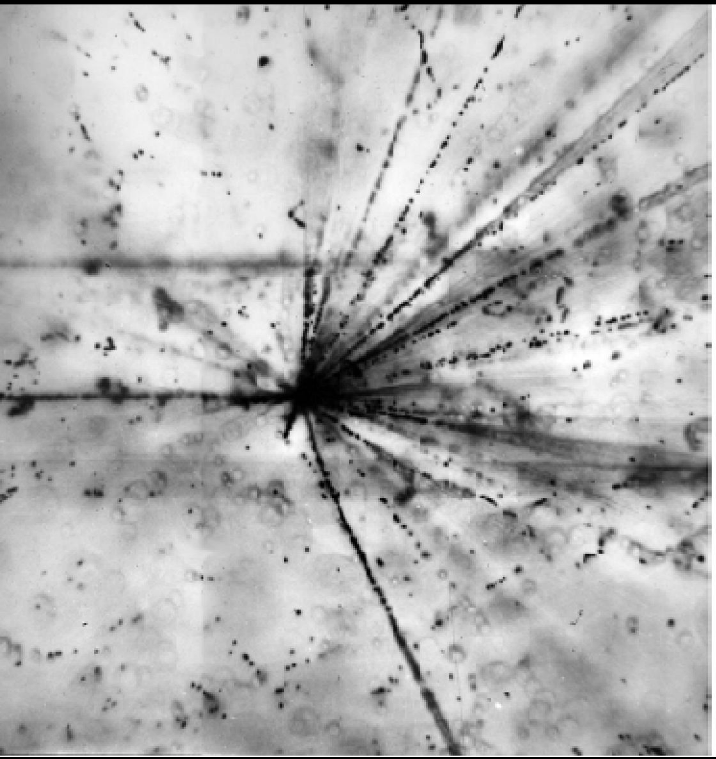
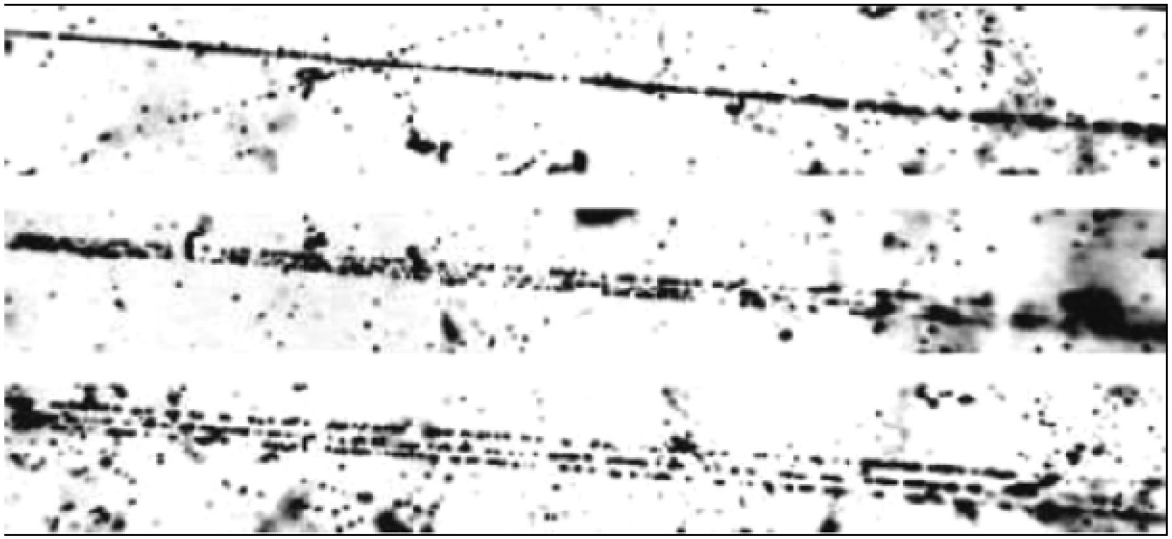
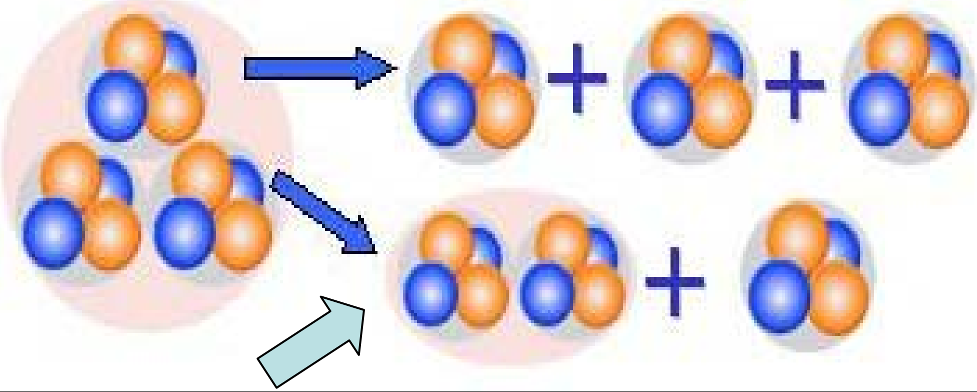
Pavel Zarubin "Overview of nuclear clustering studies in dissocation of relativistic light nuclei"



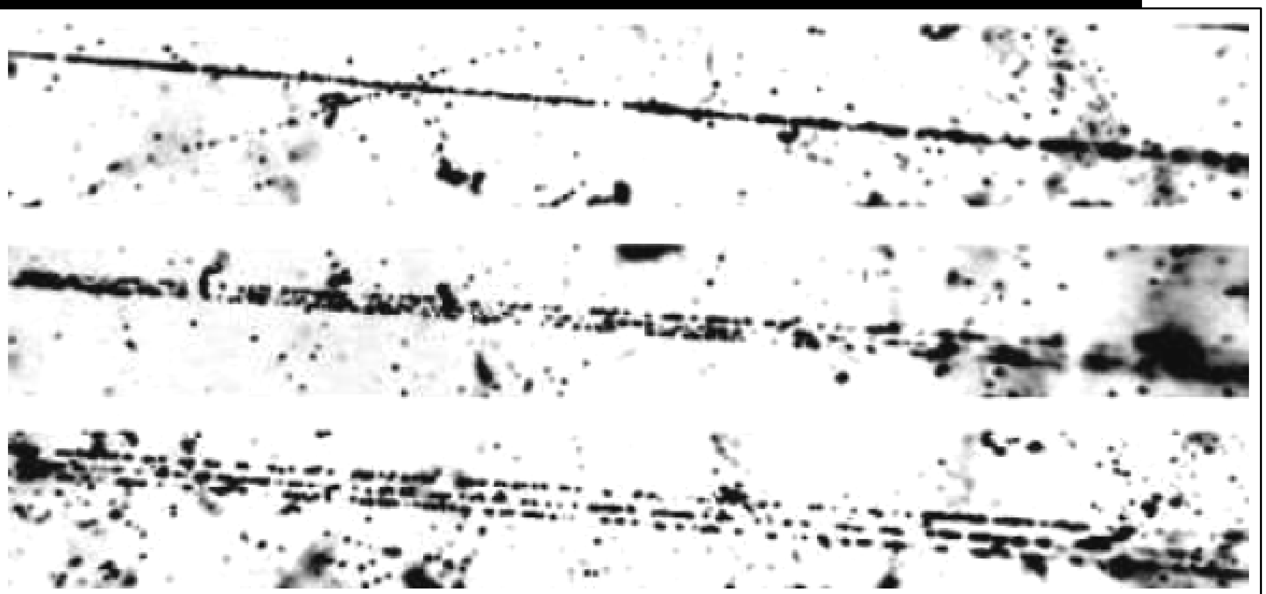


Veksler & Baldin Laboratory of High Energy Physics, JINR, Dubna, Russia



4.5A GeV/c ^{12}C Coherent Dissociation

20 %



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

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

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

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

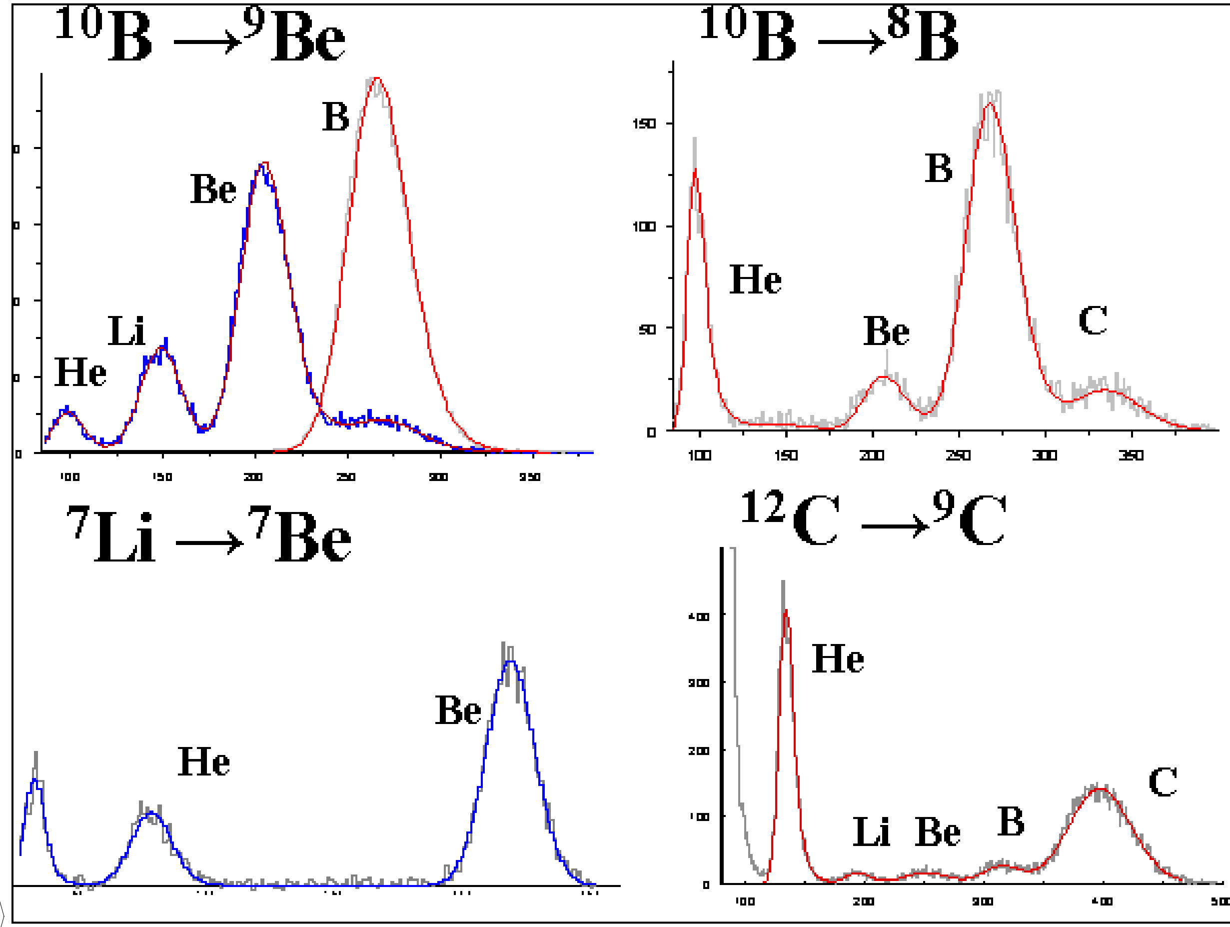
$$E_\alpha = \sqrt{P_0^2 \cdot A^2 + m_\alpha^2}$$

