Experiment BECQUEREL-2020 at Accelerator Complex NUCLOTRON/NICA

CODE OF THEME: 02-1-1087-2009/2023

Theme: **Research on Relativistic Heavy and Light Ion Physics. Experiments at Accelerator Complex Nuclotron/NICA at JINR and CERN SPS**

D.A. Artemenkov[a], V. Bradnova[a], E. Firu[b], M. Haiduc[b], N.V. Kondratieva[a], N.K. Kornegrutsa[a], E. Mitsova[a,c], A. Neagu[b], K.B. Nomozova[a], V.V. Rusakova[a], R. Stanoeva[c], A.A. Zaitsev[a], I.G. Zarubina[a], P.I. Zarubin[a]

a) Joint Institute for Nuclear Research, Dubna, Russia
b) Institute of Space Research, Magurele, Romania
c) Southwestern University, Blagoevgrad, Bulgaria

PROJECT LEADER **ZARUBIN P.I.**
PROJECT DEPUTY LEADER **ZAITSEV A.A.**

IV. New project BECQUEREL

The PAC heard the proposal for opening a new project: "Experiment BECQUEREL at the NICA accelerator complex (new project BECQUEREL)" presented by P. Zarubin.

Studies of nuclear fragmentation using nuclear emulsions have a very long history. Nevertheless, this method still keeps promising opportunities, in particular due to the high resolution in determination of emission angles of relativistic fragments. The project is devoted to experiments with various accelerators; apart from studies of multifragmentation processes, the authors plan to search for unstable states in nuclei.

Recommendation. The PAC recommends that the VBLHEP Directorate provide financial support for renovation of the equipment used in the BECQUEREL experiment in 2021. The proposal should be presented at the PAC meeting in January 2021.

EPJ A

2019 Impact factor **2.176**

Hadrons and Nuclei

The European Physical Journal A

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

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

Regular Article - Experimental Physics | Published: 06 October 2020

Unstable states in dissociation of relativistic nuclei

Recent findings and prospects of research

D. A. Artemenkov, V. Bradnova, M. M. Chernyavsky, E. Firu, M. Haiduc, N. K. Kornegrutsa, A. I. Malakhov, E. Mitsova, A. Neagu, N. G. Peresadko, V. V. Rusakova, R. Stanoeva, A. A. Zaitsev, P. I. Zarubin & I. G. Zarubina

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

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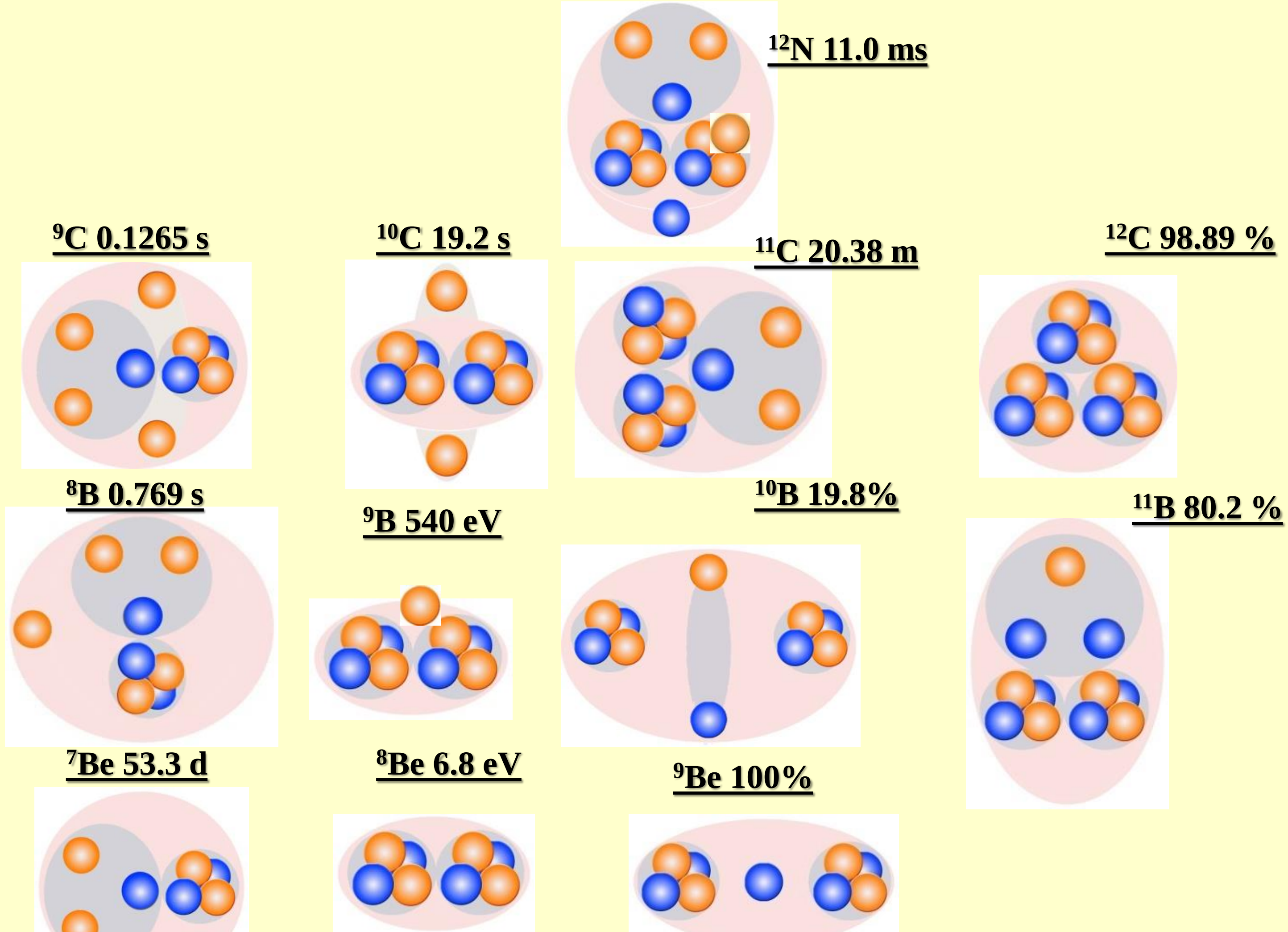
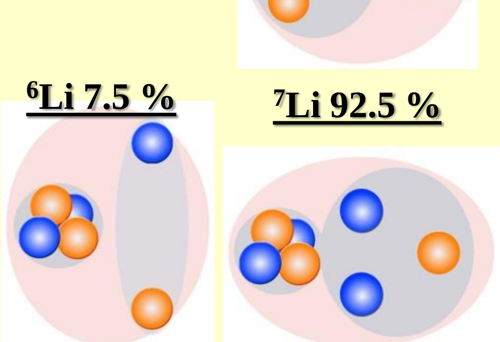


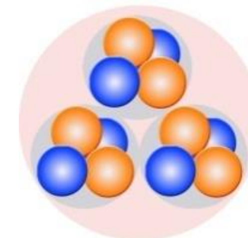


Since 2000s nuclear track emulsion is used to study clustering of light stable and radioactive nuclei in the relativistic approach in the BECQUEREL experiment at the JINR Nuclotron. The features of the nuclei $^{7.9}$Be, ^{8,10,11}B, ^{10,11}C, ^{12,14}N appeared in the probabilities of their dissociation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

Isotope → Channel (Threshold, MeV)

