Электромагнитные взаимодействия тяжелых ионов

П.И. Зарубин (ОИЯИ)

PHYSICAL REVIEW C VOLUME 24, NUMBER 4 OCTOBER 1981

Electromagnetic dissociation of relativistic ^{18}O nuclei

D. L. Olson and B. L. Berman
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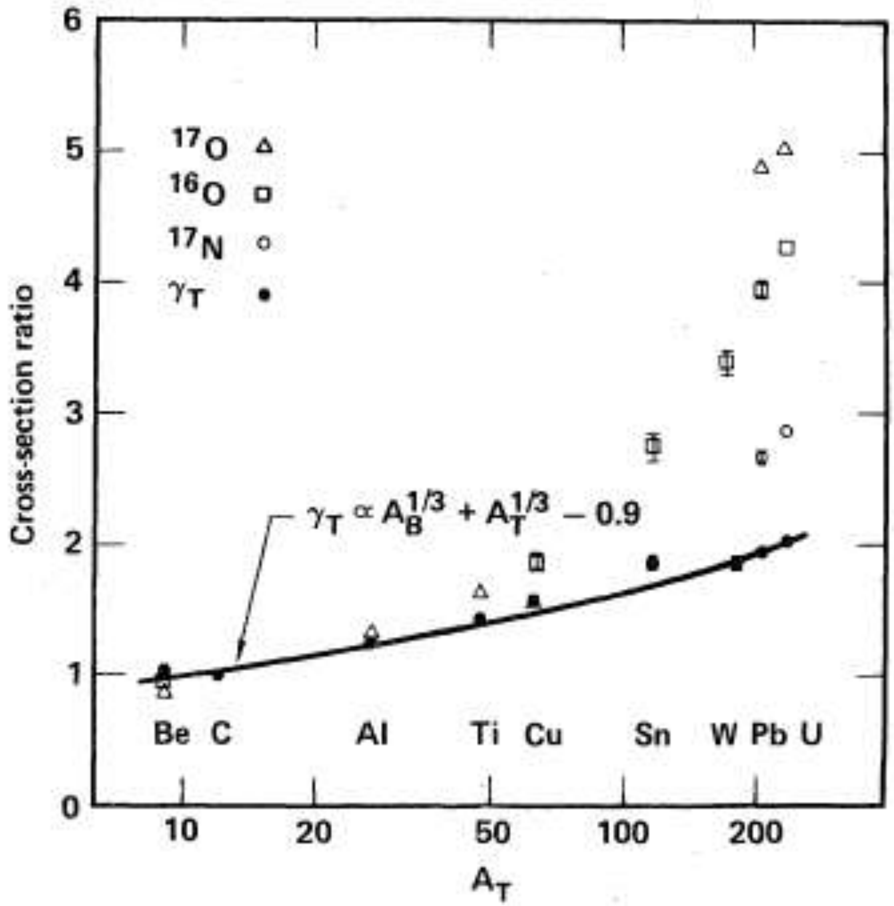

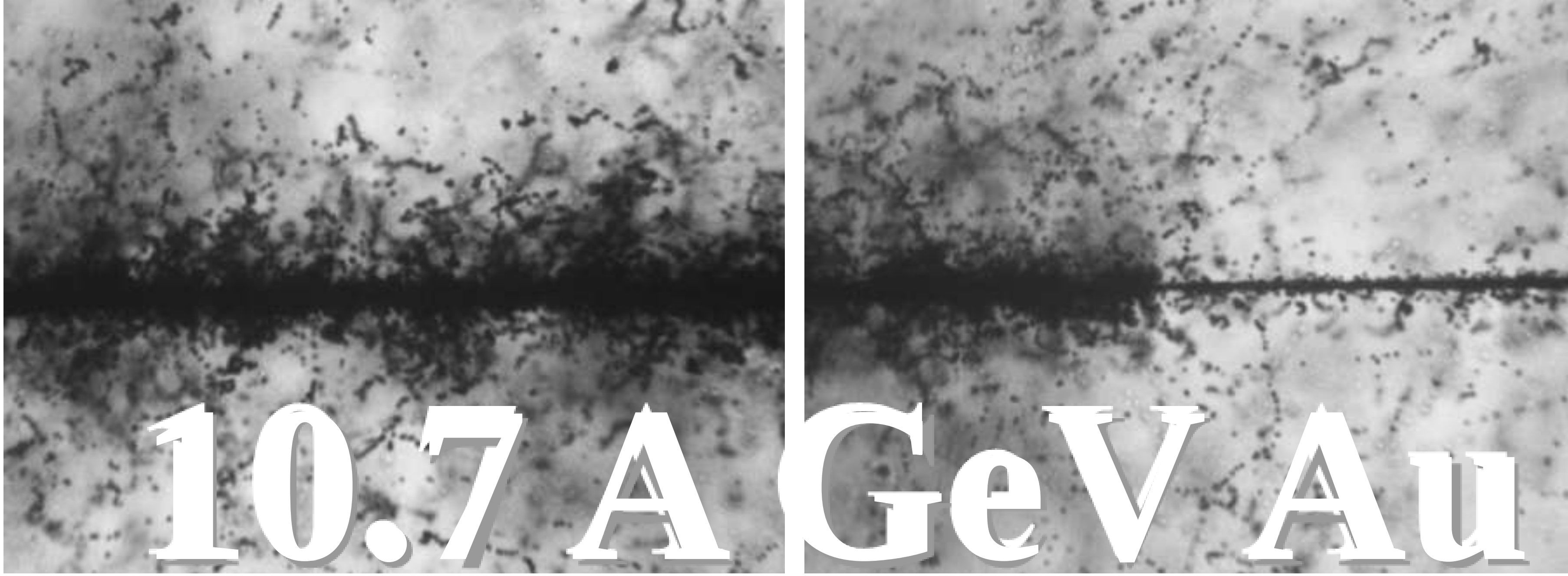

PHYSICAL REVIEW C **72**, 048801 (2005)

Multifragmentation reactions and properties of stellar matter at subnuclear densities

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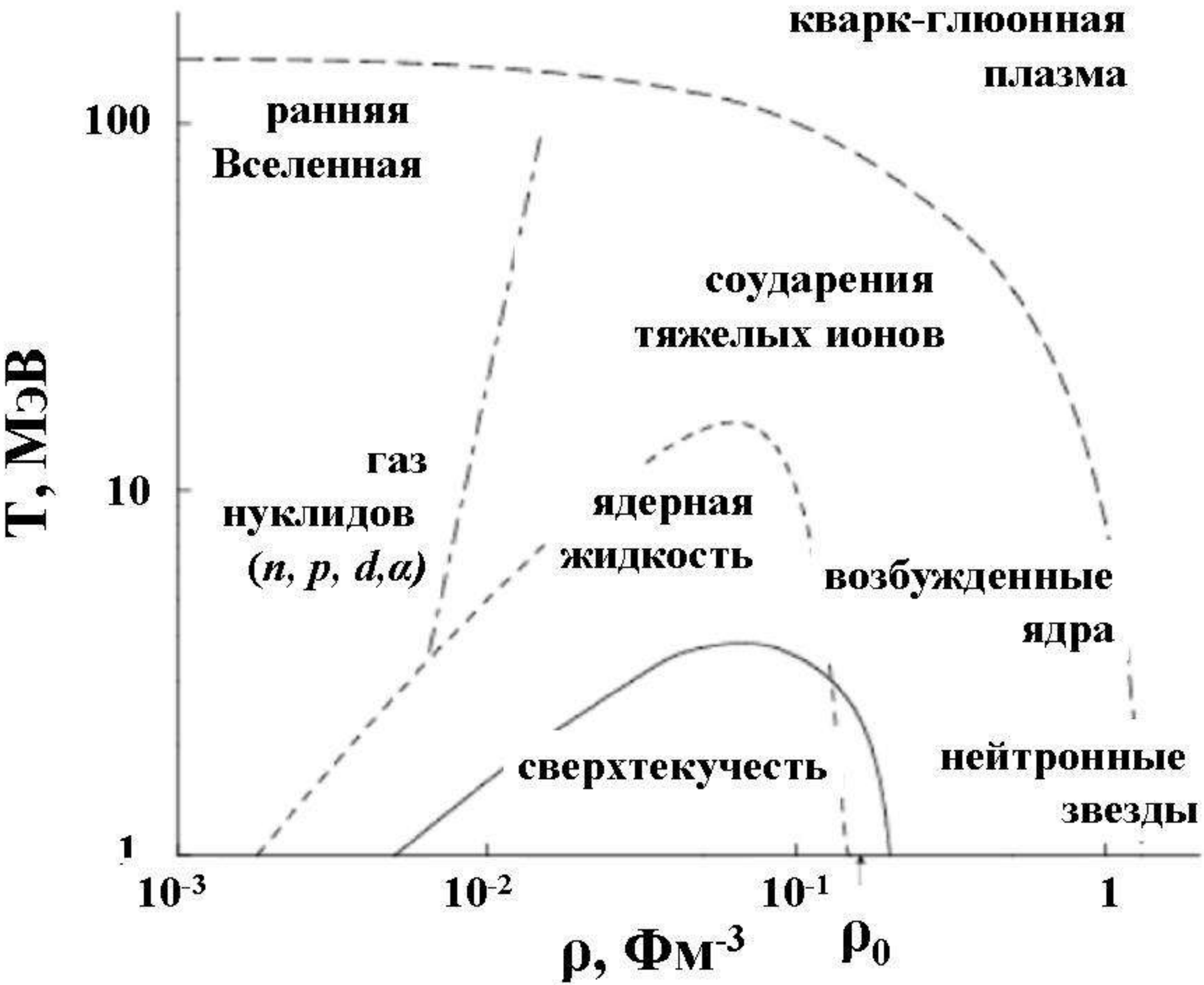
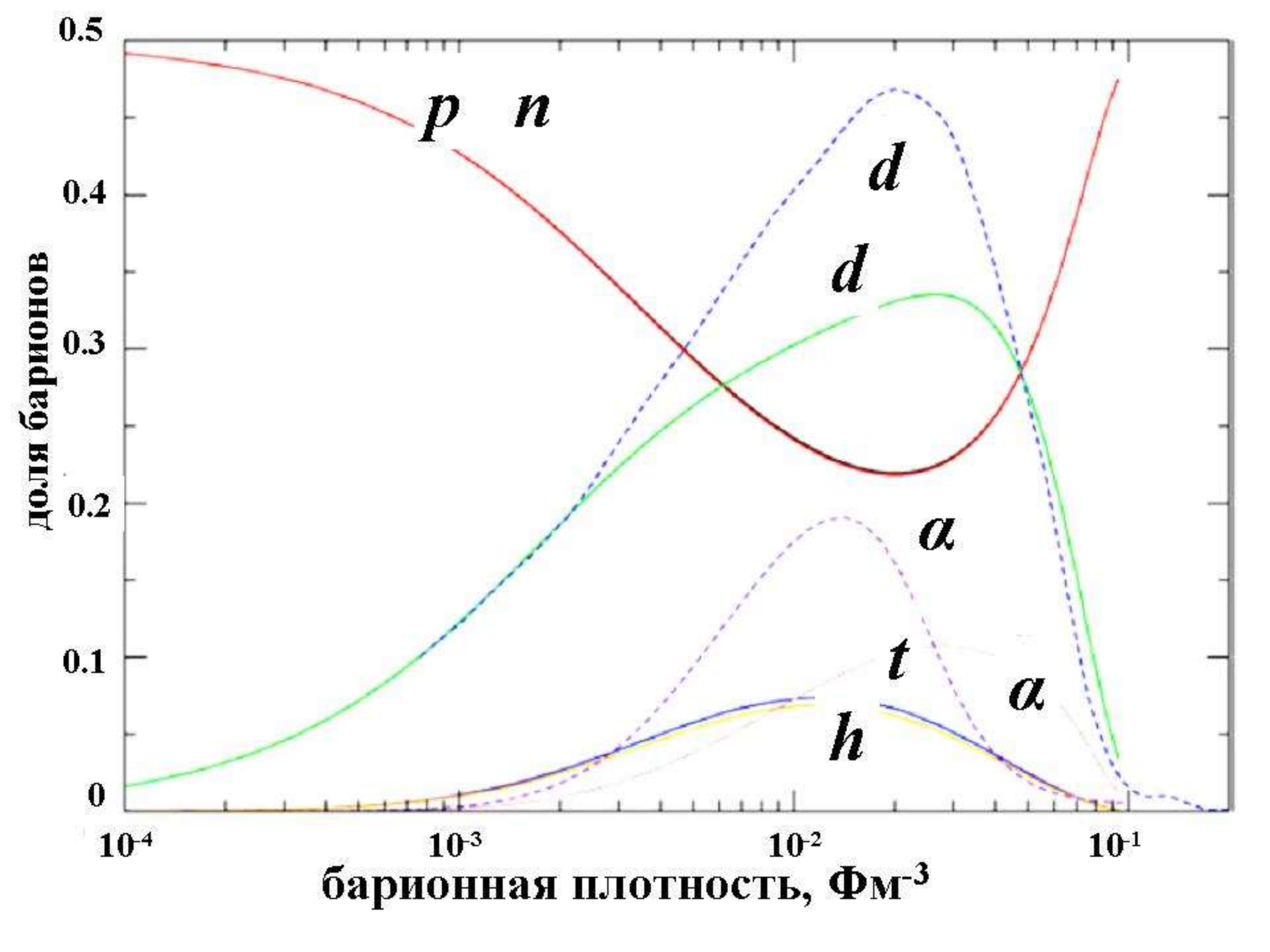
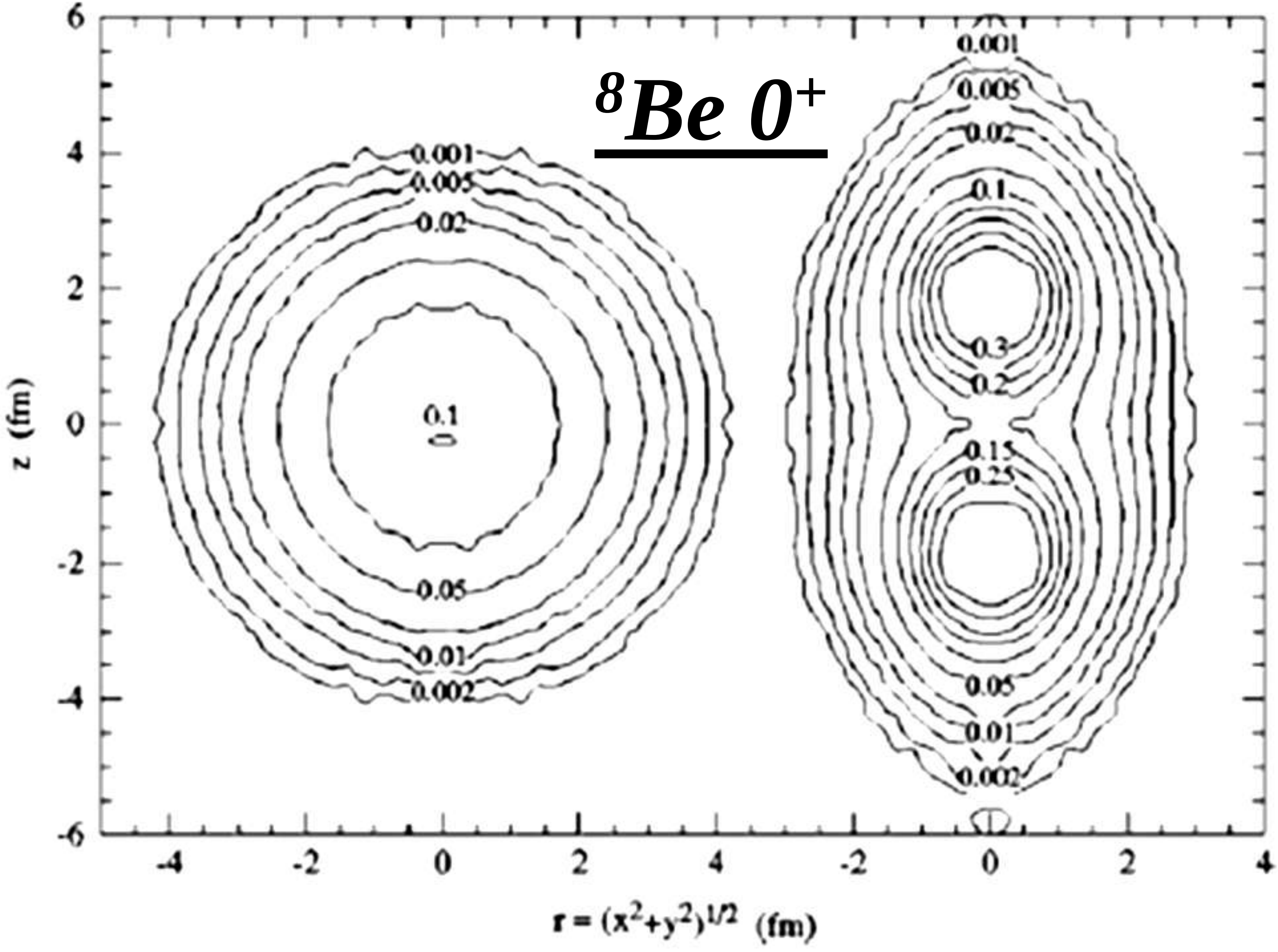
(Received 20 June 2005; published 24 October 2005)

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.

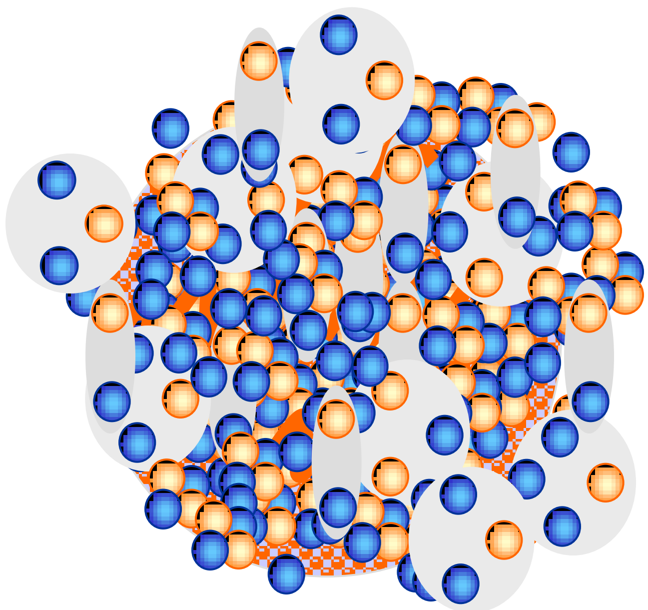

кварк-глюонная
плазма
ранняя
Вселенная
100
соударения
тяжелых ионов
T, МэВ
газ
нуклидов
(n, p, d,α)
10
ядерная
жидкость
возбужденные
ядра
сверхтекучесть
нейтронные
звезды
1
10-3
10-2
10-1
1
ρ, Фм-3
ρ0

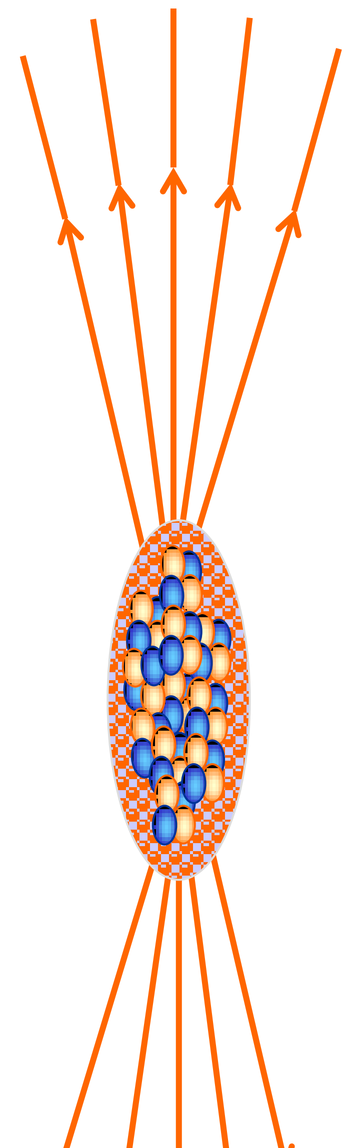


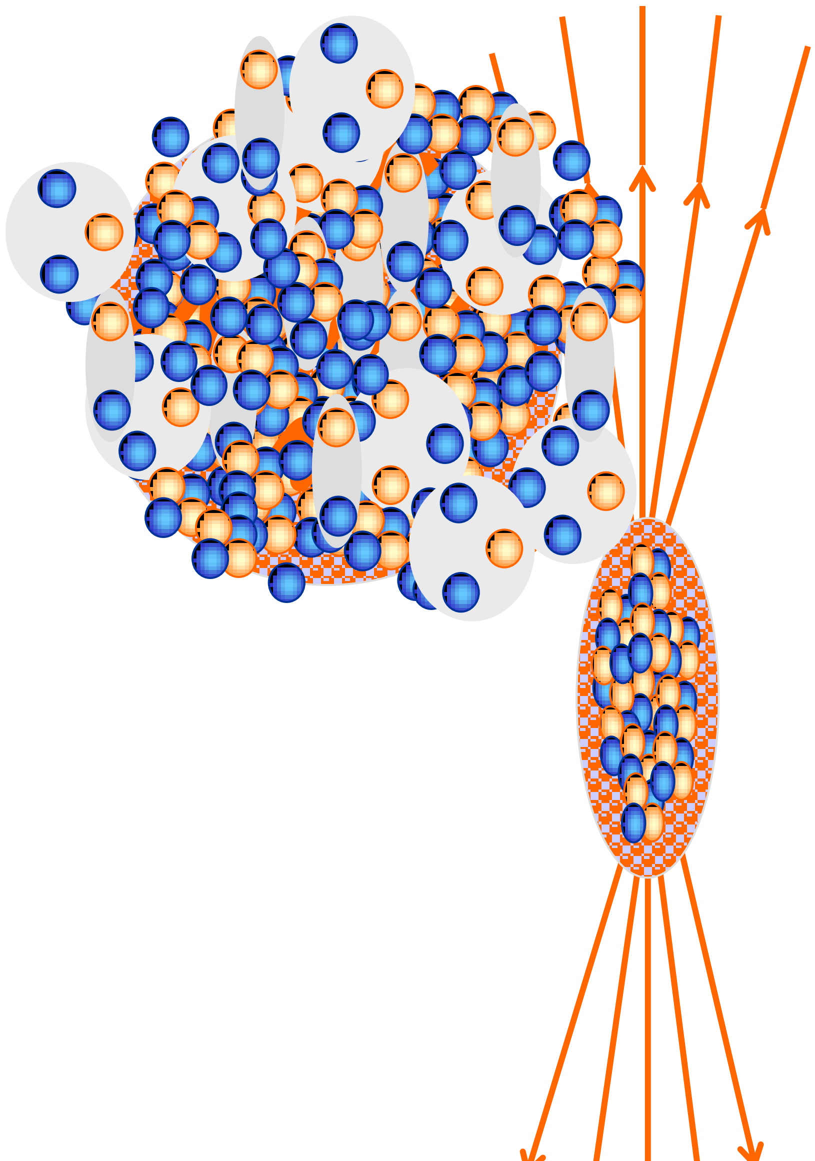
0.5
0.4
0.3
0.2
0.1
0
доля барионов
p
n
d
d
α
t
α
h
10-4
10-3
10-2
10-1
барионная плотность, Фм-3

