of nuclear track emulsions (NTE) providing unrivaled spatial resolution (0.5 µm) and a sensitivity range for measuring tracks of charged particles, starting with highly ionizing short-range ions and up to singly-charged relativistic particles. The use of NTE in newly created beams of relativistic nuclei accelerators makes it possible to make analysis that can not to be reach by electronic detection methods. The accuracy and completeness of the measurement of the angles of emission of fragments generated in peripheral interactions of relativistic nuclei provides unique opportunities for studying the nucleon clustering of light nuclei.

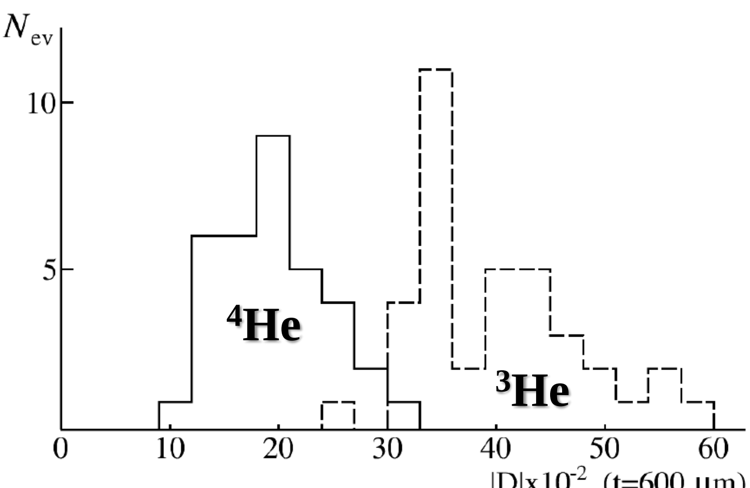
Reconstruction of emission angles of secondary fragments



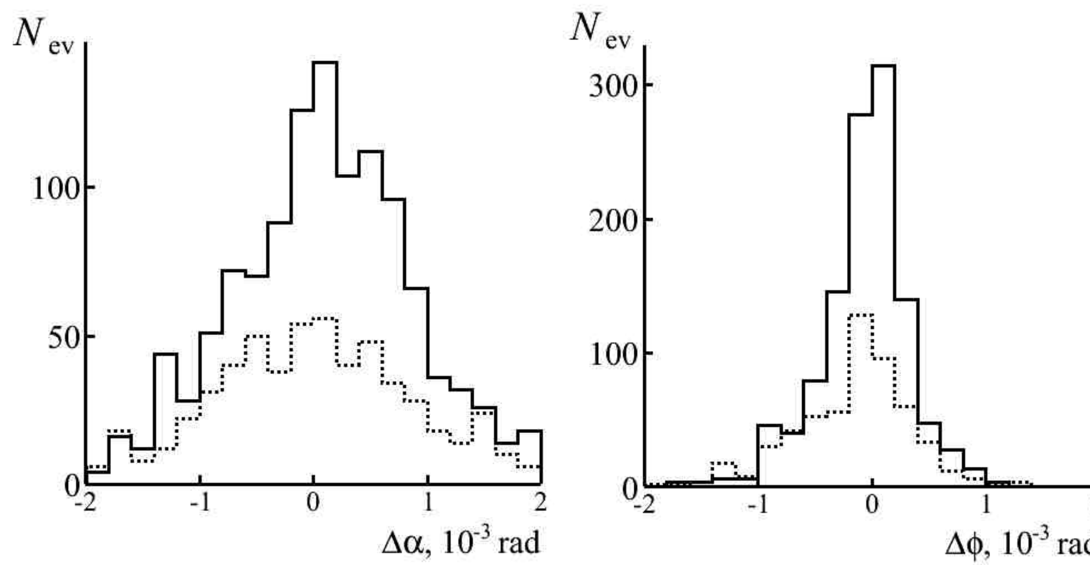
Microscope KSM-1



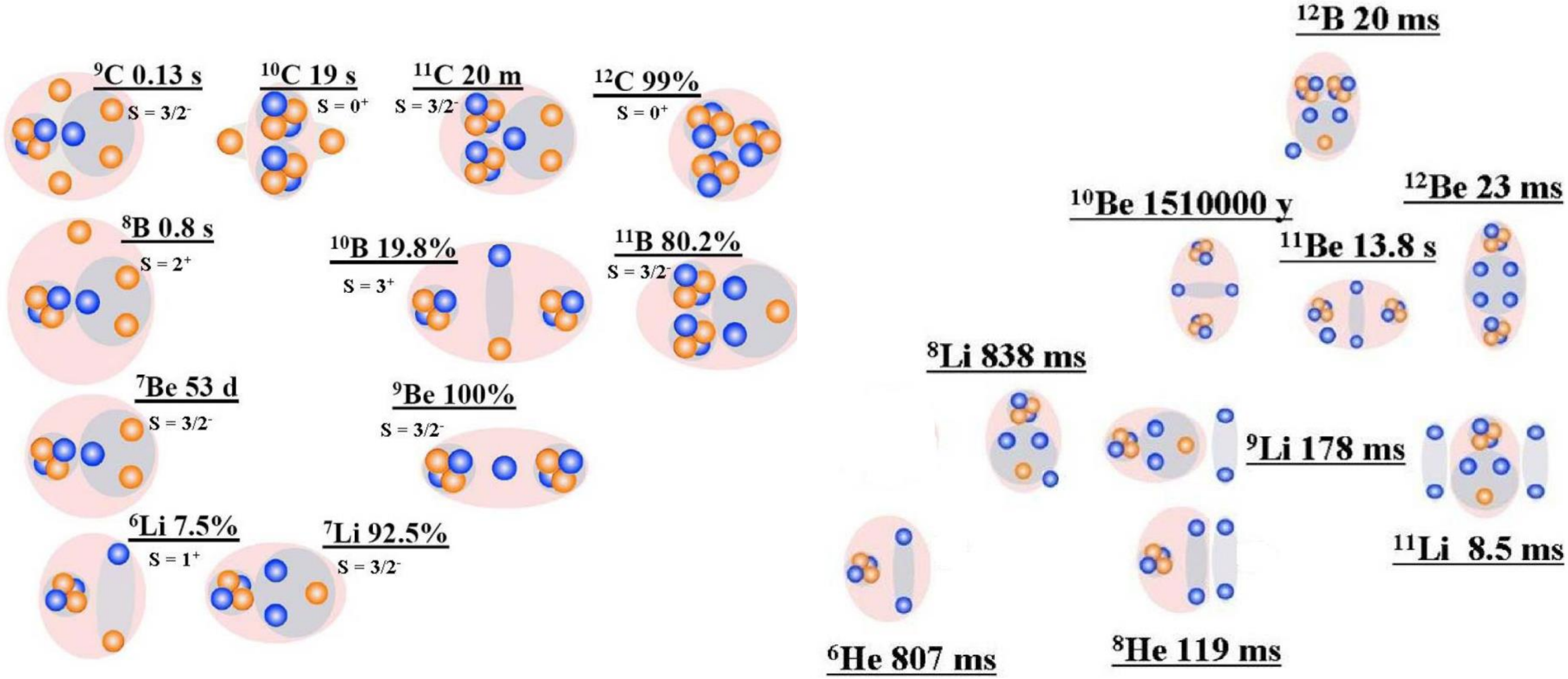
Example of the restored directions of emission of fragments in the plane of XOZ and XOY in the event №10107 by channel of $^{10}B \rightarrow 2\alpha + p$.



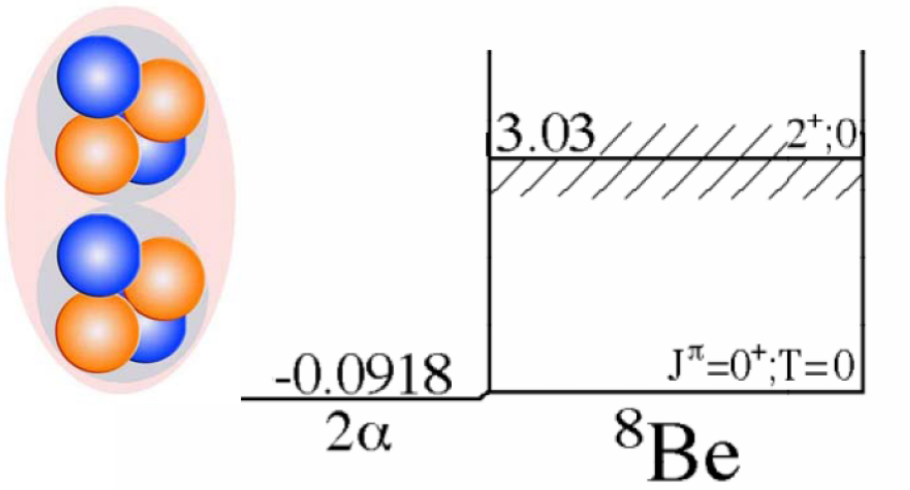
$$A_{fr} = P_{fr}\beta_{fr}c/(P_0\beta_0 c)$$



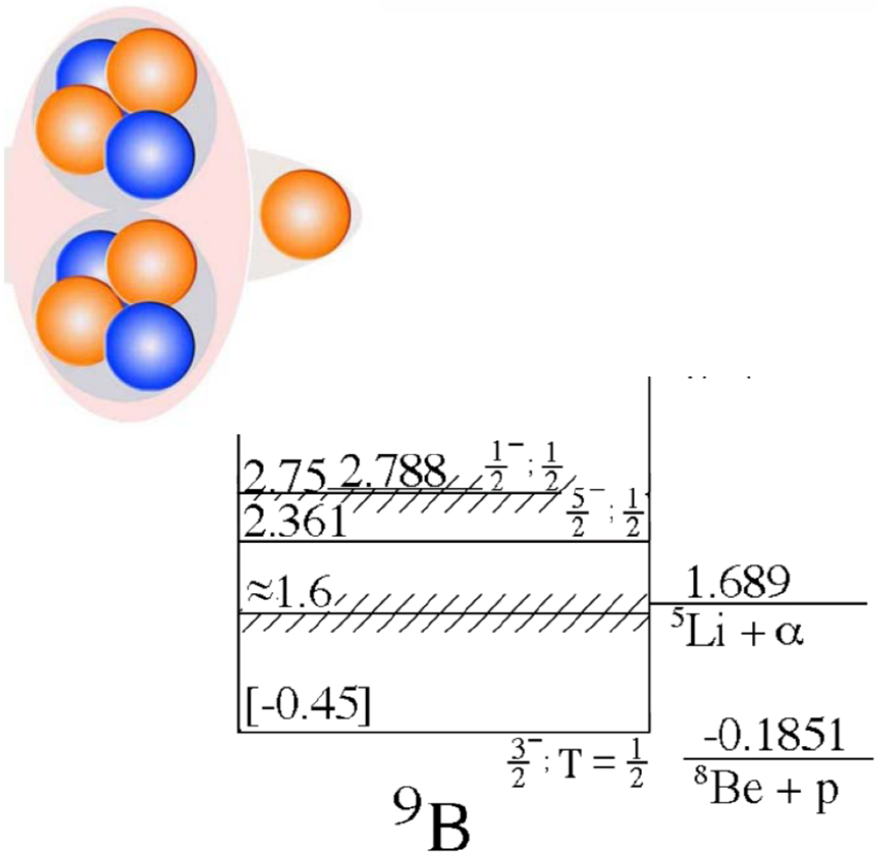
Errors in reconstruction of deep (α) и plan (φ) angles for tracks of He (solid) and H (dotted) fragments in event $^{10}B \rightarrow 2He + H$. $\langle\Delta\alpha\rangle$ = 0.08 ± 0.02 (0.78) mrad and $\langle\Delta\varphi\rangle$ = 0.06 ± 0.01 (0.39) mrad.



Earlier observations were made in NTE exposures with the nuclei ^{12}C, ^{16}O, ^{22}Ne, ^{6}Li and ^{7}Li and were carried out at the JINR Synchrotron in the 70-90s. Within the BECQUEREL Project the peripheral interactions were analyzed in NTE exposed to the following set of nuclei: ^{6}He, ^{7,9}Be, ^{8,10,11}B, ^{9,10,11}C and ^{12,14}N. These experimental results allow to present a comprehensive picture of clustering for a family of nuclei at the beginning of the isotope table.

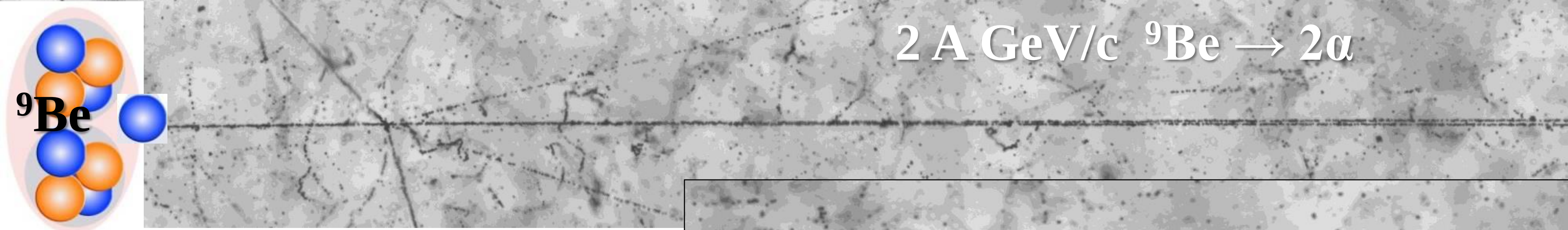


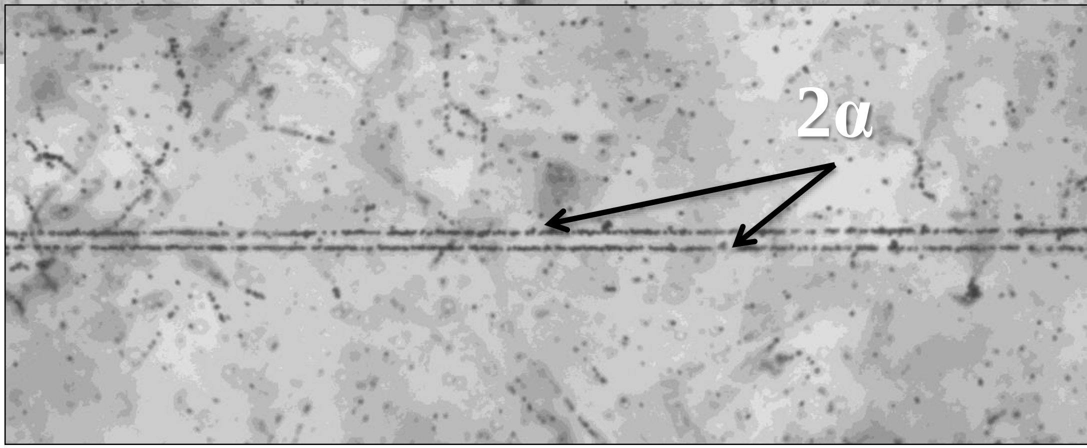
E_x (MeV ± keV)	$J^\pi;T$	Γ_{cm} (keV)	Decay
g.s.	$0^+;0$	5.57 ± 0.25 eV [i]	α
3.03 ± 10 [i]	$2^+;0$	1513 ± 15 [i]	α
[i,j]	2^+		
11.35 ± 150 [i]	$4^+;0$	≈ 3500[b]	α