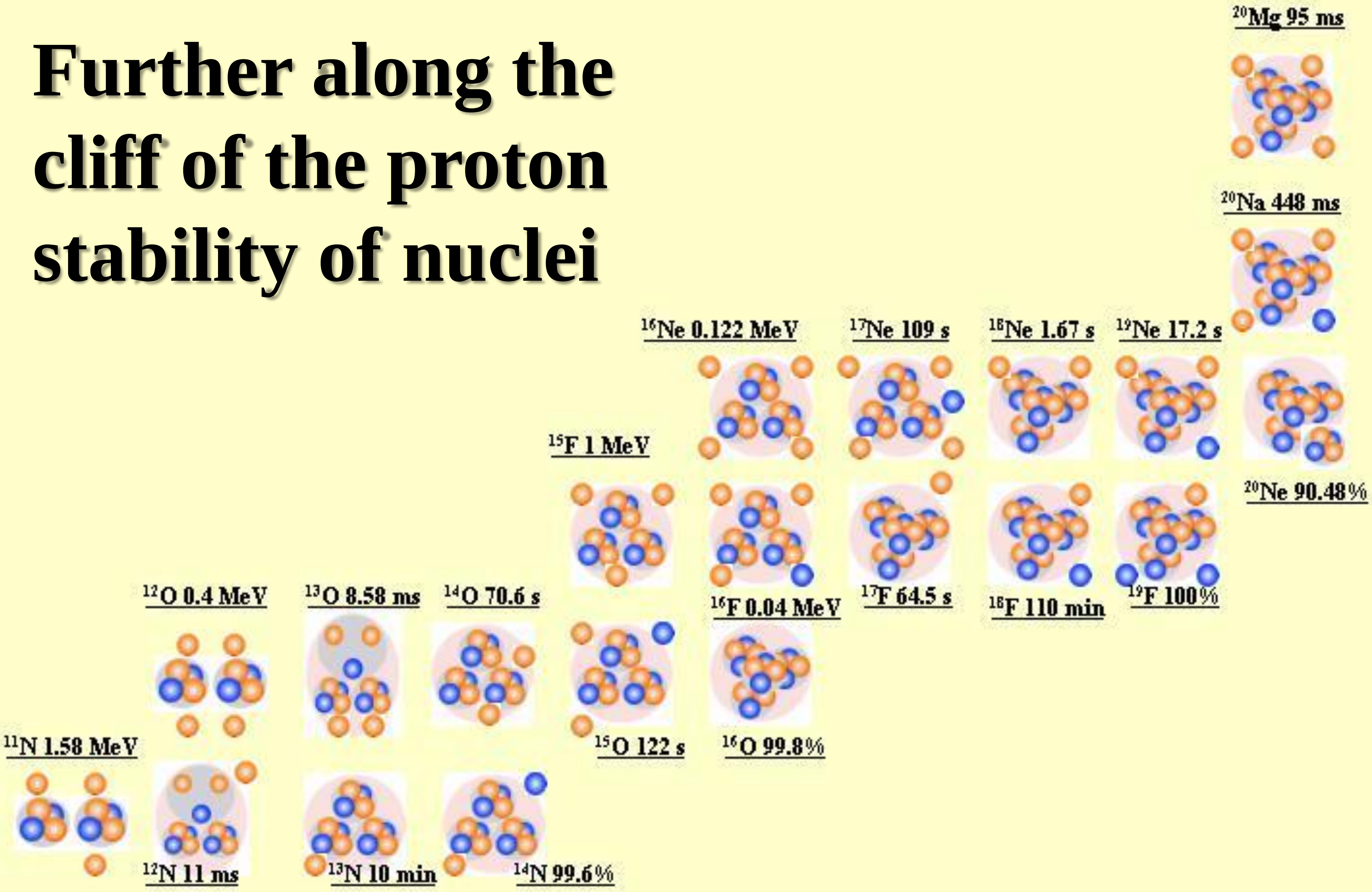
E_x (MeV ± keV)	J^π	τ_m or Γ_{cm}	
^{10}B → ^{6}Li+α (4.5)	^{8}Be+*d* (6.027)	^{9}Be+*p* (6.6)	^{9}B+*n* (8.4)
4.8 ± 0.5	3^+	7.8 ± 1.2 eV	
5.1 ± 0.6	2^-	1.0 ± 0.07 keV	
5.2 ± 0.6	2^+	1.8 ± 0.4 eV	
6.025 ± 0.6	4^+	52 ± 18 eV	
6.13 ± 0.7	3^-	1.52 ± 9.88 keV	
^{11}B → ^{7}Li+α (8.7)	^{8}Be+*t* (11.2)	^{10}Be+*p* (11.2)	^{10}B + *n* (11.5)
8.9 ± 0.11	$5/2^-$	4.374 ± 0.023 eV	
9.2 ± 1.0	$7/2^+$	$1.8\,^{+1.5}_{-1.1}$ eV	
^{11}C → ^{7}Be+α (7.5)	^{8}Be+^{3}He (9.2)	^{10}B+*p* (8.7)	^{10}C+*n* (13.1)
8.1 ± 1.7	$3/2^-$	6^{+12}_{-2} eV	
8.4 ± 2	$5/2^-$	0.030 ± 0.008 fs	

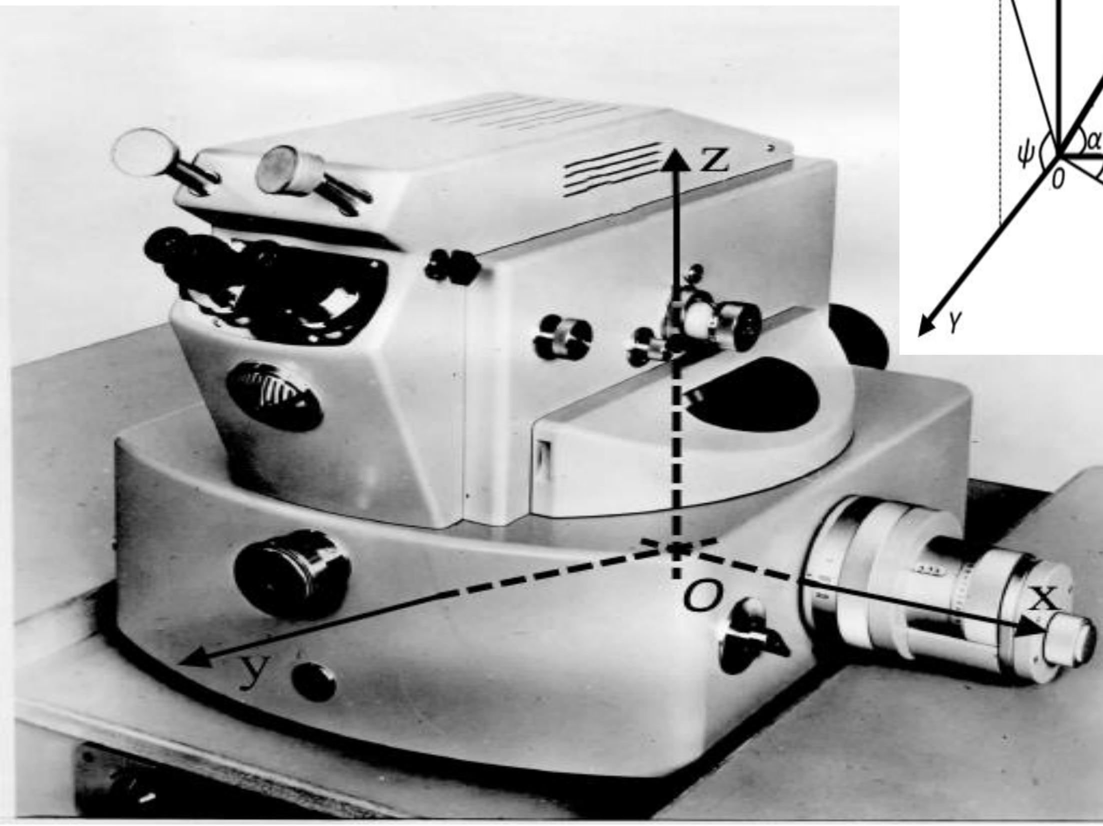
Isotope $\rightarrow$ Channel (Threshold, MeV)		
E_x (MeV ± keV)	J^π	τ_m or Γ_{cm}
$^{12}C \rightarrow$ $^{8}Be + \alpha$ (7.4)	$^{11}B+p$ (16.0)	$^{11}C+n$ (18.7)
7.7 ± 0.19	0^+	9.3 ± 0.9 eV
$^{16}O \rightarrow$ $^{12}C+\alpha$ (7.2)	$^{15}N+p$ (12.1)	$^{15}O+n$ (15.7)
8.9 ± 0.5	2^-	180 ± 16 fsec
9.9 ± 0.5	2^+	62 ± 0.10 eV
$^{20}Ne \rightarrow$ $^{16}O+\alpha$ (4.7)	$^{19}F+p$ (12.8)	$^{19}Ne+n$ (17.9)
5.6 ± 1.7	3^-	200 ± 50 fs
5.8 ± 2.6	1^-	28 ± 3 eV
8.6 ± 4	5^-	13 ± 4 eV

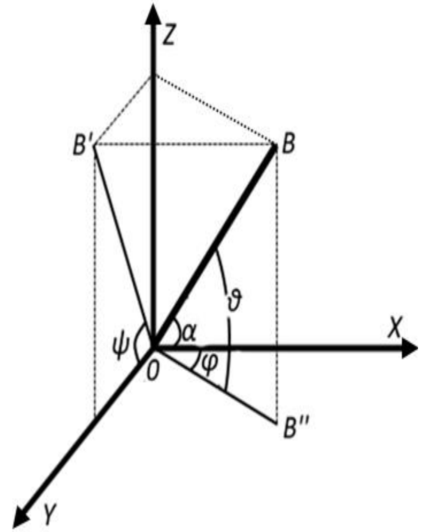


TUNL Nuclear Data Evaluation Project:

Further along the cliff of the proton stability of nuclei







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

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

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

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

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

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

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

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

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

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

Recent application in ongoing analysis

arXiv.org > nucl-ex > arXiv:2011.06265

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Nuclear Experiment

[Submitted on 12 Nov 2020]

Search for decays of the ^{9}B nucleus and Hoyle state in ^{14}N nucleus dissociation

E. Mitsova, A.A. Zaitsev, D.A. Aretemenkov, N.K. Kornegrutsa, V.V. Rusakova, R. Stanoeva, P.I. Zarubin, I.G. Zarubina

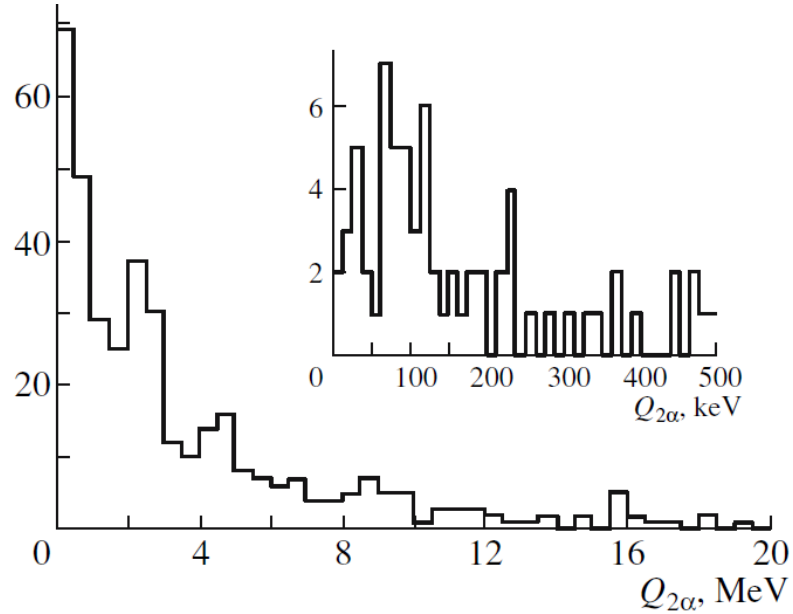
First results of an analysis to determine contribution of decays of the unstable ^{8}Be and ^{9}B nuclei and the Hoyle 3α-state to dissociation of ^{14}N $\rightarrow$ 3He (+H) are presented. As the research material, layers of nuclear track emulsion longitudinally exposed to 2.9 A GeV/c ^{14}N nuclei with at the JINR Nuclotron. Under the assumption that the He and H fragments retain momentum per nucleon of the primary nucleus, these unstable states are identified by the invariant mass calculated from the emission angles of the fragments.