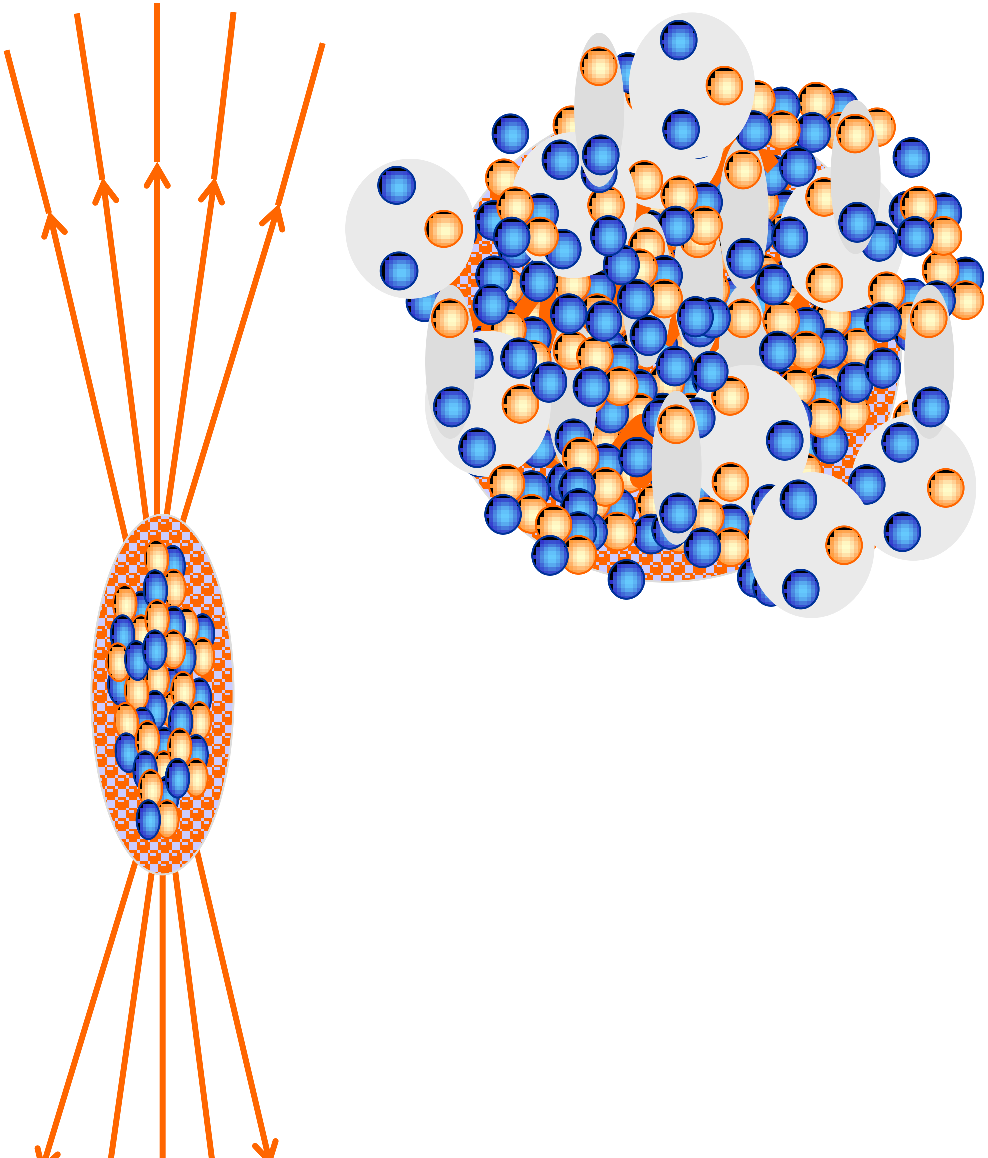


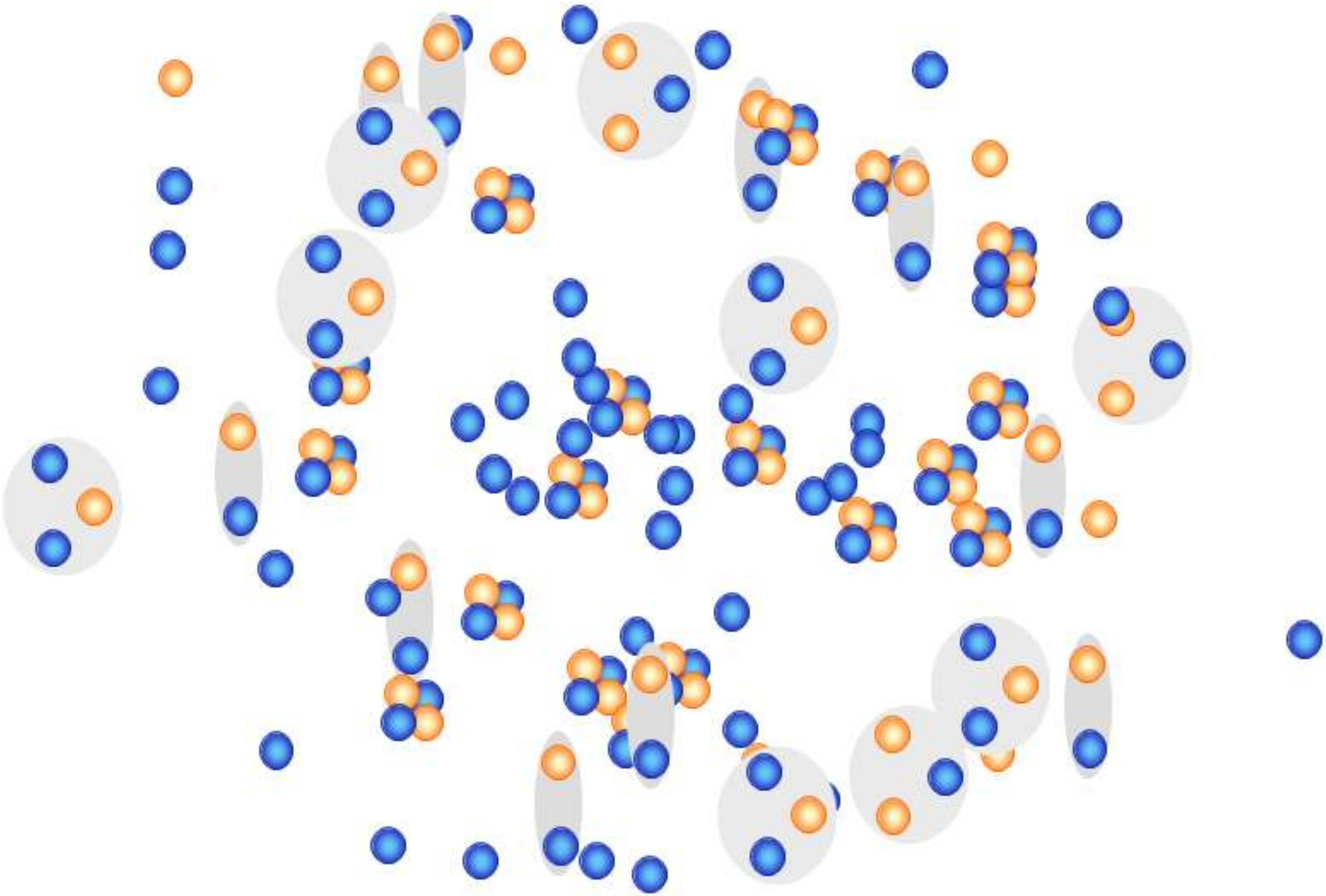
8Be 0+
0.001
0.005
0.02
0.1
0.05
0.01
0.002
0.3
0.2
0.15
0.25
z (fm)
r = (x2+y2)1/2 (fm)











PHYSICAL REVIEW C VOLUME 41, NUMBER 6 JUNE 1990

Electromagnetic dissociation of relativistic heavy ions

W. J. Llope and P. Braun-Munzinger
Department of Physics, State University of New York at Stony Brook, Stony Brook, New York 11794

In particular, electromagnetic excitation of modes based on the nuclear giant dipole resonance (GDR) may lead to very exotic final states[1,2] in which neutrons oscillate against protons with a very large amplitude. The existence and decay mechanisms of such states is unknown at present. However, this electromagnetic process efficiently excites collective states so that little or no temperature is produced during the very short time scale (of order 1 fm/c) of the collision. One may thus hope to use this type of reaction to search for fragile, weakly bound exotic states such as multineutron clusters which might be formed in the decay of the possibly strongly excited multi-GDR states.

PHYSICAL REVIEW C VOLUME 41, NUMBER 6 JUNE 1990

Electromagnetic dissociation of relativistic heavy ions

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Department of Physics, State University of New York at Stony Brook, Stony Brook, New York 11794
(Received 12 January 1990)

A framework is developed for the quantitative analysis of the electromagnetic dissociation of relativistic nuclei. This includes treatment of multiple excitations of the giant dipole resonance, coupled with calculations of the fragmentation probabilities in the framework of the statistical model.

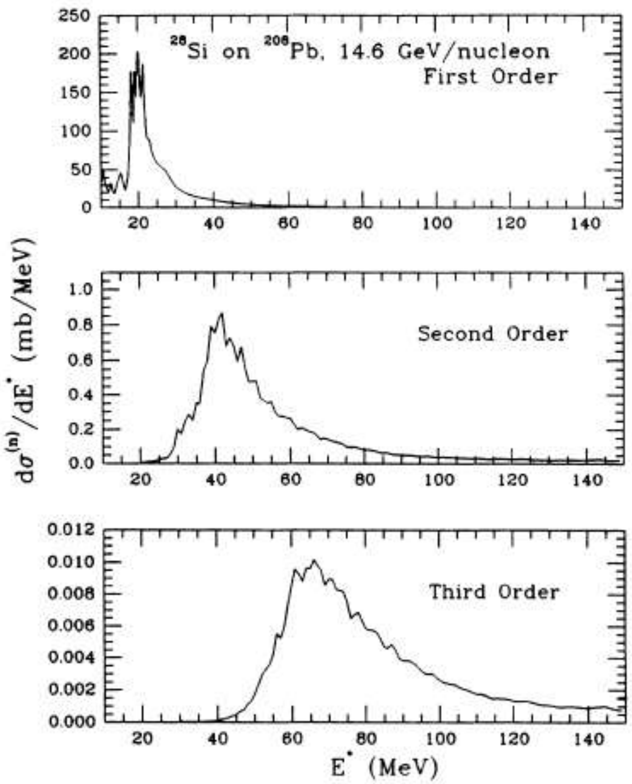
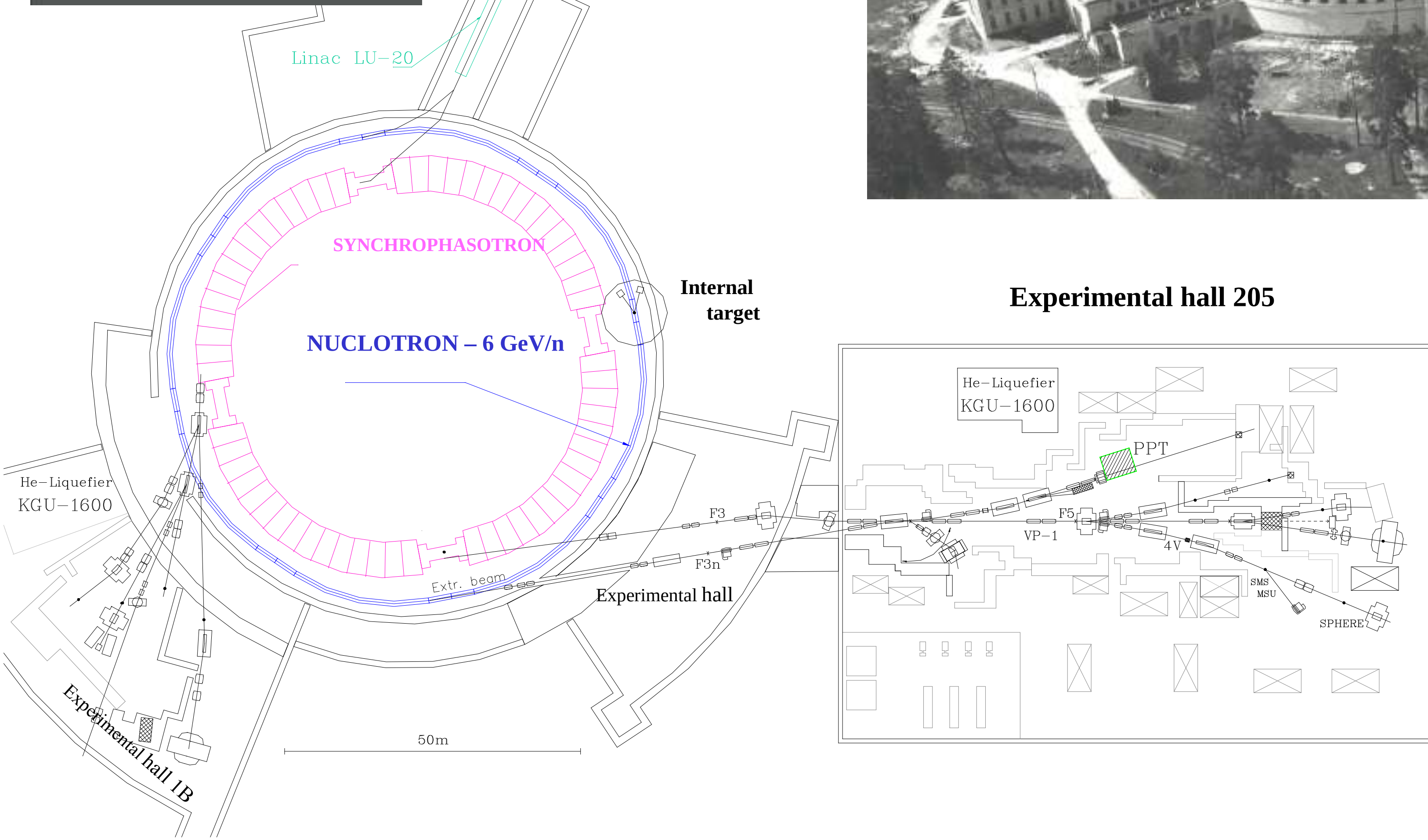
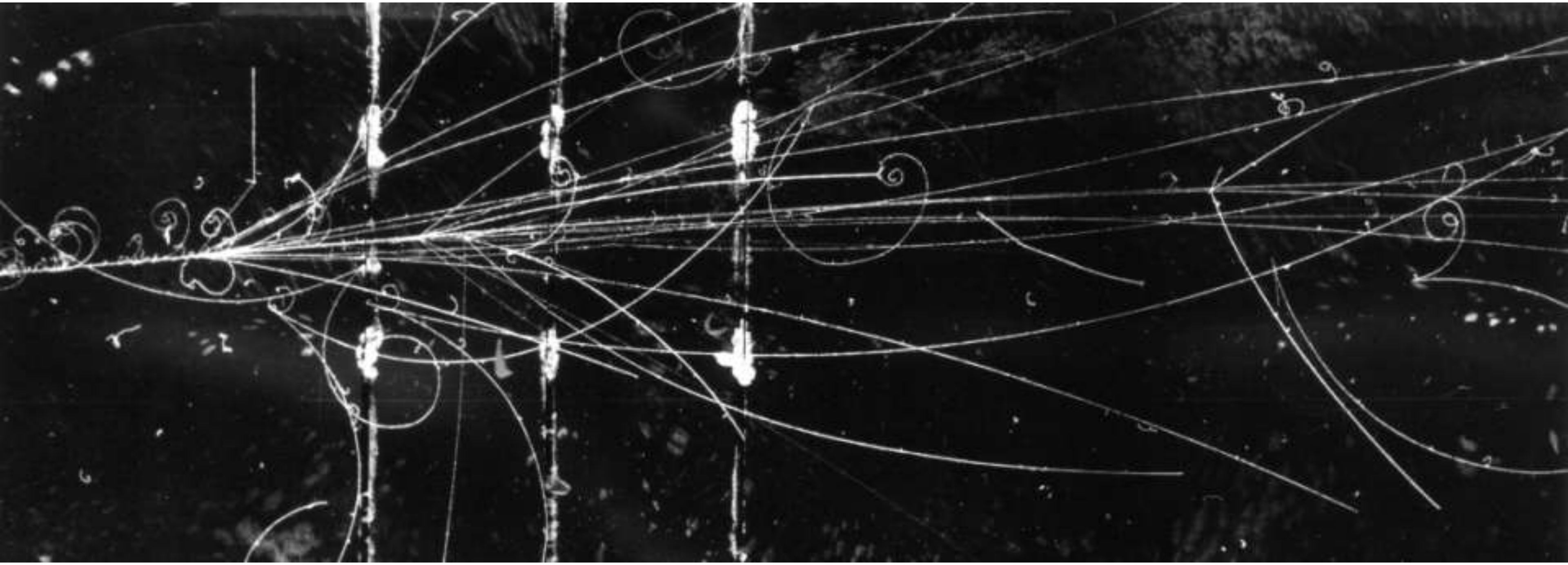


FIG. 3. The total differential Coulomb excitation cross sections for ^{28}Si on ^{208}Pb at $E_{\rm lab}/A = 14.6$ GeV for the first-, second-, and third-order processes.

Dubna: Relativistic Nuclei

Polaris – d↑
EBIS – N, Ar, Fe …
Laser – Li, B, C, F, Mg …
Duoplasmotron – p, d, α, ^{3}He





Фотография взаимодействия ядра ^{12}C с импульсом 4.5A ГэВ/с в пропановой пузырьковой камере (ЛВЭ ОИЯИ, 1974 г.).

0.5 μm resolution, identification of charges and H&He isotopes

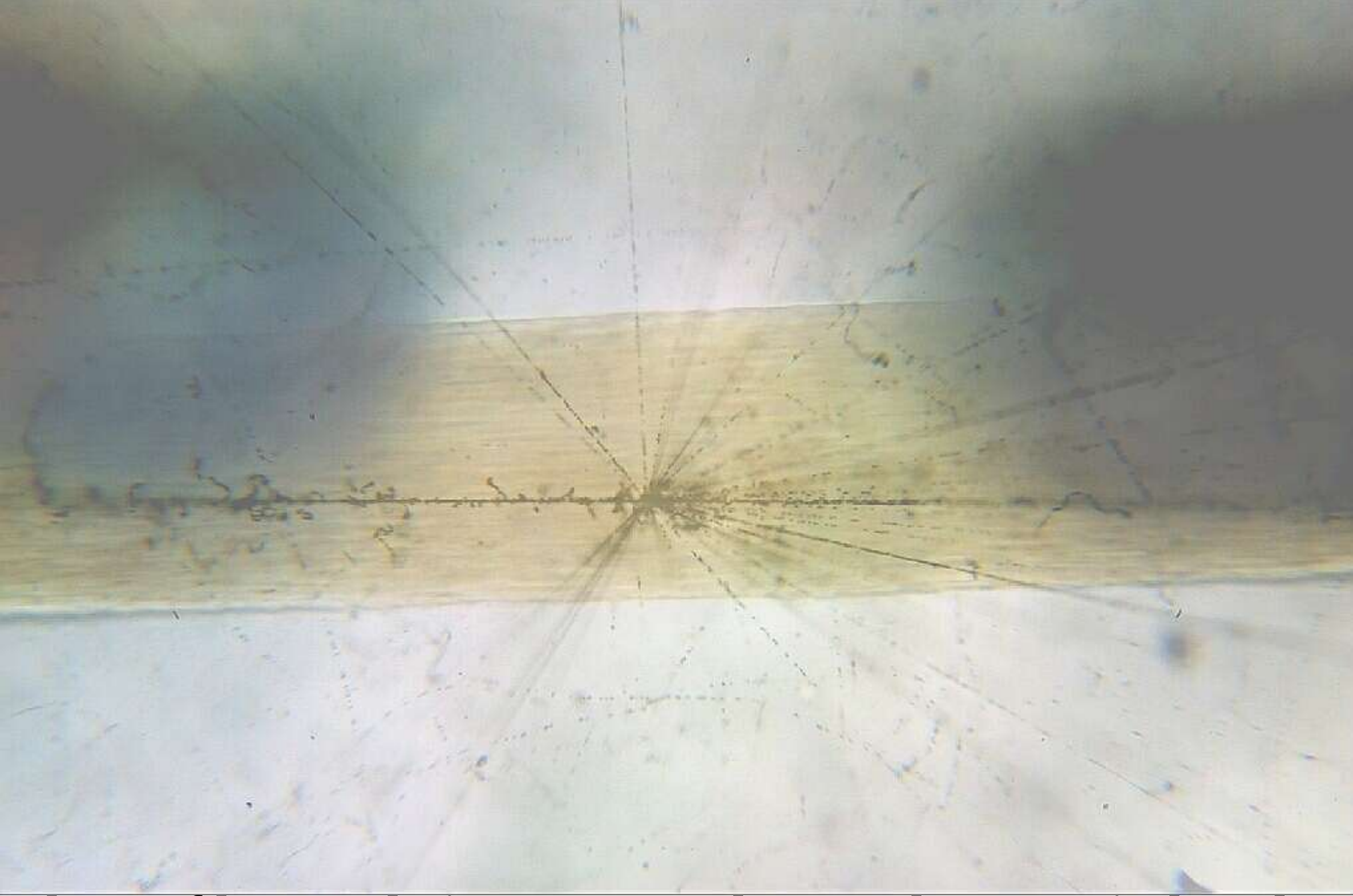


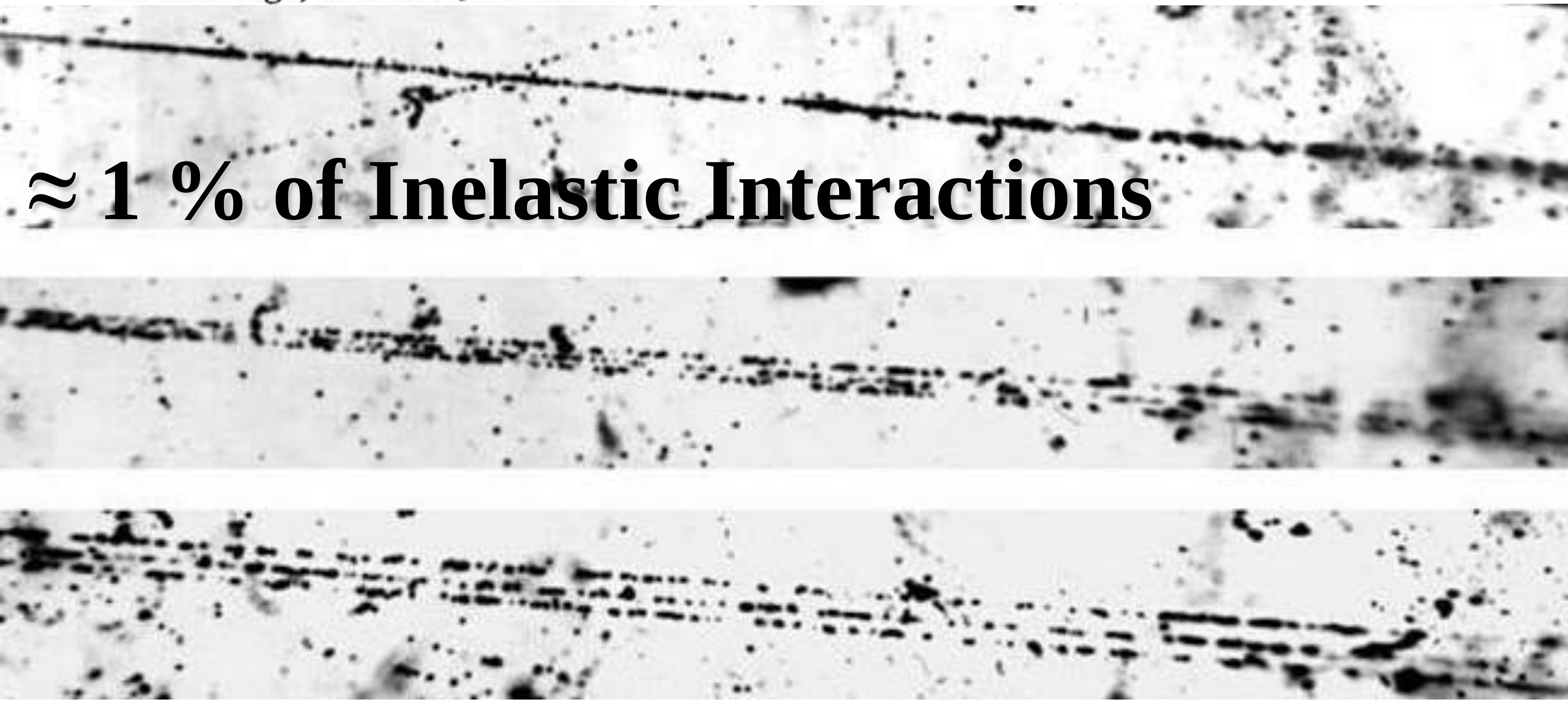
Photo of human hair superposed on nuclear star induced by relativistic sulphur nuclei in nuclear track emulsion