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

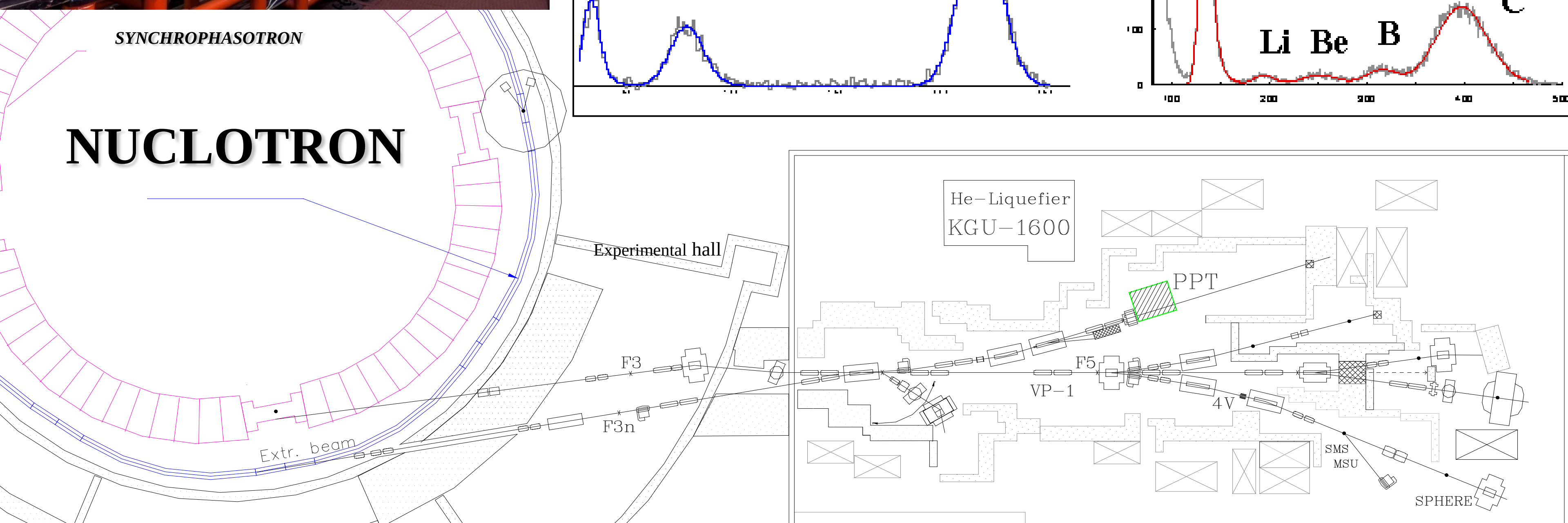
$$\mathrm{Q}_{2\alpha} = \mathrm{M}_{2\alpha} - 2 \cdot \mathrm{m}_\alpha$$

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

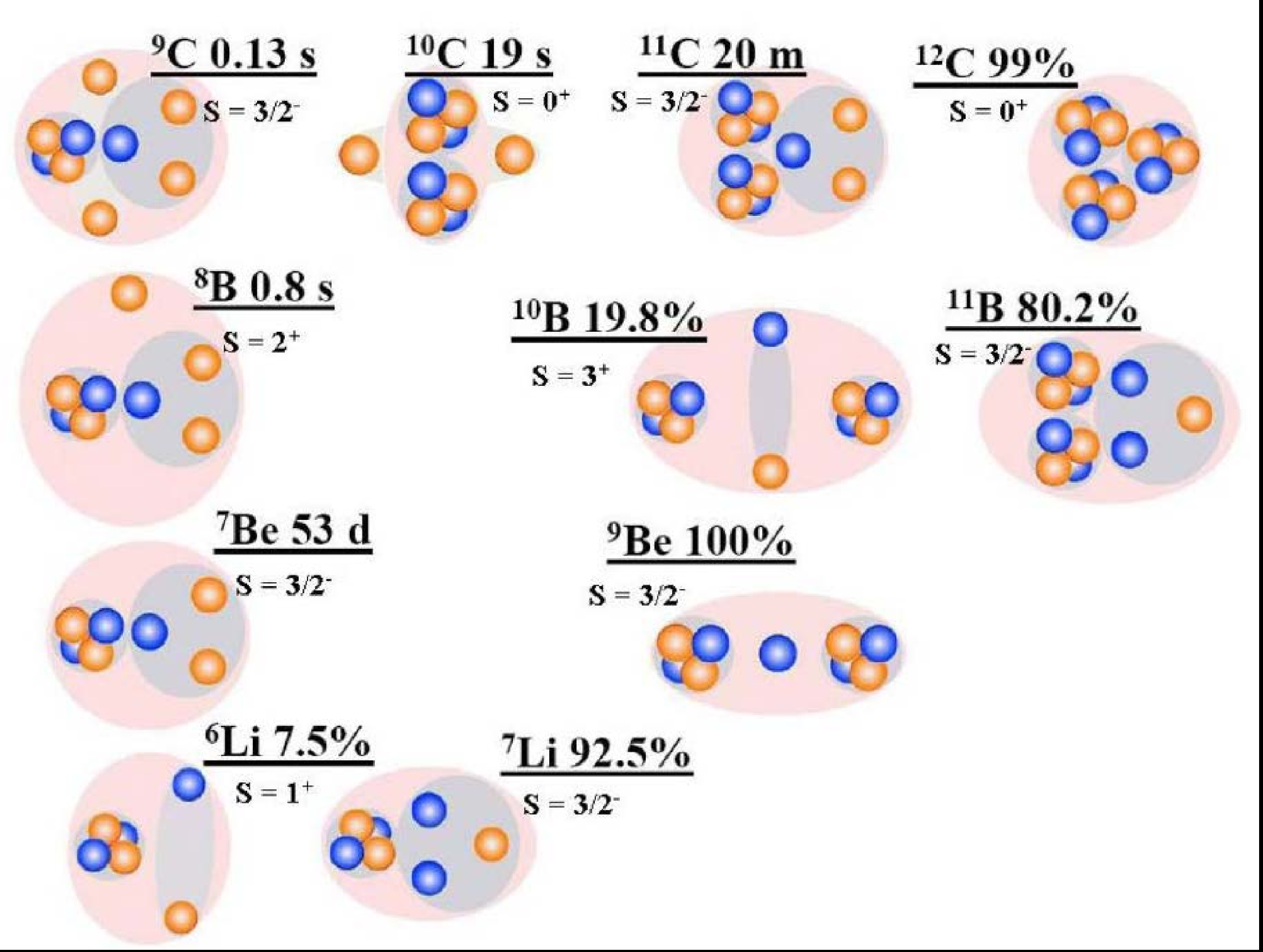
$$Q_{3\alpha} = \sqrt{3 \cdot m_\alpha^2 + 2 \cdot \sum_{i \neq j} (E_{\alpha i} \cdot E_{\alpha j} - \vec{P}_{\alpha i} \cdot \vec{P}_{\alpha j})} - 3 \cdot m_\alpha$$



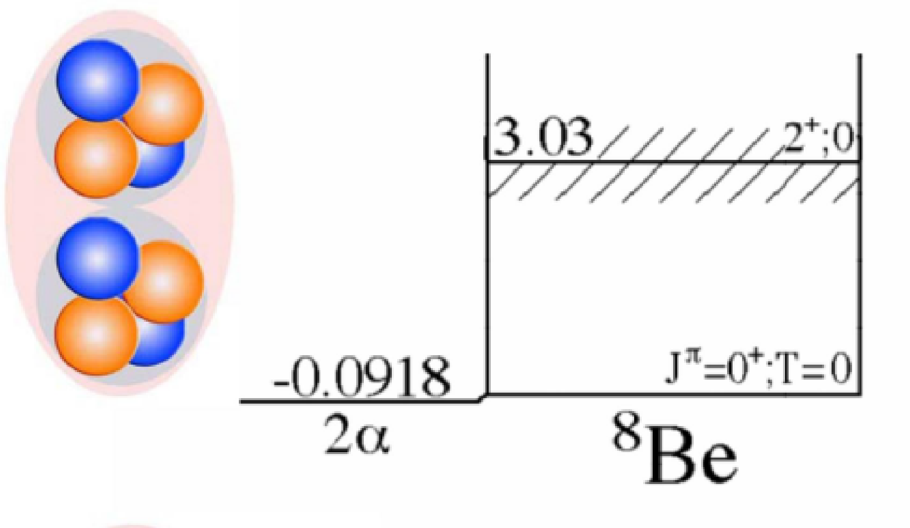
10B → 9Be
He
Li
Be
B
10B → 8B
He
Be
B
C
7Li → 7Be
He
Be
12C → 9C
He
Li
Be
B
C



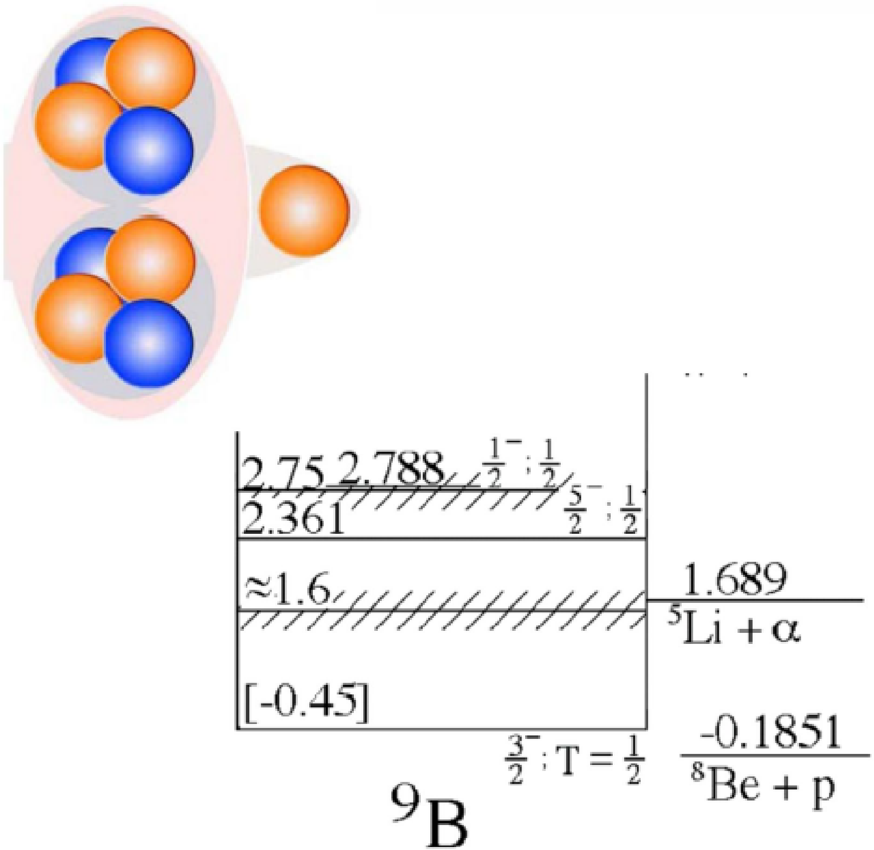
SYNCHROPHASOTRON
NUCLOTRON
Experimental hall
He–Liquefier
KGU–1600
PPT
F3
F3n
F5
VP–1
4V
Extr. beam
SMS
MSU
SPHERE



Exposures of nuclear track emulsion (NTE) to newly formed beams of relativistic nuclei, which began in the 1970s at the JINR Synchrophasotron of and LBL Bevalac (Berkeley, USA), since the early 2000s have found a continuation at the JINR Nuclotron in the BECQUEREL Experiment. A topical application of the NTE technique consists in studying the structure of light nuclei including radioactive ones on a basis of advantages of the relativistic approach. Distributions of peripheral interactions of studied nuclei over channels of dissociation into relativistic charged fragments convey features of their structure. This possibility is lacking in electronic experiments. The NTE makes it possible to observe the breakdown of nuclei up to a coherent dissociation, in which the target nuclei are not visibly destroyed in an obvious way.

