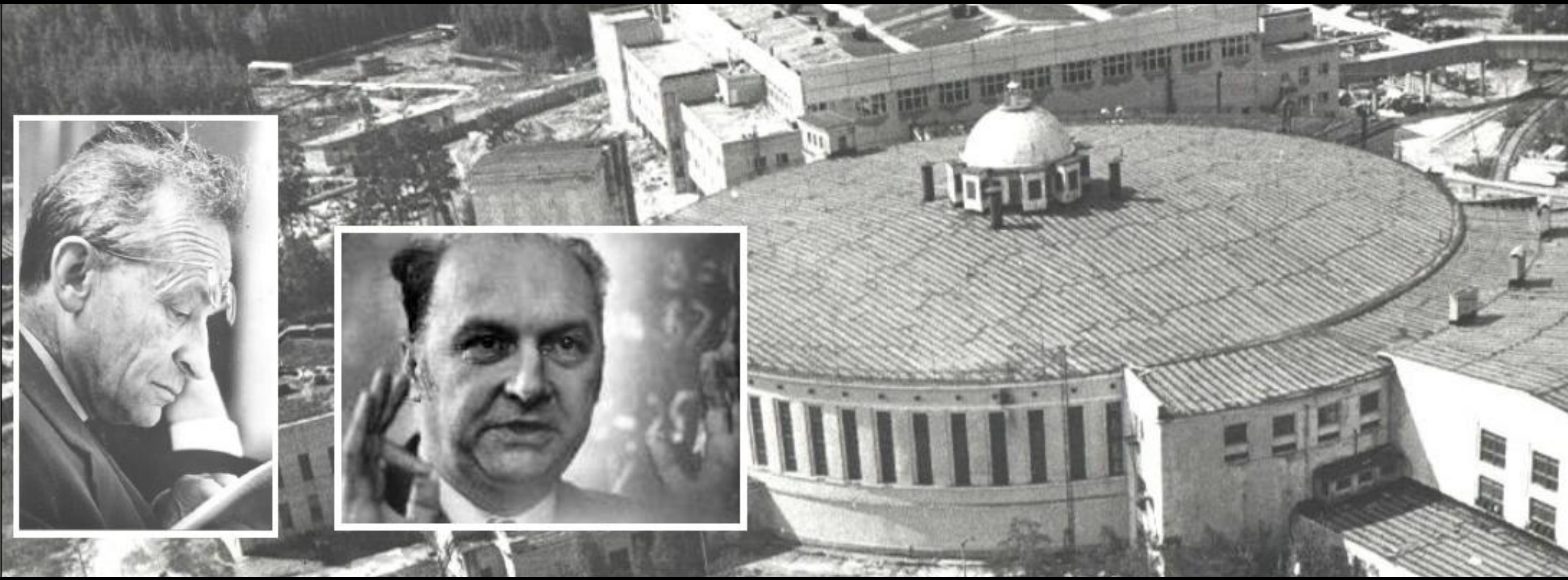
Andrei Zaitsev &Pavel Zarubin “The search for unstable α-particle states in fragmentation of relativistic medium and heavy nuclei”



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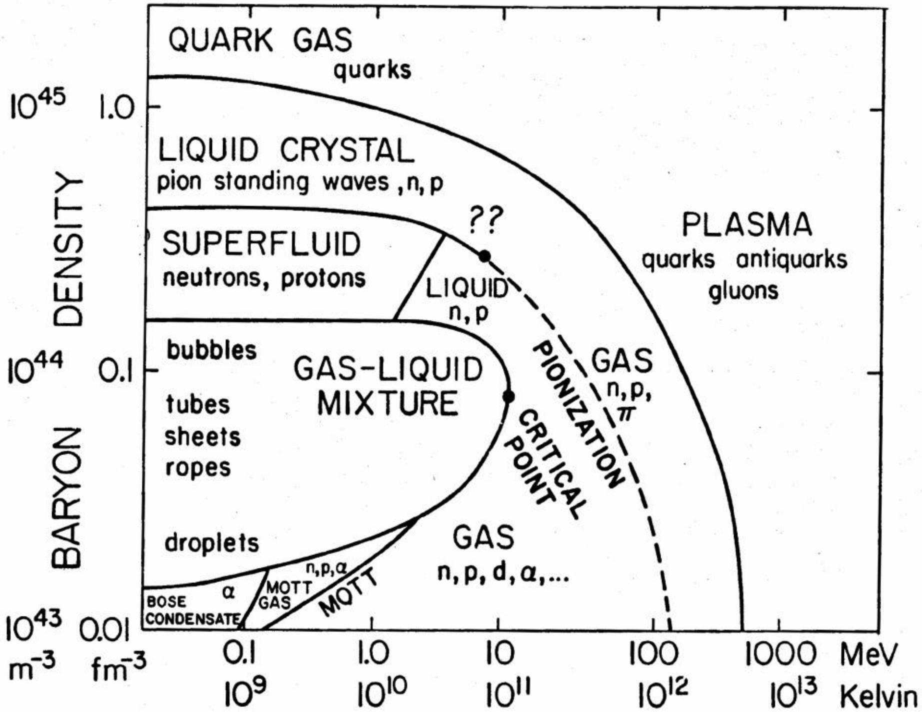
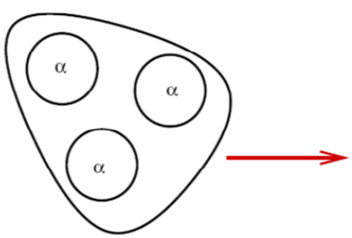
Alpha-Clusters in Nuclear Systems

P. Schuck

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

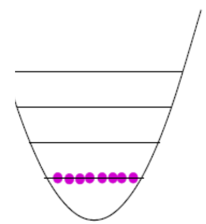


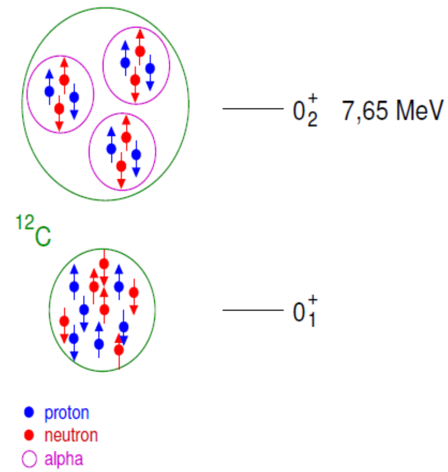
If $\;0_2^+\;$ in ^{12}C dilute α – state



