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Pavel Zarubin "Near-threshold states in dissociation of relativistic nuclei"

NATURAL SCIENCE REVIEW

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The ^{8}Be nucleus and the Hoyle state in dissociation of relativistic nuclei

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https://nsr.jinr.int/article/92/76

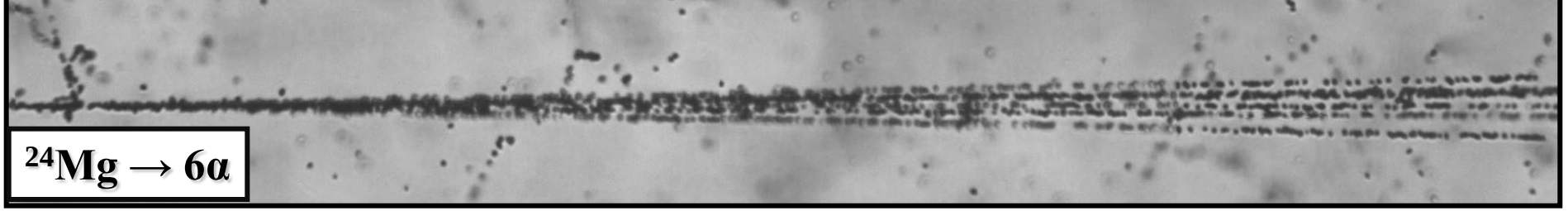


Hair - 60 μm

AgBr Crystal - 0.2 μm

Atom - 10^{-4} μm

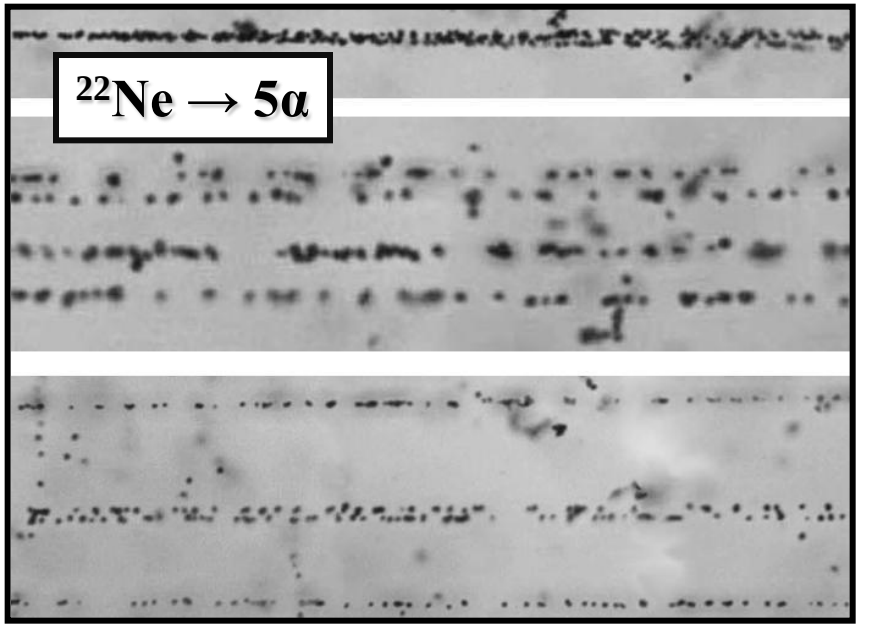
Proton - 10^{-9} μm

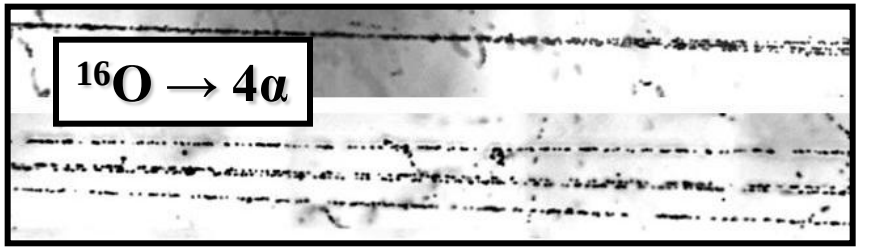


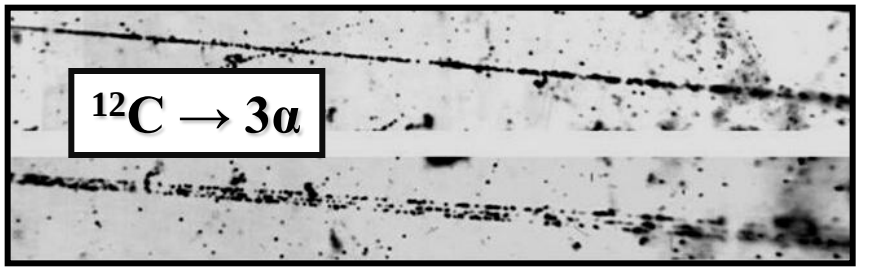
The fragmentation of relativistic nuclei observed in its entirety only in nuclear emulsion (NTE) serves as a source of ensembles of the lightest nuclei of interest to modern nuclear physics and nuclear astrophysics. NTE allows one to study such ensembles with record angular resolution and identification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

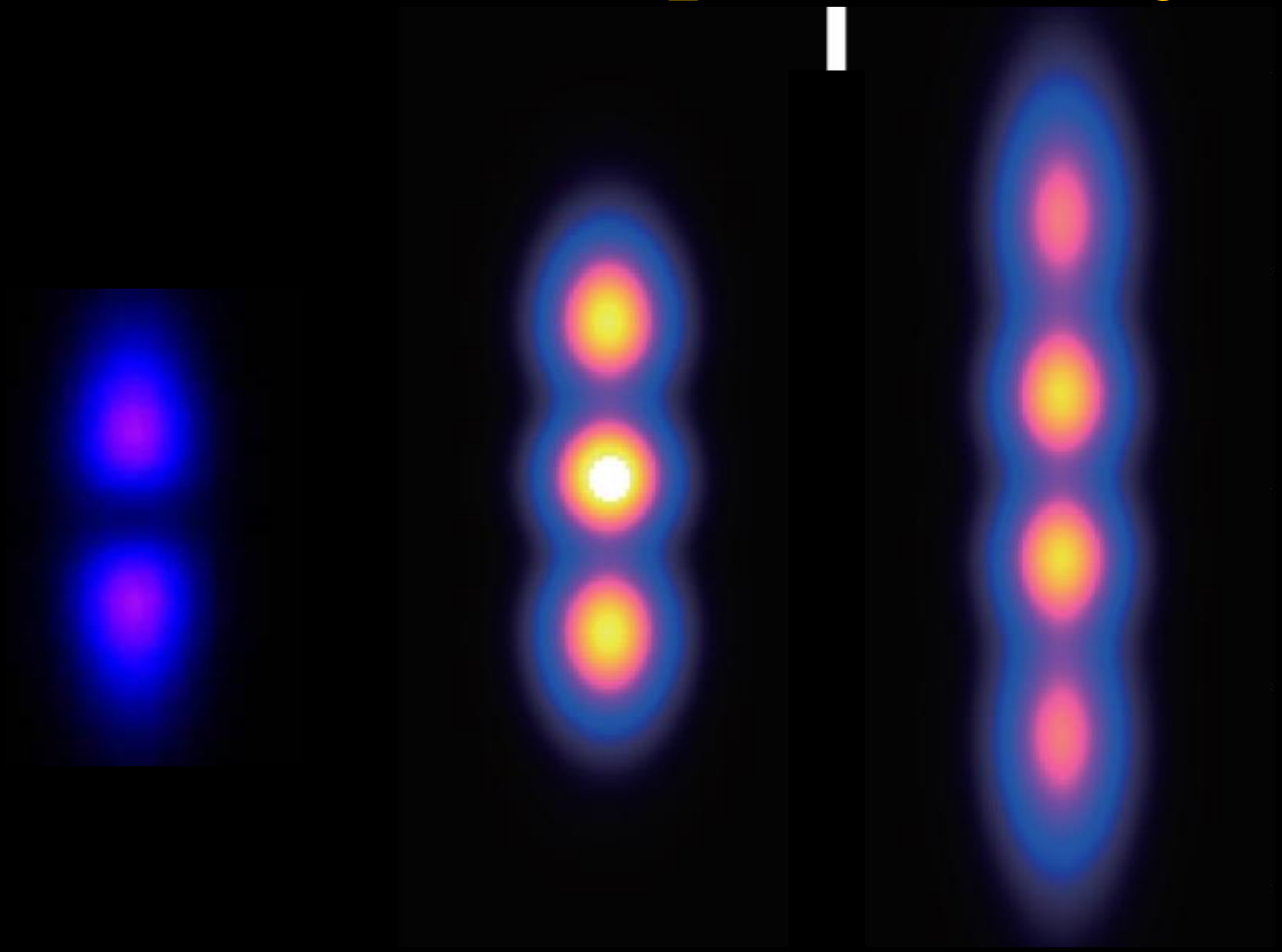
The intense "tracks" in the photos splits into the He track pairs with the opening angles of about $2 \cdot 10^{-3}$ rad corresponding to decays of the unstable ^{8}Be nucleus. Their observation testify to the completeness of observations across the spectrum of cluster excitations.



