



BECQUEREL
PROJECT

Проект
БЕККЕРЕЛЬ

Beryllium (Boron)

Clustering

Quest in

Relativistic Multifragmentation

<http://becquerel.jinr.ru>

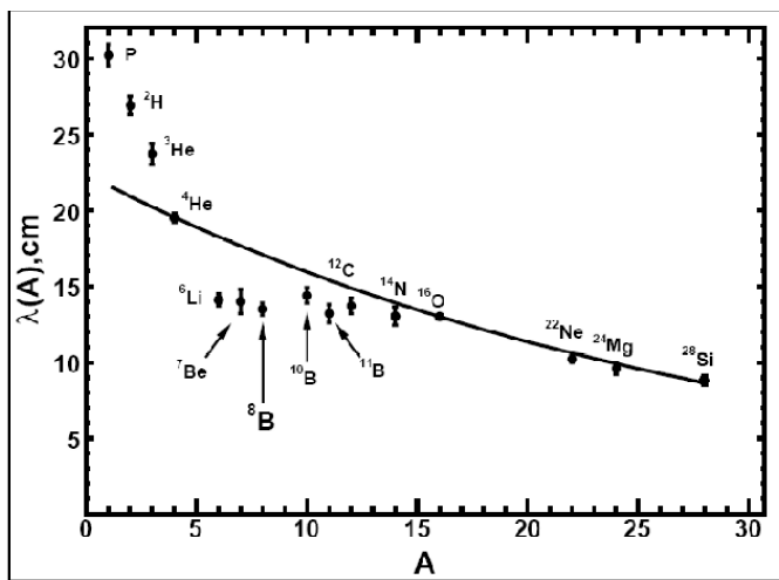
Nuclear clustering in relativistic dissociation of light nuclei: findings and prospects of research

*Andrei Zaitsev**

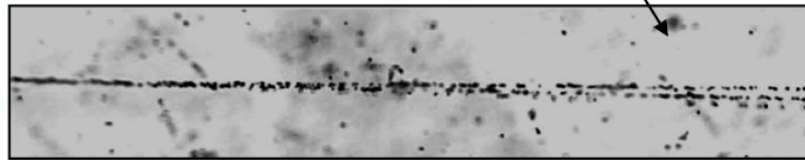
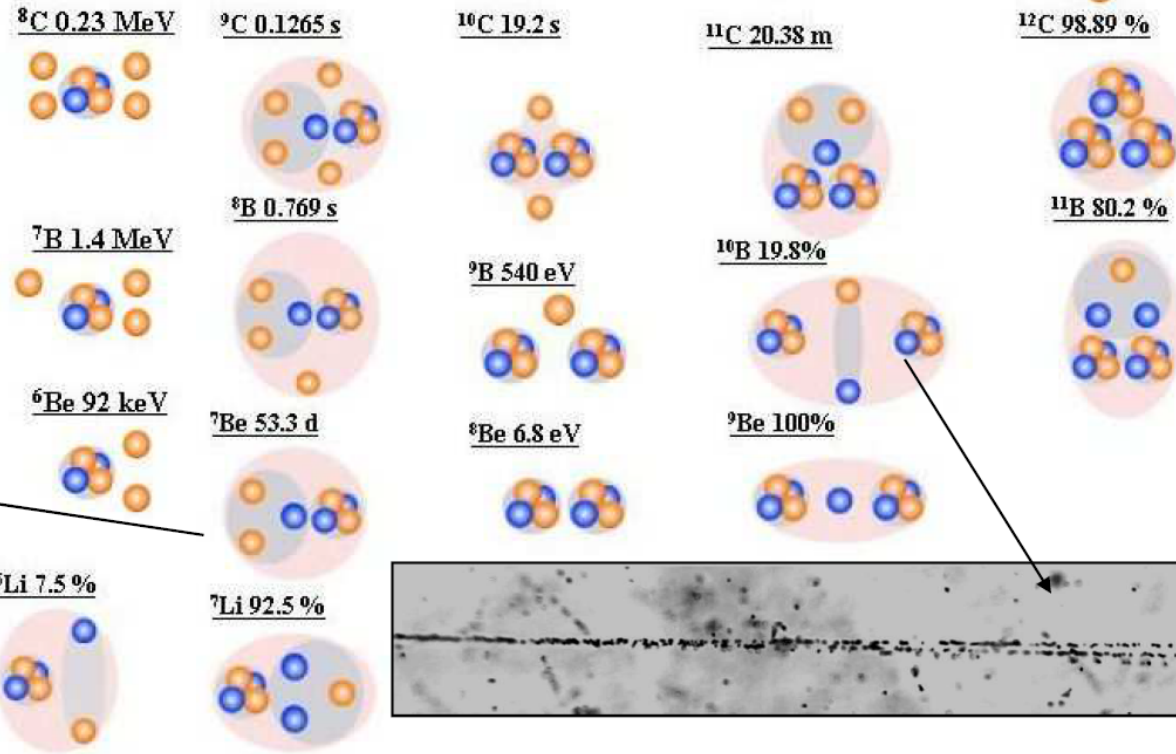
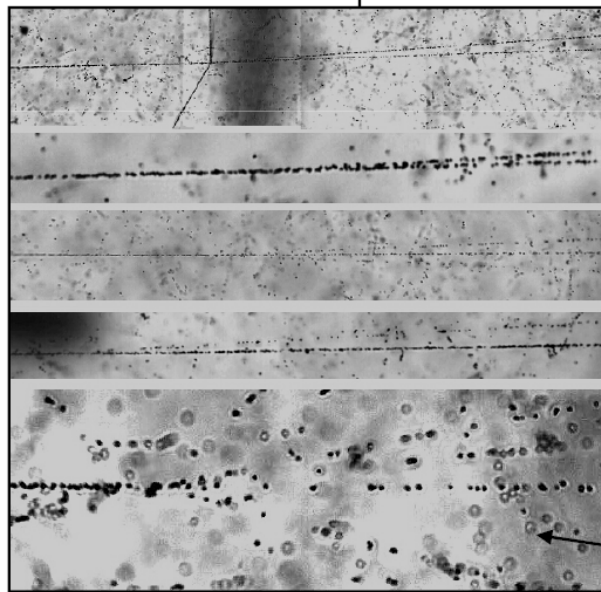
Pavel Zarubin