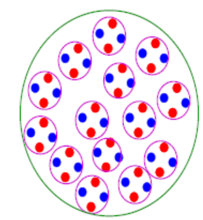
then α-condensate

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





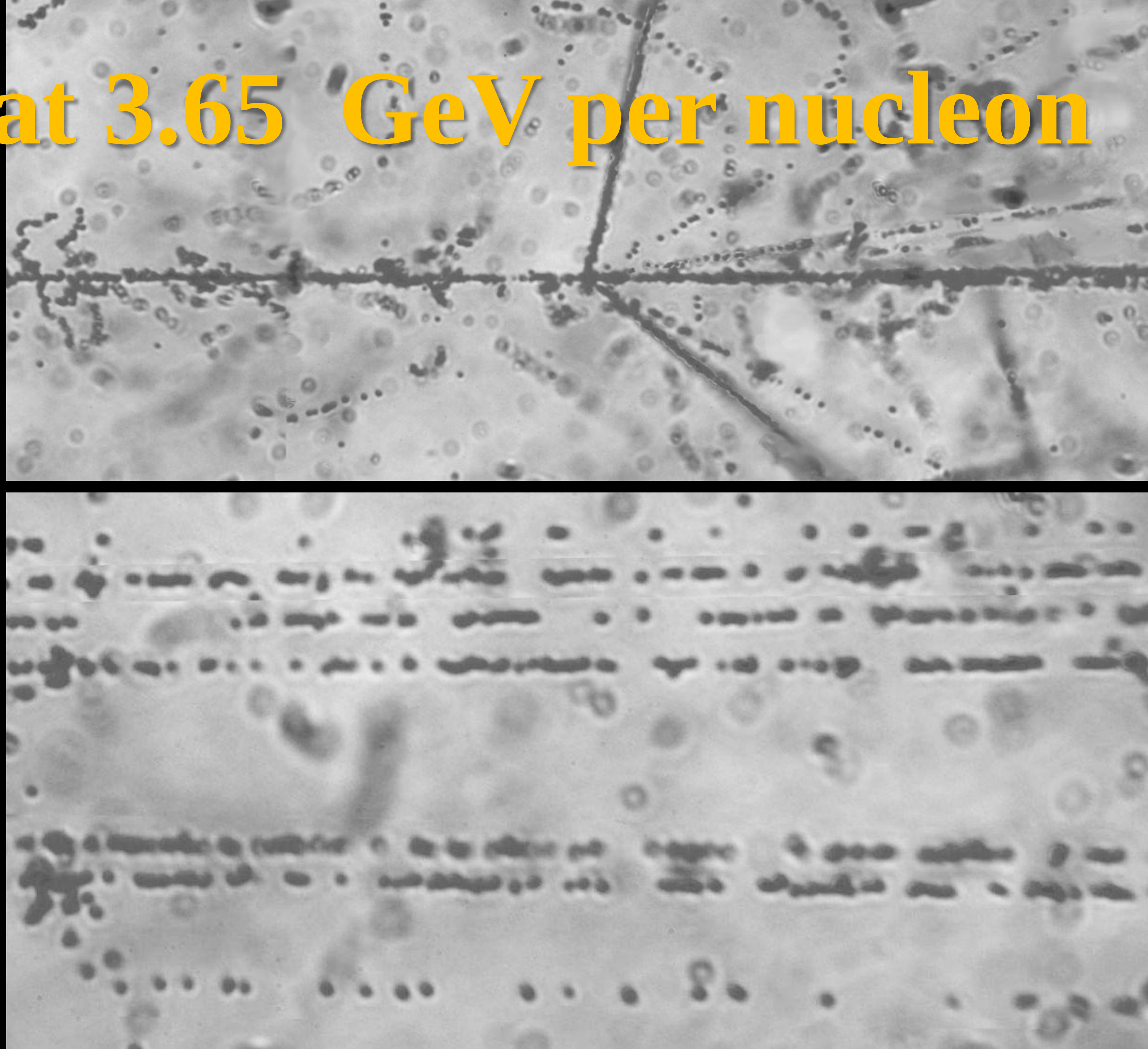
many α's
→ condensate

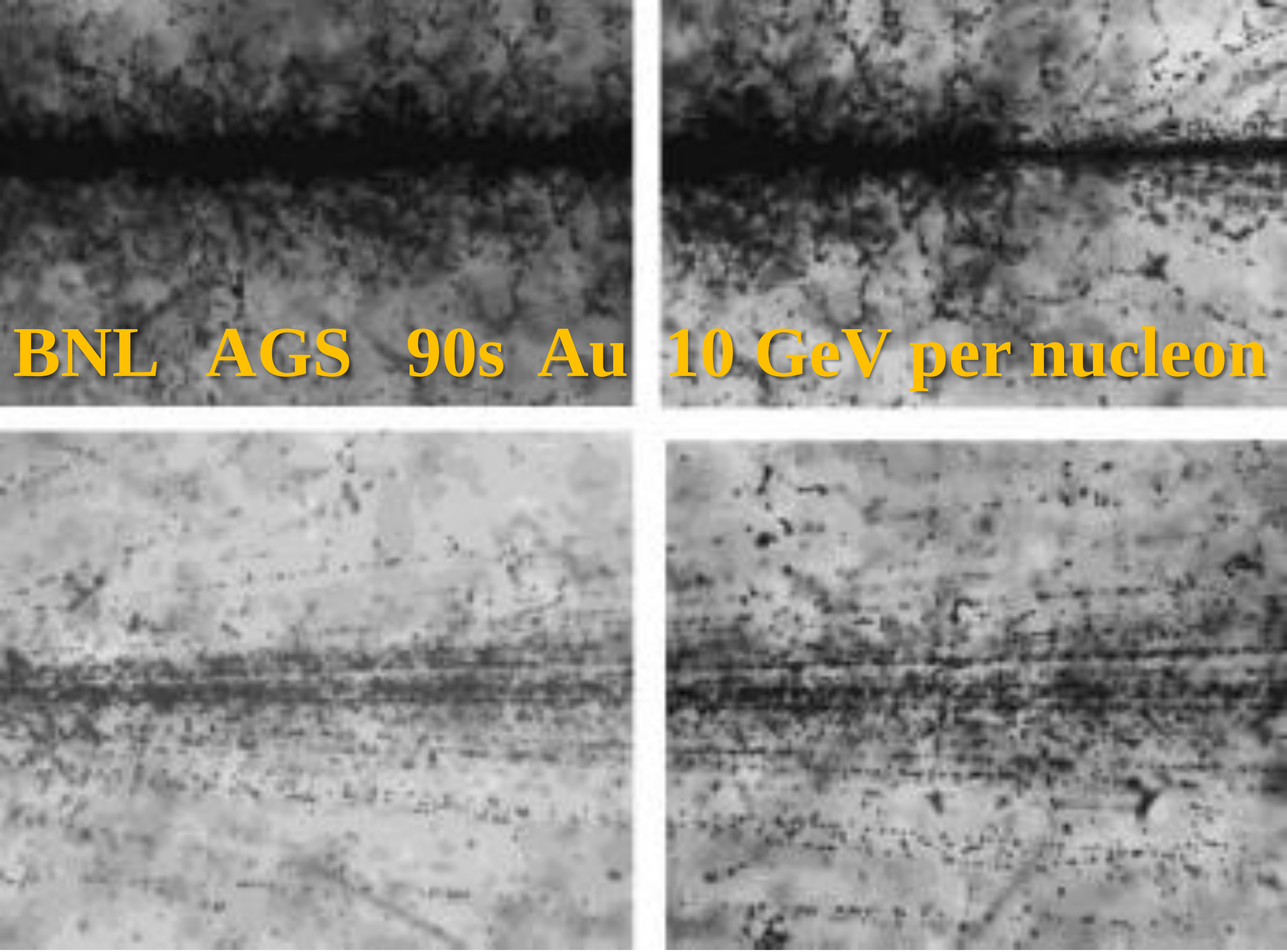


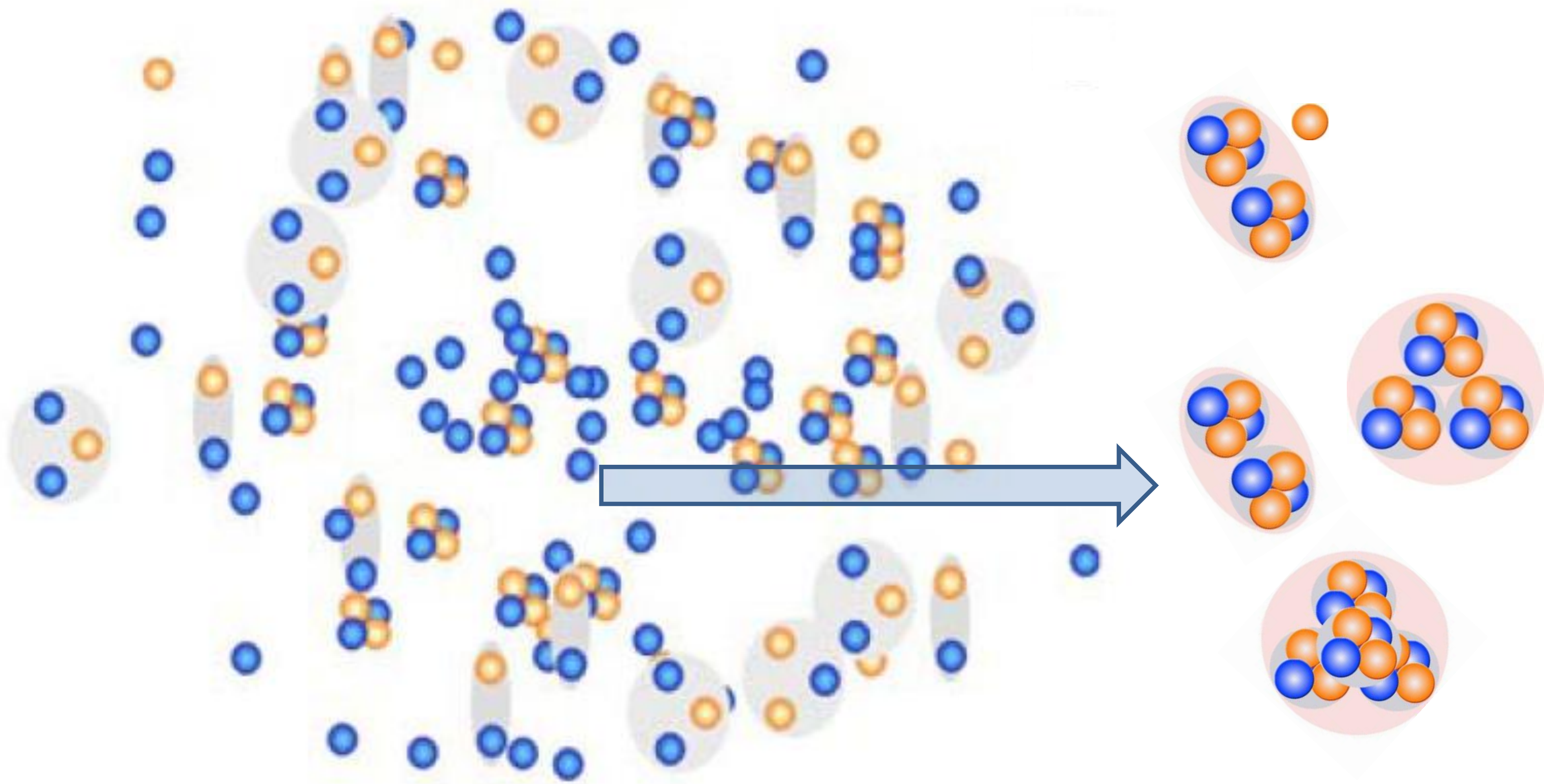
strong cluster
phenomena in
lighter nuclei

Currently, a research focus is on the theoretical concept of α-particle Bose-Einstein condensate (αBEC) - the ultra cold state of several S-wave α-particles near coupling thresholds. The unstable ^{8}Be nucleus is described as 2αBEC, and the ^{12}C(0^+_2) excitation or Hoyle state (HS) as 3αBEC. Decays ^{8}Be → 2α and ^{12}C(0^+_2) → ^{8}Beα can serve as signatures for more complex αBEC decays. Thus, the 0^+_6 state of the ^{16}O nucleus at 660 keV above the 4α threshold, considered as 4αBEC, can sequentially decay ^{16}O(0^+_6) → α^{12}C(0^+_2) or ^{16}O(0^+_6) → 2^{8}Be(0^+). Its search is being carried out in several experiments on fragmentation of light nuclei at low energies. Confirmation of the existence of this and more complex forms of αBEC could provide a basis for expanding scenarios for the synthesis of medium and heavy nuclei in nuclear astrophysics.

^{28}Si at 3.65 GeV per nucleon




BNL AGS 90s Au 10 GeV per nucleon



The invariant mass approach has been used to identify ^{8}Be and HS and search for more complex states of αBEC in fragmentation of medium and heavy nuclei. Recently, based on the statistics of dozens of ^{8}Be decays, an enhancement in probability of detecting ^{8}Be in an event with an increase in number of relativistic α-particles was found. A preliminary conclusion is drawn that contributions of ^{9}B and HS decays also increase. The exotically large sizes and lifetimes of ^{8}Be and HS allowing suggesting possibility of synthesizing αBEC by successively connecting the emerging α-particles.

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THE EUROPEAN PHYSICAL JOURNAL A

Regular Article - Experimental Physics

Unstable states in dissociation of relativistic nuclei

Recent findings and prospects of research

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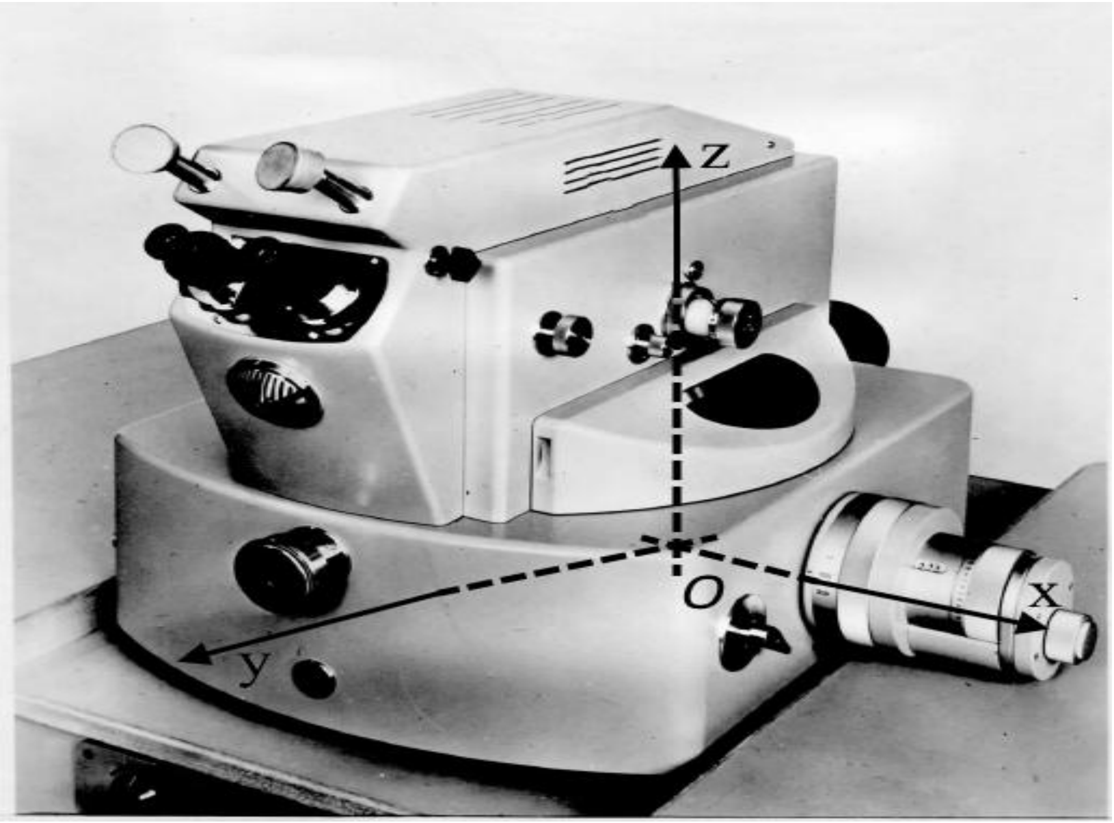
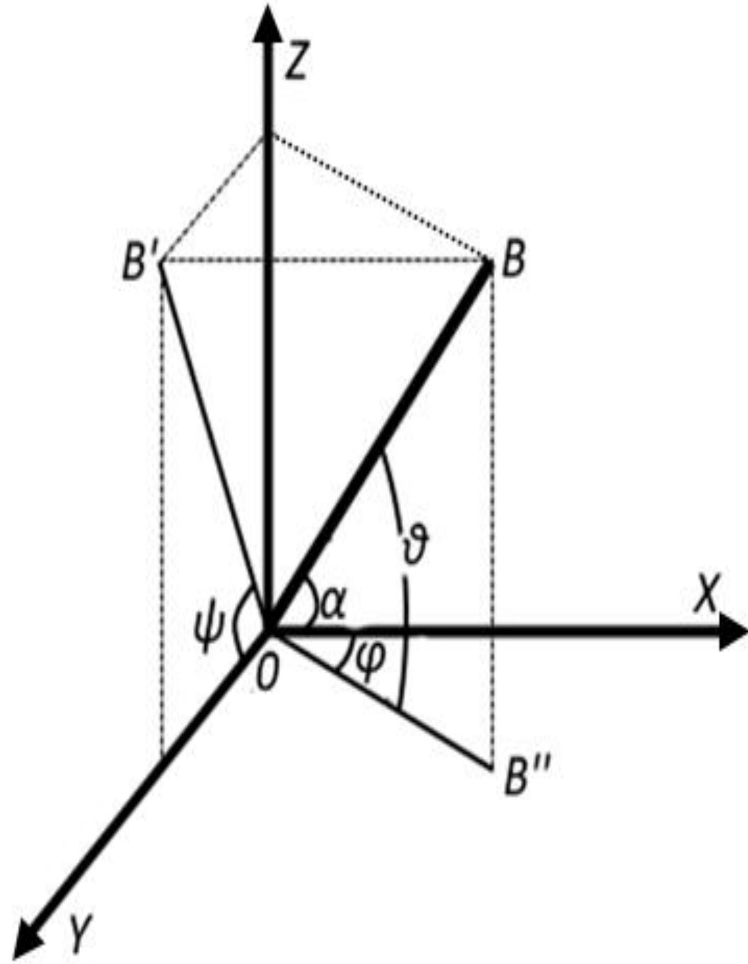
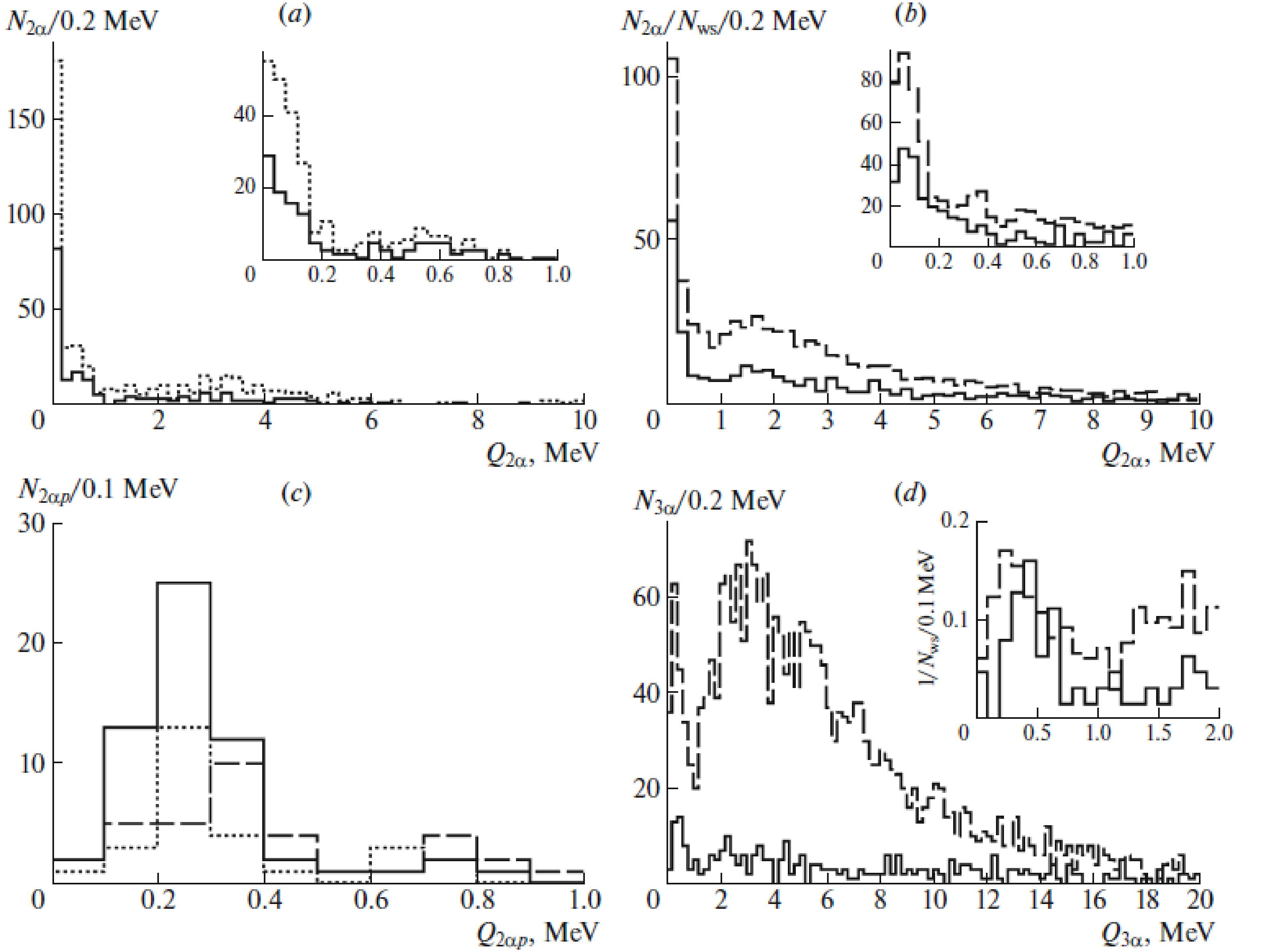