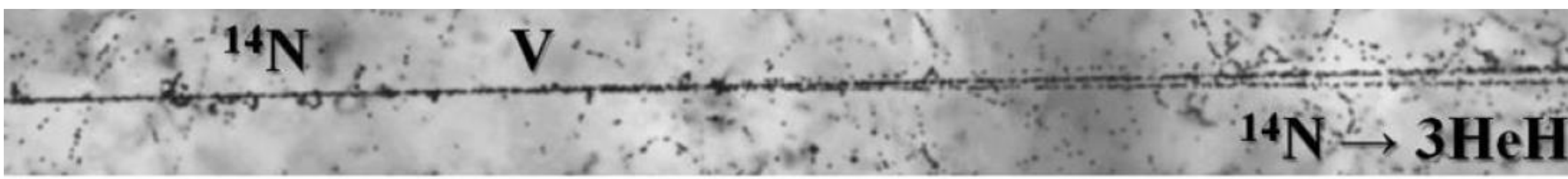
Comments: Article materials were presented in the report by A.A. Zaitsev at LXX International conference Nucleus - 2020, this https URL

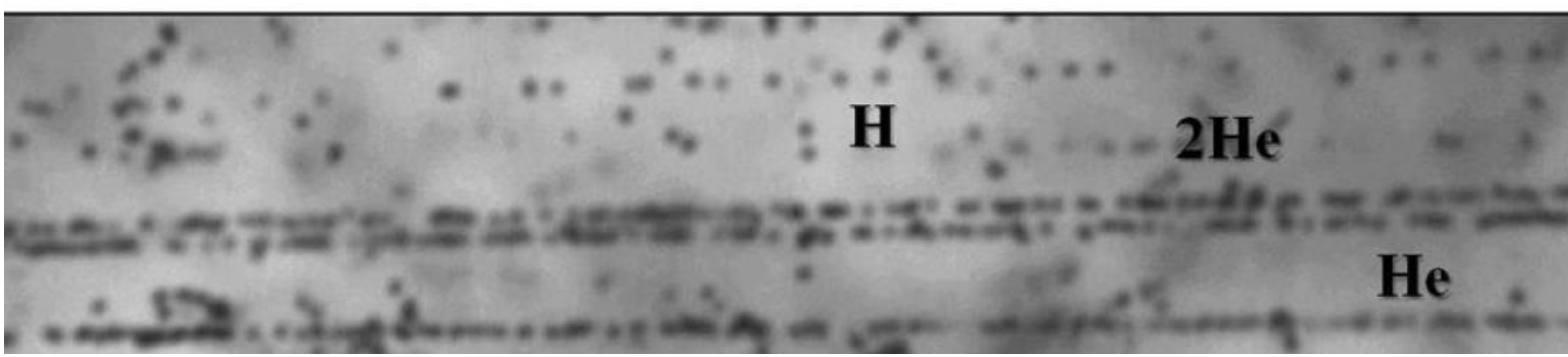
arxiv.org/abs/2011.06265

Leading channel 3HeH and ^{8}Be (arXiv)

Z_{fr}	6	5	5	4	3	3	–	–
$N_{Z=1}$	1	–	2	1	4	2	3	1
$N_{Z=2}$	–	1	–	1	–	1	2	3
N_{ws}	13	4	3	1	1	1	6	17
$N_{t.f.}$	15	1	3	3	–	2	5	32
N_{Σ}	28	5	6	4	1	3	11	49
N_{Σ}, %	26	5	5	4	1	3	10	46



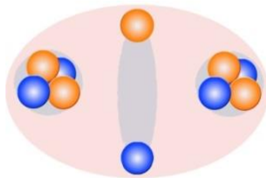




Cross-scan statistics collection

ΣZ	6		7			
$N_{Z>2}$	–	–	1	–	–	–
$N_{Z=2}$	3	2	2	2	3	3
$N_{Z=1}$	–	2	–	3	1	–
N_{ws}	11	9	9	16	59	–
N_{tf}	90	138	11	81	167	90

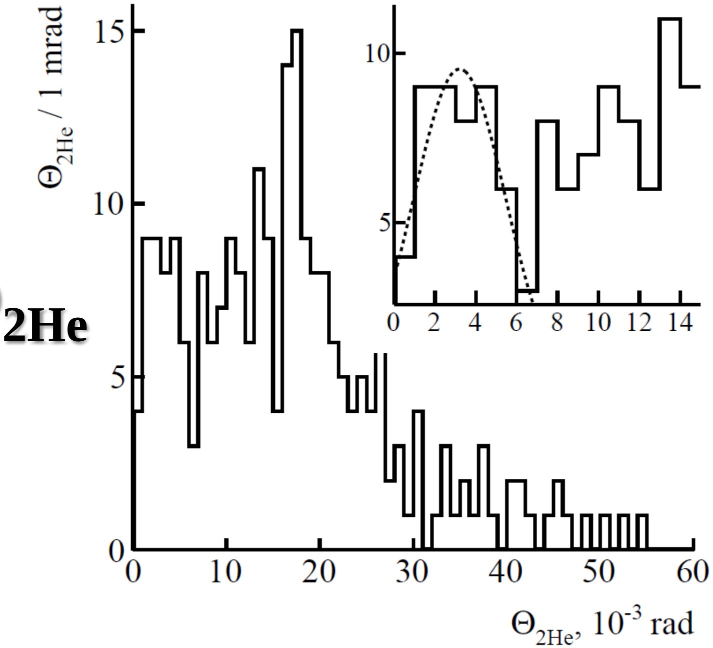
^{14}N: N_{tf} (3HeH)/N_{tf} (3He) = 1.9 ± 0.2



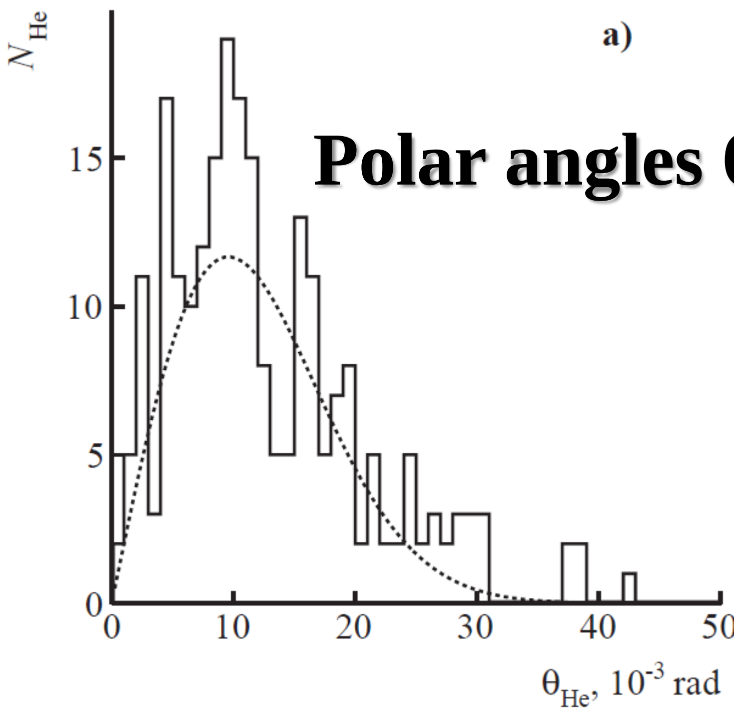
^{10}B: N_{tf} (2HeH)/N_{tf} (2He) = 2.1 ± 0.3

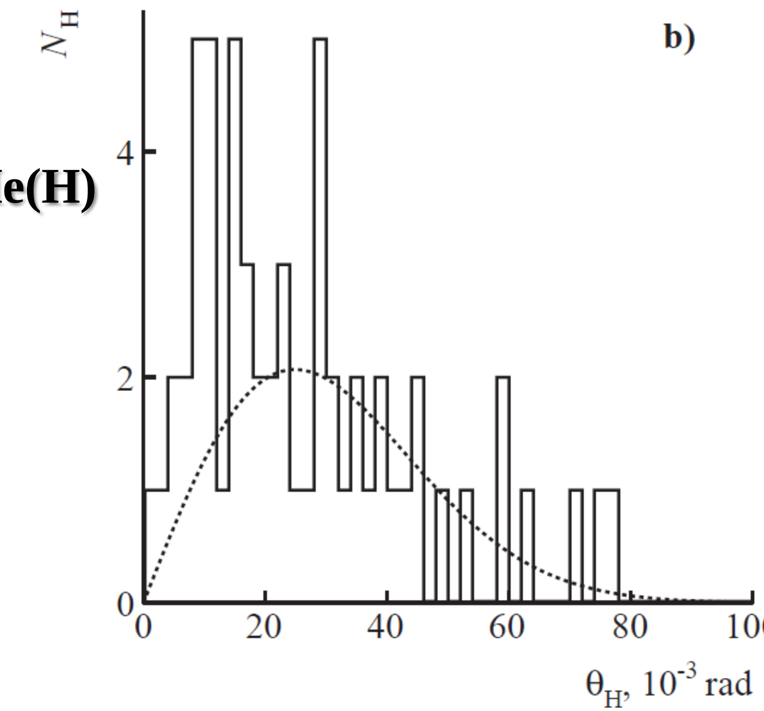
TABLE I: Distribution of “white” stars N_{ws} and peripheral interactions with target fragments N_{tf} over the number of relativistic fragments N_Z with charge Z.