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

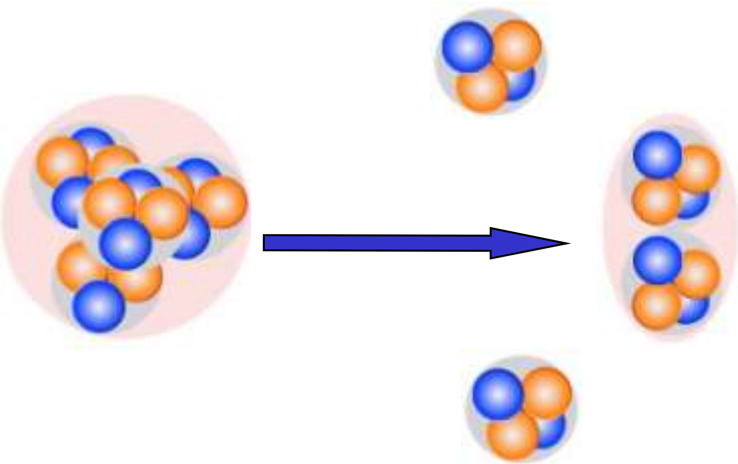
ELEMENTARY PARTICLES AND FIELDS
Experiment

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

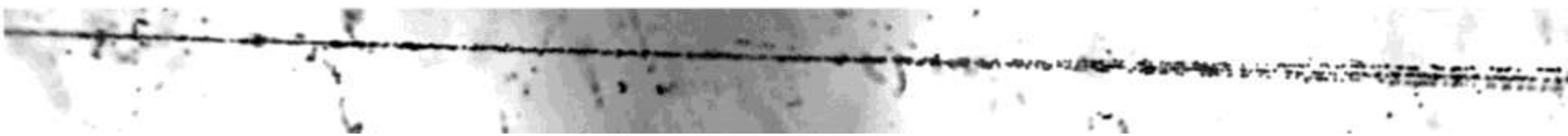
V. V. Belaga, A. A. Benjaza[1)], V. V. Rusakova, J. A. Salamov[2)], and G. M. Chernov

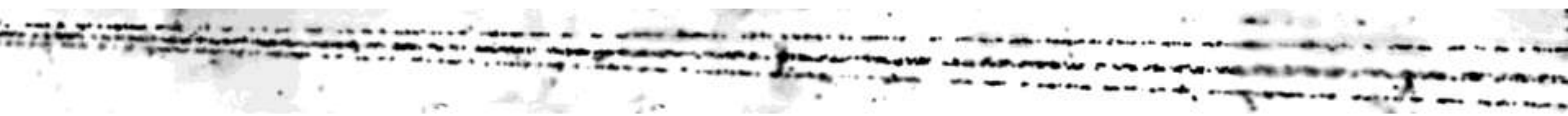


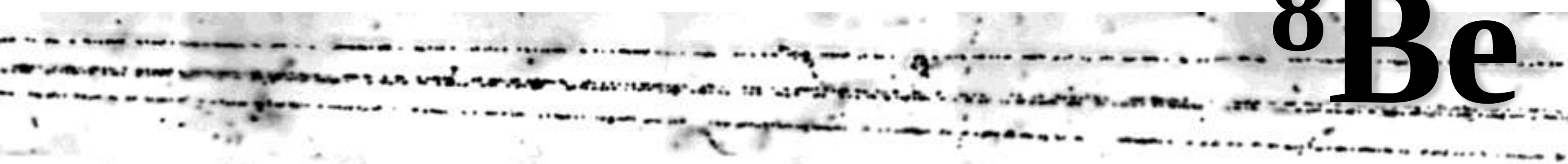
≈ 1 % of Inelastic Interactions



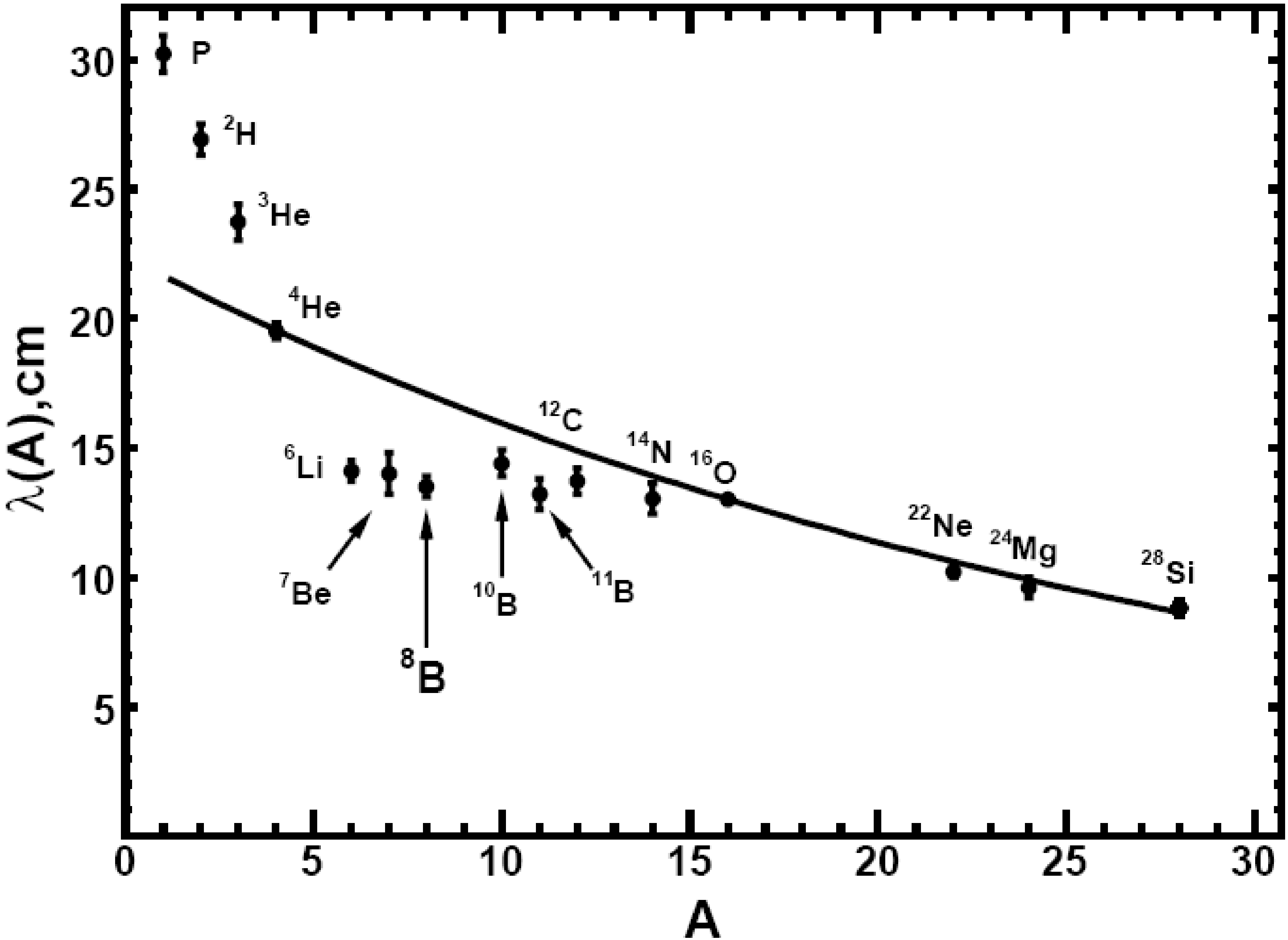
4.5A GeV/c ^{16}O







^{8}Be



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

Physics of Atomic Nuclei, Vol. 62, No. 8, 1999, pp. 1378–1387. Translated from Yadernaya Fizika, Vol. 62, No. 8, 1999, pp. 1461–1471.

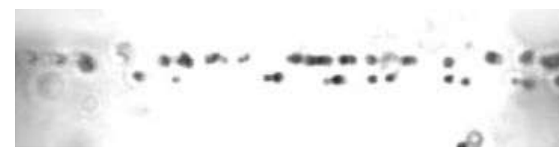
ELEMENTARY PARTICLES AND FIELDS
Experiment

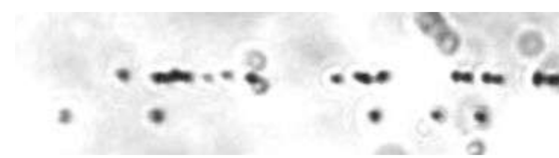
Interactions of Relativistic ^{6}Li Nuclei with Photoemulsion Nuclei

M. I. Adamovich, V. G. Bogdanov[1)], I. A. Konorov, V. G. Larionova, N. G. Peresadko, V. A. Plyushchev[1)], Z. I. Solovyeva[1)†], and S. P. Kharlamov

Number of events of ^{6}Li coherent dissociation

Dissociation channel	Number of events	
	without the excitation of the target nucleus ($N_h = 0$)	with the excitation of the target nucleus ($N_h \neq 0$)
$^{4}He + d$	23	24
$^{3}He + t$	4	1
$t + d + p$	4	3
$d + d + d$	0	2

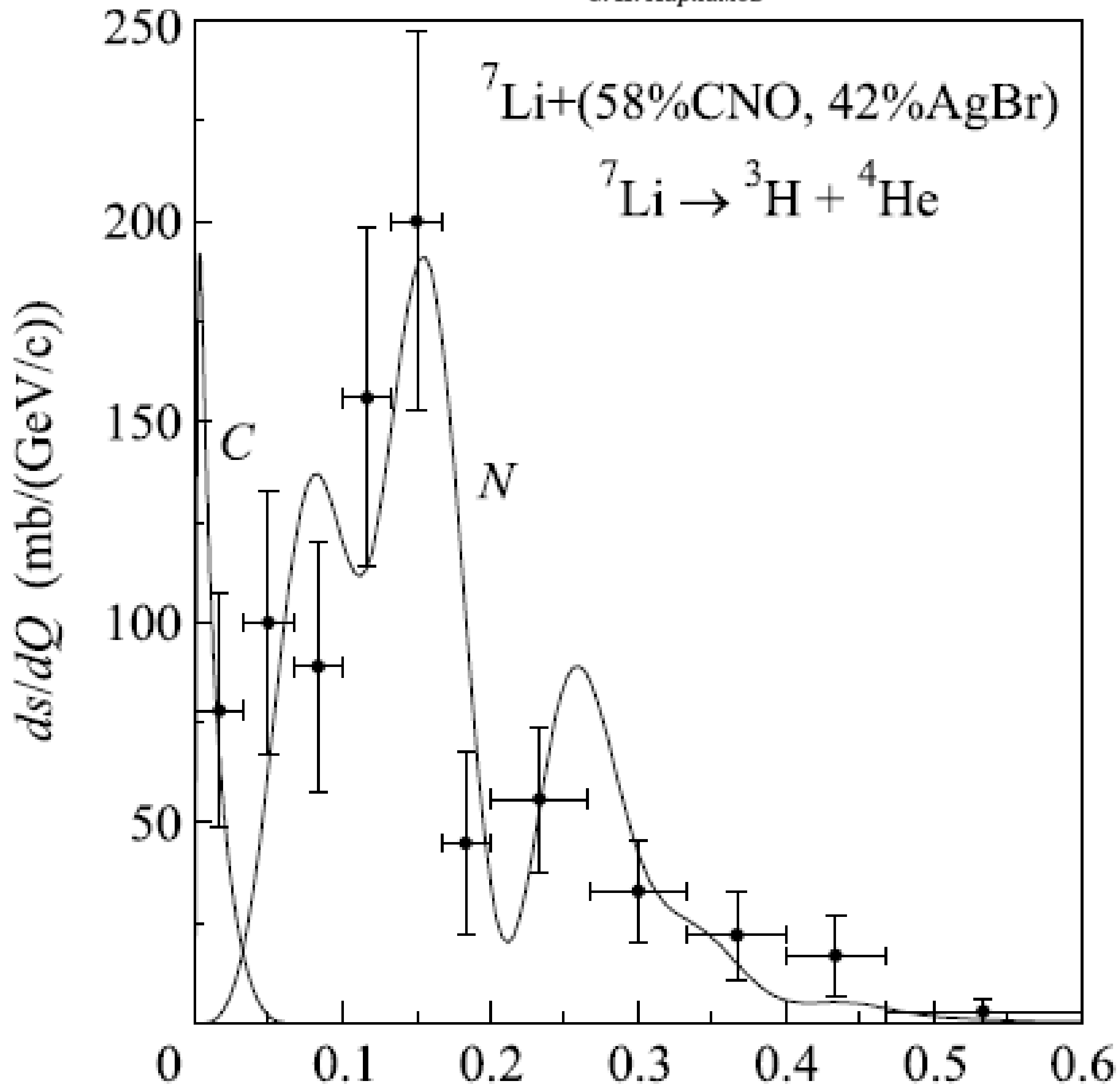




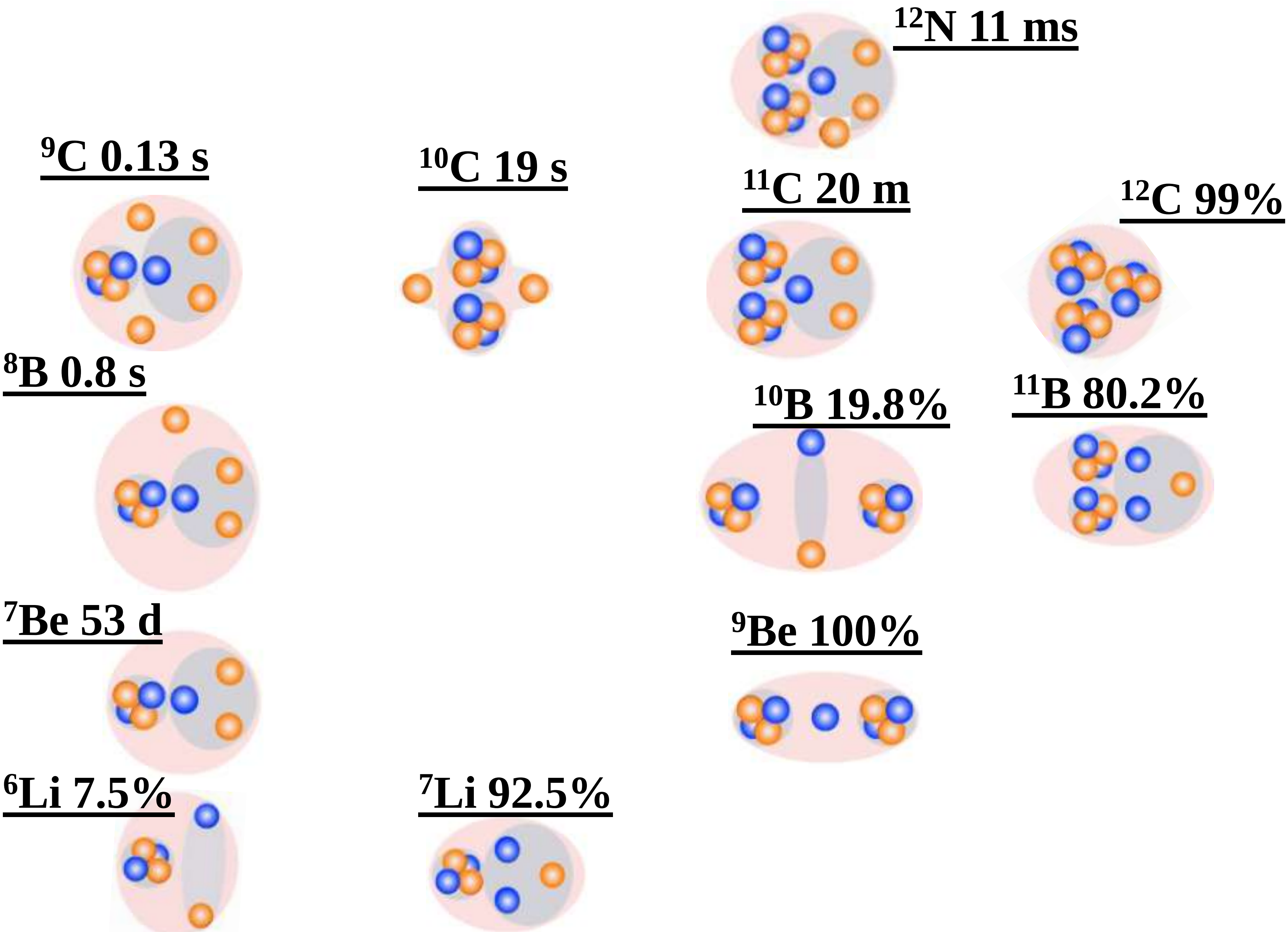
Письма в ЖЭТФ, том 88, вып. 2, с. 83 – 87

Роль ядерного и электромагнитного взаимодействий в когерентной диссоциации релятивистского ядра ^{7}Li по каналу ^{3}H + ^{4}He

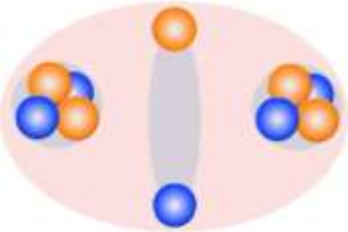
Н. Г. Пересадько, В. Н. Фетисов[1], *Ю. А. Александров, С. Г. Герасимов, В. А. Дронов, В. Г. Ларионова, Е. И. Тамм, С. П. Харламов*



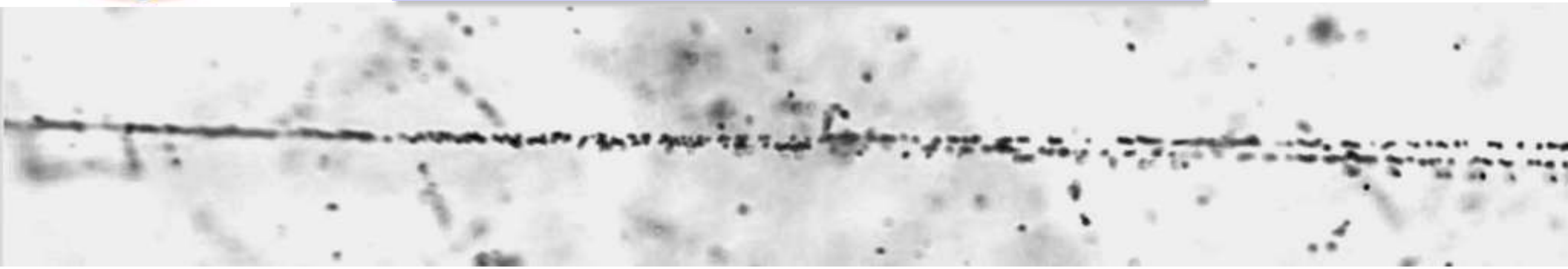
P_T (^{7}Li), GeV/*c*

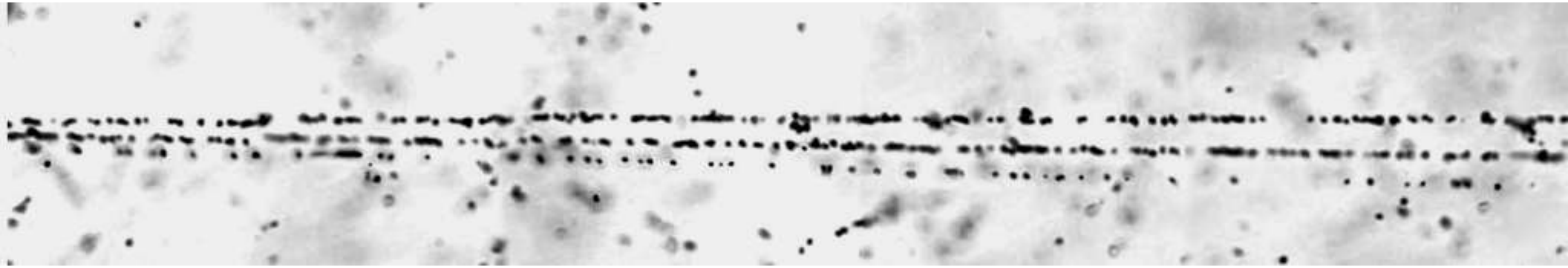


^{12}N 11 ms
^{9}C 0.13 s
^{10}C 19 s
^{11}C 20 m
^{12}C 99%
^{8}B 0.8 s
^{10}B 19.8%
^{11}B 80.2%
^{7}Be 53 d
^{9}Be 100%
^{6}Li 7.5%
^{7}Li 92.5%