In general, energy of a few-particle system Q is $Q = M^{*} - M$. M^{*} is the invariant mass defined by the sum of all products of 4-momenta $P_{i,k}$ fragments $M^{*2} = \sum(P_i \cdot P_k)$. Subtraction of mass M is a matter of convenience. The 4-momenta $P_{i,k}$ are determined in the approximation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



Invariant-mass distributions [7]: (*a*) $Q_{2\alpha}$ in ^{9}Be(1.2 GeV/nucleon) $\to 2\alpha$ (dotted curve) and white stars (solid curve); (*b*) $Q_{2\alpha}$ in ^{12}C(3.65 GeV/nucleon) $\to 3\alpha$ (solid curve) and ^{16}O(3.65 GeV/nucleon) $\to 4\alpha$ (dashed curve); (*c*) $Q_{2\alpha p}$ (<1 MeV) in ^{10}C(1.2 GeV/nucleon) $\to 2\alpha 2p$ (solid curve), ^{11}C(1.2 GeV/nucleon) $\to 2\alpha 2p$ (dotted curve), and ^{10}B(1 GeV/nucleon) $\to 2\alpha p$ (dashed curve); and (*d*) $Q_{3\alpha}$ in ^{12}C(3.65 GeV/nucleon) $\to 3\alpha$ (solid curve) and ^{16}O(3.65 GeV/nucleon) $\to 4\alpha$ (dashed curve).

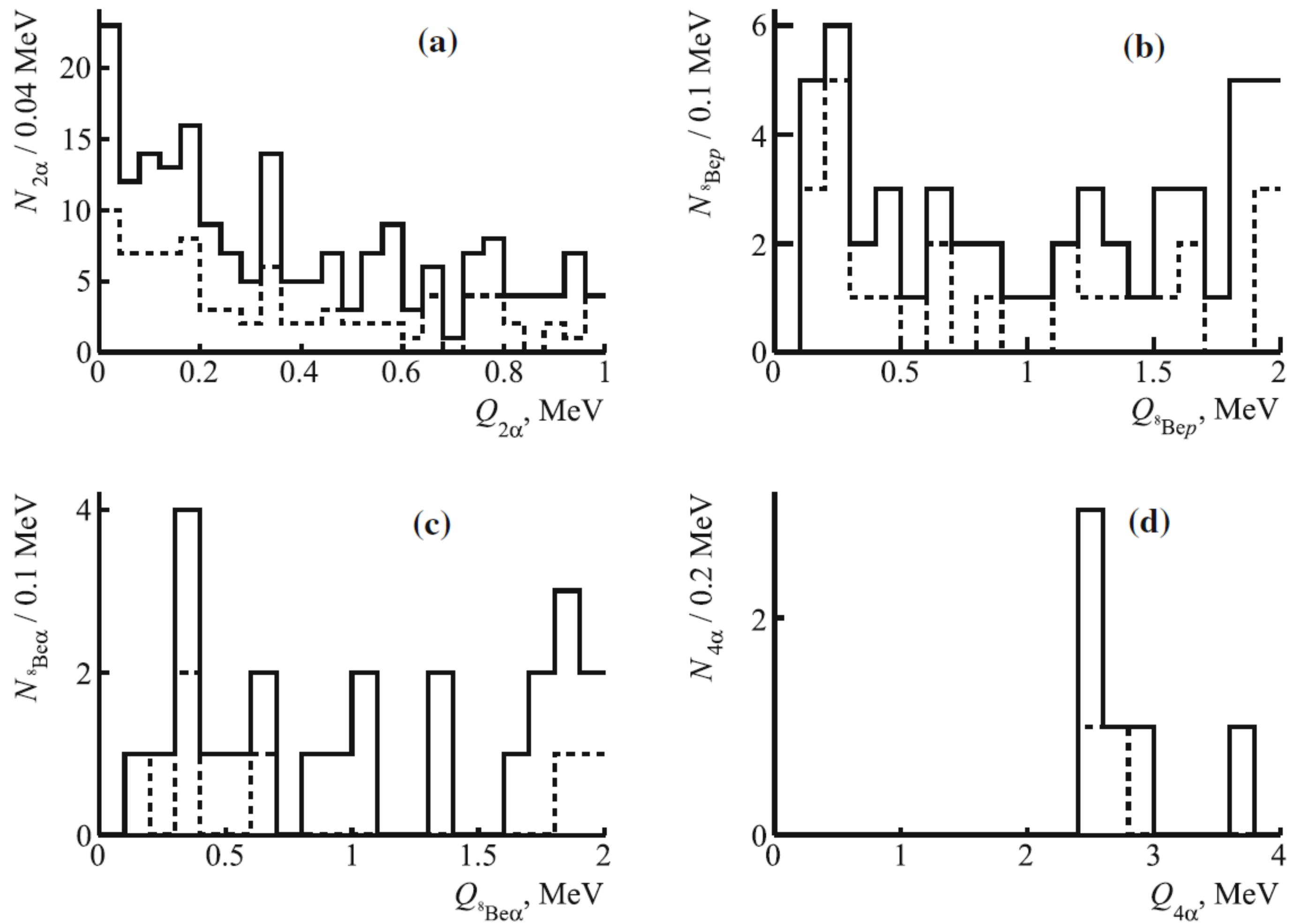
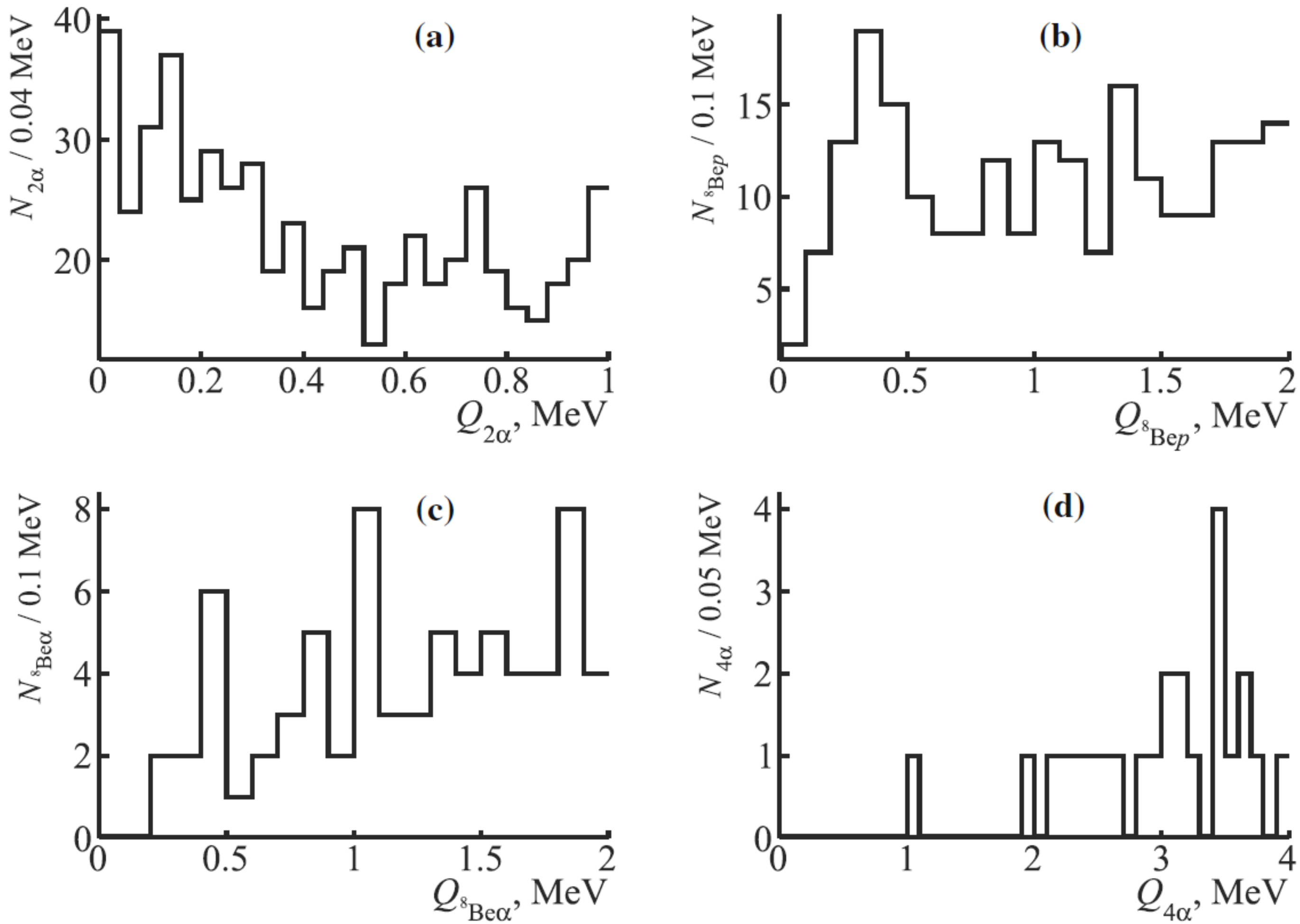


Fig. 7 Distributions of 2α, $2\alpha p$, 3α and 4α combinations from events of fragmentation of ^{28}Si nuclei at 14.6 *A* GeV over the invariant masses $Q_{2\alpha}$ (**a**), $Q_{2\alpha p}$ (**b**), $Q_{3\alpha}$ (**c**) and $Q_{4\alpha}$ (**d**) in the their small value regions, according to data for the case without sampling (points) and recent measurements in accelerated search (added by solid line)

Fig. 8 Distributions of 2α, $2\alpha p$, 3α and 4α combinations from events of fragmentation of ^{197}Au nuclei at 10.7 A GeV over the invariant masses $Q_{2\alpha}$ (**a**), $Q_{2\alpha p}$ (**b**), $Q_{3\alpha}$ (**c**) and $Q_{4\alpha}$ (**d**) in the their small value regions



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Correlation in formation of ^{8}Be nuclei and α-particles in fragmentation of relativistic nuclei

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A B S T R A C T

In the events of peripheral dissociation of relativistic nuclei in the nuclear track emulsion, it is possible to study the emerging ensembles of He and H nuclei, including those from decays of unstable ^{8}Be and ^{9}B nuclei, as well as the Hoyle state. These extremely short-lived states are identified by invariant masses calculated from the angles in 2α-pairs, $2\alpha p$- and 3α-triplets in the approximation of conservation of momentum per nucleon of the primary nucleus. In the same approach, it is possible to search for more complex states. This paper explores the correlation between the formation of ^{8}Be nuclei and the multiplicity of accompanying α-particles in the dissociation of relativistic ^{16}O, ^{22}Ne, ^{28}Si, and ^{197}Au nuclei. On the above basis, estimates of this correlation are presented for the unstable ^{9}B nucleus and the Hoyle state. The enhancement in the ^{8}Be contribution to dissociation with the α-particle multiplicity has been found. Decays of ^{9}B nuclei and Hoyle states follow the same trend.