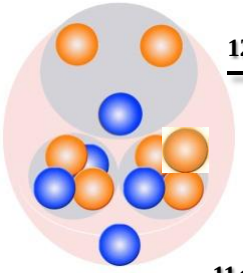




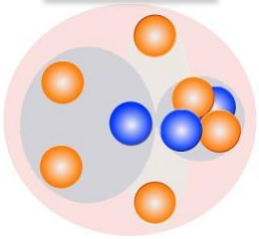
$^{8}Be(0^{+})$ $^{12}C(0^{+}_{2})$ $^{16}O(0^{+}_{6})$



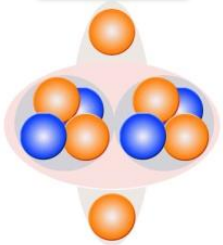
A current focus is on the concept of α-particle Bose-Einstein condensate (αBEC) – the S-wave α-particle state right above threshold. $^{8}Be(0^{+})$ is being described as 2αBEC, and the $^{12}C(0^{+}_{2})$ or Hoyle as 3αBEC. Suggested as 4αBEC $^{16}O(0^{+}_{6})$ at 660 keV can sequentially decay via $\alpha^{12}C(0^{+}_{2})$ or $2^{8}Be(0^{+})$.



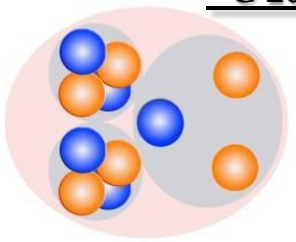
^{12}N 11.0 ms



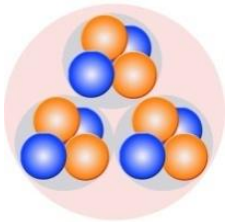
^{9}C 0.1265 s



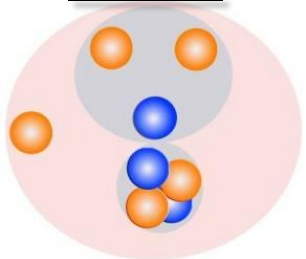
^{10}C 19.2 s



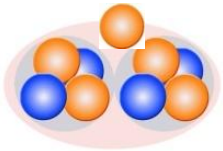
^{11}C 20.38 m



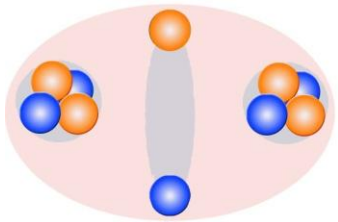
^{12}C 98.89 %



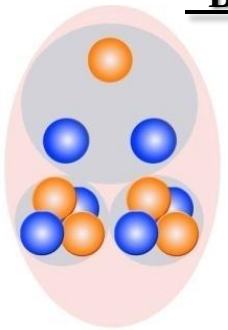
^{8}B 0.769 s



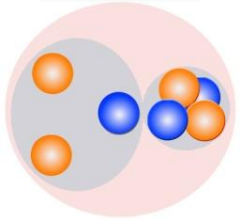
^{9}B 540 eV



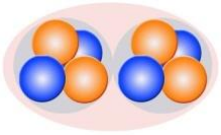
^{10}B 19.8%



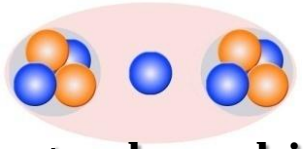
^{11}B 80.2 %