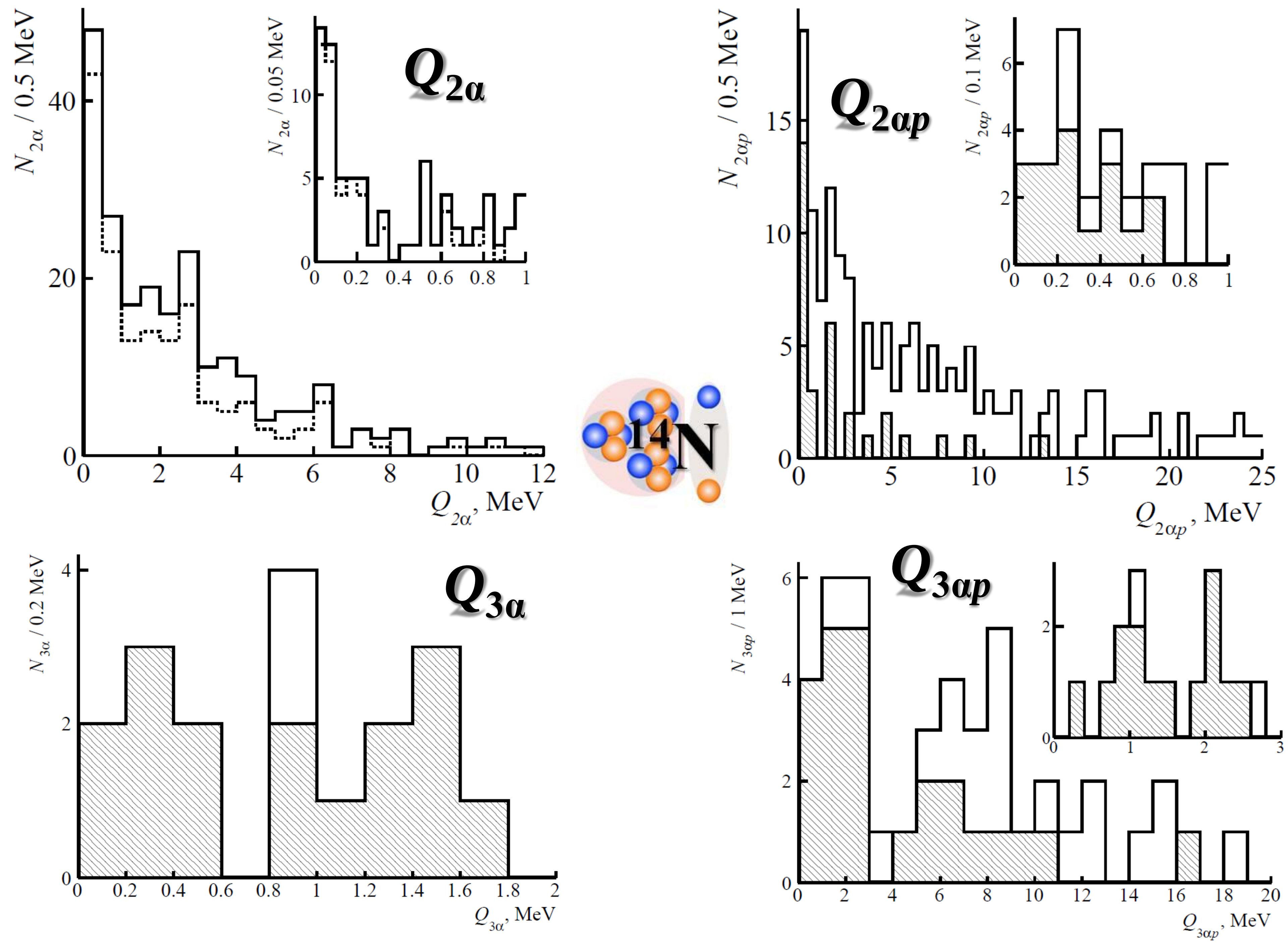
Opening angles Θ_{2He}



Polar angles $\theta_{He(H)}$



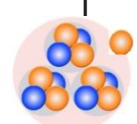


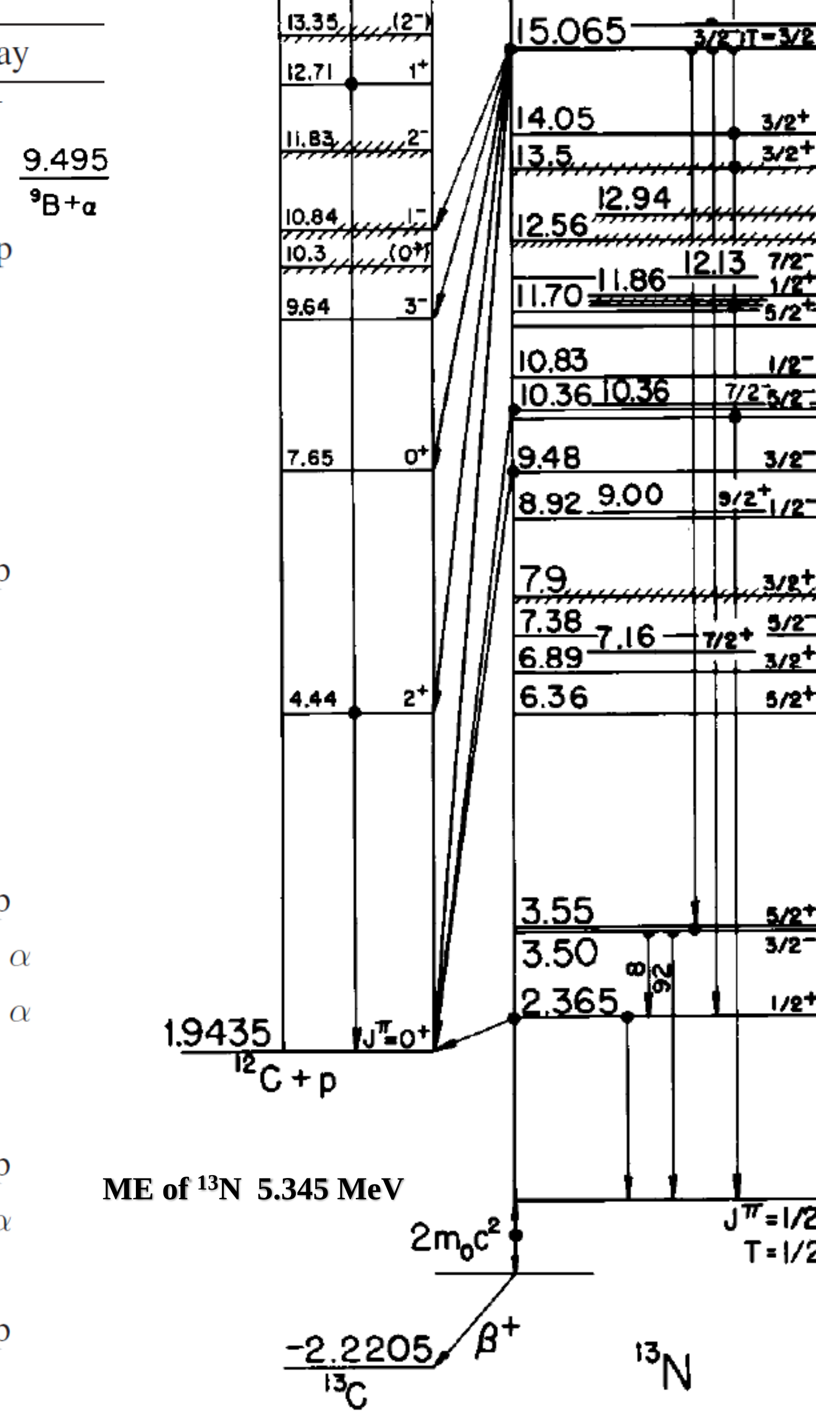


$Q_{2\alpha}$
$N_{2\alpha}$ / 0.5 MeV
$Q_{2\alpha}$, MeV
$N_{2\alpha}$ / 0.05 MeV
$Q_{2\alpha p}$
$N_{2\alpha p}$ / 0.5 MeV
$Q_{2\alpha p}$, MeV
$N_{2\alpha p}$ / 0.1 MeV
14N
$Q_{3\alpha}$
$N_{3\alpha}$ / 0.2 MeV
$Q_{3\alpha}$, MeV
$Q_{3\alpha p}$
$N_{3\alpha p}$ / 1 MeV
$Q_{3\alpha p}$, MeV