Statistics $N_{n\alpha}(^8\mathrm{Be})$ among n_α events of ^{16}O dissociation; percentage of $N_{n\alpha}(^8\mathrm{Be})$ among $N_{n\alpha}$ is indicated.

n_α	3.65 GeV/nucleon $N_{n\alpha}(^8\mathrm{Be})/N_{n\alpha}$ (%)	15 GeV/nucleon $N_{n\alpha}(^8\mathrm{Be})/N_{n\alpha}$ (%)	60 GeV/nucleon $N_{n\alpha}(^8\mathrm{Be})/N_{n\alpha}$ (%)	200 GeV/nucleon $N_{n\alpha}(^8\mathrm{Be})/N_{n\alpha}$ (%)	All $N_{n\alpha}(^8\mathrm{Be})/N_{n\alpha}$ (%)
2	32/390 (8 ± 2)	6/95 (6 ± 3)	9/97 (9 ± 3)	3/56 (5 ± 3)	50/638 (8 ± 1)
3	40/176 (23 ± 4)	13/51 (26 ± 8)	12/64 (19 ± 6)	8/29 (28 ± 11)	73/320 (23 ± 3)
4	13/28 (46 ± 15)	1/4 (25)	2/2 (100)	0/1 (0)	16/35 (46 ± 14)

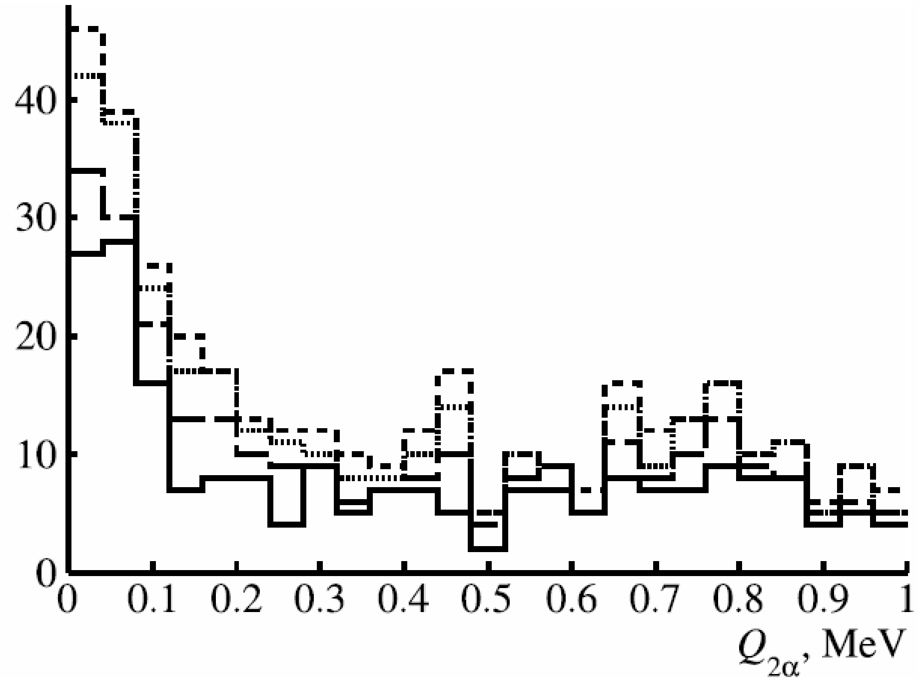


Fig. 1. Distribution of 2α-pairs $N_{(2\alpha)}$ over invariant mass $Q_{2\alpha}$ ($\leq$ 1 MeV) in fragmentation of 3.65 GeV/nucleon ^{16}O nuclei (solid line); data for 15 (long dotted line), 60 (dotted line) and 200 (short-dotted line) GeV/nucleon ^{16}O are added sequentially.

Statistics of events $N_{n\alpha}(^8\mathrm{Be})$ among $N_{n\alpha}$ events in dissociation of ^{22}Ne and ^{28}Si nuclei; the percentage of $N_{n\alpha}(^8\mathrm{Be})$ among $N_{n\alpha}$ is indicated.

n_α	^{22}Ne 3.22 GeV/nucleon $N_{n\alpha}(^8\mathrm{Be})/N_{n\alpha}$ (%)	^{28}Si 15 GeV/nucleon $N_{n\alpha}(^8\mathrm{Be})/N_{n\alpha}$ (%)
2	30/528 (6 ± 1)	5/164 (3 ± 2)
3	45/243 (19 ± 3)	47/320 (15 ± 2)
4	25/80 (31 ± 6)	55/168 (33 ± 5)
5	6/10 (60 ± 31)	24/62 (39 ± 10)
6	-	5/7 (72 ± 42)

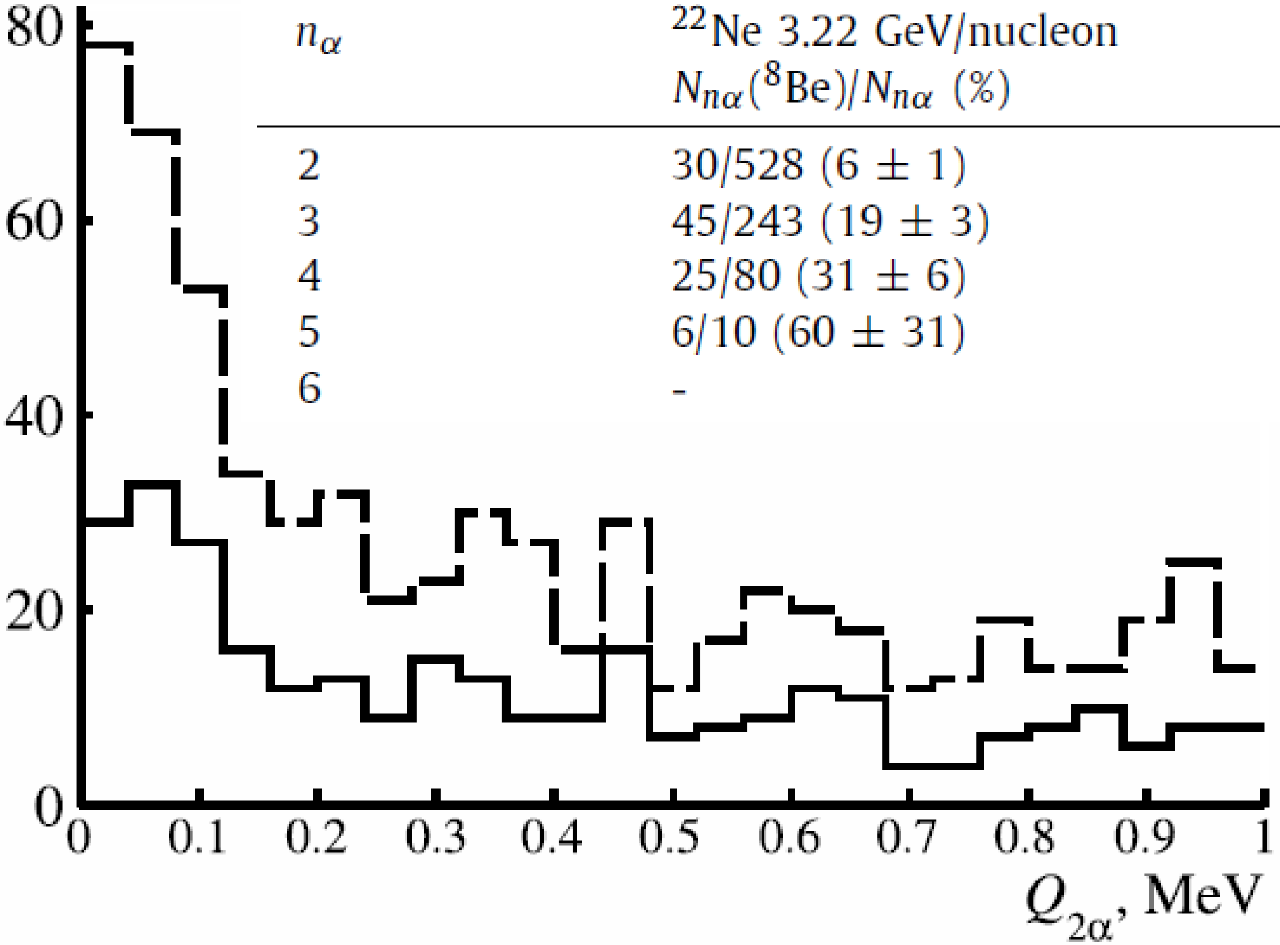


Fig. 4. Distribution of 2α-pairs $N_{(2\alpha)}$ over invariant mass $Q_{2\alpha}$ ($\leq$ 1 MeV) in fragmentation of 3.22 GeV/nucleon ^{22}Ne (solid line) and 14.6 GeV/nucleon ^{28}Si nuclei (added by the dotted line).

Statistics of $N_{n\alpha mp}(^{9}\mathrm{B})$ and $N_{n\alpha mp}(^{8}\mathrm{Be})$ decays in the fragmentation channels $N_{n\alpha mp}(^{8}\mathrm{Be})$ of $^{16}\mathrm{O}$, $^{22}\mathrm{Ne}$ and $^{28}\mathrm{Si}$ nuclei with a multiplicity of α-particles n_α and protons m_p.

$^{16}\mathrm{O}$ $N_{n\alpha mp}$	$^{16}\mathrm{O}$ $\frac{N_{n\alpha mp}(^{9}B)}{N_{n\alpha mp}(^{8}Be)}$ (%)	$^{22}\mathrm{Ne}$ $N_{n\alpha mp}$	$^{22}\mathrm{Ne}$ $\frac{N_{n\alpha mp}(^{9}B)}{N_{n\alpha mp}(^{8}Be)}$ (%)	$^{28}\mathrm{Si}$ $N_{n\alpha mp}$	$^{28}\mathrm{Si}$ $\frac{N_{n\alpha mp}(^{9}B)}{N_{n\alpha mp}(^{8}Be)}$ (%)
338 2α + (1-4)p	9/26 (35 ± 14)	429 2α + (1-6)p	8/25 (32 ± 13)	184 2α + mp	2/8 (25 ± 20)
131 3α + (1,2)p	12/31 (39 ± 13)	203 3α + (1-4)p	8/39 (21 ± 8)	320 3α + mp	8/47 (17 ± 7)
-	-	58 4α + (1,2)p	5/20 (25 ± 12)	168 4α + mp	9/55 (16 ± 6)
-	-	-	-	62 5α + mp	3/24 (13 ± 8)
-	-	-	-	7 6α + mp	0/5

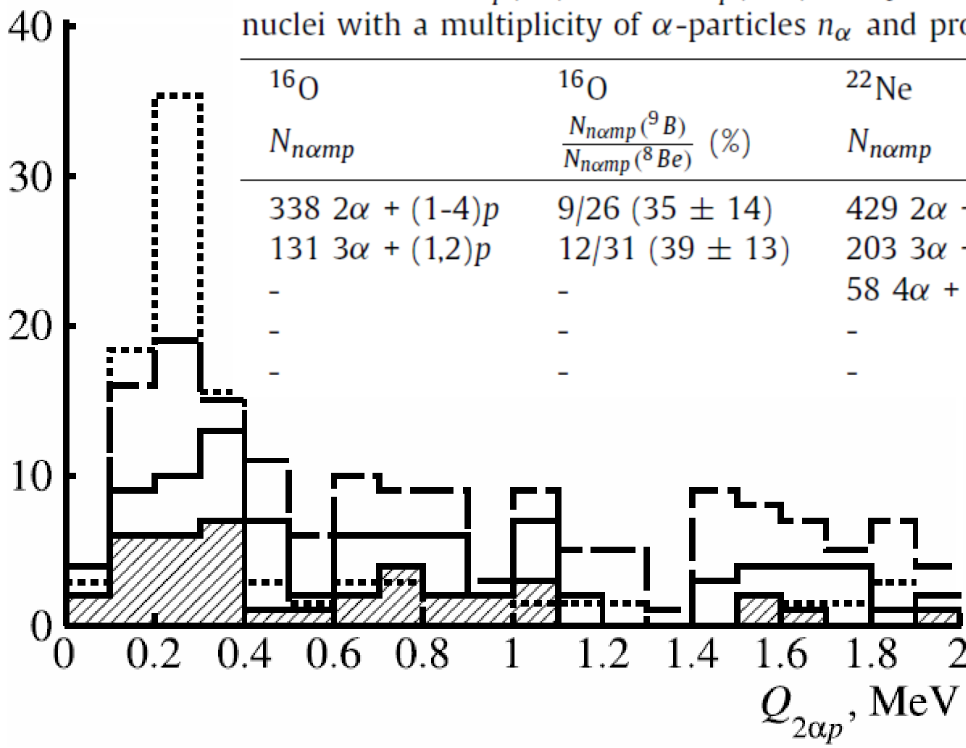


Fig. 2. Distribution of $2\alpha p$ triples $N_{(2\alpha p)}(^{8}\mathrm{Be})$ over invariant mass $Q_{2\alpha p} \le 2$ MeV in 3.65 GeV/nucleon $^{16}\mathrm{O}$ (shaded), 3.22 GeV/nucleon $^{22}\mathrm{Ne}$ fragmentation (added by the solid line) and 15 GeV/nucleon $^{28}\mathrm{Si}$ (added by the dashed line). Dots mark $N_{2\alpha p}(^{8}\mathrm{Be})$ distribution in coherent dissociation $^{10}\mathrm{C} \to 2\alpha 2p$ (normalized to $^{16}\mathrm{O}$, $^{22}\mathrm{Ne}$ and $^{28}\mathrm{Si}$ statistics).