1A GeV ^{10}B



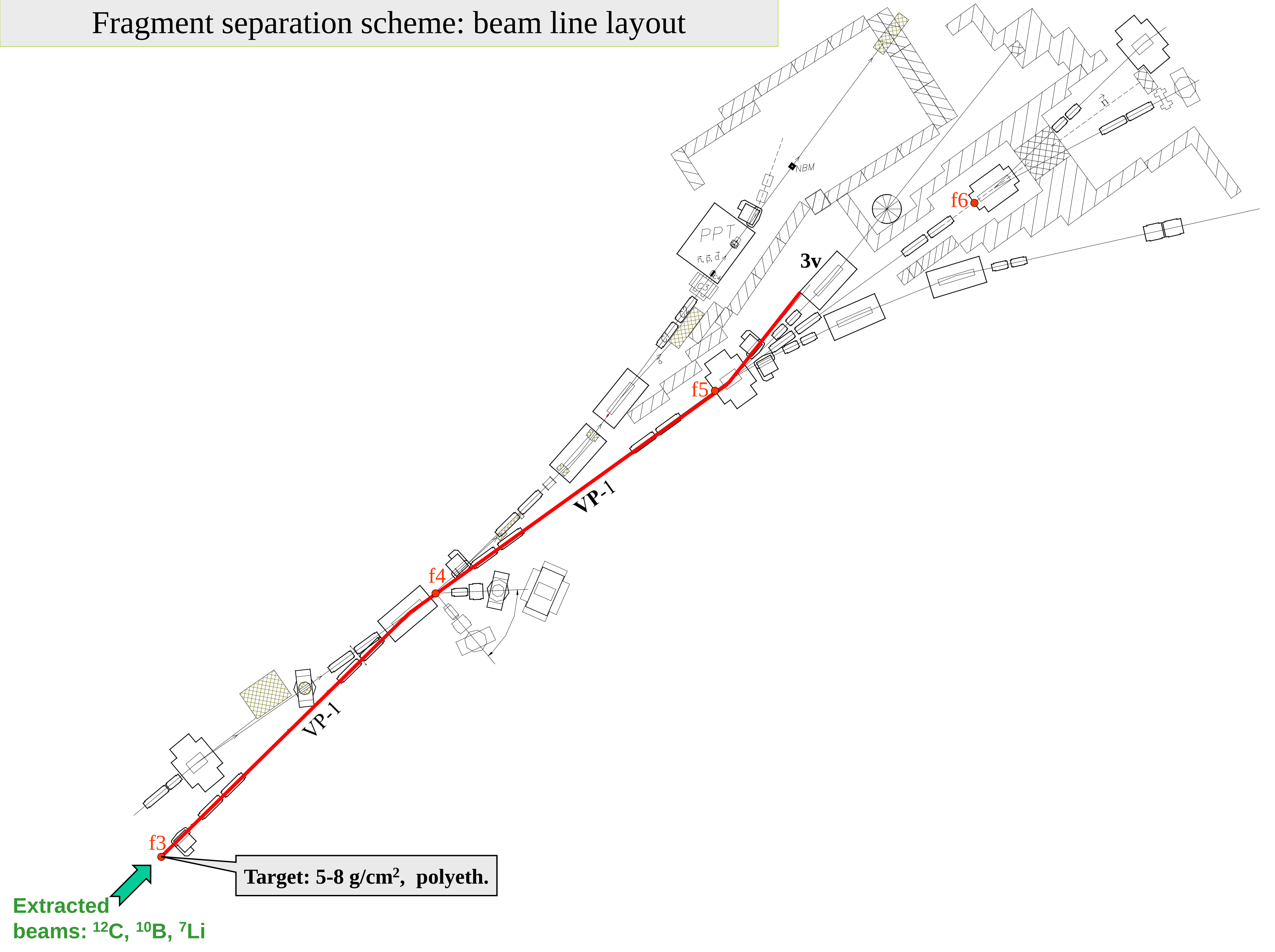


2He+H (6 MeV) - 73%

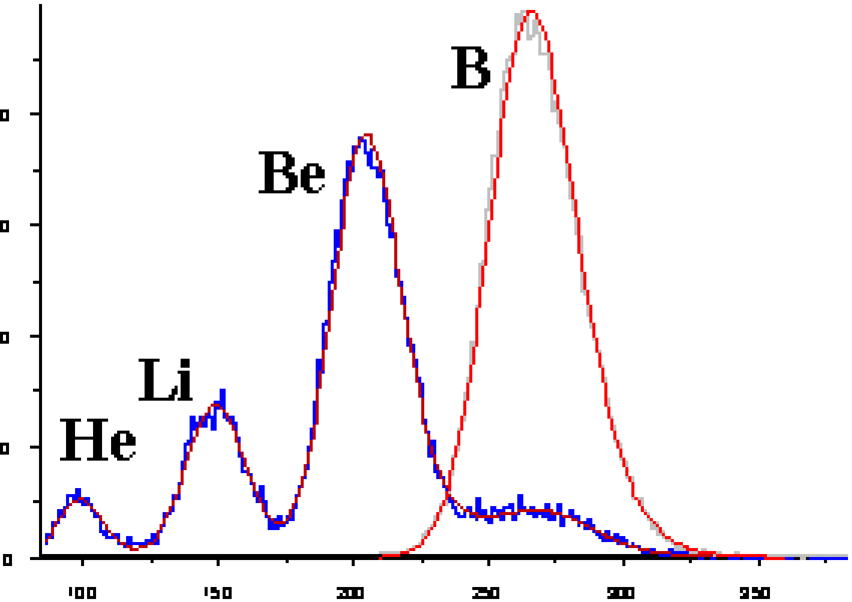
Li+He (4.5 MeV) - 12%

^{9}Be+p (6.6 MeV) - 2%

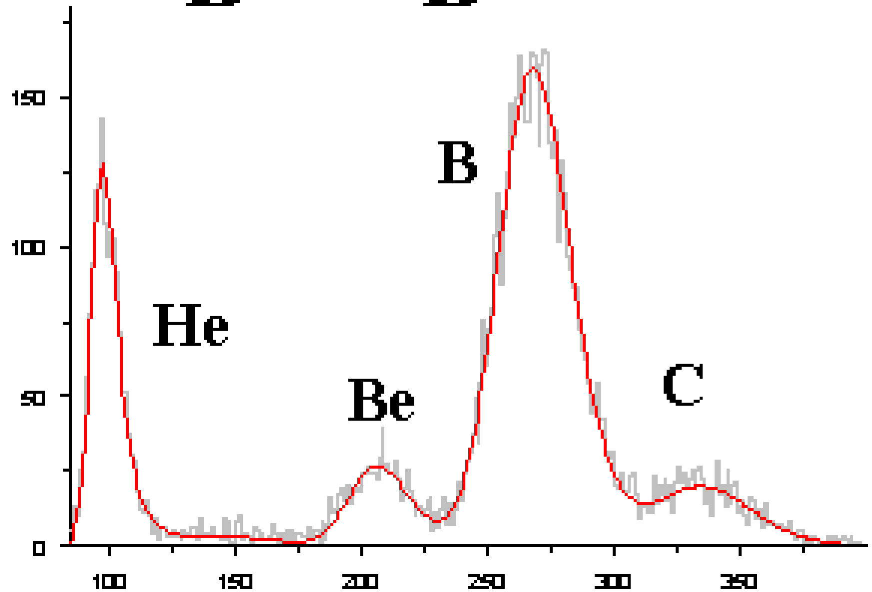
Fragment separation scheme: beam line layout



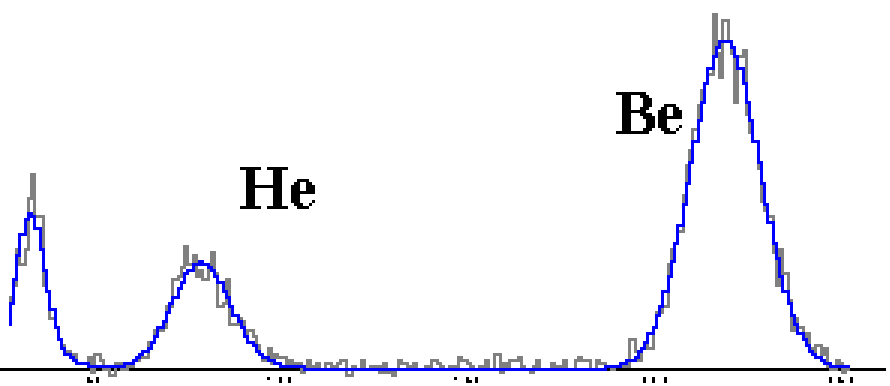
$^{10}B \rightarrow {}^{9}Be$



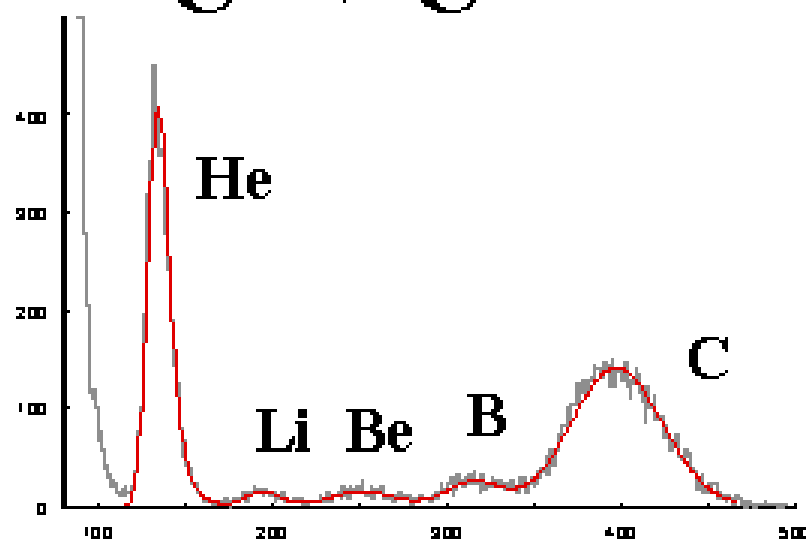
$^{10}B \rightarrow {}^{8}B$



$^{7}Li \rightarrow {}^{7}Be$



$^{12}C \rightarrow {}^{9}C$



ISSN 1063-7788, Physics of Atomic Nuclei, 2009, Vol. 72, No. 4, pp. 690–701. © Pleiades Publishing, Ltd., 2009.
Original Russian Text © R. Stanoeva, D.A. Artemenkov, V. Bradnova, S. Vokál, L.A. Goncharova, P.I. Zarubin, I.G. Zarubina, N.A. Kachalova, A.D. Kovalenko, D.O. Krivenkov, A.I. Malakhov, G.I. Orlova, N.G. Peresadko, N.G. Polukhina, P.A. Rukoyatkin, V.V. Rusakova, M. Haiduc, S.P. Kharlamov, M.M. Chernyavsky, T.V. Shchedrina, 2009, published in Yadernaya Fizika, 2009, Vol. 72, No. 4, pp. 731–742.

ELEMENTARY PARTICLES AND FIELDS
Experiment

Electromagnetic Dissociation of Relativistic ^{8}B Nuclei in Nuclear Track Emulsion

R. Stanoeva[1),2)], D. A. Artemenkov[1)], V. Bradnova[1)], S. Vokál[1),3)], L. A. Goncharova[4)], P. I. Zarubin[1)*], I. G. Zarubina[1)], N. A. Kachalova[1)], A. D. Kovalenko[1)], D. O. Krivenkov[1)], A. I. Malakhov[1)], G. I. Orlova[4)], N. G. Peresadko[4)], N. G. Polukhina[4)], P. A. Rukoyatkin[1)], V. V. Rusakova[1)], M. Haiduc[5)], S. P. Kharlamov[4)], M. M. Chernyavsky[4)], and T. V. Shchedrina[1)]

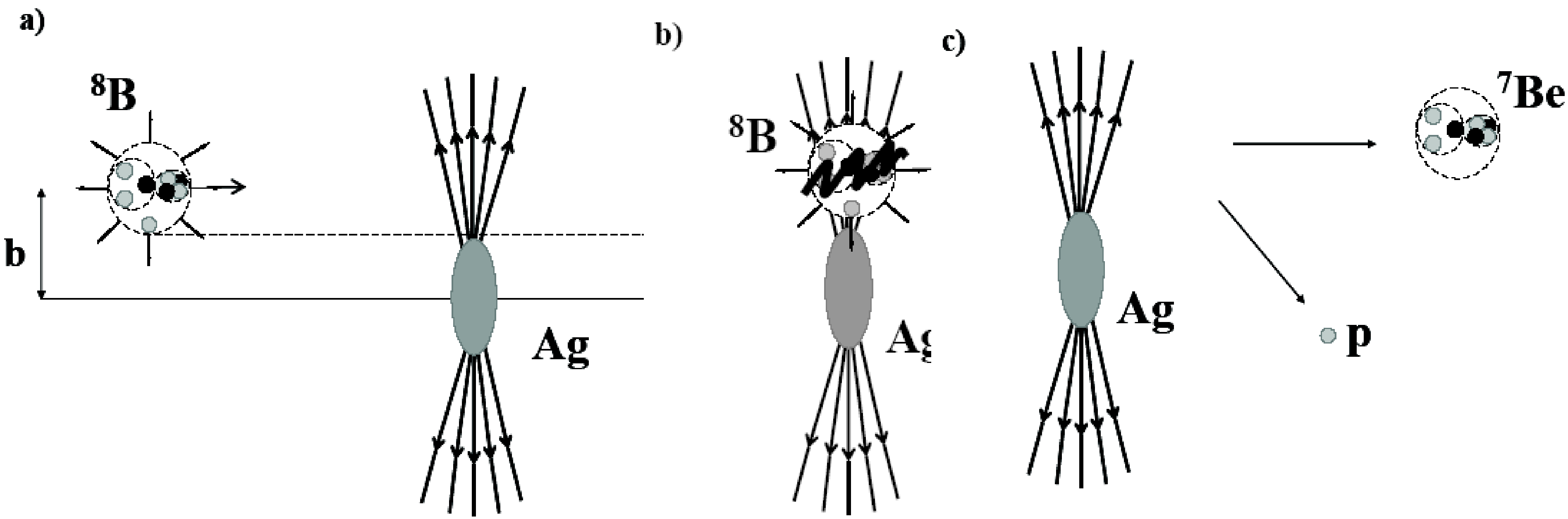
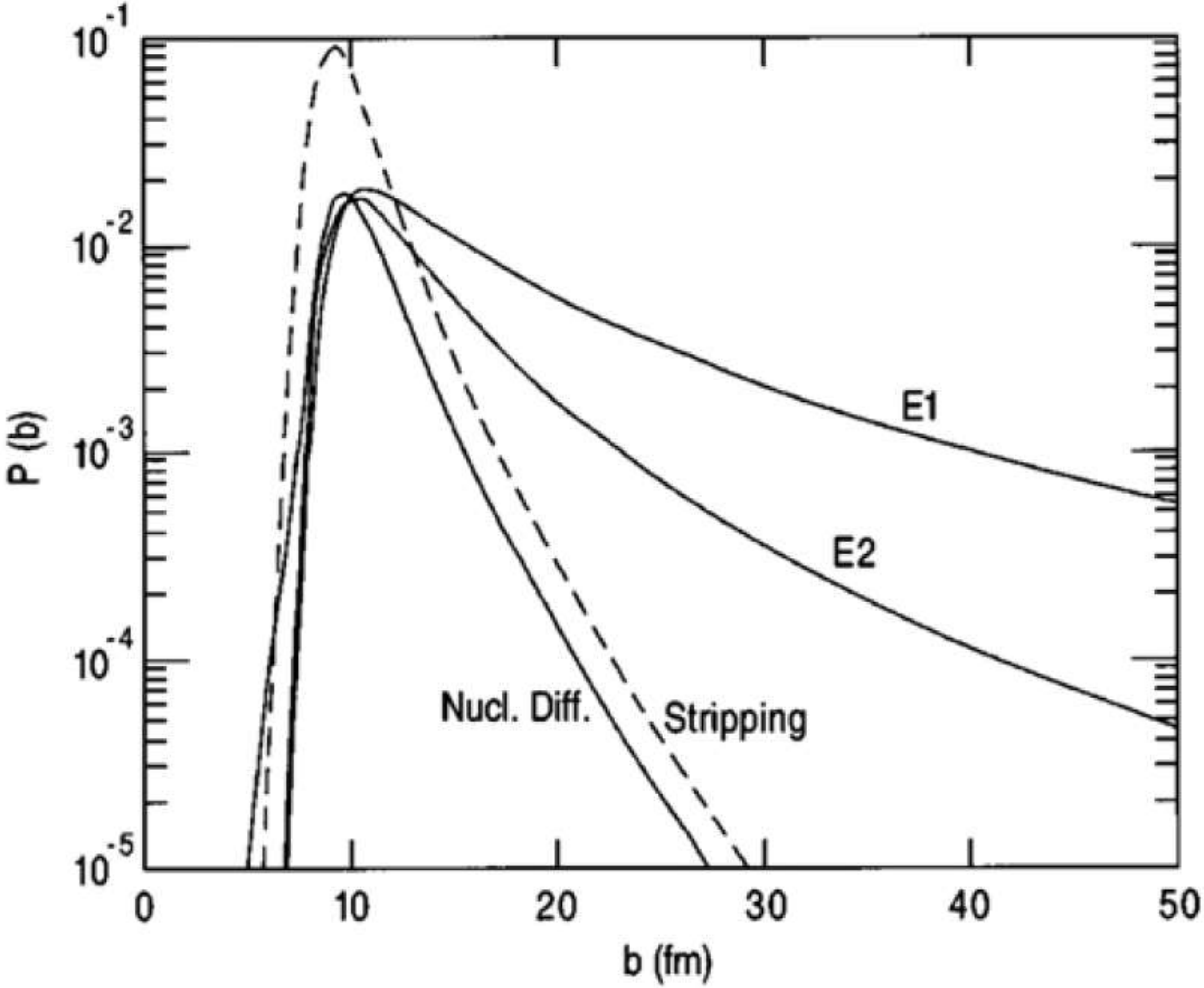


Fig. 1. Scheme of the electromagnetic dissociation of a relativistic ^{8}B nucleus in the field of a silver nucleus: (*a*) approach of the nuclei at an impact parameter *b*; (*b*) quasireal-photon absorption by the ^{8}B nucleus; and (*c*) dissociation into two fragments, *p* and ^{7}Be.