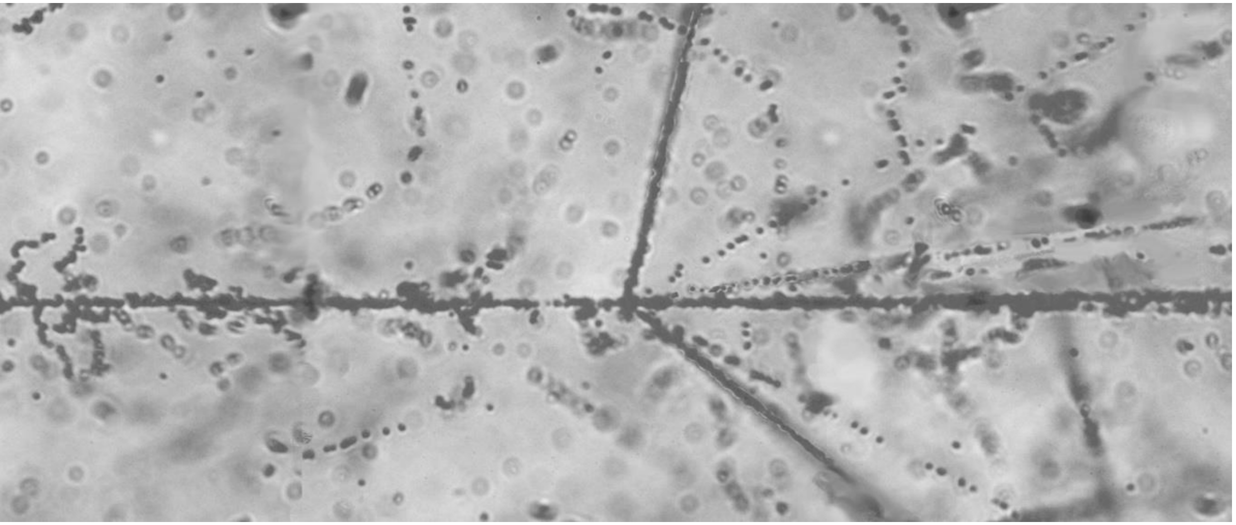
Energy levels of ^{13}N

E_x (MeV±keV)	$J^\pi; T$	$\Gamma_{c.m.}$ (keV)	Decay
g.s.	$\frac{1}{2}^-; \frac{1}{2}$	$\tau_{1/2} = 9.965 \pm 0.004$ min	β^+
10.25 ± 150	$(\frac{1}{2}^+)$	≈ 280	γ, p
10.36	$\frac{5}{2}^-$	30	p
10.36	$\frac{7}{2}^-$	76	p
10.833 ± 9	$\frac{1}{2}^-$		
11.530 ± 12	$\frac{5}{2}^+$	430 ± 35	p
11.70 ± 30	$\frac{5}{2}^-$	115 ± 30	p
11.74 ± 40	$\frac{3}{2}^+$	240 ± 30	γ, p
11.74 ± 50	$\frac{3}{2}^-$	530 ± 80	p
11.86 ± 40	$\frac{1}{2}^+$	380 ± 50	p
12.13 ± 50	$\frac{7}{2}^-$	250 ± 30	p
12.558 ± 23		> 400	
12.937 ± 24		> 400	
13.5 ± 200	$\frac{3}{2}^+$	≈ 6500	γ, p
14.05 ± 20	$\frac{3}{2}^+; \frac{1}{2}$	165 ± 20	γ, p, α
15.06457 ± 0.4 [b]	$\frac{3}{2}^-; \frac{3}{2}$	0.86 ± 0.12	γ, p, α
15.3 ± 200	$(\frac{3}{2}^+)$	350 ± 150	γ, p
15.99 ± 30	$\frac{7}{2}^+; \frac{1}{2}$	135 ± 90	p, α
16.0		≈ 500	p
17.5			γ, p

