Alpha-particle states in relativistic nuclear fragmentation

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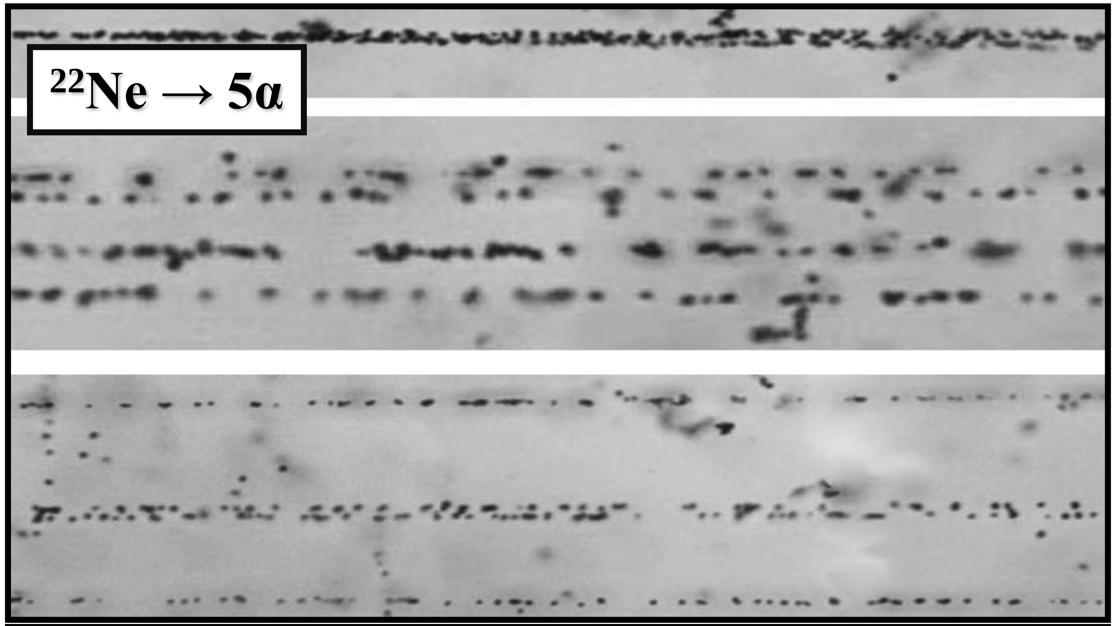
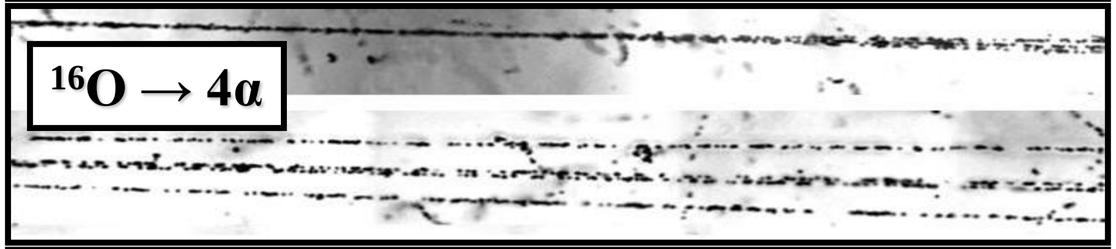
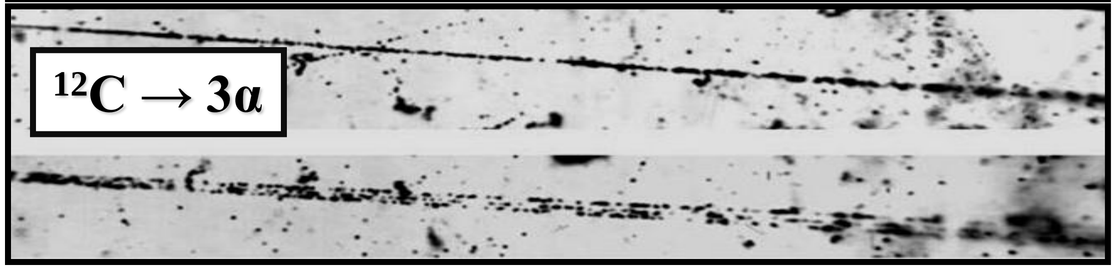
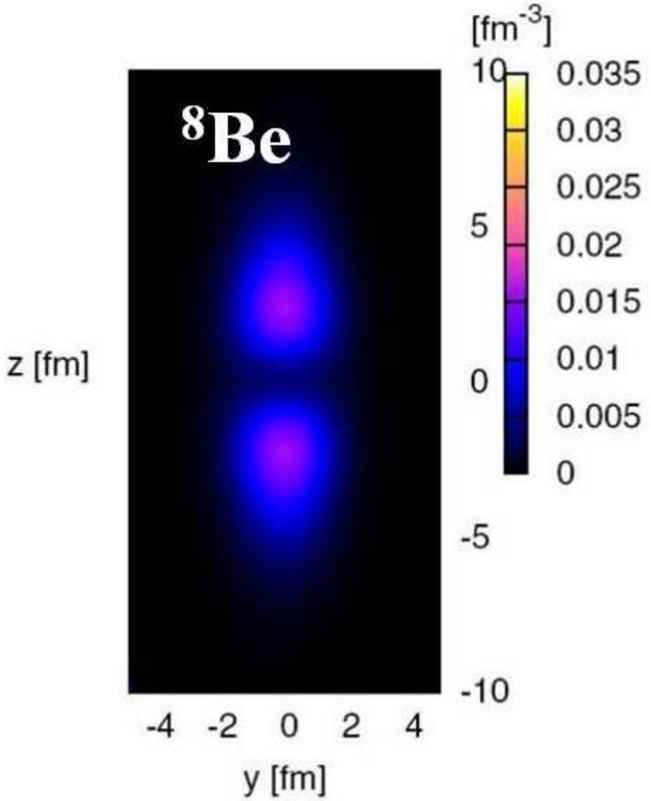
Events of peripheral dissociation, reflecting the individual characteristics of incident nuclei, are observed in nuclear emulsions as often and completely as in central impacts. They indicate the fundamental opportunity of studying the nuclear structure in the cone of relativistic fragmentation. However, in this aspect, the use of traditional magnetic spectrometers with coordinate and scintillation detectors turned out to be very limited. The difficulties have appeared due to the dramatic difference in the ionization of the beam nuclei and relativistic fragments with their extremely small angular divergence, which often approximately coincide in magnetic rigidity. For these reasons, the measurements were carried out registering relativistic fragments in the charge as close as possible to the nucleus under study.