P (b)
b (fm)
E1
E2
Nucl. Diff.
Stripping

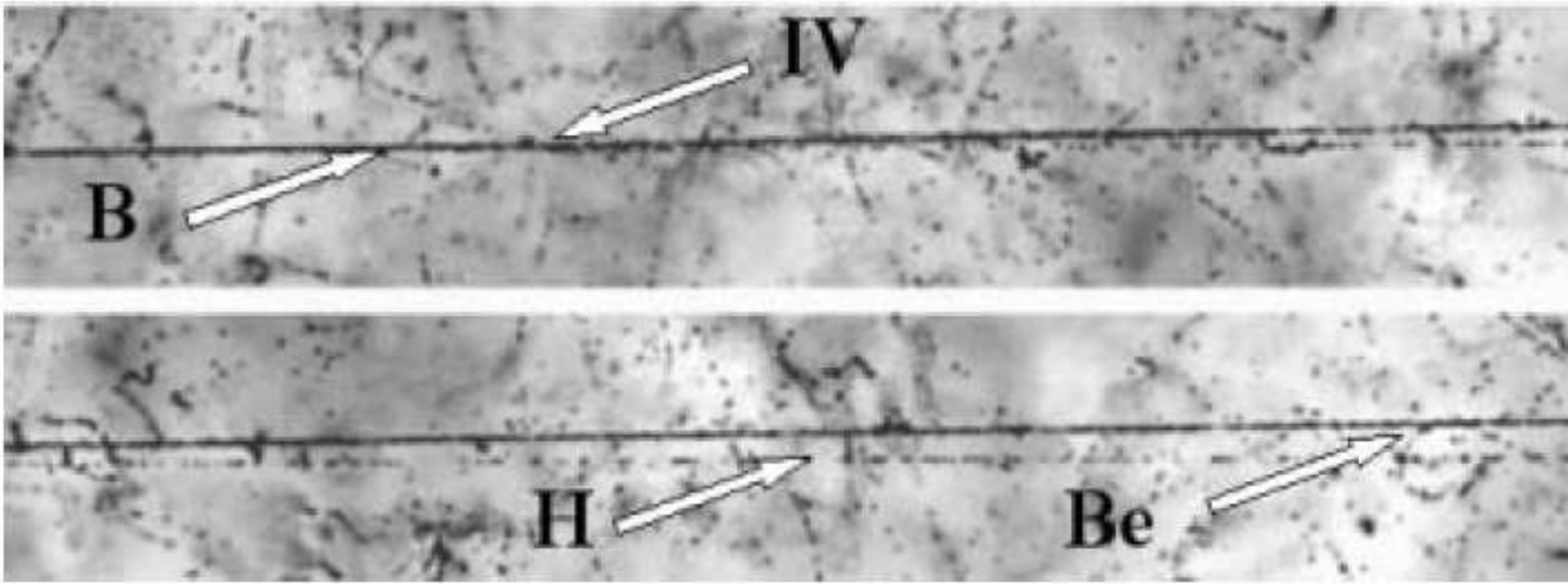
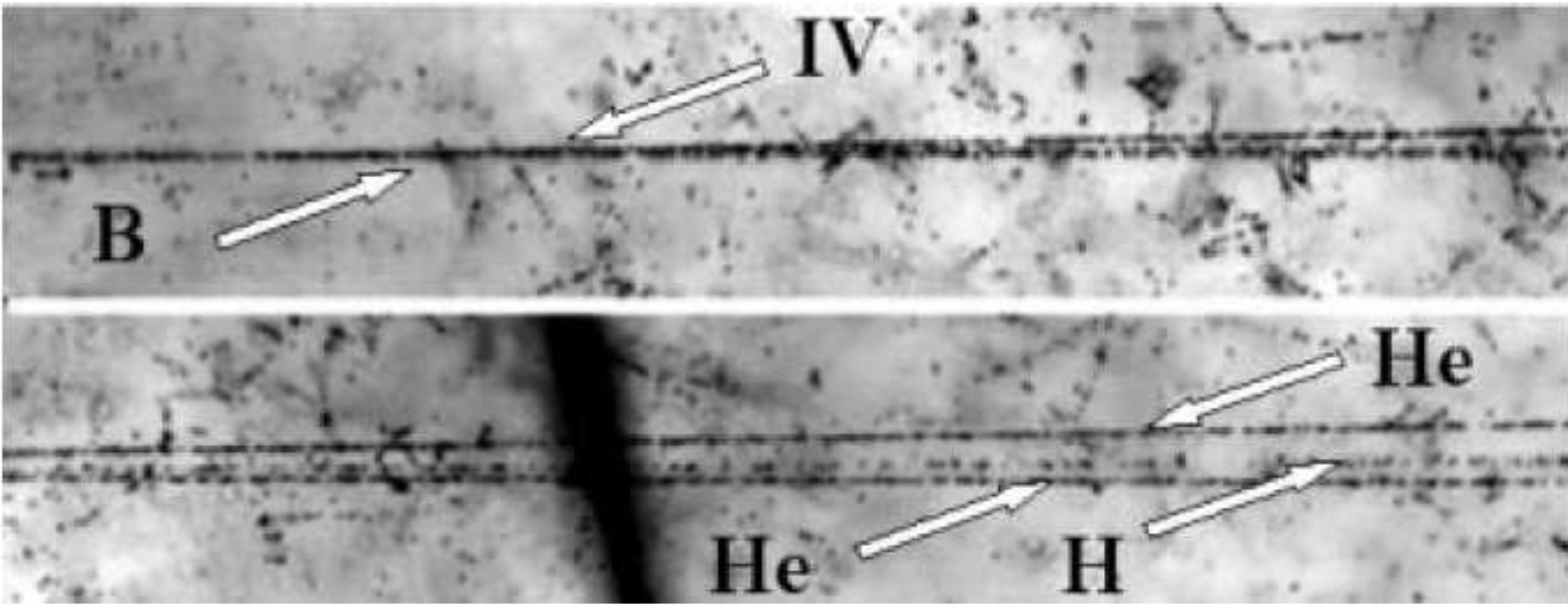
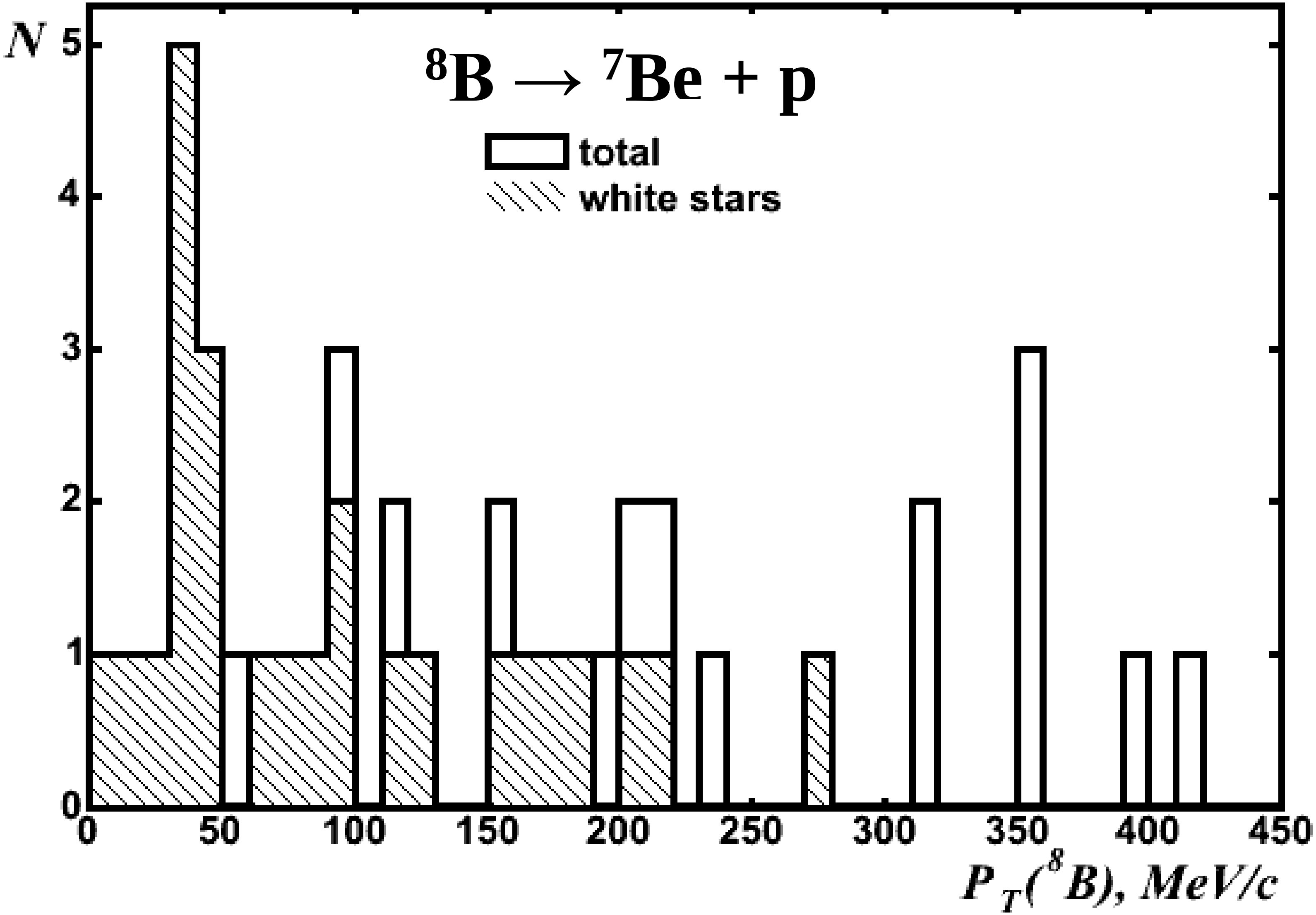


FIG. 1: Example of peripheral interaction of a 1.2 A GeV $^8B \rightarrow ^7Be+p$ in a nuclear track emulsion ("white" star). The interaction vertex (indicated as **IV**) and nuclear fragment tracks (**H** and **Be**) in a narrow angular cone are seen on the upper and bottom microphotograph.

$^{8}B \rightarrow 2He + H$



	Q_{min} (^{10}B), МэВ	N_{ws} (^{10}B)	% (^{10}B)	Q_{min} (^{8}B), МэВ	N_{ws} (^{8}B)	% (^{8}B)
2He+H	6.0	30	73	1.724	14	27
He+3H	25	5	12	8.6	12	23
Be+H	6.6	1	2	0.138	25	48
B		-	-		1	2
Li+He	4.5	5	13	3.7	-	-



N
$^{8}B \rightarrow {}^{7}Be + p$
total
white stars
0
1
2
3
4
5
0
50
100
150
200
250
300
350
400
450
$P_T(^8B)$, MeV/c

PHYSICAL REVIEW C, VOLUME 61, 054606

Systematic study of ^8B breakup cross sections

Henning Esbensen
Physics Division, Argonne National Laboratory, Argonne, Illinois 60439

Kai Hencken
Institut für Physik, Universität Basel, 4056 Basel, Switzerland

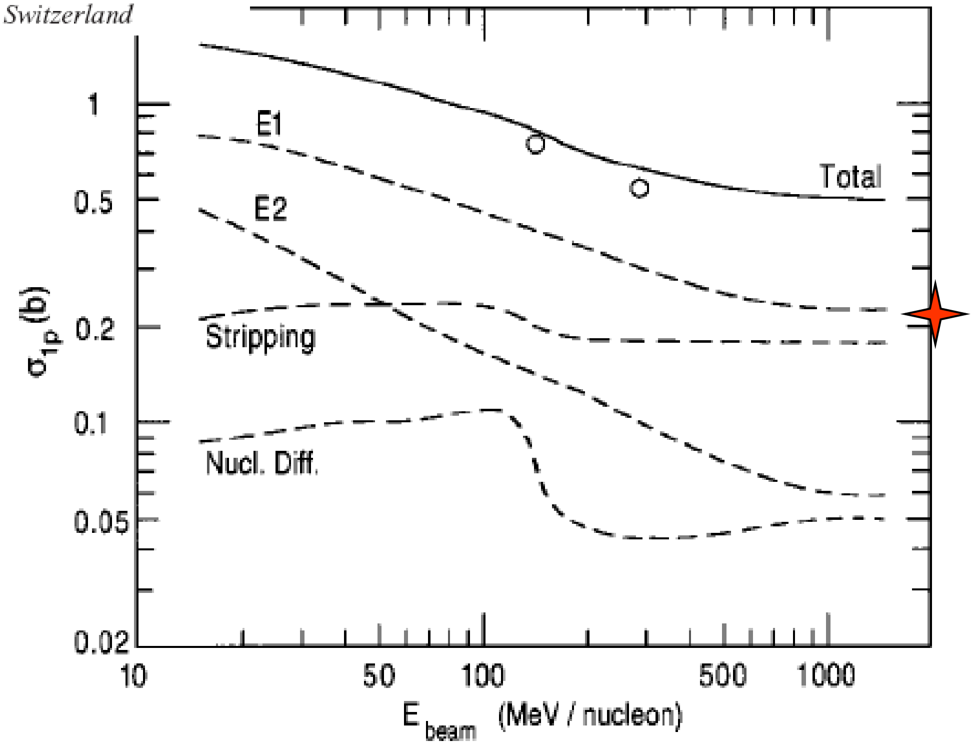


FIG. 8. One-proton removal cross section (solid curve) for ^8B on a Pb target, as a function of the beam energy. The dashed curves show the contributions from stripping, nuclear induced diffraction, and the $E1$ and $E2$ Coulomb dissociation. The two data points are from Ref. [8].

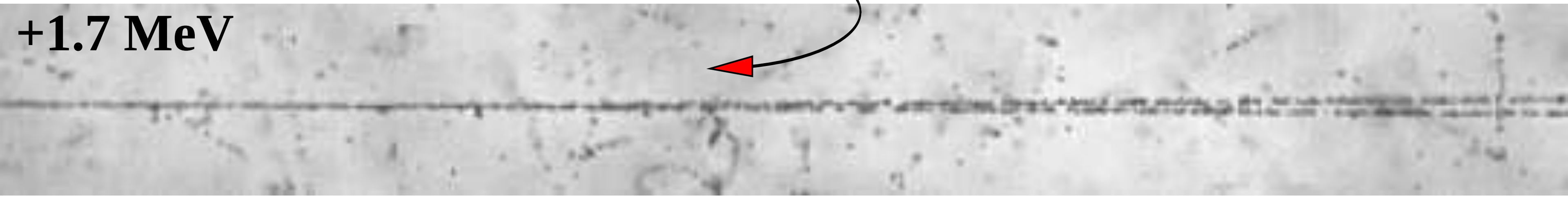
Few Body Syst (2008) 44: 273–276
DOI 10.1007/s00601-008-0307-6
Printed in The Netherlands

Few-Body Systems

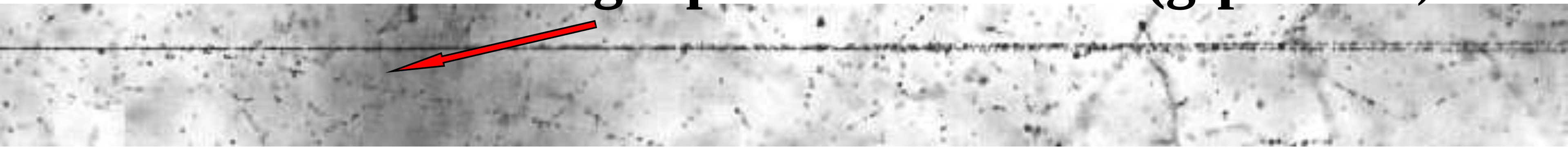
Detailed study of relativistic ^{9}Be → 2α fragmentation in peripheral collisions in a nuclear track emulsion*

D. A. Artemenkov**, D. O. Krivenkov, T. V. Shchedrina, R. Stanoeva, P. I. Zarubin

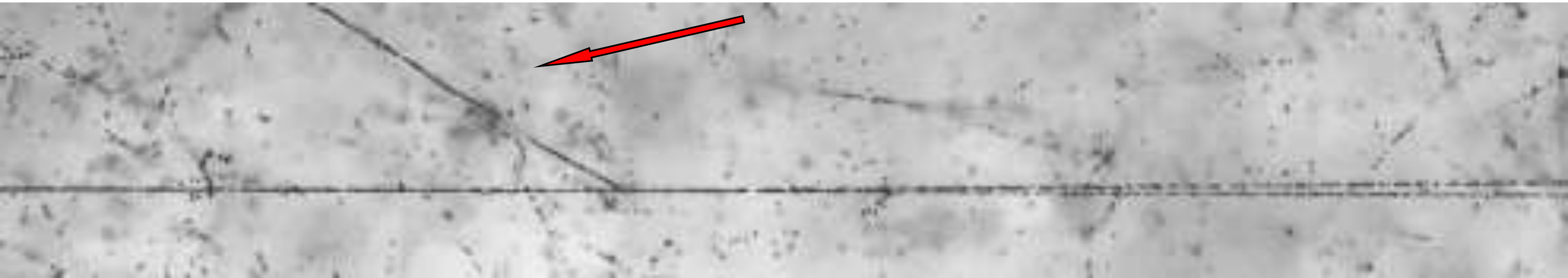
“white” stars

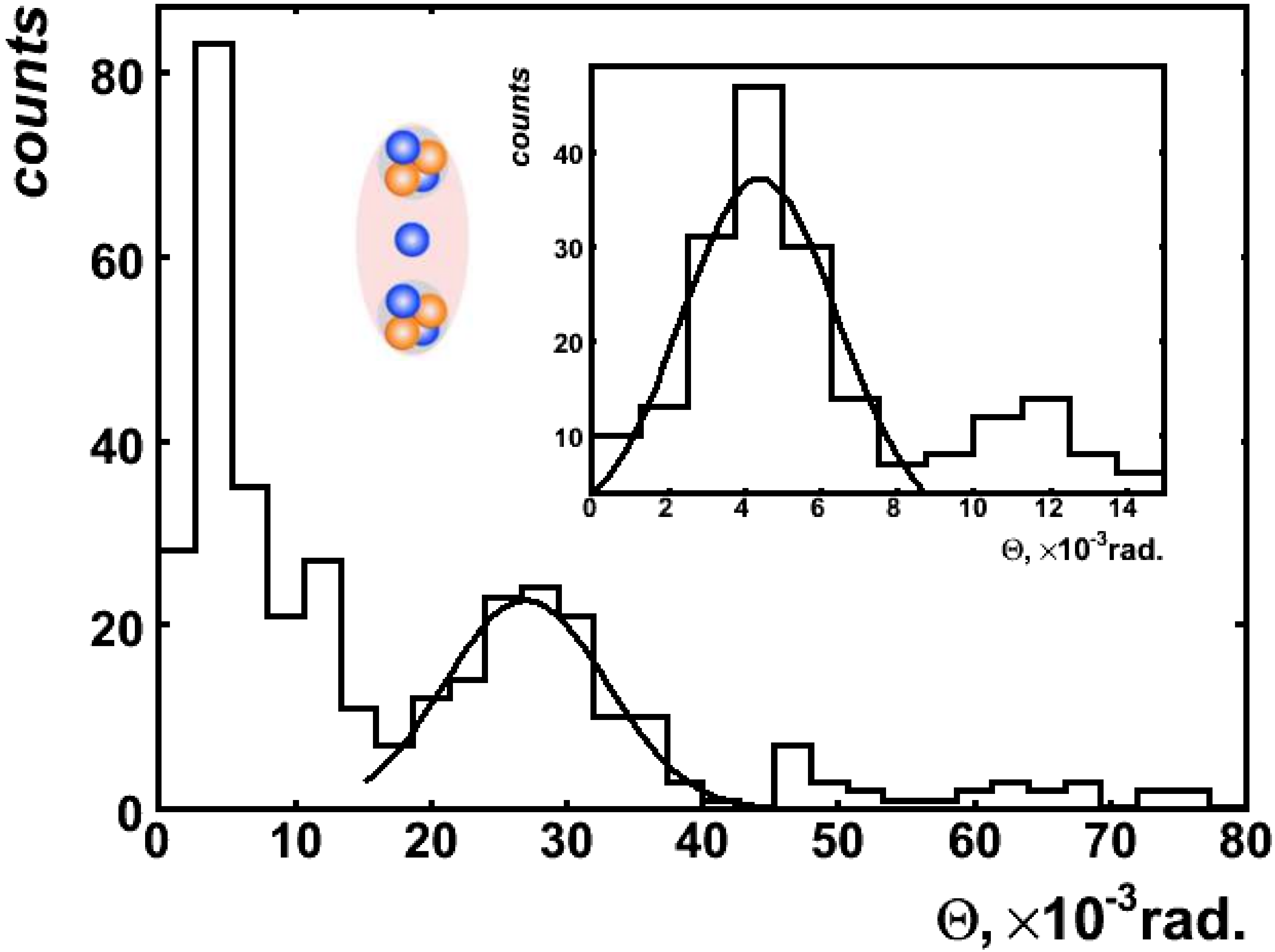


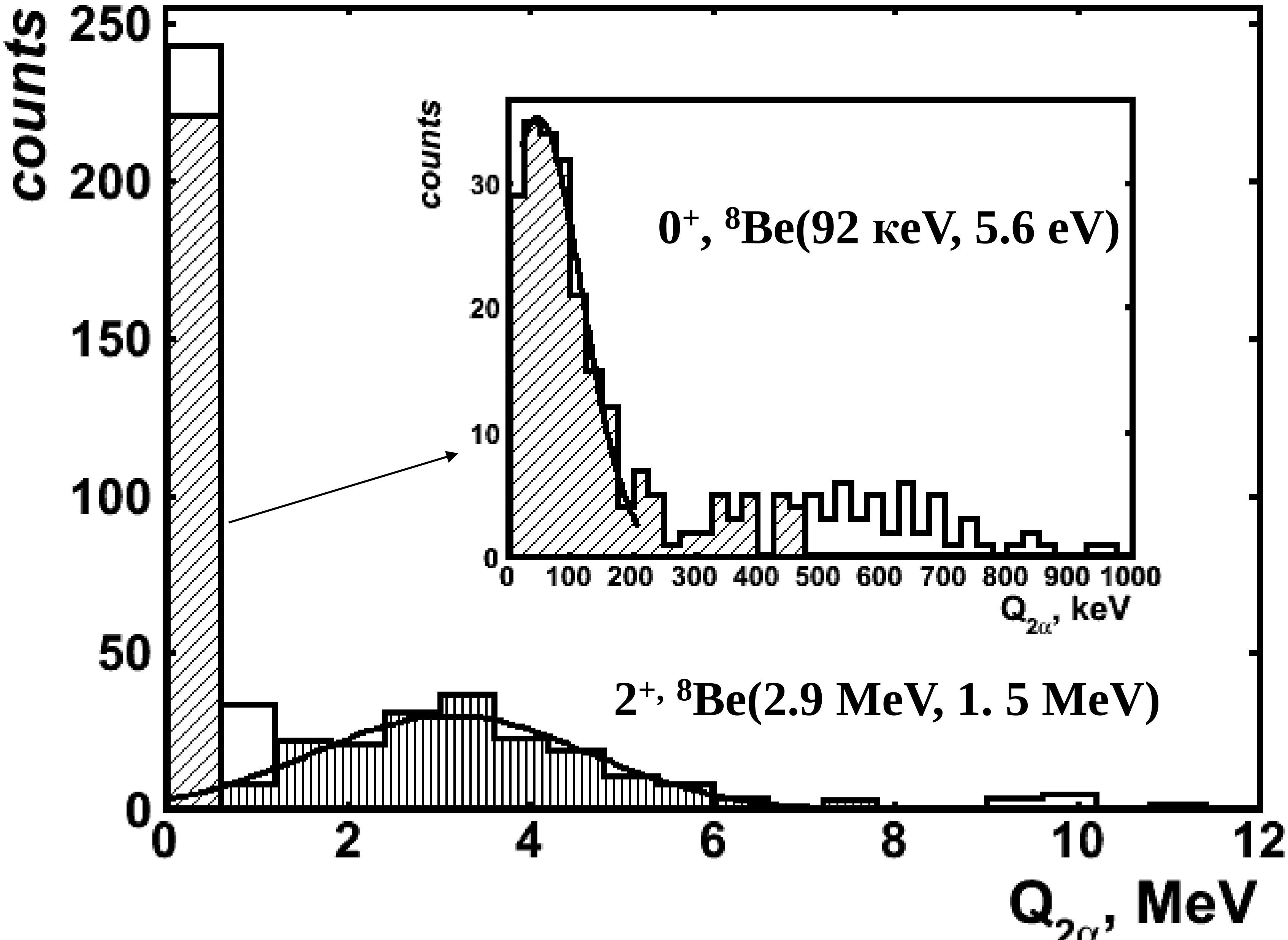
stars with target proton like recoil (g-particle)



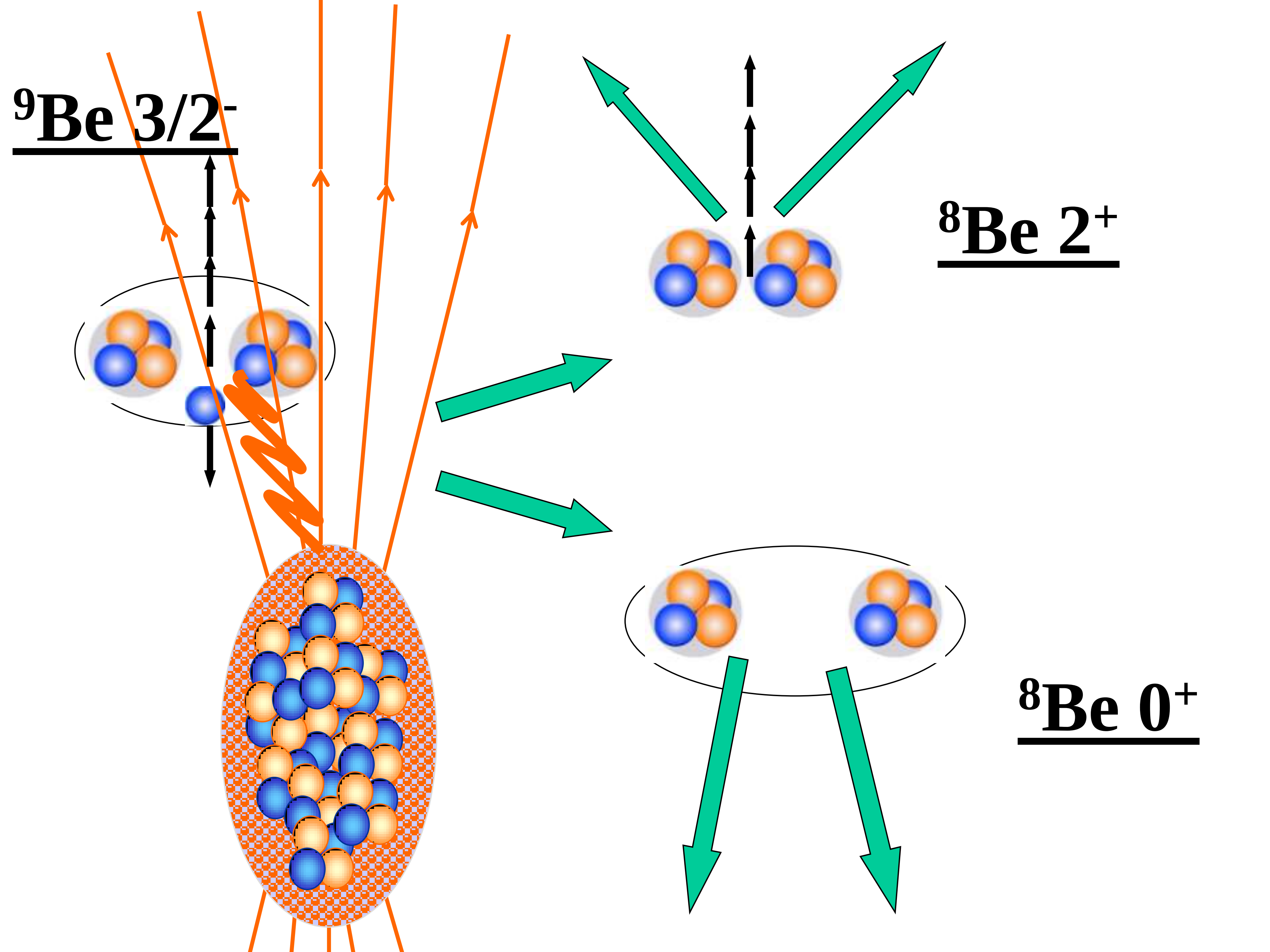
stars with heavy fragment of target nucleus (b-particle)




counts
80
60
40
20
0
0
10
20
30
40
50
60
70
80
Θ, ×10-3rad.
counts
40
30
20
10
0
2
4
6
8
10
12
14
Θ, ×10-3rad.



counts
250
200
150
100
50
0
0
2
4
6
8
10
12
Q2α, MeV
counts
30
20
10
0
0
100
200
300
400
500
600
700
800
900
1000
Q2α, keV
0+, 8Be(92 кeV, 5.6 eV)
2+, 8Be(2.9 MeV, 1. 5 MeV)



^{9}Be 3/2^{-}
^{8}Be 2^{+}
^{8}Be 0^{+}

$$\left|{}^{9}Be(3/2^{-})\right\rangle = \varpi_{0^{+}}\left|\left[{}^{8}Be(0^{+})\otimes n_{p(3/2)}\right]_{3/2^{-}}\right\rangle + \varpi_{2^{+}}\left|\left[{}^{8}Be(2^{+})\otimes n_{p(3/2)}\right]_{3/2^{-}}\right\rangle$$

где $\omega_{0+} = 0.535$ и $\omega_{2+} = 0.465$ – весовые коэффициенты.

