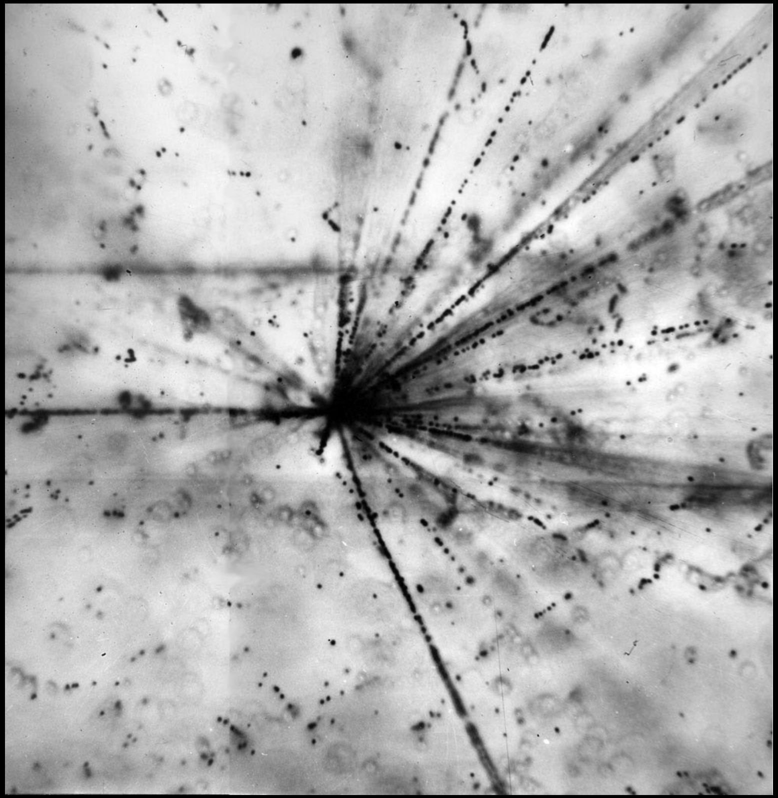
"Overview of unstable nuclear state studies in dissociation of relativistic nuclei"



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Joint Institute for Nuclear Research, Dubna

PHYSICAL REVIEW VOLUME 77, NUMBER 1

The Heavy Nuclei of the Primary Cosmic Radiation

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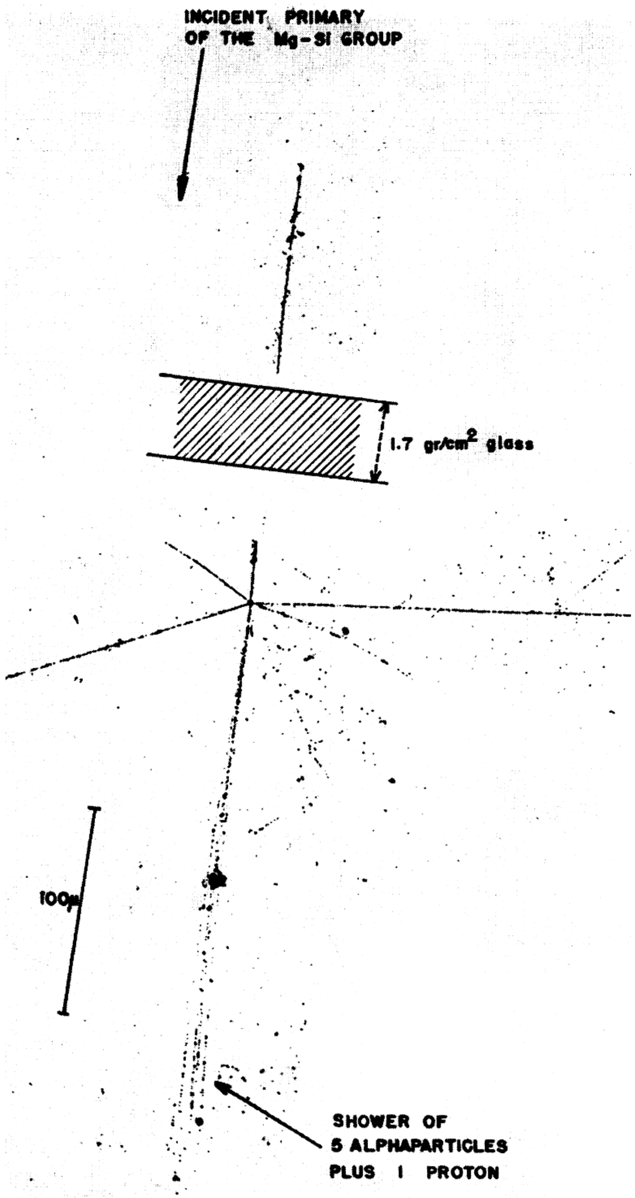
University of Rochester, Rochester, New York

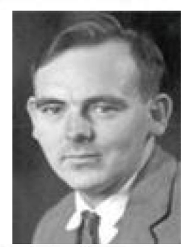
(Received September 9, 1949)



The Study of Elementary Particles by the Photographic Method

An account of
The Principal Techniques and Discoveries
illustrated by
An Atlas of Photomicrographs

BY
C. F. POWELL
P. H. FOWLER and D. H. PERKINS
H. H. WILLS PHYSICAL LABORATORY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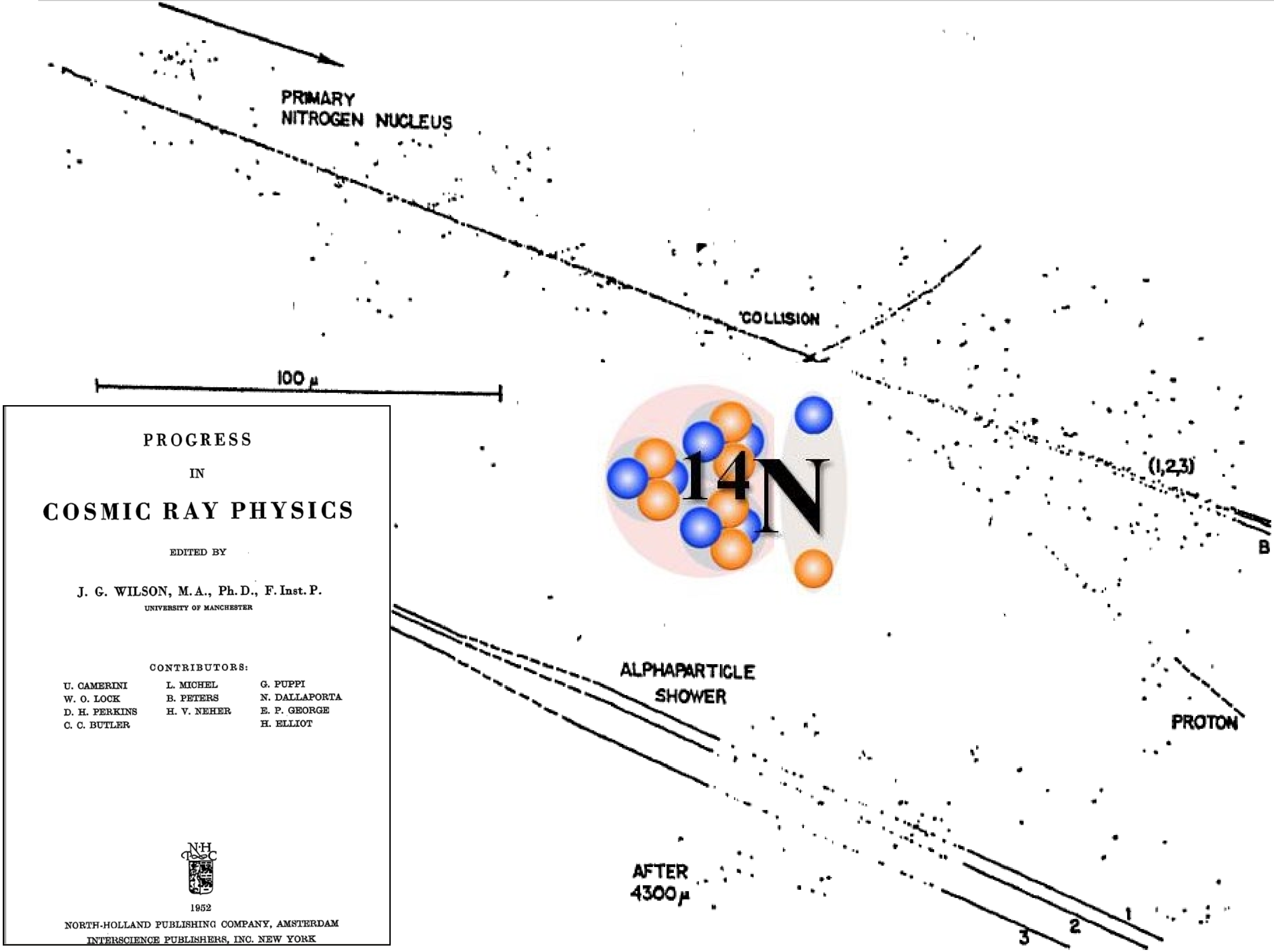
1959


Hair - 60 μm
AgBr Crystal - 0.2 μm
Atom - 10^{-4} μm
Proton - 10^{-9} μm



PROGRESS

IN

COSMIC RAY PHYSICS

EDITED BY

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UNIVERSITY OF MANCHESTER

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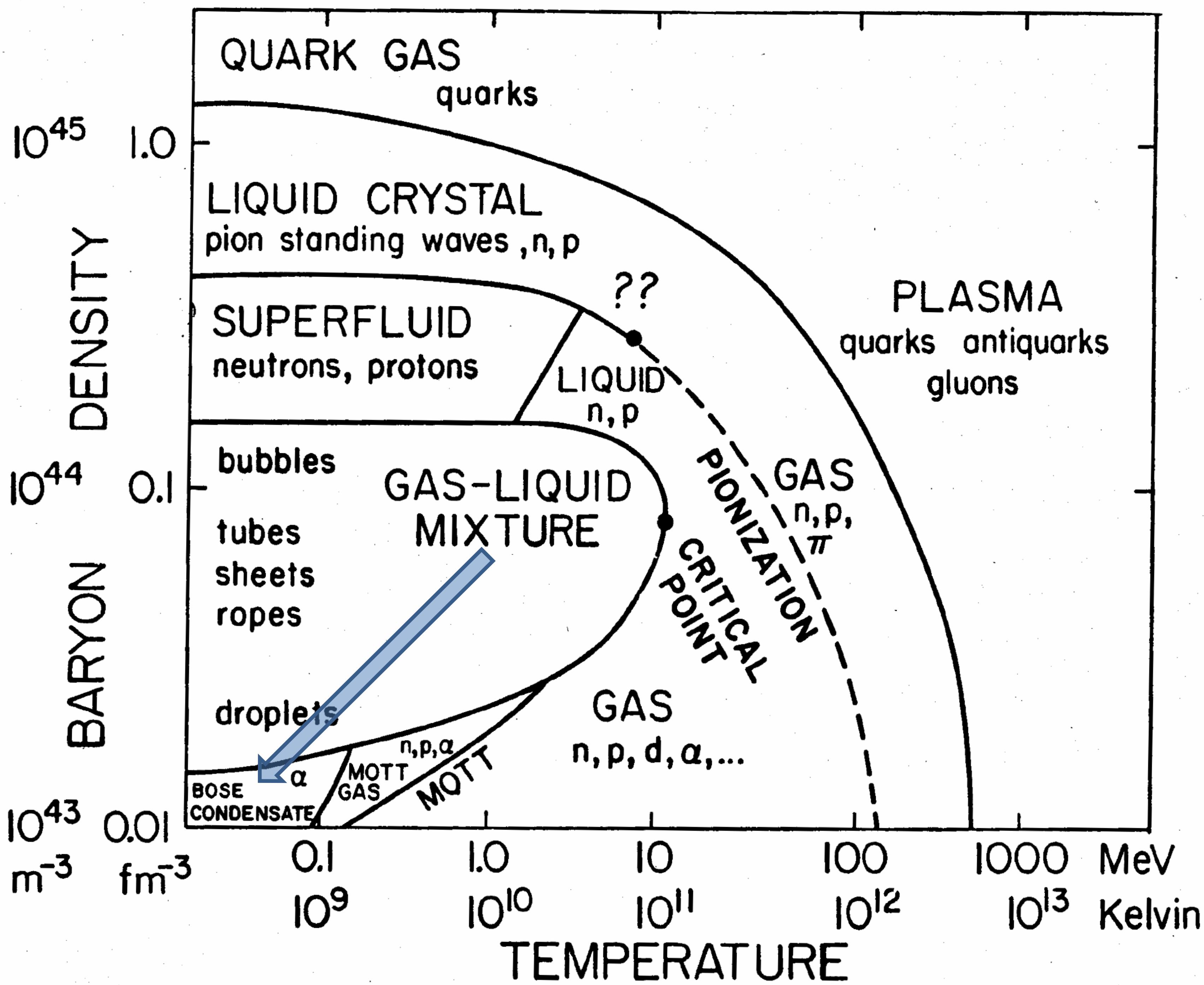
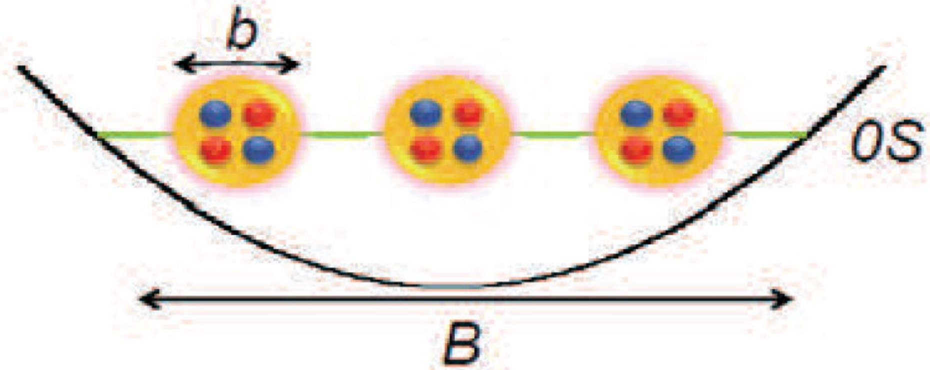

QUARK GAS
quarks
LIQUID CRYSTAL
pion standing waves ,n, p
??
PLASMA
quarks antiquarks
gluons
SUPERFLUID
neutrons, protons
LIQUID
n, p
bubbles
GAS-LIQUID
MIXTURE
tubes
sheets
ropes
droplets
PIONIZATION
GAS
n, p, π
CRITICAL
POINT
GAS
n, p, d, α, ...
n,p,α
α
MOTT
GAS
MOTT
BOSE
CONDENSATE
DENSITY
BARYON
10^45 1.0
10^44 0.1
10^43 0.01
m^-3 fm^-3
0.1 1.0 10 100 1000 MeV
10^9 10^10 10^11 10^12 10^13 Kelvin
TEMPERATURE

Alpha-Clusters in Nuclear Systems

P. Schuck



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

A current focus is on the concept of α-particle Bose-Einstein condensate (αBEC) – the S-wave α-particle state right above threshold. ^{8}Be(0^+) is being described as 2αBEC, and the ^{12}C(0^+_2) or Hoyle as 3αBEC. Suggesteded as 4αBEC ^{16}O(0^+_6) at 660 keV can sequentially decay via α^{12}C(0^+_2) or 2^{8}Be(0^+).

The nuclei ^{8}Be and ^{9}B and a number of excitations of light isotopes unstable near the thresholds of binding to the emission of α-particles and nucleons have lifetimes of the order of fs or widths from eV to keV.

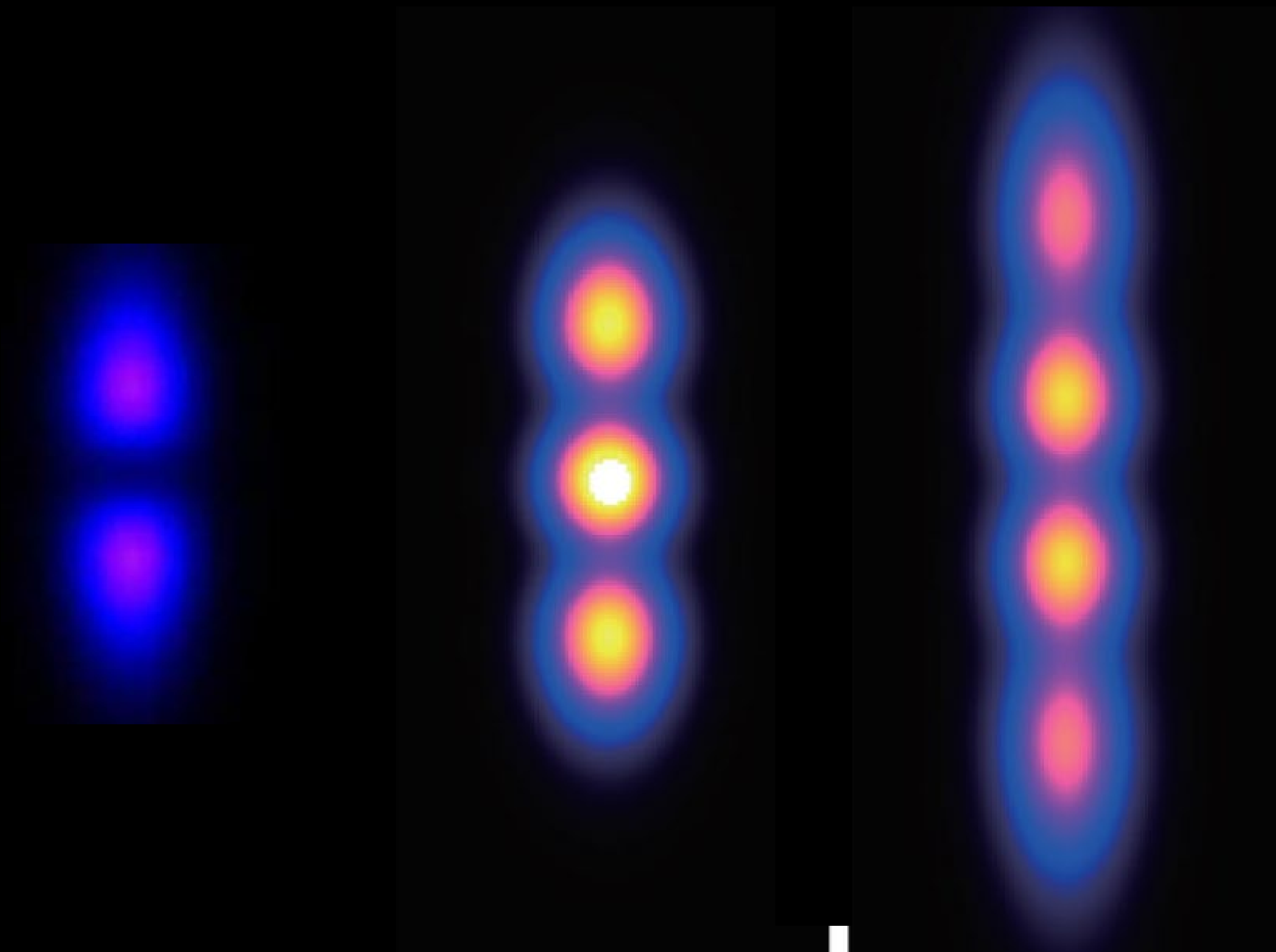
Unusually long-lived on a nuclear scale, they can be defined as a special class at the lower limit of nuclear density and temperature.