Statistics of events $N_{n\alpha}$(HS) among events $N_{n\alpha}$ in dissociation of ^{22}Ne nuclei and ^{28}Si; the percentage of $N_{n\alpha}(^8\text{Be})$ among $N_{n\alpha}$ is indicated.

n_α	^{22}Ne $N_{n\alpha}$(HS)/$N_{n\alpha}$ (% $N_{n\alpha}$)	^{22}Ne N(HS)/$N_{n\alpha}(^8\text{Be})$, %	^{28}Si $N_{n\alpha}$(HS)/$N_{n\alpha}$ (% $N_{n\alpha}$)	^{28}Si N(HS)/$N_{n\alpha}(^8\text{Be})$, %
3	3/243 (1.2 ± 0.6)	7 ± 4	4/320 (1.2 ± 0.6)	4/47 (9 ± 5)
4	10/80 (13 ± 5)	40 ± 15	7/168 (4 ± 2)	7/55 (13 ± 5)
5	1/10	17	7/62 (11 ± 5)	7/24 (29 ± 12)
6	-	-	1/7 (14)	1/5 (20)

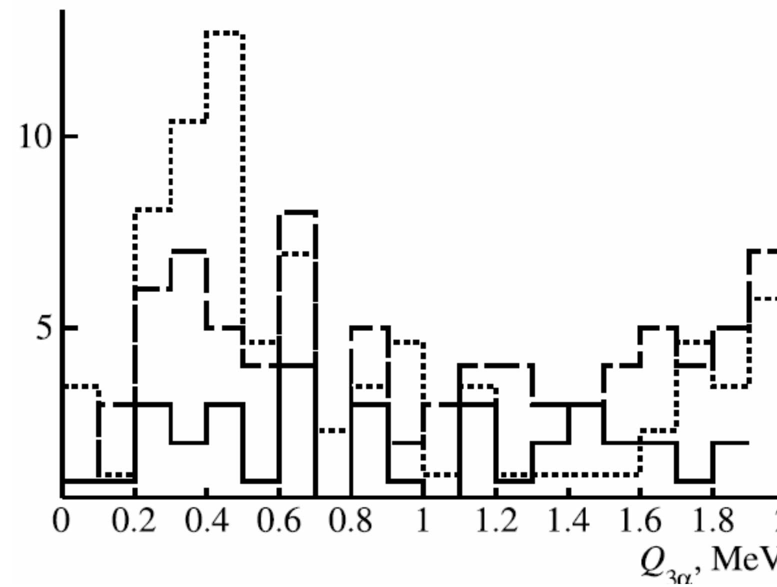
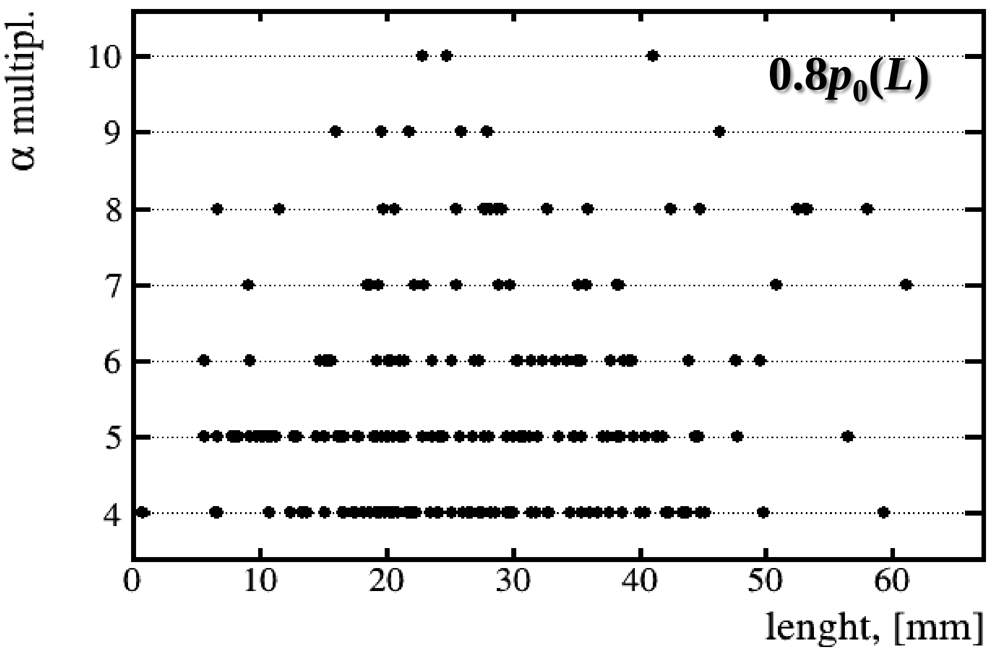


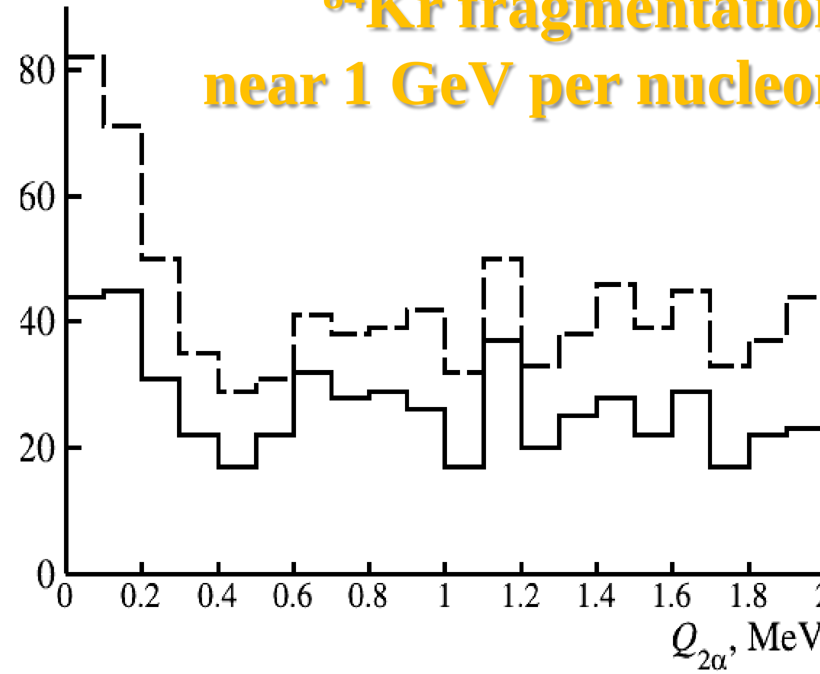
Fig. 5. Distribution of 3α-triplets $N_{(3\alpha)}(^8\text{Be})$ over invariant mass in 3.22 GeV/nucleon ^{22}Ne fragmentation (solid line) and ^{28}Si at 14.6 GeV/nucleon (dashed line). Dots mark distribution $N_{(3\alpha)}(^8\text{Be})$ in dissociation $^{12}\text{C} \to 3\alpha$ normalized to ^{22}Ne and ^{28}Si statistics.

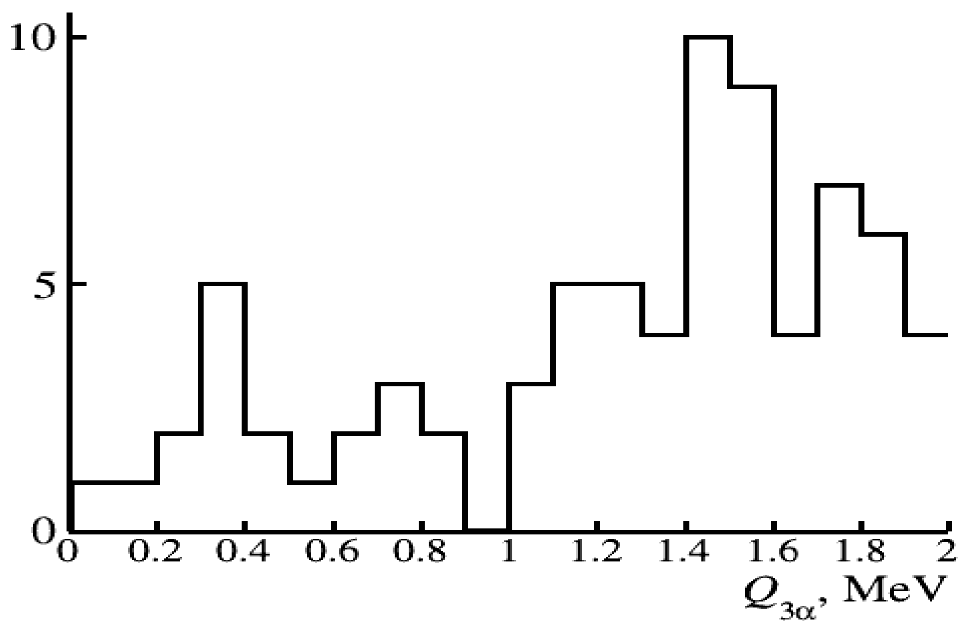
Statistics of events containing at least one ^{8}Be, ^{9}B or HS decay, or at least two ^{8}Be provided $Q_{2\alpha}$ (^{8}Be) $\leq$ 0.4 MeV among the events $N_{n\alpha}$ of ^{197}Au fragmentation with multiplicity n_α; the total statistics of the channels $n_\alpha \geq 11$ is given in italics.

n_α	$N_{n\alpha}(^8\mathrm{Be})/N_{n\alpha}$ (% $N_{n\alpha}$)	$N_{n\alpha}(^9\mathrm{B})$ (% $N_{n\alpha}(^8\mathrm{Be})$)	$N_{n\alpha}(\mathrm{HS})$ (% $N_{n\alpha}(^8\mathrm{Be})$)	$N_{n\alpha}(2^8\mathrm{Be})$ (% $N_{n\alpha}(^8\mathrm{Be})$)
2	3/133 (2 ± 1)	-	-	-
3	14/162 (9 ± 3)	1 (7)	-	-
4	25/161 (16 ± 4)	7 (28 ± 12)	2 (8 ± 6)	-
5	23/135 (17 ± 4)	5 (22 ± 11)	-	1 (4)
6	31/101 (31 ± 7)	9 (29 ± 11)	2 (6 ± 4)	-
7	31/90 (34 ± 7)	6 (19 ± 9)	2 (6 ± 4)	3 (10 ± 6)
8	32/71 (45 ± 10)	8 (25 ± 10)	2 (6 ± 4)	2 (7 ± 5)
9	29/54 (54 ± 13)	9 (31 ± 12)	3 (10 ± 6)	5 (17 ± 8)
10	22/39 (56 ± 15)	4 (18 ± 10)	-	5 (23 ± 12)
11	10/15 (67 ± 27)	3 (30 ± 20)	1 (10)	2 (20 ± 16)
	19/30 (63 ± 19)	*7 (37 ± 16)*	*2 (11 ± 8)*	*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

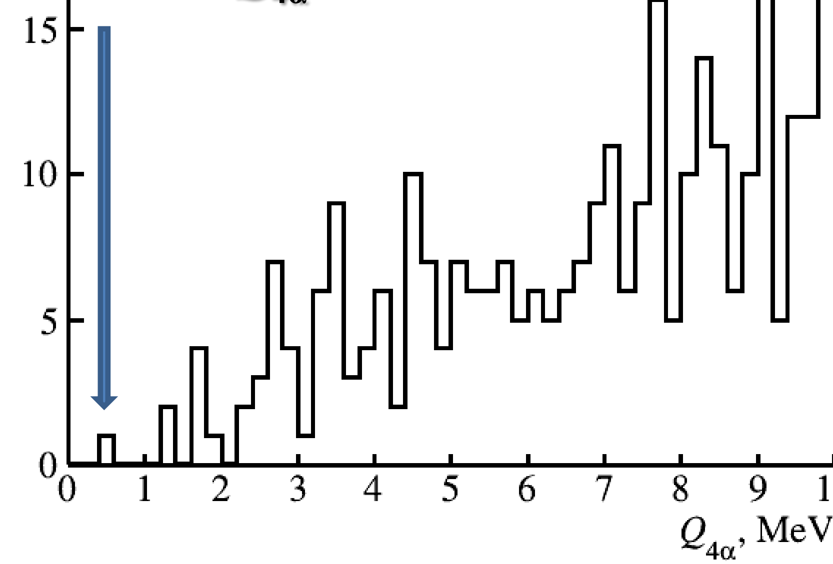
^{84}Kr fragmentation near 1 GeV per nucleon