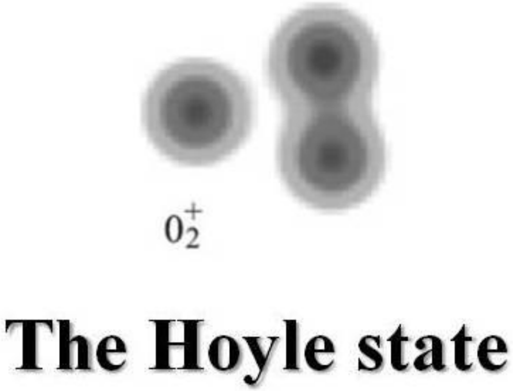


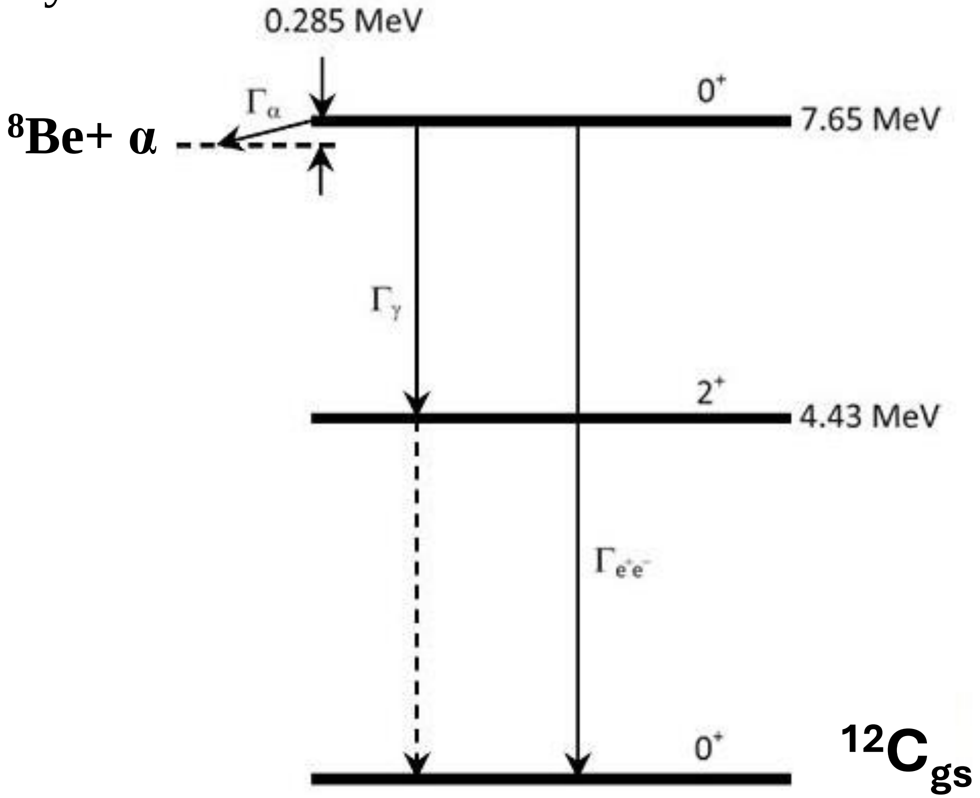




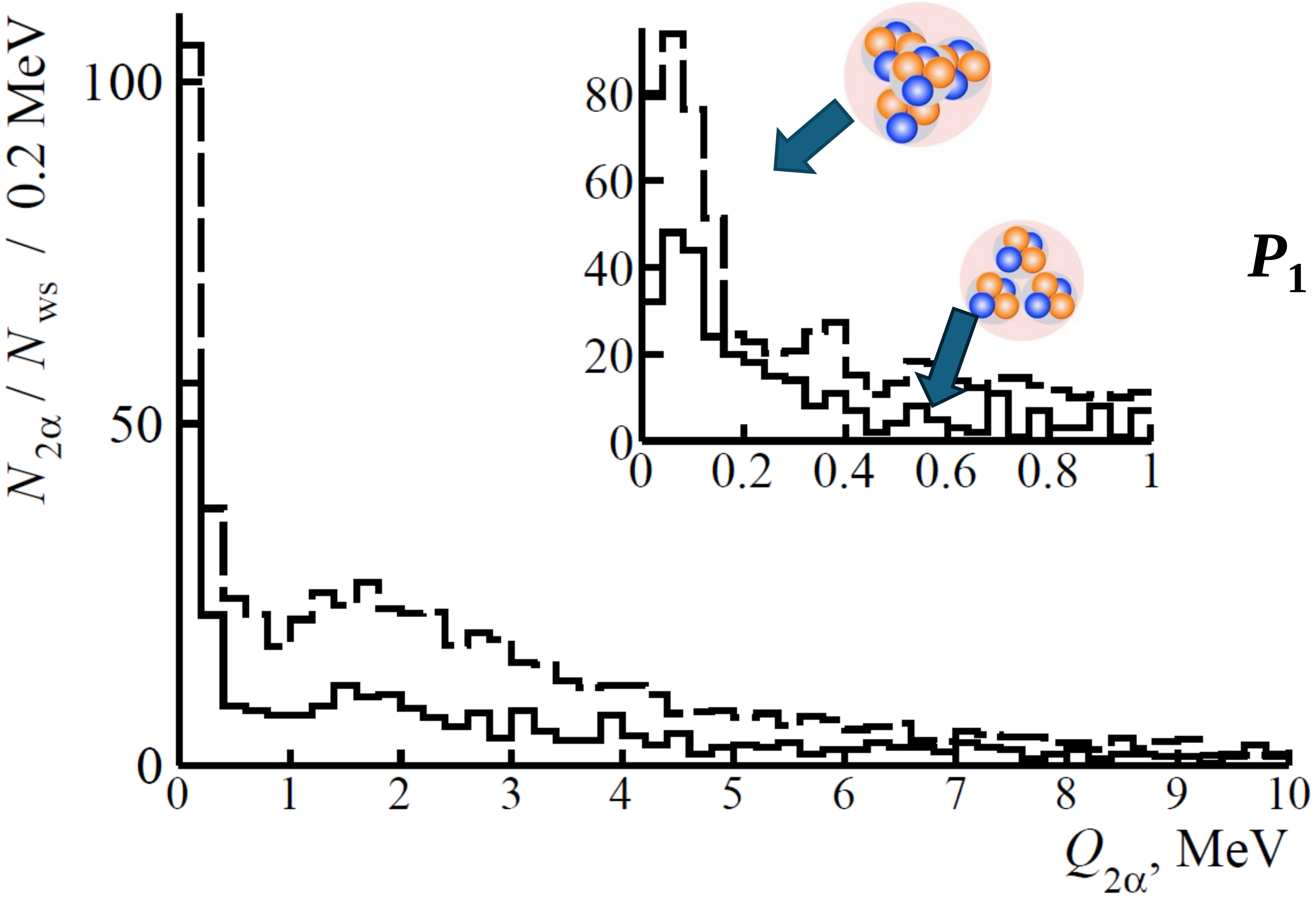
The Hoyle state is the second excited state of ^{12}C at **378 keV** above the 3α threshold. The ^{8}Be nucleus inevitably appears among the products of ^{9}B and Hoyle state decays.







The isolated position of the Hoyle state at the beginning of the ^{12}C excitation spectrum and the width of 9.3 eV, corresponds to its 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 →^{12}C(0^+_2) →^{12}C (+2γ or e^+e^- with the probability of about 10^{-4}). The further synthesis via the fusion reaction α^{12}C →^{16}Oγ over the ^{16}O level at the appropriate energy is forbidden on the parity. This is the circumstance which 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.



$P_1 \approx P_0$

$$P_x = P_0 \cdot A \cdot cos(\alpha)cos(\phi)$$

$$P_y = P_0 \cdot A \cdot cos(\alpha)sin(\phi)$$

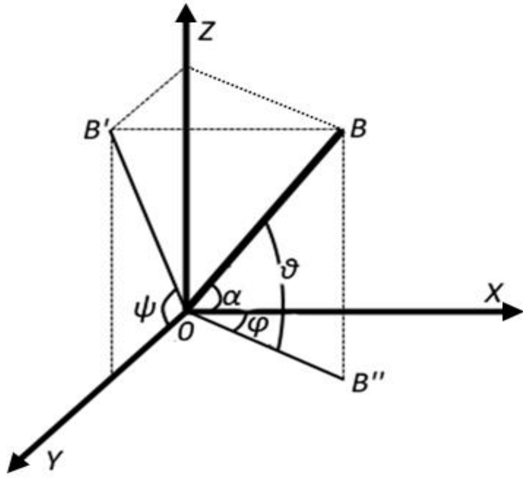
$$P_z = P_0 \cdot A \cdot sin(\alpha)$$

$$E_1 = \sqrt{P_0^2 \cdot A^2 + m_1^2}$$

$$\Theta_{12} = \frac{P_{x1} \cdot P_{x2} + P_{y1} \cdot P_{y2} + P_{z1} \cdot P_{z2}}{P_1 \cdot P_2}$$

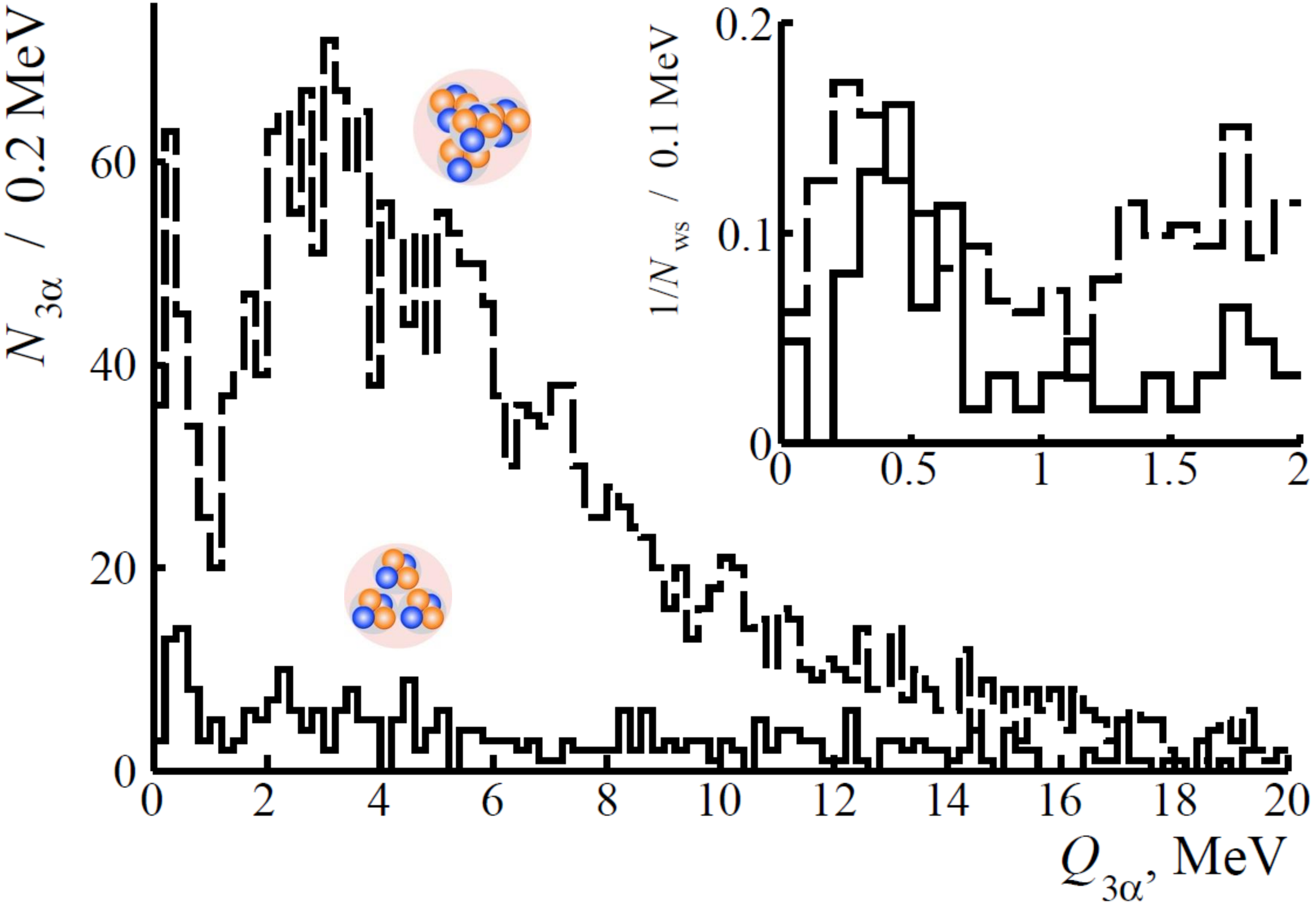
$$\mathfrak{M} = \sqrt{\left(\sum_{i=1}^{n} E_i\right)^2 - \left(\sum_{i=1}^{n} p_i\right)^2}$$