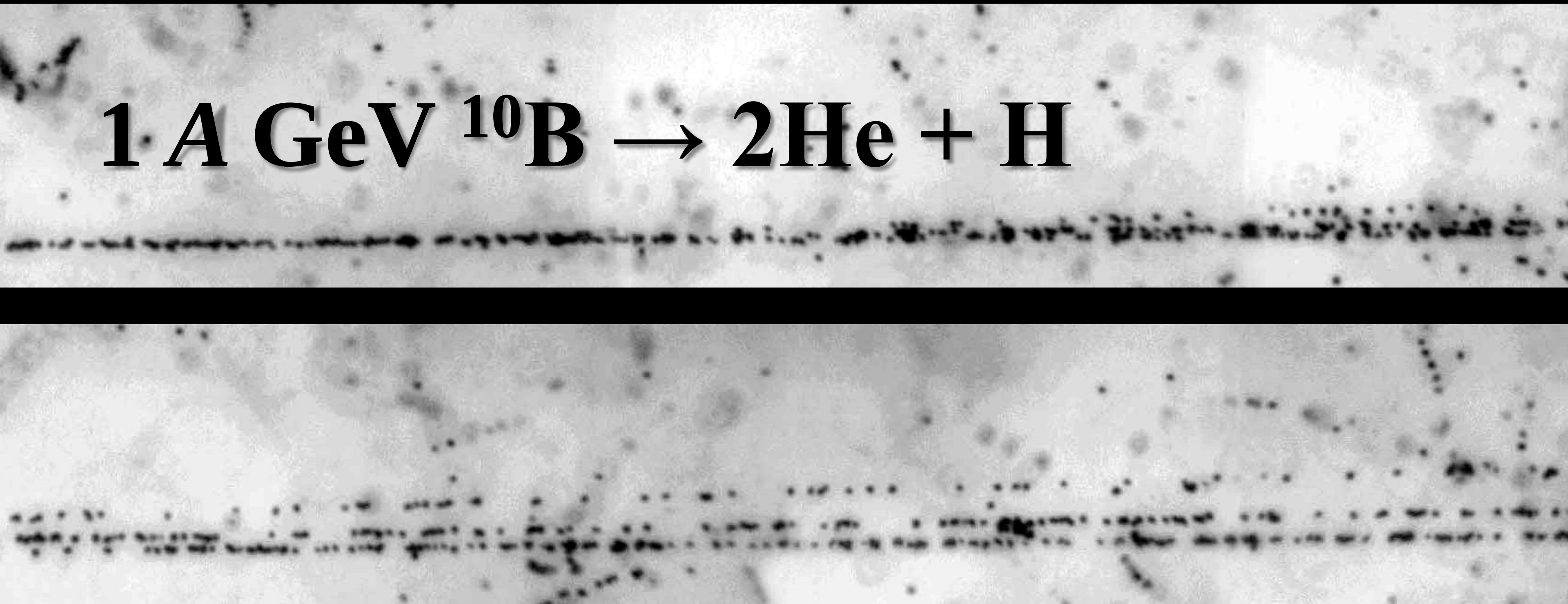


E_x (MeV ± keV)	$J^\pi; T$	Γ_{cm} (keV)	Decay
g.s.	$0^+; 0$	5.57 ± 0.25 eV [i]	α
3.03 ± 10 [i]	$2^+; 0$	1513 ± 15 [i]	α
[i,j]	2^+		
11.35 ± 150 [i]	$4^+; 0$	≈ 3500[b]	α



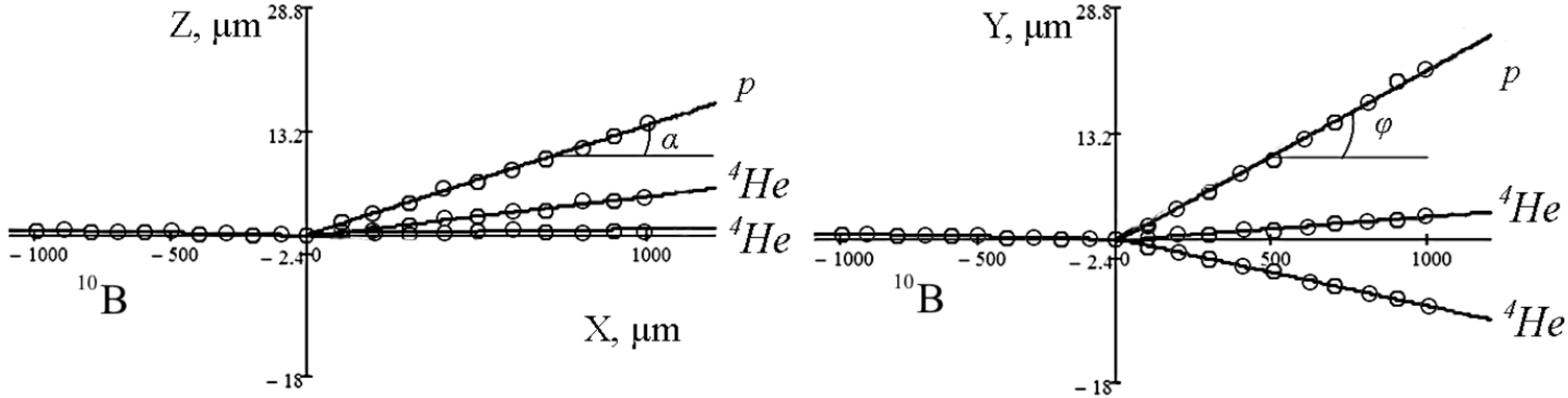
E_x [a] (MeV ± keV)	$J^\pi; T$	$\Gamma_{c.m.}$ (keV)	Decay
g.s.	$\frac{3}{2}^-; \frac{1}{2}$	0.54 ± 0.21	p
≈ 1.6 [b]			p, (α)
2.361 ± 5	$\frac{5}{2}^-; \frac{1}{2}$	81 ± 5	p, α
2.75 ± 300 [c]	$\frac{1}{2}^-; \frac{1}{2}$	3130 ± 200	p
2.788 ± 30	$\frac{5}{2}^+; \frac{1}{2}$	550 ± 40	p, α
4.3 ± 200 [d]		1600 ± 200	
6.97 ± 60	$\frac{7}{2}^-; \frac{1}{2}$	2000 ± 200	p
11.65 ± 60 [e]	$(\frac{7}{2})^-; \frac{1}{2}$	800 ± 50	p

1 *A* GeV $^{10}B \rightarrow 2He + H$

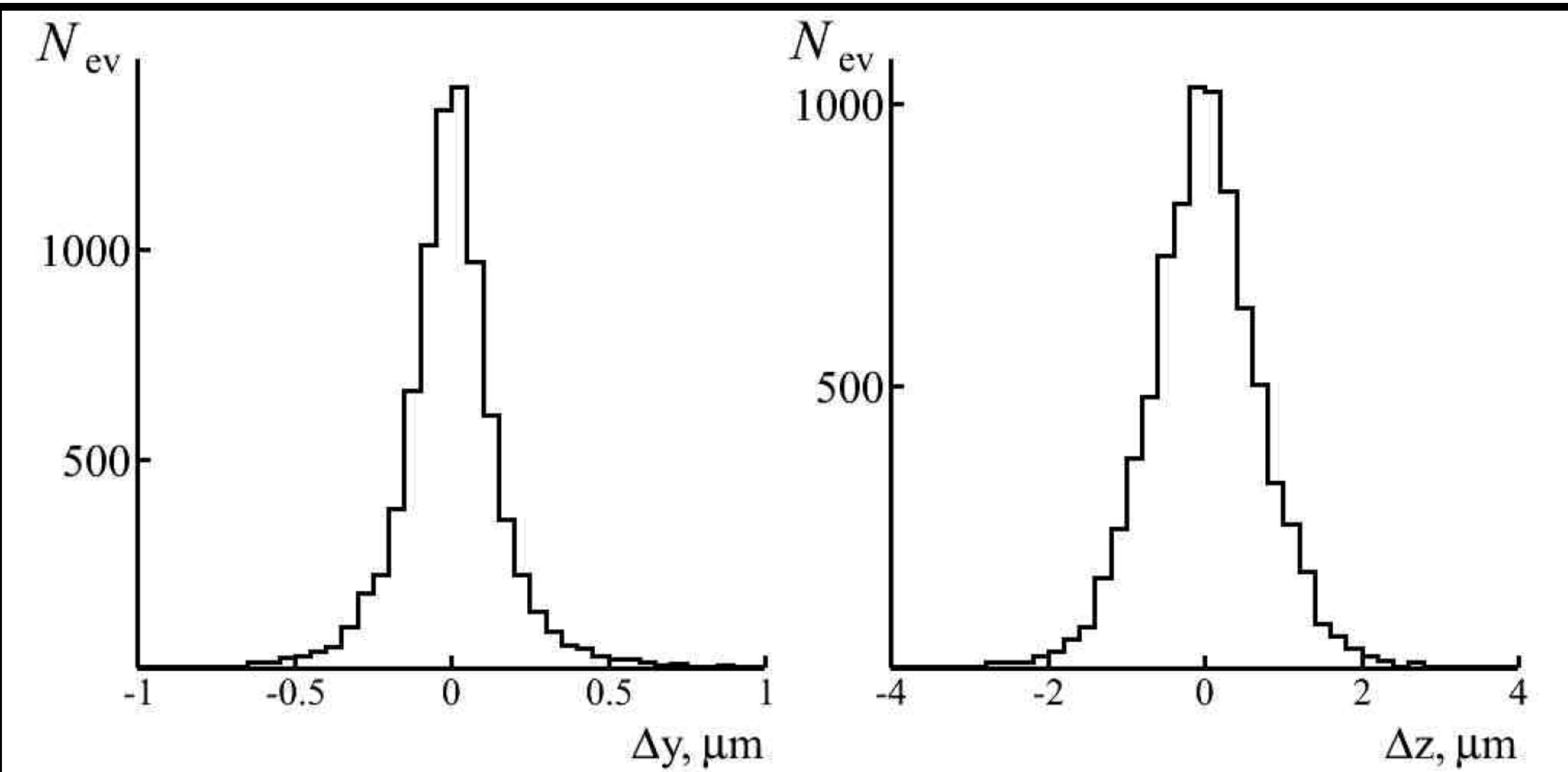


In general, energy of a few-particle system *Q* can be defined as difference between the invariant mass of the system M^* and a primary nucleus mass or a sum of masses of the particles *M*, that is, $Q = M^* - M$. M^* is defined as the sum of all products of 4-momenta $P_{i,k}$ fragments $M^{*2} = (\Sigma P_j)^2 = \Sigma(P_i P_k)$. Subtraction of *M* is a matter of convenience and *Q* is also named an invariant mass. Reconstruction of *Q* makes possible to identify decays unstable particles and nuclei.