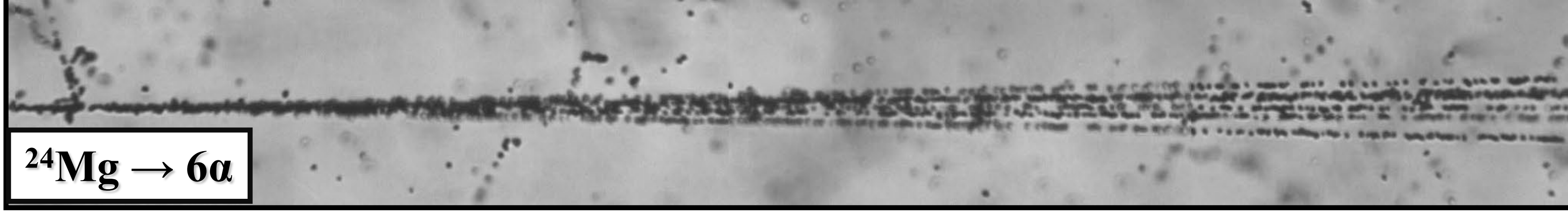
In the concepts of molecular-like or α-condensate structures, these unstable states are represented as spatially separated groups of nucleons bound into clusters. Their occurrence in the final states of collisions of light nuclei may indicate the realization of conditions corresponding to extremely low-energy reactions of nucleosynthesis.

Reconstructions of the decays of known states of this type make it possible to search for analogs decaying into them.

The exotically large sizes of unstable states allow us to propose a scenario for their formation in the resonant interaction of pairs of fragments with minimal values of invariant Lorentz factors of relative motion, and then the subsequent pickup of other fragments.

$^{8}Be(0^{+})$ $^{12}C(0^{+}_{2})$ $^{16}O(0^{+}_{6})$

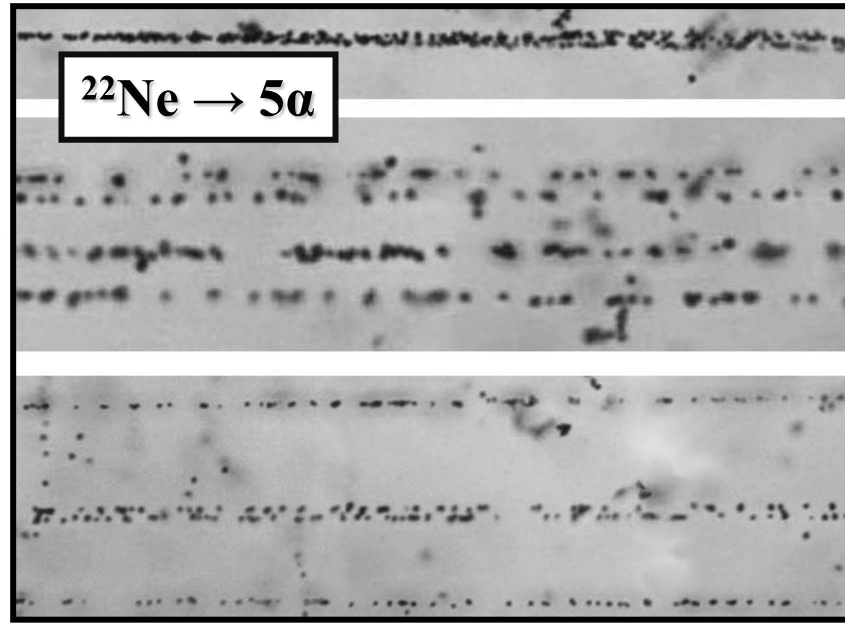


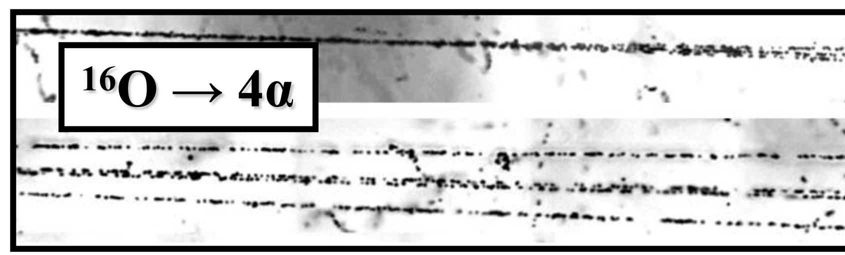


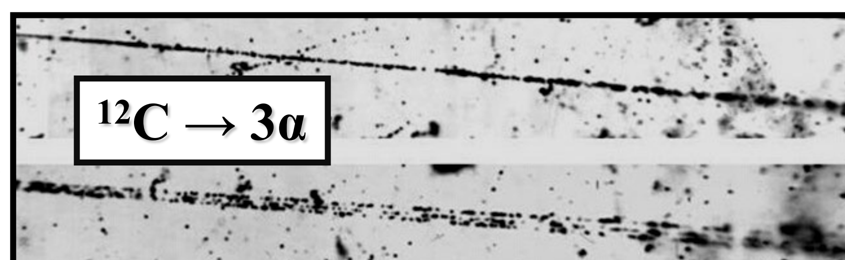
The fragmentation of relativistic nuclei observed in its entirety only in nuclear emulsion (NTE) serves as a source of ensembles of the lightest nuclei of interest to modern nuclear physics and nuclear astrophysics. NTE allows one to study such ensembles with record angular resolution and identification He and H isotopes.

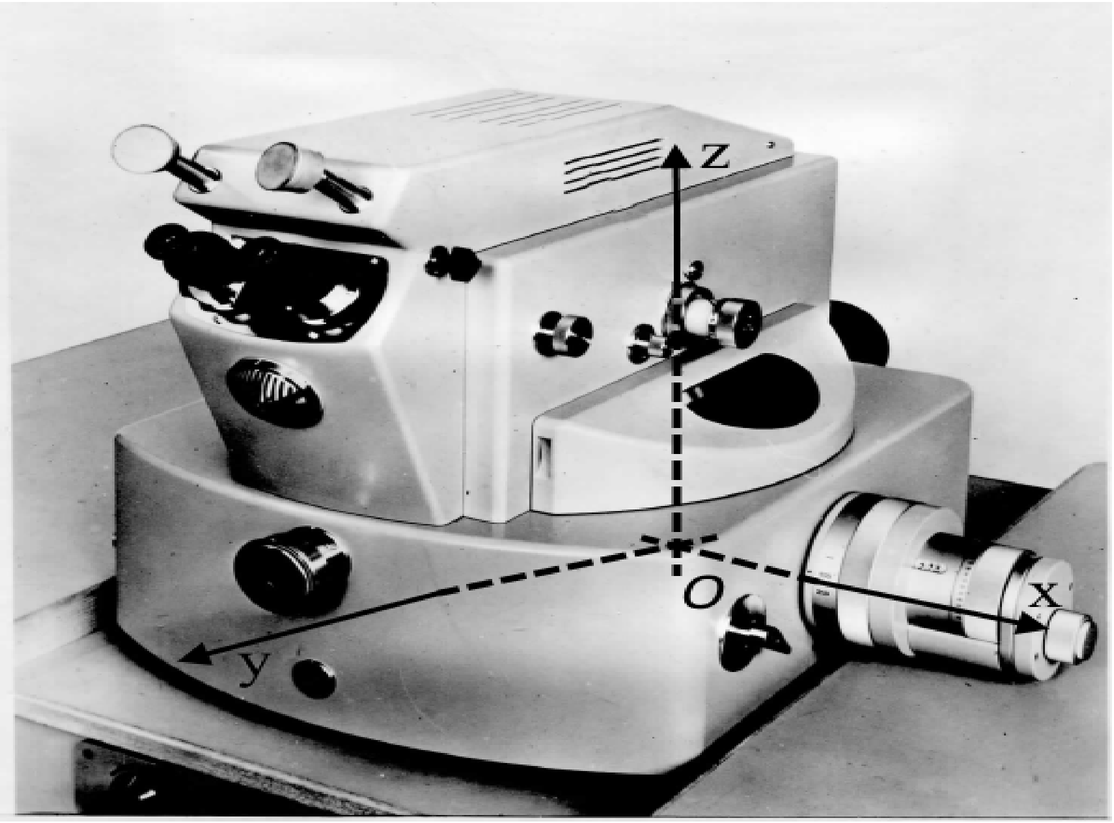
Electronic experiments in this direction run into fundamental difficulties due to the quadratic dependence of ionization on the charges of the nuclei, extremely small angular divergence of relativistic fragments, and, often, an approximate coincidence in magnetic rigidity with the beam nuclei. Therefore, the NTE method retains its uniqueness in the relativistic fragmentation cone.

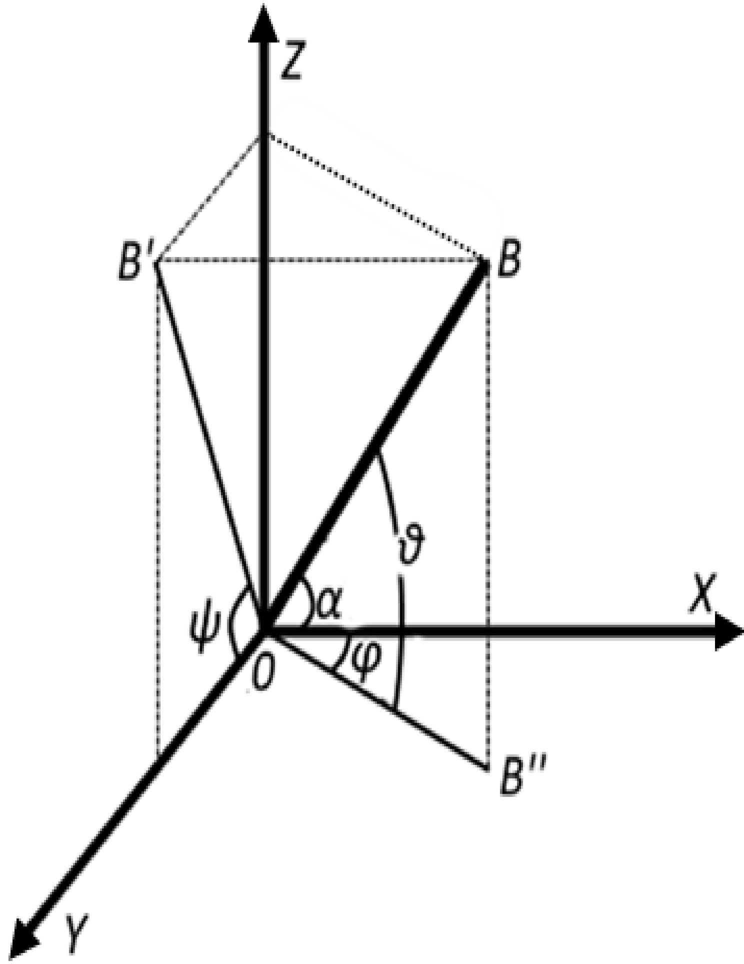
The intense “tracks” in the photos splits into the He track pairs with the opening angles of about $2{\cdot}10^{-3}$ rad corresponding to decays of the unstable ^{8}Be nucleus. Their observation testify to the completeness of observations across the spectrum of cluster excitations.



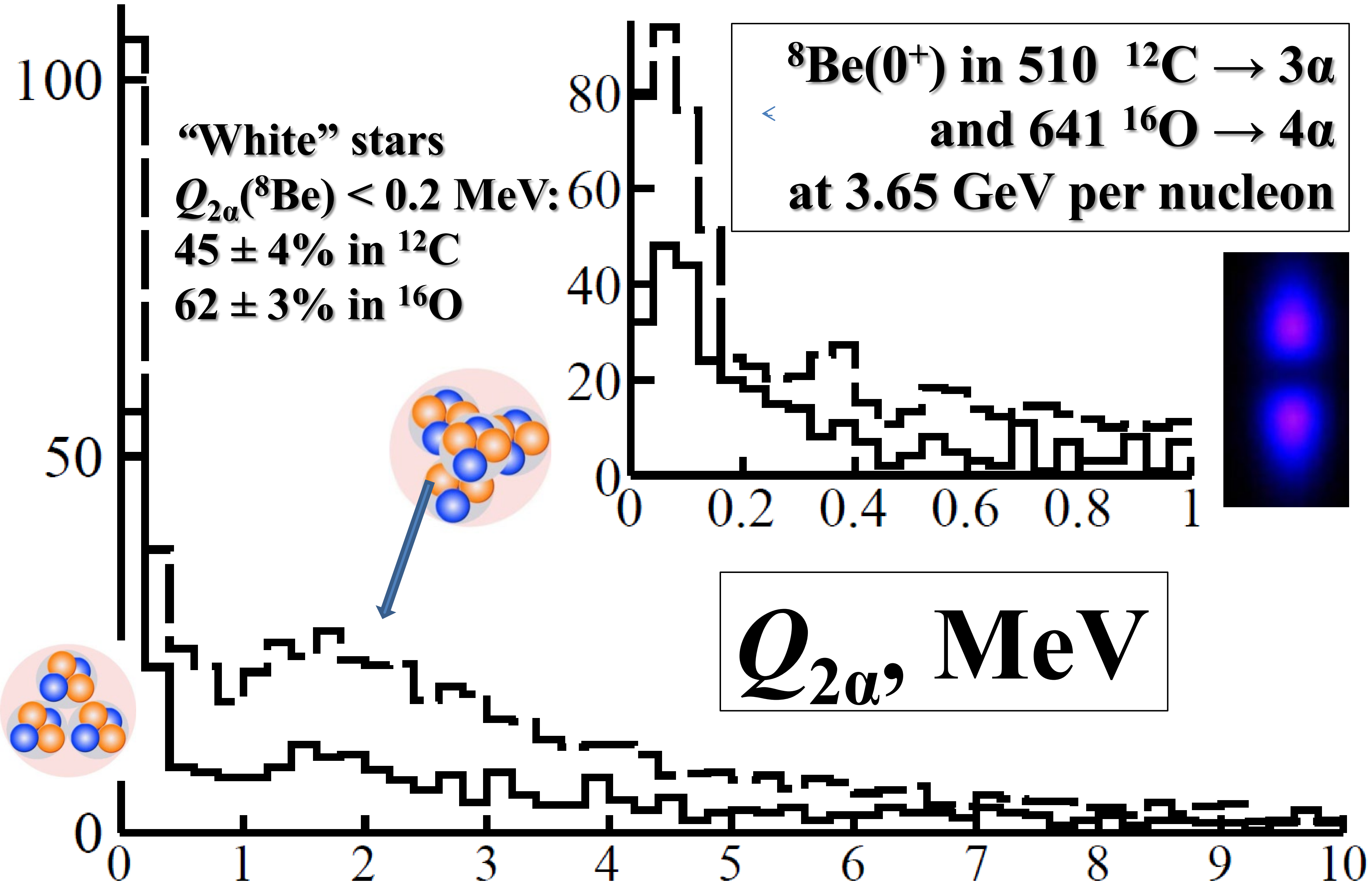




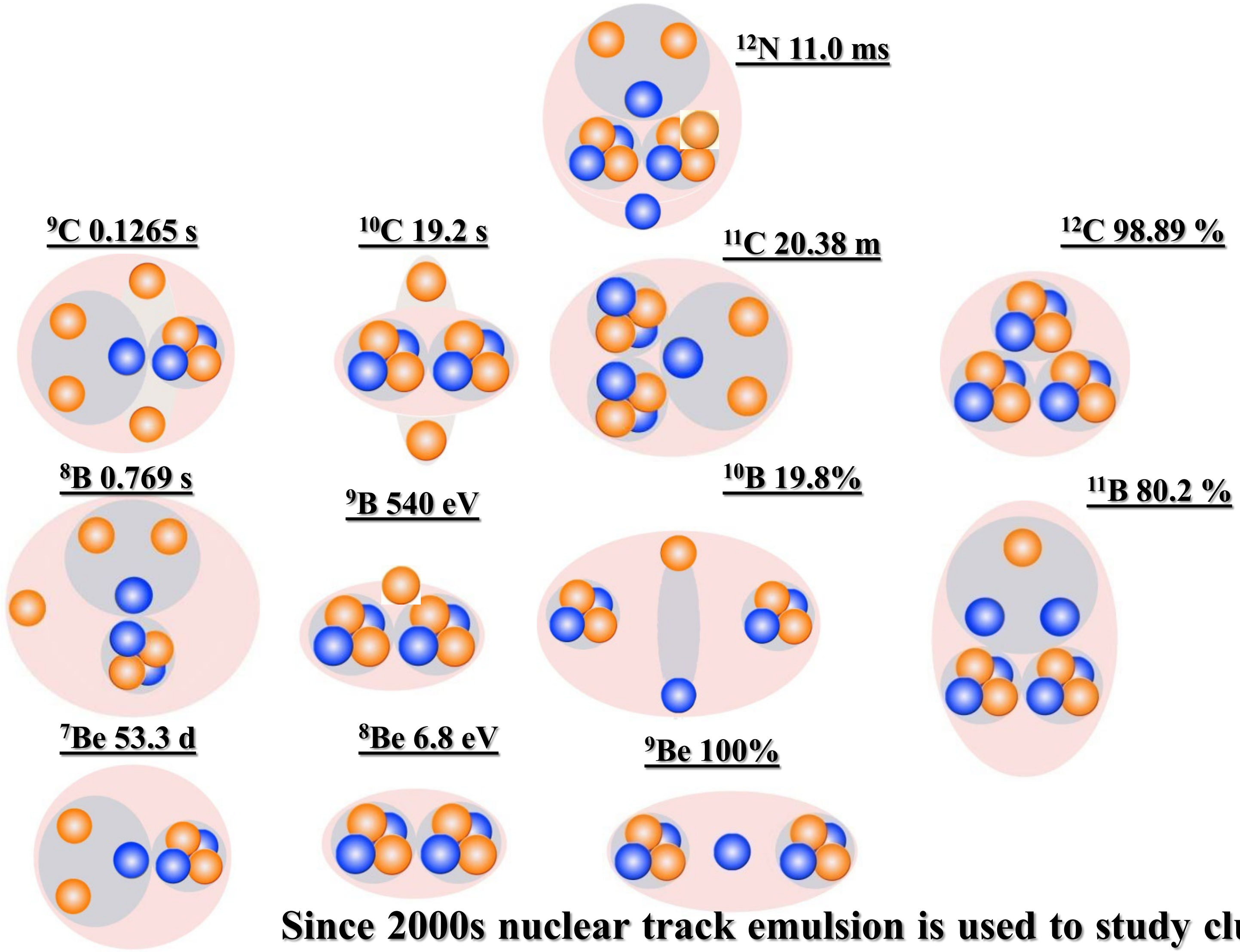


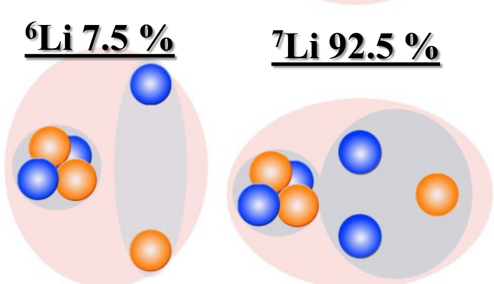


In general, energy of a few-particle system Q is $Q = M^* - M$. M^* is the invariant mass defined by the sum of all products of *4*-momenta $P_{i,k}$ fragments $M^{*2} = \sum(P_i \cdot P_k)$. Subtraction of mass M is a matter of convenience. The *4*-momenta $P_{i,k}$ are determined in the approximation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