$$Q = \mathfrak{M} - \sum_{i=1}^{n} m_i$$



Selected under the cleanest conditions, the criterion $Q_{2\alpha}$(^{8}Be) < 0.2 MeV includes the accepted approximations, the kinematic ellipse of the ^{8}Be decay, and the resolution of angular measurements. Its application has allowed us to determine the ^{8}Be contribution to the statistics of "white" stars equal to **45 ± 4%** for ^{12}C → 3α and **62 ± 3%** for ^{16}O → 4α.

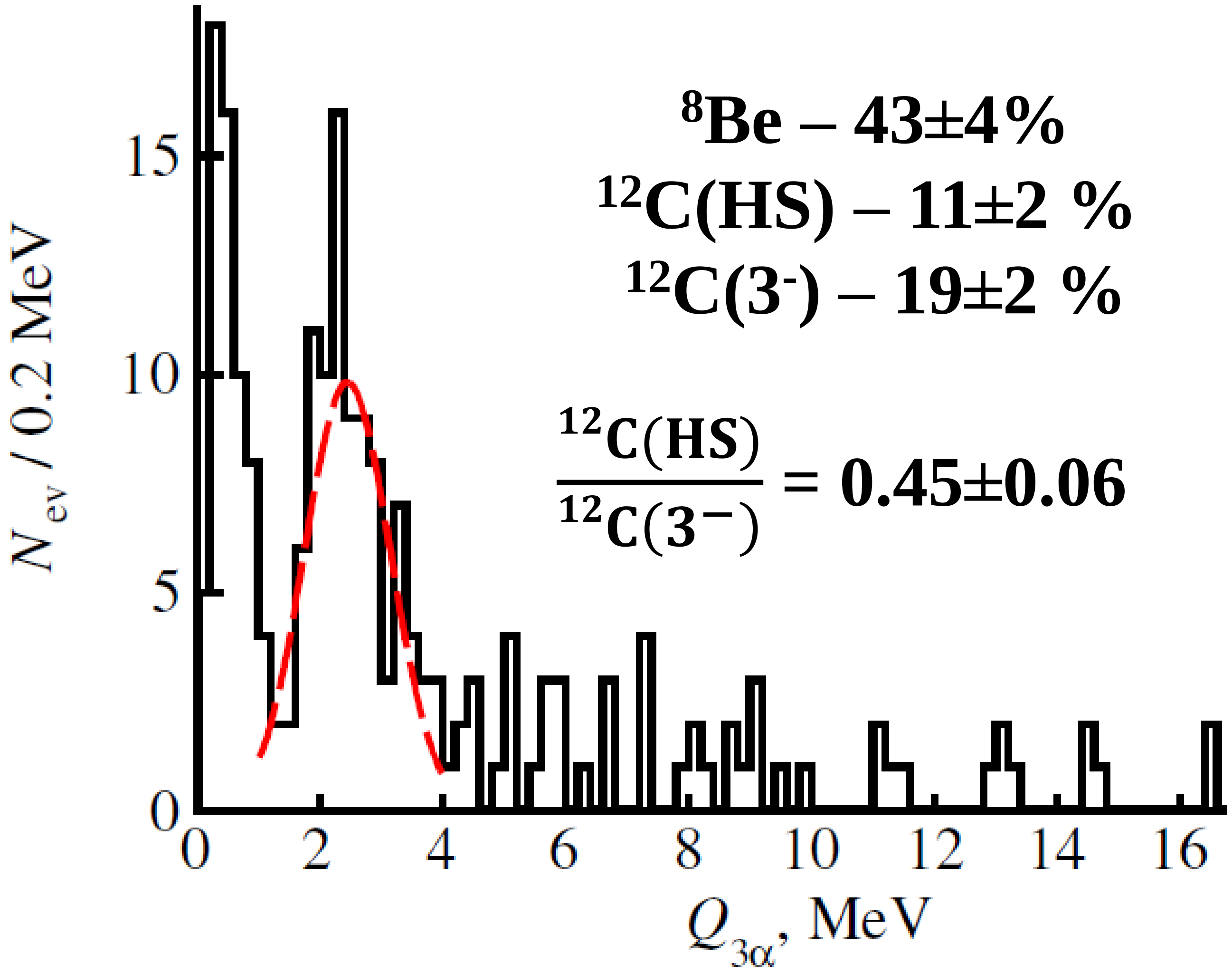
Distribution of the number of 3α-triples $N_{3\alpha}$ over the invariant mass $Q_{3\alpha}$ of 316 "white" stars $^{12}C \to 3\alpha$ (solid) and 641 "white" stars $^{16}O \to 4\alpha$ (dashed) at 3.65 *A* GeV; inset: the enlarged view of distributions in the region of $Q_{3\alpha}$ < 2 MeV, is normalized to the number of "white" N_{ws} stars in the both cases.



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

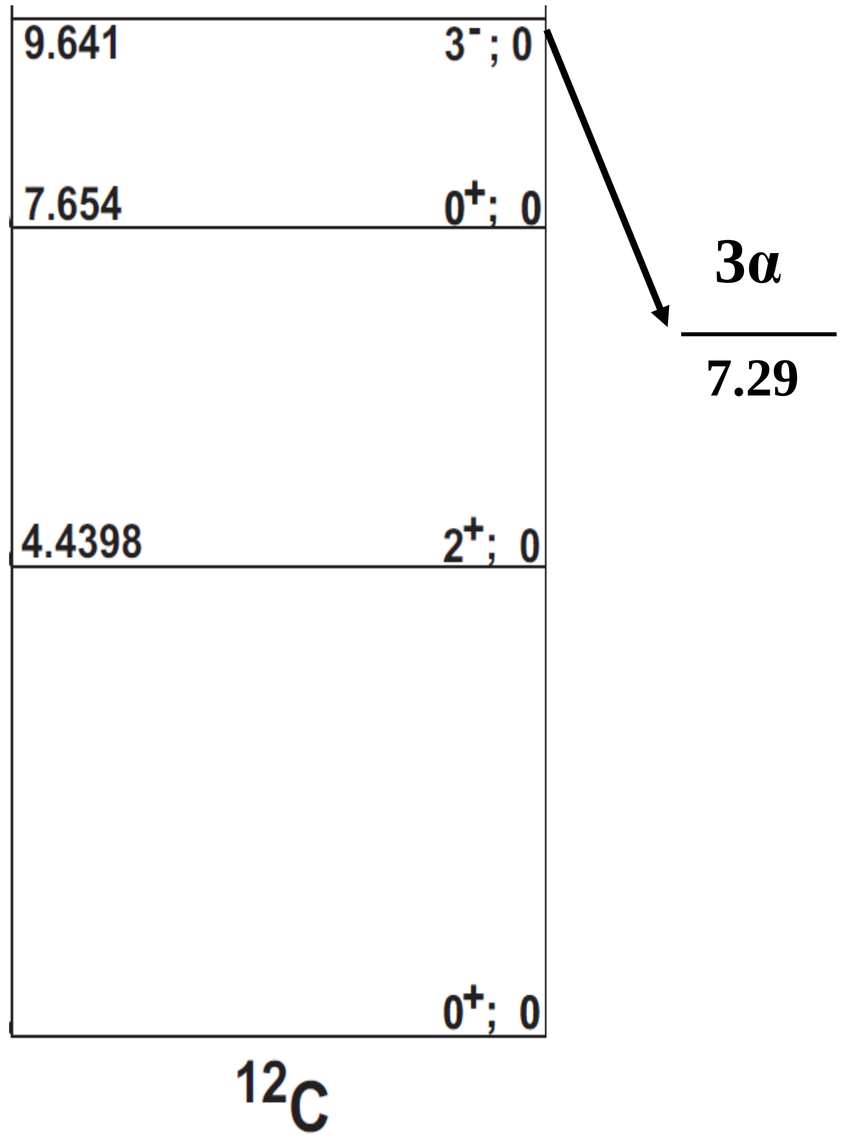
$$N_{HS}(^{16}O)/N_{8Be}(^{16}O) = 0.35 \pm 0.04$$