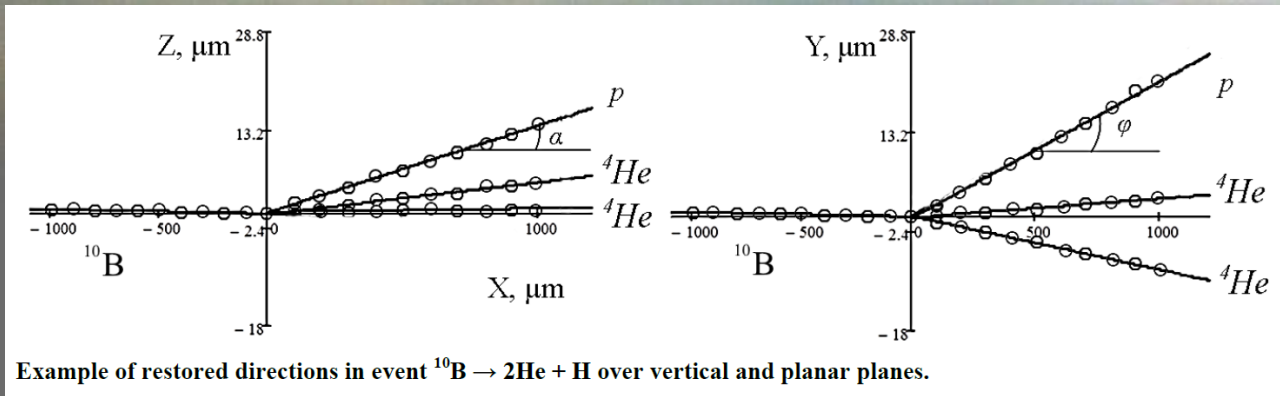
BECQUEREL experiment
JINR, Dubna



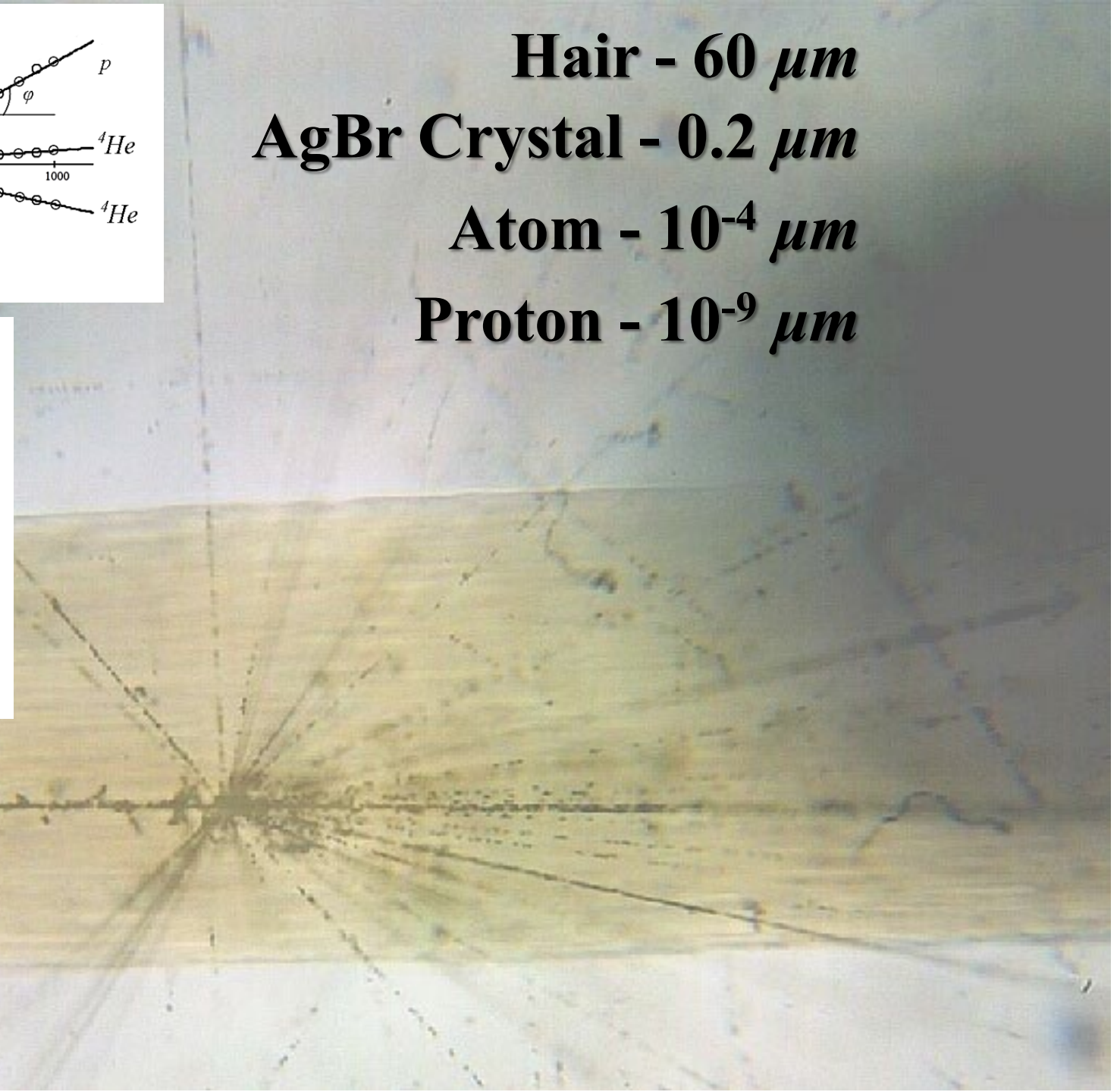
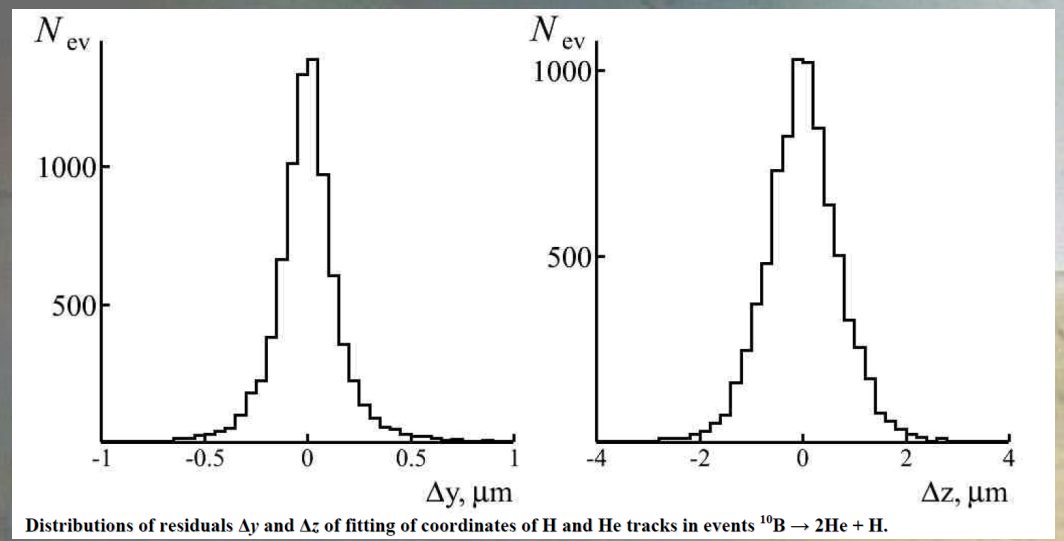