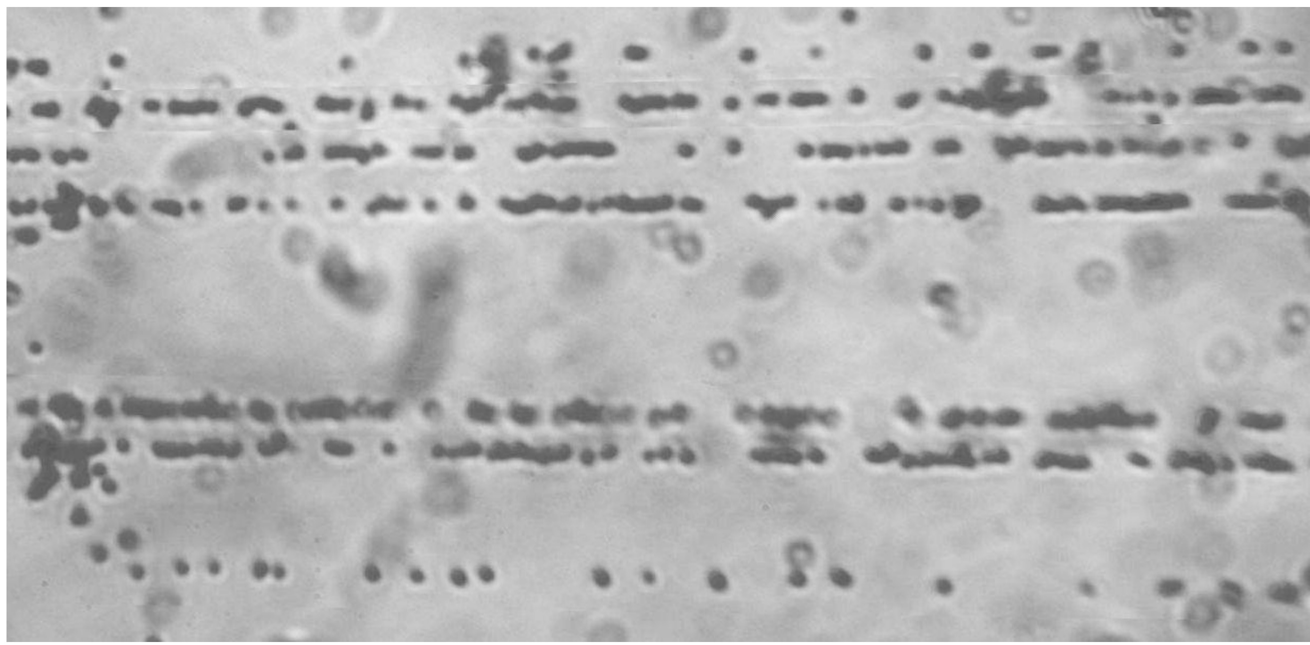




ME of ^{13}N 5.345 MeV

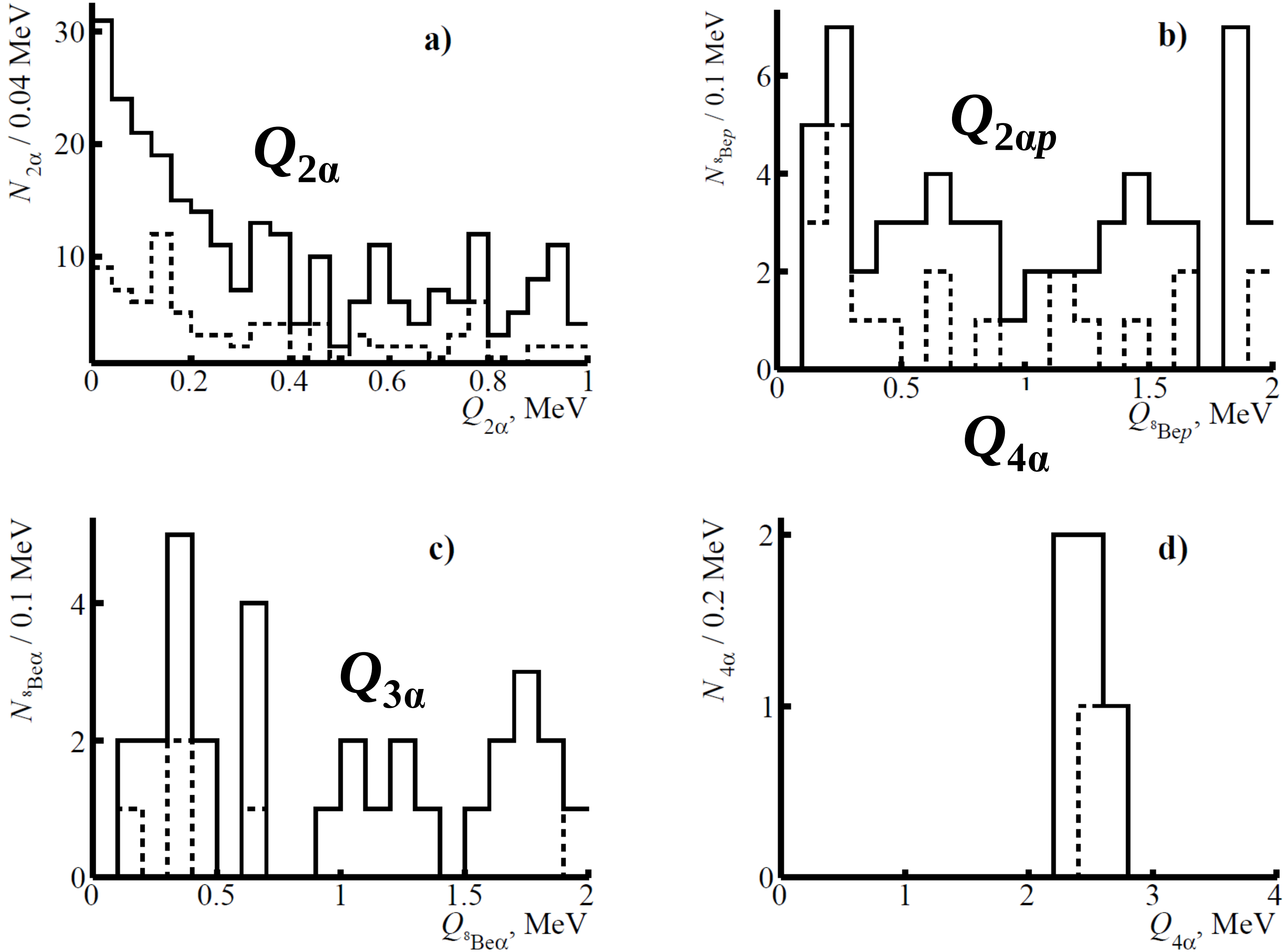


3.65 A GeV ^{28}Si along track paths 61.3 m 6252 stars Among them 6α (12), 5α(67), 4α (170), 2 fragments (101), 14H (2)



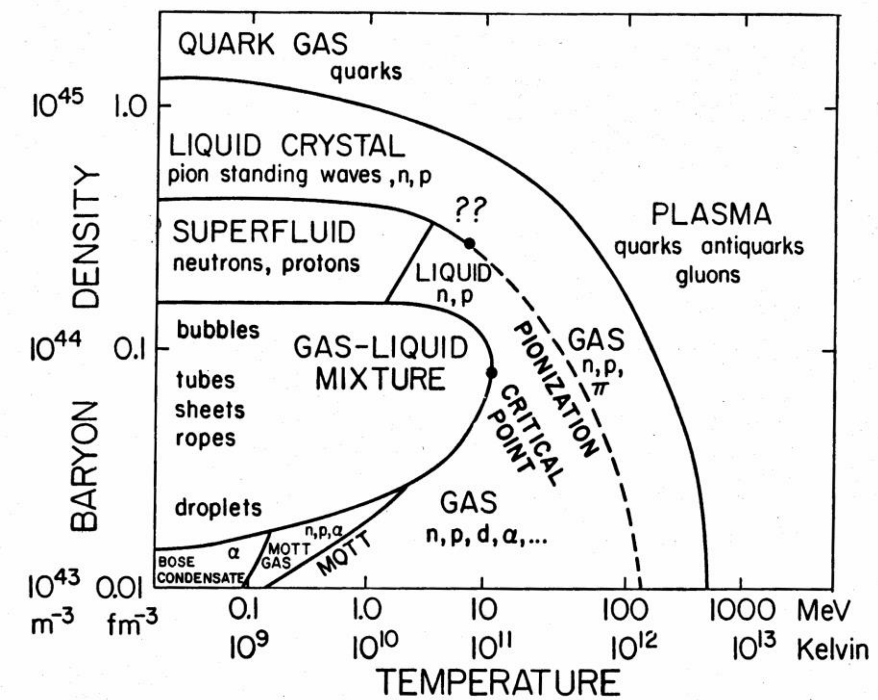
A similar analysis will be carried out in the NTE layers which were exposed relativistic nuclei ^{22}Ne and ^{28}Si at the JINR Synchrophasotron in the late 80s and used for overview analysis. Despite the past decades this experimental material has retained the necessary quality.

14.6 *A* GeV ^{28}Si



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

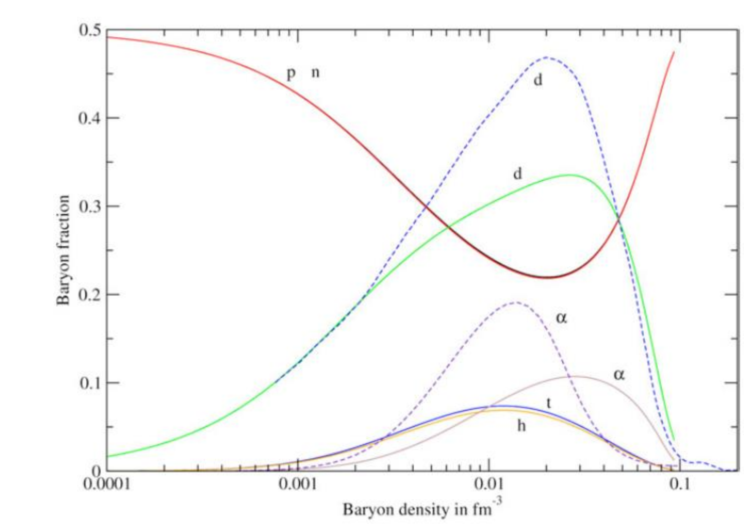
n_α	^{22}Ne 3.22 *A* GeV $N_{n\alpha}(^8\text{Be})/N_{n\alpha}$ (%)	^{28}Si 15 *A* GeV $N_{n\alpha}(^8\text{Be})/N_{n\alpha}$ (%)	^{28}Si 15 *A* GeV $N_{n\alpha}(^8\text{Be})/N_{n\alpha}$ (%)
2	30/528 (6 ± 1)	5/164 (3 ± 2)	$n_\alpha \geq 3$
3	45/243 (19 ± 3)	10/75 (13 ± 5)	33/231 (14 ± 3)
4	25/80 (31 ± 6)	11/25 (44 ± 16)	39/121 (32 ± 6)
5	6/10 (60 ± 31)	8/17 (47 ± 20)	16/42 (38 ± 11)
6		1/1 (100)	4/6 (67± 43)