^{12}C (3^-) state in ^{12}C dissociation



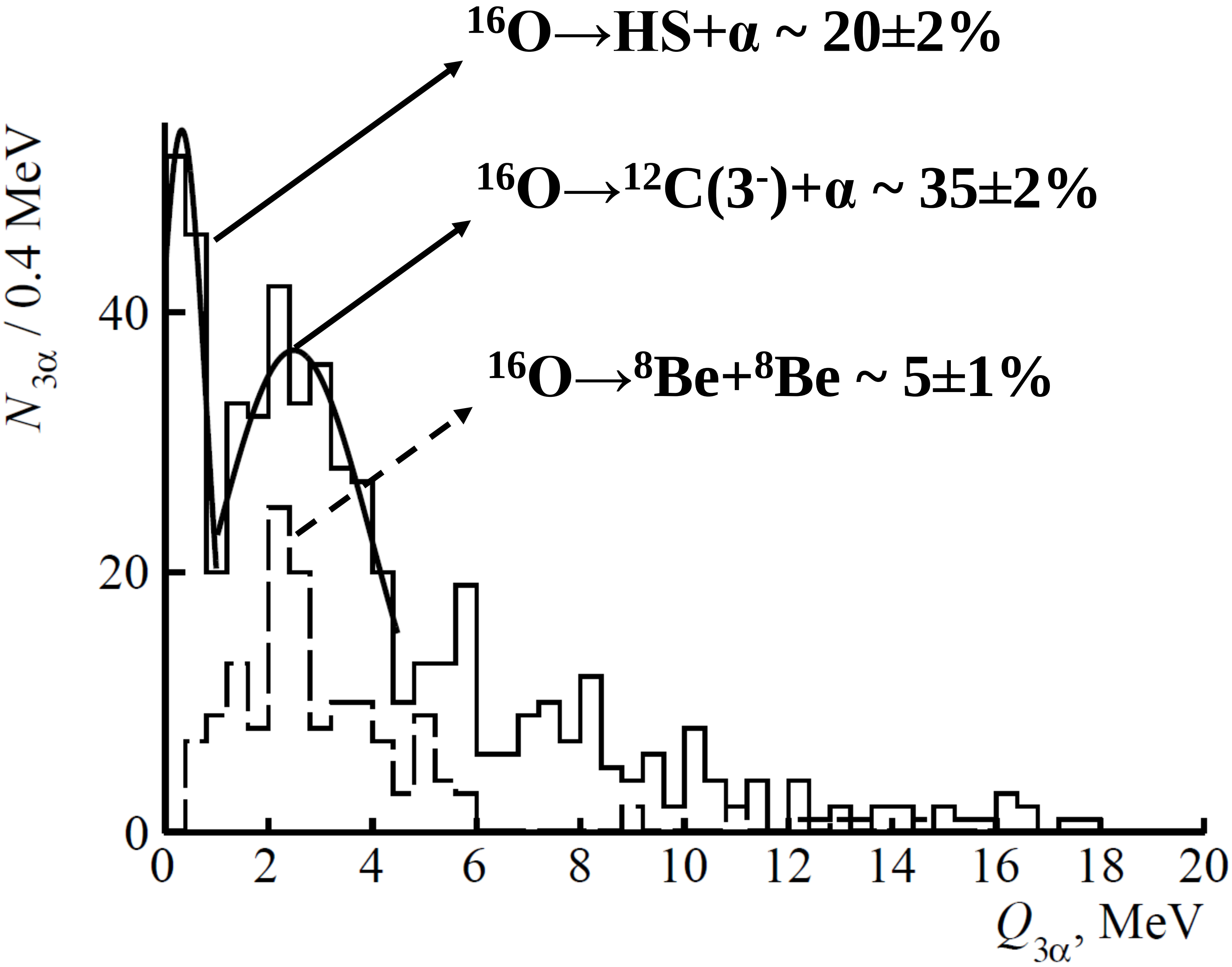
^{8}Be – 43±4%
^{12}C(HS) – 11±2 %
^{12}C(3^-) – 19±2 %

$$\frac{^{12}C(HS)}{^{12}C(3^-)} = 0.45 \pm 0.06$$



Distribution over invariant masses $Q_{3\alpha}$ of triplets of α-particles in dissociation ^{12}C → 3α at 4.5 GeV/*c* per nucleon under condition $Q_{2\alpha}$(^{8}Be) < 200 keV; the curve approximates ^{12}C (3^-) by Gaussian.

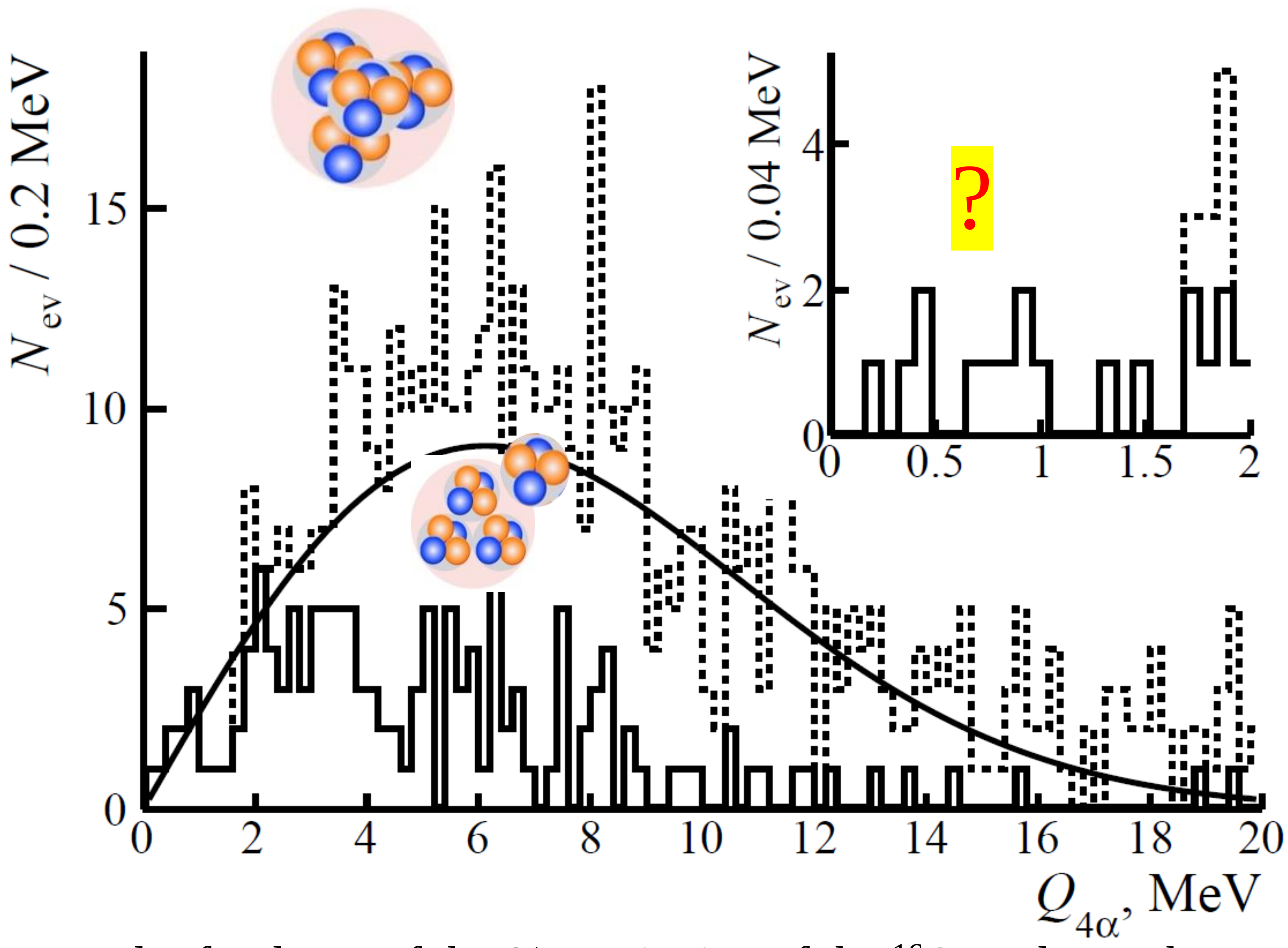
The HS and $^{12}C(3^-)$ states in relativistic $^{16}O \to 4\alpha$ dissociation