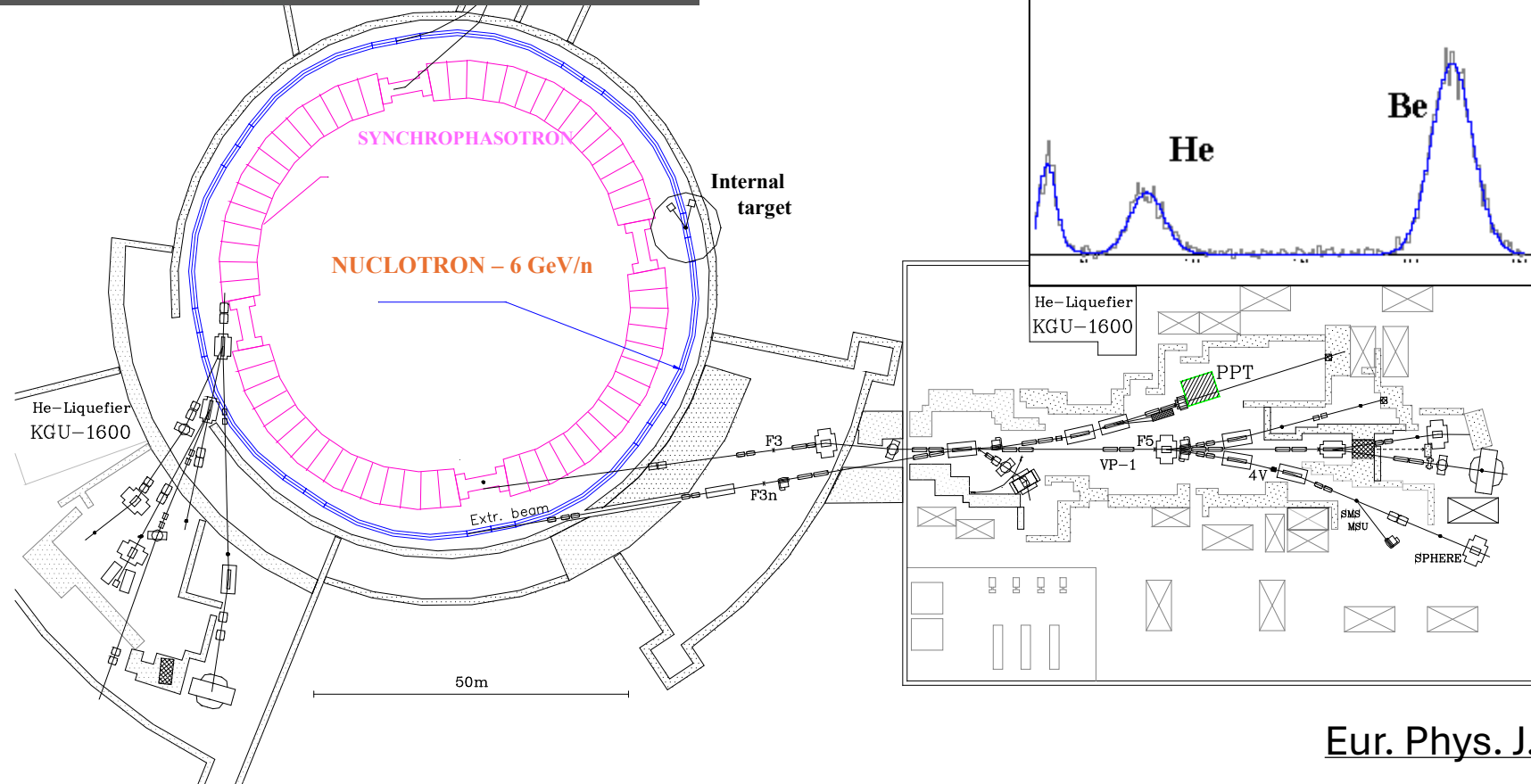
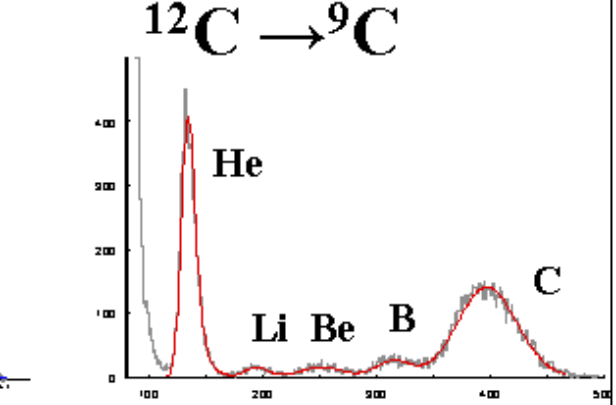
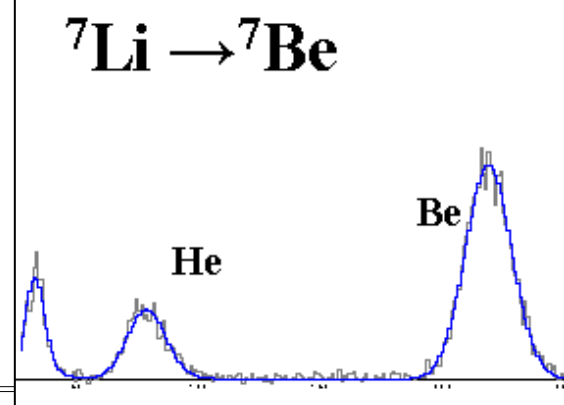
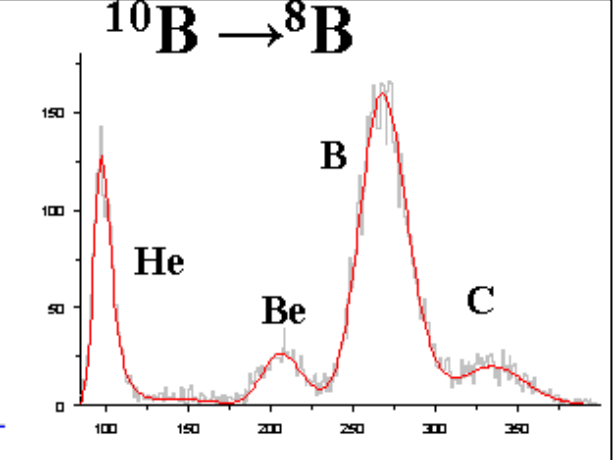
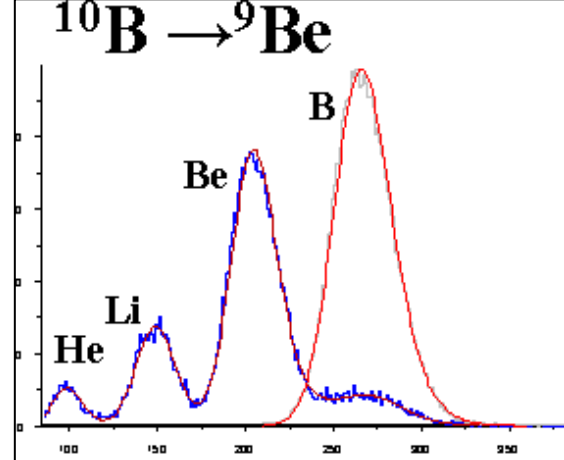
The use of accelerated nuclei, including radioactive ones, qualitatively diversifies the cluster spectroscopy. Configuration overlap of a fragmenting nucleus and final cluster states manifests in the dissociation at the periphery of the target nucleus. The definition of interactions as peripheral ones is simplified at energy above 1A GeV due to the collimation of the fragments. The detection thresholds disappear and energy loss in detector material are minimal. These statements are particularly true for the light nuclei with an excess of protons.