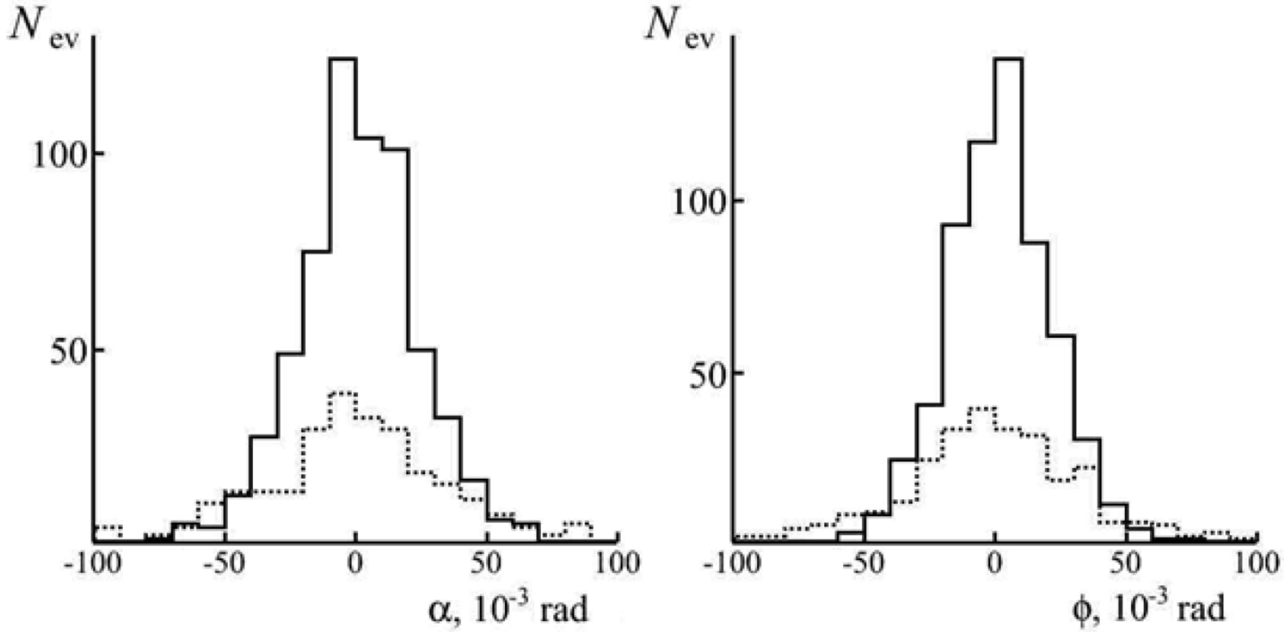
For the most part, fragments of a relativistic nucleus are contained in a narrow cone of the polar angle θ, which is estimated as $\theta = 0.2/P_0$, where the factor 0.2 GeV/*c* is determined by the spectator-nucleon transverse momentum, while P_0 is the momentum of the accelerated-projectile nucleon. The fragment 4-momenta $P_{i,k}$ in the cone can be determined in assumption of conservation of momentum per nucleon by fragments of a projectile (or its velocity). This approximation is well grounded when primary energy above 1 *A* GeV.



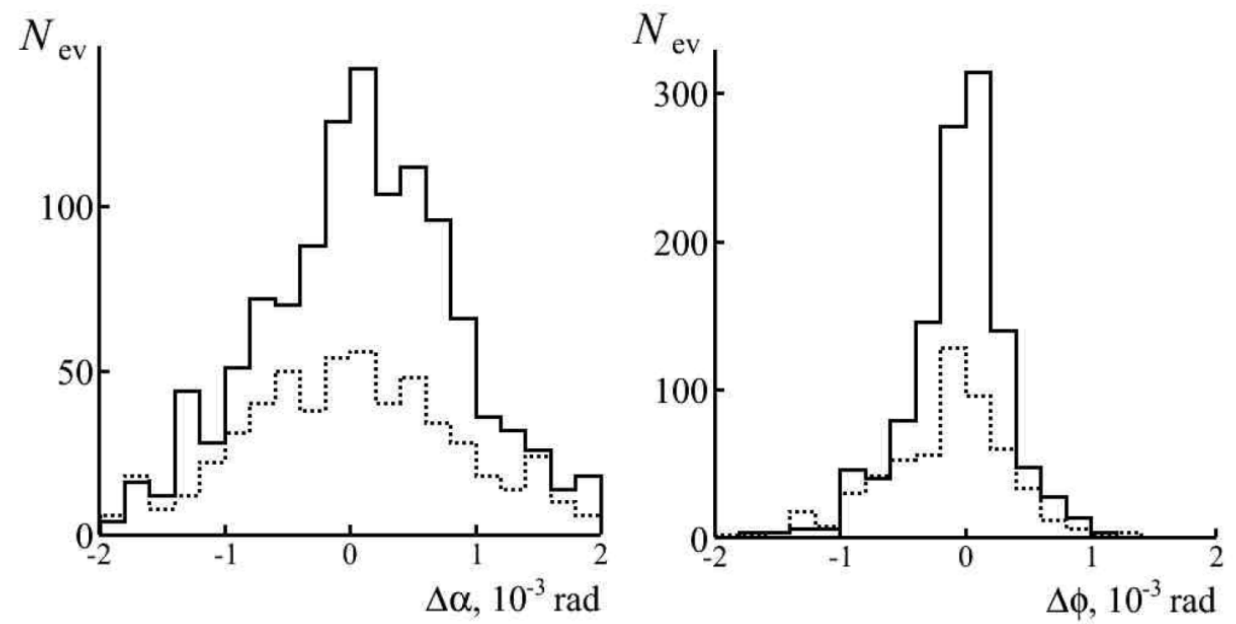
Example of restored directions in event $^{10}B \rightarrow 2He + H$ over vertical and planar planes.



Distributions of residuals Δy and Δz of fitting of coordinates of H and He tracks in events $^{10}B \rightarrow 2He + H$.

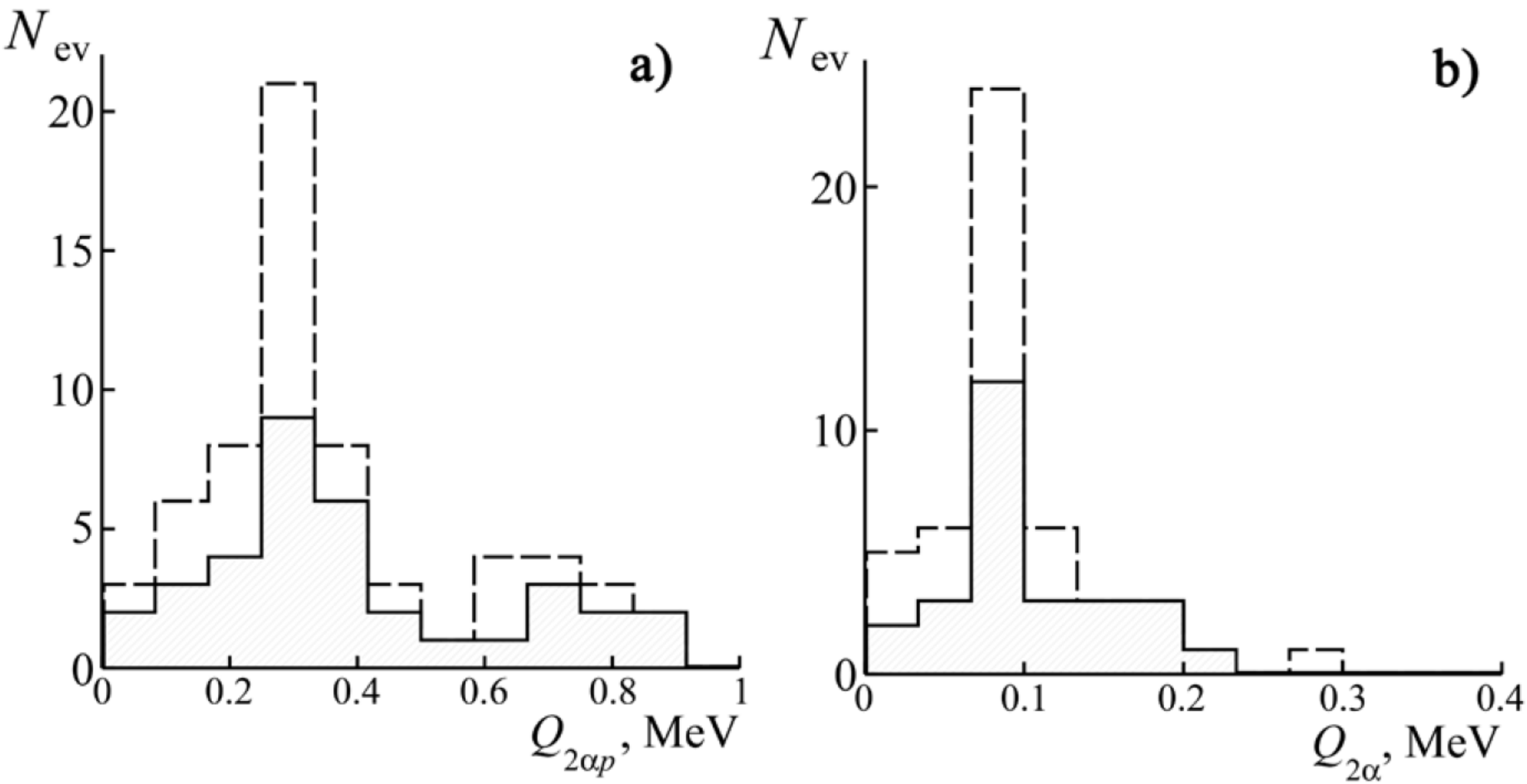


Distributions of fragments He (solid) and H (dotted) over dip and planar angles α and φ in events $^{10}B \rightarrow 2He + H$.



Distribution of errors in determining dip (α) and planar (φ) angles for fragments He (solid) and H (dotted) in events $^{10}B \rightarrow 2He + H$.

Reconstruction of values $Q_{2\alpha p}$ and $Q_{2\alpha}$ for the ^{10}B and ^{11}C fragmentation is presented in the range which is relevant for ^{9}B. In these cases the ^{9}B decays serves as source of ^{8}Be. The distribution mean values (RMS) $\langle Q_{2\alpha p}\rangle = 265 \pm 14$ (100) keV and $\langle Q_{2\alpha}\rangle = 91 \pm 7$ (53) keV match the accepted values and expected resolution. The condition 200 keV $< Q_{2\alpha}$ is a practical cut-off for ^{8}Be identification.

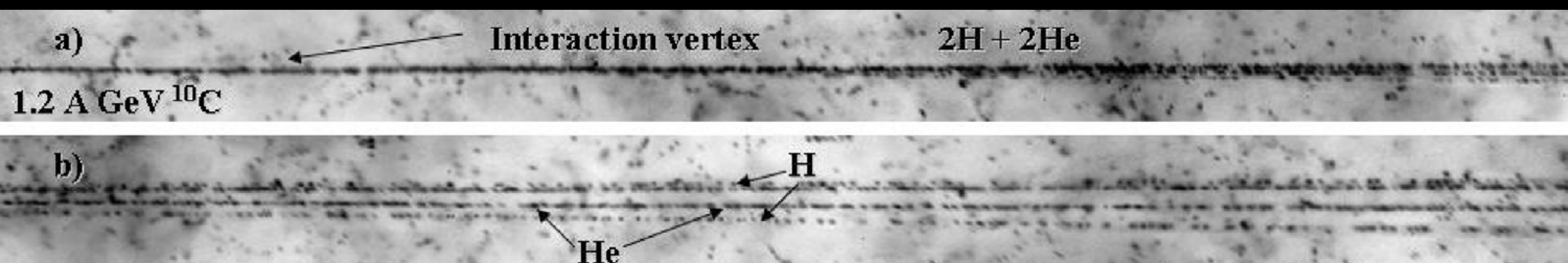


Distributions of triples $2\alpha p$ over invariant mass $Q_{2\alpha p}$ (a) for fragmentation ^{10}B → 2He + H at 1.6 *A* GeV/*c* (solid) and ^{11}C → 2He + 2H at 2.0 A GeV/*c* (added, dashed) and $Q_{2\alpha}$ of α-pairs in the range 400 keV < $Q_{2\alpha p}$ identified in these events (b); statistics of 99 events ^{10}B → 2He + H and 212 events ^{11}C → 2He + 2H.