1. Y. L. Parfenova and Ch. Leclercq-Willain, «Hyperfine anomaly in Be isotopes and neutron spatial distribution: A three-cluster model for ^{9}Be», Phys. Rev. C 72, 054304 (2005).
2. Y. L. Parfenova and Ch. Leclercq-Willain, «Hyperfine anomaly in Be isotopes in the cluster model and the neutron spatial distribution», Phys. Rev. C 72, 024312(2005).

Доли событий Θ_{0+} и Θ_{2+} составляют 0.56 ± 0.04 и 0.44 ± 0.04. Эти величины демонстрируют соответствие весам 0^{+} и 2^{+} состояний, принятым в теоретических работах [1,2]. Они указывают присутствие этих состояний как компонент основного состояния ядра ^{9}Be.

Резюме

Впервые выполнено исследование структуры $2\alpha + n$ ядра ^9Be методом релятивистской фрагментации. В основном, фрагментация $^9Be \rightarrow 2\alpha$ (*81 %*) протекает через состояния 0^+ и 2^+ ядра ^8Be с близкими вероятностями.

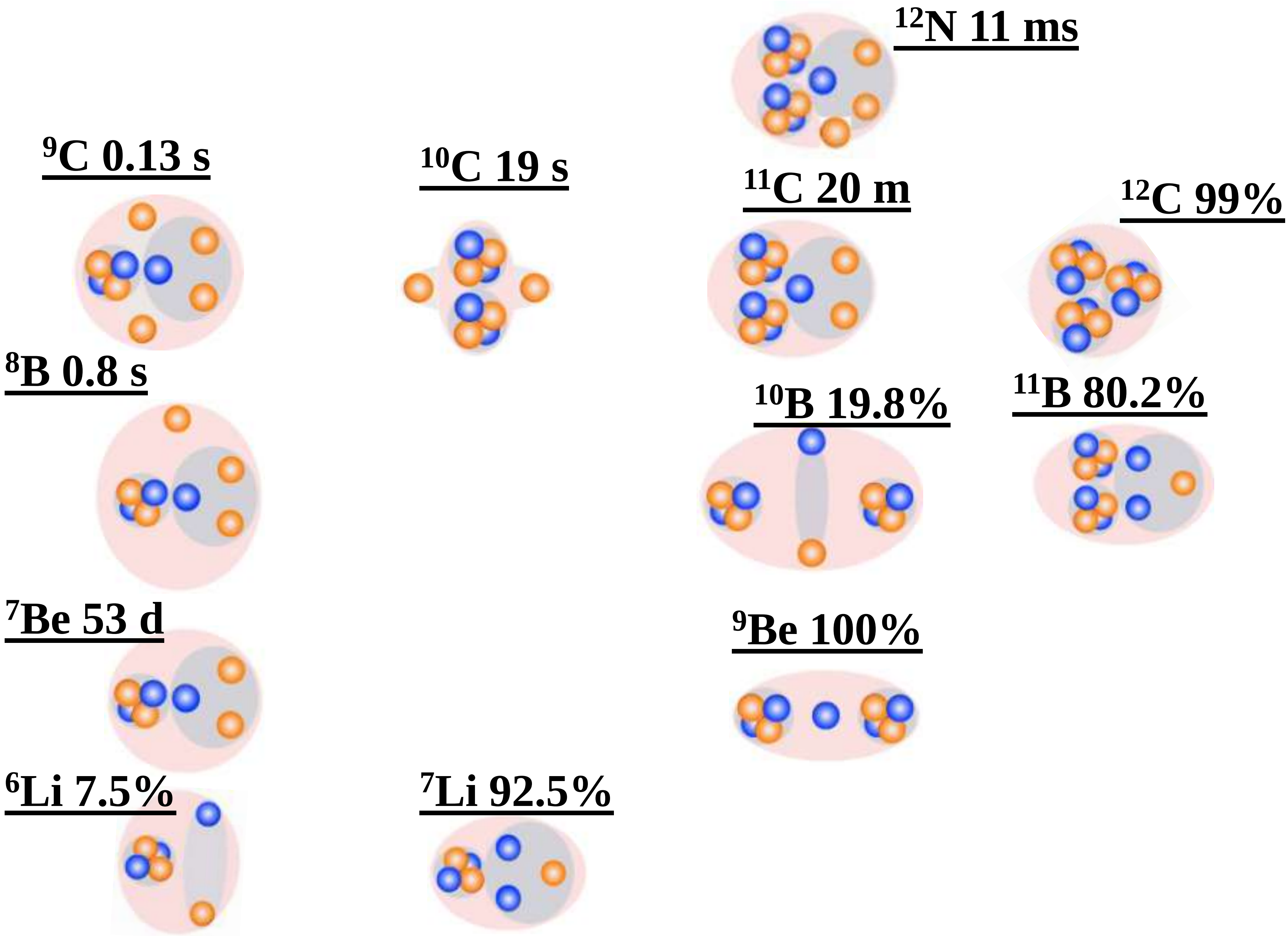
Для когерентной диссоциации $^9Be \rightarrow 2\alpha$ на тяжелых ядрах наблюдается уменьшение среднего значения поперечного импульса P_{Tsum} α-пары по сравнению с взаимодействиями на протонах мишени.

Для основной части событий когерентной диссоциации распределение величин суммарного поперечного импульса P_{Tsum} пар α-частиц, может быть объяснено в рамках статистической модели недостающим поперечным импульсом нейтрона – фрагмента ядра ^9Be.

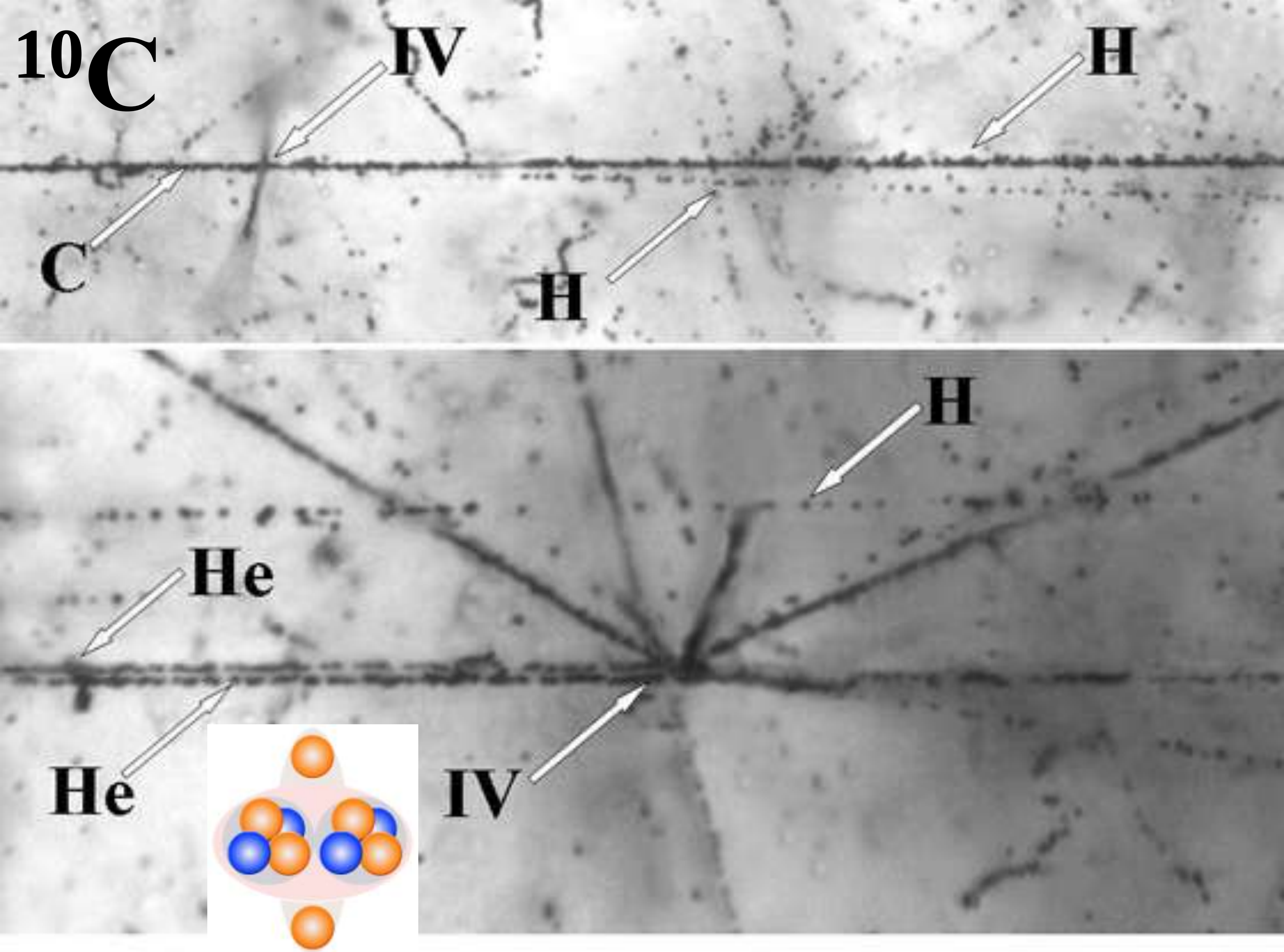
Отсутствует значимое различие распределений по P_{Tsum} для событий когерентной диссоциации через состояния 0^+ и 2^+ ядра ^8Be. Это обстоятельство указывает на схожий механизм возникновения α-пар и их одновременное присутствие этих состояний с близкими весами в основном состоянии ядра ^9Be.

В целом, представленные данные можно рассматривать как доказательство того, что в структуре ядра ^9Be с высокой вероятностью имеется кор в виде двух состояний ядра ^8Be и внешнего нейтрона.

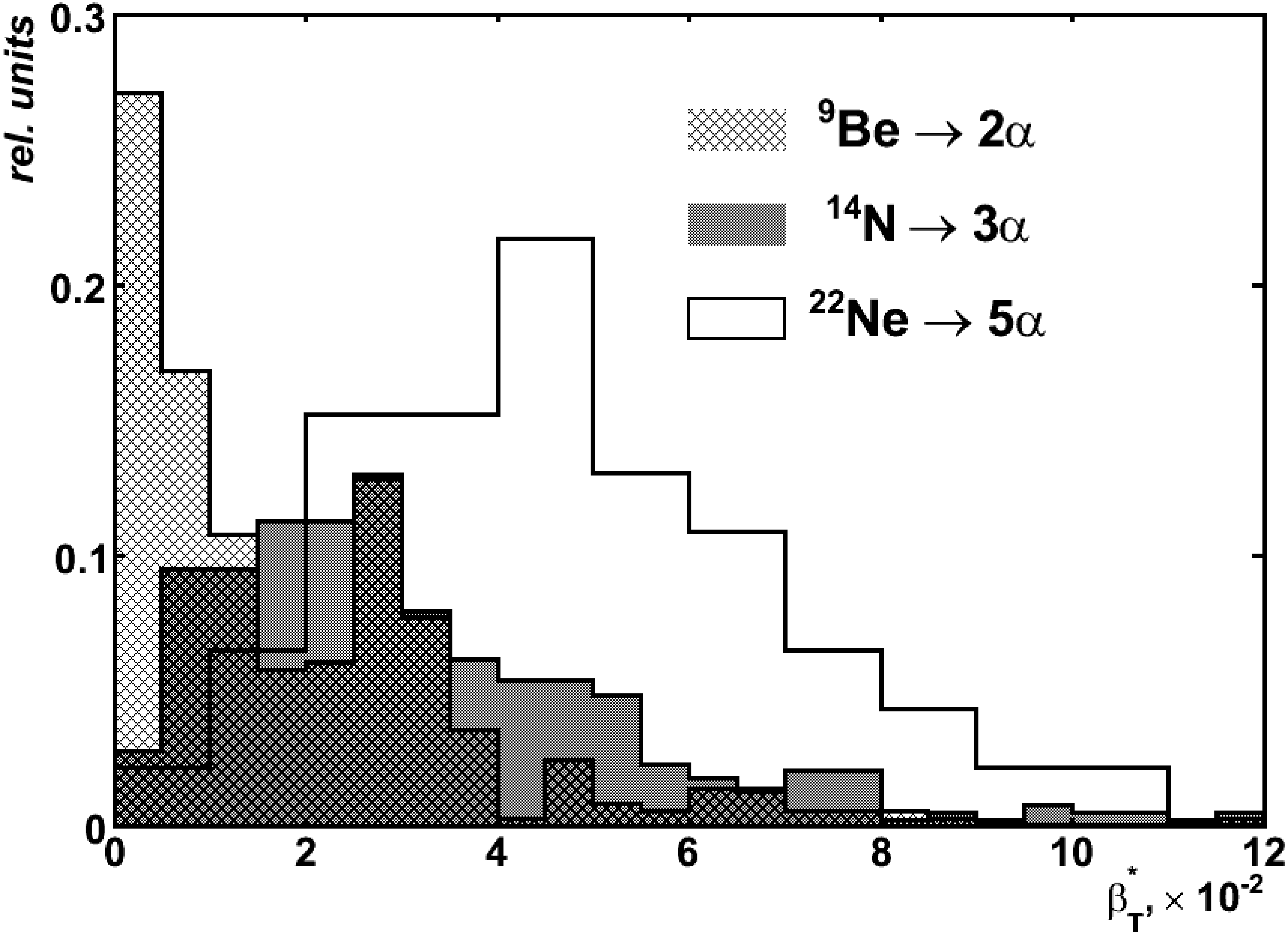
Полученные результаты согласуются с теоретическими работами по описанию структуры ядра ^9Be, предполагающими присутствие в его основном состоянии состояния 0^+ и 2^+ ядра ^8Be приблизительно с одинаковыми весами.



^{12}N 11 ms
^{9}C 0.13 s
^{10}C 19 s
^{11}C 20 m
^{12}C 99%
^{8}B 0.8 s
^{10}B 19.8%
^{11}B 80.2%
^{7}Be 53 d
^{9}Be 100%
^{6}Li 7.5%
^{7}Li 92.5%

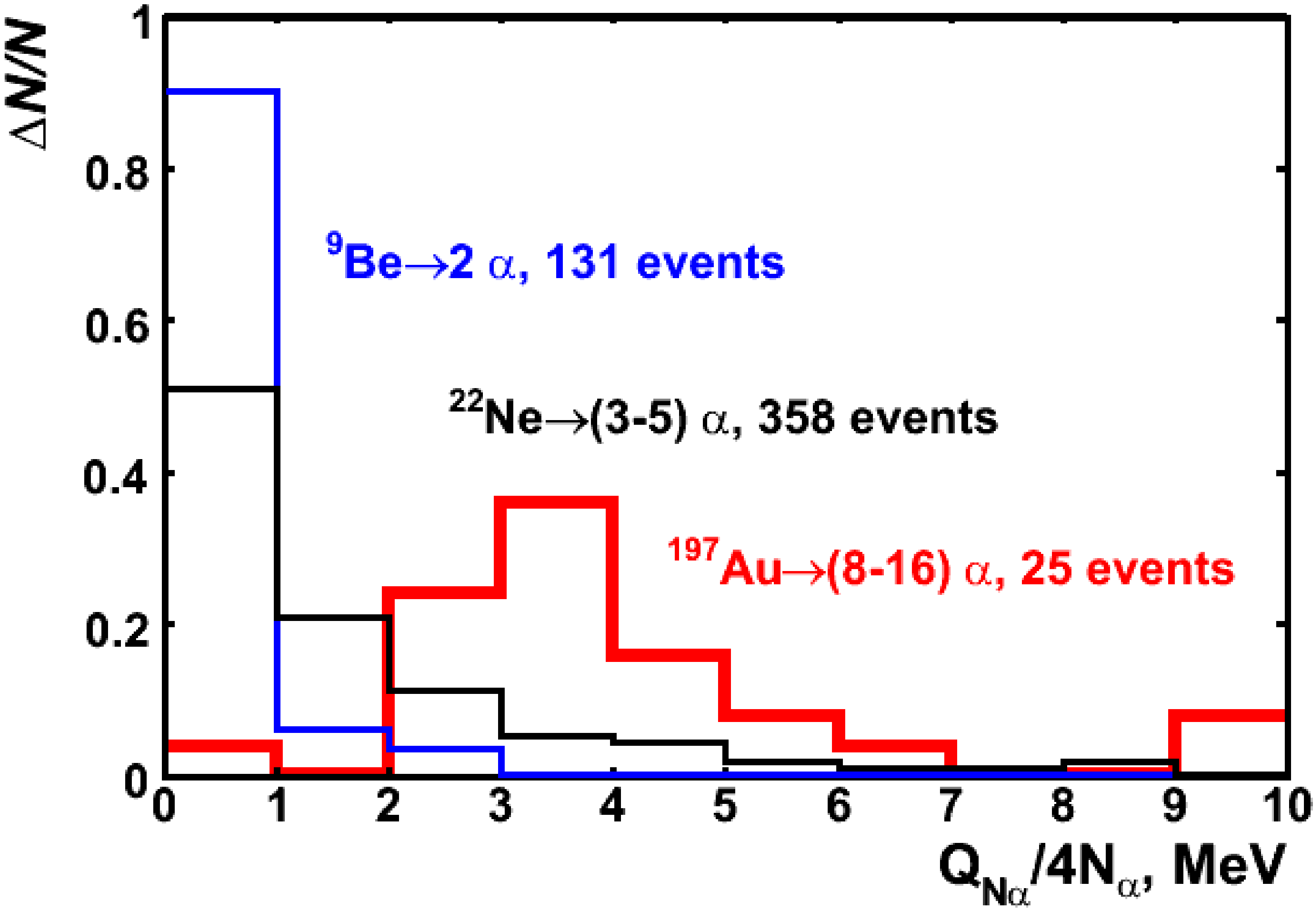


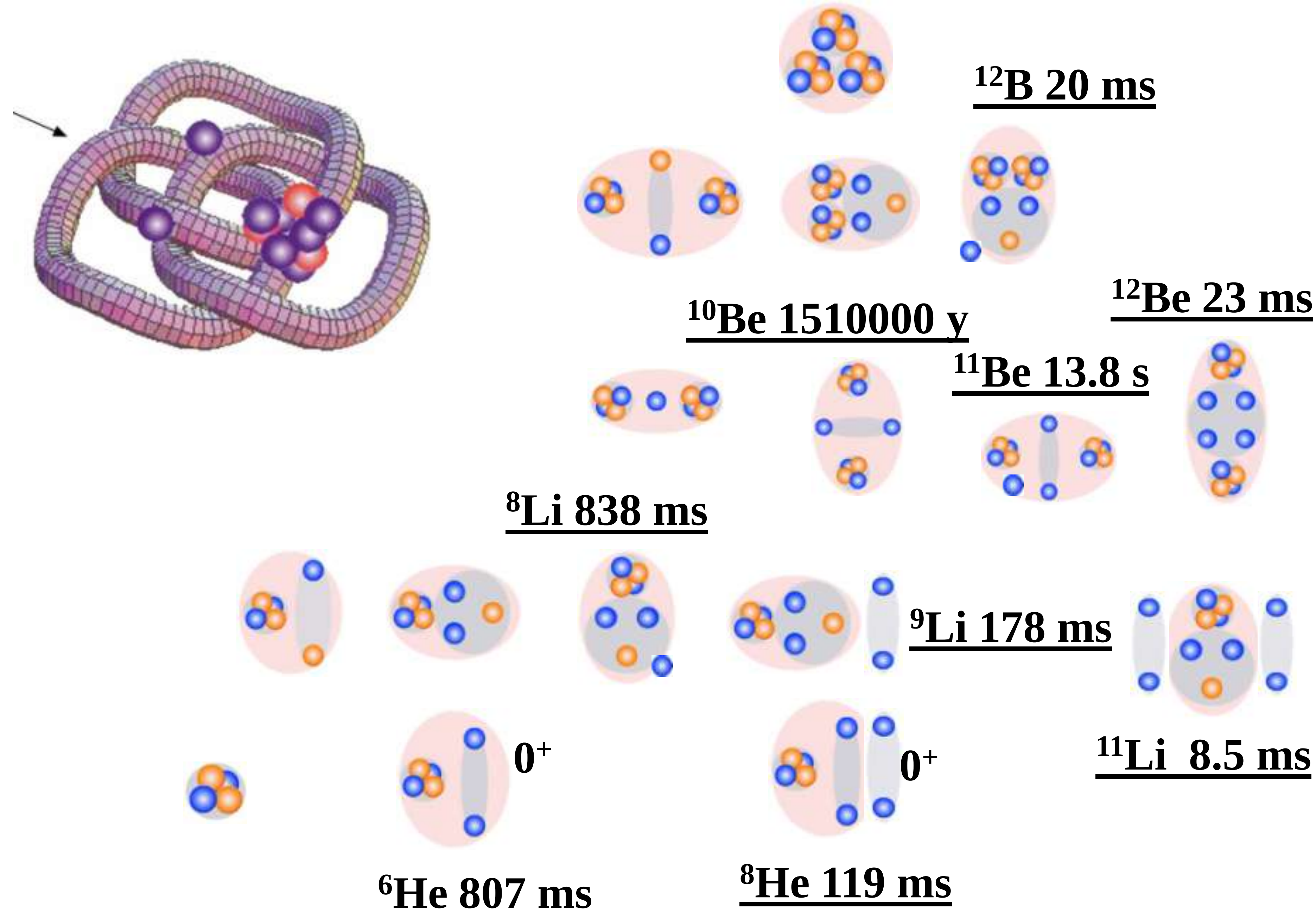
10C
IV
H
C
H
H
He
He
IV



rel. units
0.3
0.2
0.1
0
0
2
4
6
8
10
12
^{9}Be → 2α
^{14}N → 3α
^{22}Ne → 5α
β^{*}_{T}, × 10^{-2}