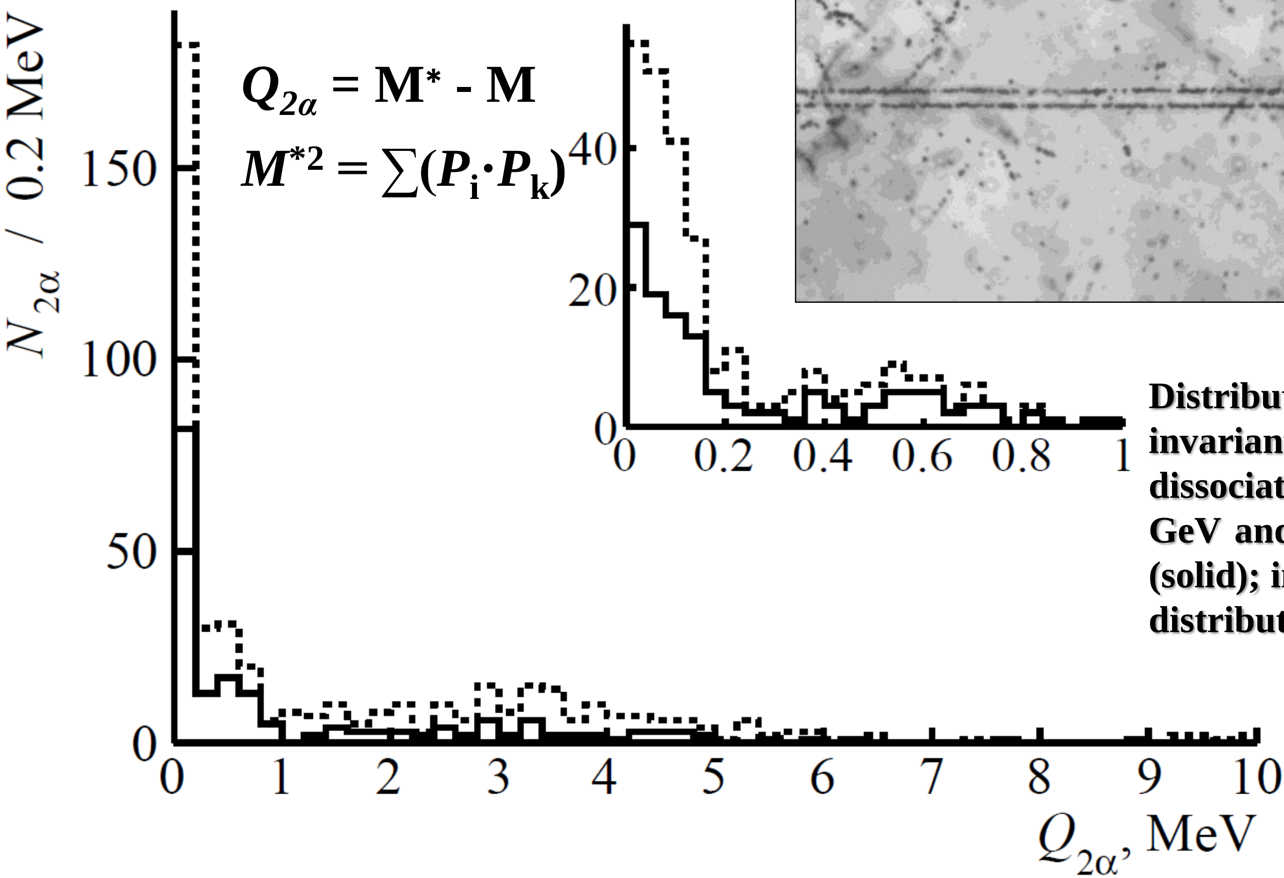


E_x [a] (MeV ± keV)	$J^\pi;T$	$\Gamma_{c.m.}$ (keV)	Decay
g.s.	$\frac{3}{2}^-;\frac{1}{2}$	0.54 ± 0.21	p
≈ 1.6 [b]			p, (α)
2.361 ± 5	$\frac{5}{2}^-;\frac{1}{2}$	81 ± 5	p, α
2.75 ± 300 [c]	$\frac{1}{2}^-;\frac{1}{2}$	3130 ± 200	p
2.788 ± 30	$\frac{5}{2}^+;\frac{1}{2}$	550 ± 40	p, α
4.3 ± 200 [d]		1600 ± 200	
6.97 ± 60	$\frac{7}{2}^-;\frac{1}{2}$	2000 ± 200	p
11.65 ± 60 [e]	$(\frac{7}{2})^-;\frac{1}{2}$	800 ± 50	p

2 A GeV/c $^{9}Be \rightarrow 2\alpha$



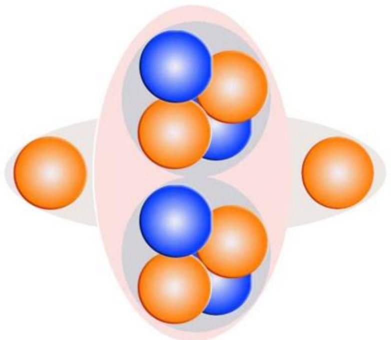


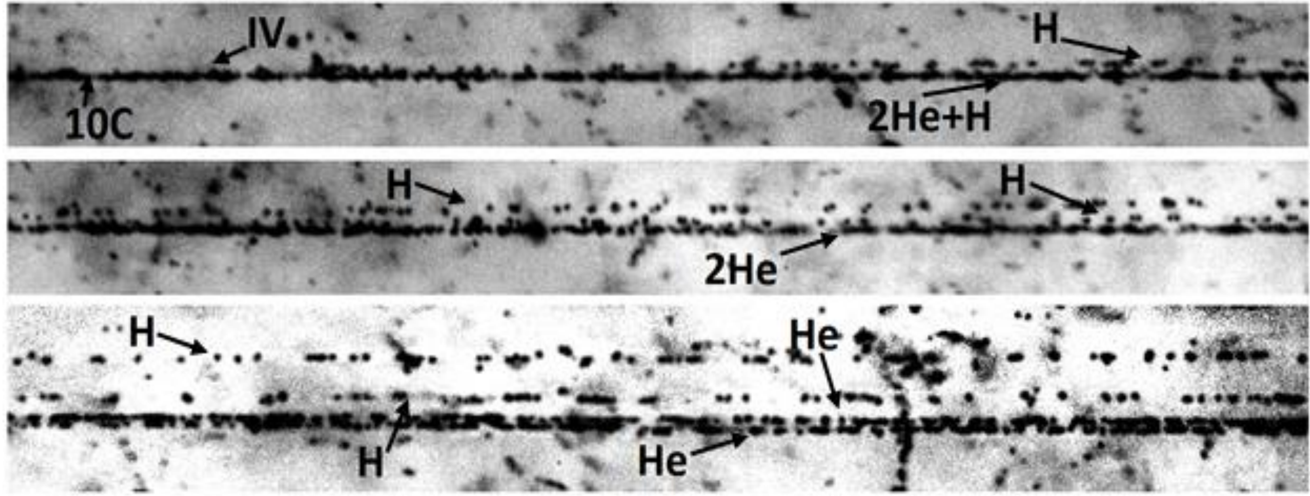


Distribution of number of 2α-pairs $N_{2\alpha}$ over invariant mass $Q_{2\alpha}$ in all 500 events of dissociation $^{9}Be \rightarrow 2\alpha$ (dotted line) at 1.2 *A* GeV and in 198 “white” stars out of them (solid); in the inset, the enlarged part of the distributions $Q_{2\alpha}$ < 1 MeV.

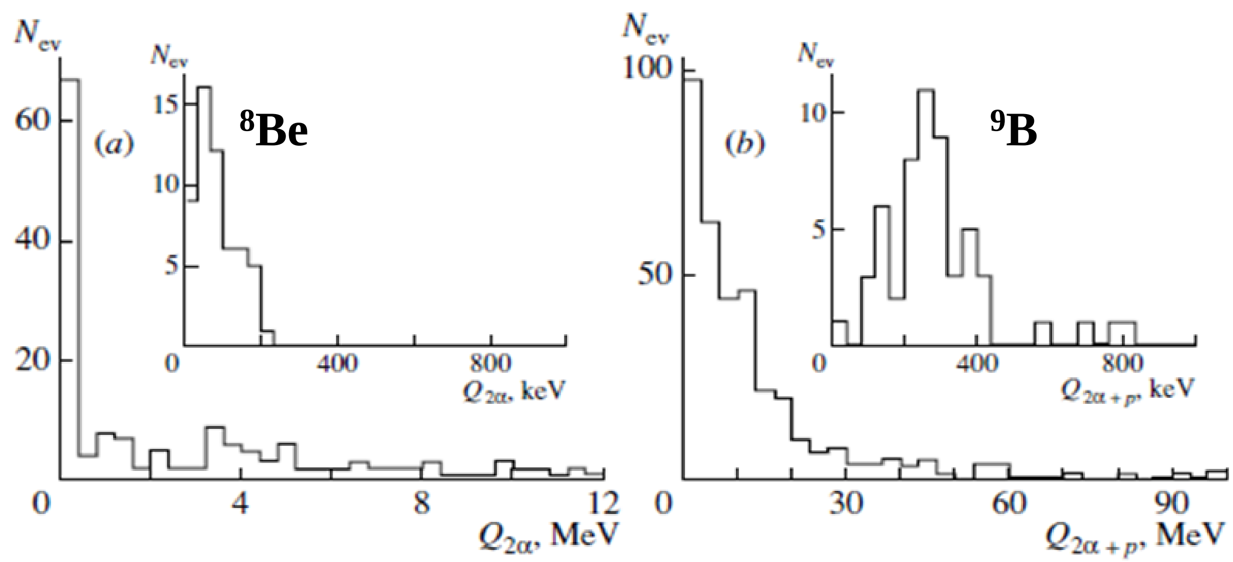
The distribution over $Q_{2\alpha}$ of 2α-pairs ($N_{2\alpha}$ = 500), including “white” 2α-stars (N_{ws} = 198), indicates the condition $Q_{2\alpha}(^{8}Be)$ < 0.2 MeV. Then the fraction of decays ^{8}Be 36 ± 3 and 41 ± 5%, respectively. Two “influxes” deserve to be noted around 0.6 and 3 MeV. The 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 $^{8}Be_{2+}$.

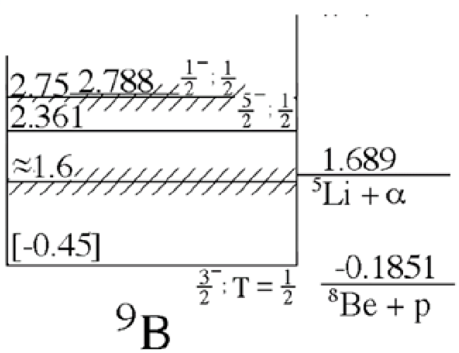
^{10}C



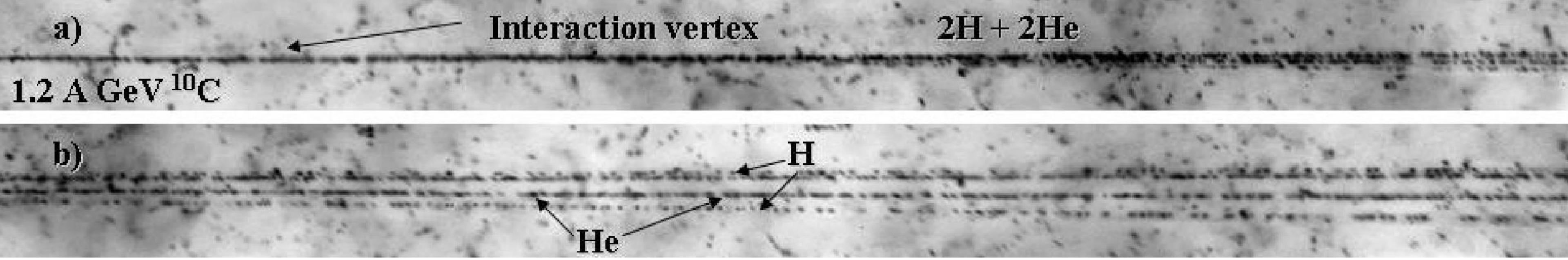


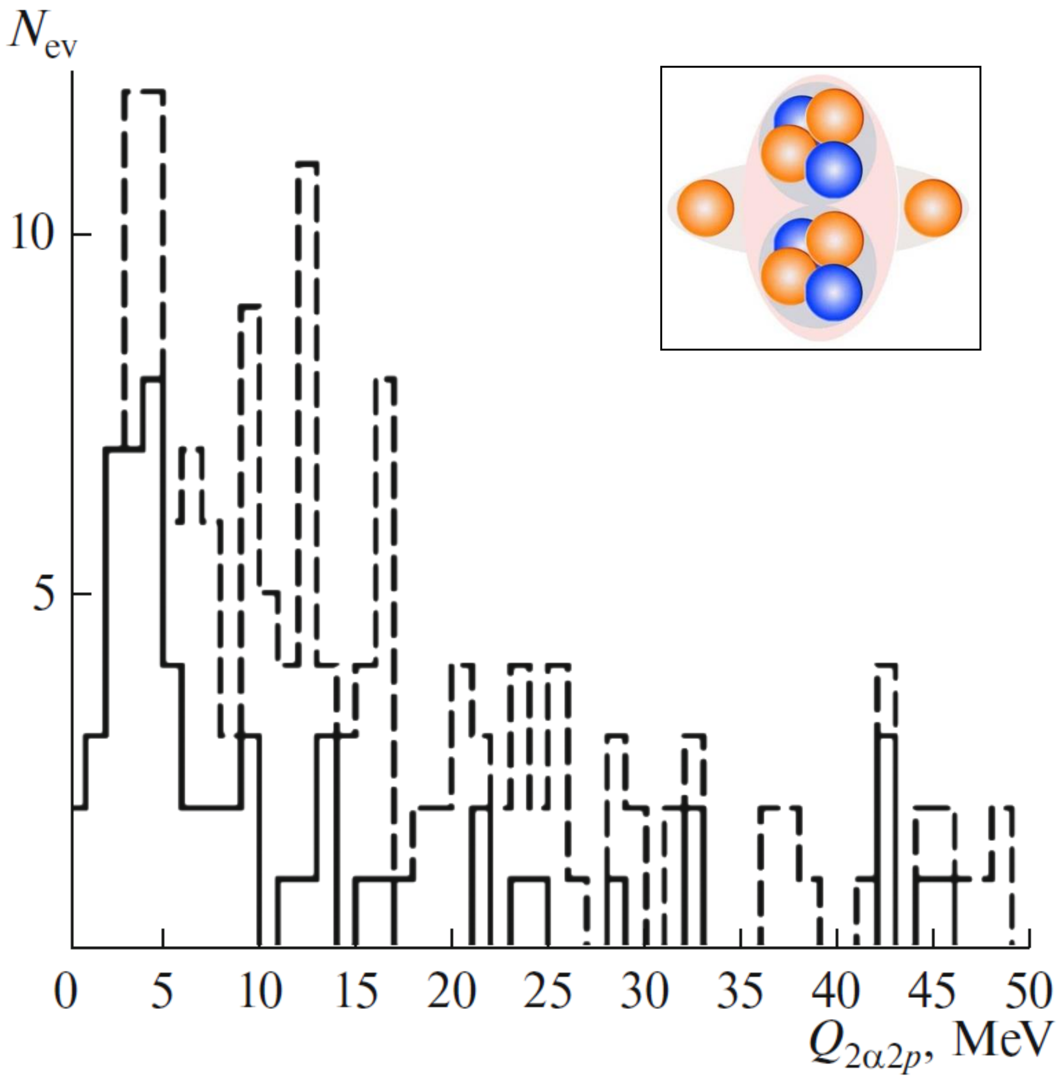
Channel	Ratio
2He + 2H	82%
He + 4H	5%
6H	4%
3He	3%
Li + 3H	3%
Be + He	1%



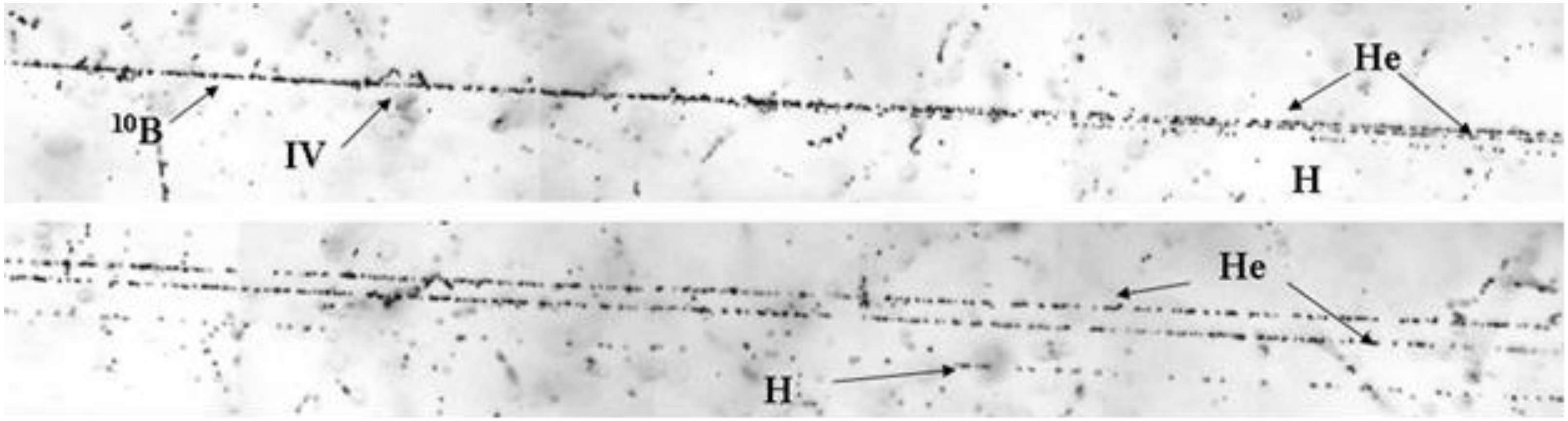


A clear correlation between $Q_{2\alpha}$ and $Q_{2\alpha p}$ points to the cascade process $^{10}C \rightarrow {}^{9}B \rightarrow {}^{8}Be$. The contribution of these decays allows concluding that the ^{9}B nucleus manifests itself with a probability of (30 ± 4)% in the ^{10}C structure.