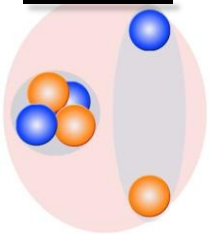
^{7}Be 53.3 d



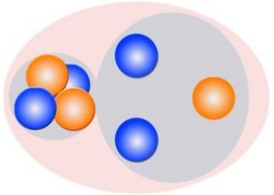
^{8}Be 6.8 eV



^{9}Be 100%



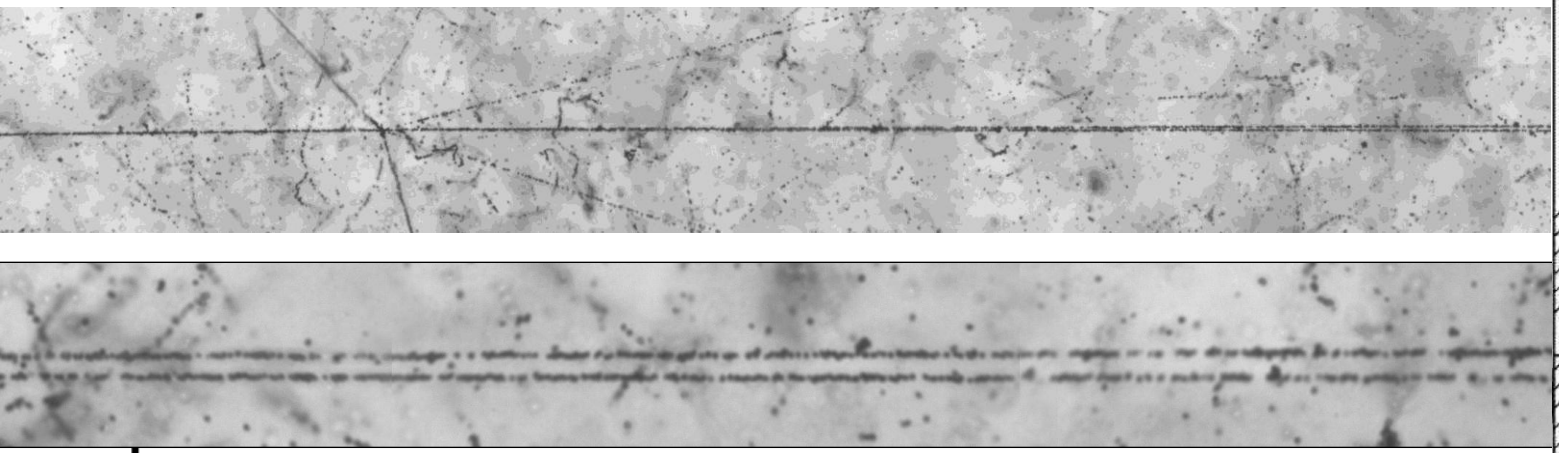
^{6}Li 7.5 %

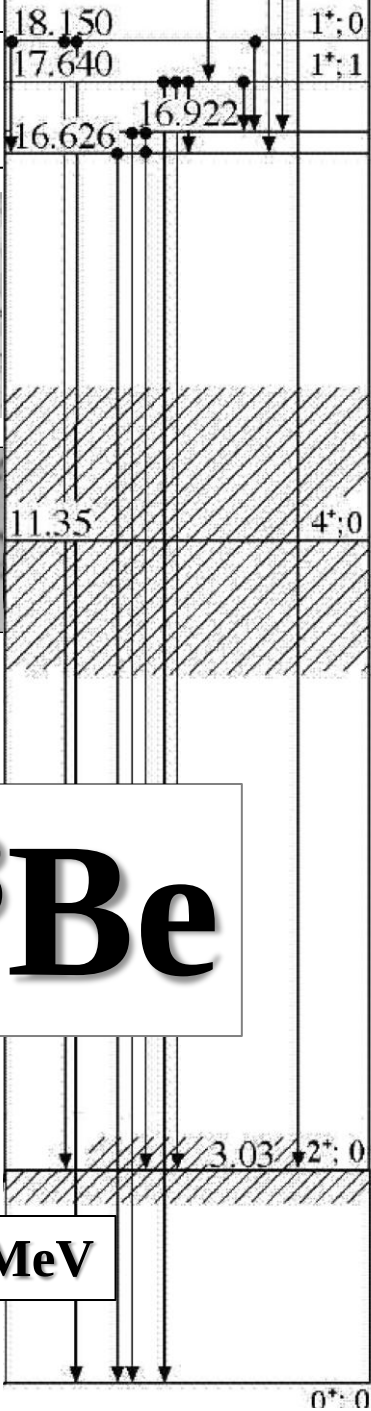


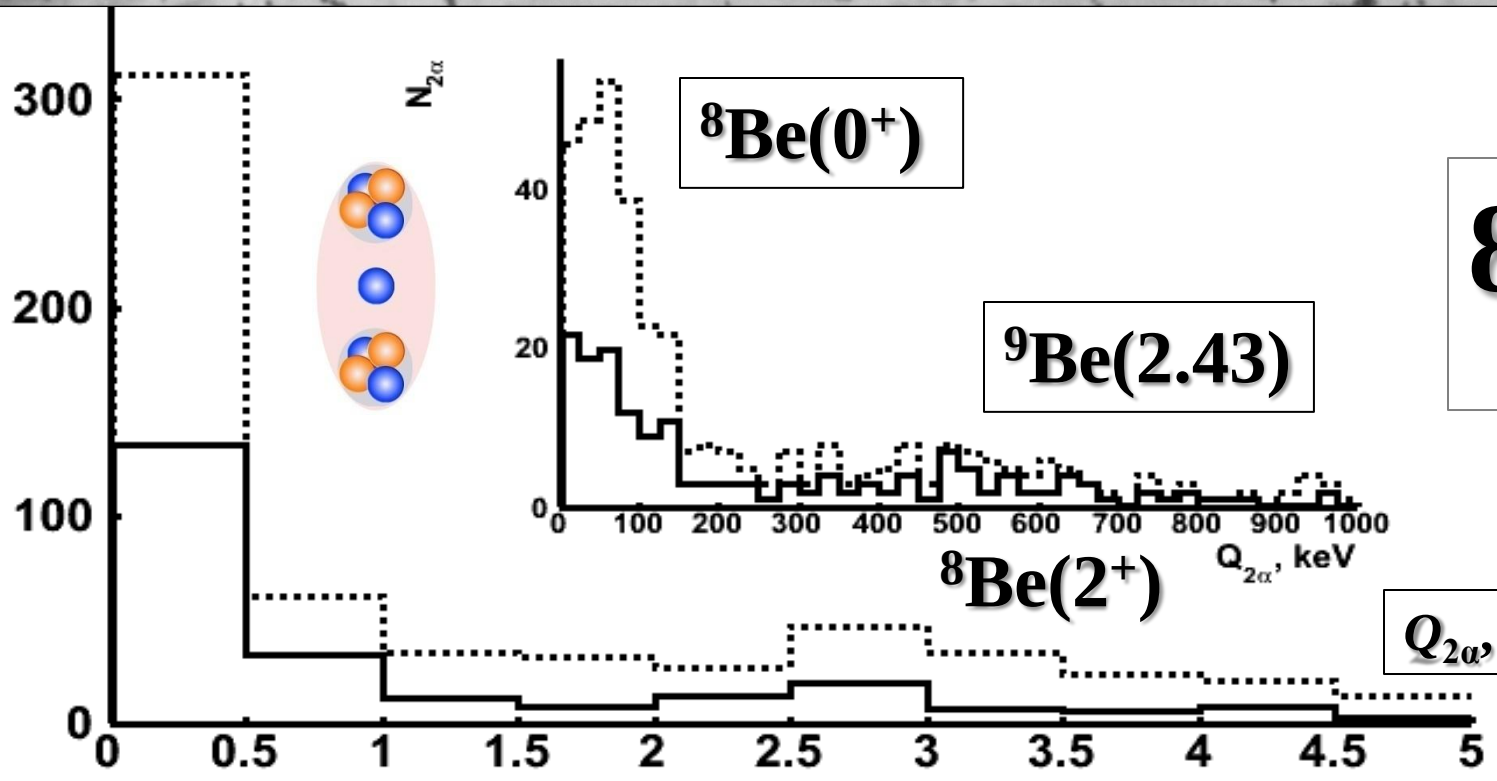
^{7}Li 92.5 %

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

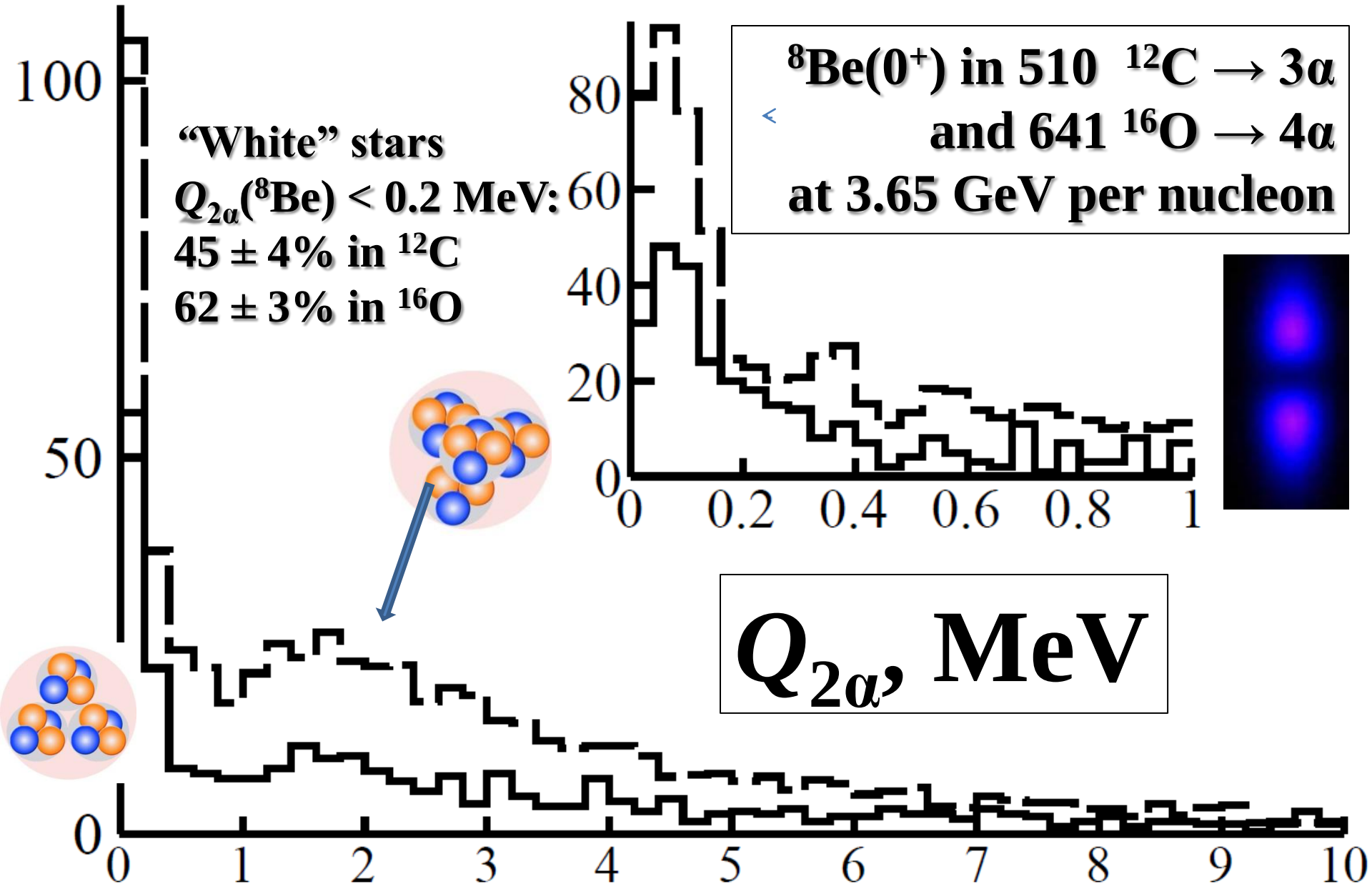
712 ^{9}Be → 2α at 1.2 GeV per nucleon





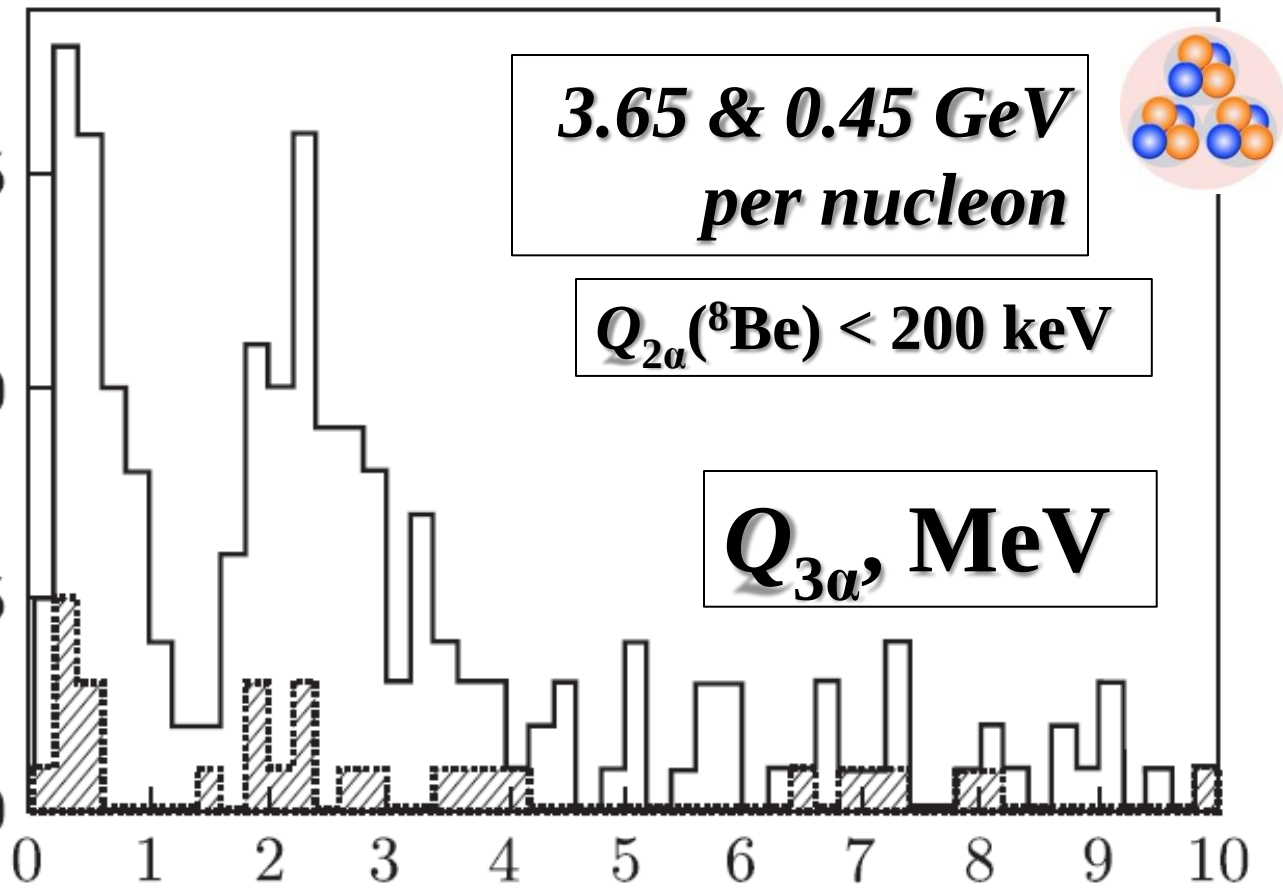


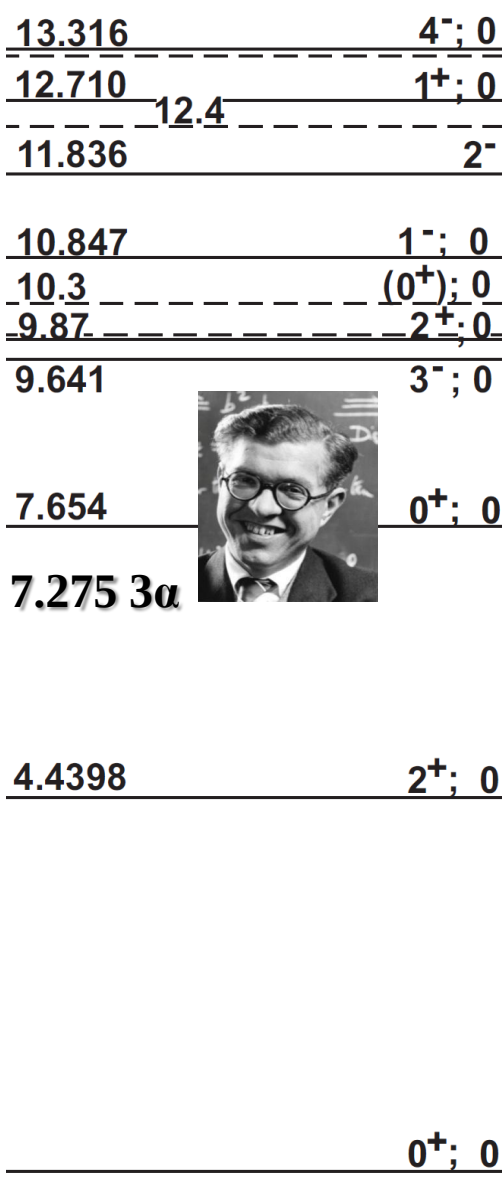
^{8}Be



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