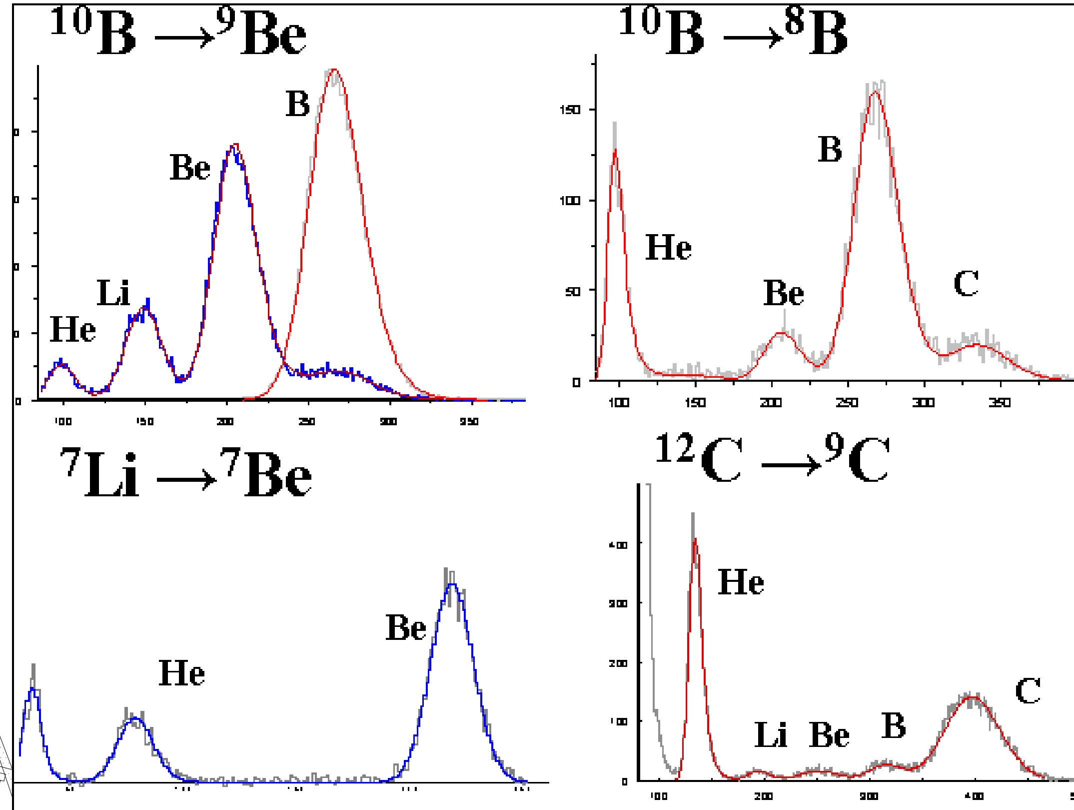
$Q = M^{*} - M$. M^{*} is defined by the sum of all products of *4*-momenta $M^{*2} = \sum(P_i \cdot P_k)$.

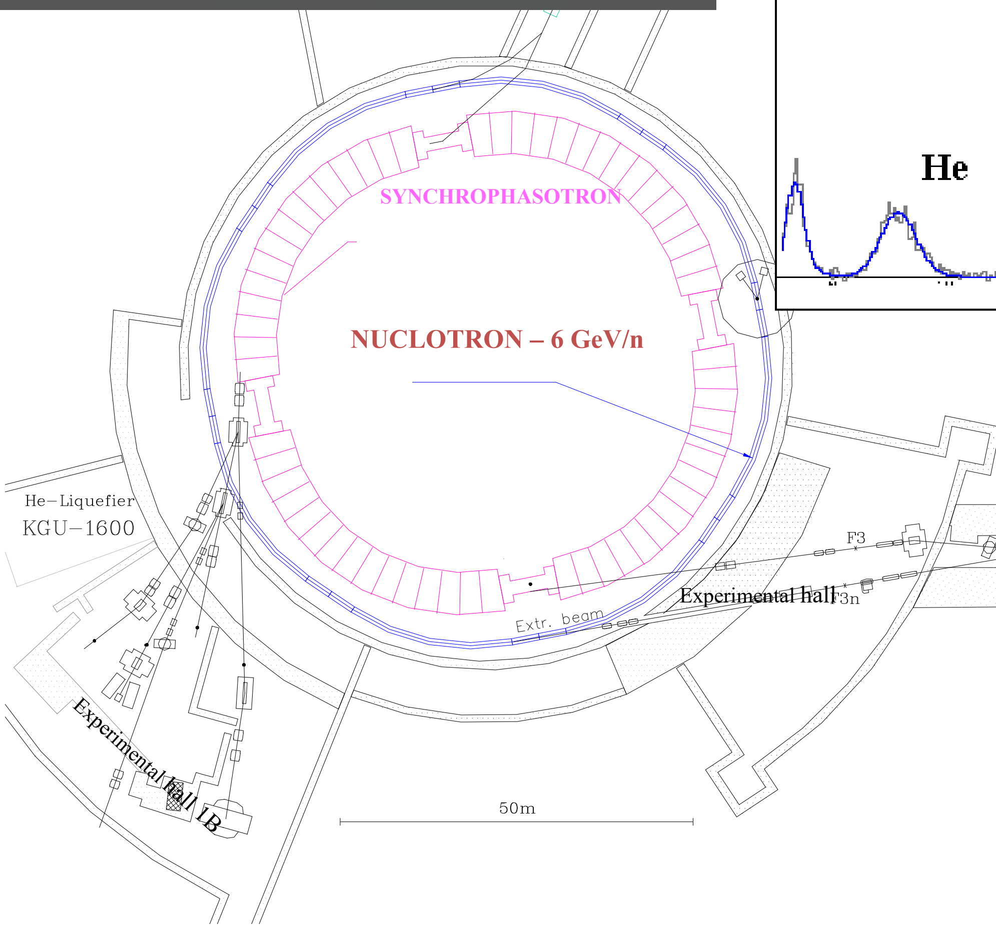


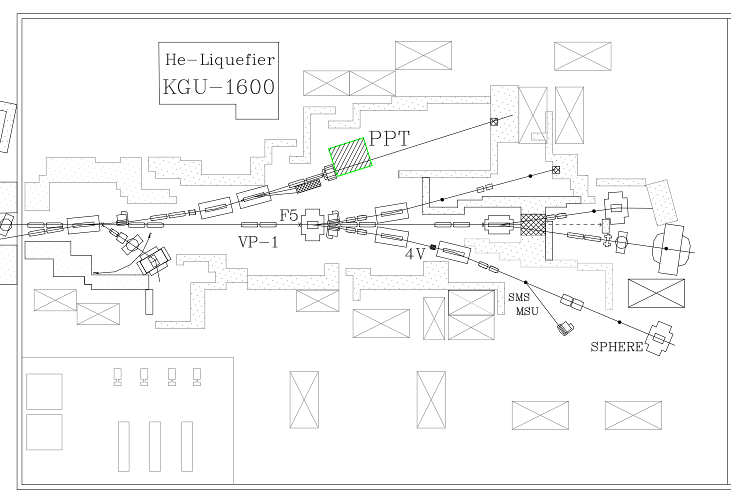


Since 2000s nuclear track emulsion is used to study clustering of light stable and radioactive nuclei in the relativistic approach in the BECQUEREL experiment at the JINR Nuclotron. The features of the nuclei ^{7,9}Be, ^{8,10,11}B, ^{10,11}C, ^{12,14}N appeared in the probabilities of their dissociation channels. In dissociation of isotopes ^{10}B, ^{10}C, and ^{11}C, decays ^{9}B → ^{8}Be are identified

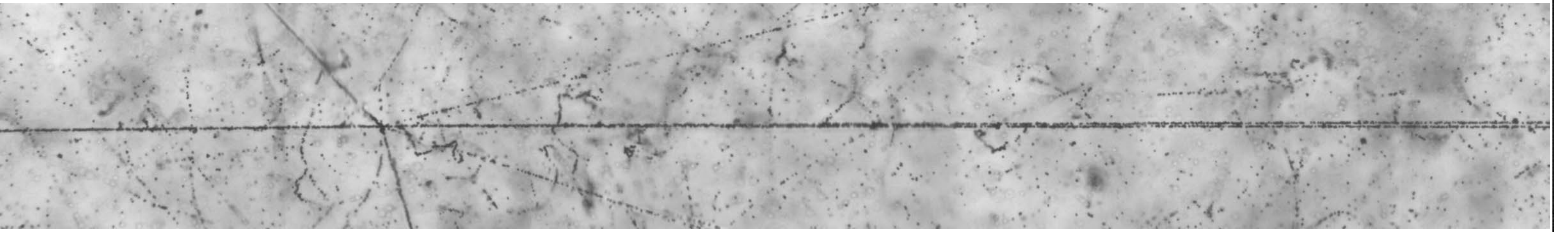

CO2 laser

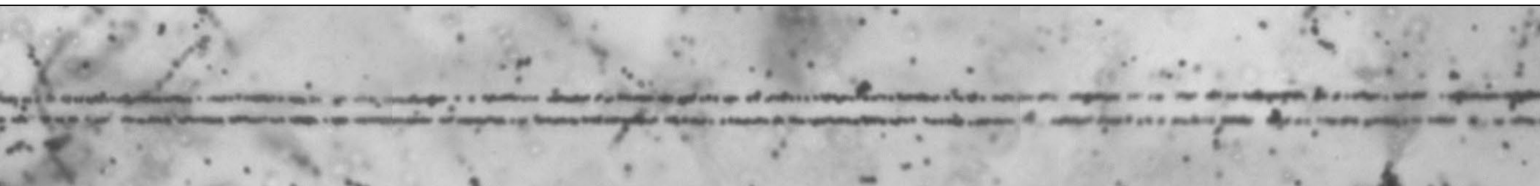

$^{10}B \rightarrow {}^{9}Be$
He
Li
Be
B
$^{10}B \rightarrow {}^{8}B$
He
Be
B
C
$^{7}Li \rightarrow {}^{7}Be$
He
Be
$^{12}C \rightarrow {}^{9}C$
He
Li
Be
B
C

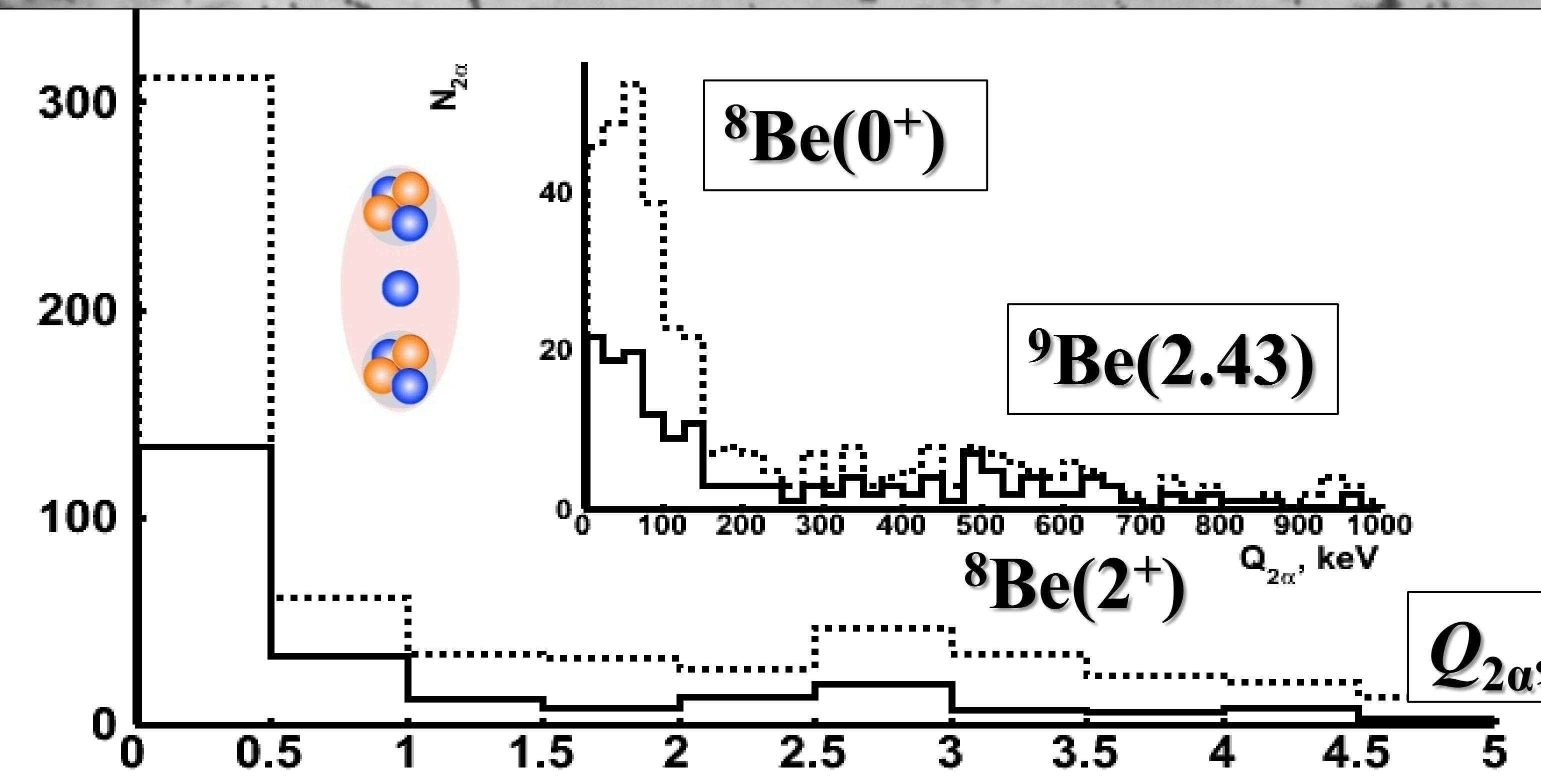

SYNCHROPHASOTRON
NUCLOTRON – 6 GeV/n
He–Liquefier
KGU–1600
Extr. beam
F3
F3n
Experimental hall
Experimental hall 1B
50m