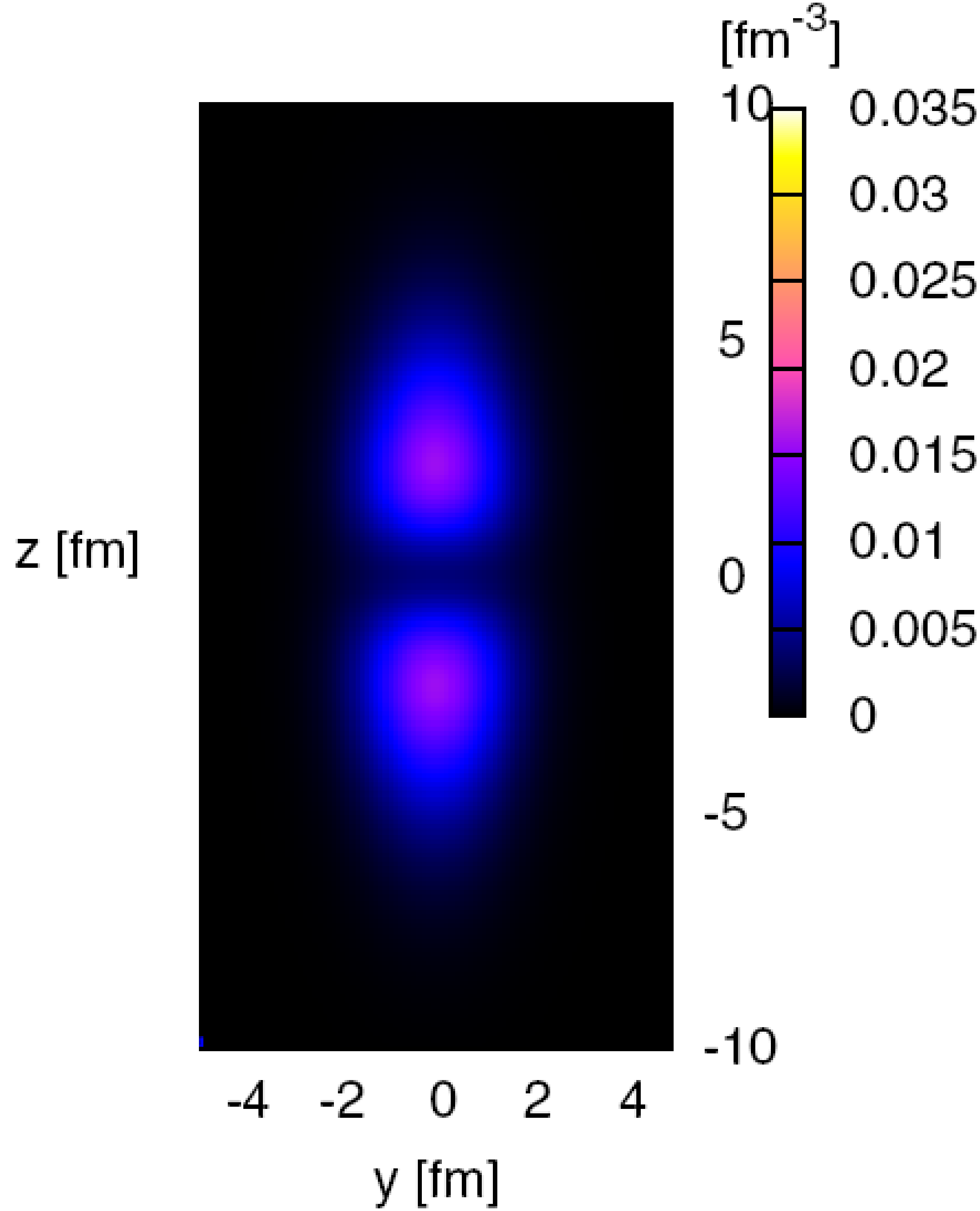
Nucleus (P_0, A GeV/c)	$<\Theta_{2\alpha}>$ (RMS), 10^{-3} rad ($Q_{2\alpha}$ < 300 keV)	$<Q_{2\alpha}>$ (RMS), keV
^{12}C (4.5)	2.1 ± 0.1 (0.8)	109 ± 11 (83)
^{14}N (2.9)	2.9 ± 0.2 (1.9)	119.6 ± 9.5 (72)
^{9}Be (2.0)	4.4 ± 0.2 (2.1)	86 ± 4 (48)
^{10}C (2.0)	4.6 ± 0.2 (1.9)	63 ± 7 (83)
^{11}C (2.0)	4.7 ± 0.3 (1.9)	77 ± 7 (40)
$^{11}C(2.0) \rightarrow {}^{9}B \rightarrow {}^{8}Be$		94 ± 15 (86)
^{10}B (1.6)	5.9 ± 0.2 (1.6)	101 ± 6 (46)
$^{10}B(1.6) \rightarrow {}^{9}B \rightarrow {}^{8}Be$		105 ± 9 (47)
^{12}C (1.0)	10.4 ± 0.5 (3.9)	107 ± 10 (79)

Nucleus	$<Q_{2\alpha p}>$, (RMS), keV ($Q_{2\alpha p}$ < 400 keV)
^{10}B	249 ± 19 (91)
^{10}C	254 ± 18 (96)
^{11}C	273 ± 18 (82)

Channel	^{12}C	^{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	100 (100 %)	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 %)



Events of this kind, called "white" stars, account for several percent of a total number of interactions. They are the most valuable for interpreting the structure, since in them distortion of an initial state of a nucleus that experiences dissociation can be considered minimal. Among the key results of the BECQUEREL experiment is determination of contribution of unstable ^{8}Be and ^{9}B nuclei in dissociation of relativistic nuclei $^{10,11}C$ and ^{10}B. Meaning of this fact is as follows. As is known, nucleosynthesis involving ^{8}Be and ^{9}B is suppressed due to absence of the bound ground states. Nevertheless, this circumstance does not prevent the substantial contribution of ^{8}Be and ^{9}B.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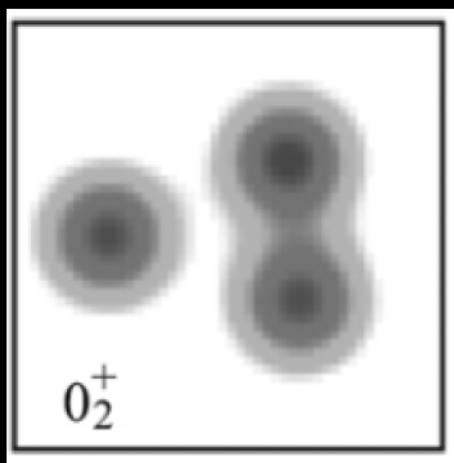
-2
0
2
4
y [fm]

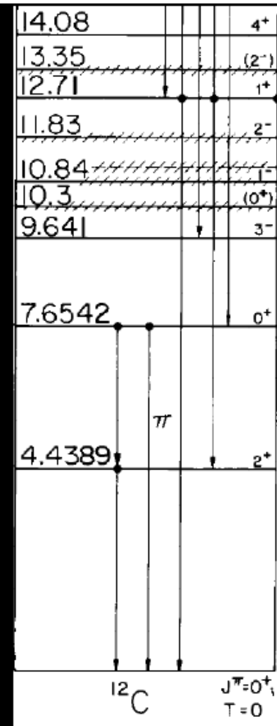
ON NUCLEAR REACTIONS OCCURRING IN VERY HOT STARS. I. THE SYNTHESIS OF ELEMENTS FROM CARBON TO NICKEL