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



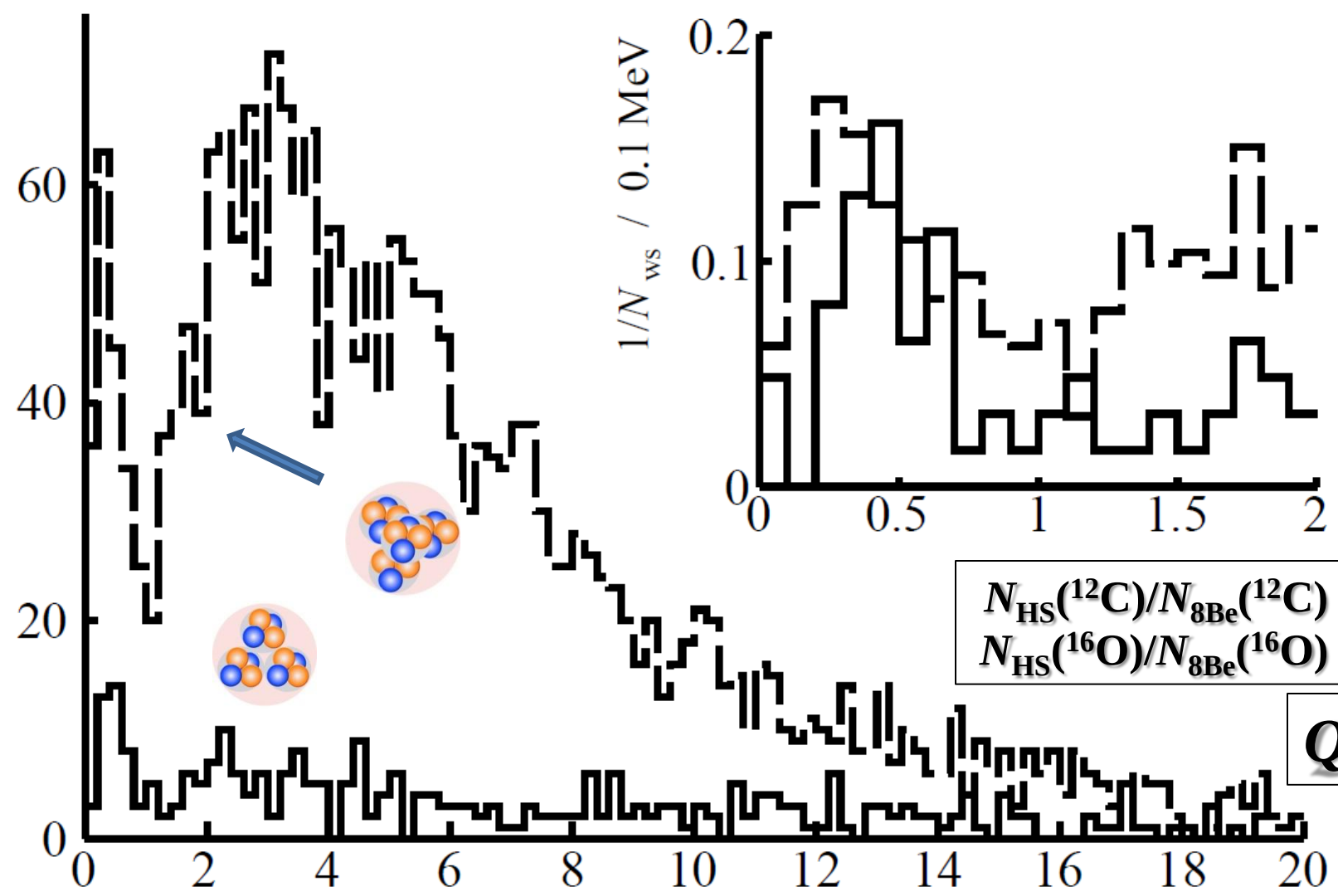


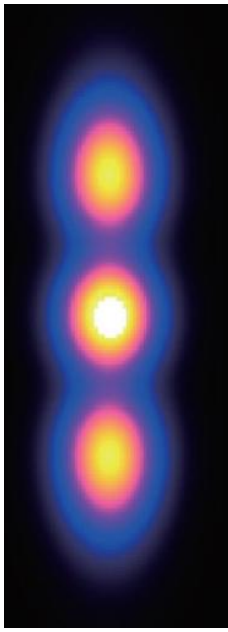
The 1st peak $\langle Q_{3\alpha} \rangle$ (RMS) = 417 ± 27 (165) keV is $^{12}C(0^+_2)$, and the 2nd σ ($Q_{3\alpha}$) = 2.4 ± 0.1 MeV – $^{12}C(3^-)$.

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 $^{16}O \rightarrow 4\alpha$



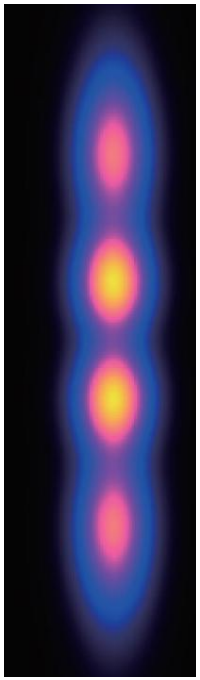


$N_{HS}(^{12}C)/N_{8Be}(^{12}C) = 0.36 \pm 0.06$
$N_{HS}(^{16}O)/N_{8Be}(^{16}O) = 0.35 \pm 0.04$