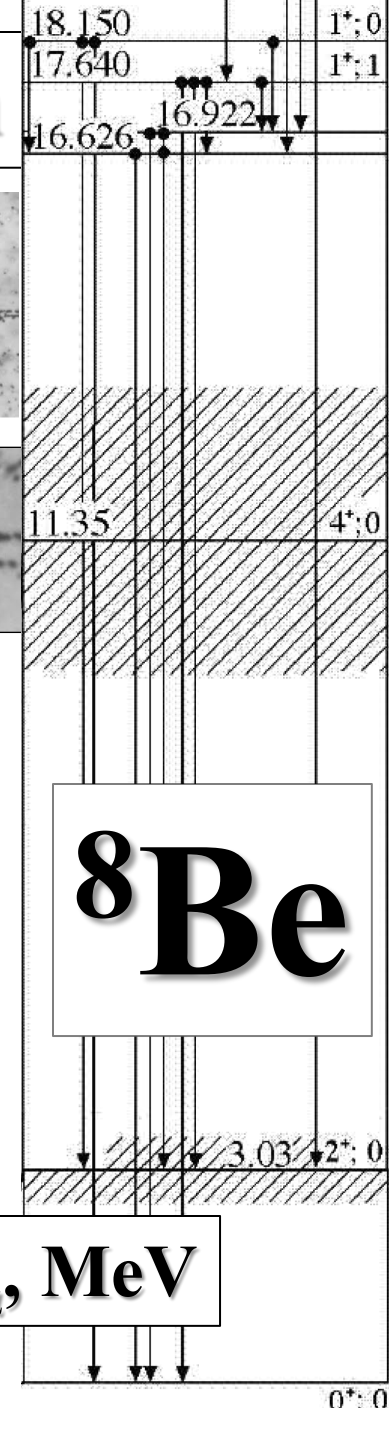

He–Liquefier
KGU–1600
PPT
F5
VP–1
4V
SMS
MSU
SPHERE

712 $^9Be \to 2\alpha$ at 1.2 GeV per nucleon

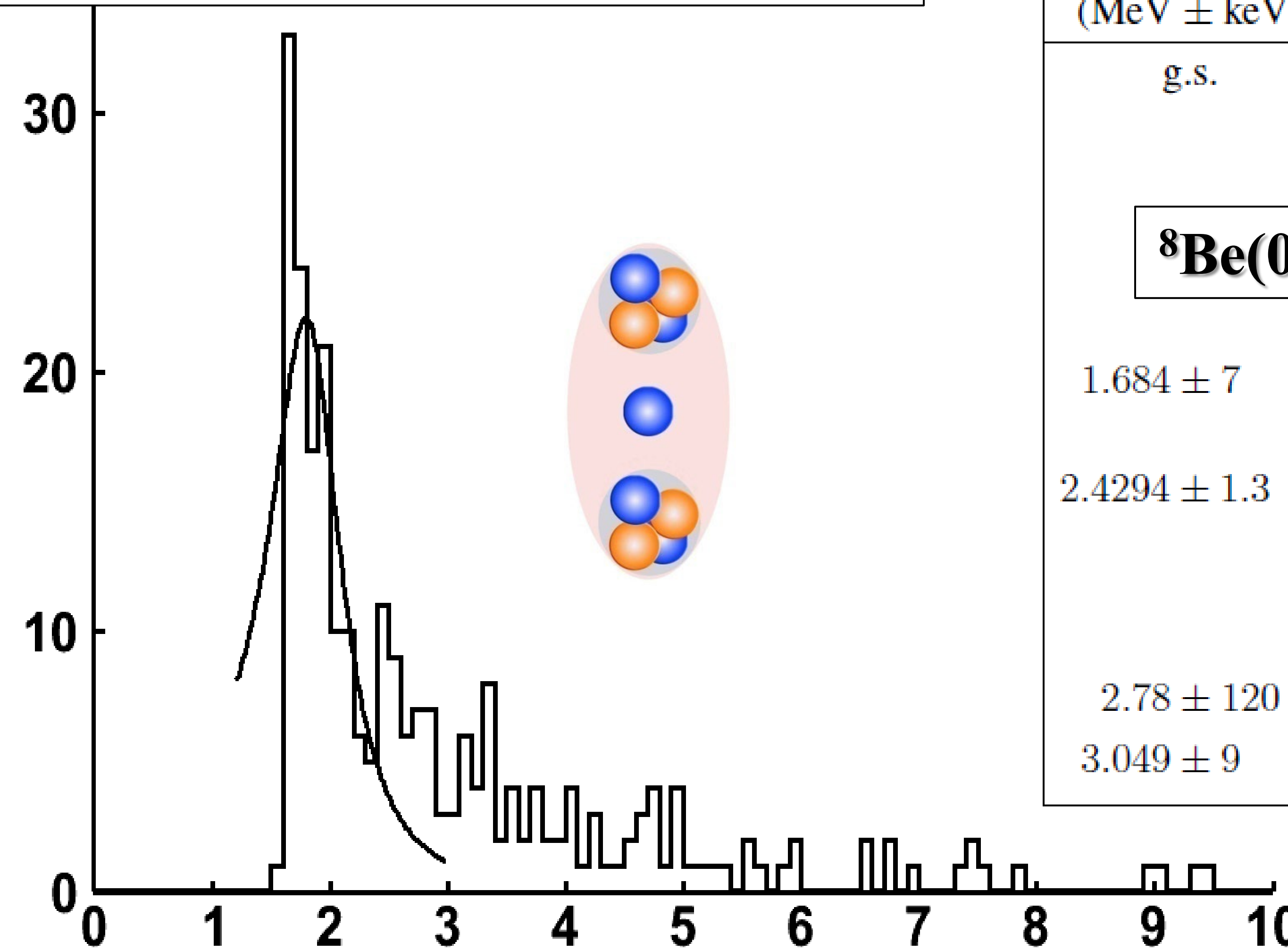








$^9Be^*(1.684)$ in $^9Be \rightarrow 2\alpha$



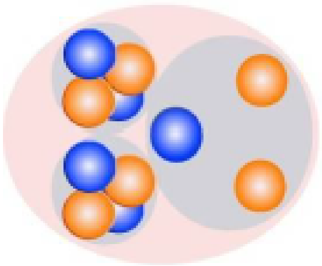
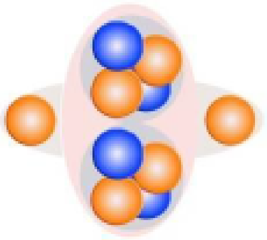
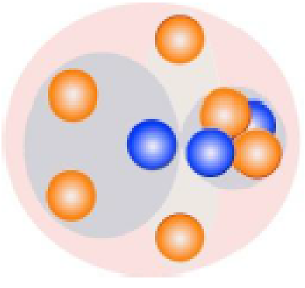
E_x (MeV ± keV)	$J^\pi; T$	Γ_{cm} (keV)
g.s.	$\frac{3}{2}^-; \frac{1}{2}$	
1.684 ± 7	$\frac{1}{2}^+$	217 ± 10
2.4294 ± 1.3	$\frac{5}{2}^-$	0.78 ± 0.13
2.78 ± 120	$\frac{1}{2}^-$	1080 ± 110
3.049 ± 9	$\frac{5}{2}^+$	282 ± 11

$^8Be(0^+)n$ 1.665 MeV

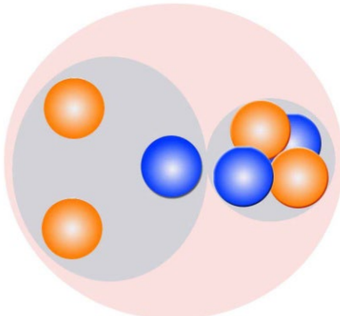
$\langle P_{T2\alpha} \rangle$ in $^9Be \rightarrow 2\alpha$ is about 10 MeV/*c* per nucleon is several times less than the Fermi momentum (100-200 MeV/*c*). P_{Tn} carried away by neutrons can be estimated and, then, $Q_{2\alpha n}$. The resonance 1.80 ± 0.01 MeV consistent with $^9Be^*(1.684)$. contributing 33 ± 4% to $^9Be \rightarrow {}^8Be(0^+)$. $^9Be(2.43)$ is than 4% of $^9Be \rightarrow 2\alpha$.

Coherent dissociation (or “white” stars) at 1.2 GeV per nucleon

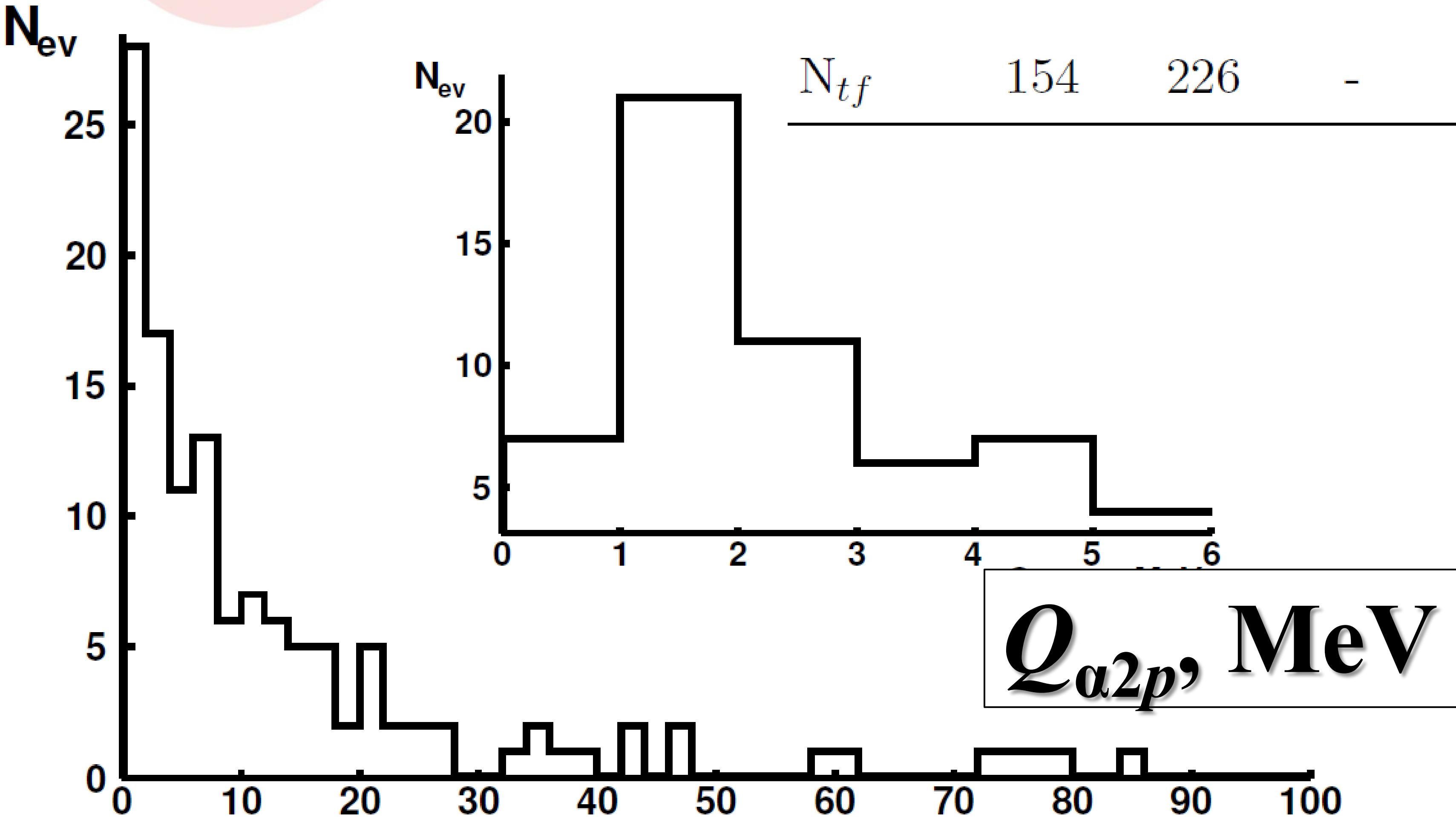
	^{11}C	^{10}C	^{9}C
B + H	6 (5 %)	1 (0.4 %)	15 (14 %)
Be + He	18 (13 %)	6 (2.6 %)	
Be + 2H			16 (15 %)
3He	25 (17 %)	12 (5.3 %)	16 (15 %)
2He + 2H	72 (50 %)	186 (82 %)	24 (23 %)
He + 4H	15 (11 %)	12 (5.3 %)	28 (27 %)
Li + He + H	5 (3 %)		
Li + 3H		1 (0.4 %)	2 (2 %)
6H	3 (2 %)	9 (4 %)	6 (6 %)