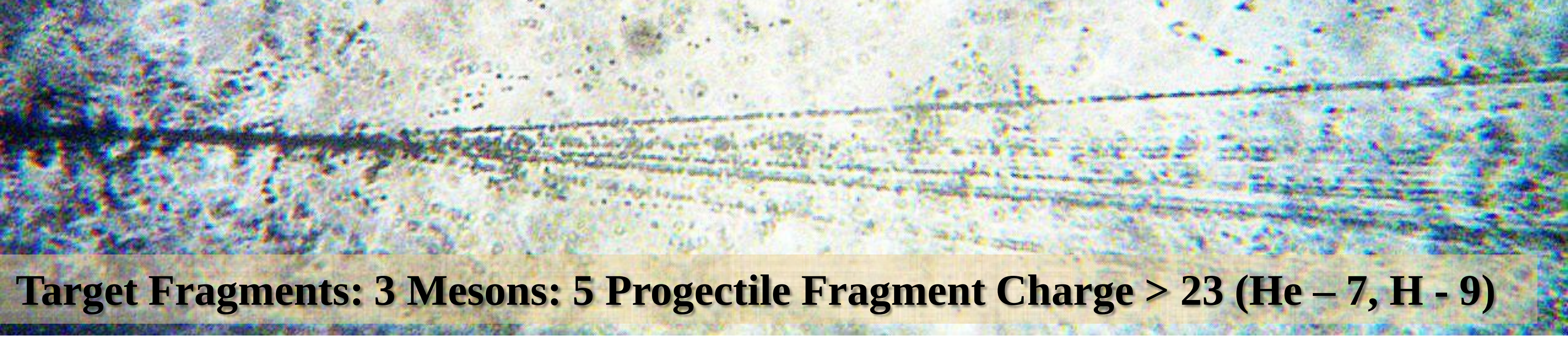






32 мм n_α = 6
2^{8}Be $Q_{4\alpha}$= 0.6 МэВ

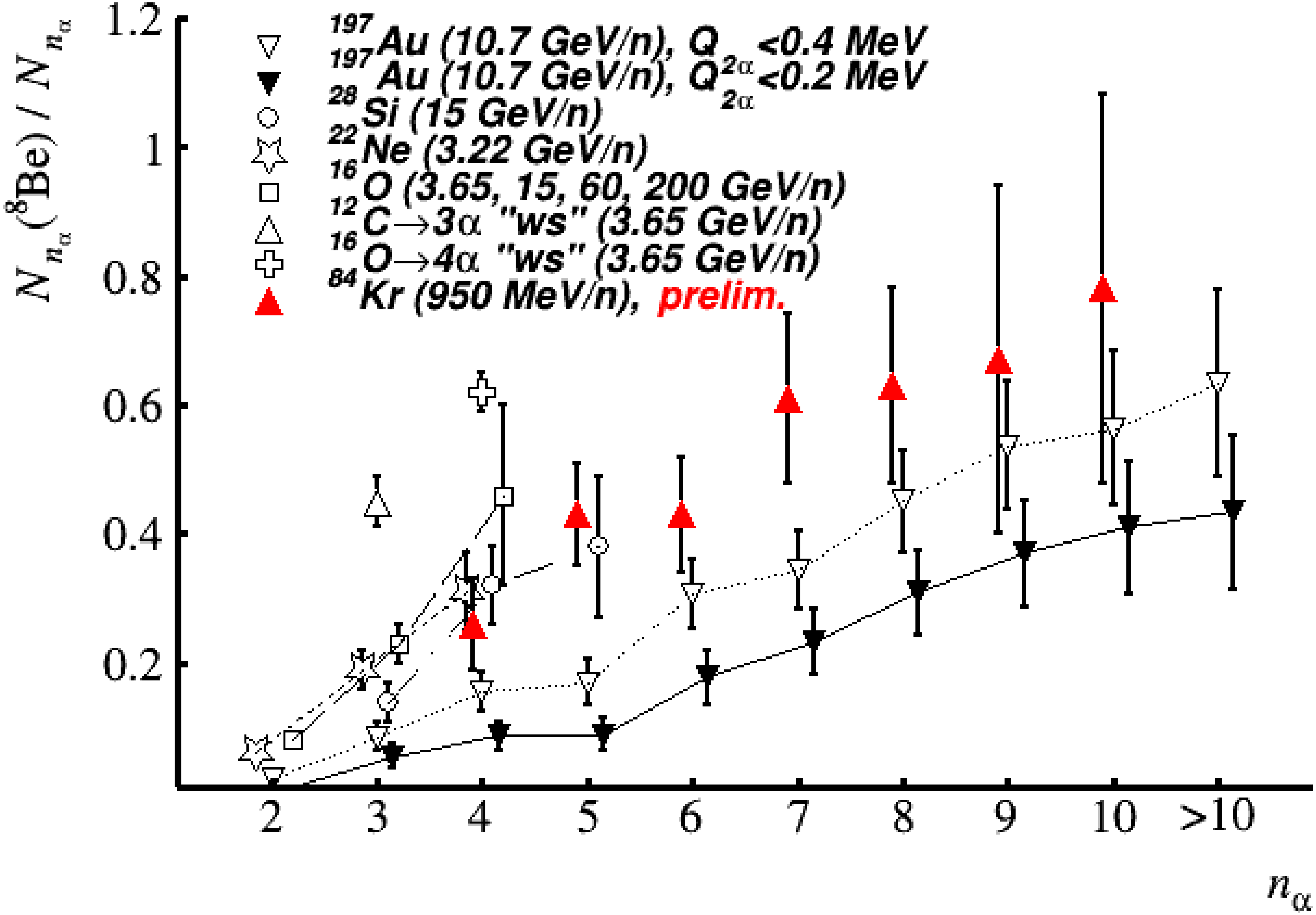




^{84}Kr fragmentation near 1 GeV per nucleon

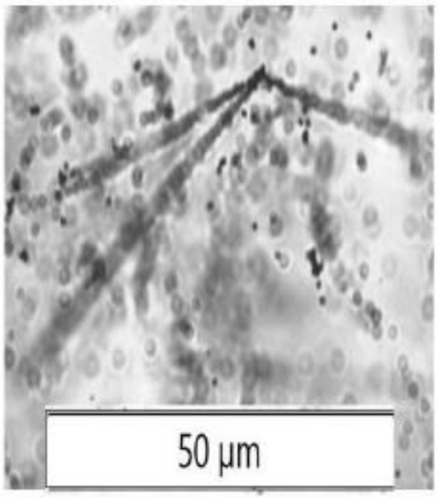
Table 1. Statistics $N_{n\alpha}$ of $n\alpha > 3$ stars (statistics of the data sample from [14] is given in parentheses)

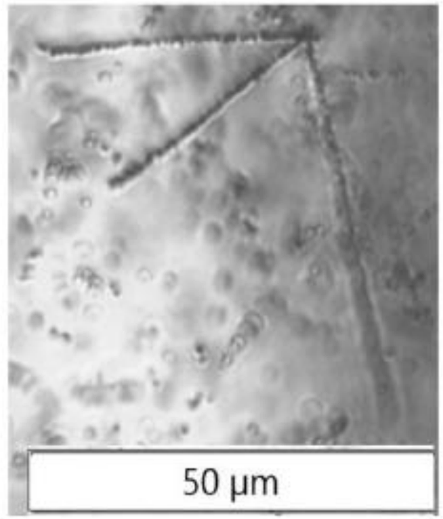
$n\alpha$	4	5	6	7	8	9–13
$N_{n\alpha}$	40(69)	50(54)	21(27)	10(19)	15(12)	7(3)
$N_{n\alpha}/N_{\mathrm{ev}}$, %	(7.9 ± 1.0)	(6.2 ± 0.9)	(3.1 ± 0.6)	(2.2 ± 0.5)	(1.4 ± 0.4)	(0.4 ± 0.2)
$N_{n\alpha}(\geqslant 1\,^8\mathrm{Be})$	5(15)	16(10)	12(13)	4(10)	11(8)	4(3)
$N_{n\alpha}(\geqslant 1\,^8\mathrm{Be})/N_{n\alpha}$,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

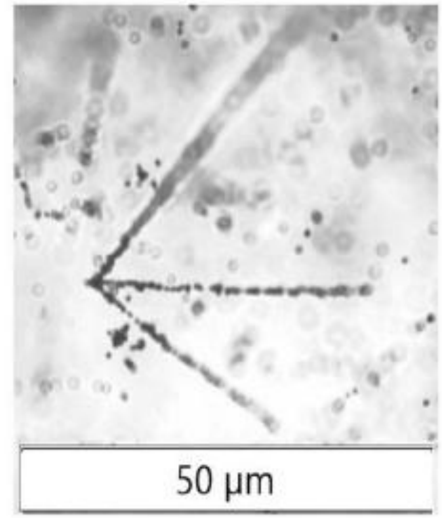


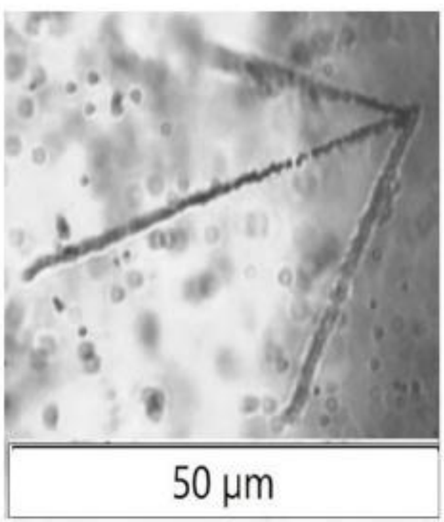
$N_{n_\alpha}(^8Be) / N_{n_\alpha}$
^{197}Au (10.7 GeV/n), $Q_{2\alpha}$<0.4 MeV
^{197}Au (10.7 GeV/n), $Q_{2\alpha}$<0.2 MeV
^{28}Si (15 GeV/n)
^{22}Ne (3.22 GeV/n)
^{16}O (3.65, 15, 60, 200 GeV/n)
$^{12}C \to 3\alpha$ "ws" (3.65 GeV/n)
$^{16}O \to 4\alpha$ "ws" (3.65 GeV/n)
^{84}Kr (950 MeV/n), prelim.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

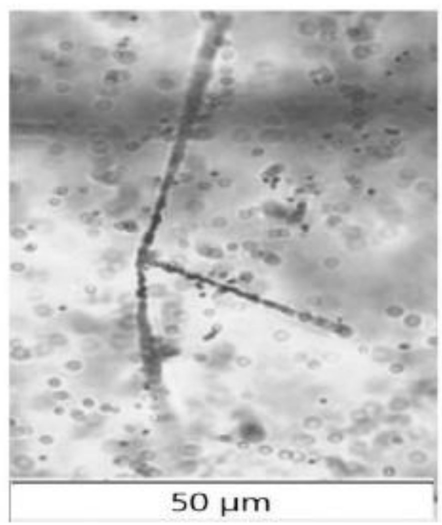
Projectile neutrons in ^{84}Kr fragmentation near 1 GeV per nucleon