F. HOYLE*

MOUNT WILSON AND PALOMAR OBSERVATORIES
CARNEGIE INSTITUTION OF WASHINGTON
CALIFORNIA INSTITUTE OF TECHNOLOGY

Received December 22, 1953

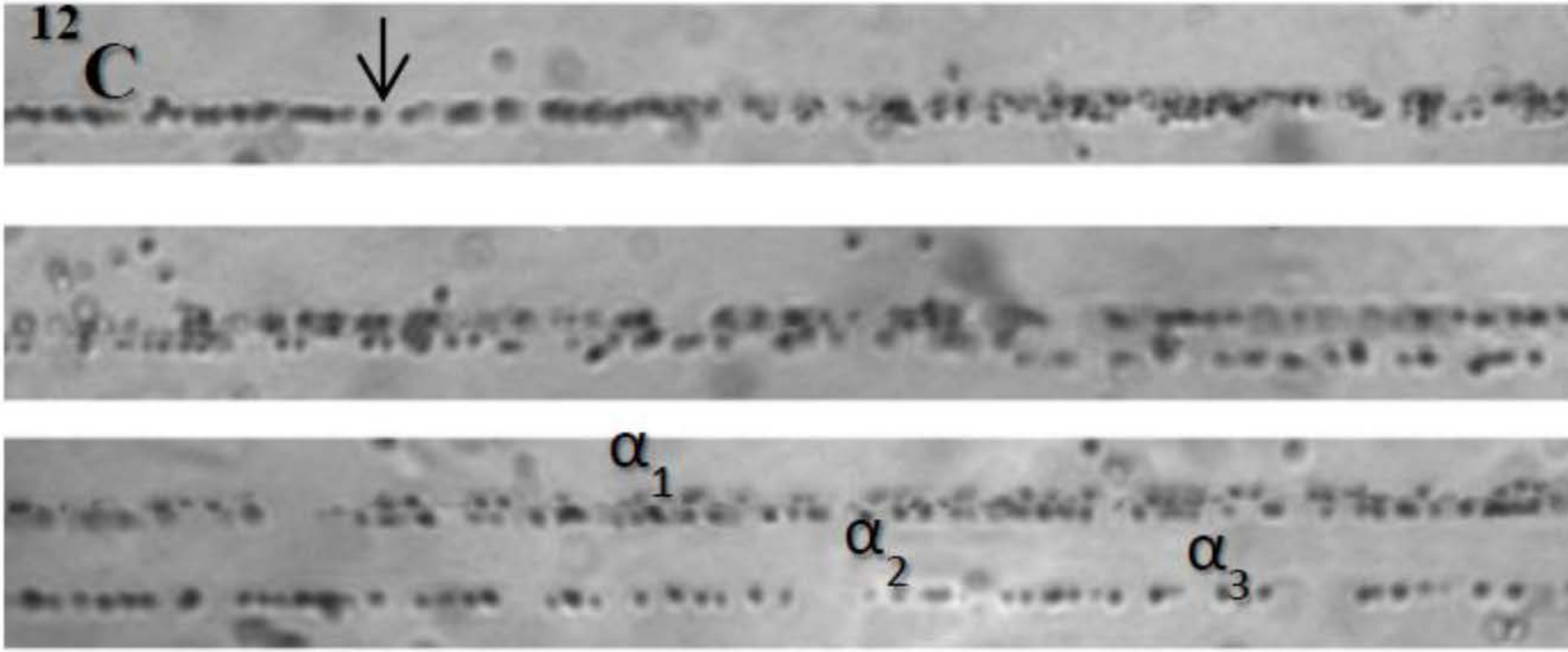




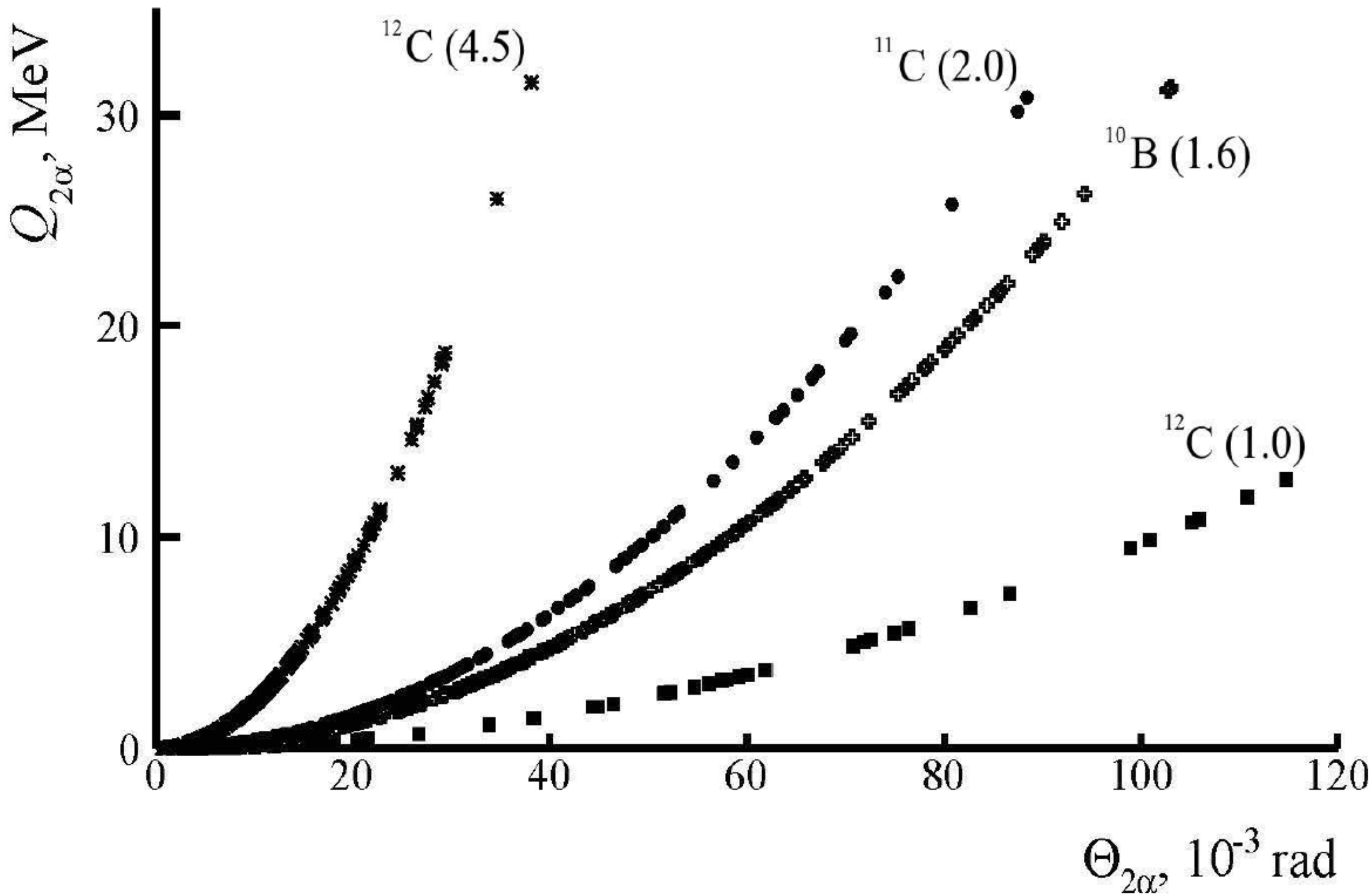
E_x in ^{12}C (MeV ± keV)	J^π ; T	$\Gamma_{c.m.}$ (keV)	Decay
g.s	0^+; 0	-	stable
4.43891 ± 0.31	2^+; 0	$(10.8 \pm 0.6) \times 10^{-6}$	γ
7.6542 ± 0.15	0^+; 0	$(8.5 \pm 1.0) \times 10^{-3}$	γ, π, α

The second excited state of the ^{12}C nucleus is is named after the astrophysicist F. Hoyle who postulated its existence to explain the prevalence of the ^{12}C isotope. Following an accurate prediction of the HS energy it was experimentally confirmed that the ^{12}C nucleus has the excited state located at only 378 keV above the mass threshold of the three α particles. Although it is unstable, its width is only 8.5 eV. Such a value indicates that the HS lifetime is comparable with the values for ^8Be or π^0-meson. Observation of HS at a contrast of relativistic energy and the minimum possible energy stored by 3α-ensembles can demonstrate HS as a nuclear-molecular object similar to ^8Be. First of all it is necessary to establish the very possibility of HS appearance in the relativistic fragmentation.

The current material for the HS search is a set 200 μm NTE pellicles on 2 mm glass of size 9 to 12 cm which is irradiated longitudinally ^{12}C nuclei at initial momentum P_0 = 1 A GeV/c. This exposure was performed recently in the medical-biological beam of the Institute of High Energy Physics (Protvino). This ^{12}C beam has energy of about 400 A MeV and used for medical and biological studies. 2% irradiation homogeneity is provided by application of two rotating electrostatic wobblers. The steps taken in December 2016 and April 2017 resulted in the controllable irradiation with a particle density at the area of irradiation of 2000−4500 nuclei/cm^2.

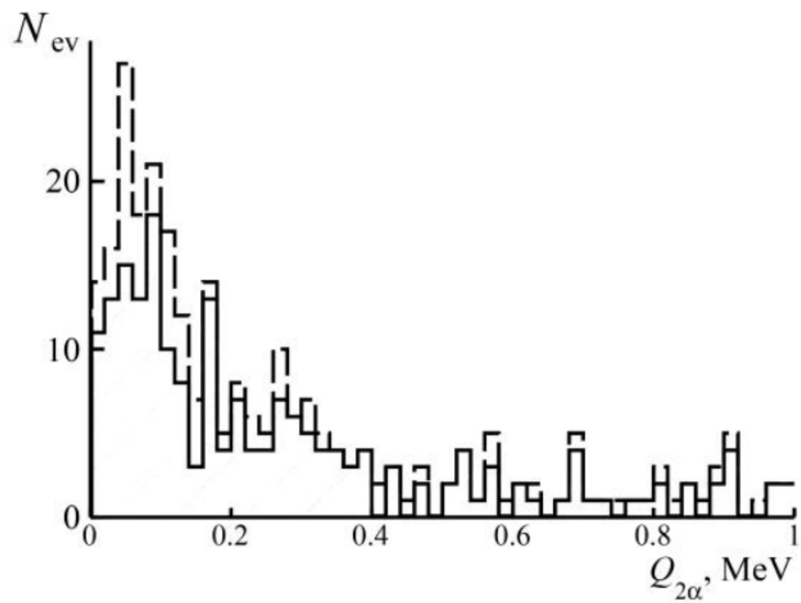


Consecutive frames of coherent dissociation $^{12}C \to 3\alpha$ at 1 *A* GeV/*c* ("white" star); arrow indicate interaction vertex; grain sizes are about 0.5 μm. Accelerated search for 3α-events the developed pellicles is carried out by scanning along bands that are transverse to the beam direction. By May 2018, 86 $^{12}C \to 3\alpha$ events, including 36 "white" stars, are found and measured in exposure at IHEP (Protvino).



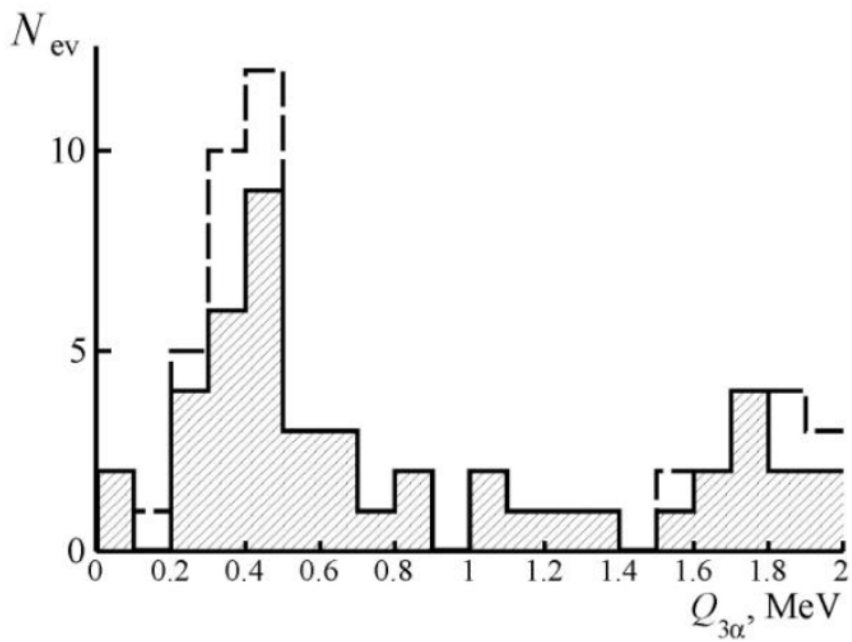
Dependence of calculated invariant masses of α-pairs $Q_{2\alpha}$ over opening angles in them $\Theta_{2\alpha}$ in events of dissociation of ^{12}C, ^{11}C and ^{10}B nuclei; momentum values are indicated in parentheses (A GeV/c).

The $Q_{2\alpha}$ distributions obtained on a basis of angular measurements of events $^{12}C \rightarrow 3\alpha$ at two values P_0 are presented jointly. Both are distributions do not differ within statistics. The region $Q_{2\alpha}$ < 200 keV contains a peak pressed to the origin which corresponds to decays of ^{8}Be. Although the ^{8}Be signal is present the $Q_{2\alpha}$ distribution appears to be significantly wider.



Distribution of α-pairs over invariant mass $Q_{2\alpha}$ < 1 MeV in the dissociation $^{12}C \rightarrow 3\alpha$ at 4.5 (solid) and 1 *A* GeV/*c* (added).

In the $Q_{3\alpha}$ distribution over the invariant mass of the α-triples there is a peak in the region $Q_{3\alpha} < 1$ MeV where HS decays could be reflected. For events at 4.5 *A* GeV/*c* the mean value for the events at the peak $\langle Q_{3\alpha} \rangle$ (at RMS) is 441 ± 34 (190) keV, and at 1 A GeV/c, respectively, 346 ± 28 (85) keV. According to the "soft" condition $Q_{3\alpha} < 1$ MeV in the 4.5 *A* GeV/*c* exposure 30 (of 186) events can be attributed to HS and 9 (of 86) including 5 "white" stars (of 36) in 1 *A* GeV/*c* exposure.