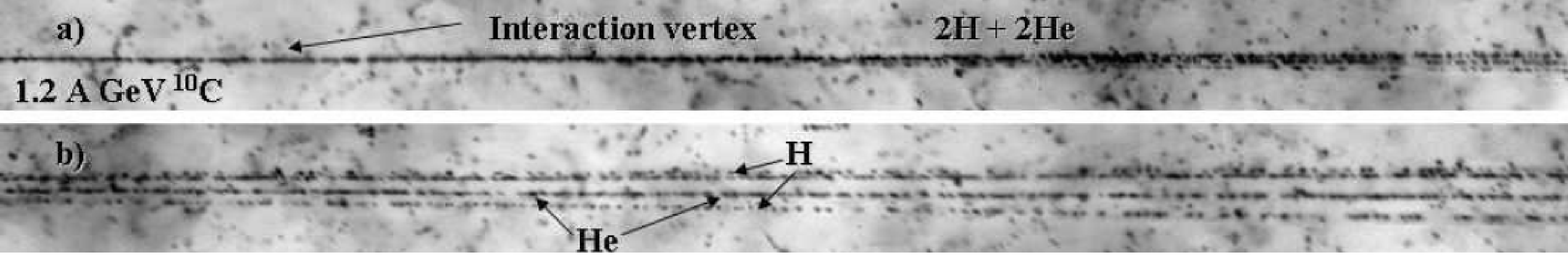




^{6}Be(1.37) in ^{7}Be dissociation at 1.2 GeV per nucleon

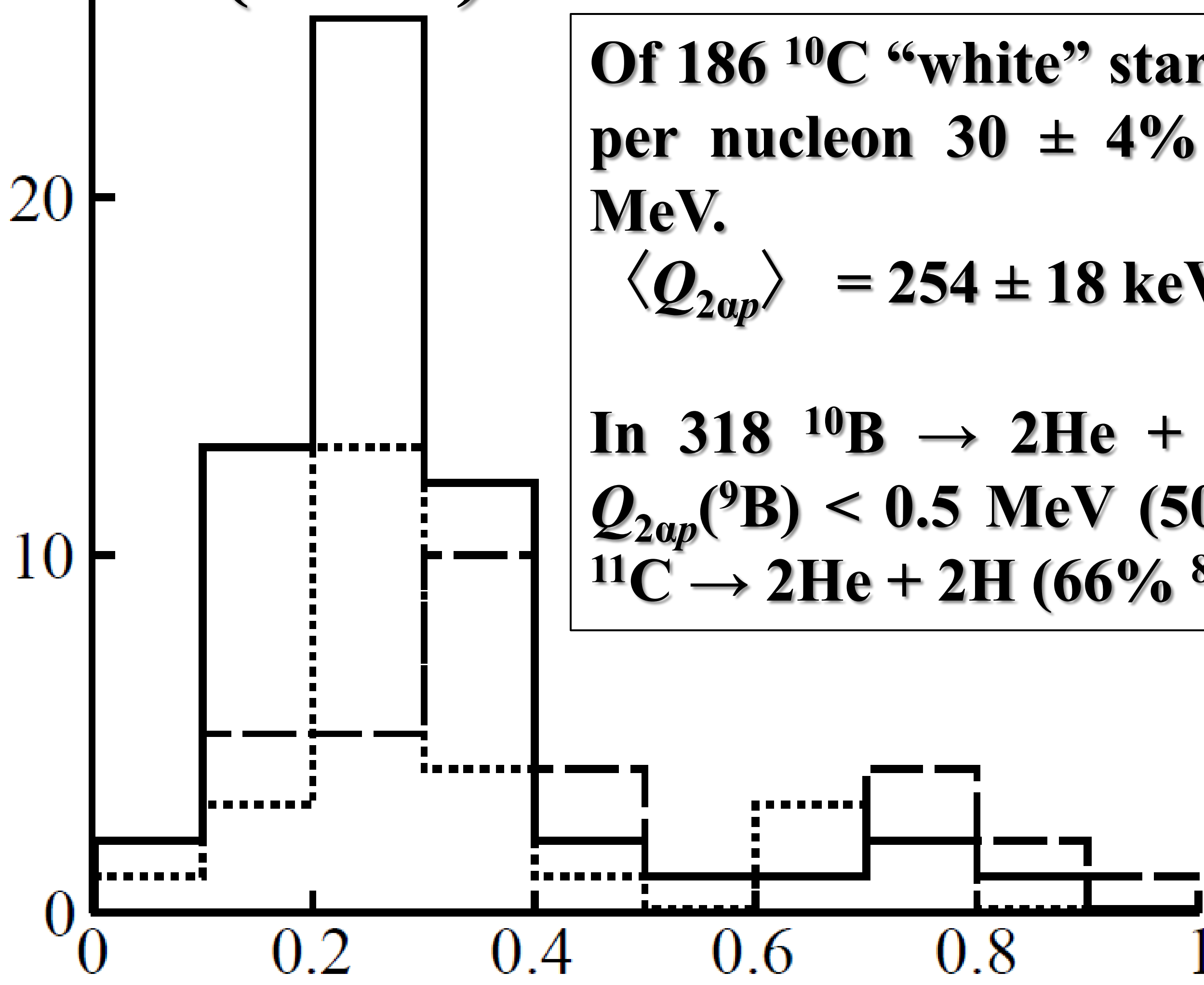


Channel	2He	He + 2H	4H	Li + H
N_{ws}	115	157	14	3
N_{tf}	154	226	-	-





^{9}B(0.185) in dissocaition of ^{10}C, ^{11}C and ^{10}B

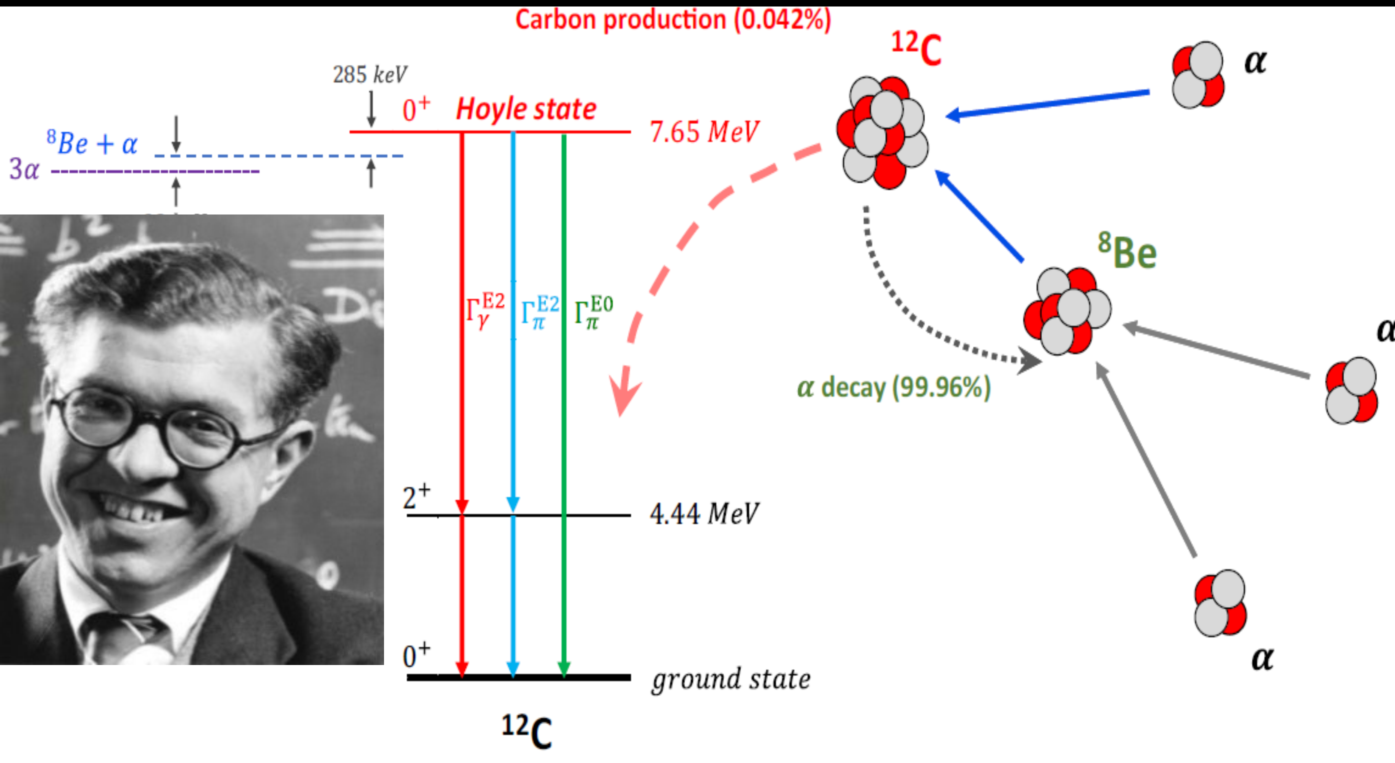


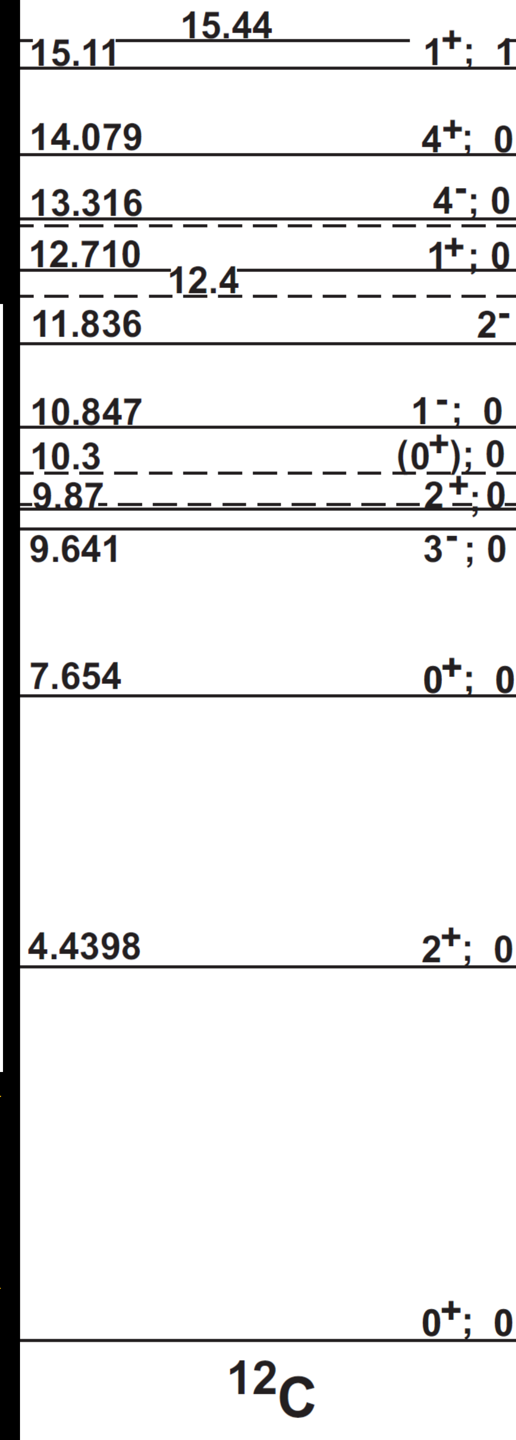
Of 186 ^{10}C "white" stars 2He + 2H. at 1.0 GeV per nucleon 30 ± 4% satisfy $Q_{2\alpha p}(^{9}B) < 0.5$ MeV.

$\langle Q_{2\alpha p} \rangle$ = 254 ± 18 keV RMS 96 keV.

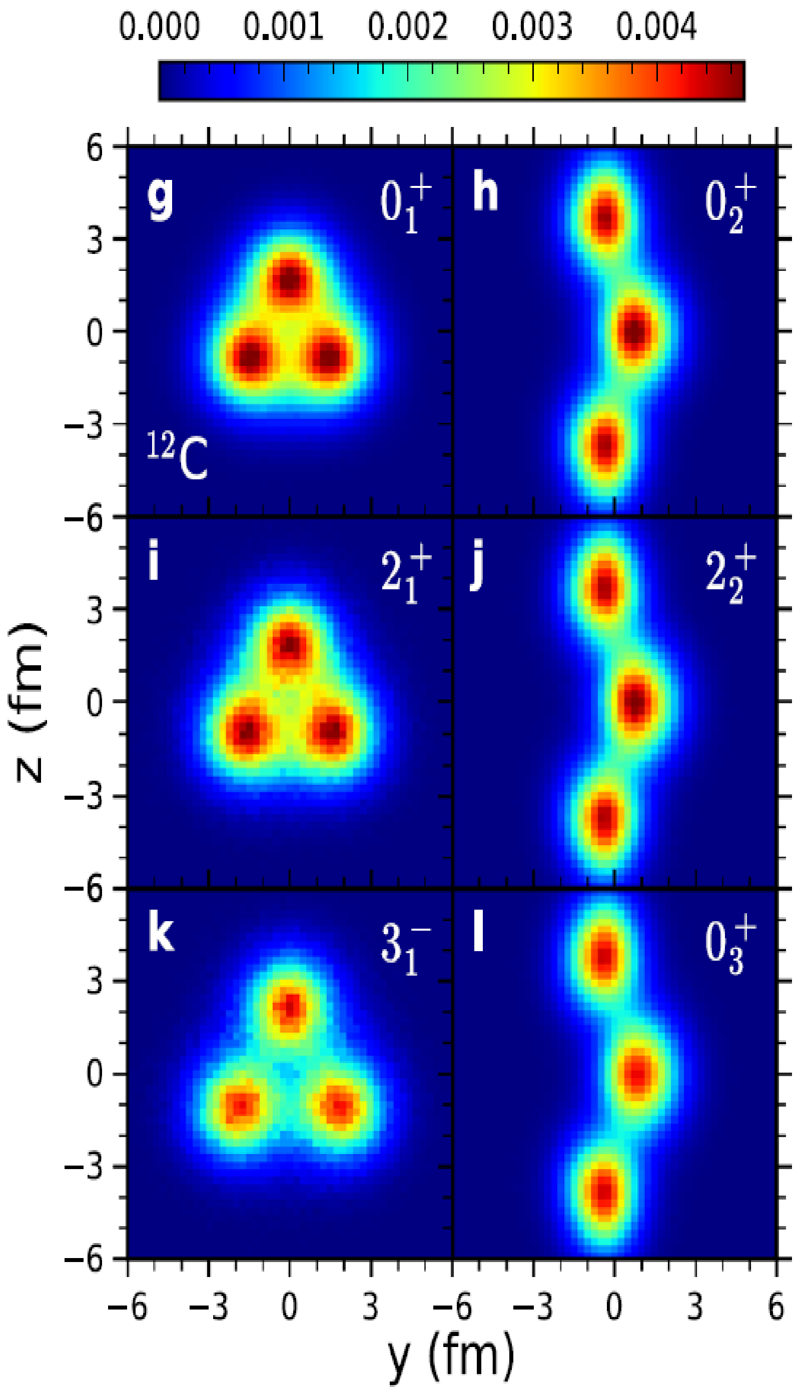
In 318 ^{10}B → 2He + H stars, 20 decays of $Q_{2\alpha p}(^{9}B) < 0.5$ MeV (50% ^{8}Be) and 22 in 154 ^{11}C → 2He + 2H (66% ^{8}Be) were identified.

The Hoyle state





The Hoyle state is the second excited state $^{12}C(0^+_2)$ at 378 keV above the 3α threshold. The $^8Be(0^+)$ inevitably appears in ^9B and Hoyle state decays. The isolated position of $^{12}C(0^+_2)$ at the beginning of the excitation spectrum and the width of 9.3 eV indicate it as a 3α analogue $^8Be(0^+)$.



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Article

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Emergent geometry and duality in the carbon nucleus

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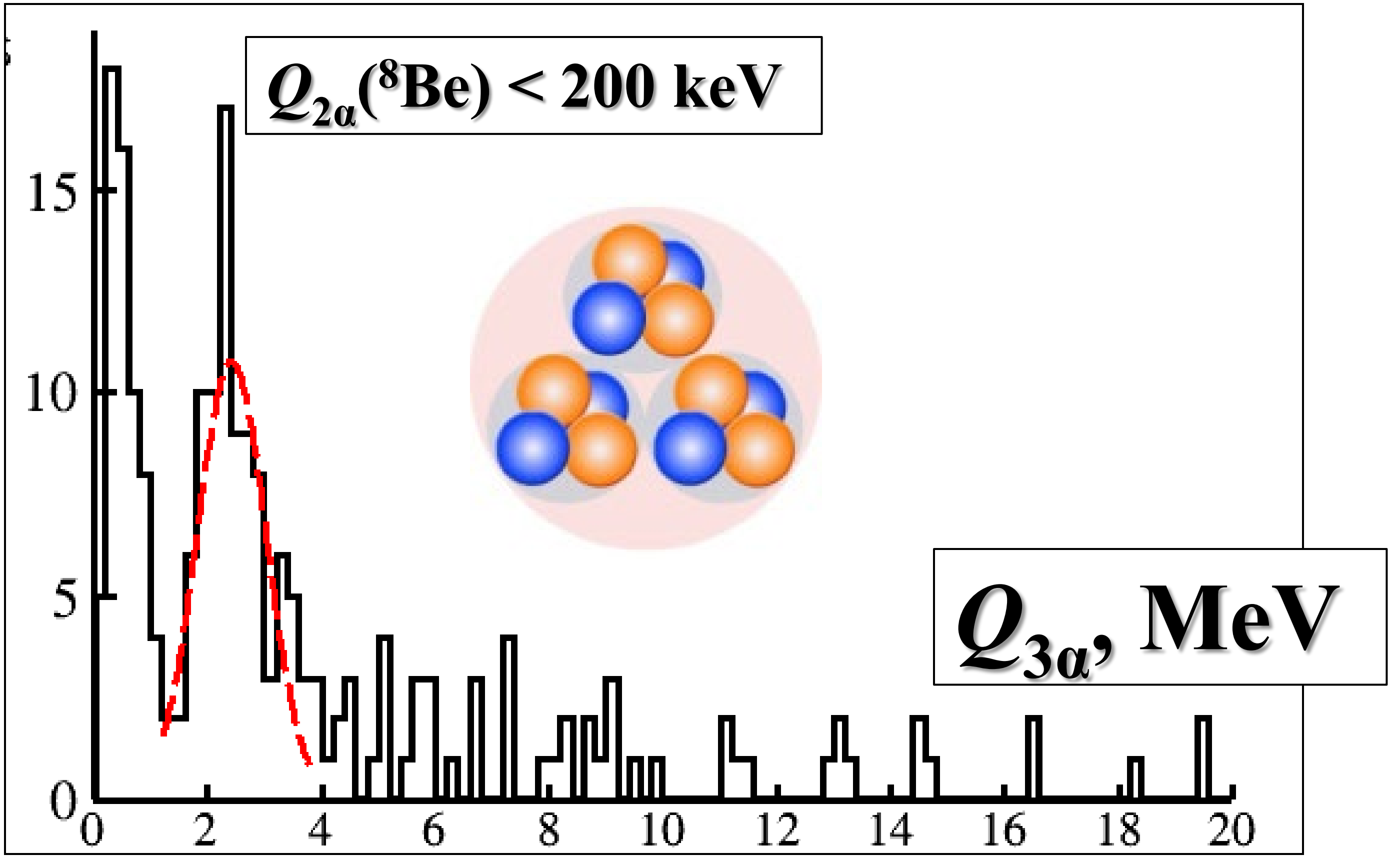
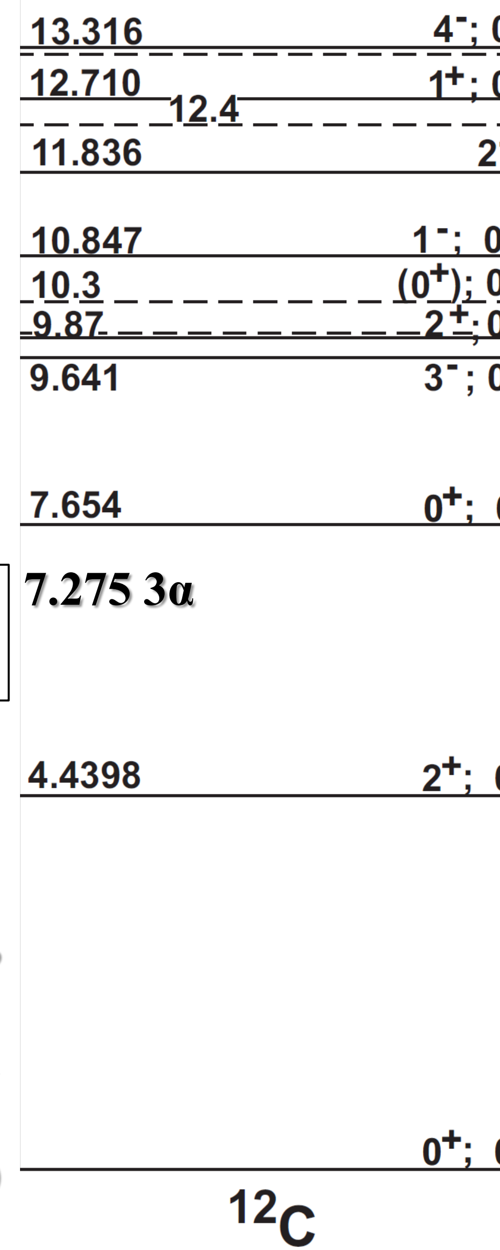
Shihang Shen[1], Serdar Elhatisari[2,3], Timo A. Lähde[1,4], Dean Lee[5], Bing-Nan Lu[6] & Ulf-G. Meißner[1,2,4,7]

The carbon atom provides the backbone for the complex organic chemistry composing the building blocks of life. The physics of the carbon nucleus in its predominant isotope, ^{12}C, is similarly full of multifaceted complexity. Here we provide a model-independent density map of the geometry of the nuclear states of ^{12}C using the ab initio framework of nuclear lattice effective field theory. We find that the well-known but enigmatic Hoyle state is composed of a "bent-arm" or obtuse triangular arrangement of alpha clusters. We identify all of the low-lying nuclear states of ^{12}C as having an intrinsic shape composed of three alpha clusters forming either an equilateral triangle or an obtuse triangle. The states with the equilateral triangle formation also have a dual description in terms of particle-hole excitations in the mean-field picture.

$^{12}C(0^+_2)$ and $^{12}C\ (3^-)$ in 510 $^{12}C \rightarrow 3\alpha$



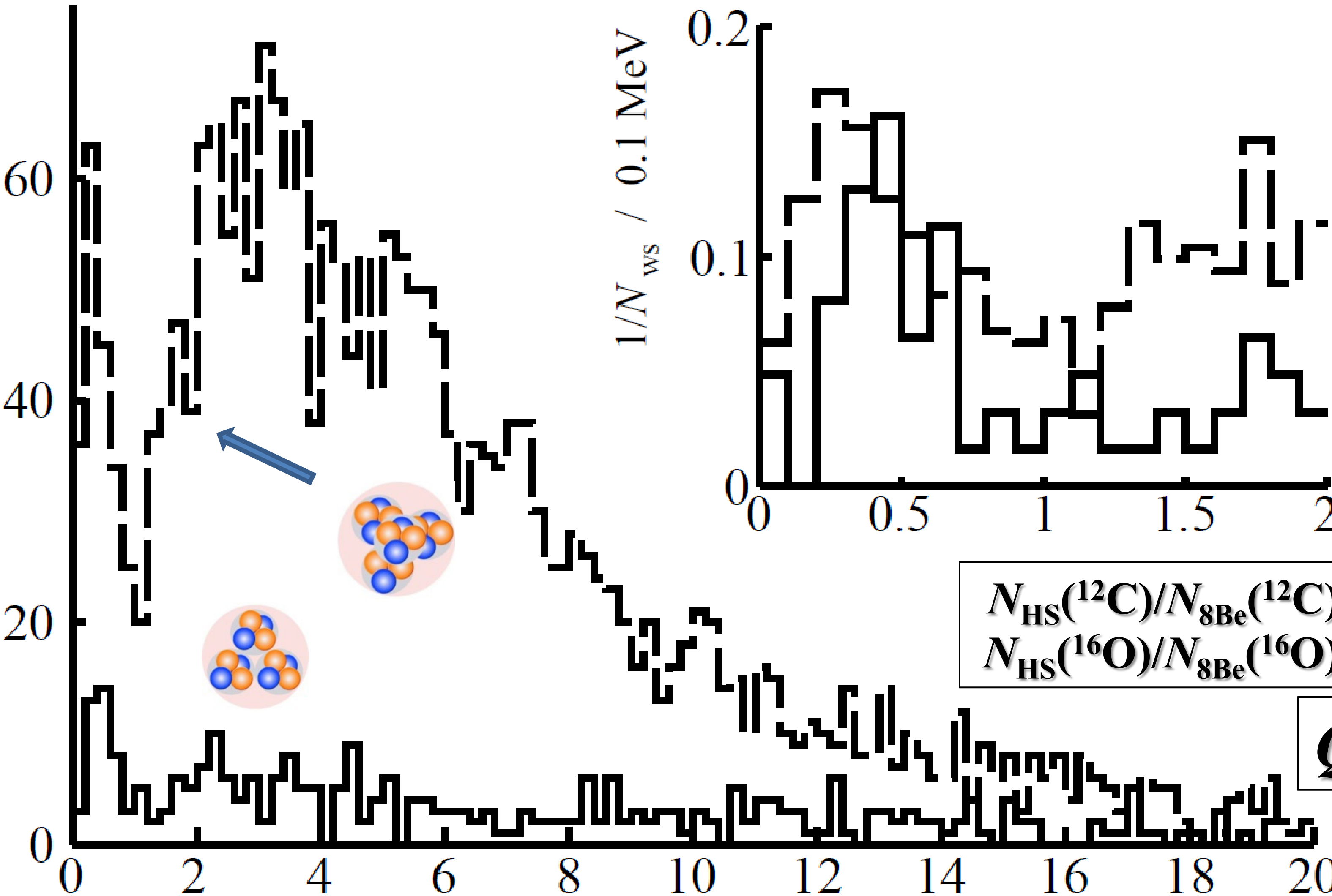


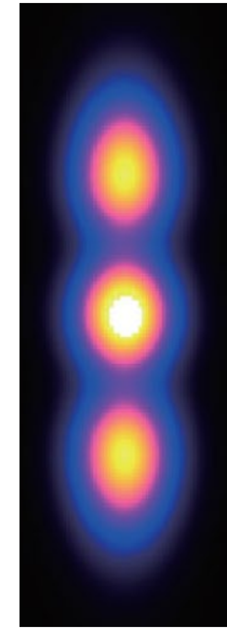
The 1st peak $\langle Q_{3\alpha} \rangle$ (RMS) = 417 ± 27 (165) keV is $^{12}C(0^+_2)$, and the 2nd σ ($Q_{3\alpha}$) = 2.4 ± 0.1 MeV – $^{12}C(3^-)$.