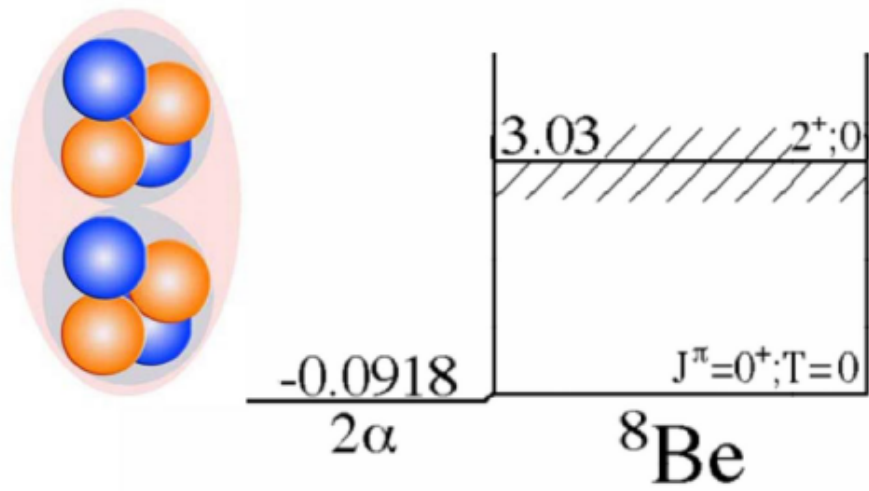




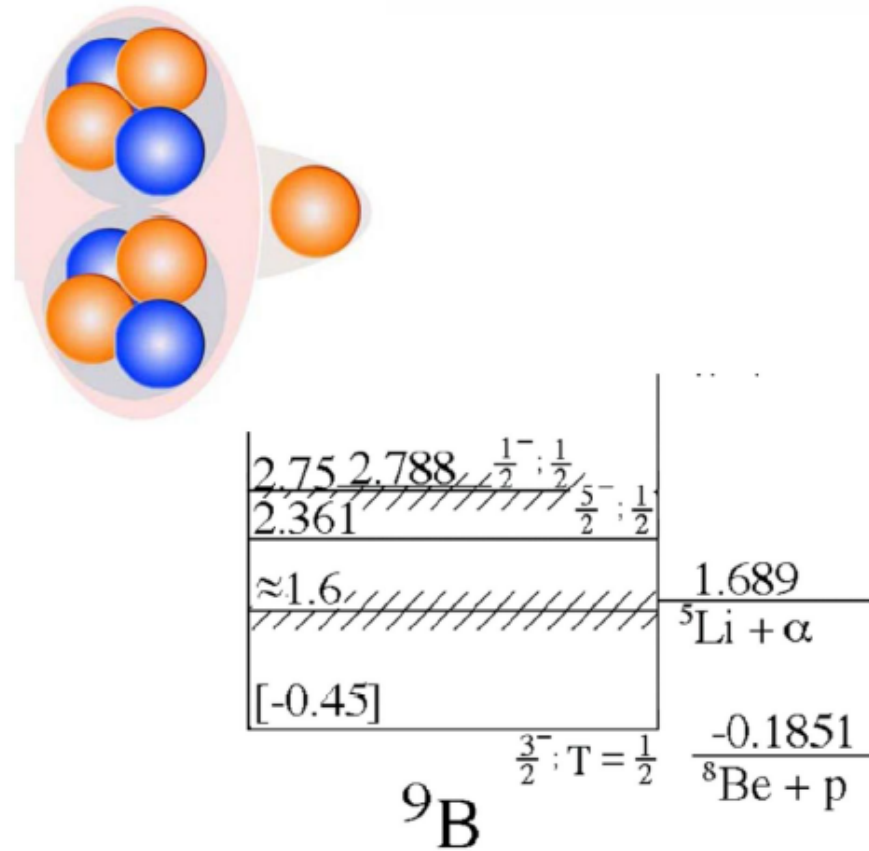
Hair - $60 \mu\text{m}$
AgBr Crystal - $0.2 \mu\text{m}$
Atom - $10^{-4} \mu\text{m}$
Proton - $10^{-9} \mu\text{m}$