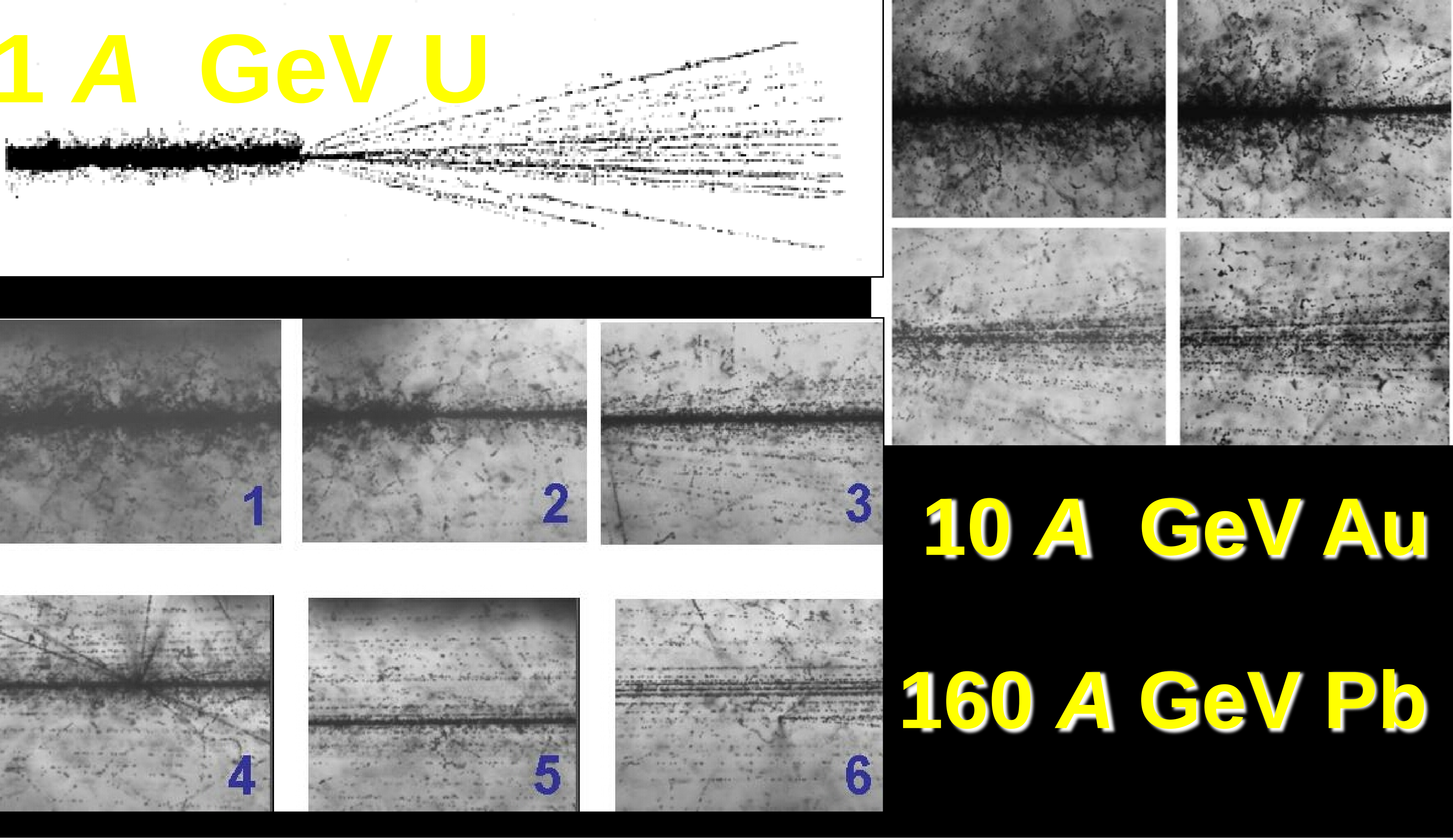


Distribution of α-triples over invariant mass $Q_{3\alpha} < 2$ MeV in dissociation of $^{12}C \rightarrow 3\alpha$. at 4.5 *A* GeV/*c* (solid) and 1 *A* GeV/c (added).

Conclusions

HS is identified at 4.5 and 1 *A* GeV/*c* on the basis of the most precise measurements in NTE performed by different researchers on different exposures that are separated in time by two decades. In itself, this fact demonstrates the thoroughness of the NTE method. As a result of the studies шt can be concluded that HS is observed with a contribution of about 10-15%. However, the method does not allow one to investigate the features of the HS decay. Reconstruction of HS on the invariant mass of relativistic α-triples can be used to study processes with the HS formation as an integral object at large momenta and for other fragmenting nuclei, except for ^{12}C.

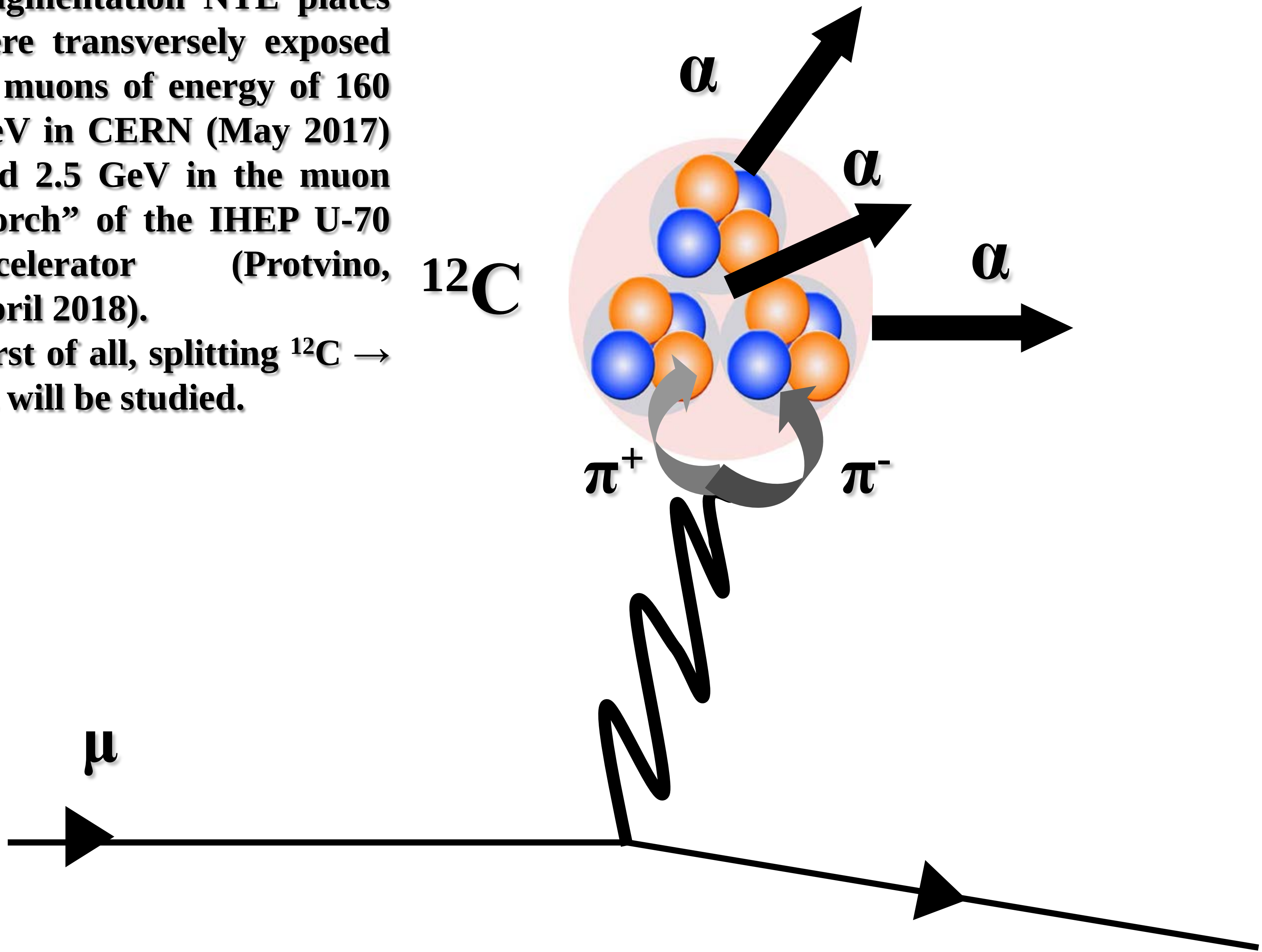
It is possible that HS can not be reduced to only the excitation of ^{12}C but can manifest itself as a universal object in the fragmentation of heavier nuclei, similarly to ^{8}Be. In this respect, the closest source of HS is the ^{14}N nucleus. Even more convenient are the ^{13}N and ^{13}C nuclei whose beams can be formed in the ^{14}N fragmentation. It can be expected that the nuclear-molecular objects ^{8}Be and HS will become reference points for the search for more complex states of sparse nuclear matter in the relativistic approach.



The studies of light nuclei are only the first steps toward complex cluster-nucleon ensembles He – H – n produced in the dissociation of heavy nuclei. The question that has to be answered is what kind of physics underlies the “catastrophic” destruction shown in Fig. Events of multiple fragmentation of relativistic nuclei down to a complete destruction into the lightest nuclei and nucleons without visible excitation of target nuclei were reliably observed in NTE for Au and Pb and even U projectile nuclei. The existence of this phenomenon is certain. It is possible that it confirms the essential role of the long-range quantum electrodynamics interaction. The charges of heavy nuclei make possible multiphoton exchanges and transitions in many-particle states.

In order to study the origin of nuclear multiple fragmentation NTE plates were transversely exposed to muons of energy of 160 GeV in CERN (May 2017) and 2.5 GeV in the muon “torch” of the IHEP U-70 accelerator (Protvino, April 2018).

First of all, splitting $^{12}C \to 3\alpha$ will be studied.



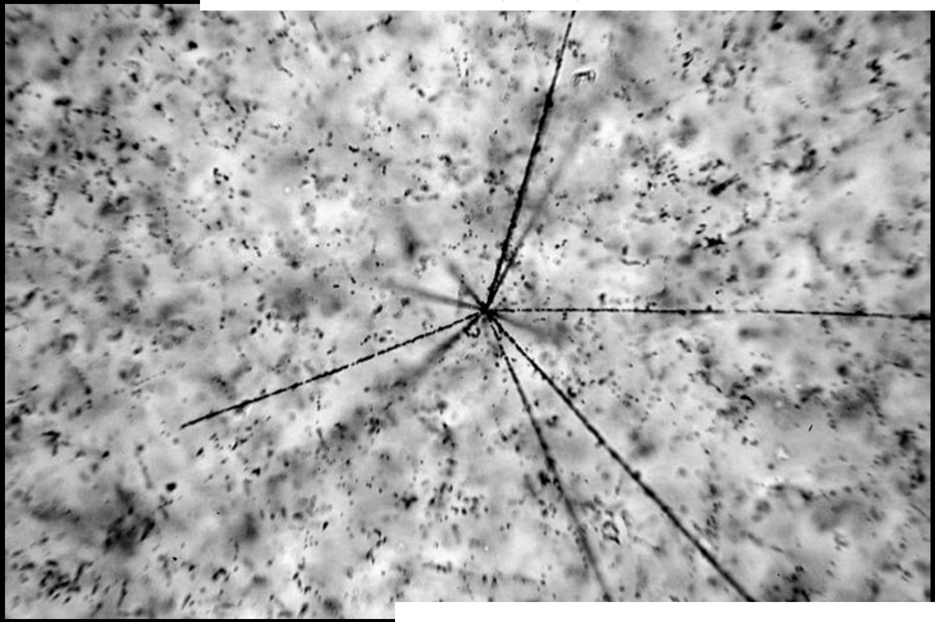
Study of nuclear multifragmentation induced by ultrarelativistic μ-mesons in nuclear track emulsion

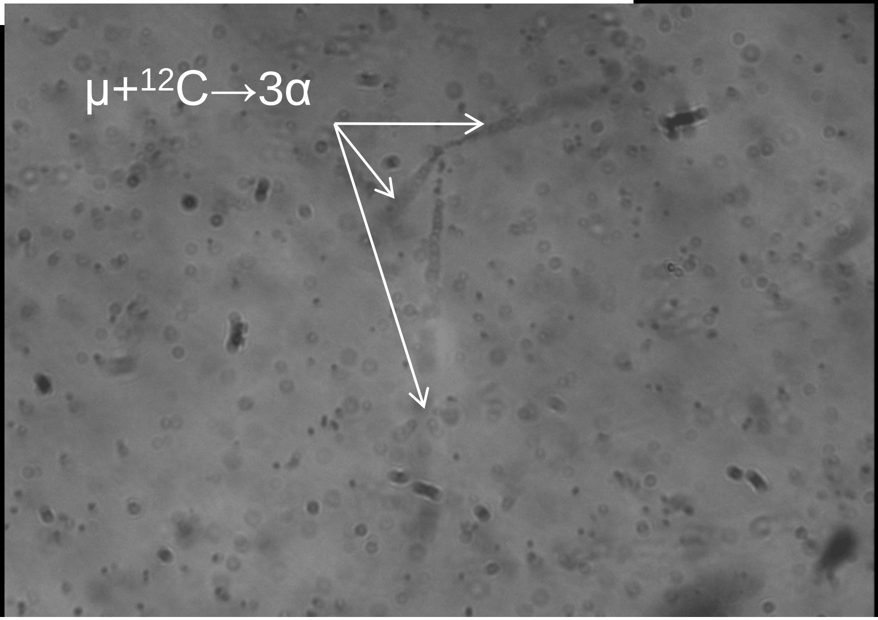
D A Artemenkov[1,2], V Bradnova[1], E Firu[3], N K Kornegrutsa[1], M Haiduc[3], K Z Mamatkulov[1], R R Kattabekov[1], A Neagu[3], P A Rukoyatkin[1], V V Rusakova[1], R Stanoeva[4], A A Zaitsev[1,5], P I Zarubin[1,5] and I G Zarubina[1,5]

[1] Joint Institute for Nuclear Research, Dubna, Russia
[2] National Research Nuclear University MEPhI (Moscow Engineering Physics Institute), Kashirskoe highway 31, Moscow, 115409, Russia
[3] Institute of Space Science, Magurele, Romania
[4] South-Western University, Blagoevgrad, Bulgaria
[5] P. N. Lebedev Physical Institute of the Russian Academy of Sciences, Moscow, Russia

E-mail: zarubin@lhe.jinr.ru

Abstract. Exposures of test samples of nuclear track emulsion were analyzed. The formation of high-multiplicity nuclear stars was observed upon irradiating nuclear track emulsions with ultrarelativistic muons. Kinematical features studied in this exposure of nuclear track emulsions for events of the muon-induced splitting of carbon nuclei to three α-particles are indicative of the nuclear-diffraction interaction mechanism.