The contributions of $^8Be(0^+)$, $^{12}C(0^+_2)$ and $^{12}C(3^-)$ are 43 ± 4, 11 ± 2, 19 ± 2%.

The contribution to $^8Be(0^+)$ of $^{12}C(0^+_2)$ is 26 ± 4%, and $^{12}C(3^-)$ is 44 ± 6% and their ratio is 0.6 ± 0.1.

$^{12}C(0^+_2)$ in 641 "white" stars $^{16}O \to 4\alpha$

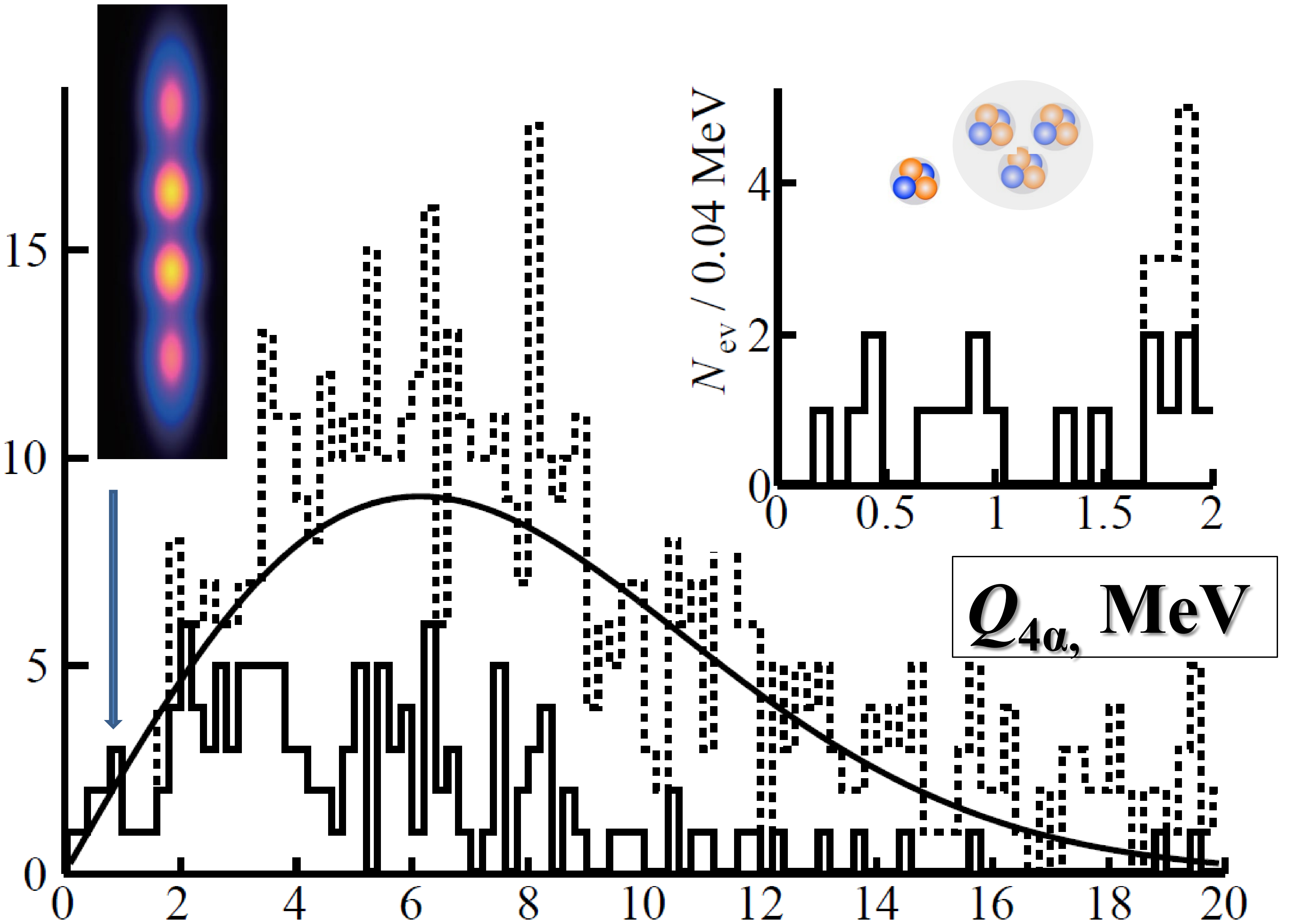




$N_{HS}(^{12}C)/N_{8Be}(^{12}C) = 0.36 \pm 0.06$

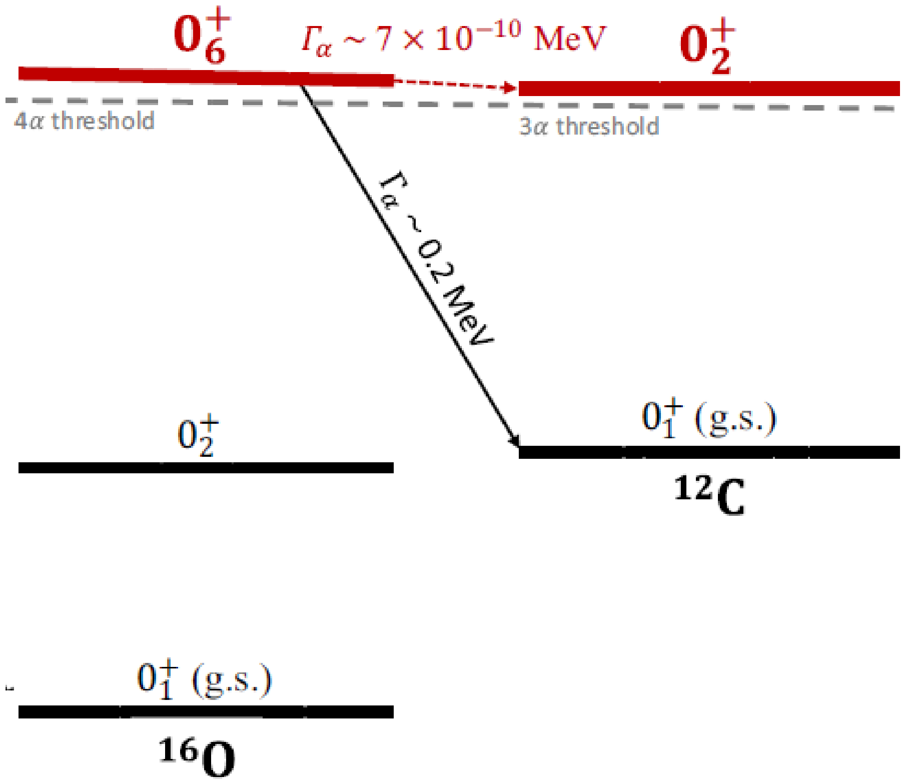
$N_{HS}(^{16}O)/N_{8Be}(^{16}O) = 0.35 \pm 0.04$

Distribution of the number of 3α-triples $N_{3\alpha}$ over the invariant mass $Q_{3\alpha}$ of 316 "white" stars $^{12}C \to 3\alpha$ (solid) and 641 "white" stars $^{16}O \to 4\alpha$ (dashed) at 3.65 *A* GeV. The α-particle enhancement $^{8}Be(0^+)$ and $^{12}C(0^+_2)$ allows to assume the fusion $2\alpha \to {}^{8}Be(0^+)\alpha \to {}^{12}C(0^+_2)\alpha \to {}^{16}O(0^+_6)$.

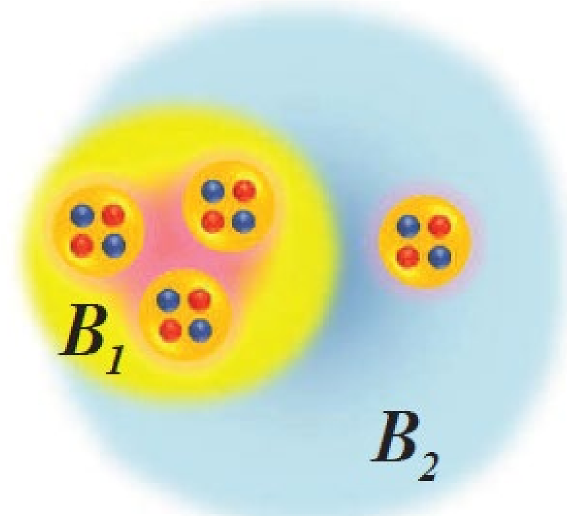


15
10
5
0
0
2
4
6
8
10
12
14
16
18
20
N_{ev} / 0.04 MeV
4
2
0
0
0.5
1
1.5
2
$Q_{4\alpha,}$ MeV

15.095 keV   Γ = 165 keV

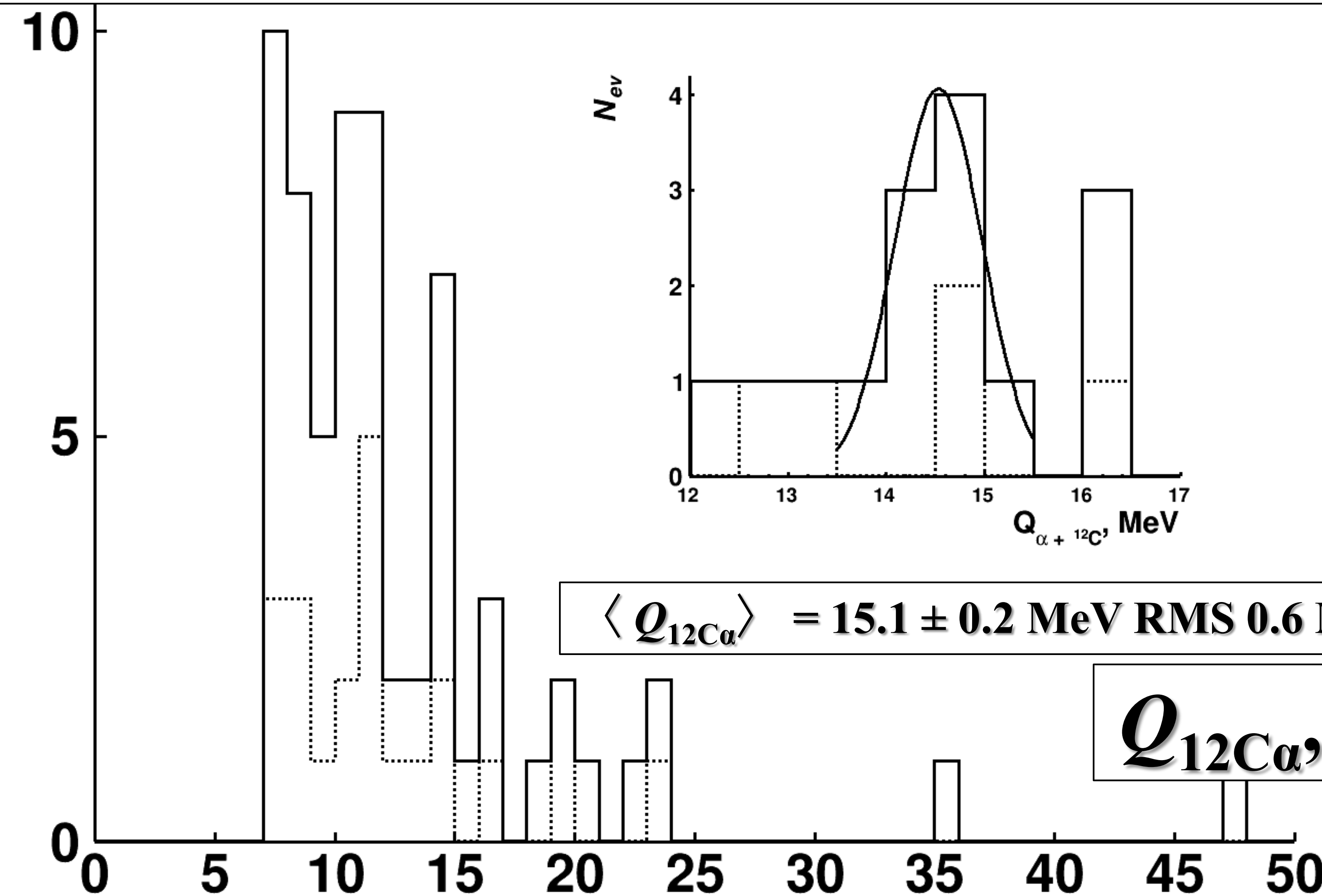


Just 296 keV !

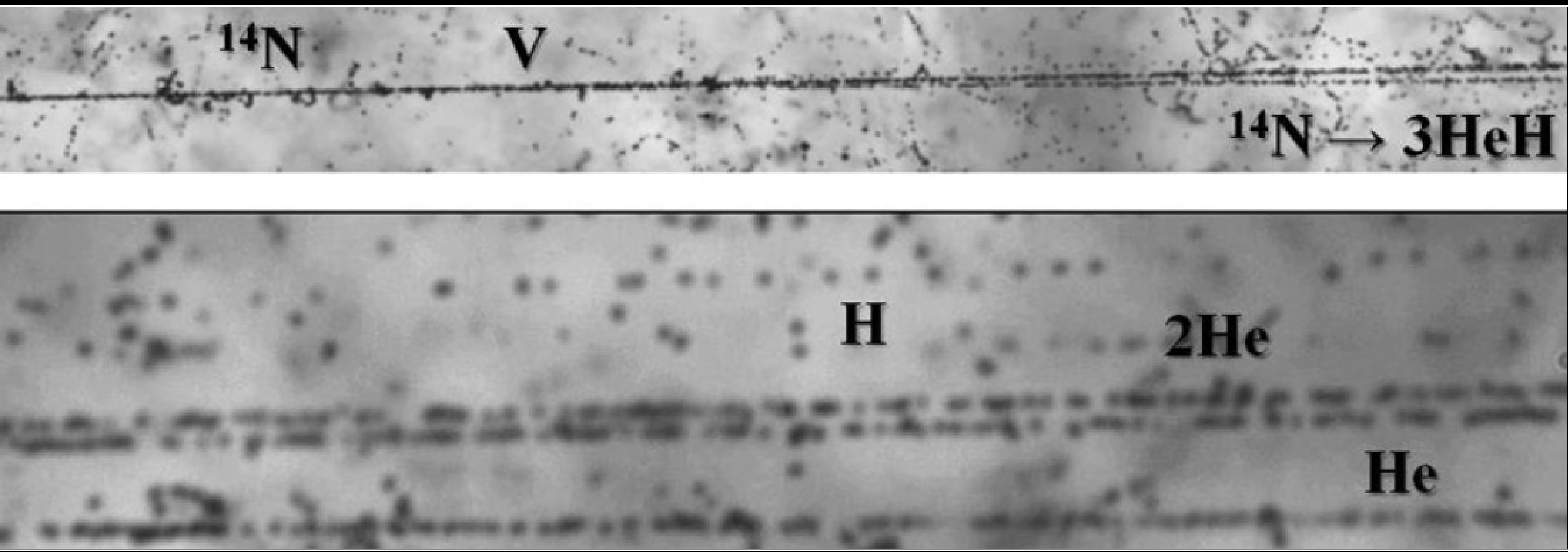


The search for the decay $^{16}O(0^+_6) \rightarrow {}^{12}C(0^+_1)\alpha$ is important in the context of nuclear astrophysical synthesis of the isotope ^{12}C. It can serve as an alternative to the fusion $^{8}Be(0^+)\alpha \rightarrow {}^{12}C(0^+_2)$ with the formation of e^+e^- pairs or 2γ-decay $0^+ \rightarrow 2^+ \rightarrow 0^+$ with a probability of 1/2500. In the case of $^{16}O(0^+_6) \rightarrow {}^{12}C(0^+_1)\alpha$ one of the α-particles in the quartet serves as a kind of catalyst, removing the need for an electromagnetic transition. The coexistence of the decays $^{12}C(0^+_2)\alpha$ and $^{12}C(0^+_1)\alpha$ within the 165 keV width of $^{16}O(0^+_6)$ cannot be ruled out.