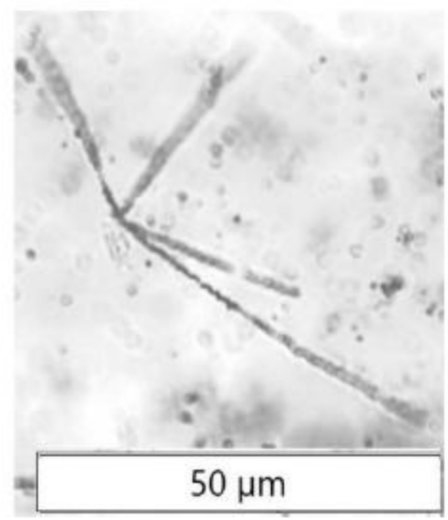




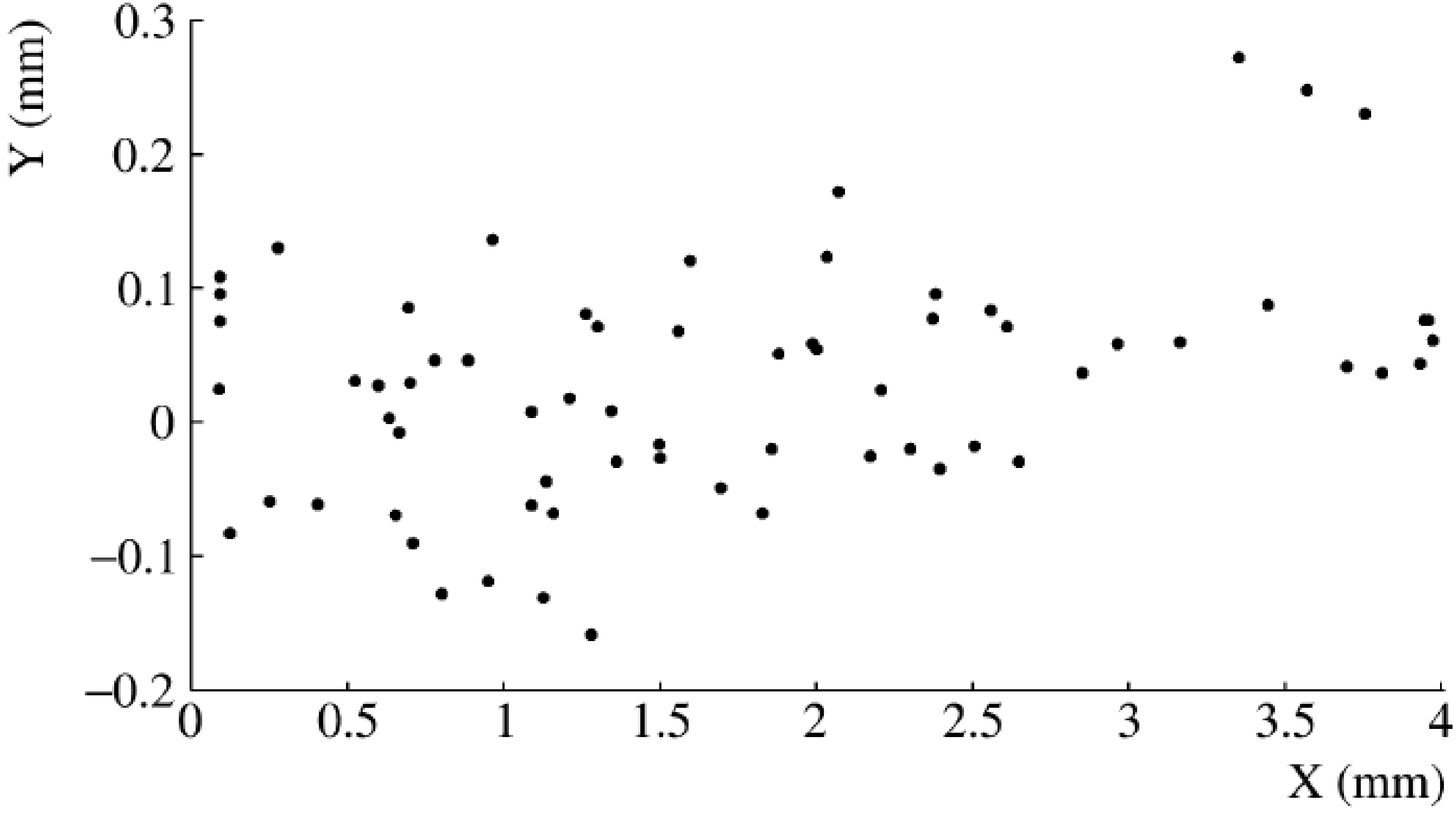




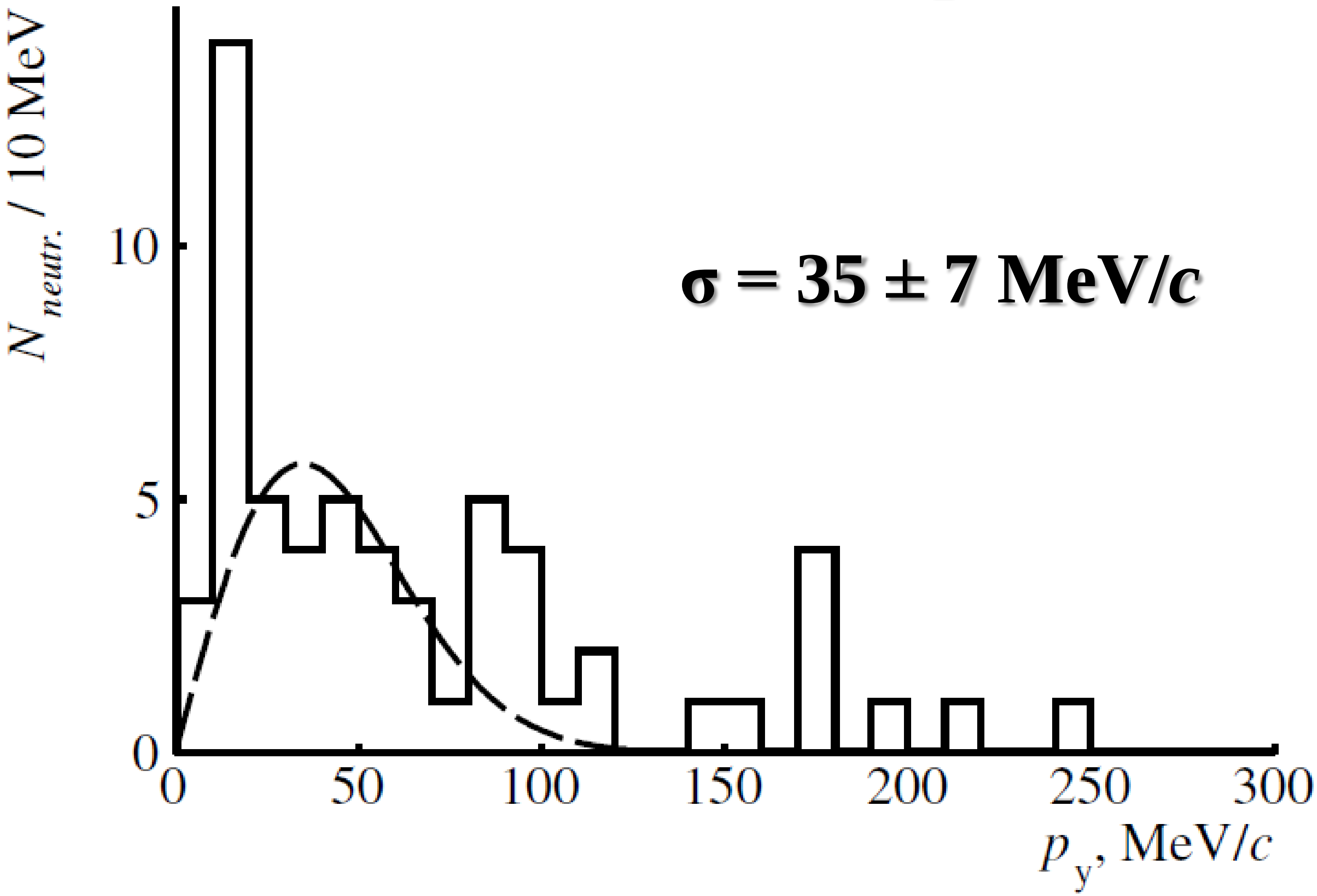




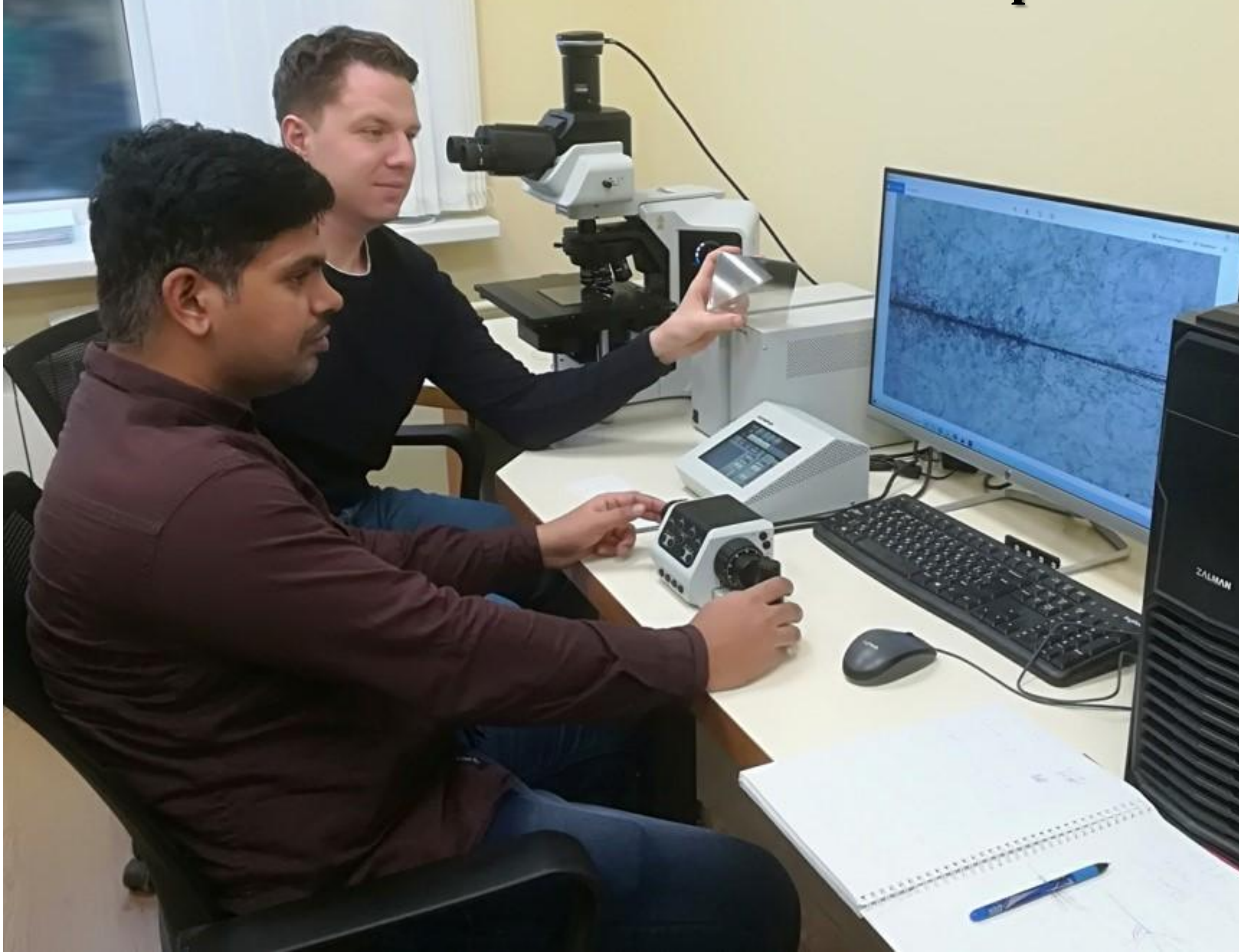
Projectile neutrons in ^{84}Kr fragmentation near 1 GeV per nucleon