$$\frac{\mathbf{HS}}{^{12}\mathbf{C}(3^-)} = \mathbf{0.58 \pm 0.07}$$

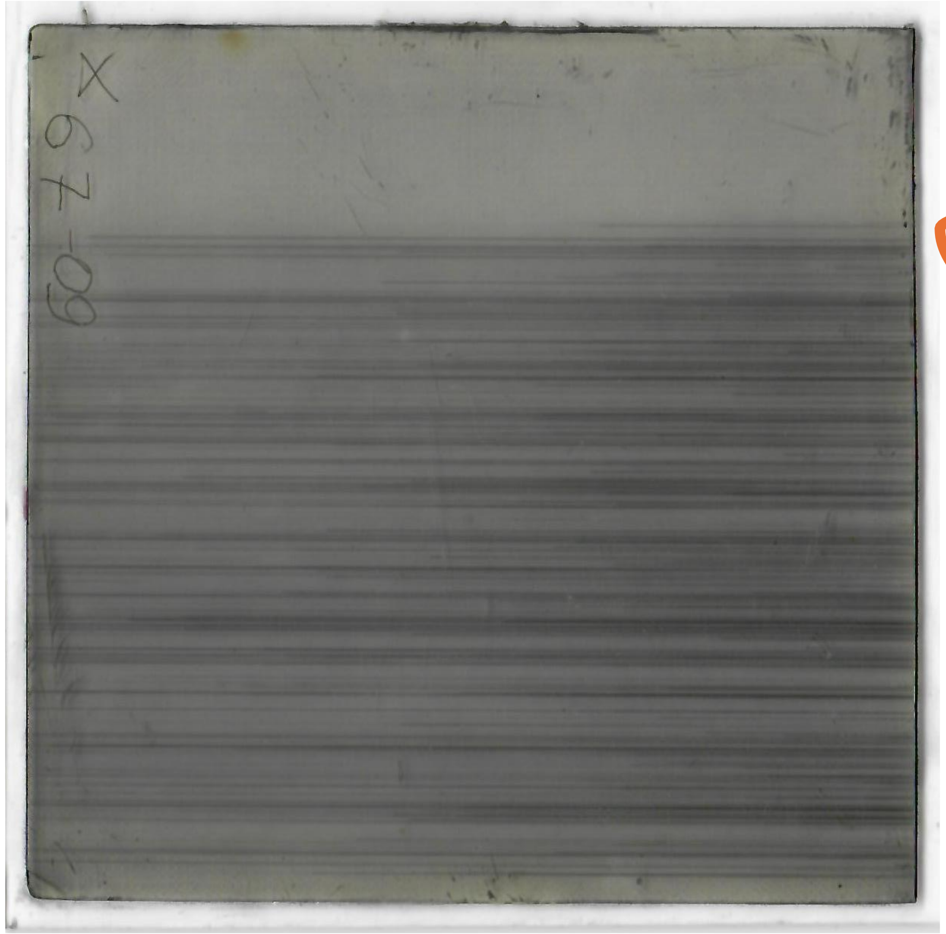
The solid line is the distribution by the value Q for 3 alpha particles with the condition for only one $^{8}Be_{gs}$ ($Q_{2\alpha}$<0.2 MeV) in event and no contribution of events from HS decay in the region of $Q_{3\alpha}$ > 0.7 MeV. The dotted line represents events with the formation of the $^{8}Be_{gs}$ pair.

Possible candidate for 4αBEC state

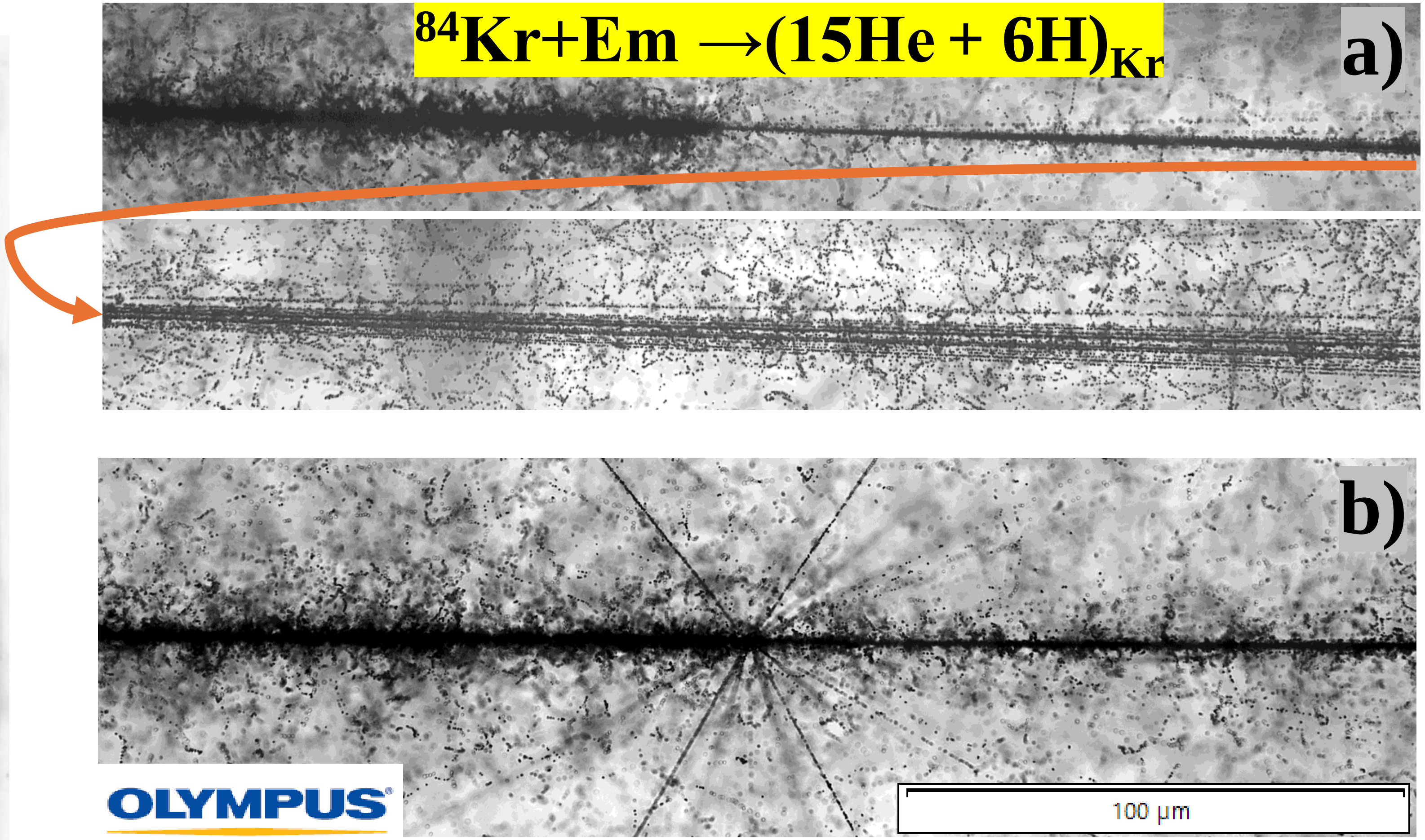


HS can occur as a result of α decay of the 0^+_6 excitation of the ^{16}O nucleus. The condition $Q_{3\alpha}$ (HS) < 700 keV shifts the $Q_{4\alpha}$ distribution and indicates 9 events $Q_{4\alpha}$ < 1 MeV. The contribution of ^{16}O (0^+_6) → α + HS decays has been estimated to be 7 ± 2% for normalization to HS. It can be concluded that the direct dissociation of α + HS dominates in the formation of HS.

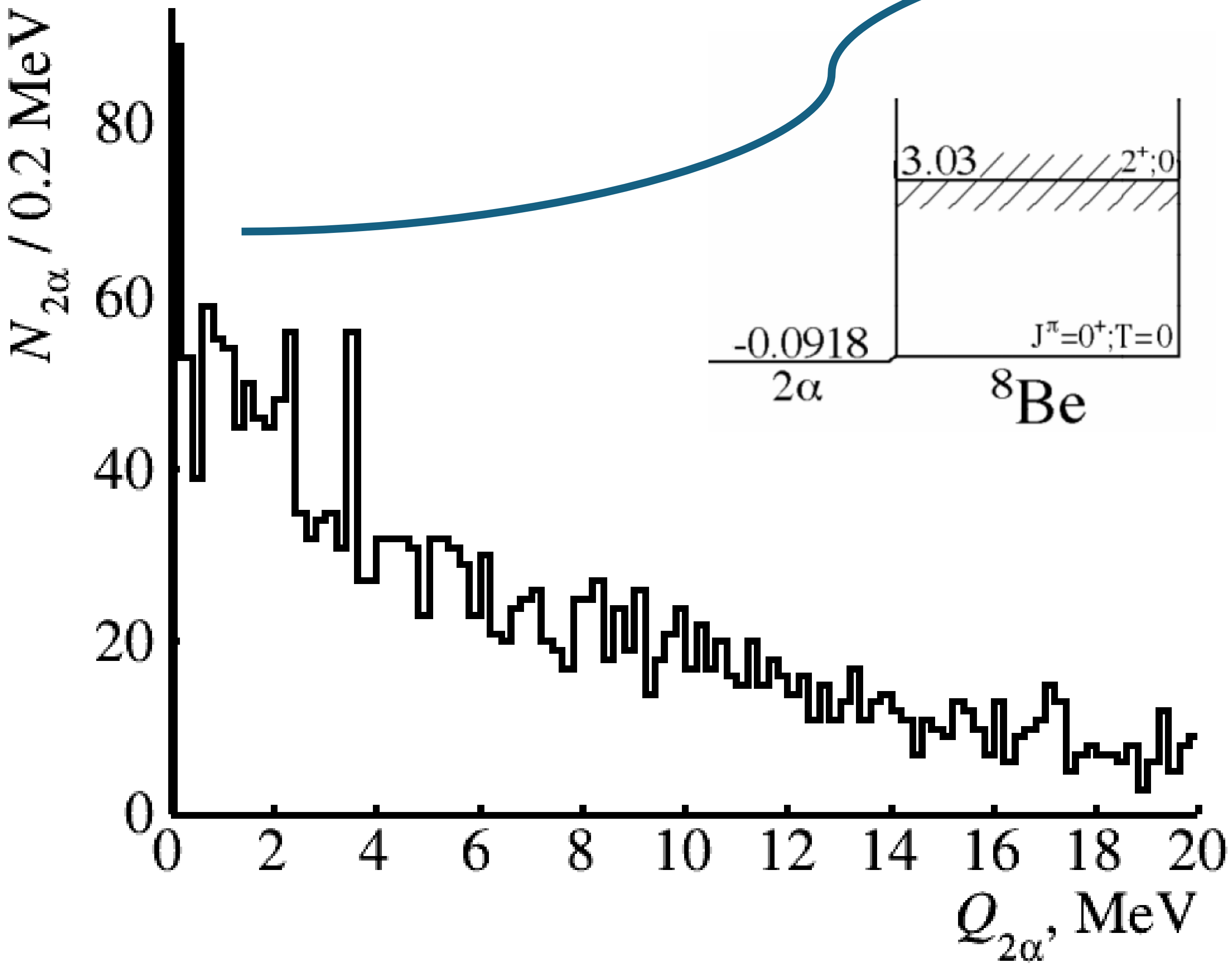
^{84}Kr nucleus interactions in NTE at 800-950 MeV/nucleon