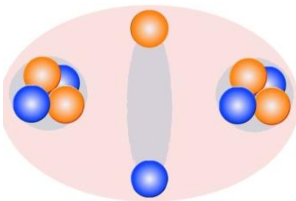




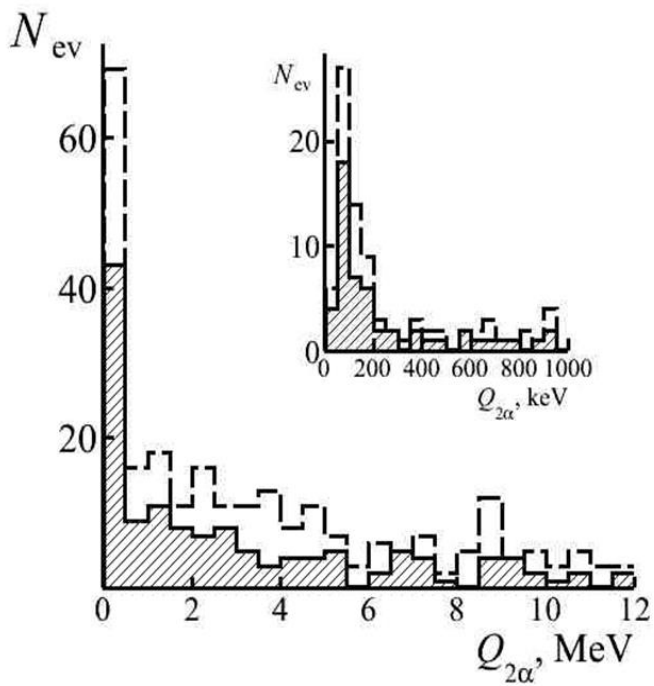
Distributions over energy $Q_{2\alpha 2p}$ of all "white" stars $^{10}C \rightarrow 2He + 2H$ (dashed) and the ones with the presence of ^{9}B (solid). The distribution $Q_{2\alpha 2p}$ for the ^{10}C stars containing ^{9}B decays features the distinct peak with a maximum at 4.1 ± 0.3 MeV at RMS of 2.0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

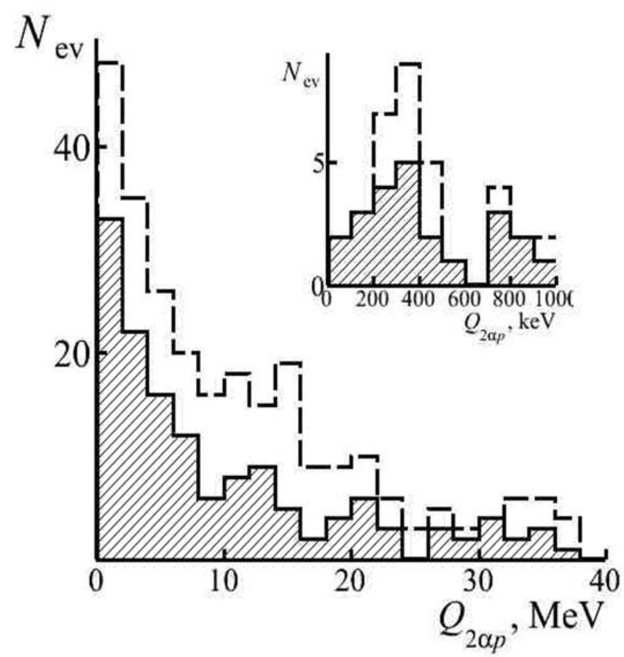


^{10}B



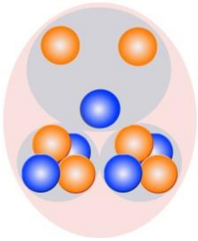
Channel	Ratio
2He + H	77%
He + 3H	13%
Li + He	4%
Li + 2H	4%
Be + H	1%
5H	1%



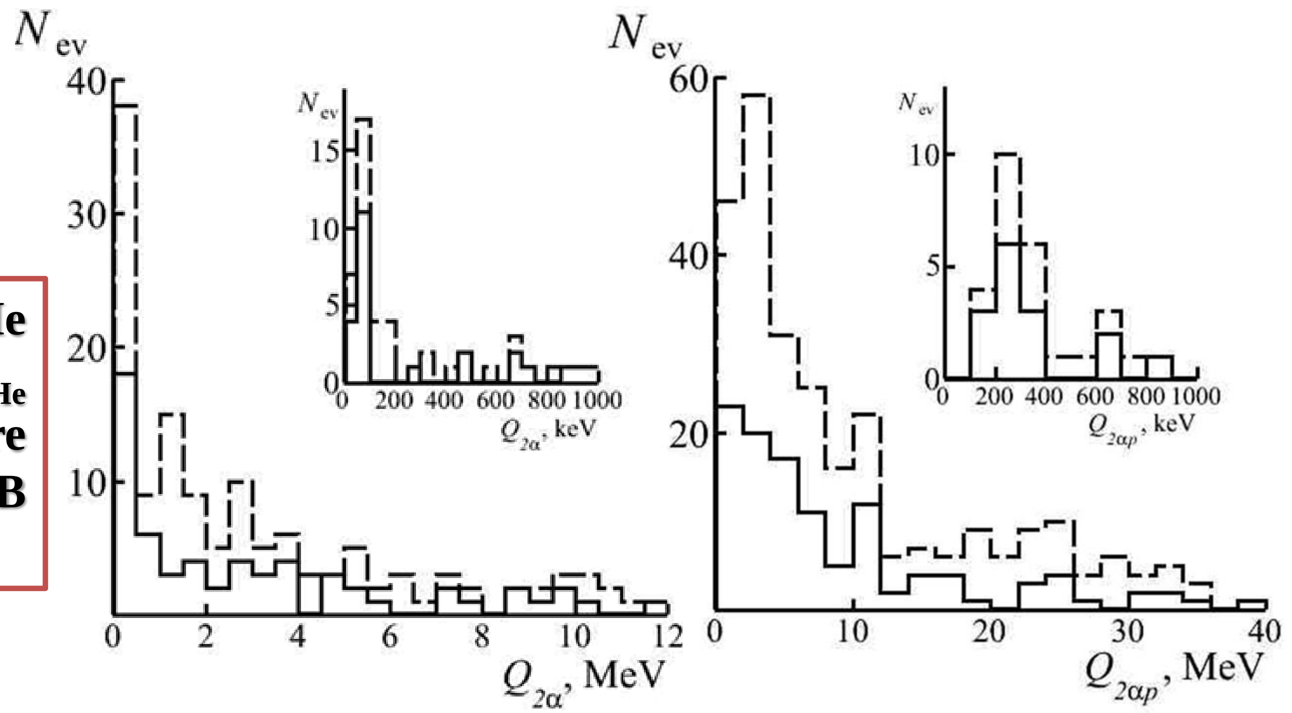


The $^{8}Be_{g.s.}$ nucleus is manifested in the coherent dissociation $^{10}B \rightarrow 2He + H$ with a probability of 25% including 13% of ^{9}B decays.

^{11}C



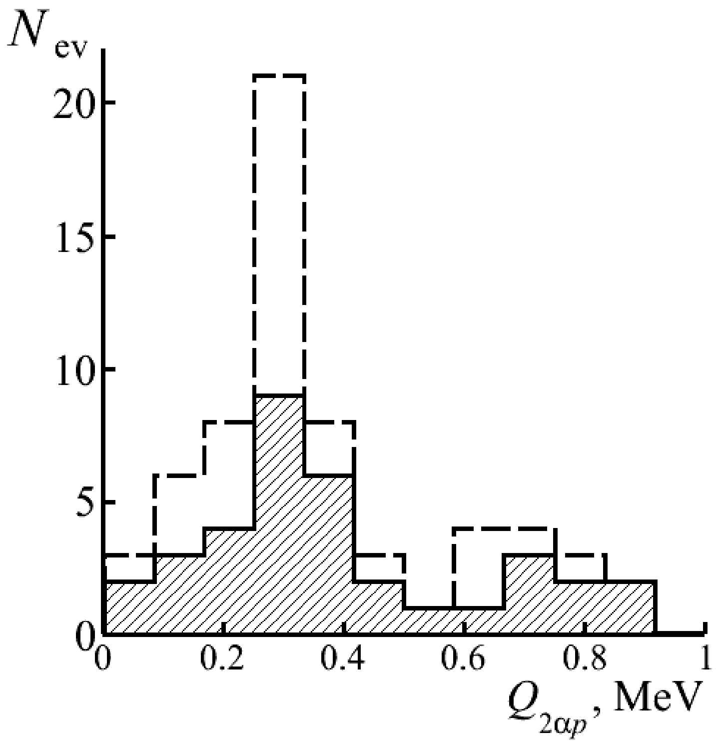
The distributions of He fragments over the Q_{2He} show that $^{8}Be_{g.s.}$ decays are presented in 20% and ^{9}B with 13% in 2He + 2H .



Channel	^{11}C [12]	^{10}C [9]	^{9}C [5]
B + H	6 (4 %)	1 (0.4 %)	15 (14 %)
Be + He	17 (12 %)	6 (2.6 %)	-
Be + 2H	-	-	16 (15 %)
3He	26 (18 %)	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 + 3He	-	1 (0.4 %)	2 (2 %)

Table. Distribution of white stars produced by carbon isotopes (of energy 1.2 GeV per nucleon) among charge channels of the dissociation of nuclei.

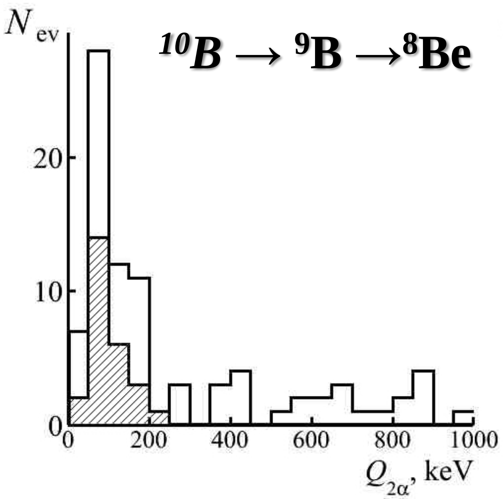
Reconstruction of ^{9}B nucleus

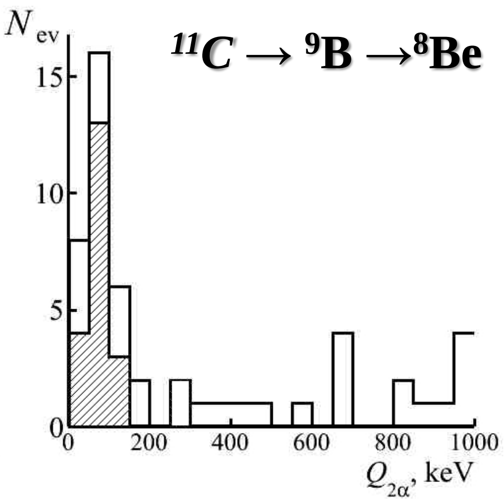


The distribution over the invariant mass of $2\alpha + p$ triples in the events of the dissociation of ^{10}B nuclei (shaded histogram) and added for ^{11}C (dotted line).

The combined data on the average value of $Q_{2\alpha p}$ in observed events with narrow triples $2\alpha p$.

Nucleus (P_0, A GeV/c)	$\langle \Theta_{2\alpha p} \rangle$ ($\Theta_{2\alpha}$ < 10.5 mrad), RMS	$\langle Q_{2\alpha p} \rangle$ ($Q_{2\alpha p}$ < 400 keV), RMS
^{10}B (1.6)	11.8 ± 1.1, 2.5 mrad	227 ± 24, 96 keV
^{10}C (2.0)	9.5 ± 0.3, 5.0 mrad	254 ± 18, 96 keV
^{11}C (2.0)	11.3 ± 0.1, 4.8 mrad	256 ± 15, 68 keV





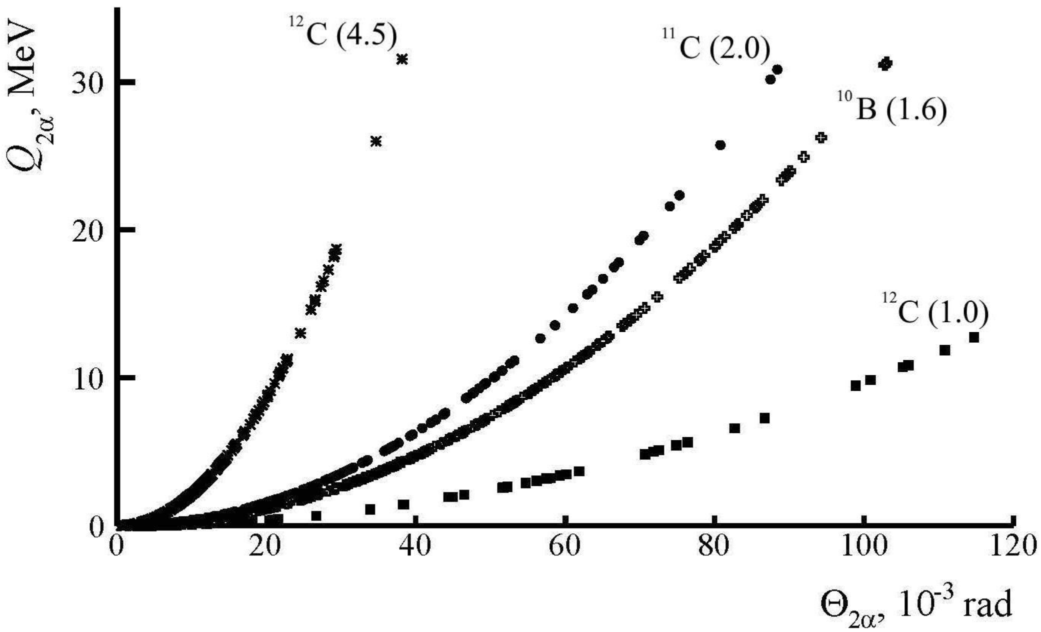
In the fragmentation of ^{10}B nuclei only 50% $^{8}Be_{gs}$ decays arise from ^{9}B decays, and for ^{11}C – 66%. In the case of the ^{10}C nucleus – 100%.

Unstable ^{8}Be nucleus in dissociation of light relativistic nuclei

Average value $\langle\Theta_{2\alpha}\rangle$ ($Q_{2\alpha}$ < 300 кэВ) и $\langle Q_{2\alpha}\rangle$

Nucleus (P_0, A GeV/c)	$\langle\Theta_{2\alpha}\rangle$ (RMS), mrad ($Q_{2\alpha}$ < 300 keV)	$\langle Q_{2\alpha}\rangle$ (RMS), keV
^{12}C (4.5)	2.1 ± 0.1 (0.8)	109 ± 11 (83)
^{16}O (4.5)	1.8 ± 0.3 (0.6)	81 ± 2 (50)
^{22}Ne (4.1)	1.9 ± 0.1 (0.8)	82 ± 5 (52)
^{14}N (2.9)	2.9 ± 0.2 (1.9)	120 ± 10 (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)	4.8 ± 0.3 (1.9) 5.3 ± 0.5 (1.5)	77 ± 7 (40) 68 ± 17 (42)
^{11}C (2.0) → ^{9}B → ^{8}Be	4.5 ± 0.3 (1.3)	94 ± 15 (86)
^{10}B (1.6)	5.9 ± 0.2 (1.6)	101 ± 6 (46)
^{10}B (1.6) → ^{9}B → ^{8}Be	5.6 ± 0.3 (1.3)	105 ± 9 (47)
^{12}C (1.0)	10.4 ± 0.5 (3.9)	107 ± 10 (79)

$$Q_{2\alpha} = \sqrt{2\cdot[m_\alpha^2 + E_\alpha^2 - \vec{P}_{\alpha1}\cdot\vec{P}_{\alpha2}]} - 2\cdot m_\alpha$$



The dependence of the calculated invariant masses of α-pairs $Q_{2\alpha}$ on the angles of expansion of $\Theta_{2\alpha}$ into them in the events of dissociation *^{12}C*, *^{11}C* и *^{10}B*; nuclei; impulse values are indicated in brackets (*A* GeV/*c*).