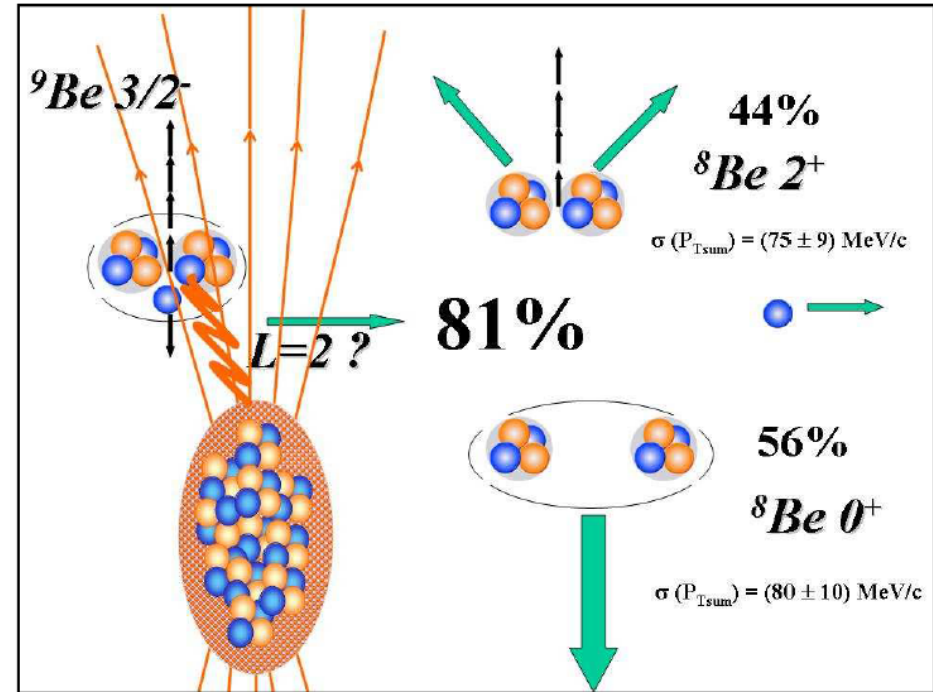
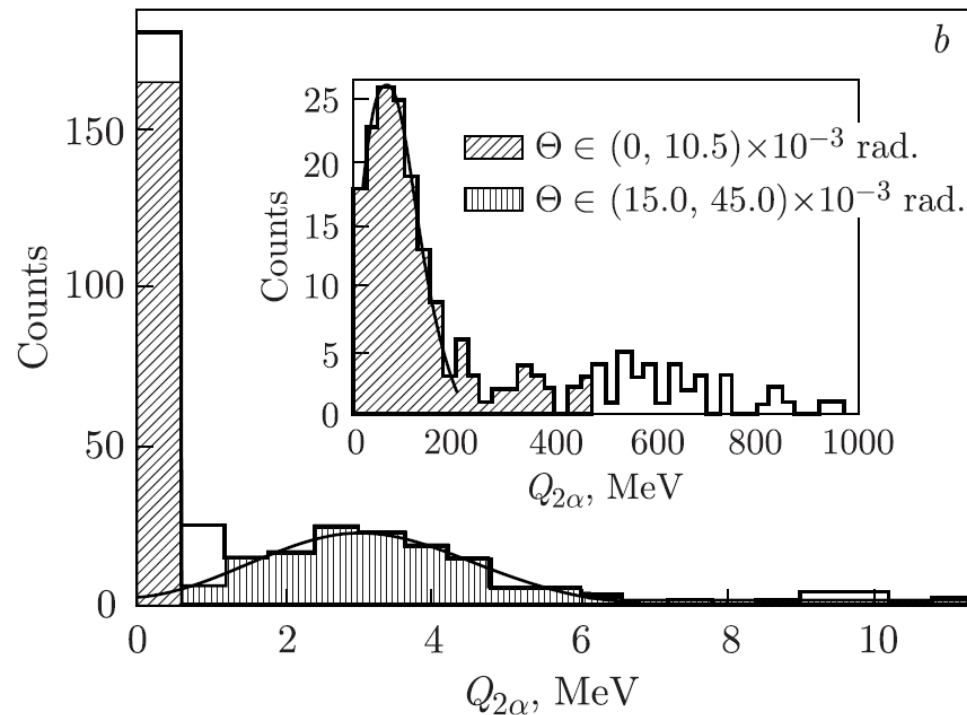
E_x (MeV \pm keV)	$J^\pi; T$	Γ_{cm} (keV)	Decay
g.s.	$0^+; 0$	$5.57 \pm 0.25 \text{ eV}^i$	α
3.03 ± 10^i	$2^+; 0$	1513 ± 15^i	α
ij 11.35 ± 150^i	2^+ $4^+; 0$	$\approx 3500^b$	α



E_x^a (MeV \pm keV)	$J^\pi; T$	$\Gamma_{\text{c.m.}}$ (keV)	Decay
g.s.	$\frac{3}{2}^-; \frac{1}{2}$	0.54 ± 0.21	p
$\approx 1.6^b$			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	n