1.2A GeV ^{9}Be 3.22A GeV ^{22}Ne 10.7A GeV ^{197}Au





^{12}B 20 ms
^{10}Be 1510000 y
^{12}Be 23 ms
^{11}Be 13.8 s
^{8}Li 838 ms
^{9}Li 178 ms
0^{+}
0^{+}
^{11}Li 8.5 ms
^{6}He 807 ms
^{8}He 119 ms

Beta Decay of a C^9 Nucleus*

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Department of Physics, University of Wisconsin, Madison, Wisconsin
(Received June 29, 1956)

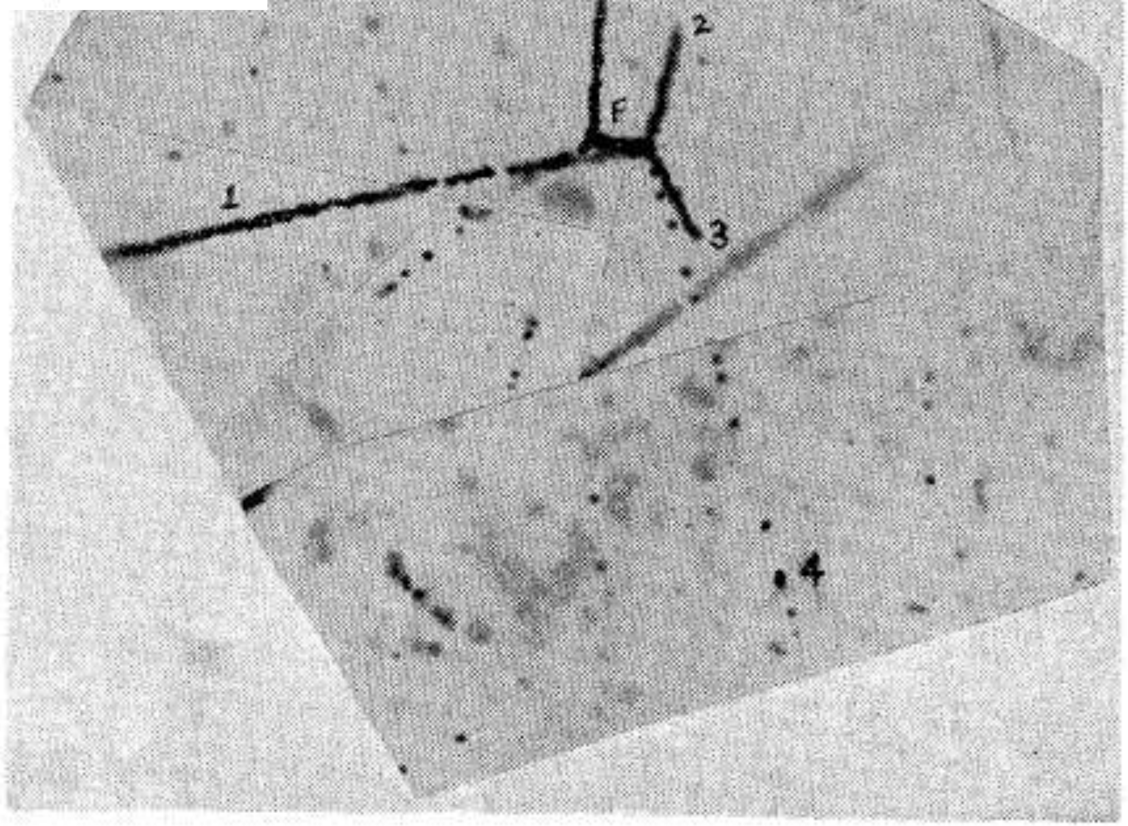
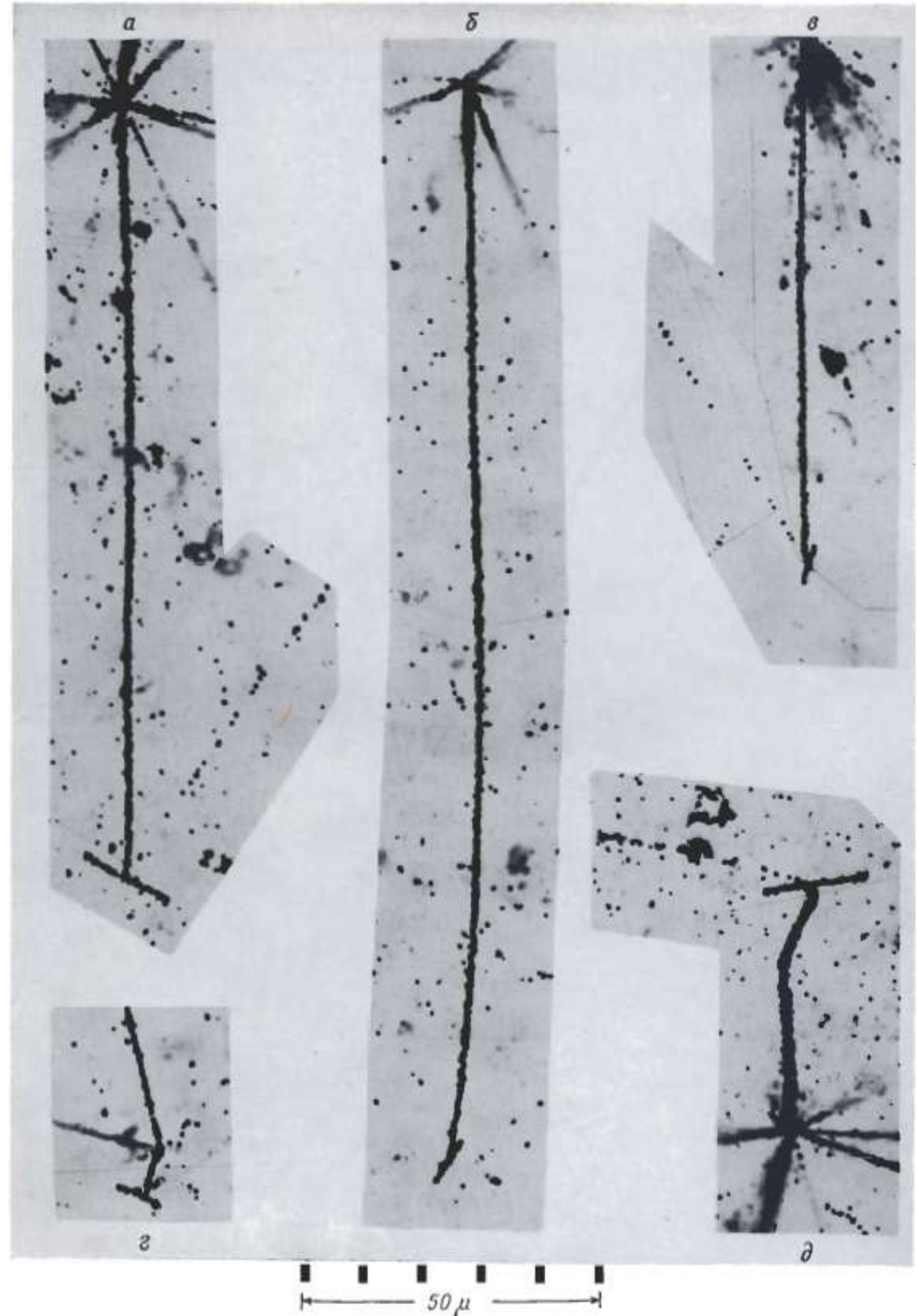


FIG. 1. A photograph of an event interpreted as the beta decay of C^9. The C^9 nucleus (track *F*) was produced in star (*A*) and disintegrated into a proton, two alpha particles, and a positron (tracks 1, 2, 3, and 4, respectively).

Hammer tracks in cosmic ray events:

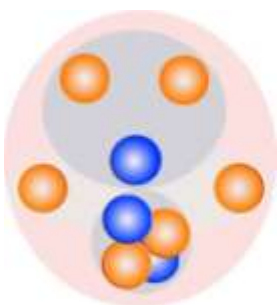
^{8}Be produced in β-delayed decay of stopped ^{8}B and ^{8}Li

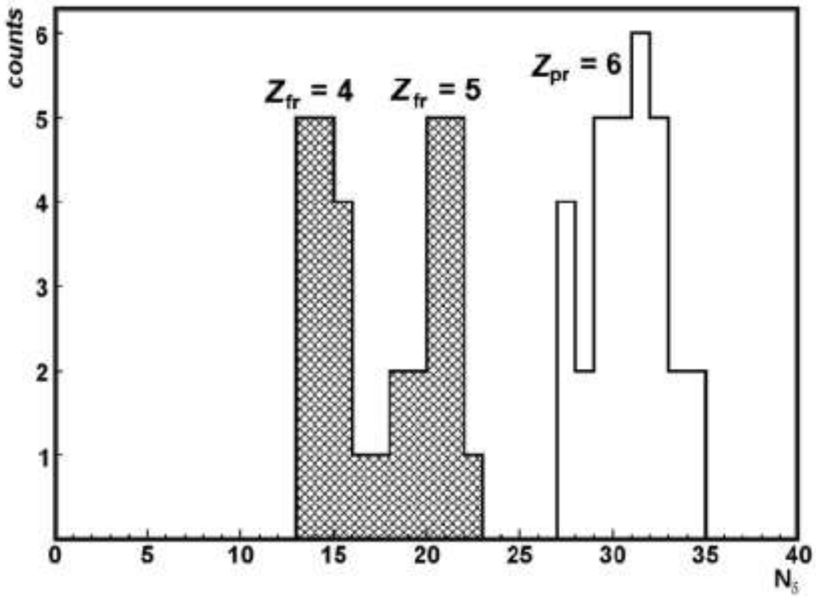


^{9}C exposure

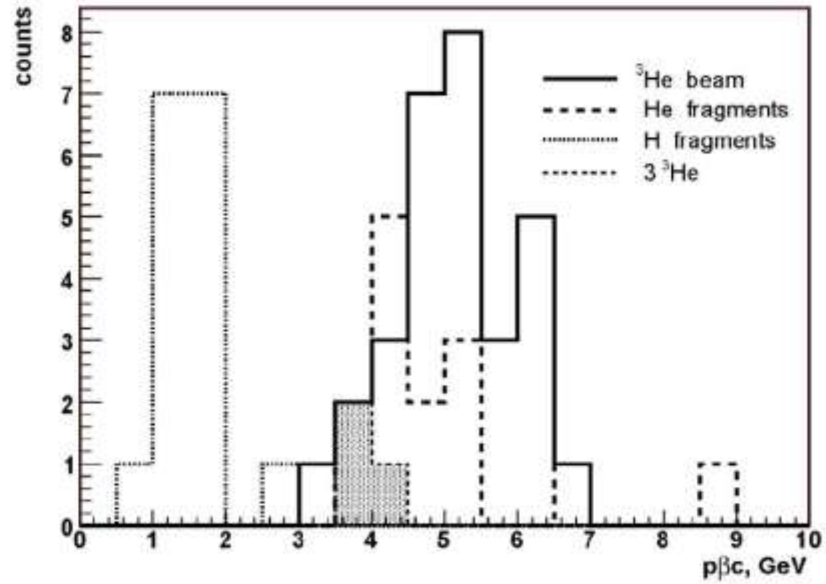
Distribution of 160 "white" stars N_{ws} in charge configurations $\sum Z_{fr}$

$\sum Z_{fr}$	Z_{fr}						N_{ws}
	6	5	4	3	2	1	
7	-	-	-	-	-	7	1
7 (Z_{pr} = 7)	-	1	-	-	-	2	1
7	-	-	-	-	1	5	3
7					2	3	5
6 (Z_{pr} = 6)	-	1	-	-	-	1	15
6 (Z_{pr} = 6)	-	-	1	-	-	2	16
6	-	-	-	-	3	-	16
6	-	-	-	1	-	3	2
6	-	-	-	-	1	4	28
6	-	-	-	-	2	2	24
6	-	-	-	-	-	6	6
5 (Z_{pr} = 5)	-	-	1	-	-	1	2
5 (Z_{pr} = 5)	-	-	-	1	-	2	3
5	-	-	-	-	-	5	2
5	-	-	-	-	1	3	19
5	-	-	-	-	2	1	13
4	-	-	-	-	1	2	5

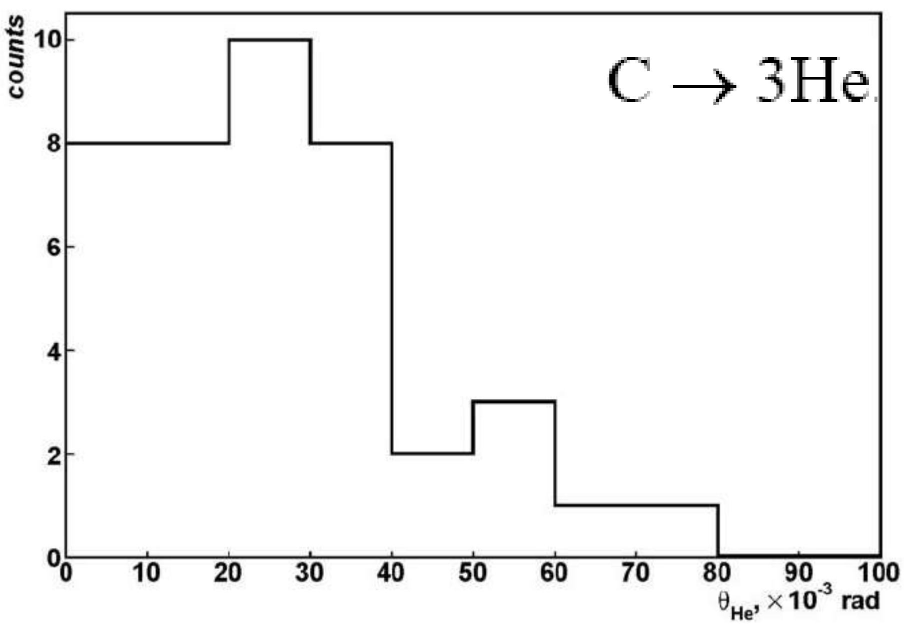




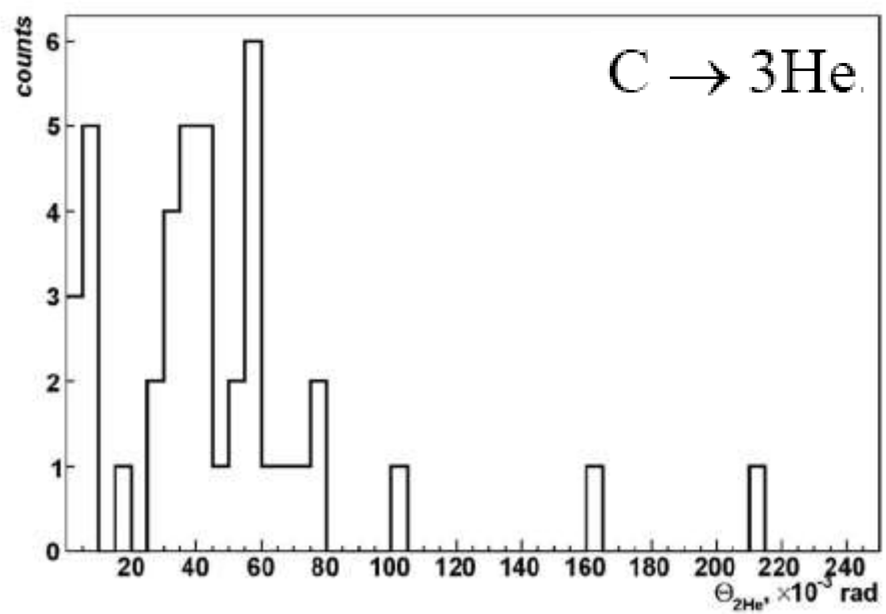
δ -electrons density for beam particles and relativistic fragments with charges $Z_{fr} > 2$ from "white" stars $\sum Z_{fr} = 5 + 1$ and $4 + 1 + 1$



pβ*c* for beam ^{3}He nuclei, H fragments of the "white" stars $\sum Z_{fr} = 5 + 1$ and $4 + 1 + 1$, He fragments of the "white" stars 3He and from the 3^{3}He event



Polar angles θ for doubly charged fragments in the "white" stars C → 3He



Opening angles Θ_{2He} between fragments in the "white" stars C → 3He

ISSN 1063-7788, Physics of Atomic Nuclei, 2007, Vol. 70, No. 7, pp. 1226–1229. © Pleiades Publishing, Ltd., 2007.
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ELEMENTARY PARTICLES AND FIELDS
Experiment

Fragmentation Channels of Relativistic ^{7}Be Nuclei in Peripheral Interactions

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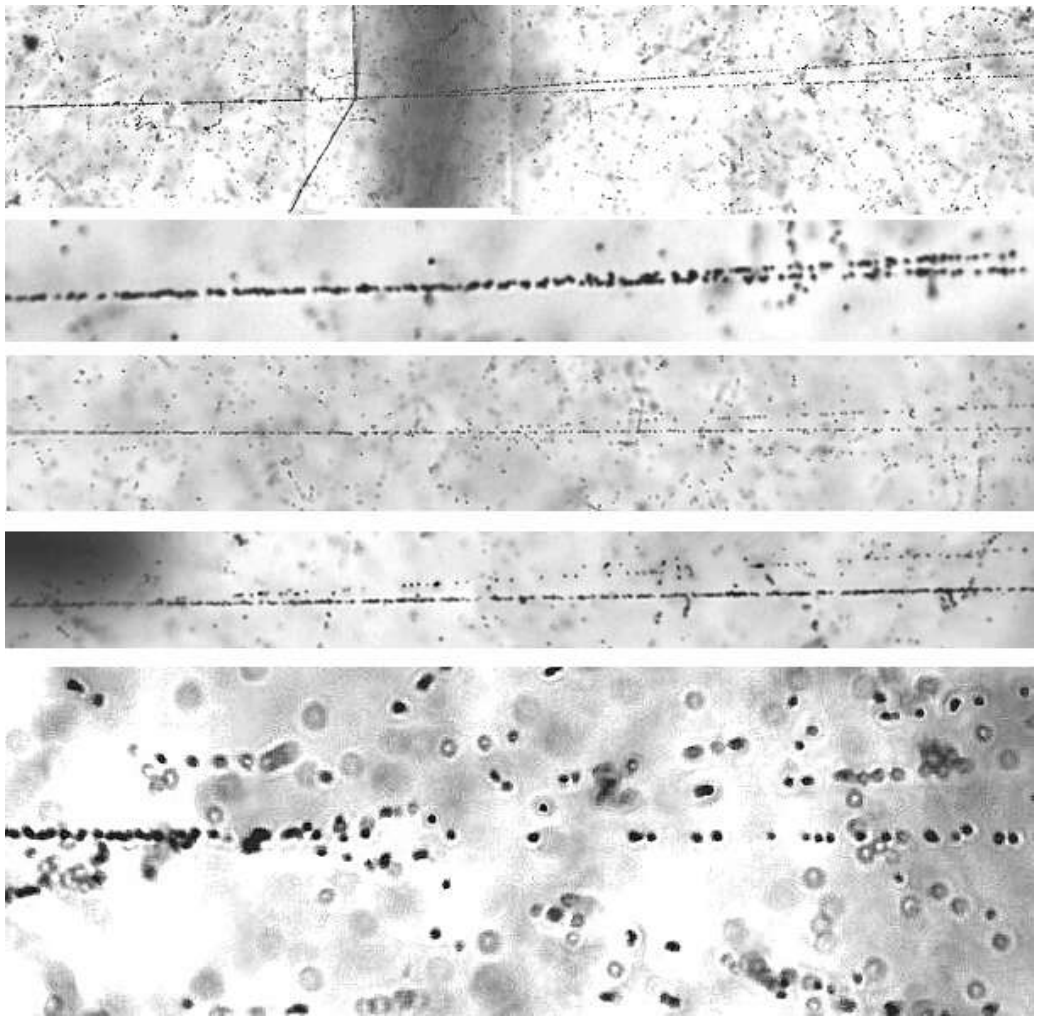
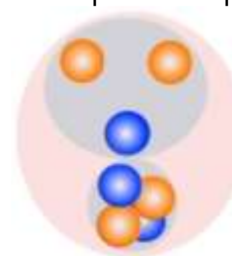
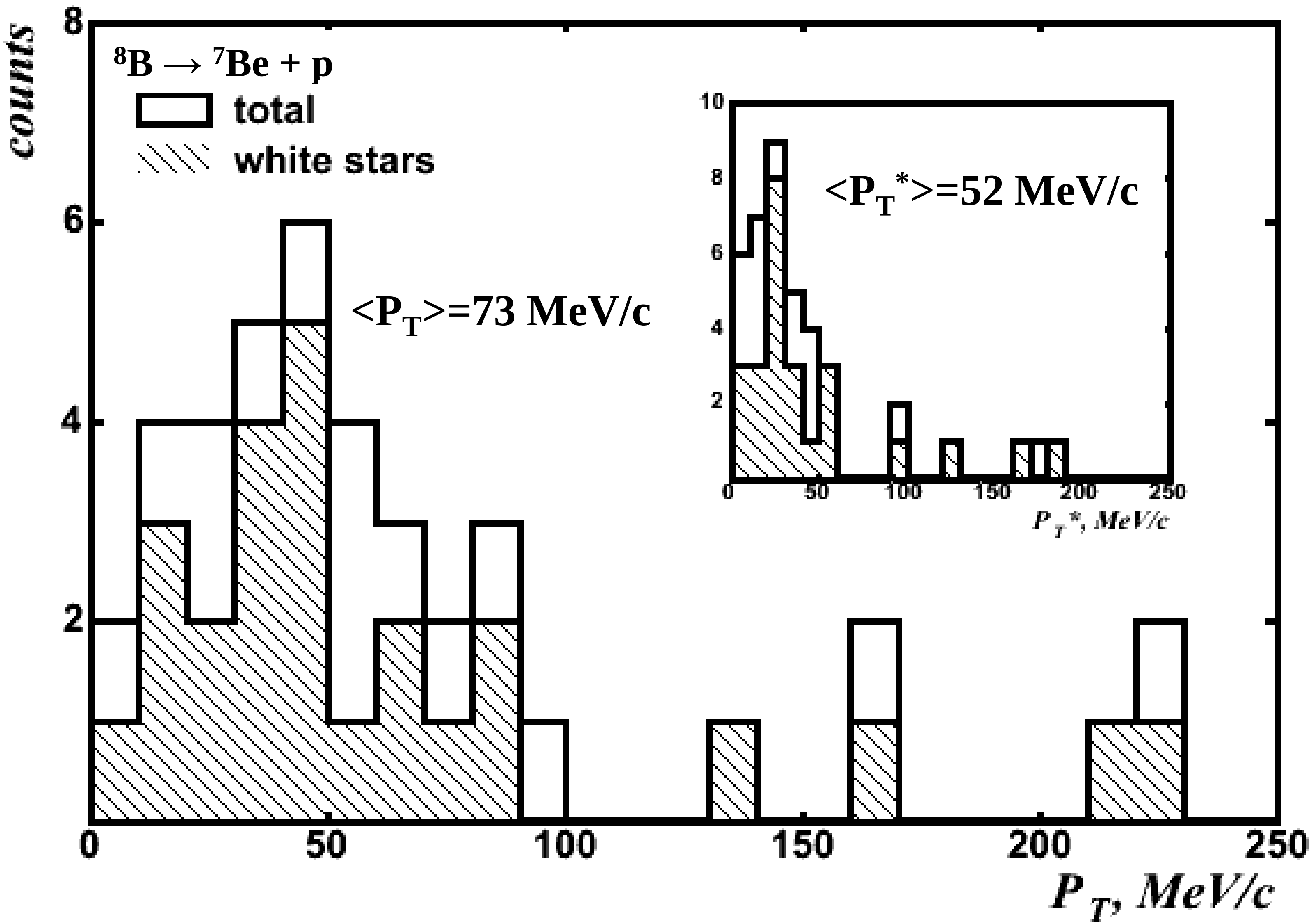