ON NUCLEAR REACTIONS OCCURRING IN VERY HOT STARS. I. THE SYNTHESIS OF ELEMENTS FROM CARBON TO NICKEL

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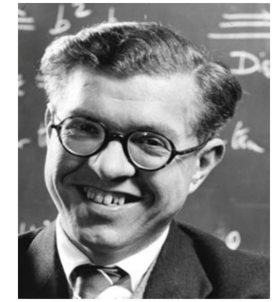
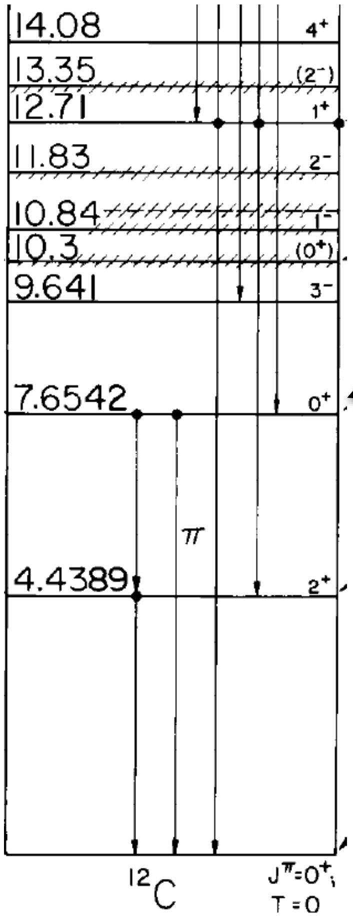
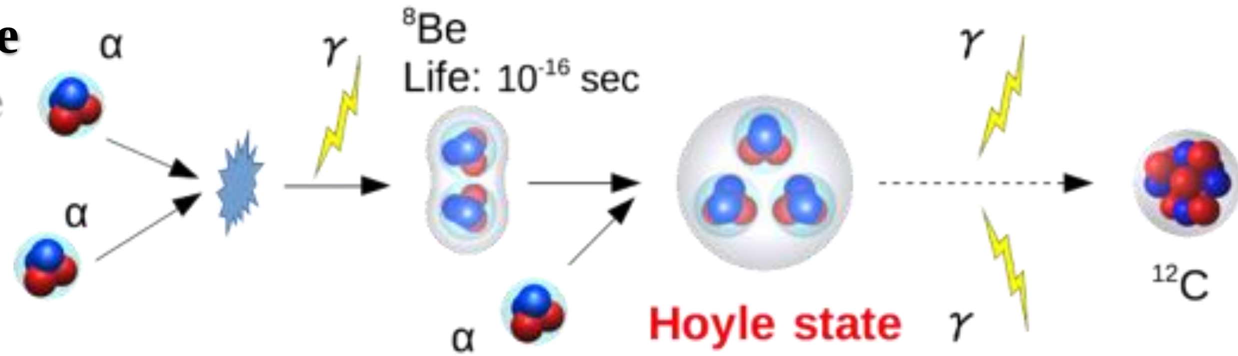
Received December 22, 1953





Hoyle State

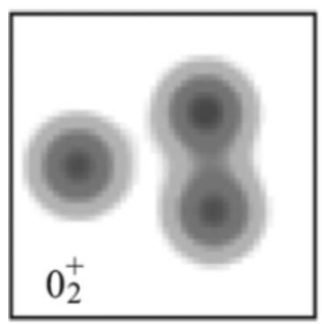
Energy level of ^{12}C



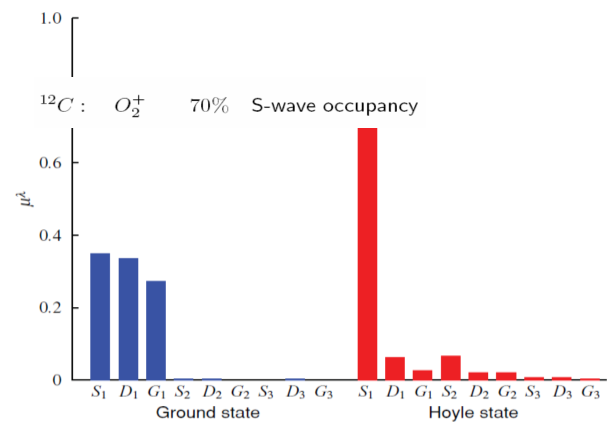
Scheme of ^{12}C nucleus synthesis

RADIUS - ?

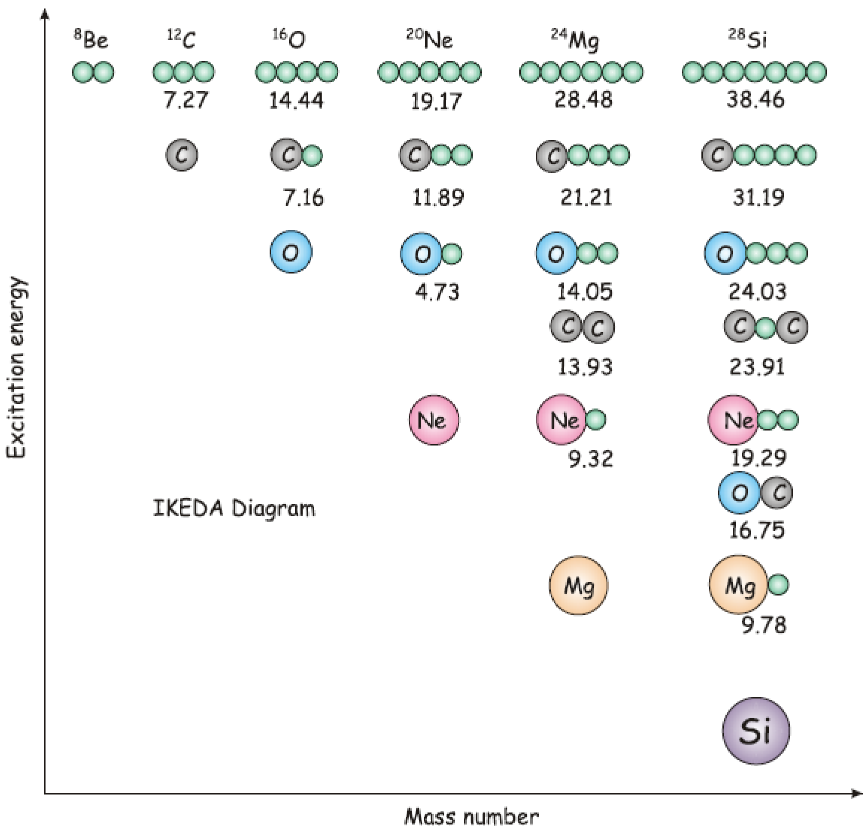
STRUCTURE- ?



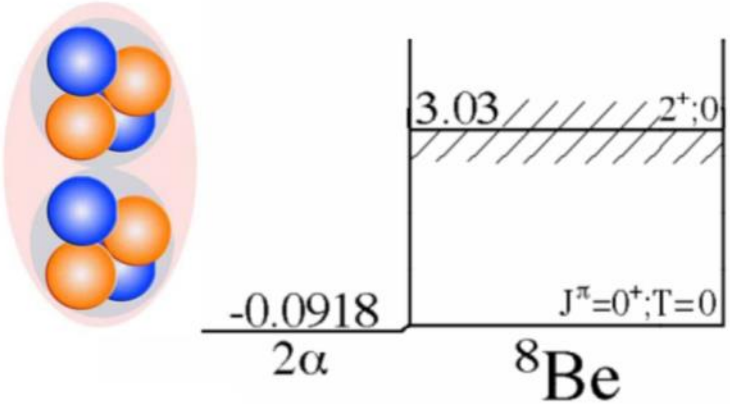
AMD density of HS



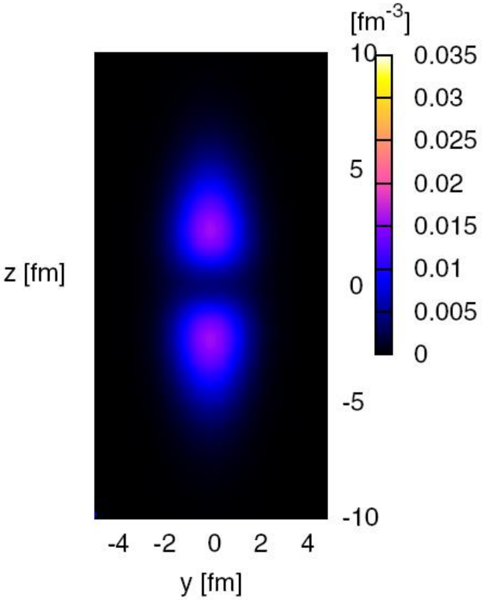
Occupation of the single-α orbitals of the Hoyle state of ^{12}C compared with the ground state.



The ‘Ikeda diagram’, showing the development of cluster structure within α-conjugate nuclei as excitation energy is increased.



“Dumbbell” configuration



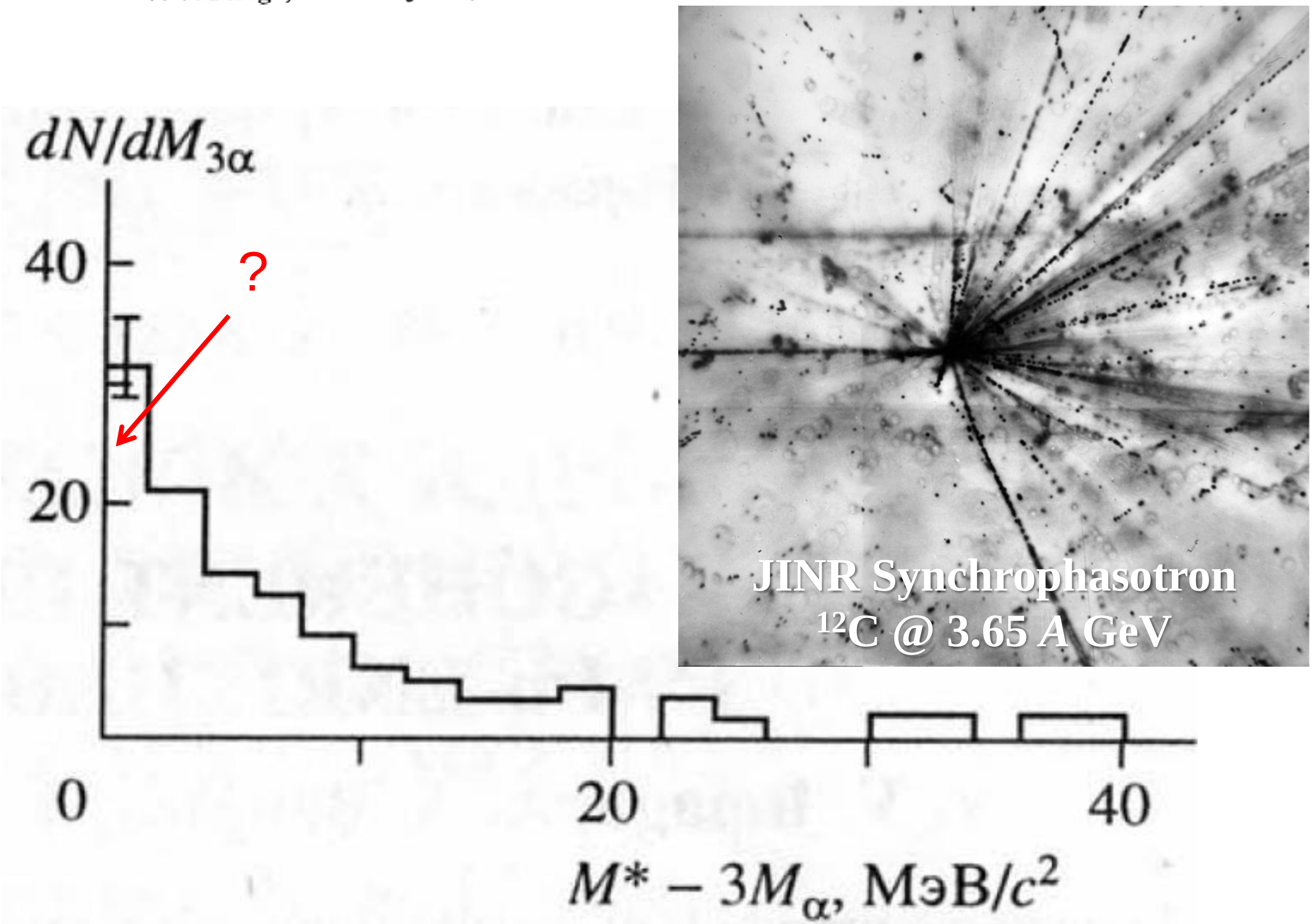
Example of calculating the density distribution of the ^{8}Be nucleus (TSHR model; Bose-Einstein alpha condensate)

Physics of Atomic Nuclei, Vol. 58, No. 11, 1995, pp. 1905 - 1910. Translated from Yadernaya Fizika, Vol. 58, No. 11, 1995, pp. 2014 - 2020.

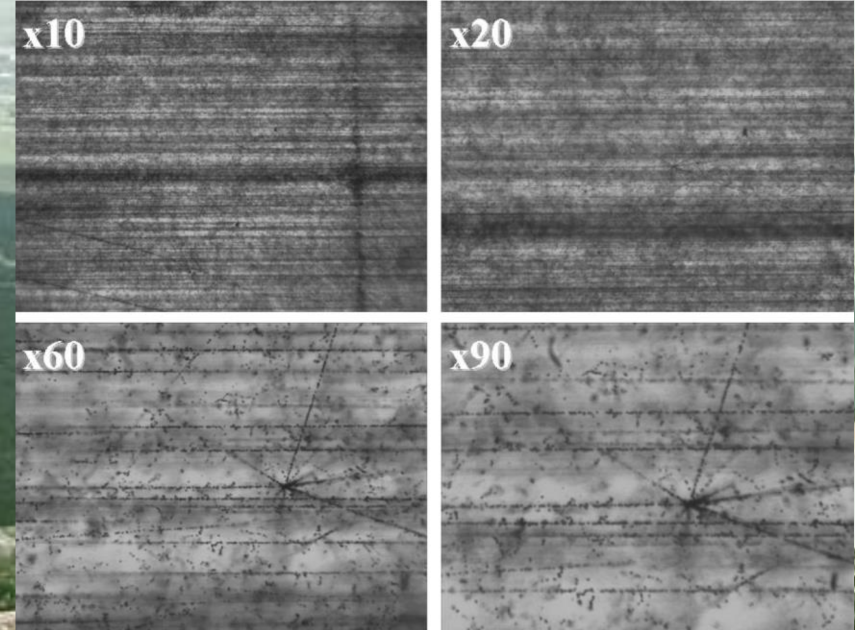
ELEMENTARY PARTICLES AND FIELDS
Experiment

Coherent Dissociation $^{12}C \to 3\alpha$ in Lead-Enriched Emulsion at 4.5 GeV/c per Nucleon

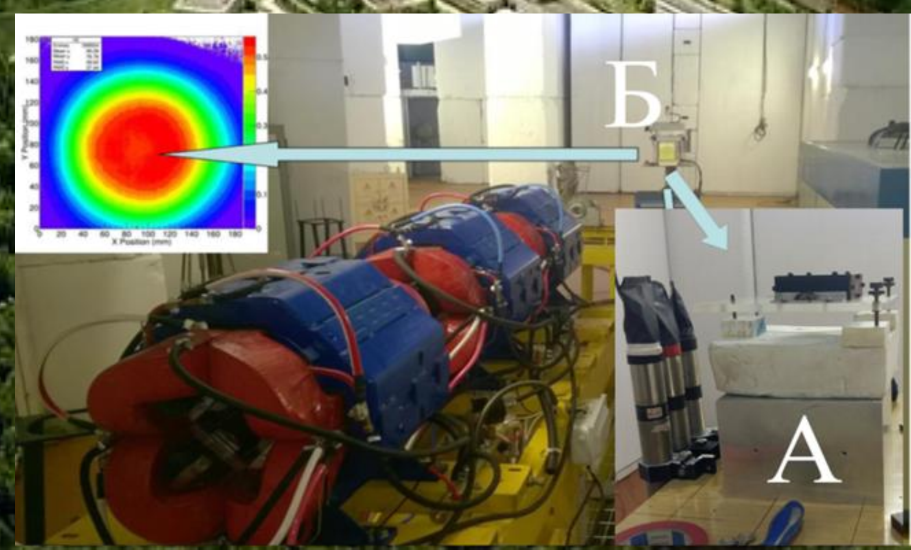
V. V. Belaga, A. A. Benjaza[1)], V. V. Rusakova, J. A. Salamov[2)], and G. M. Chernov



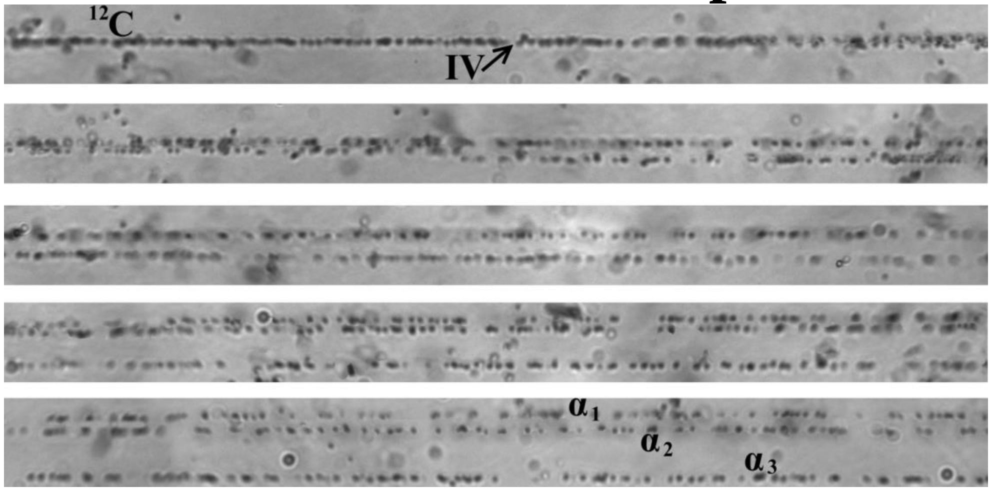
IHEP, Protvino
^{12}C 450 *A* MeV



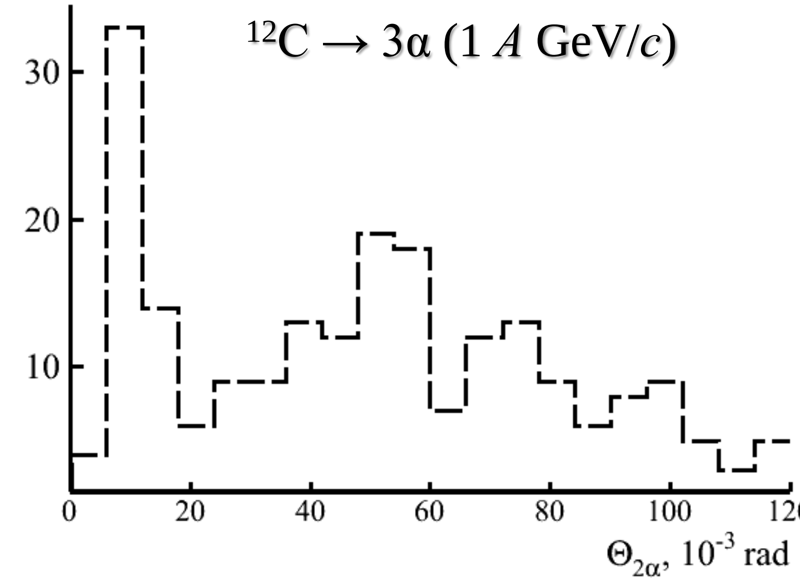
A medical beam of ^{12}C nuclei in IHEP, used at the initial stage, ensures the required uniformity of irradiation. It has an energy corresponding to the maximum of the cross section of electromagnetic dissociation. Its working intensity, which is not less than 10^8 nuclei per cycle, must be at least reduced 10^3 times to avoid overexposure and to provide beam monitoring. The solution of this problem is not simple, since high intensity provides feedback for the tuning of the accelerator.