$Q_{3\alpha}$, MeV

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

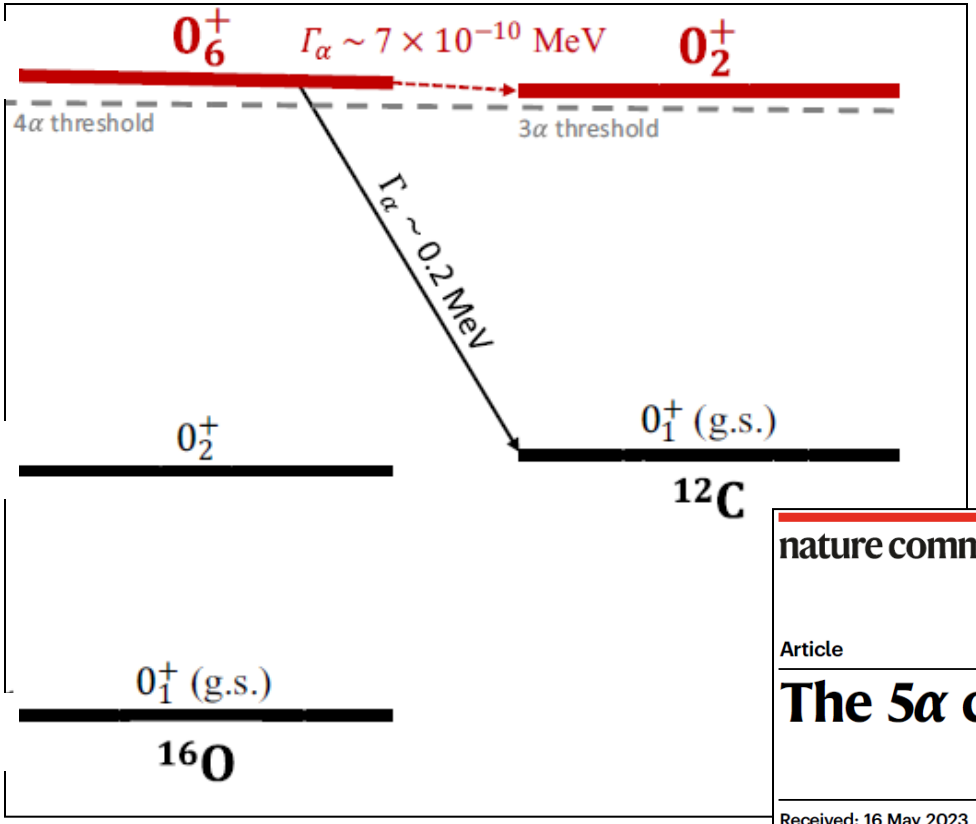
$^{16}O(0^+_6)$ in "white" stars $^{16}O \rightarrow 4\alpha$?

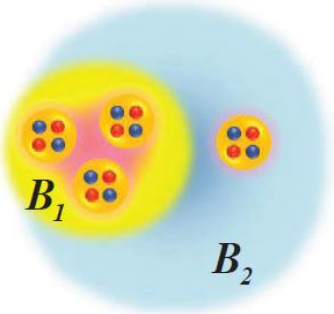


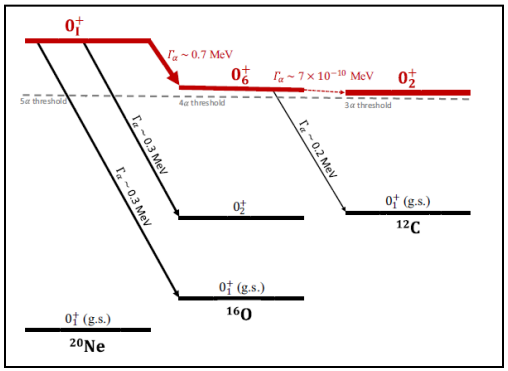
$Q_{4\alpha}$, MeV

15.095 keV Γ = 165 keV

Just 296 keV !







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Article

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The 5α condensate state in ^{20}Ne

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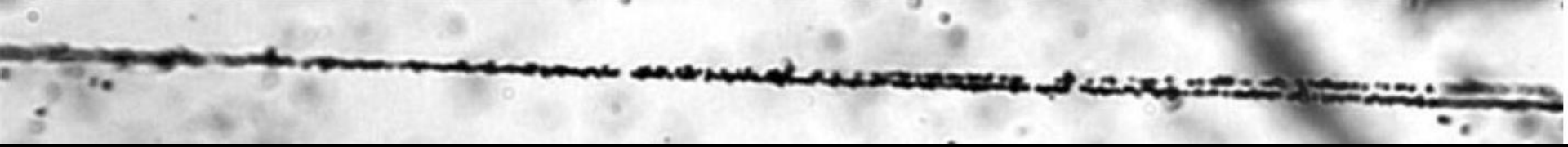
Bo Zhou[1,2] ✉, Yasuro Funaki[3] ✉, Hisashi Horiuchi[4], Yu-Gang Ma[1,2], Gerd Röpke[5], Peter Schuck[6], Akihiro Tohsaki[4] & Taiichi Yamada[3]

The formed ^{4}He (α) clusters consisting of two neutrons and two protons can be a building block in light nuclear systems. Intriguingly, these alpha clusters could potentially form alpha condensate states within the nuclear system. The Hoyle state at 7.65 MeV in ^{12}C, which plays an essential role in stellar nucleosynthesis, is now considered to be a phase transition, namely the 3α Bose-Einstein condensate. Confirming the existence of Hoyle-analog states in $N\alpha$ nuclei ($N > 3$) remains a major challenge. Here we show microscopic five-body calculations for the ^{20}Ne nucleus. We find that one excited 0^+ state has a distinct gas-like characteristic and represents the condensate state. Identifying the 5α condensate state is an important step in establishing the concept of α condensation in nuclear fermion systems.

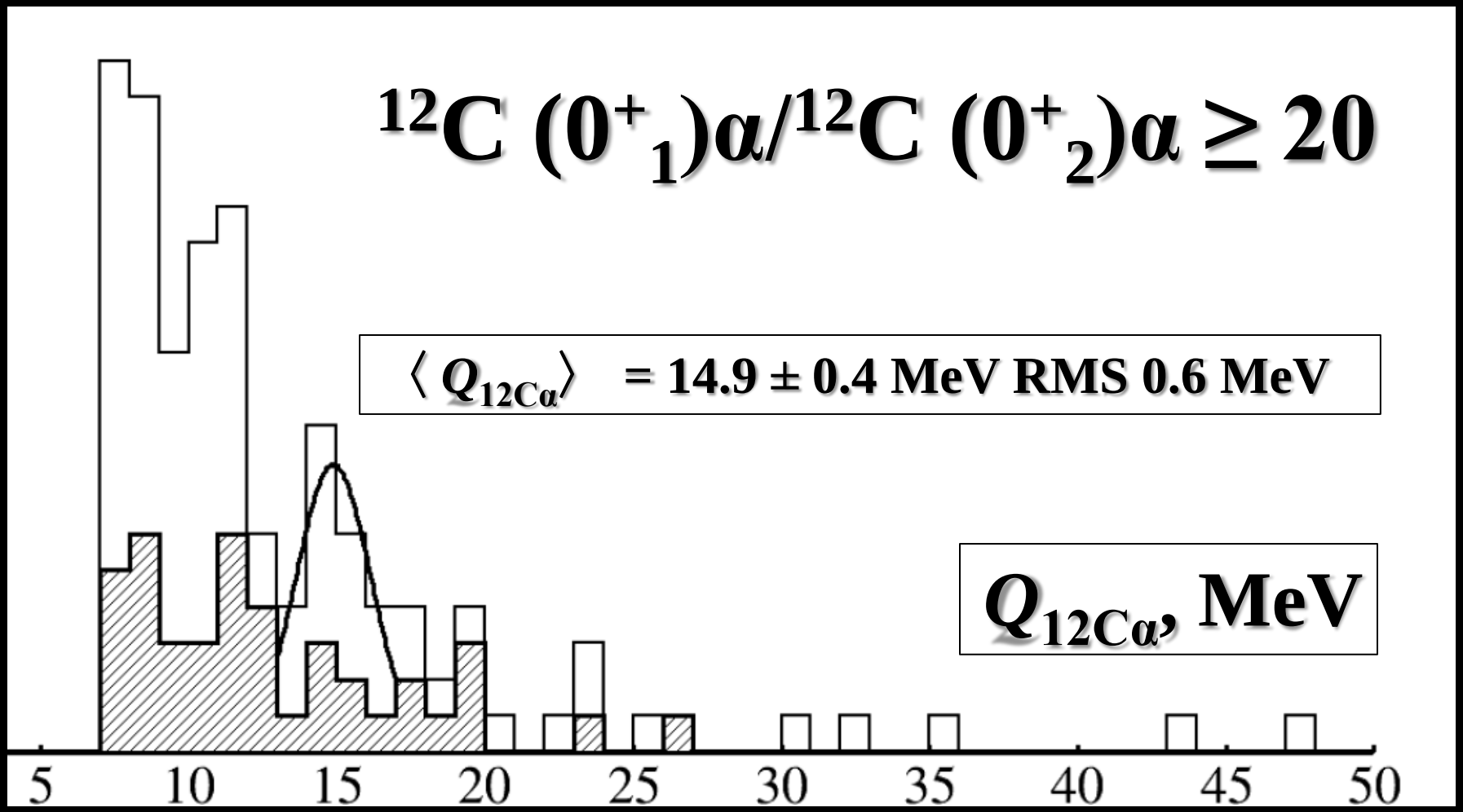
Charge topology of the fragments of the coherent dissociation of ^{16}O nuclei at 3.65 A GeV per nucleon