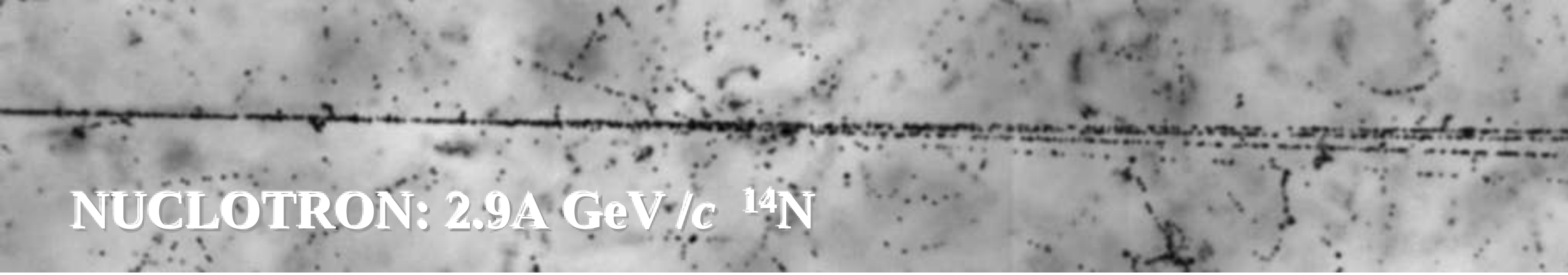
TABLE III: ^{7}Be fragmentation channel (number of events)

MeV	Channel	2He	2He	He+2H	He+2H	4H	4H	Li+H	Li+H	Sum
		$n_b=0$	$n_b>0$	$n_b=0$	$n_b>0$	$n_b=0$	$n_b>0$	$n_b=0$	$n_b>0$	
1.6	^{3}He+^{4}He	30	11							41
	^{3}He+^{3}He	11	7							18
	^{4}He+2p			13	9					22
6.9	^{4}He+d+p			10	5					15
	^{3}He+2p			9	9					18
	^{3}He+d+p			8	10					18
25.3	^{3}He+2d			1						1
21.2	^{3}He+t+p			1						1
	3p+d					2				2
	2p+2d					1				1
5.6	^{6}Li+p							9	3	12
	Sum	41	18	42	33	2	1	9	3	149

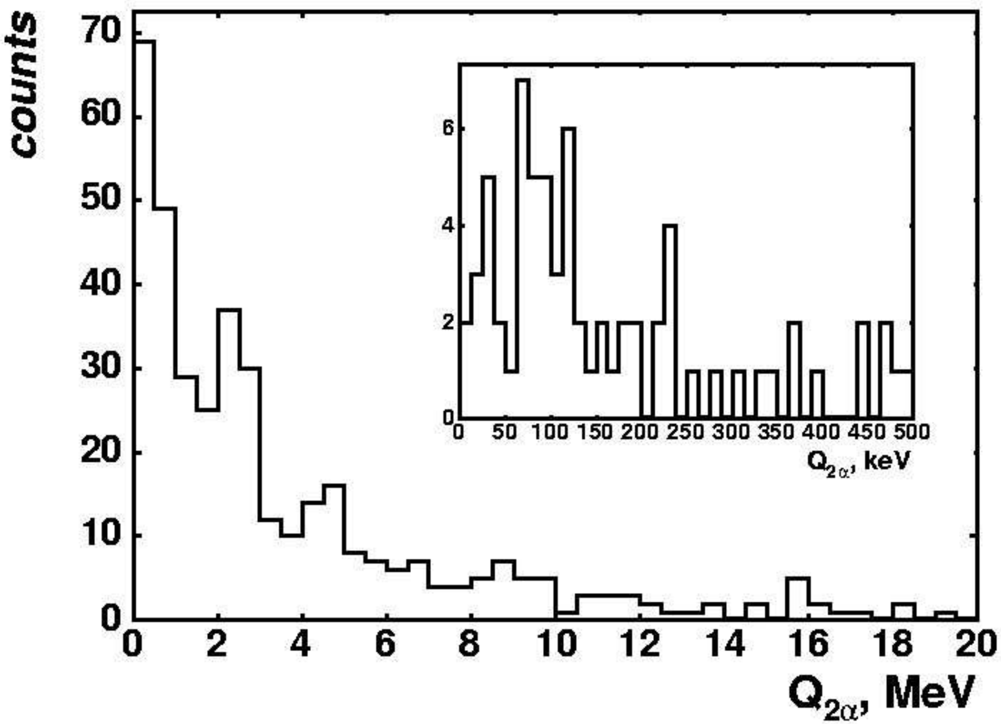


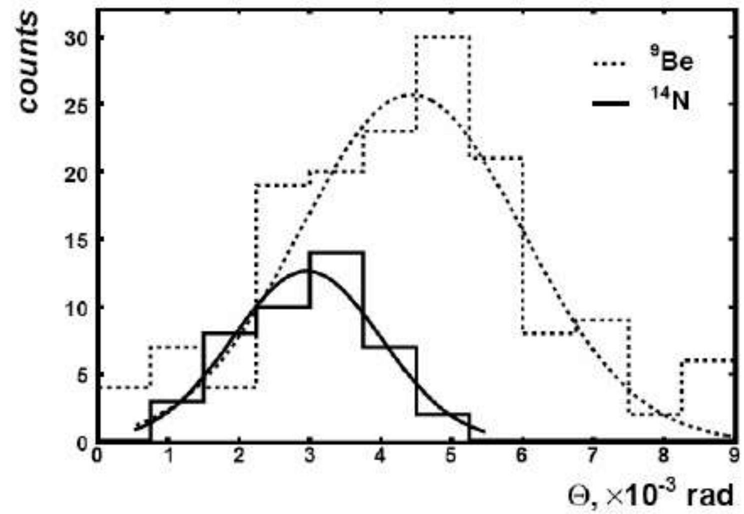


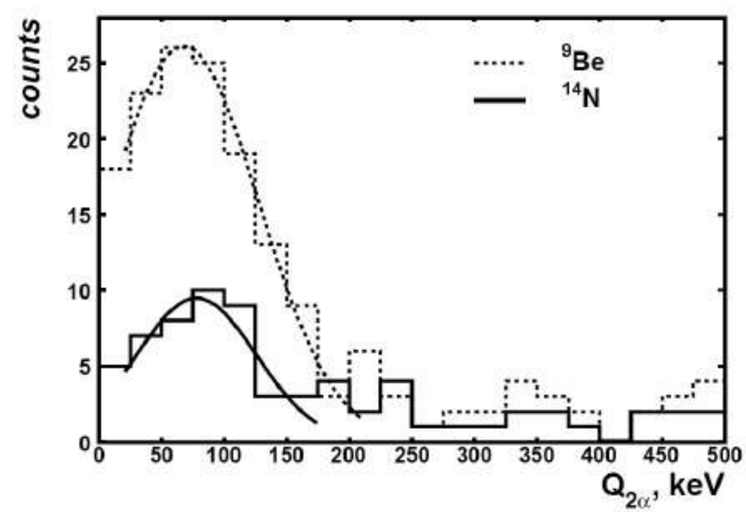
counts
8B → 7Be + p
total
white stars
<PT>=73 MeV/c
<PT*>=52 MeV/c
PT*, MeV/c
PT, MeV/c

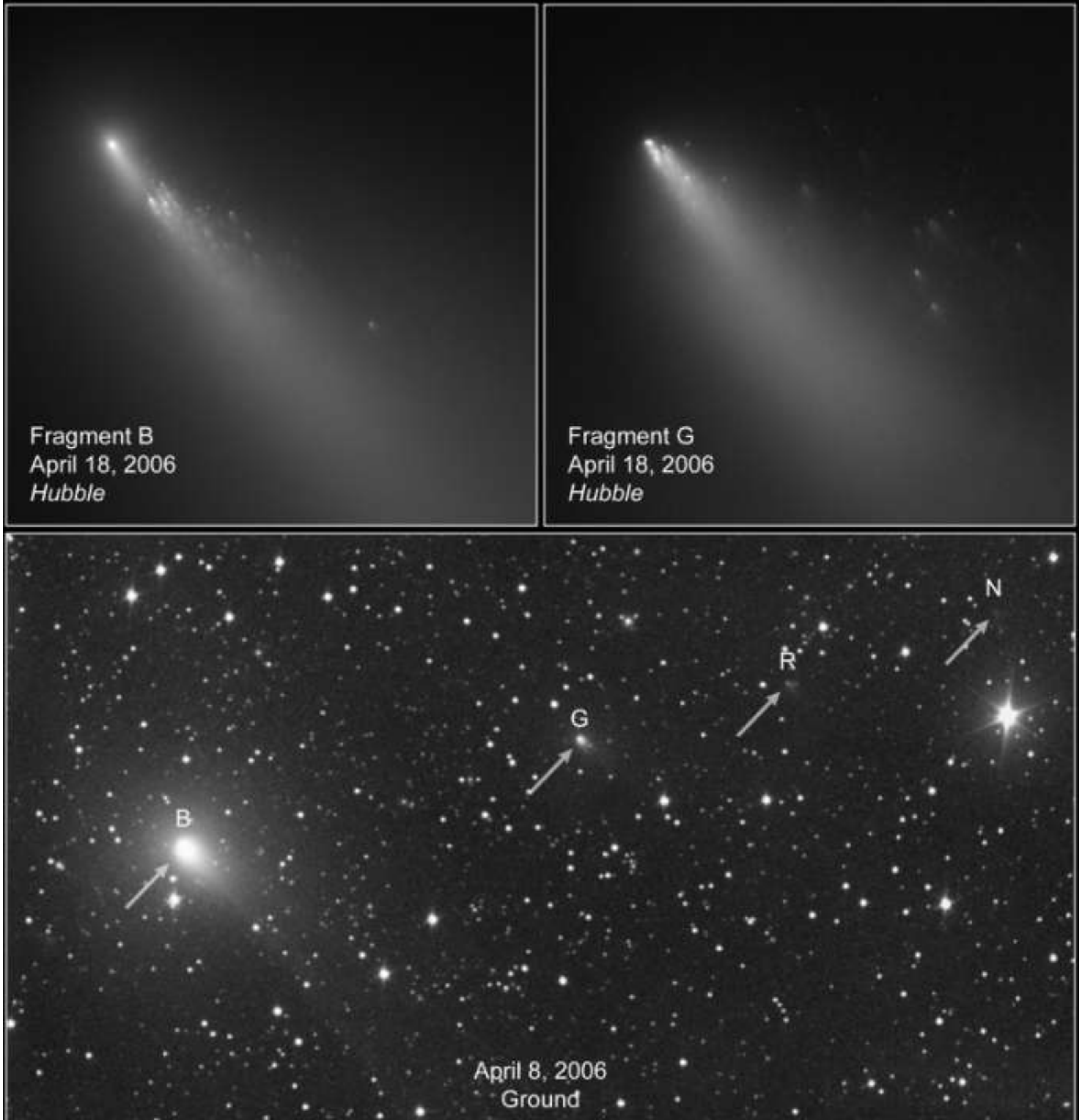


NUCLOTRON: 2.9A GeV /*c* ^{14}N







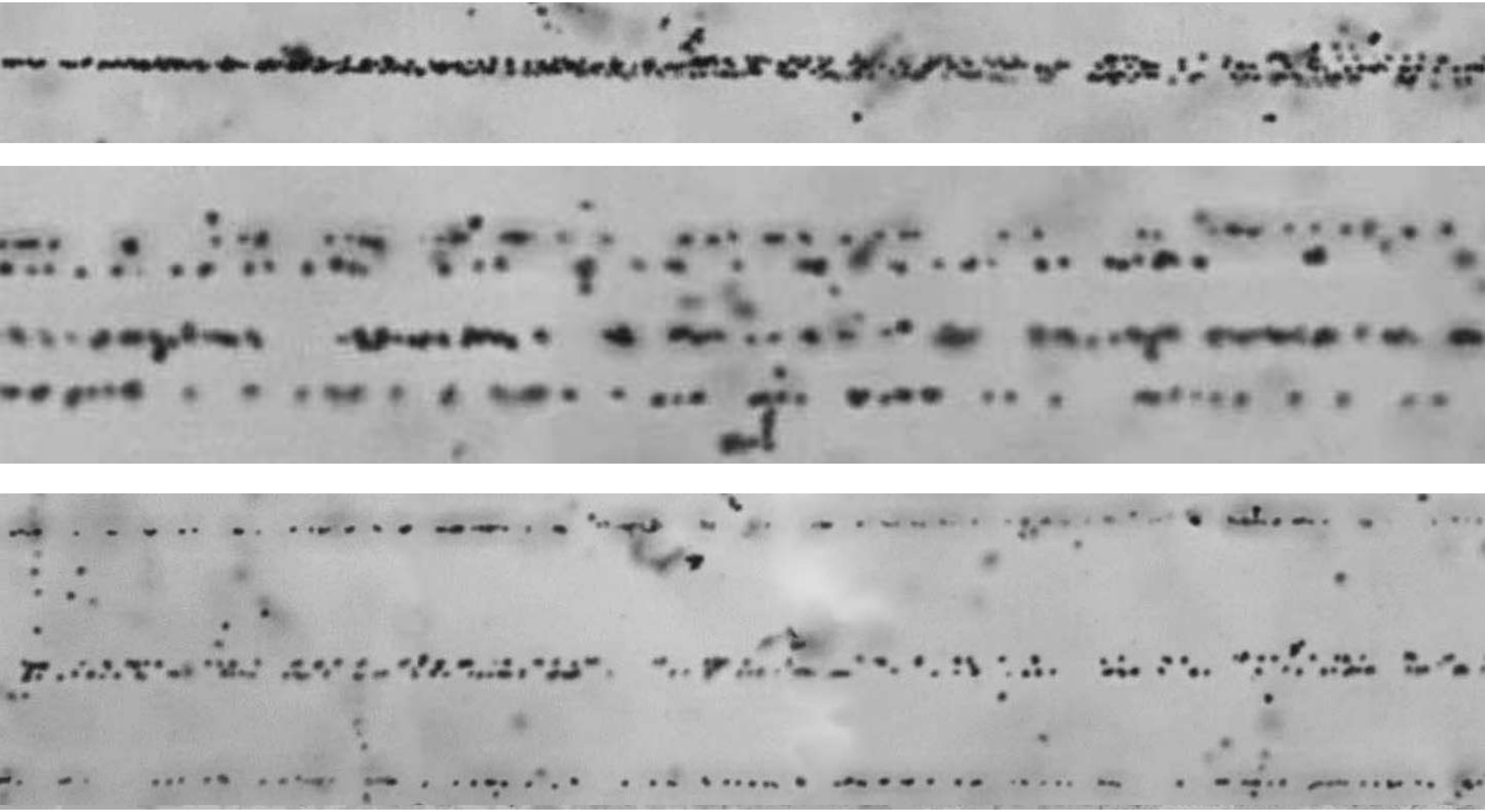

Fragment B
April 18, 2006
Hubble
Fragment G
April 18, 2006
Hubble
N
R
G
B
April 8, 2006
Ground

T_α : 0.05-2 MeV

The detection of such "ultracold" 5α states is a serious argument in favor of the reality of the phase transition of α clusterized nuclei to the dilute Bose gas of α-particles. It gives a special motivation to explore lighter $n\alpha$ systems produced as potential "building blocks" of the dilute α-particle Bose gas.

λ : 10-1 fm

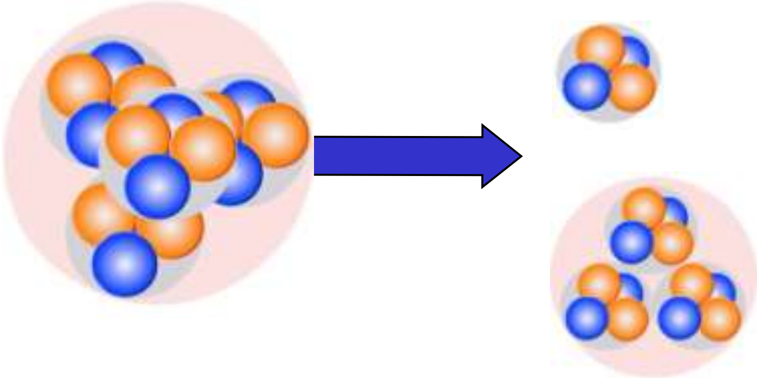
3.65A GeV ^{20}Ne 2+2+2+2+2



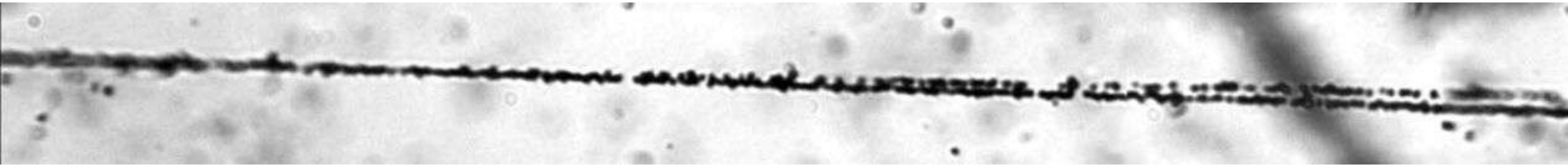
n_b	0	0	1	2	3	>3
n_g	0	1	0	0	0	0
F +H	26 (19.5)	9 (15.0)	13 (44.8)	2	-	1
O + He	54 (40.6)	19 (31.7)	2 (6.9)	-	1	1
O + 2H	12 (9.0)	7 (11.7)	-	-	-	-
N + He + H	12 (9.0)	7 (11.7)	4 (13.8)	1	-	-
N + 3H	3 (2.3)	3 (5.0)	-	-	-	-
C + 2He	5 (3.8)	3 (5.0)	3 (10.3)	1	-	-
C + 2He + 2H	5 (3.8)	3 (5.0)	3 (10.3)	-	-	-
C + 4H	2 (1.0)	-	-	-	-	-
B + Li +H	1 (0.8)	-	-	-	-	-
B + 2He + H	2 (1.5)	1 (1.7)	-	-	-	-
B + He + 3H	2 (1.5)	1 (1.7)	-	-	-	-
B + 5H	1 (0.8)	-	1 (3.4)	-	-	-
2Be + 2H	-	1 (1.7)	-	-	1	-
Be + Li + 3H	1 (0.8)	-				
Be + 3He	2 (1.5)	-				
Be + He + 4H	1 (0.8)	-				
Li + 3He + H	-	1 (1.7)	-	-	-	-
5He	3 (2.3)	-	1 (3.4)	2	-	1
4He + 2H	1 (0.8)	5 (8.3)	2 (6.9)	-	-	-

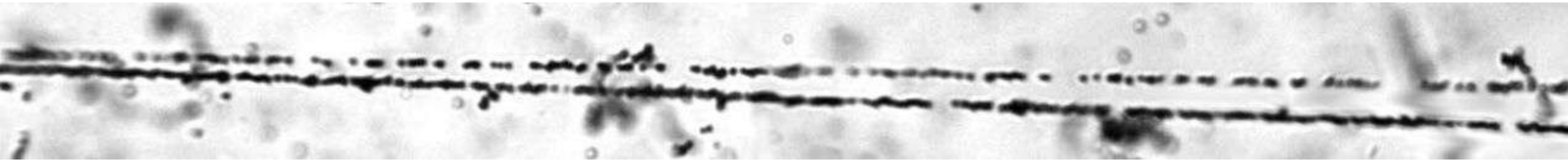
^{22}Ne 3.22A GeV

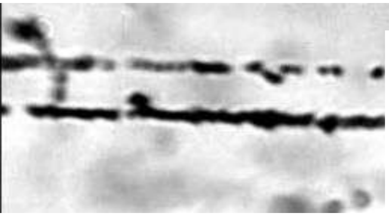
4100 Inelastic Interactions



4.5 A GeV/c ^{16}O







$Z_{fr} > 3$	N	C	C	B	B	Be	Be	-	-
$N_{Z=1}$	1	-	2	3	1	-	2	-	2
$N_{Z=2}$	-	1	-	-	1	2	1	4	3
N_{ev}	18	21	7	2	10	1	1	9	3