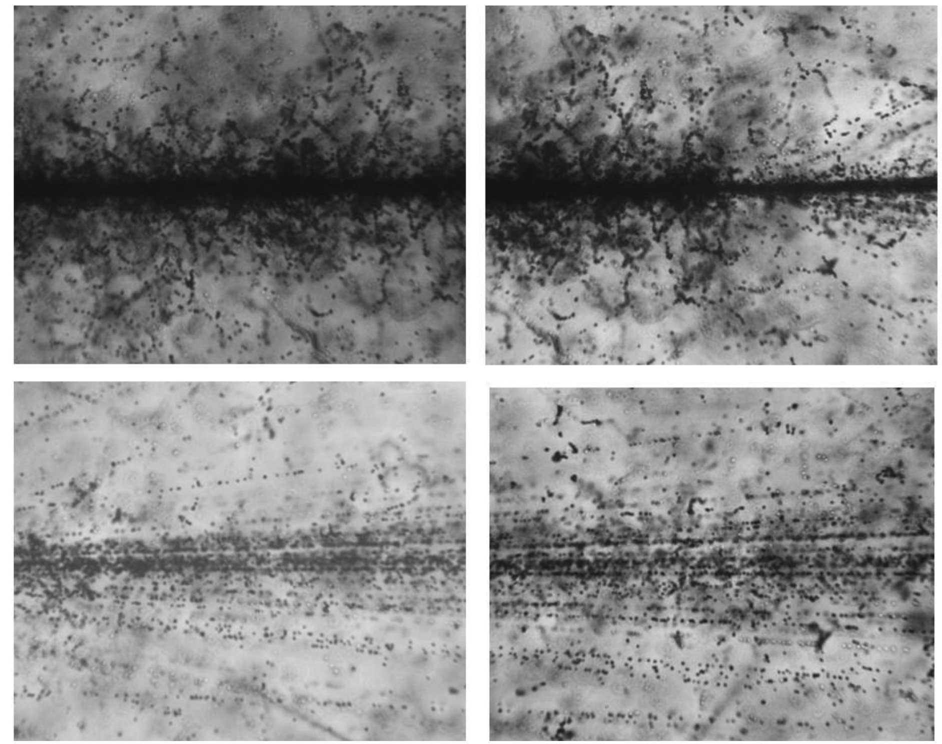


Composition of symmetric nuclear matter

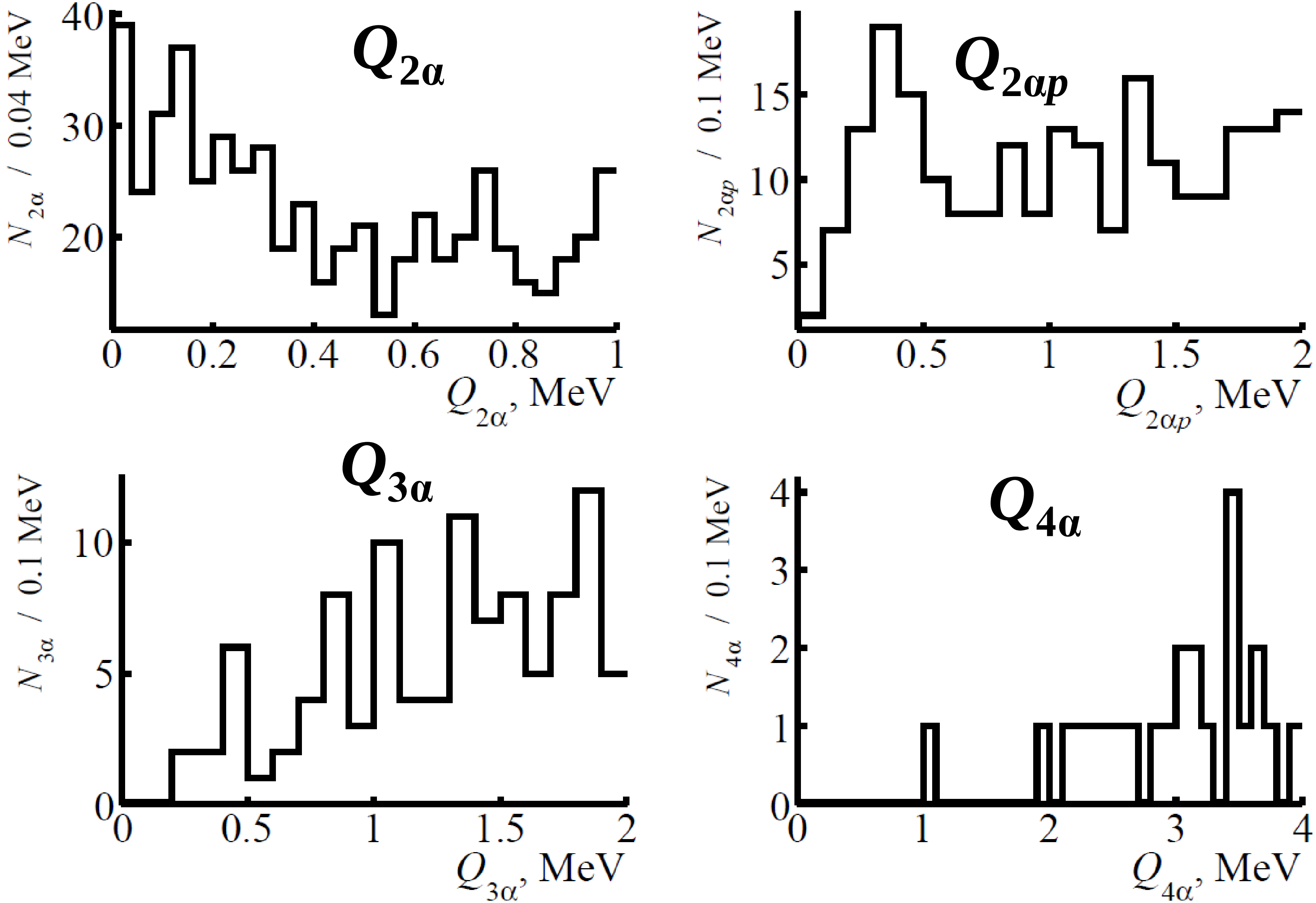
G.Ropke, A.Grigo, K. Sumiyoshi, Hong Shen, Phys.Part.Nucl.Lett. **2**, 275 (2005)

T=10 MeV

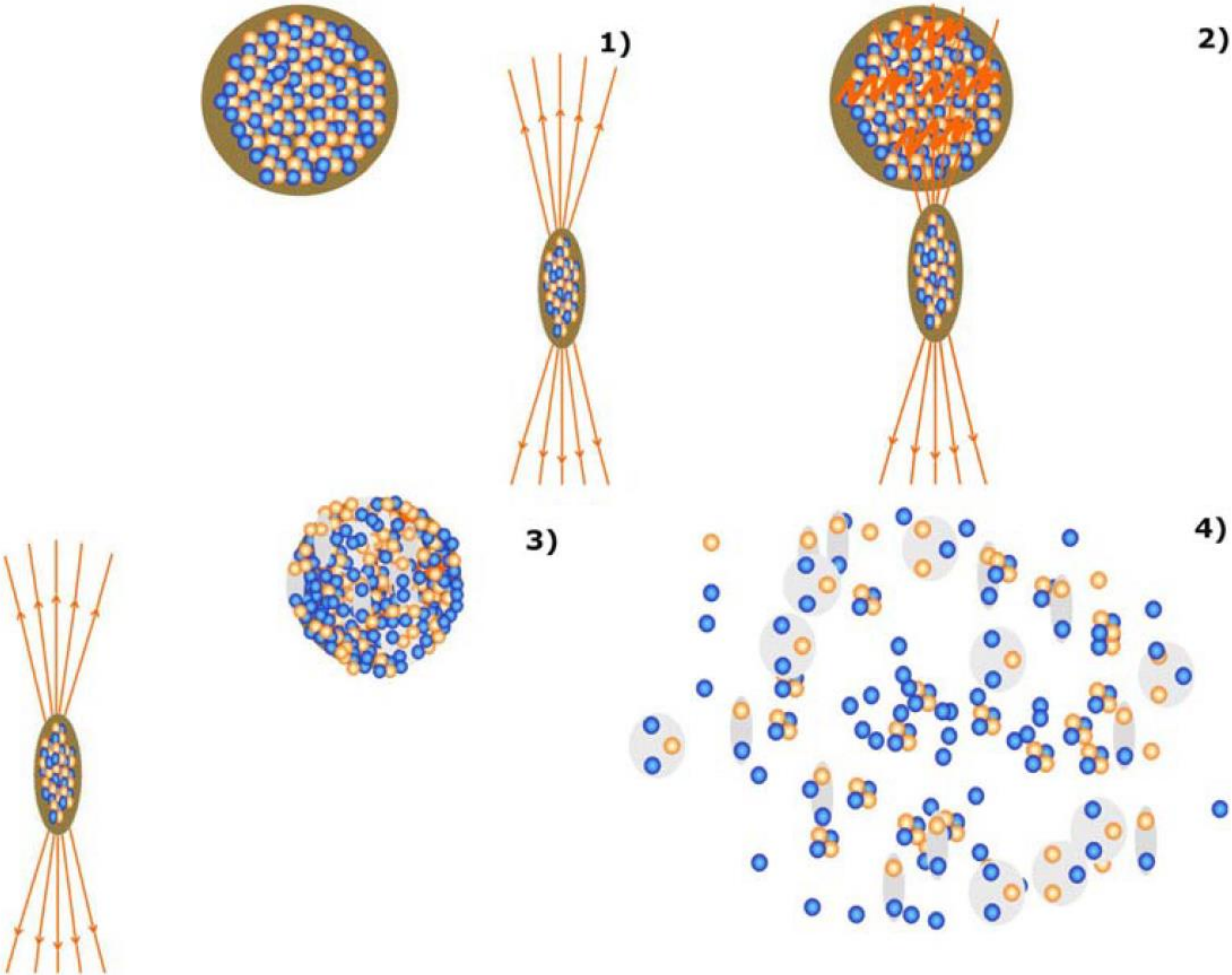




Au 10.7 *A* GeV



1316 interactions of 10.7 *A* GeV Au; 160 α-pairs $Q_{2\alpha}$ < 0.2 MeV; 40 events with 2α*p*-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.


1)
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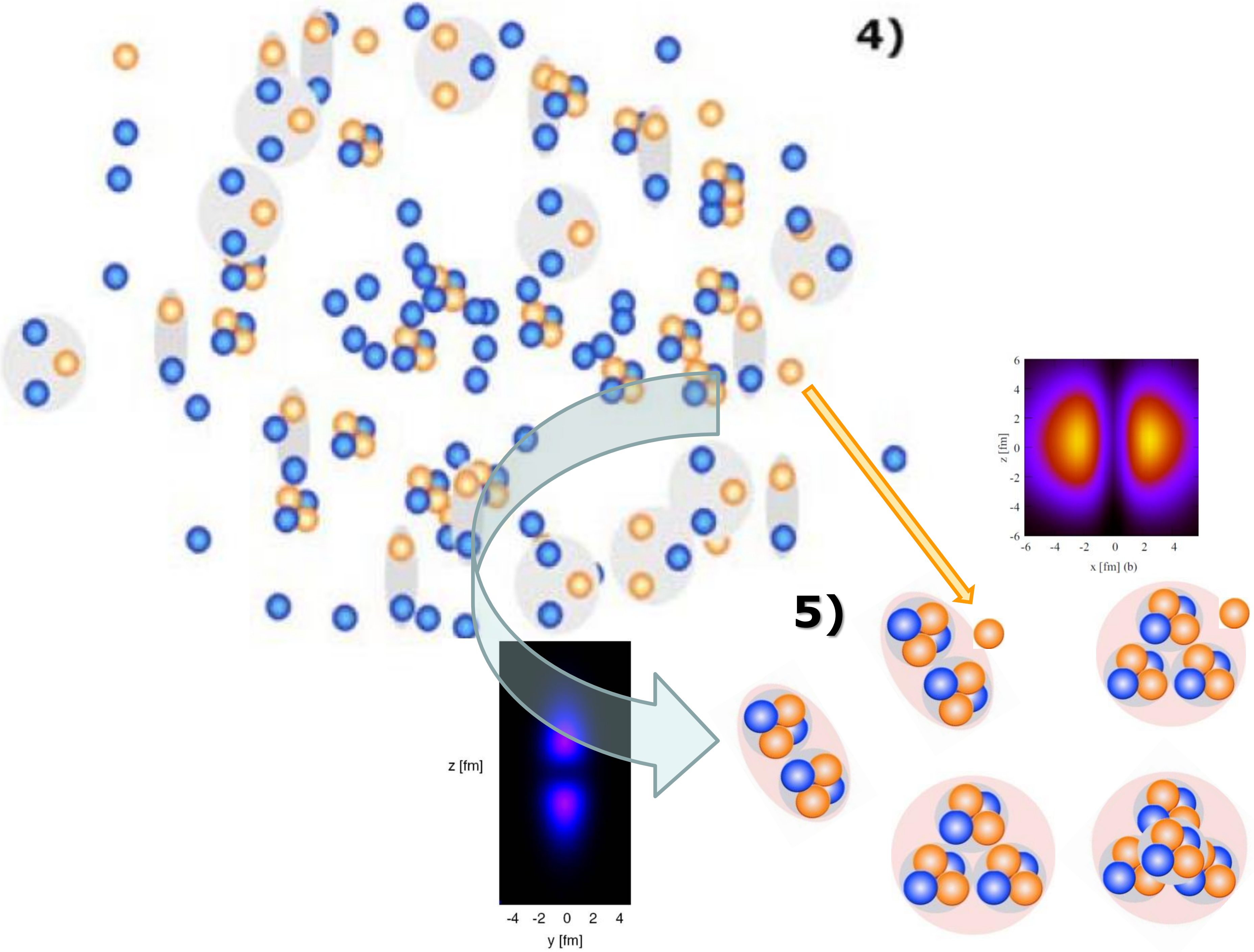