N+H	C+He	C+2H	B+3H	B+He+H	Be+He	Be+He+H	4He	3He+2H
18	21	7	2	10	1	1	9	3

^{16}O(0^+_6) at $Q_{4\alpha} \leq 1$ MeV was not observed in the ^{12}C(0^+_2)+α and ^{8}Be(0^+)+^{8}Be(0^+) channels. This conclusion is consistent with low-energy experiments. Such suppression can be explained by the extremely small energy difference between ^{16}O(0^+_6) and ^{12}C(0^+_2)+α, leading to the ^{16}O(0^+_6) width of only 10^{-9} MeV. The ^{16}O(0^+_6) structure in the container model allows the internal conversion of the ^{12}C(0^+_2) sub-unit to the ^{12}C(0^+_1) ground state with a width of 0.2 MeV. By allowing the ^{16}O(0^+_6) state to be considered as an excitation near the 4α threshold, this scenario motivated the search for binary decays ^{16}O(0^+_6) → ^{12}C(0^+_1) +α .



130 (19) pairs $^{16}O\ (0^+_6) \rightarrow {}^{12}C + \alpha$ at 3.65 *A* GeV including 42 (7) "white" stars



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THE EUROPEAN PHYSICAL JOURNAL A

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Review

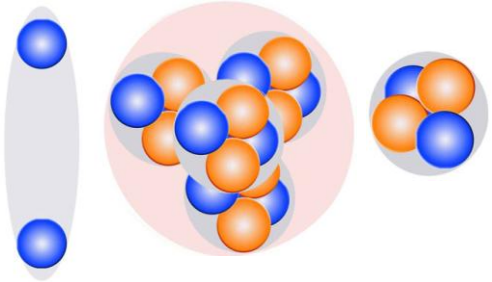
The ^{22}Ne(α,n)^{25}Mg reaction - state of the art, astrophysics, and perspectives

In massive stars, ^{22}Ne$(\alpha, n)^{25}$Mg is the main source of neutrons for the weak *s*-process, which is responsible for the production of elements with $60 < A < 90$. It is activated via α capture on the ^{14}N ashes of the CNO cycle that fueled the preceding hydrogen burning phase. This fuel material is rapidly converted by the reaction sequence ^{14}N$(\alpha, \gamma)^{18}$F$(\beta^{+}\nu)^{18}$O$(\alpha, \gamma)^{22}$Ne, during the end of core He