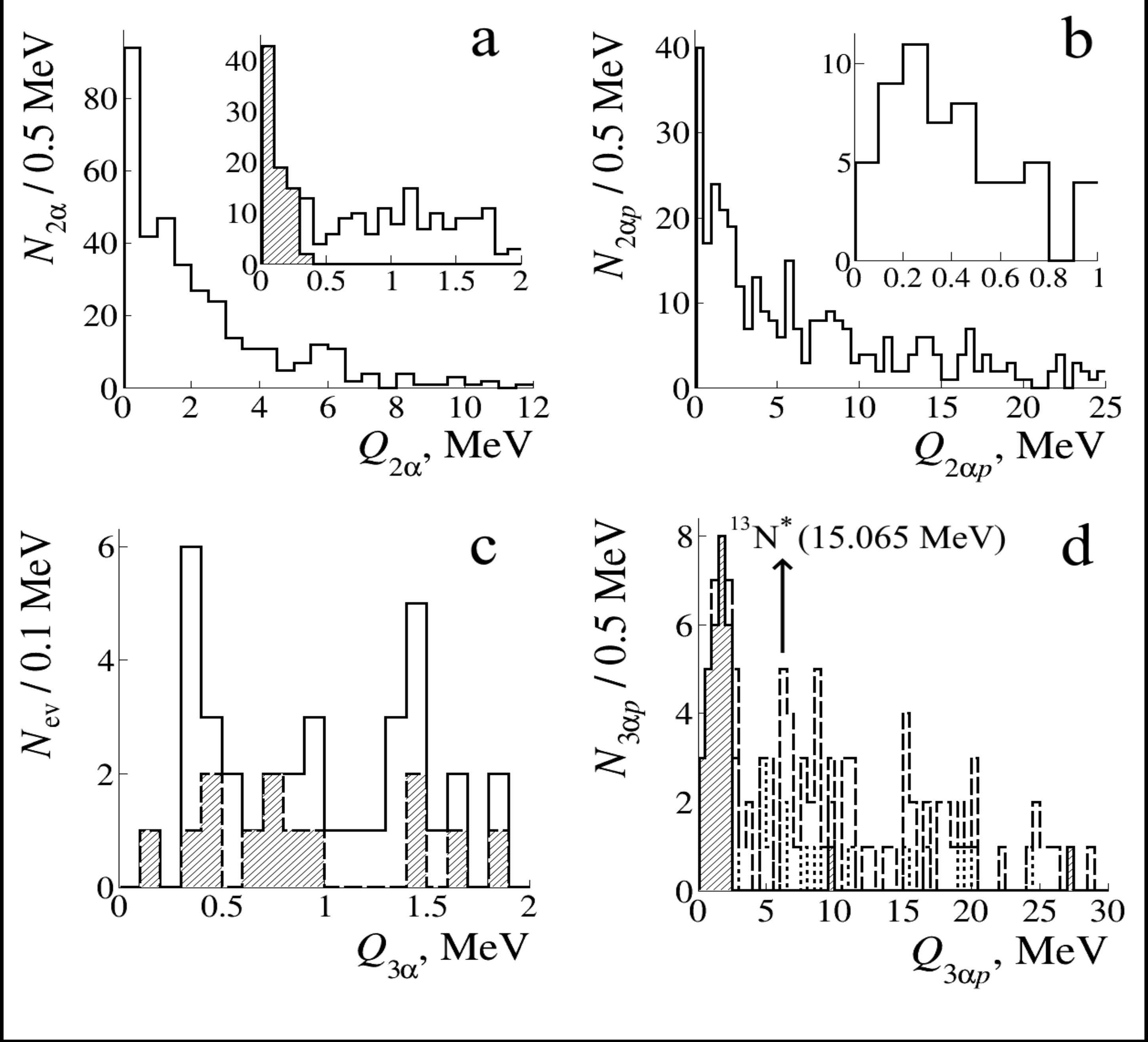
$^{16}O(0^+_6)$ in ^{16}O (4.5 GeV/*c* per nucleon) → $^{12}C\alpha$?



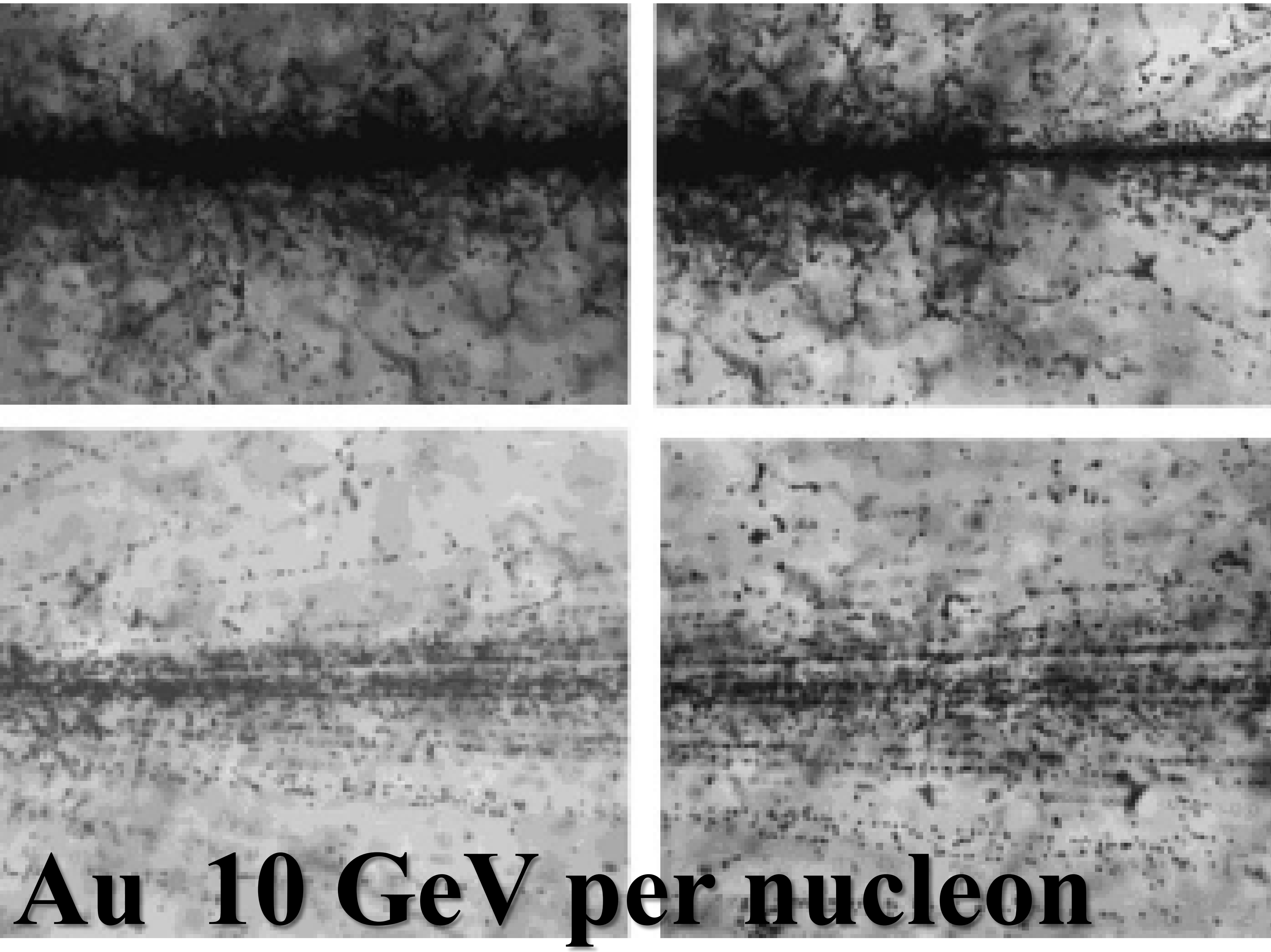
Search for ^{9}B and $^{12}C(0^+_2)$ in 128 $^{14}N \rightarrow 3\alpha p$ at 2 GeV per nucleon

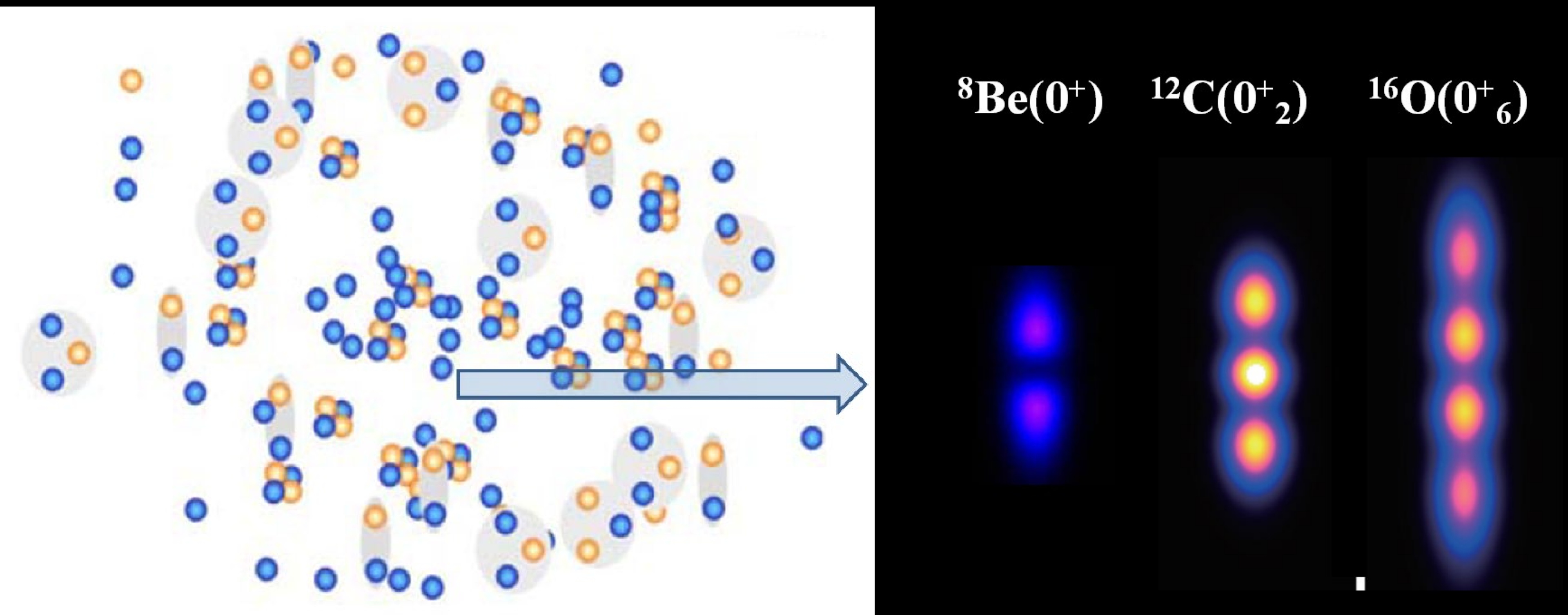


The channel $^{14}N \rightarrow 3\alpha p$ presents a half of peripheral interactions with the transfer of the primary charge to the fragmentation cone. It is a common source of $^{8}Be(0^+)$, ^{9}B and $^{12}C(0^+_2)$. Transverse scanning of emulsion layers found 226 $^{14}N \rightarrow 3\alpha p$ stars which 128 are measured including 29 “white” stars.



^{9}B or $^{12}C(0^+_2)$: $\langle Q_{3\alpha p}\rangle = 2.5 \pm 0.1$ MeV RMS 0.6 MeV


Au 10 GeV per nucleon


^{8}Be(0^{+})
^{12}C(0^{+}_{2})
^{16}O(0^{+}_{6})

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

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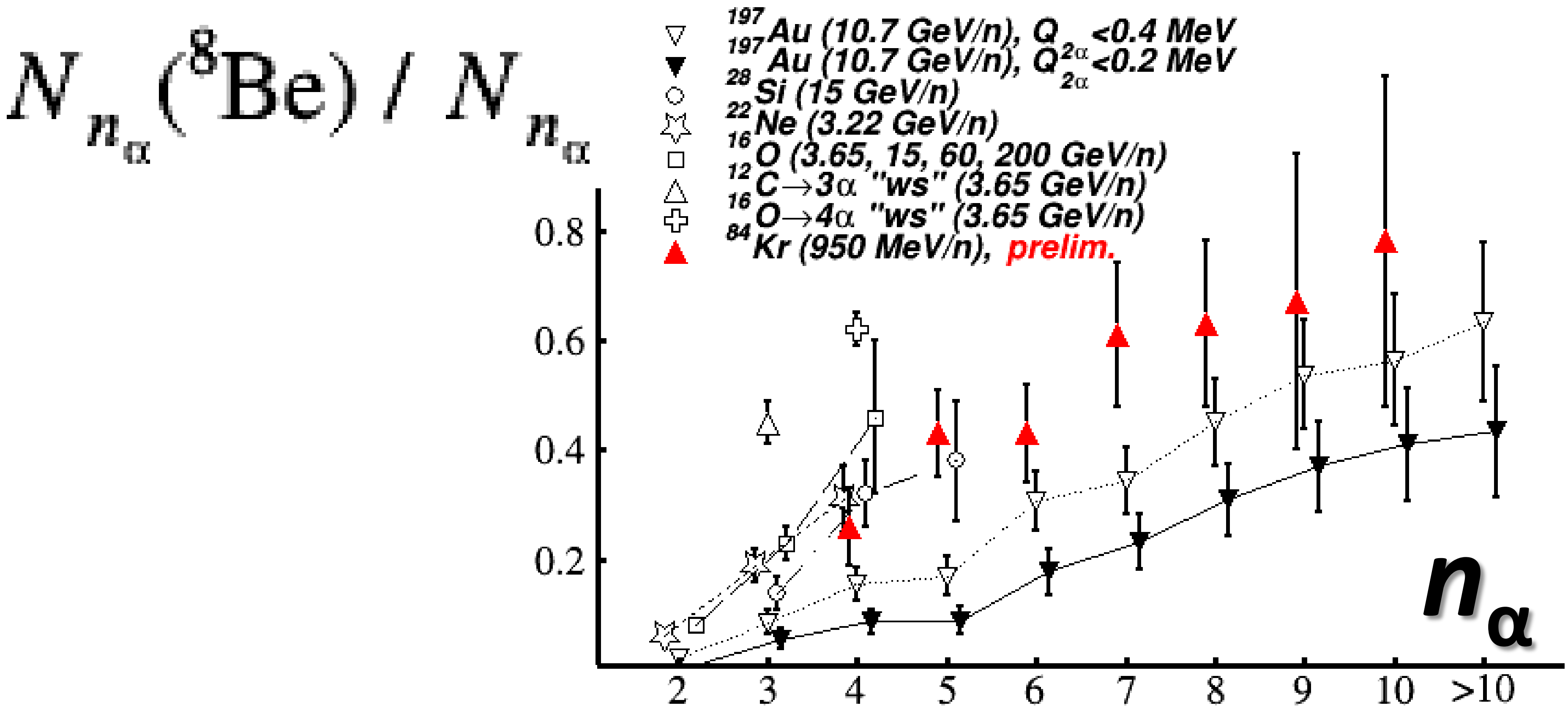
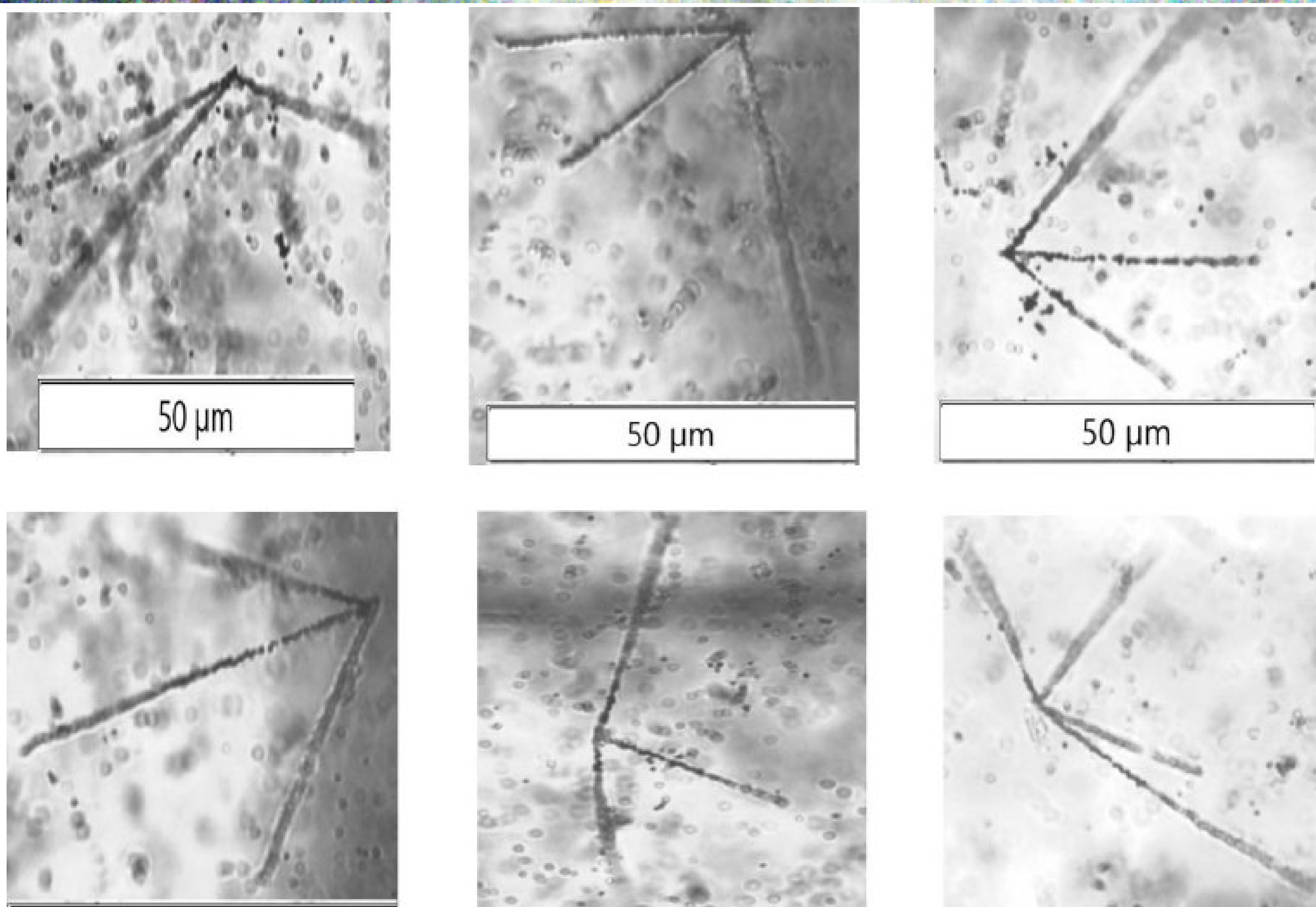