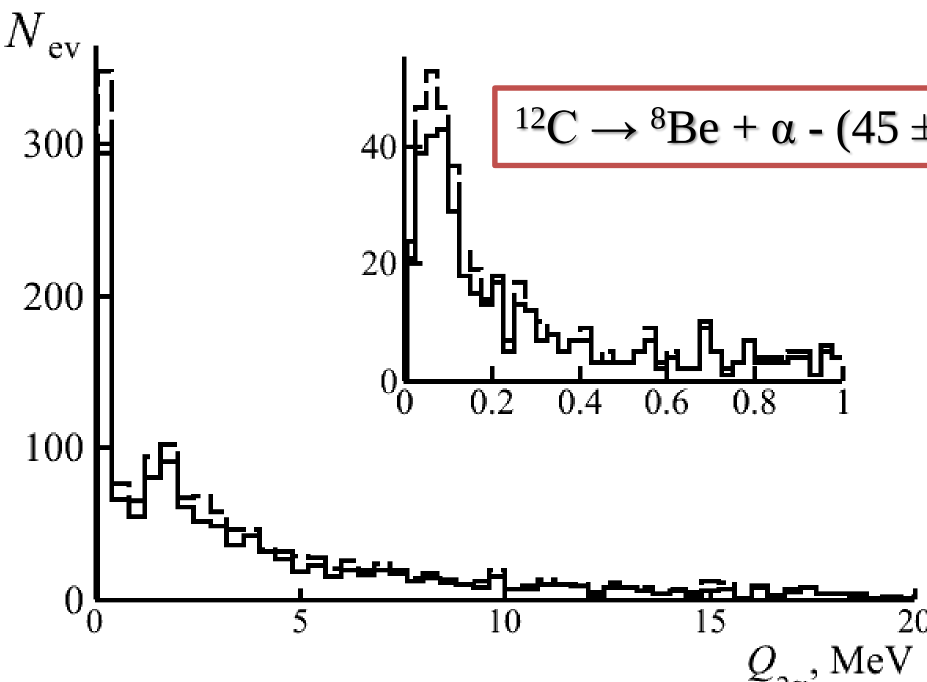


Observation of narrow α-pairs in dissociation of ^{12}C nucleus

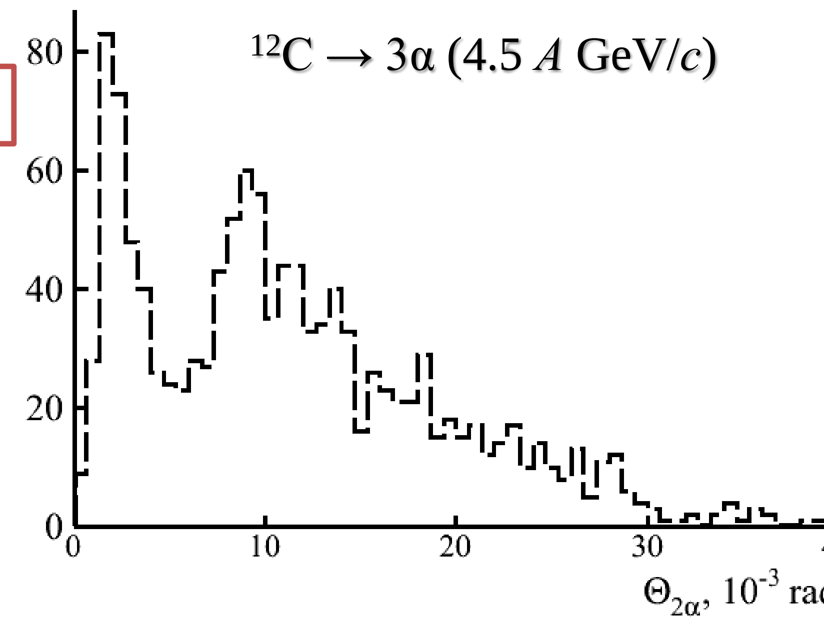


Sequential microphoto of event $^{12}C \to 3\alpha$ (P_0 1 A GeV/c), IV – position of the interaction vertex. The main characteristics of the event : θ_{12} = 8 mrad, θ_{13} = 15 mrad, θ_{23} = 8 mrad, Q_{12} = 57 keV, Q_{13} = 227 keV, Q_{23} = 61 keV, $Q_{3\alpha}$ = 230 keV.

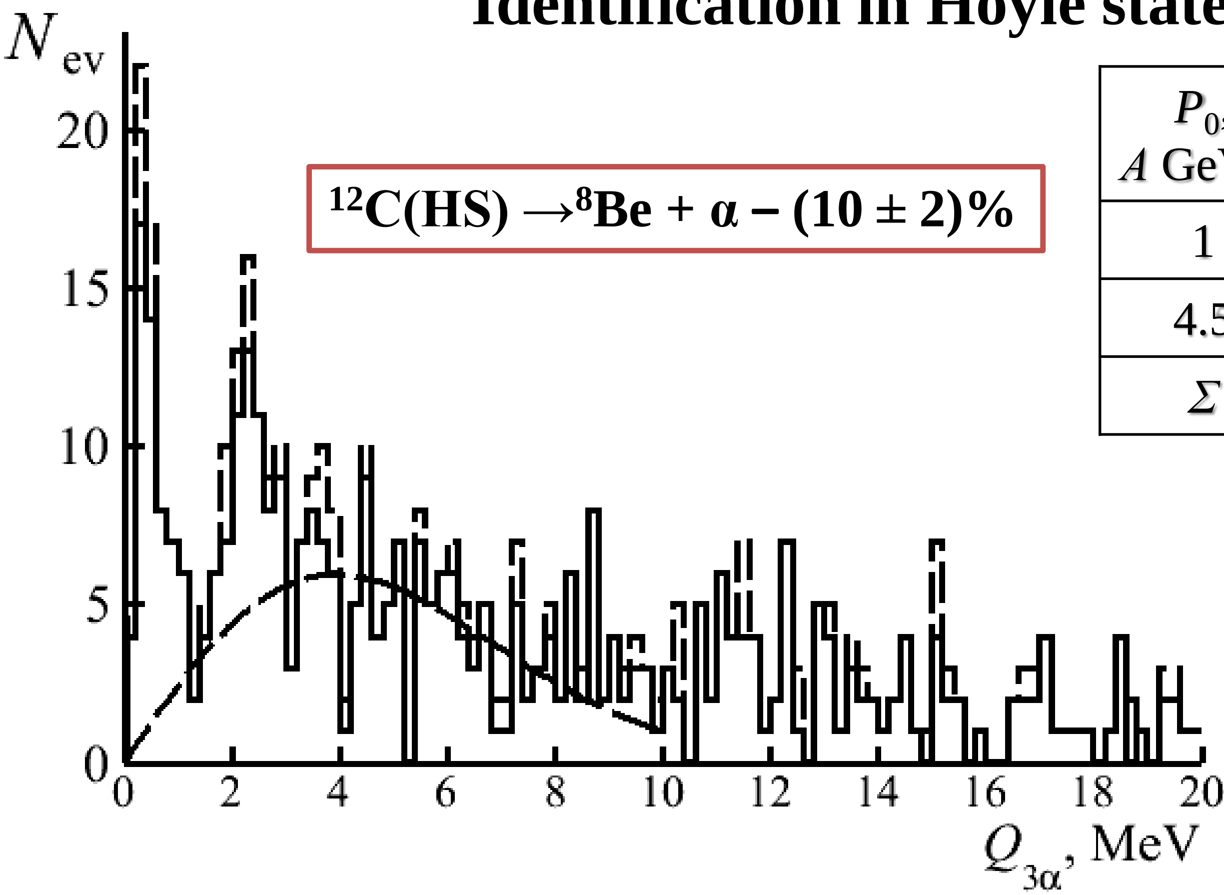




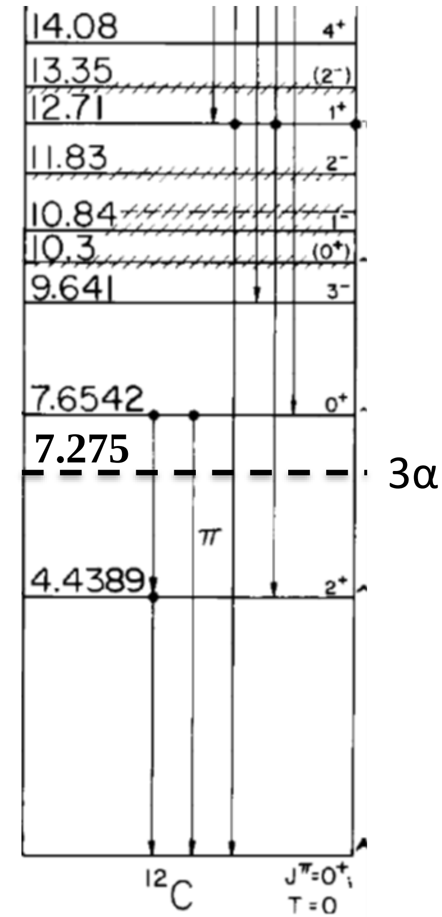
$^{12}C \to {}^{8}Be + \alpha$ - (45 ± 4) %



Identification in Hoyle state events



P_0, A GeV/c	$\langle Q_{3\alpha}\rangle$, МэВ ($Q_{3\alpha}$ < 1МэВ)	Events Number(tot)
1	346 ± 28	9 (86)
4.5	397 ± 26	42 (424)
Σ	415 ± 28	51 (510)

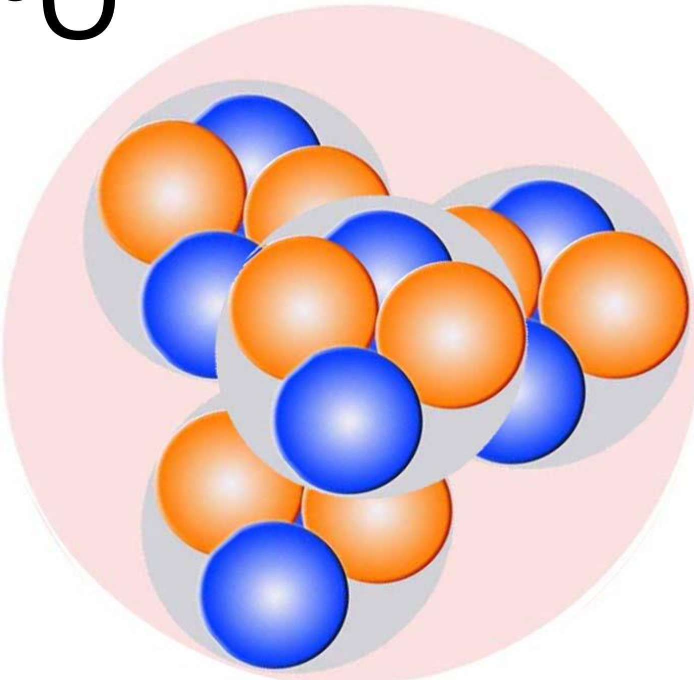


The distribution of the invariant mass of the α-triples $Q_{3\alpha}$ in the dissociation of $^{12}C \to 3\alpha$ with 4.5 A GeV/c (hatched) and 1 A GeV/c (added); inset: region up to $Q_{2\alpha}$ < 2 MeV.

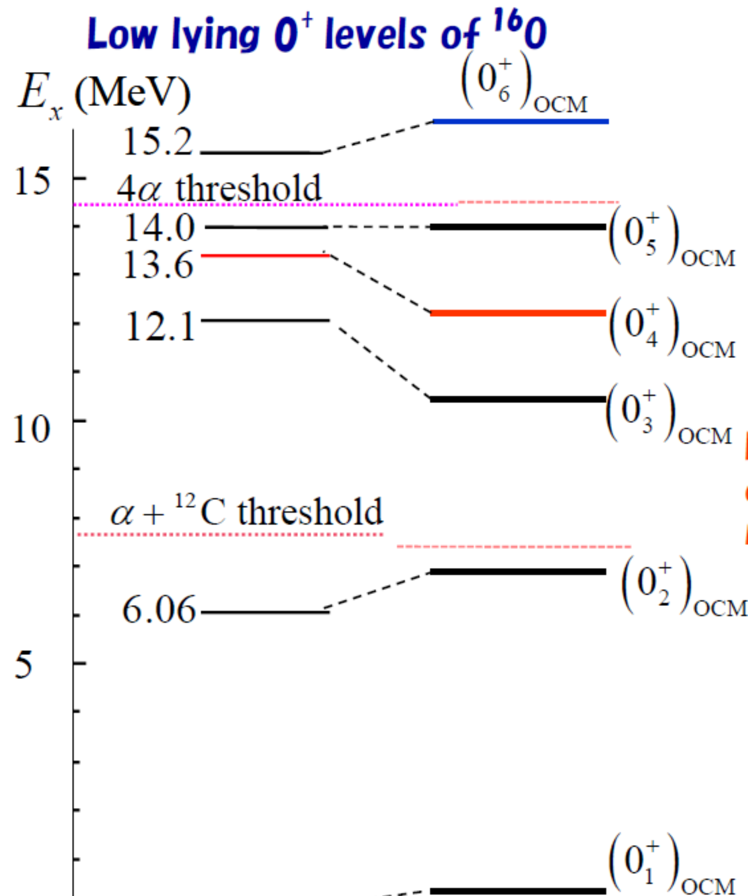
$$Q_{3\alpha} = \sqrt{3m_\alpha^2 + 2\cdot\sum(E_i \cdot E_j - p_i \cdot p_j)} - 3m_\alpha$$