2A GeV/c ${}^9\text{Be} \rightarrow 2\alpha$ “white” star

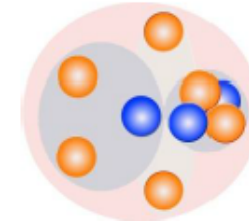
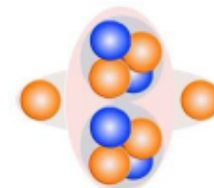
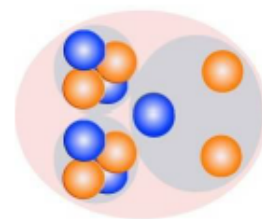
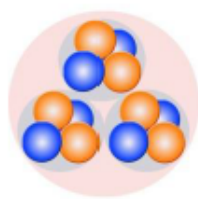
The secondary ${}^9\text{Be}$ beam was obtained by fragmentation of accelerated ${}^{10}\text{B}$ nuclei. When scanning the exposed emulsion 500 events ${}^9\text{Be} \rightarrow 2\alpha$ in a fragmentation cone of 0.1 rad have been found. About 81% α -pairs form roughly equal groups on $\Theta_{2\alpha}$: “narrow” ($0 < \Theta_n < 10.5$ mrad) and “wide” ($15.0 < \Theta_w < 45.0$ mrad) ones. The Θ_n pairs are consistent with ${}^8\text{Be}$ decays from the ground state 0^+ , and pairs Θ_w - from the first excited state 2^+ . The Θ_n and Θ_w fractions are equal to 0.56 ± 0.04 and 0.44 ± 0.04 . These values are well corresponding to the weights of the ${}^8\text{Be}$ 0^+ and 2^+ states $\omega_{0^+} = 0.54$ and $\omega_{2^+} = 0.47$ in the two-body model $n - {}^8\text{Be}$, used to calculate the magnetic moment of the ${}^9\text{Be}$ nucleus.