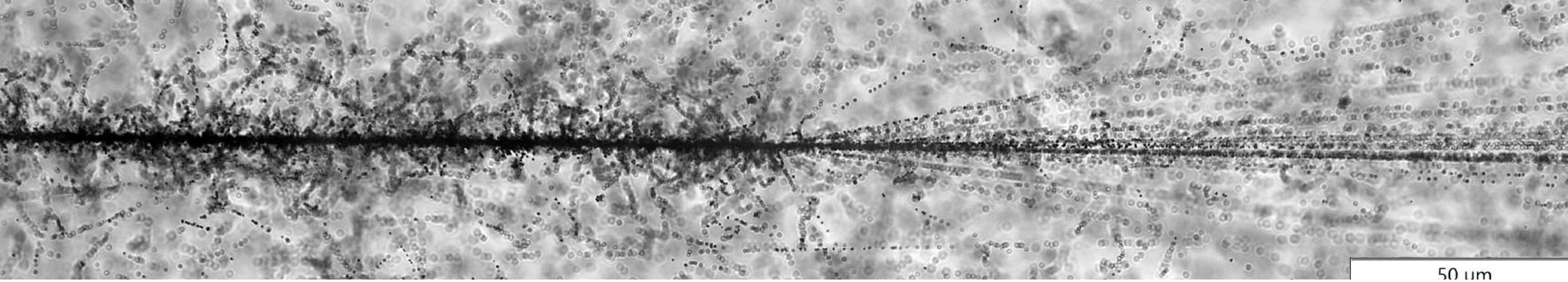


Projectile neutrons in ^{84}Kr fragmentation near 1 GeV per nucleon

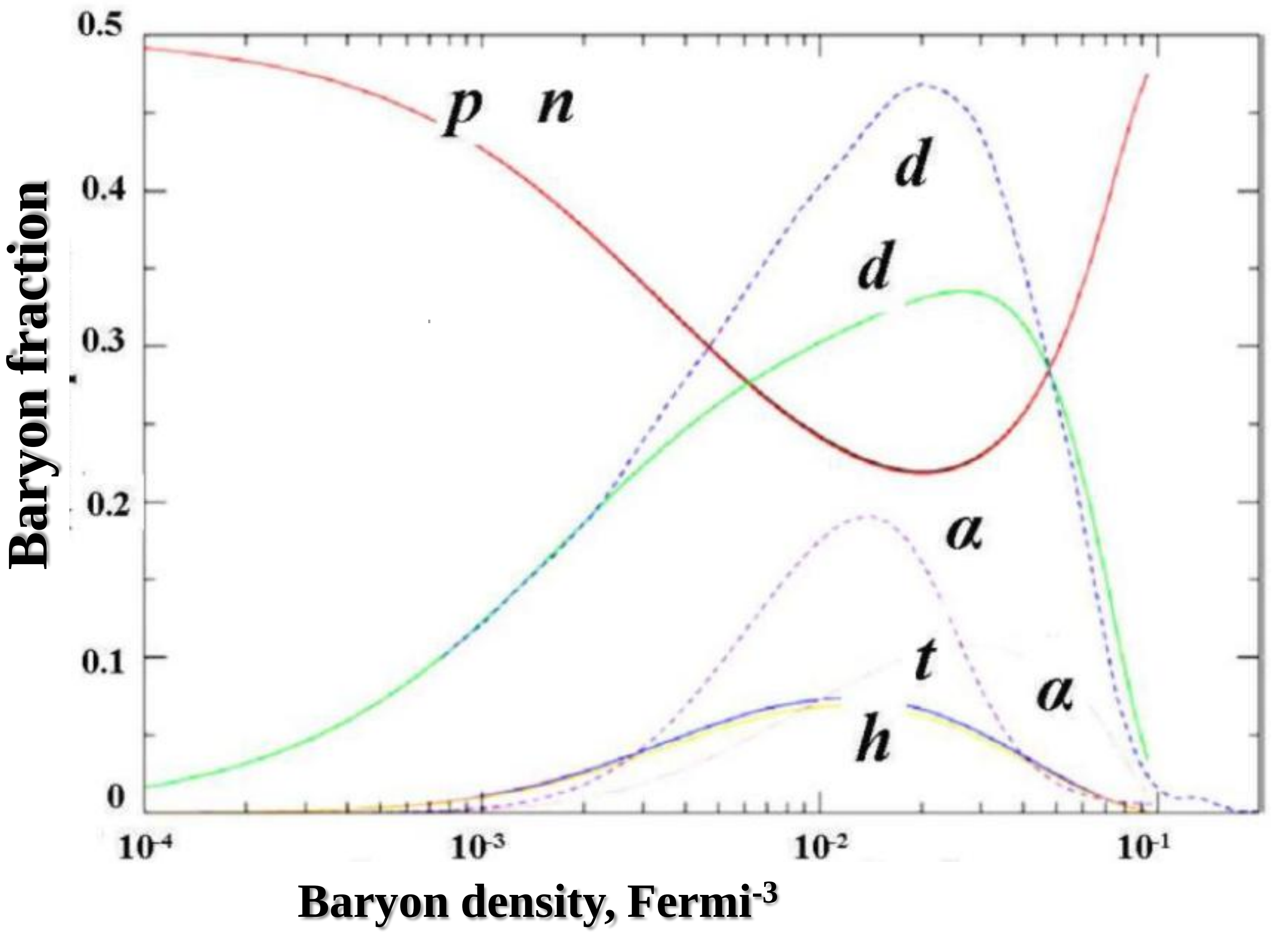


Nuclotron December 2022 ^{124}Xe 3.8 GeV per nucleon





Nuclotron
December
2022
^{124}Xe
3.8 *A* GeV



6. Summary

The preserved and recently supplemented data on the relativistic fragmentation of ^{16}O, ^{22}Ne, ^{28}Si, and ^{197}Au nuclei in a nuclear track emulsion helped us to identify decays of ^{8}Be, ^{9}B nuclei and Hoyle state in the invariant mass distributions of 2α-pairs, $2\alpha p$- and 3α-triplets. The determination of the invariant mass from the fragment emission angles in the velocity conservation approximation turns out to be an adequate approximation. Starting with the ^{16}O fragmentation, the presented analysis has indicated a relative enhancement in the ^{8}Be contribution while increasing in the number of relativistic α-particles per event and remaining proportional contributions of HS and ^{9}B. In the ^{197}Au fragmentation, the tendency is traced up to at least 10 relativistic α-particles per event. This observation has assumed the development of the theory of relativistic nucleus fragmentation taking into account the α-particle interactions, that is characteristic for low-energy nuclear physics.

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Fragmentation of relativistic oxygen nuclei in interactions with a proton

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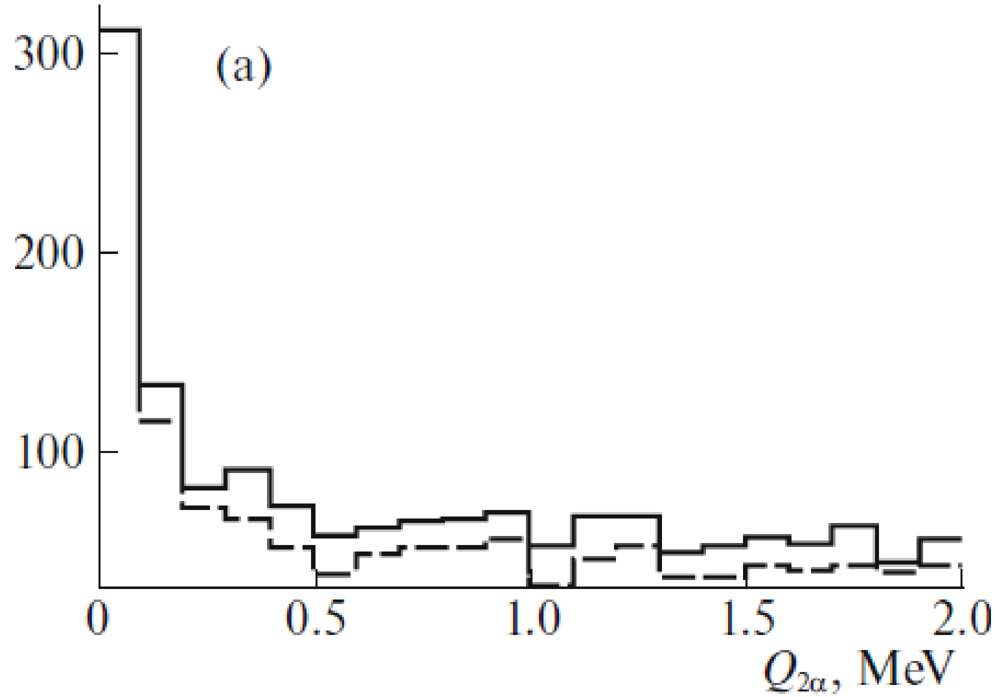
A 1-meter liquid hydrogen bubble chamber of JINR placed in a magnetic provided measured 11000 interactions of ^{16}O nuclei at P_0 = 3.25 GeV/c per nucleon with protons. To determine the charges of fragments, the equality to 9 of the sum of the charges is sufficient. Due to the approximate quantization P_{fr}, their mass numbers are determined by the ratios P_{fr}/P_0.



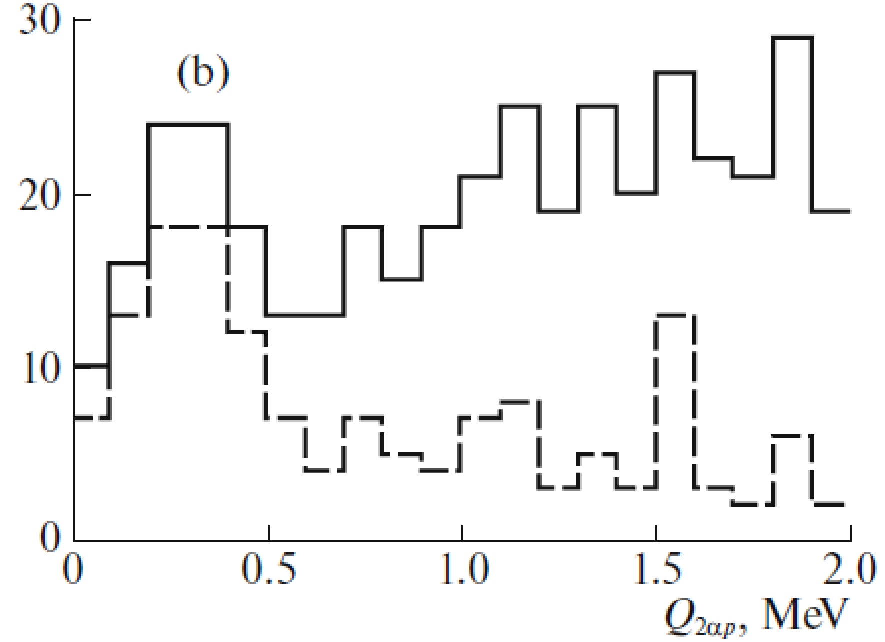
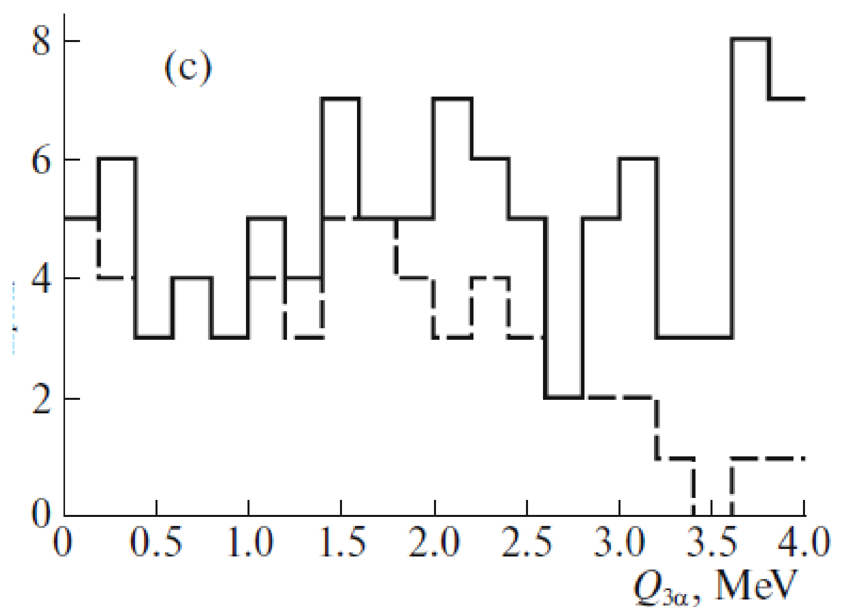
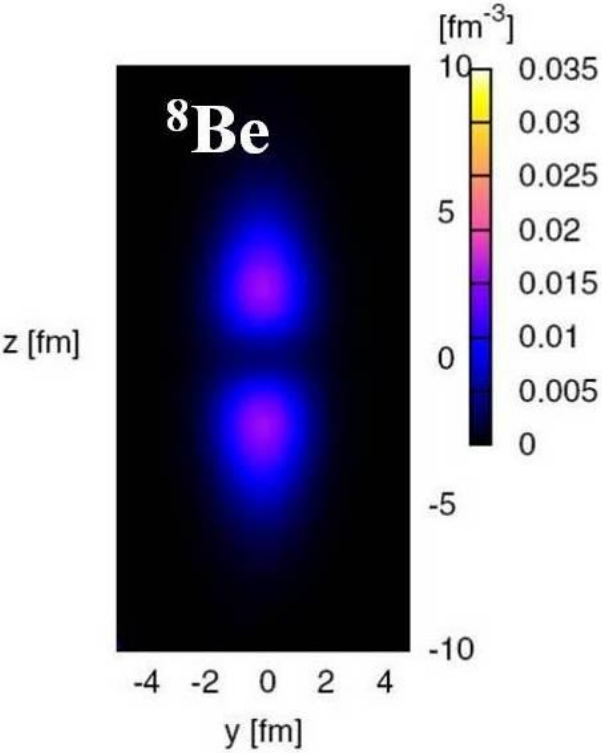


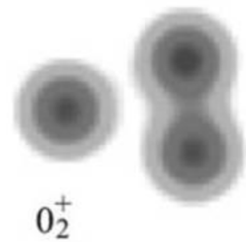
Table 1. Statistics of ^{16}O + p events in VPK-100 containing at least one ^{8}Be decay candidate $N_{n\alpha}(^8\mathrm{Be})$, ^{9}B, or HS provided $Q_{2\alpha}(^8\mathrm{Be}) \leq 0.2$ MeV among $N_{n\alpha}$ events of fragmentation of ^{16}O nuclei on protons with multiplicity n_α

n_α	$N_{n\alpha}(^8\mathrm{Be})/N_{n\alpha}$ (% $N_{n\alpha}$)	$N_{n\alpha}(^9\mathrm{B})$ (% $N_{n\alpha}(^8\mathrm{Be})$)	$N_{n\alpha}(\mathrm{HS})$ (% $N_{n\alpha}(^8\mathrm{Be})$)
2	111/981 (11 ± 1)	29 (26 ± 6)	—
3	203/522 (39 ± 3)	31 (15 ± 3)	36 (18 ± 3)
4	27/56 (48 ± 11)	—	11 (41 ± 15)

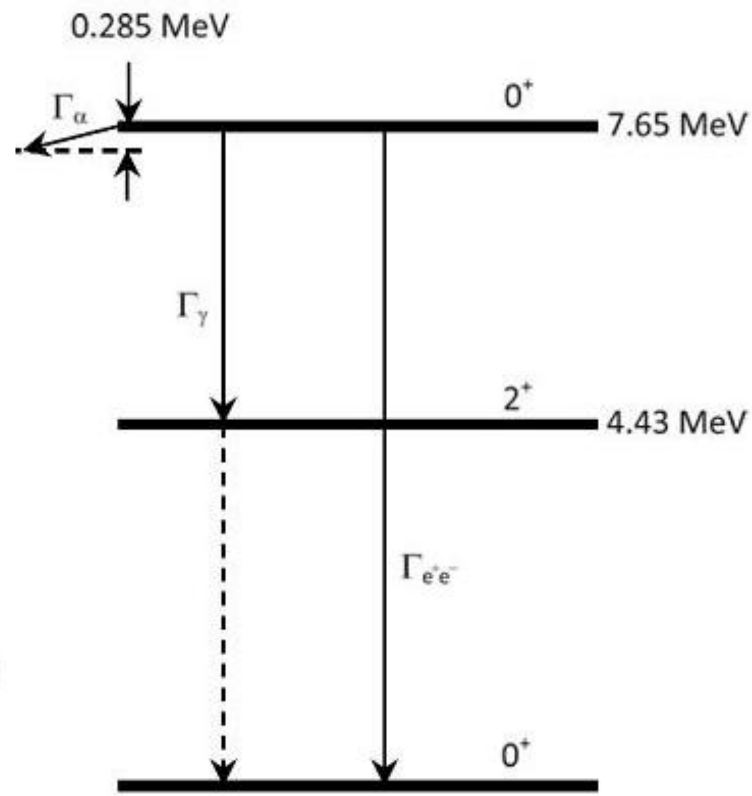


The Hoyle state is the second excited state of ^{12}C at 378 keV above the 3α threshold. The ^{8}Be nucleus inevitably appears among products of ^{9}B and Hoyle state decays.





The Hoyle state



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