^{16}O

Extensions to heavier nuclei

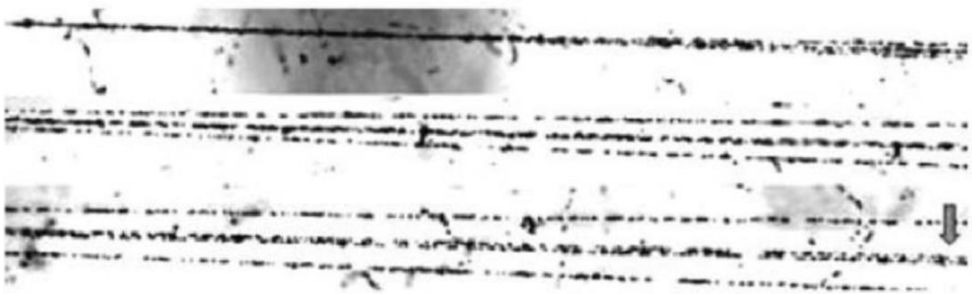


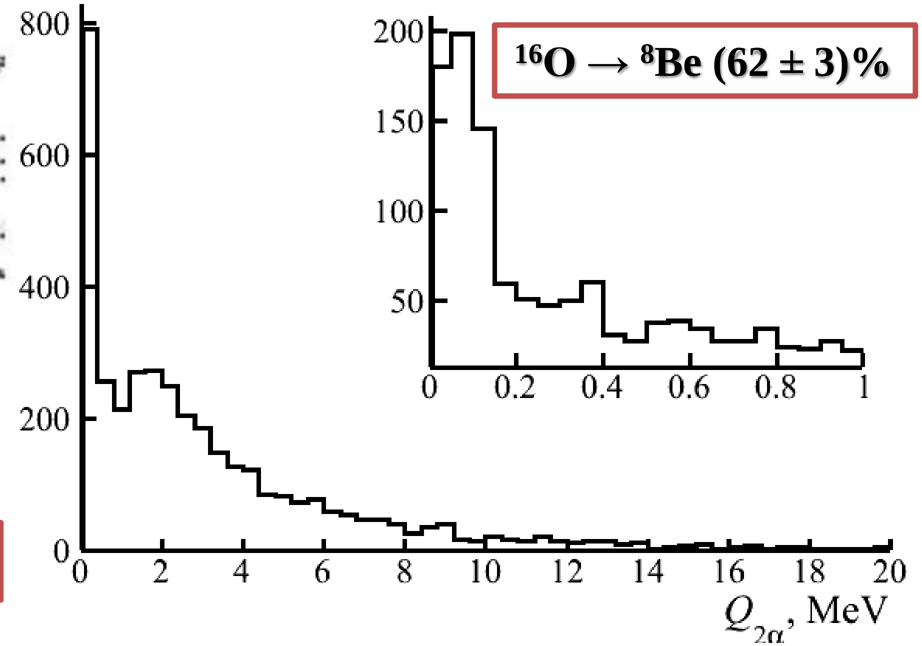
E_x (MeV ± keV)	J^π; T	K^π	$\Gamma_{c.m.}$ or τ_m (keV)	Decay
14.620 ± 20	$4^{(+)}$		490 ± 15	α
14.660 ± 20	5^-	0^-	670 ± 15	α
14.8153 ± 1.6	6^+; 0		70 ± 8	α
14.926 ± 2	2^+		54 ± 5	p, α
15.097 ± 5	0^+		166 ± 30	p, α
15.196 ± 3	2^-; 0		63 ± 4	p, α
15.26 ± 50	2^+; (0)		300 ± 100	p, α



Energy level of oxygen-16

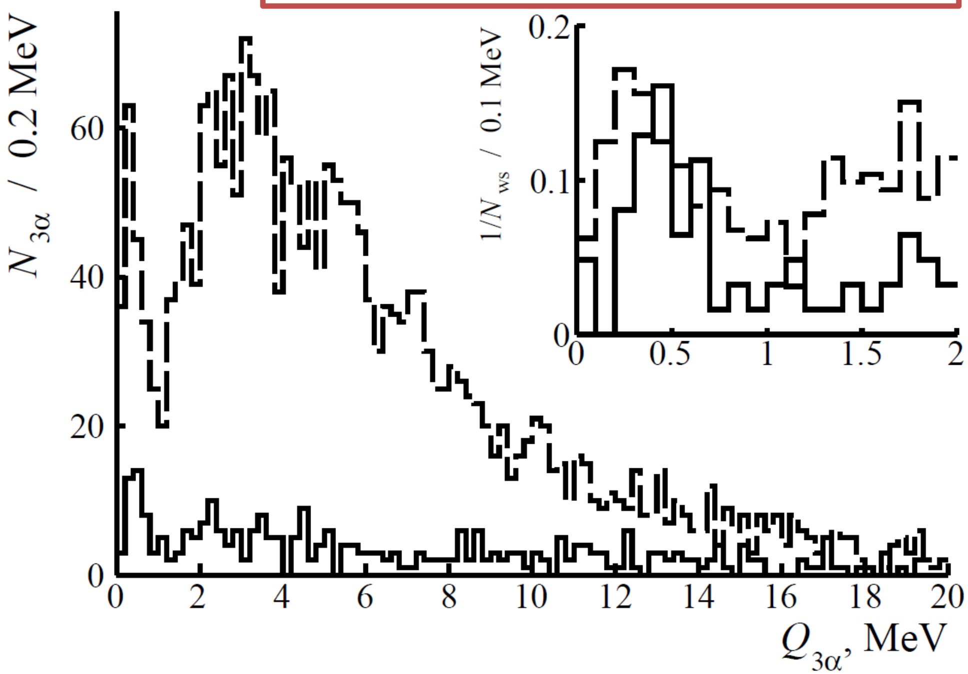
Coherent dissociation of ^{16}O → 4α at 4.5 *A* GeV/*c*

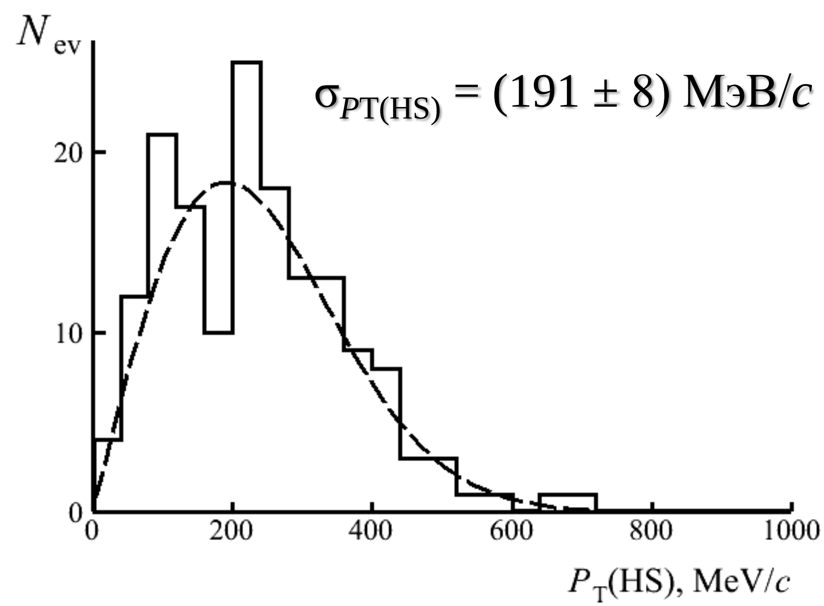




Fragmentation of a relativistic ^{16}O nucleus at 4.5 *A* GeV/*c* in the peripheral interaction on heavy nucleus

^{16}O → ^{12}C*(HS) + α – (22 ± 2) %

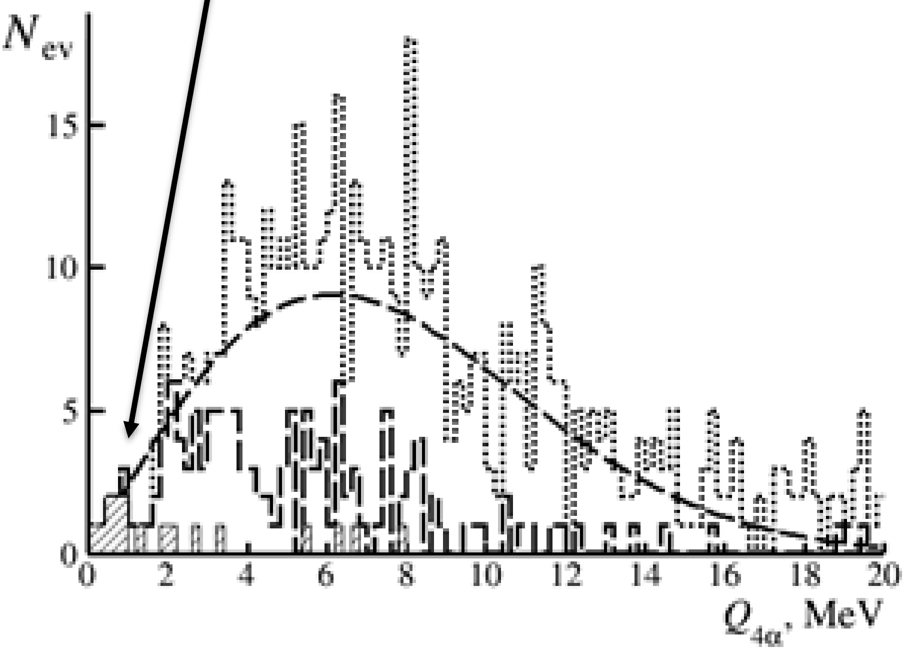


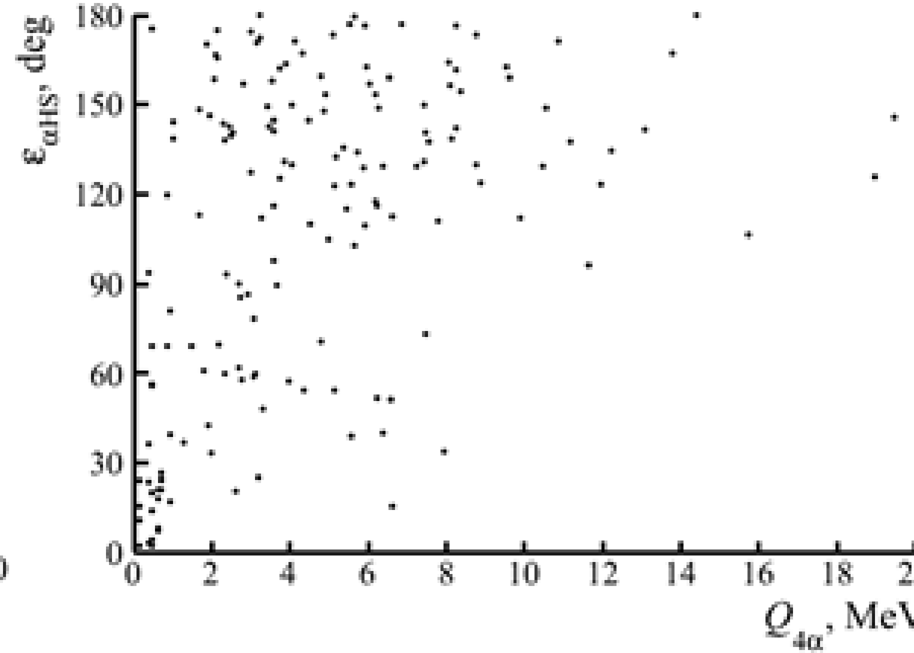


Coherent dissociation of $^{16}O \rightarrow 4\alpha$ at 4.5 *A* GeV/*c*

$^{16}O(0^{+}_{6}) \rightarrow {}^{12}C^{*}(\rightarrow 3\alpha) + \alpha$ – (7 ± 1) %

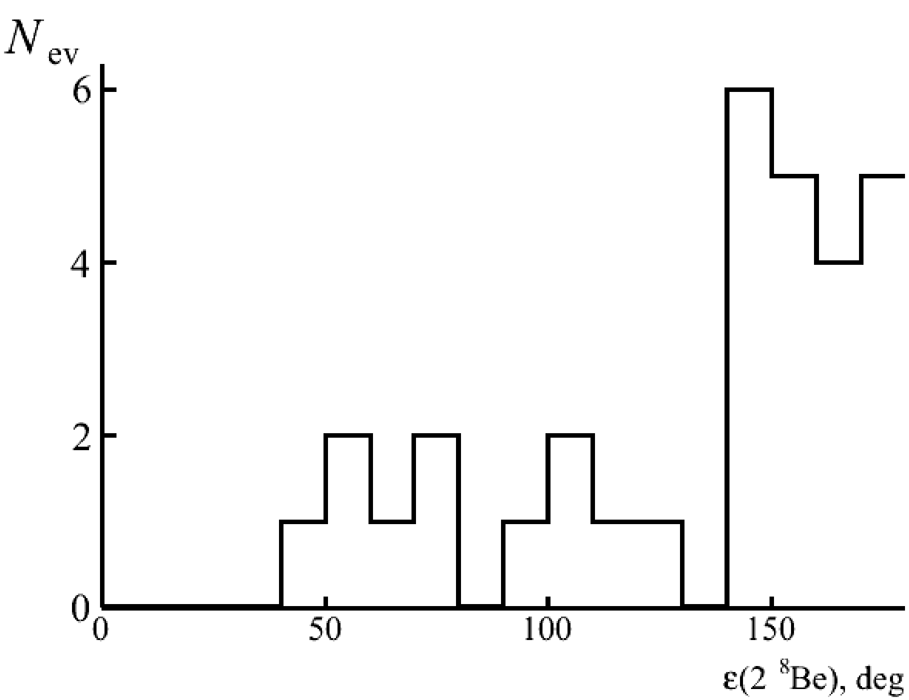
$\langle Q_{4\alpha} \rangle$ = (624 ± 84) keV

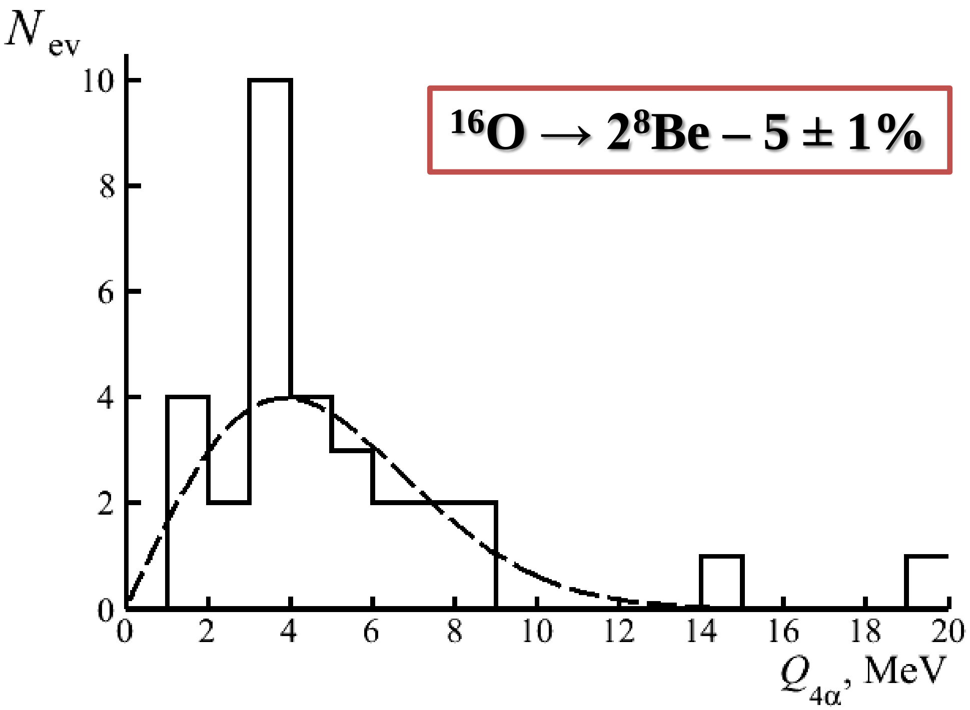




Distribution over the invariant mass $Q_{4\alpha}$ in 641 "white" star $^{16}O \rightarrow 4\alpha$ at 3.65 *A* GeV of all 4α-quartets (dotted line), αHS events (dashed line), and αHS events satisfying $\varepsilon(\alpha HS) < 45^{0}$ (hatched); the line is the Rayleigh distribution.

Search for $^{16}O \rightarrow 2\ ^{8}Be$ events



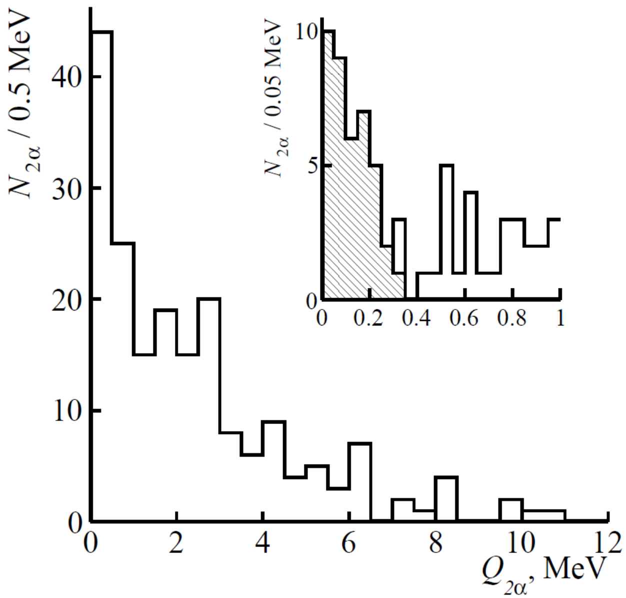


Distribution of events $^{16}O \rightarrow 2^{8}Be$ over azimuth angle $\varepsilon(2^{8}Be)$ between ^{8}Be fragment.