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n (14.1 MeV) + ^{12}C → 3α

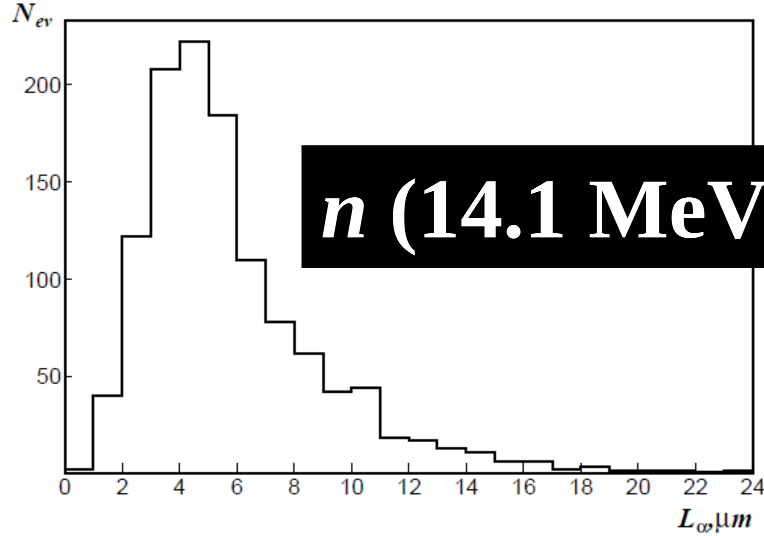


FIG. 1: Distribution of α-particles over ranges L_α.

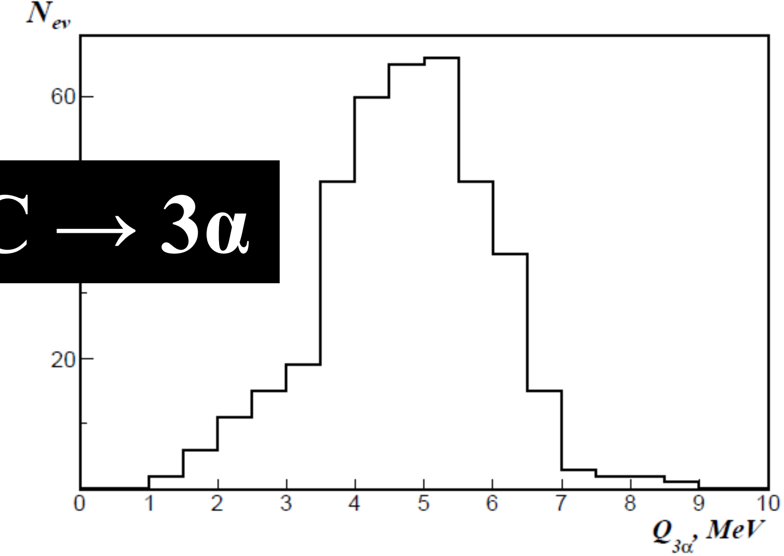


FIG. 3: Distribution triples of α-particles over energy $Q_{3\alpha}$.

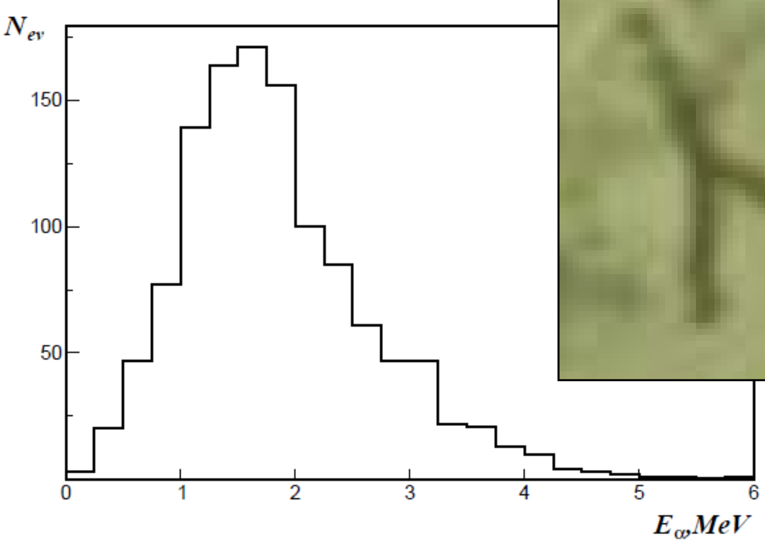


FIG. 2: Distribution of α-particles over energy E_α.

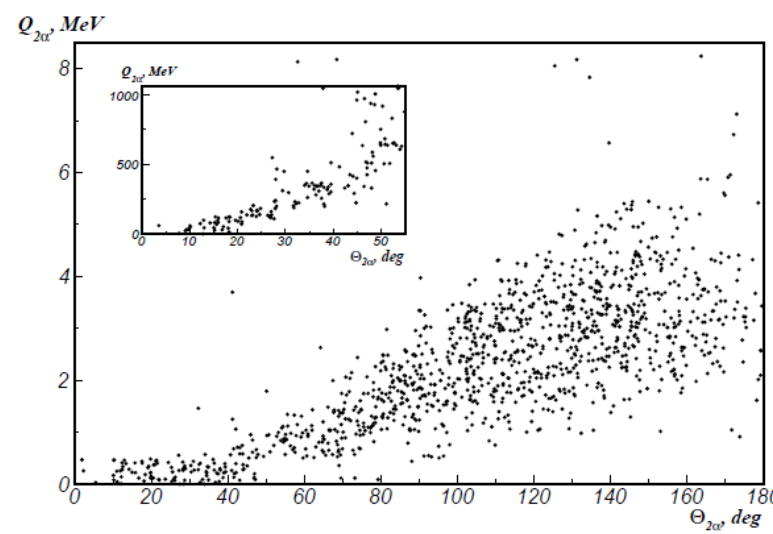
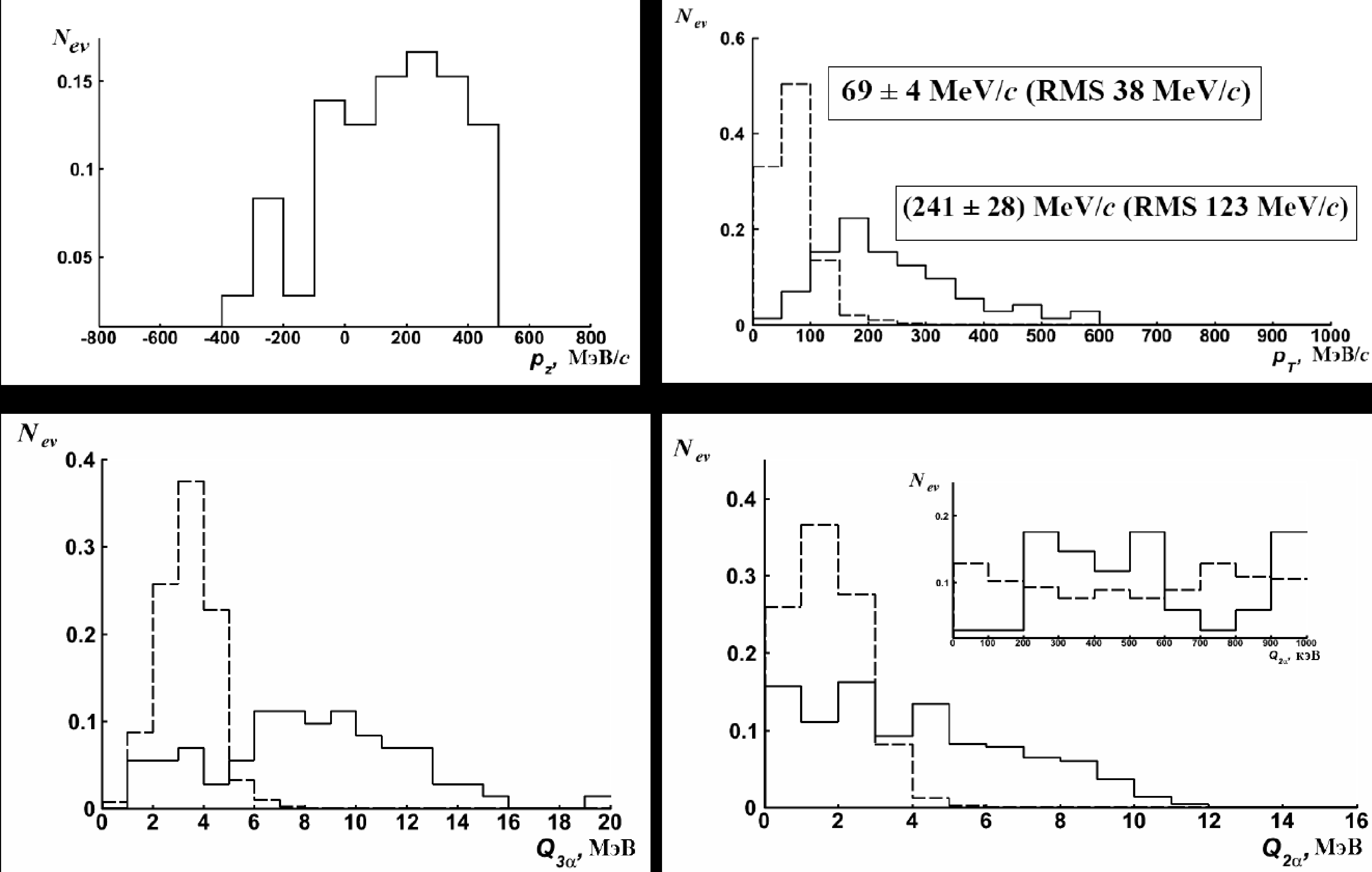


FIG. 4: Correlation over energy $Q_{2\alpha}$ and opening angles $\Theta_{2\alpha}$ in α-particle pairs.



72 stars containing only a triple of *b*-particles stopped in NTE are assigned to the disintegration $\mu + {}^{12}C \rightarrow 3\alpha$ and compared with the case $n(14.1\ \text{MeV}) + {}^{12}C \rightarrow 3\alpha + n$.

Three stacks of 10 layers with an emulsion thickness 1000 μm and 3 of 10 layers with a thickness of 200 μm are irradiated perpendicular to the beam. Nearby monitor is 8 × 8 cm^2. The fluences are 9.3 × 10^6, 45 × 10^6, and 57 × 10^6. The average energy of muons is 2.5 GeV on average.

3 stacks (2 of 10 layers 100 microns and 1 of 10 200 microns) are irradiated in the hadrons beam: pions - 60%, protons - 35% and kaons - 5%.