^{14}N (99.7%) **^{18}F 110 min.**

^{17}O (0.04%) **^{18}O (0.21%)**

^{20}Ne (90.48%) **^{21}Ne (0.27%)** **^{22}Ne (9.25%)**

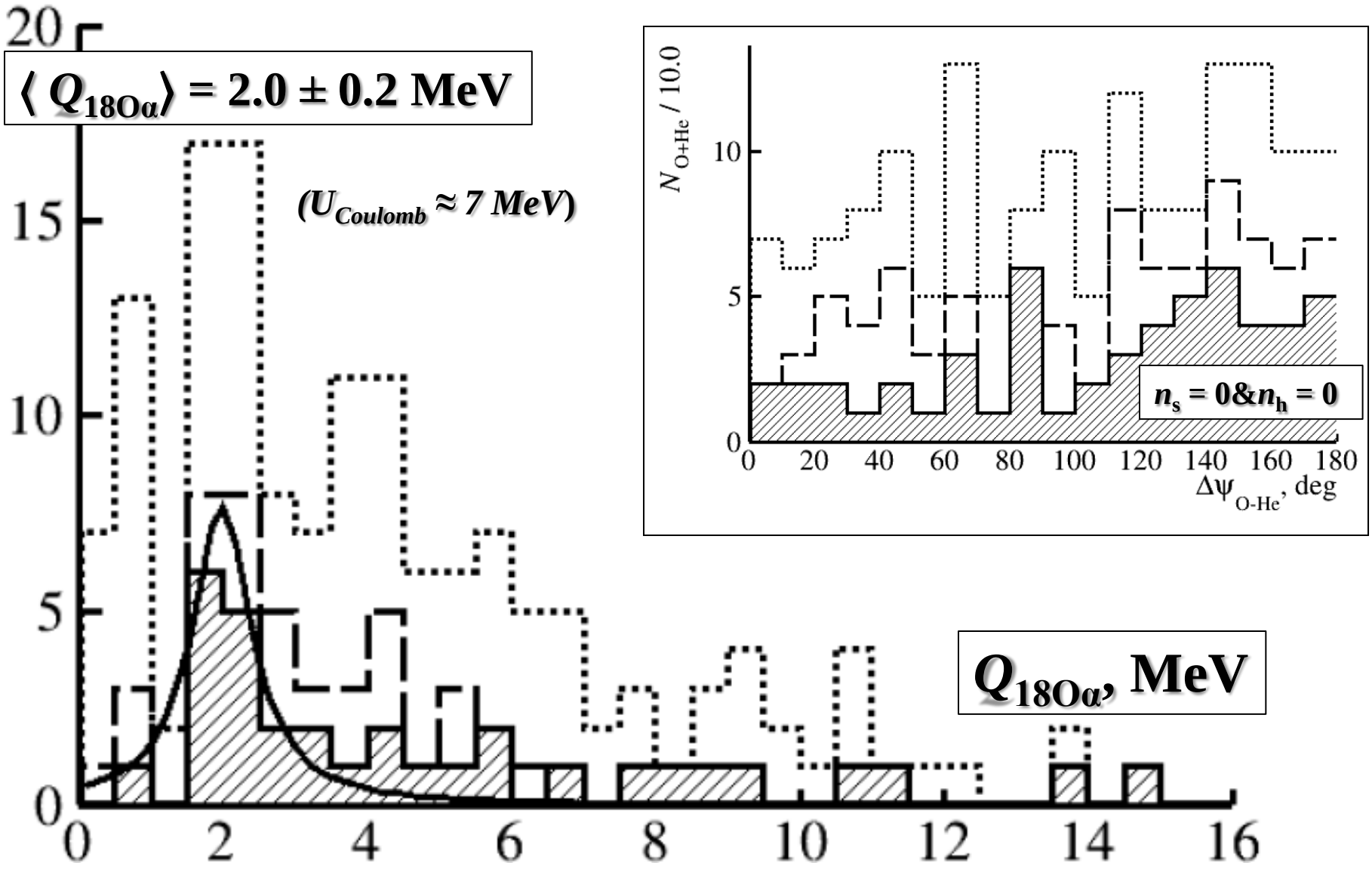


The preserved measurements of 4307 stars produced in NE by ^{22}Ne nuclei at 3.22 GeV per nucleon allow uscontinue the search for near-threshold resonances to in heavy fragment and α-particle pairs. Among them, the charge 10 was transferred to relativistic fragments in 855 stars, including 121 "white" stars (17%). The leading ones are 158 pairs O + He, including 54 "white" stars (34%).

Initially, this feature was attributed to splitting into a pair of doubly magic nuclei ^{16}O + ^{4}He + (2*n*). However, the breakup threshold of ^{22}Ne into ^{18}Oα, equal to 9.7 MeV, is noticeably lower than those for $^{16}O_{\alpha 2n}$ (16.5 MeV), $^{17}O_{\alpha n}$ (17.7 MeV) and ^{16}O^{6}He (20.9 MeV). Its value indicates a strong binding of the neutron pair to the ^{16}O core and the possibility of the formation of ^{18}Oα resonance.

O+He 54 (40.6%)

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+H	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+3H	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)	–	–	–



Distribution of O + He pairs from the dissociation of ^{22}Ne nuclei at 3.22 GeV per nucleon over the invariant mass $Q_{18O\alpha}$ (dots), "white" stars (dashed line) and "white" stars (hatched line) with the condition $\Delta\psi_{O\alpha} > 100^{\circ}$.

CONCLUSIONS

The invariant mass distribution of $^{12}C+\alpha$ pairs produced in the dissociation of ^{16}O confirms the hypothesis of decay of the $^{16}O(0^+_6)$ state via conversion of its $^{12}C(0^+_2)$ substructure to $^{12}C(0^+_1)$. This opens up the possibility of synthesizing the isotope ^{12}C without a radiative transition, as a supplement to the known 3α-process.

The invariant mass distribution of $^{18}O\alpha$ pairs in the dissociation of ^{22}Ne exhibits a peak with a mean value of about 11.6 MeV. This energy corresponds to the sub-barrier $^{18}O + \alpha$ fusion region and provides further evidence for the feasibility of nucleosynthesis reactions in the fragmentation cone of relativistic nuclei.

The search for near-threshold resonances deserves to be continued in the dissociation of $^{18}O \rightarrow {}^{14}C + \alpha$ and $^{14}C \rightarrow {}^{10}Be + \alpha$. The choice of several GeV per nucleon in the context of nuclear clustering is determined by historical reasons. Longwise NE exposures should be performed in the region of several hundred MeV per nucleon where achieving beam profile uniformity and isotope separation is easier.





Trento 2019





Nuclotron December 2022

^{124}Xe 3.8 GeV per nucleon



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Physics Letters B 820 (2021) 136460

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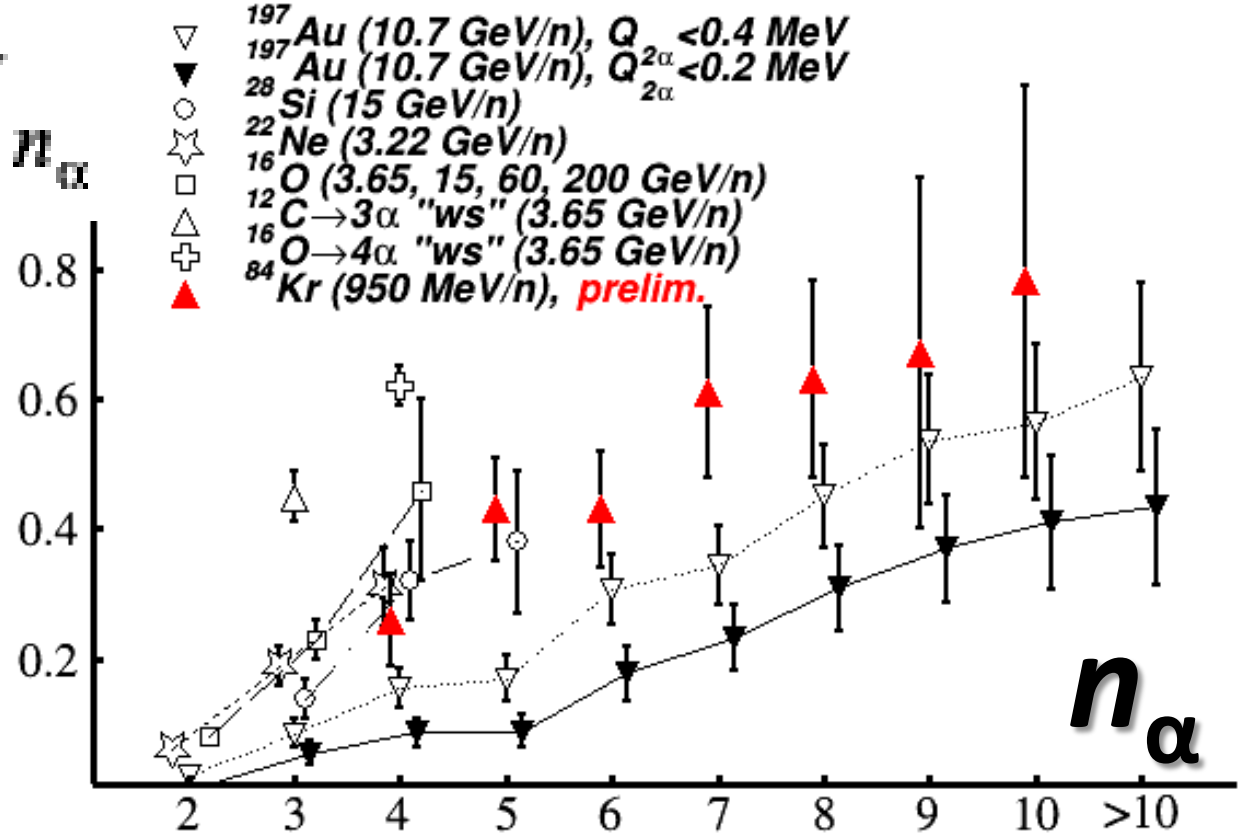
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Correlation in formation of ^{8}Be nuclei and α-particles in fragmentation of relativistic nuclei

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$$N_{n_\alpha}(^{8}\mathrm{Be}) \,/\, N_{n_\alpha}$$





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 $^8Be(0^+)$.