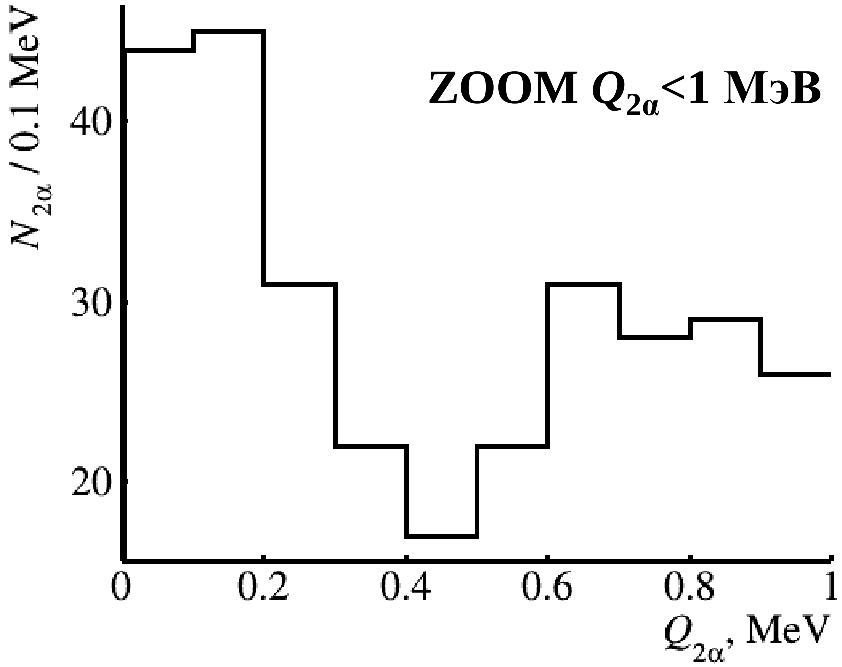


NTE plate exposed with Kr nucleus beam at GSI.

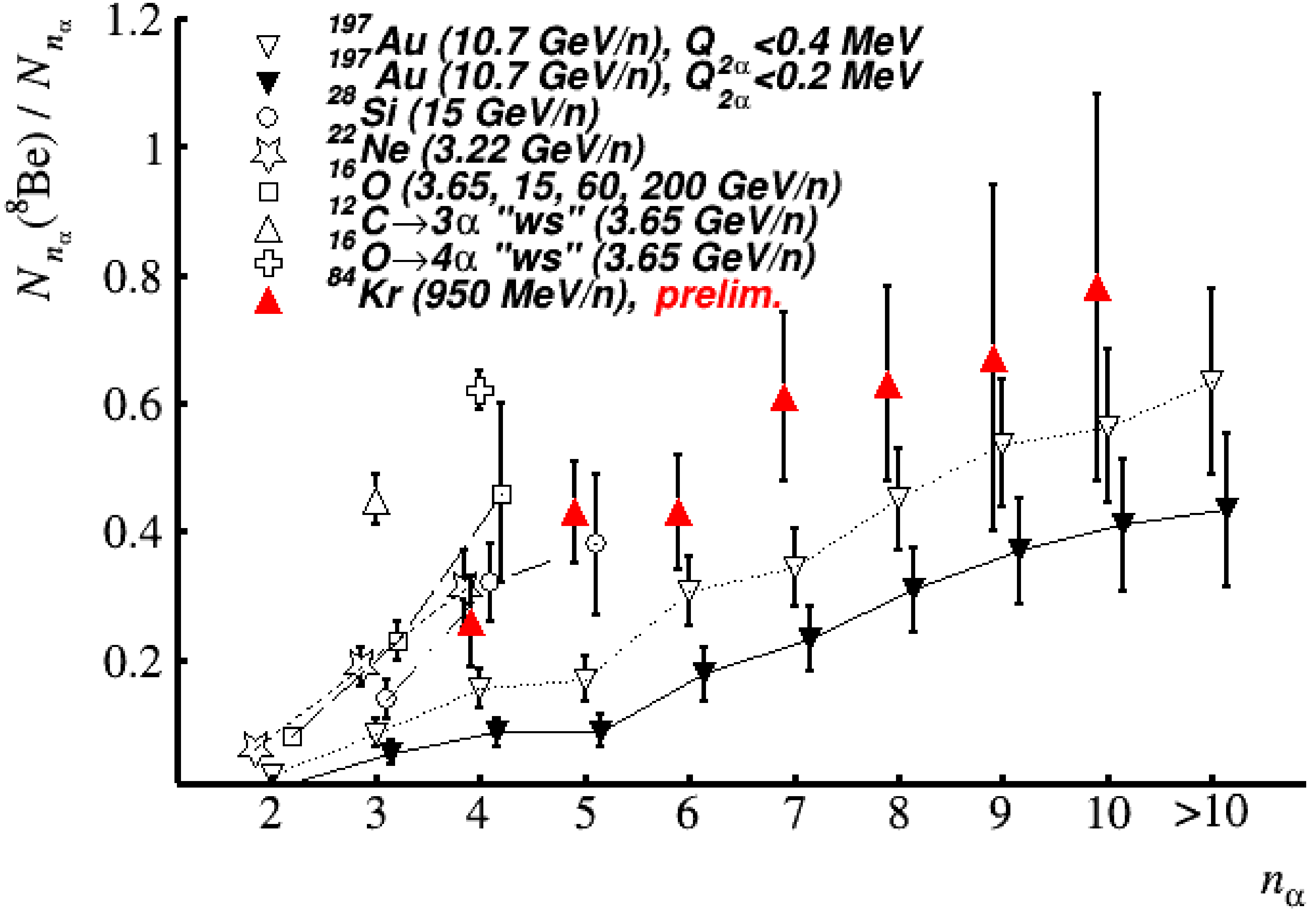


a) Peripheral interaction of Kr projectile nucleus with a NTE nucleus, without produced mesons and fragments of the target nucleus. This type of interaction is called "white" stars.
b) Interaction of Kr nucleus with a large impact parameter results in observing the target nucleus fragments.