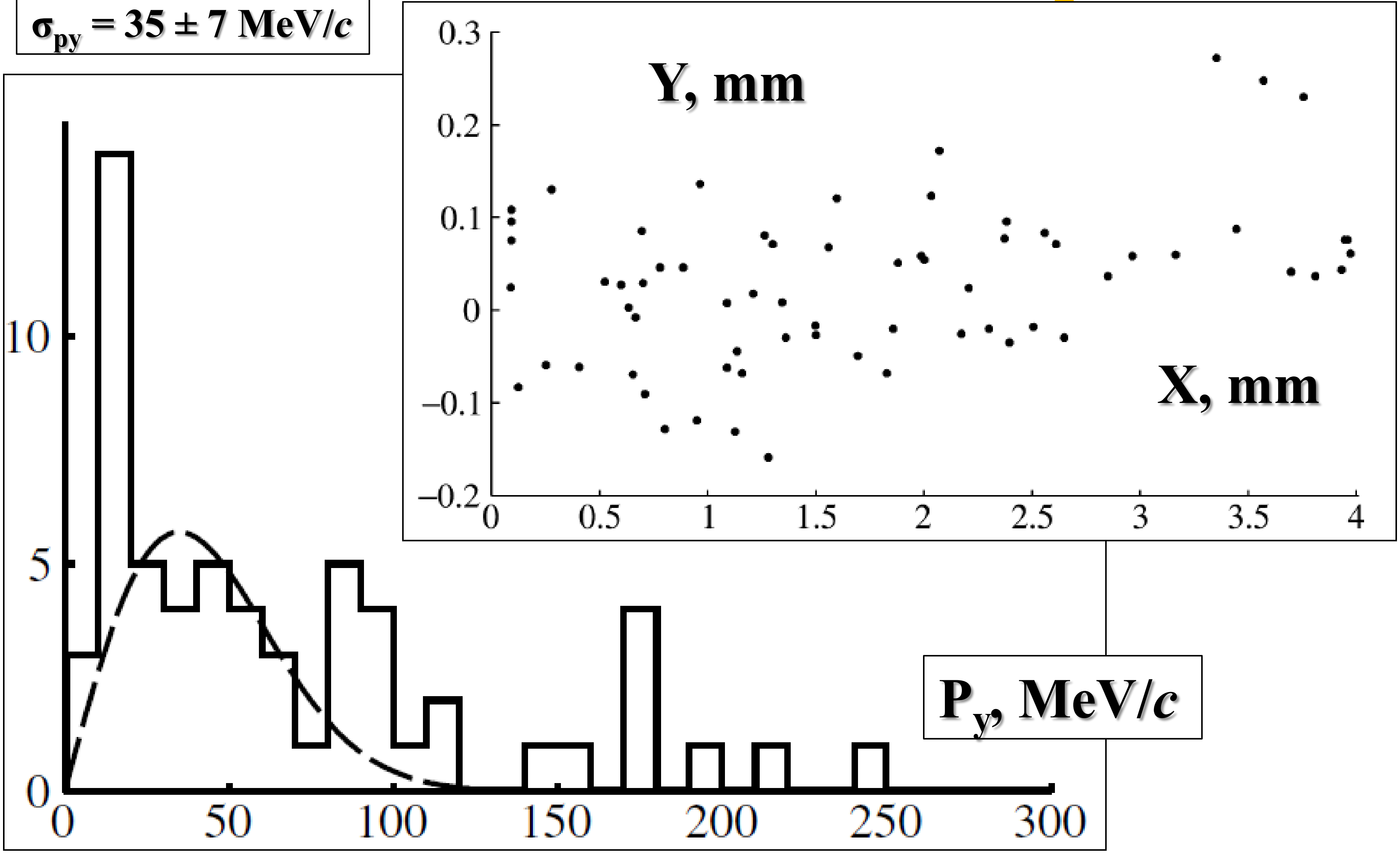
^{84}Kr 1 GeV per nucleon

Target Fragments: 3 Mesons: 5 Progectile Fragment Charge > 23 (He – 7, H - 9)



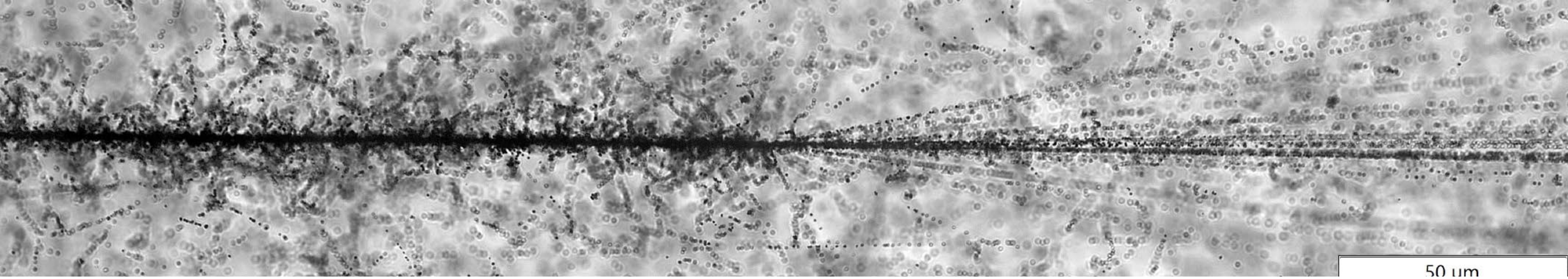
Projectile neutrons in ^{84}Kr fragmentation near 1 GeV per nucleon

σ_{py} = 35 ± 7 MeV/c

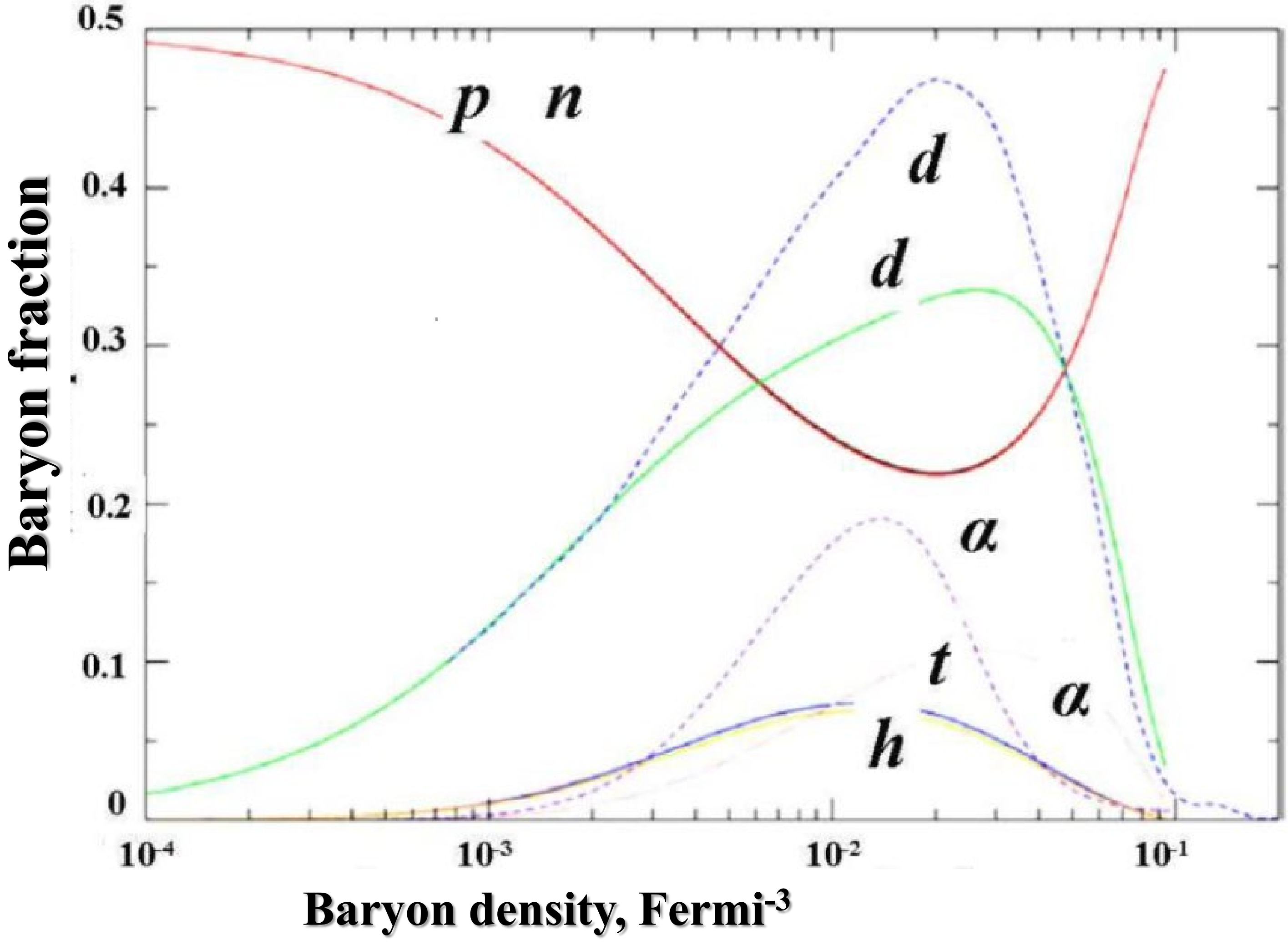


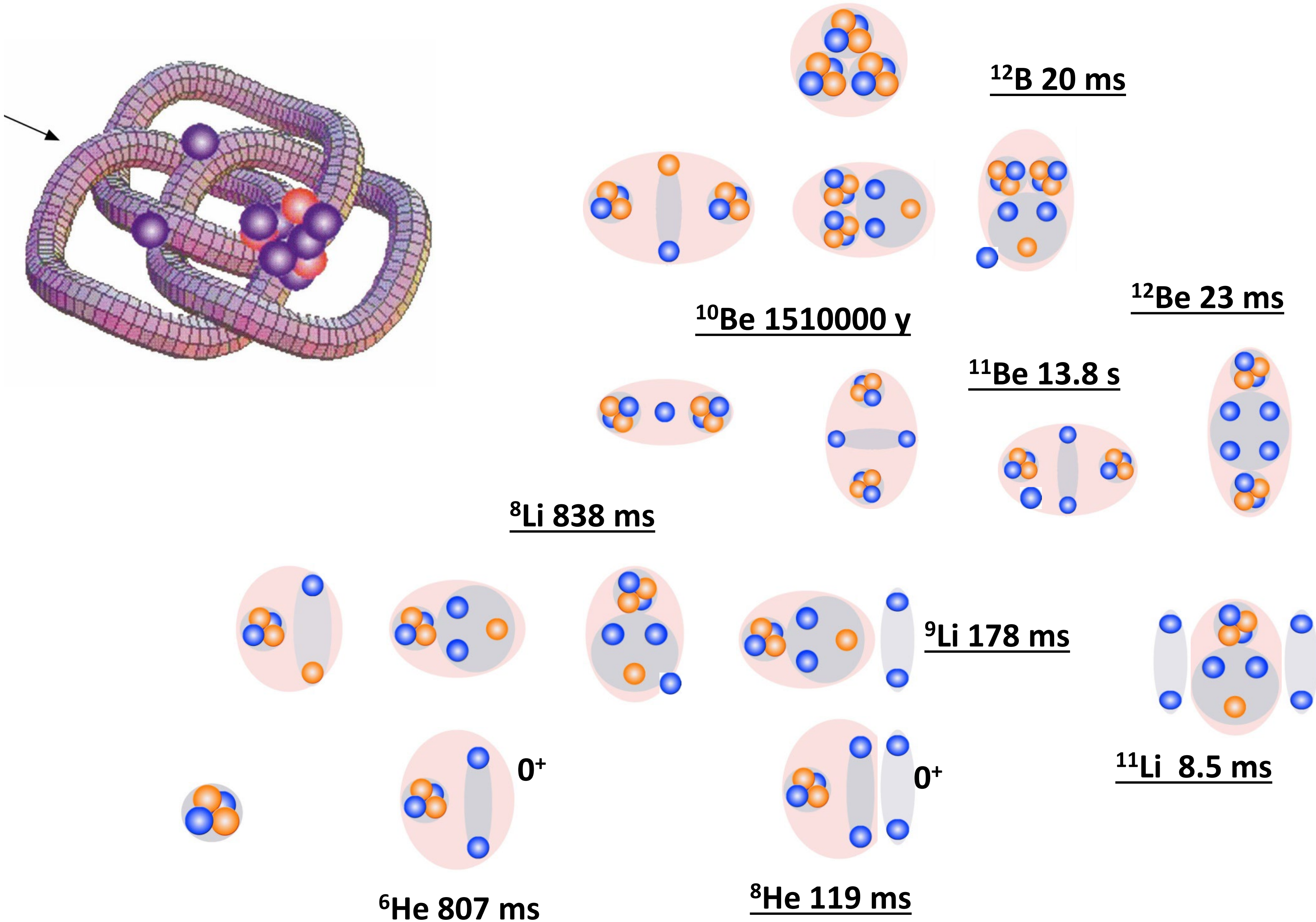
P_y, MeV/c


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

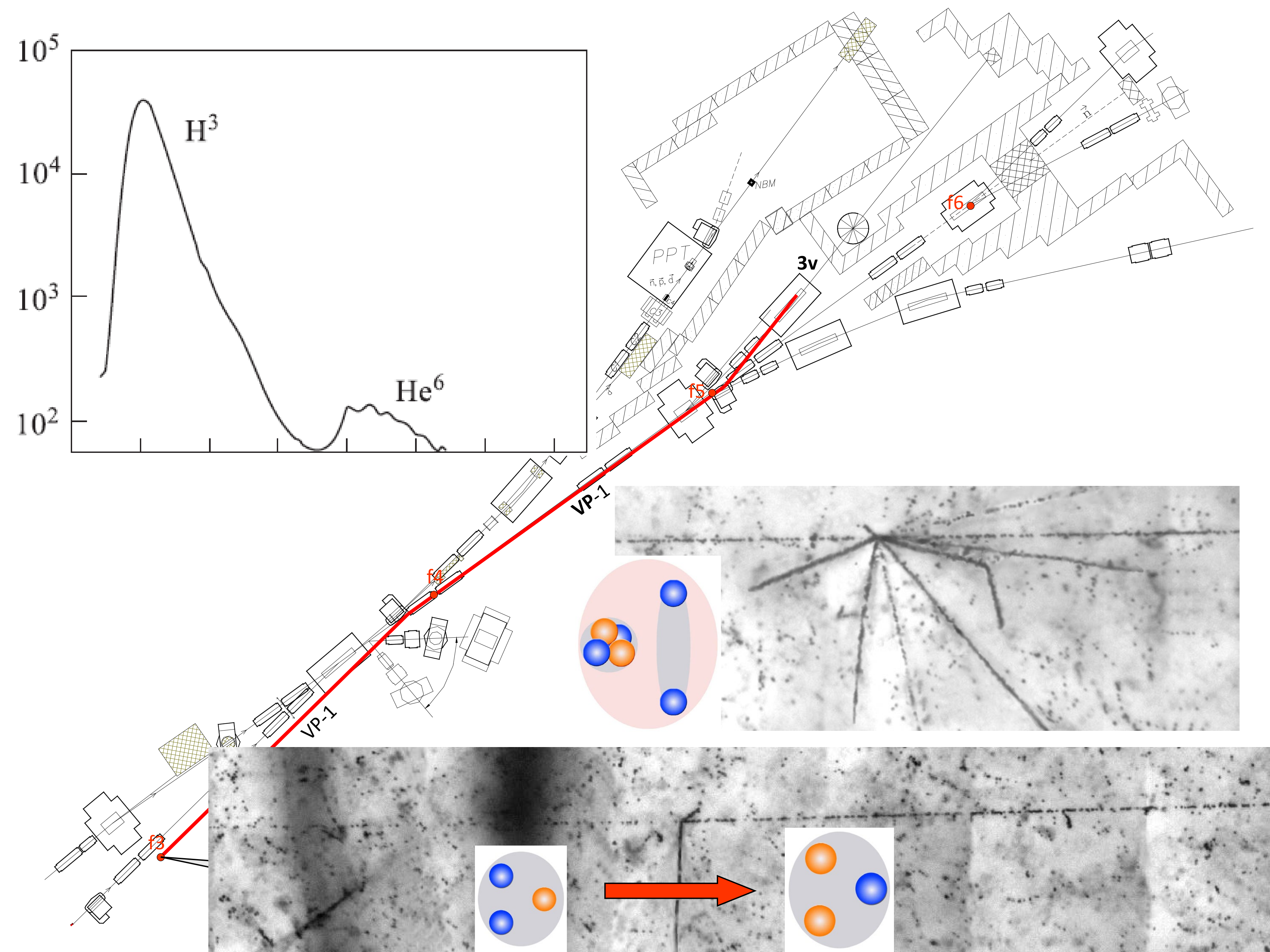


Nuclotron December 2022 ^{124}Xe 3.8 *A* GeV





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



10^5
10^4
10^3
10^2
H^3
He^6
PPT
NBM
3v
f6
f5
f4
f3
VP-1
VP-1

Conclusion

- **Productivity of the nuclear emulsion method in studies nuclear clustering and states of the lowest density and temperature is confirmed.**
- **Determination of the invariant masses from the fragment emission angles assuming conservation of momentum per nucleon of the parent nucleus allowed identifying the decays of ^{8}Be(0^{+}), ^{8}Be(2^{+}), ^{9}Be(1.7), ^{9}B, ^{6}Be, ^{12}C(0^{+}_{2}), and ^{12}C(3^{-}).**
- **The observations of ^{8}Be(0^{+}) and ^{12}C(0^{+}_{2}) points out that conditions of nuclear astrophysics can be reproduced in the relativistic fragmentation.**
- **Despite relativistic scale unstable states may emerge in final state interactions of lowest energy nuclear physics.**
- **Progress in microscope image analysis opens up new horizons to the method in nuclear structure studies.**
- **Such a development stays on foundations laid in cosmic ray physics more than seven decades ago.**
- **Recent review on the topic can be found here arXiv:2509.09636**