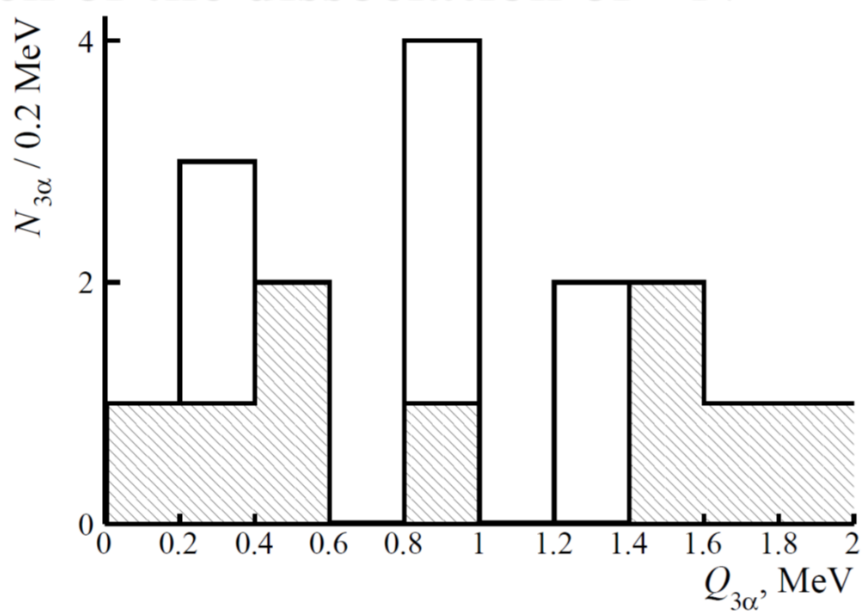
Distribution of events $^{16}O \rightarrow 2^{8}Be$ over invariant mass $Q_{4\alpha}$; line - Rayleigh distribution

$$\frac{^{16}O \rightarrow \alpha HS}{^{16}O \rightarrow 2^{8}Be} = (4.5 \pm 0.4)$$

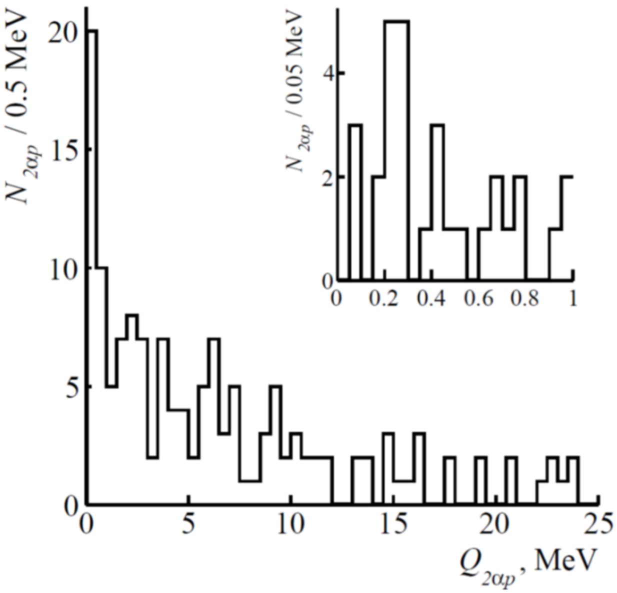
Preliminary results of research of the dissociation of ^{14}N



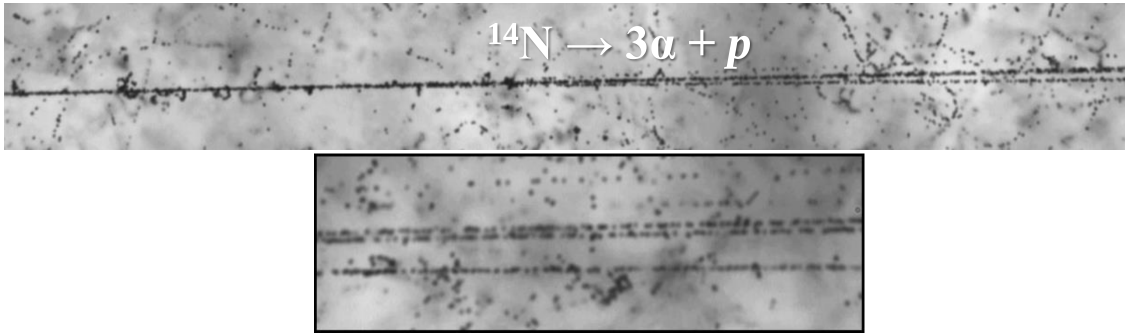
Distribution over Q of a system of 2α-particles. Solid line is the combination of all pairs of α-particles in the events $^{14}N \rightarrow 3\alpha +$ H, the shaded line is the limitation in the angle of expansion $\Theta_{2\alpha}$<6 mrad. Contribution of $^{8}Be_{gs}$ nuclei is 46 ± 8%.



Distribution over Q of triplets of α-particles. The solid line is all events $^{14}N \rightarrow 3\alpha$ (+ H), the shaded line - the events without identified ^{9}B nucleus. For 4 "pure" correspond to the HS events.

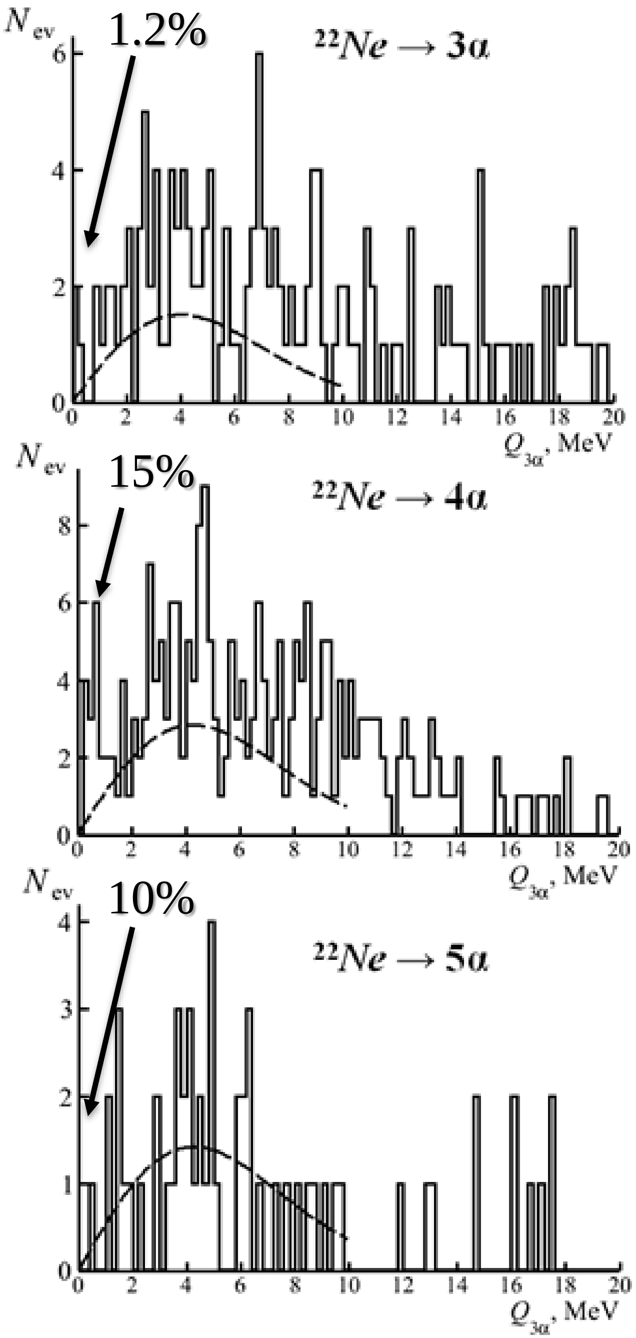


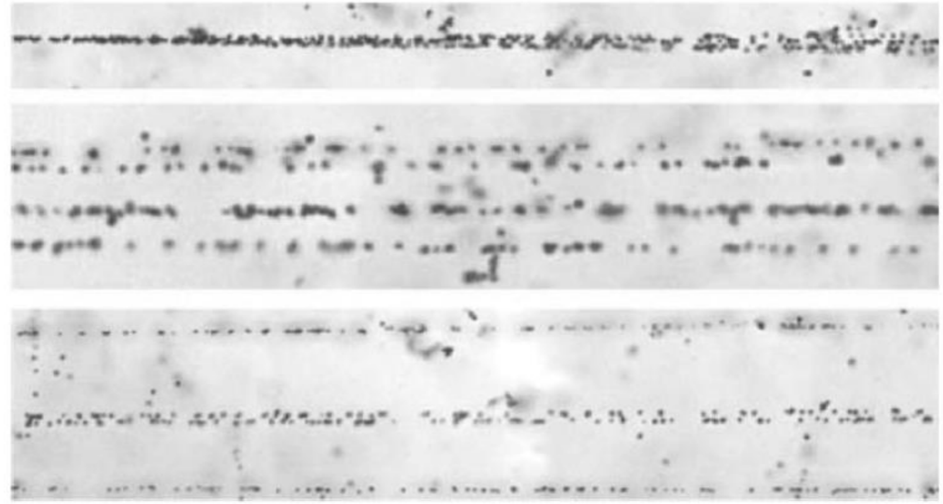
Distribution over Q of a system of 2α-particles and a proton. Contribution of ^{9}B - (10 ± 4)%



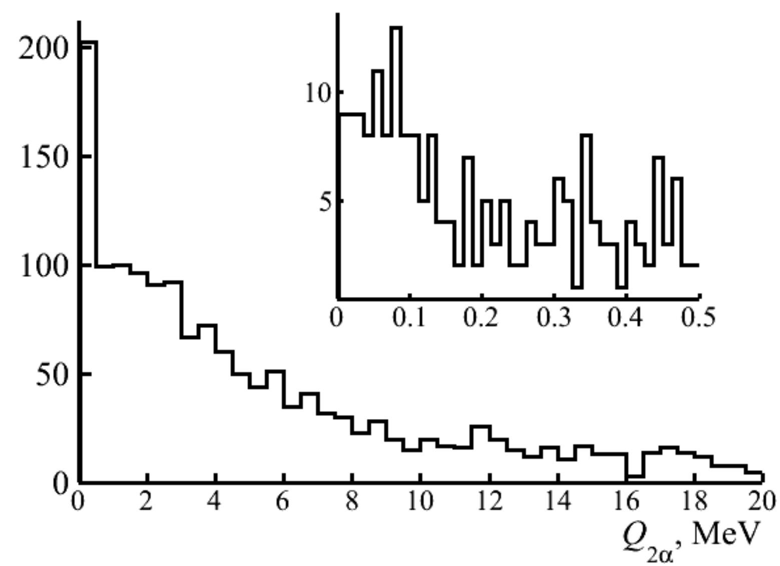
Measurements are on progress now

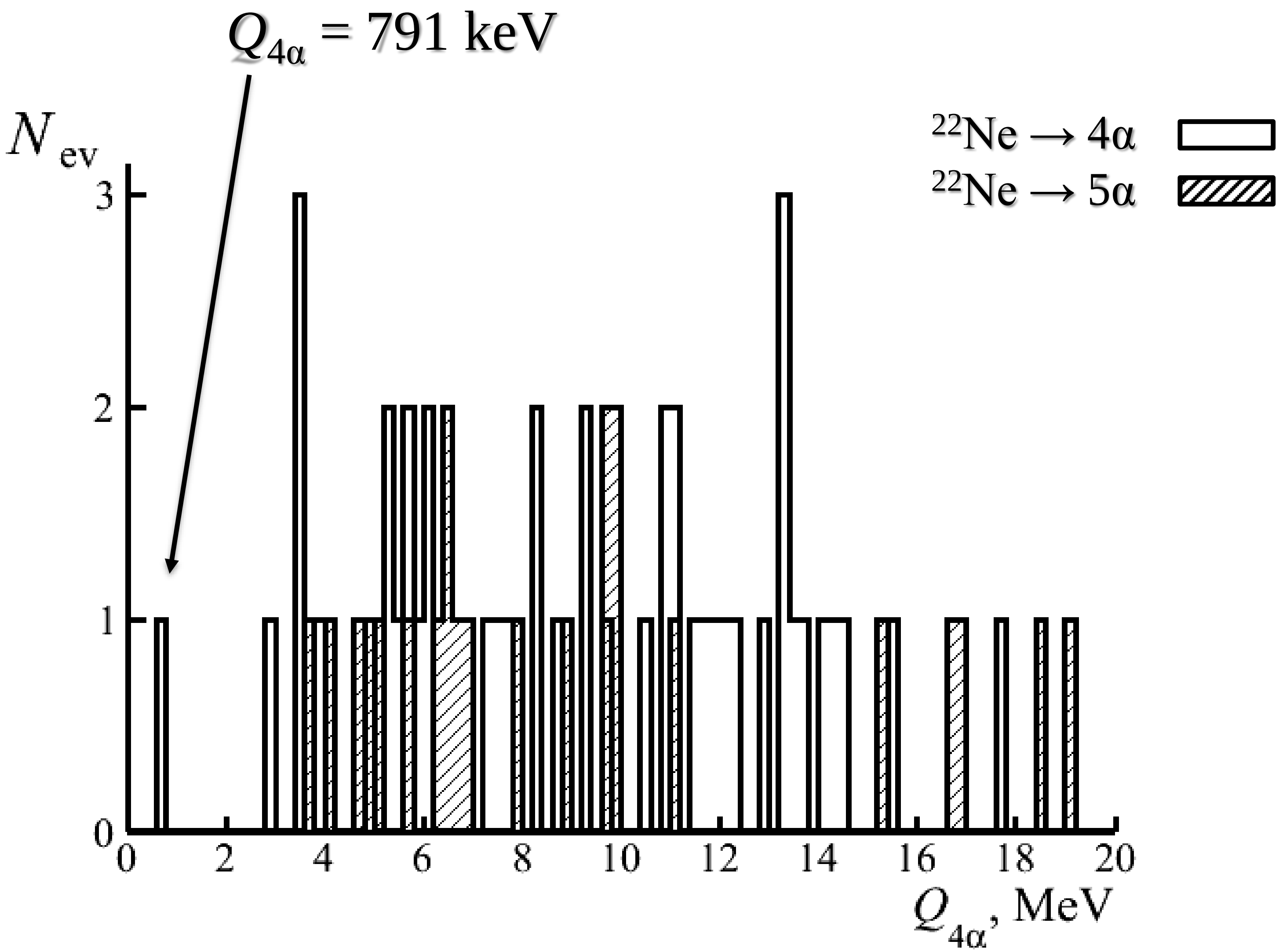
Fragmentation of relativistic ^{22}Ne nucleus



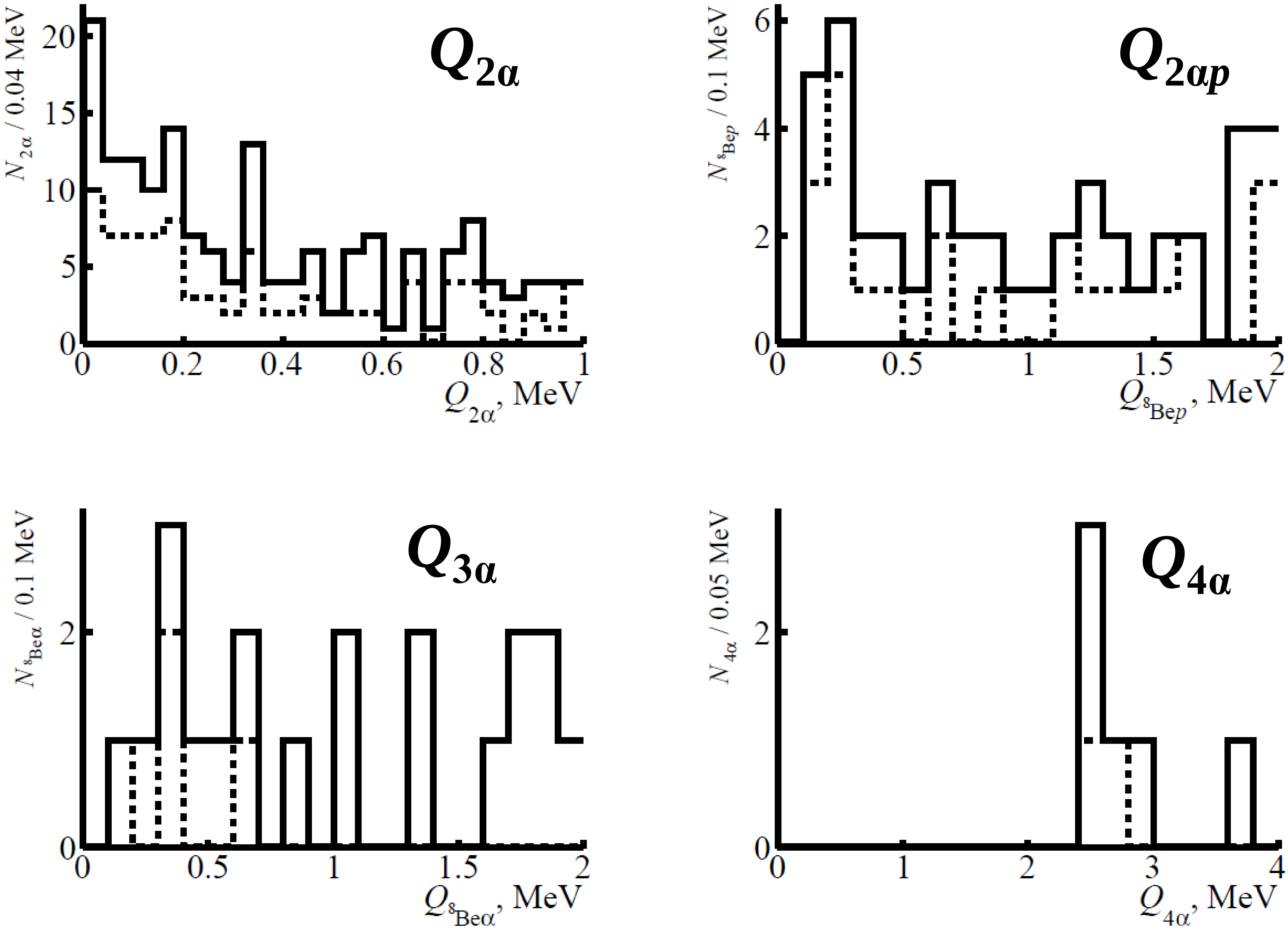


Fragmentation of the relativistic nucleus ^{22}Ne → 5α at 4.1 *A* GeV/*c* in the peripheral interaction