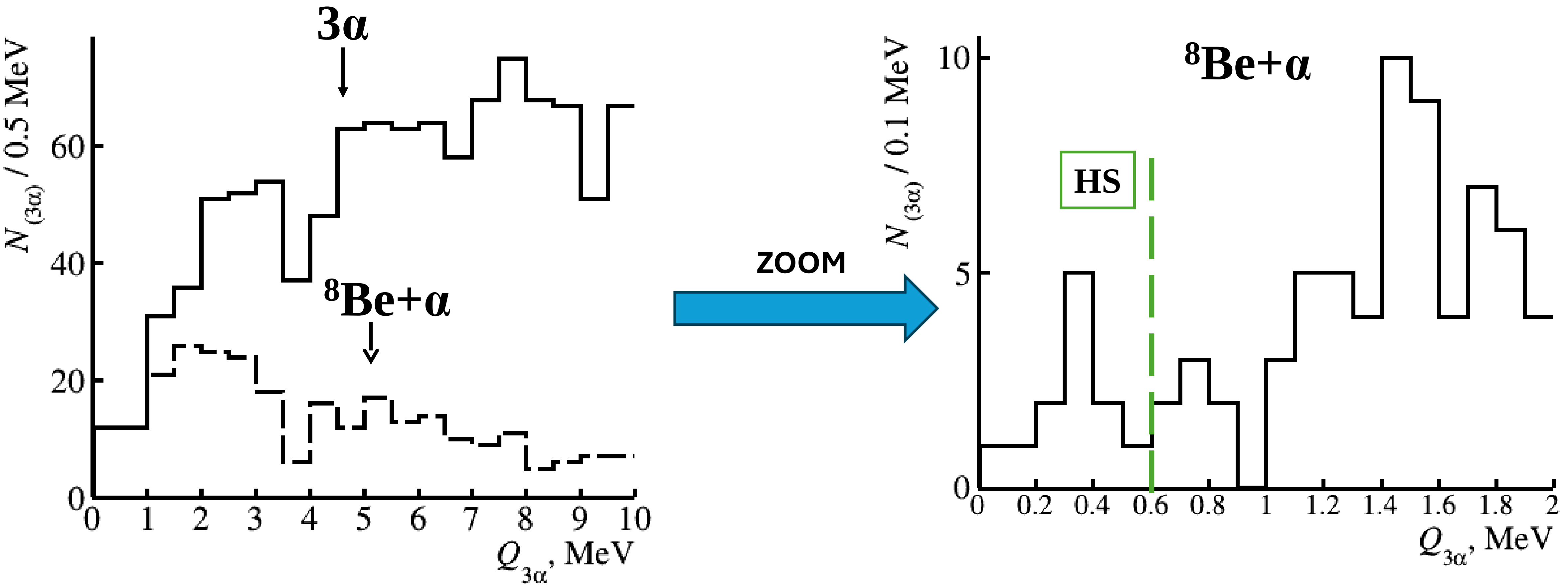




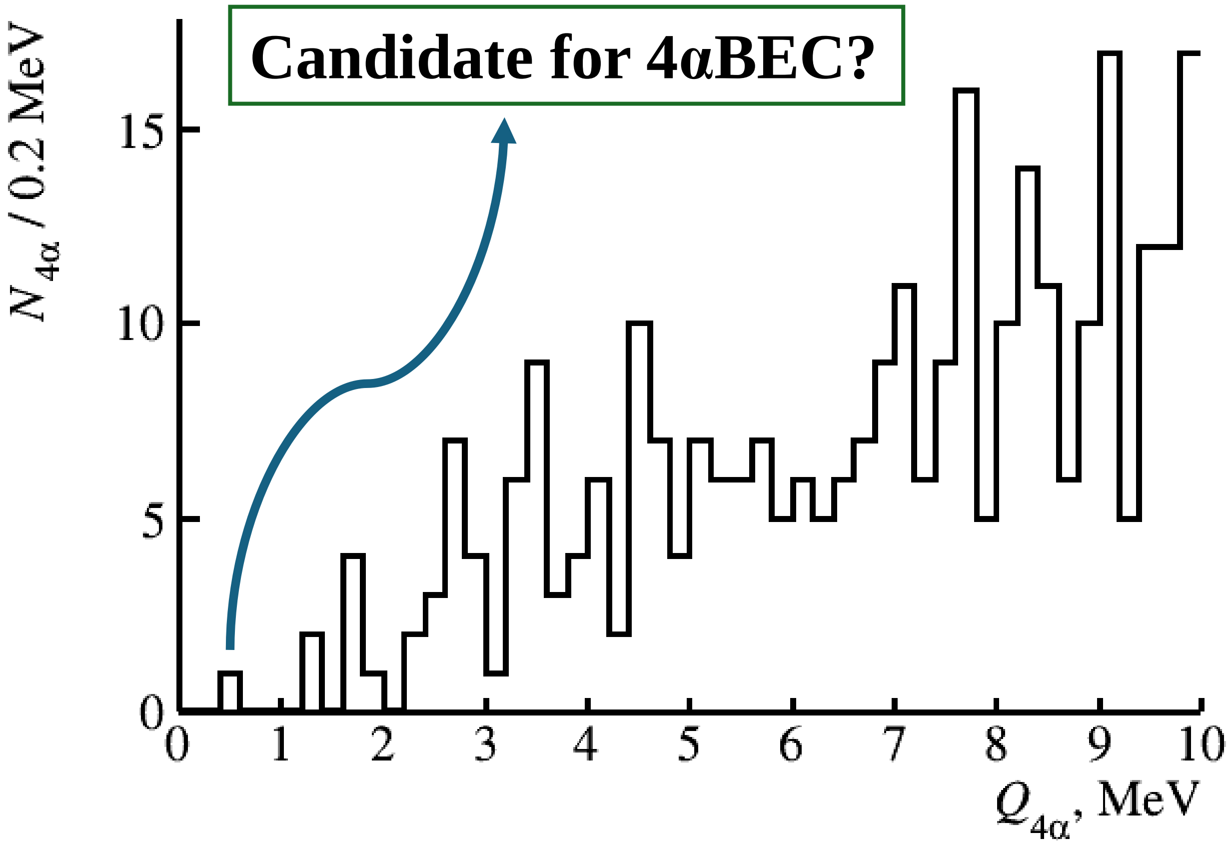
Q value distribution of α-particle pairs in Kr→(4-10)α events with correction p_0 = 0.8*p(L). The number of events with at least one ^{8}Be (number of ^{8}Be pairs) for $Q_{2\alpha}$<0.4 MeV is **96 (17)**, for $Q_{2\alpha}$<0.2 MeV this number is **68 (9)**.



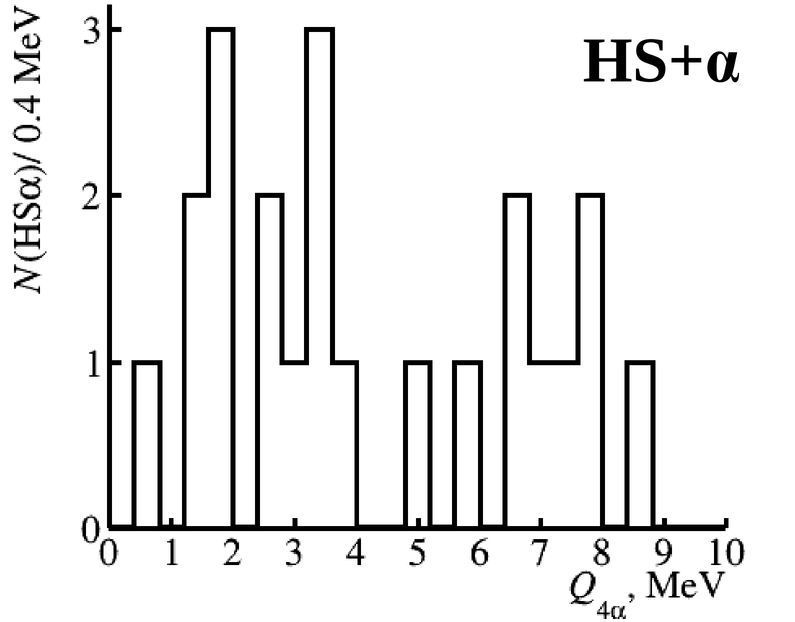
Dependence of relative contribution of $N_{n\alpha}(^8\text{Be})$ decays to statistics of $N_{n\alpha}$ events with α-particle multiplicity nα in relativistic fragmentation of C, O, Ne, Si, and Au nuclei; marked “white” stars $^{12}\text{C} \rightarrow 3\alpha$ and $^{16}\text{O} \rightarrow 4\alpha$ (WS); points are slightly shifted from the values of n_α and connected with the dotted line.

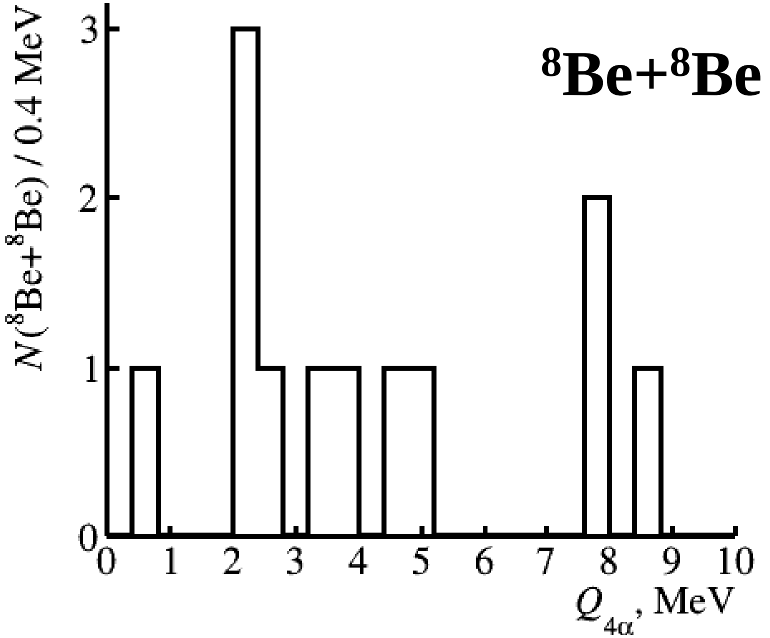


Q value distribution of α-particle triplets in Kr→(4-10)α events.
The number of events satisfying the soft condition $Q_{3\alpha} < 0.6$ MeV
is equal to **11 events**