4)
5)
z [fm]
x [fm] (b)
6
4
2
0
-2
-4
-6
-6 -4 -2 0 2 4
z [fm]
-4 -2 0 2 4
y [fm]

Statistics of events containing at least one ^{8}Be, ^{9}B or HS decay, or at least two ^{8}Be among the events $N_{n\alpha}$ in dissociation of ^{197}Au nuclei; the total statistics of the channels $n_\alpha \geq 11$ are highlighted.

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

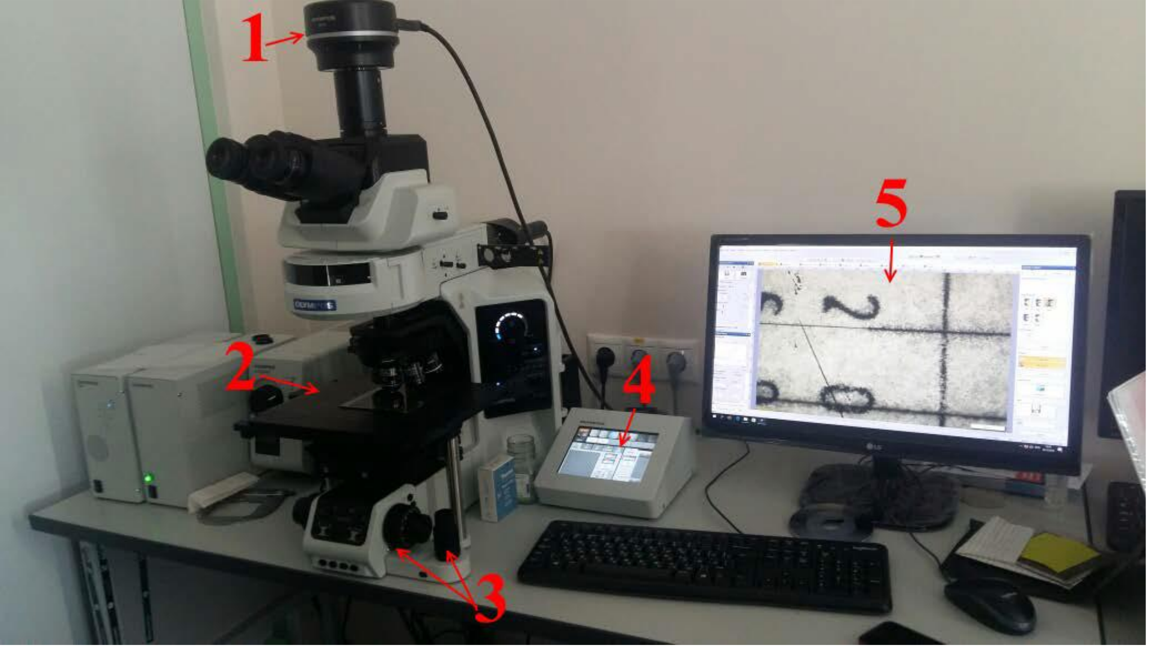
The preserved and recently supplemented data made it possible to identify decays of ^{8}Be, ^{9}B nuclei and Hoyle state in the invariant mass distributions of 2*α*-pairs, 2*αp*- and 3*α*-triplets.

The presence of these unstable states as virtual components in parent nuclei can be assumed. However, maintaining such universality with an increase in the mass number of nuclei under study seems to be more and more problematic.

An alternative consists in the ^{8}Be formation during the final state interaction of the produced α-particles and the subsequent pick-up of accompanying α-particles and nucleons with the emission of the necessary γ-quanta. The consequence would be an increase in the ^{8}Be yield with a multiplicity of α-particles t, and possibly ^{9}B and HS decaying through ^{8}Be.

Indeed, the presented analysis indicates a tendency towards an increase in the ^{8}Be contribution with an increase in the number of relativistic α-particles and the remaining proportional contributions of HS and ^{9}B.

This observation requires taking into account the concepts of low energy nuclear physics.


1
2
3
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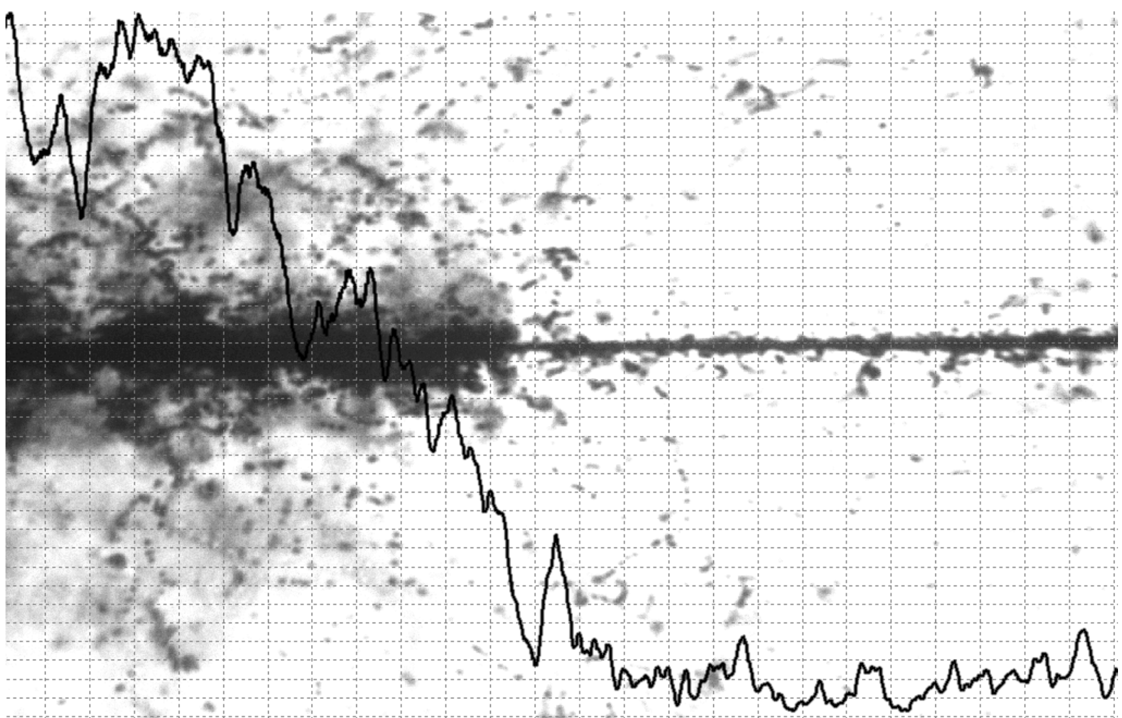
5


RIGOL
POZOR!



Estimated expenditures for the Project: "**Study of Multiple Fragmentation of Relativistic Nuclei in Nuclear Track Emulsion (The BECQUEREL-2020 Experiment)**"

№	Name of the items cost	full cost (k$)		2021		2022		2023	
		Theme 1087		Theme 1087		Theme 1087		Theme 1087	
1.	Accelerator (Nuclotron), hour	150		50		50		50	
2.	Computer communications								
3.	LHEP Design bureau	-		-		-		-	
4.	LHEP Workshop	-		-		-		-	
5.	Materials	75		25		25		25	
6.	Equipment	80		80		-		-	
7.	Payment research	-		-		-		-	
8.	Travel allowance, including:	120		40		40		40	
	(a) to non-rouble zone countries	60		20		20		20	
	b) in the rouble zone	60		20		20		20	
	c) protocol-based	-		-		-		-	
Σ		275		145		65		65	
Total direct expenses:		275		145		65		65	

Theme 1087 – VBLHEP
PROJECT LEADER P.Zarubin P.I. Zarubin

VBLHEP DIRECTOR V.D. Kekelidze

SUMMARY

The recent achievements of the participants of the BECQUEREL experiment in studies with light relativistic nuclei and the preserved microscopic and chemical-technological basis give reason to expect in the future about three years the following physical and methodological results:

Light nuclei **An answer will be obtained to the question of the universal nature of the formation of triples of α-particles in the Hoyle state in the dissociation of the nuclei ^{14}N and ^{28}Si. Possibility of existence of more complex states of this type will be investigated.**

Heavy nuclei **In the existing layers of nuclear energy exposed to 950 *A* MeV Kr several dozen dissociation events will be selected and documented. In the selected interactions, charge topology distributions of lightest fragments accompanied by their identification will be obtained; neutron transverse momentum distributions restored, and mean number neutrons estimated.**