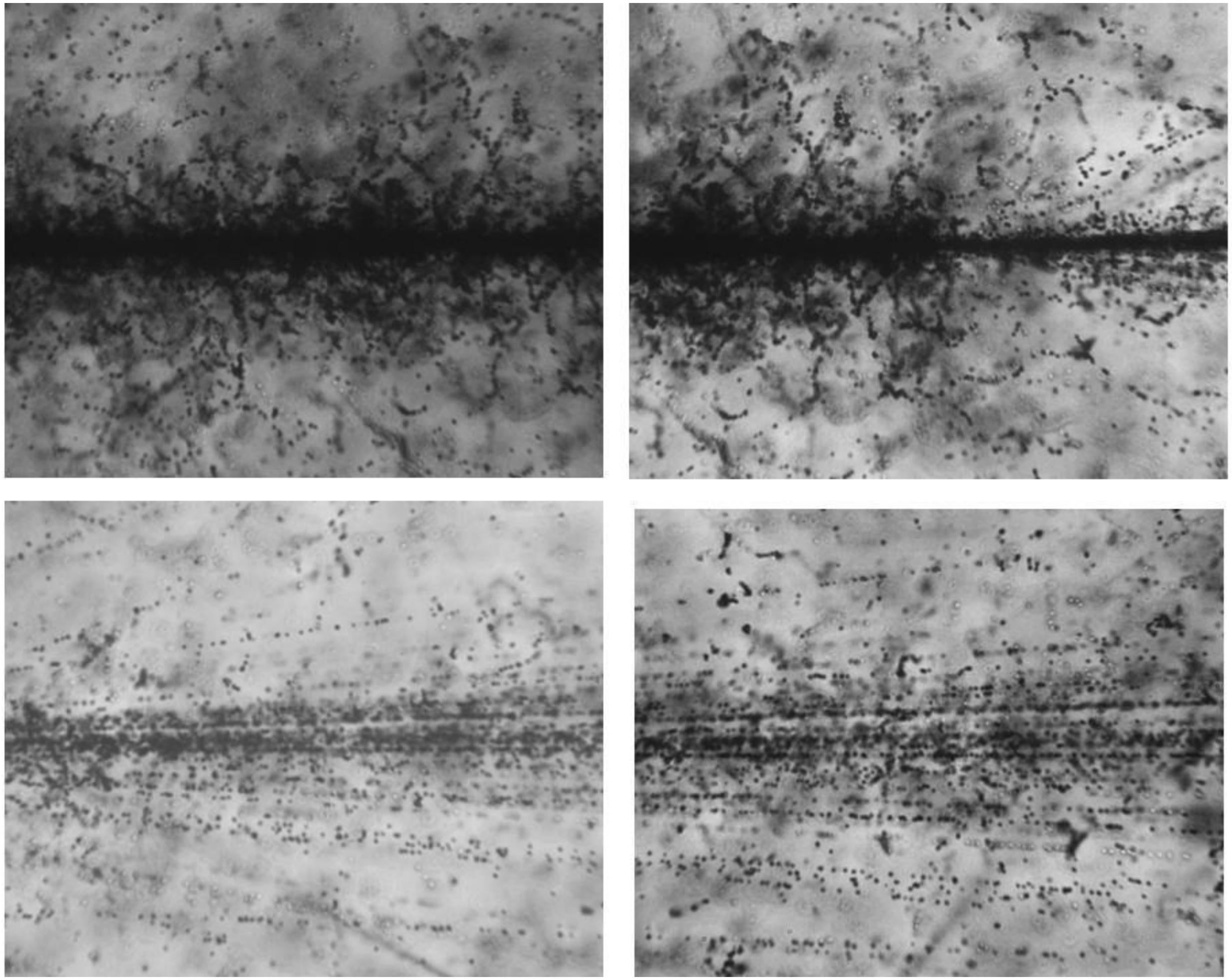
$Q_{4\alpha}$ = 791 keV
N_{ev}
^{22}Ne → 4α
^{22}Ne → 5α
0
1
2
3
0 2 4 6 8 10 12 14 16 18 20
$Q_{4\alpha}$, MeV

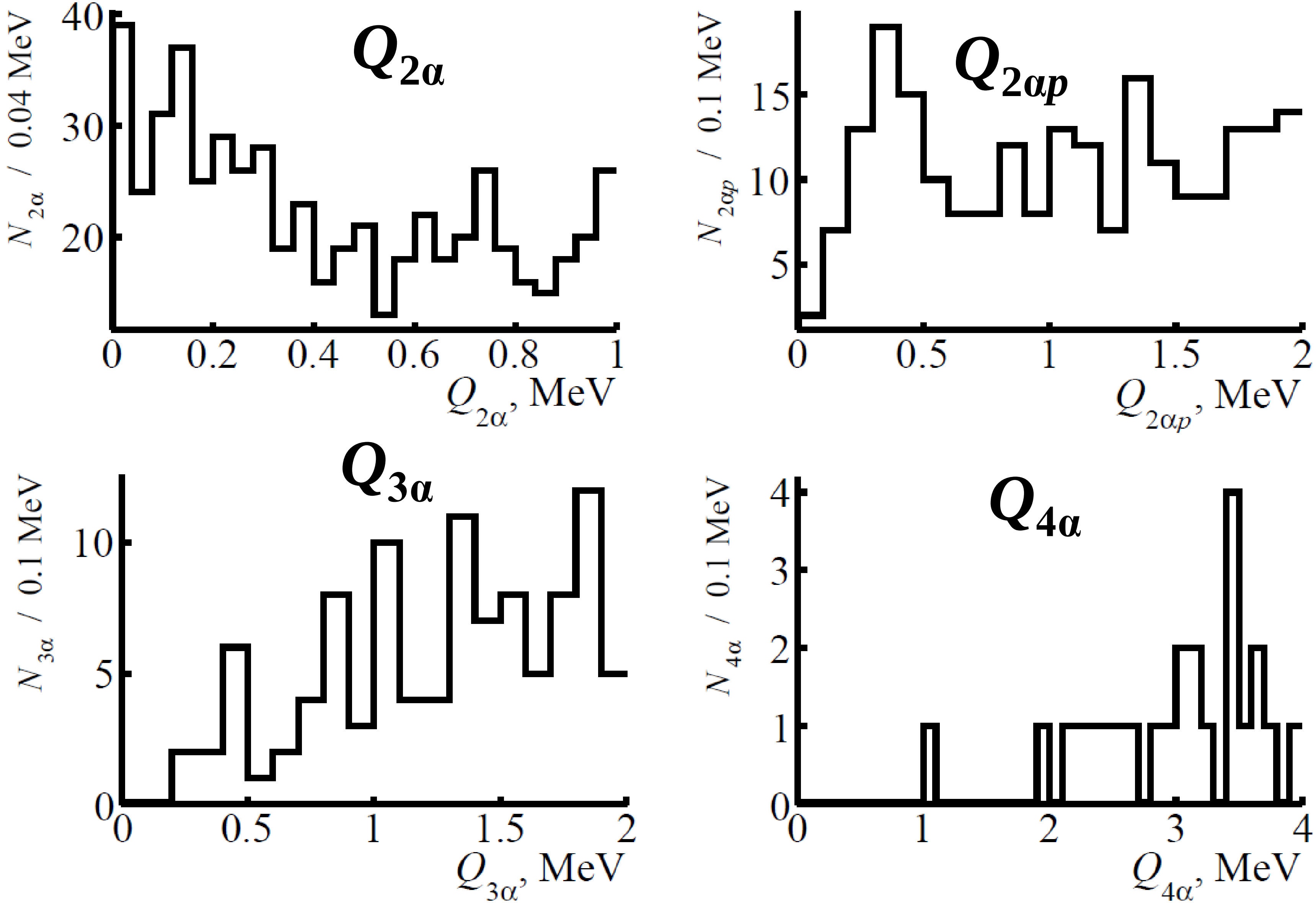


14.6 *A* GeV ^{28}Si:

52 events $Q_{2\alpha}$ < 0.2 MeV; 15 events $Q_{2\alpha p}$ < 0.5 MeV (^{9}B); 9 events $Q_{3\alpha}$ < 0.7 MeV (HS).

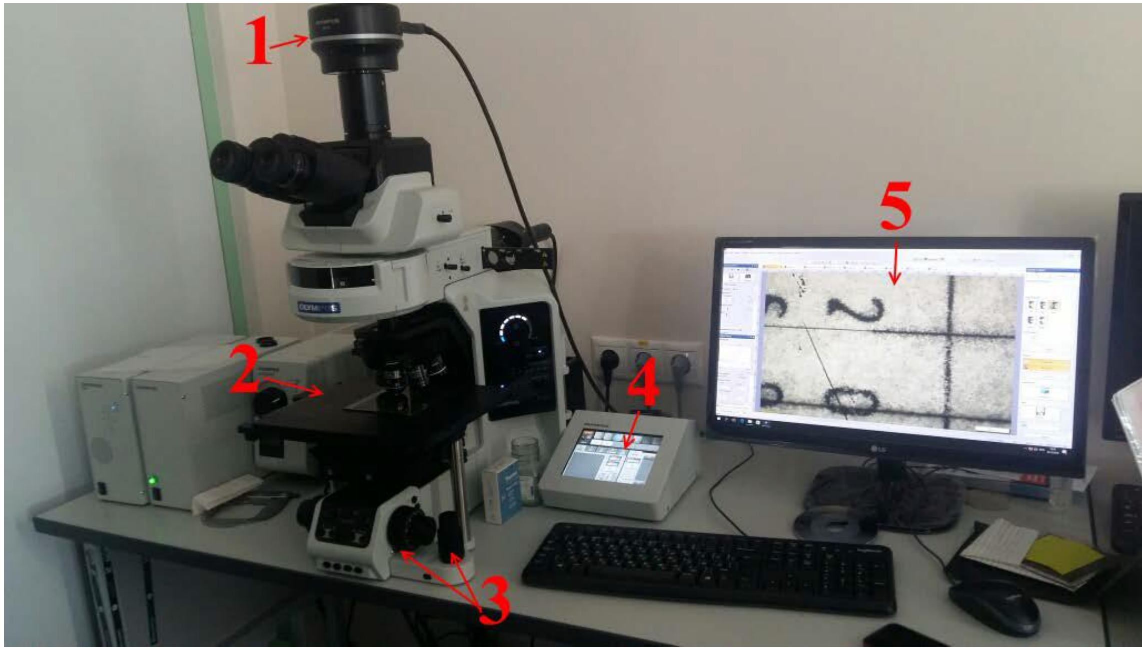
Au 10.7 *A* GeV

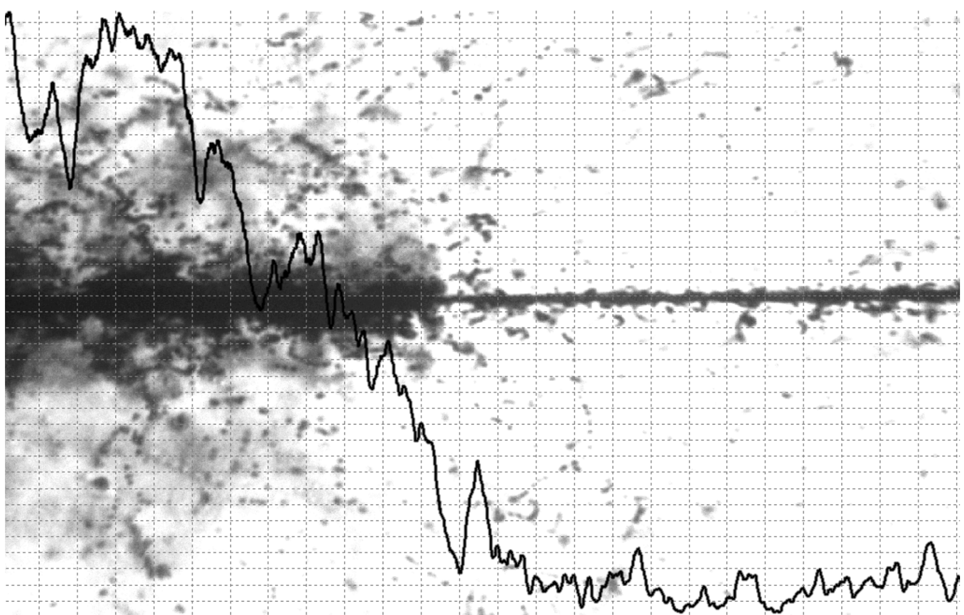




1316 interactions of 10.7 *A* GeV Au; 160 α-pairs $Q_{2\alpha} < 0.2$ MeV; 40 events with 2*αp*-triples $Q_{2\alpha p} < 0.5$ MeV (^{9}B); 12 events with α-triples $Q_{3\alpha} < 0.7$ MeV (Hoyle state); 1 event with α-quartet $Q_{4\alpha} = 1$ MeV.

New is well forgotten old





Conclusions

Preserved and recently obtained data on interactions of light relativistic nuclei in a nuclear track emulsion allowed to establish the contribution in their dissociation of unstable nuclei ^{8}Be and ^{9}B and the Hoyle state as well as to assess the prospects of such research in relation to medium and heavy nuclei. These three states are uniformly identified by the invariant masses calculated from the measured angles of emission of He and H fragments under the assumption of conservation of the primary momentum per nucleon.

The ^{8}Be selection in dissociation of the isotopes ^{9}Be, ^{10}B, ^{10}C, and ^{11}C is determined by the restriction from above of the invariant mass of 2α-pairs up to 0.2 MeV, and the ^{9}B *2αp*-triple mass up to 0.5 MeV. The certainty in the ^{8}Be and ^{9}B identification of became the basis for the search for decays from the Hoyle state in the dissociation $^{12}C \rightarrow 3\alpha$. In the latter case, the 3α triple invariant mass is set to be limited to 0.7 MeV. The choice of these three conditions as "cut-offs from above" is sufficient because the decay energy values of these three states are noticeably lower than the nearest excitations with the same nucleon compositions, and the reflections of more complex excitations is small for these nuclei.

Being tested in the studies of the light nuclei, a similar selection is applicable to the dissociation of heavier nuclei to search for more complex states. In turn, the products of α-particle or proton decay of these states could be the Hoyle state or ^{9}B, and then ^{8}Be. A possible decay variant is the occurrence of more than one state from this triple. In any case, the initial stage of searches should be the selection of events containing relativistic ^{8}Be decays.

Dozens of ^{8}Be and ^{9}B decays are identified in the relativistic fragmentation cone of Si and Au nuclei. At the same time, the small number of 3α triples attributable to the decay of the Hoyle state which requires increasing statistics to the current ^{8}Be equivalent. Then, the search for the excited state $^{16}O(0^{+}_{6})$ will become feasible. There are no fundamental problems along this path since there are a sufficient number of earlier exposed NTE layers, with transverse scanning of which the required α ensemble statistics is achievable. This whole complex of problems, united by questions of identification of unstable states, is in the focus of the application in the BECQUEREL experiment in the present time.

It is hoped that the rapid progress in image analysis will give a whole new dimension to the use of the NTE method in the study of nuclear structure in the relativistic approach. The solution of the tasks set requires investment in modern automated microscopes and the reconstruction of NTE technology at a modern level. At the same time, such a development will be based on the classical NTE method, the foundations of which were laid seven decades ago in cosmic ray physics.