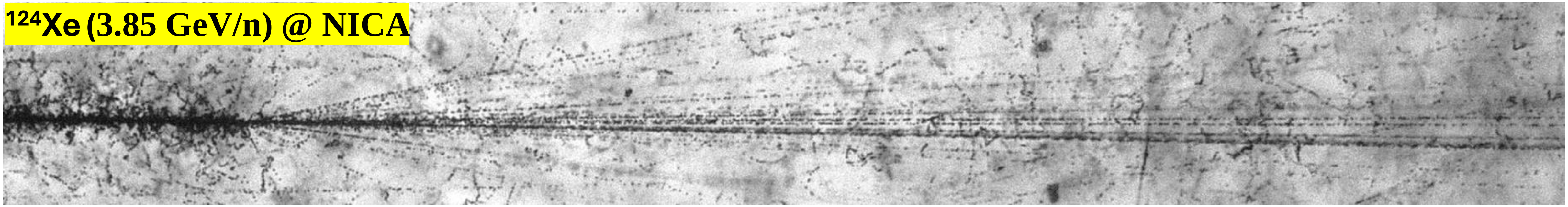


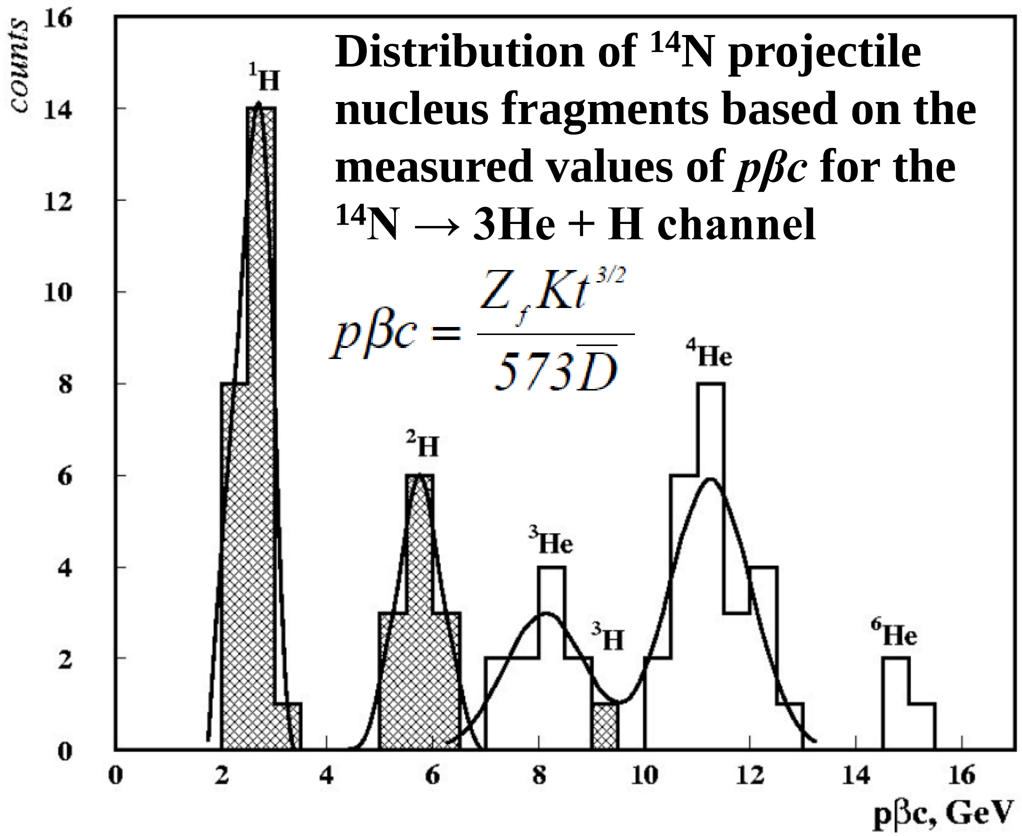
Distribution over Q value of 4α-particles.
Event $Q_{4\alpha} < 1$ MeV (nα = 6):
$Q_{4\alpha} = 0.584$ MeV

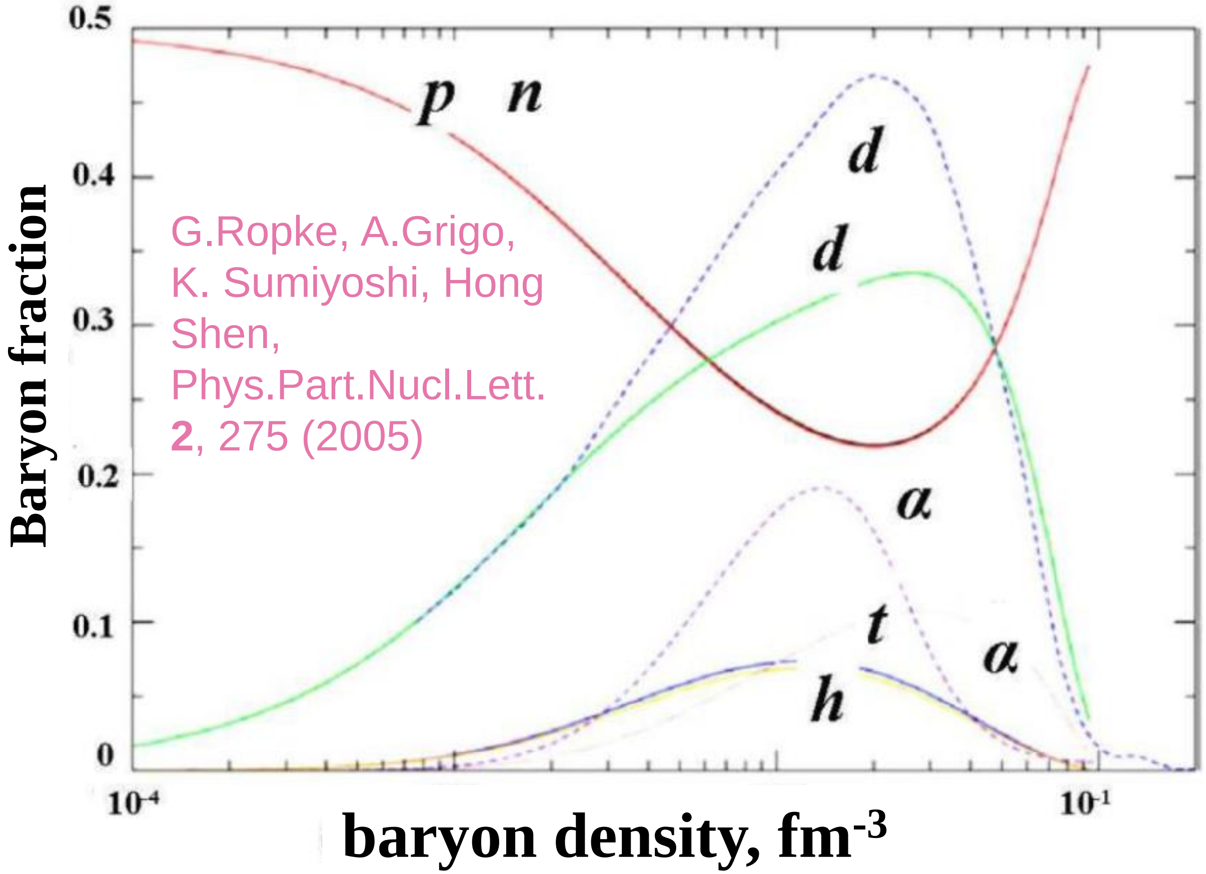




The reconstructed decay sequence: $^{16}O \rightarrow HS(\rightarrow {}^{8}Be+\alpha) + {}^{8}Be \rightarrow 4\alpha$


124Xe (3.85 GeV/n) @ NICA


Distribution of 14N projectile nucleus fragments based on the measured values of pβc for the 14N → 3He + H channel
$$p\beta c = \frac{Z_f K t^{3/2}}{573\overline{D}}$$
counts
1H
2H
3He
3H
4He
6He
pβc, GeV
0
2
4
6
8
10
12
14
16


Baryon fraction
baryon density, fm-3
p
n
d
d
α
t
h
α
0.5
0.4
0.3
0.2
0.1
0
10-4
10-1
G.Ropke, A.Grigo, K. Sumiyoshi, Hong Shen, Phys.Part.Nucl.Lett. 2, 275 (2005)

Conclusion

- The presented results on the study of the alpha-particle states in dissociation of relativistic nuclei indicate the unique productivity of the nuclear emulsion method.
- Determination of the invariant masses of α-particle ensembles allows one to identify the decays of $^{8}Be(0^{+})$, $^{12}C(0^{+}_{2})$ and $^{12}C(3^{-})$ in mentioned above reactions.
- Using the existing statistics with the production of (3-10) alpha particles per event, the decays of unstable nuclear states ^{8}Be and $^{12}C(0^{+}_{2})$ have been reconstructed. The presented data are the first contribution to the dedicated search for 4αBEC states.
- Recently the exposed NTE layers have been obtained to study multiple states of α-particles and nucleons in Xe nucleus interactions with NTE at the energy of 3.85 GeV/n.

Thank you for your attention!

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