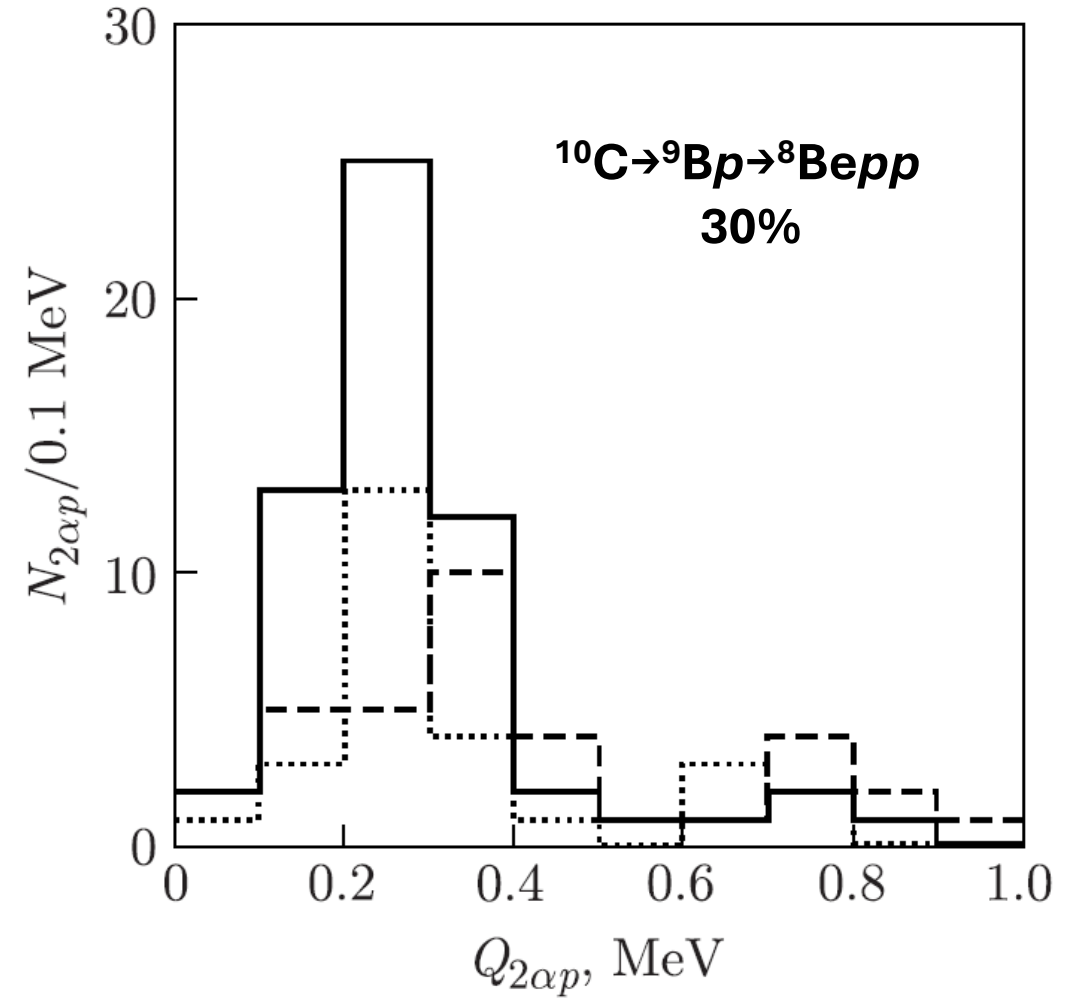
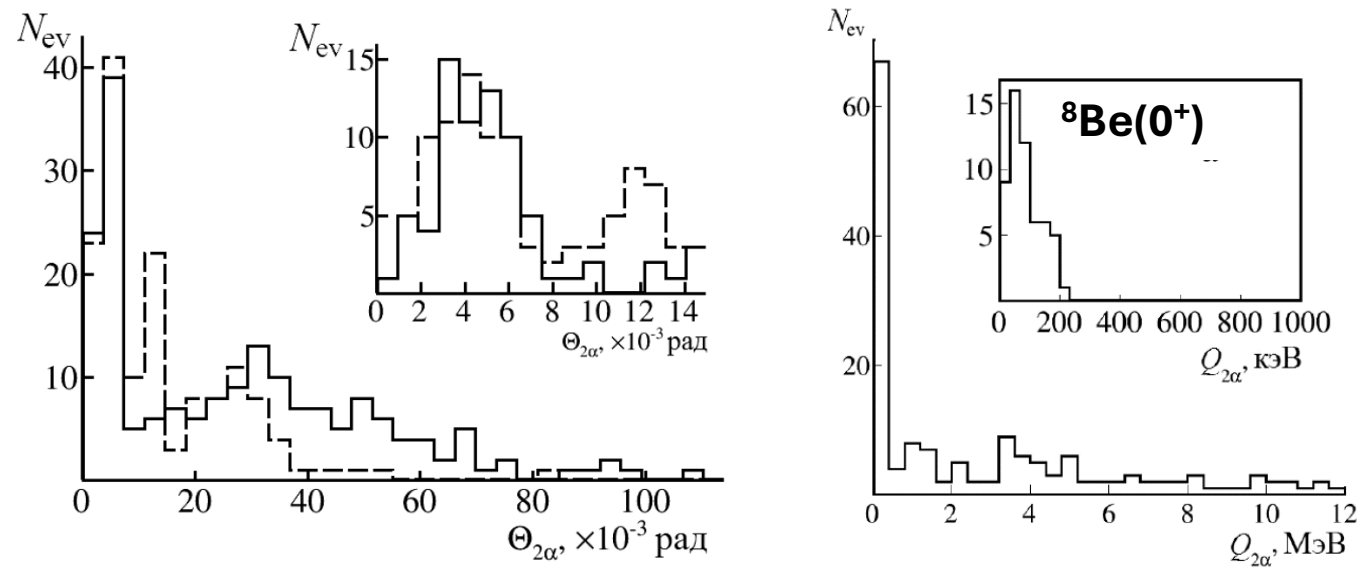
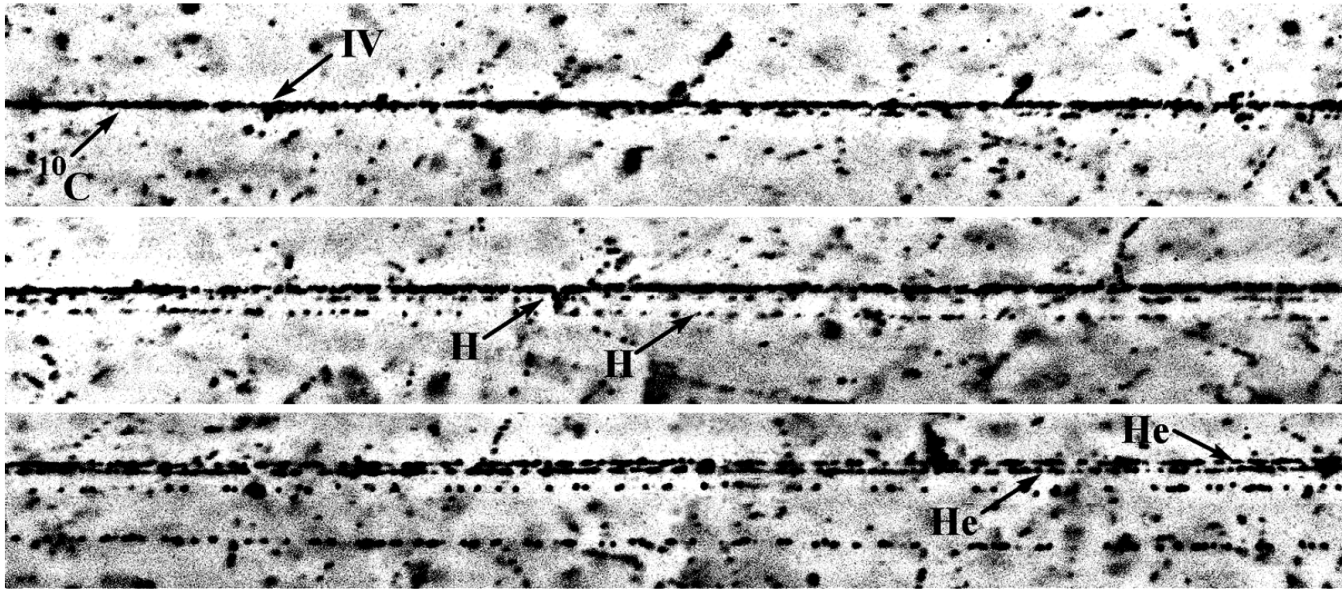
For the coherent dissociation ${}^9\text{Be} \rightarrow 2\alpha + n$, the average value of the total α -pair transverse momentum is equal to $\langle P_{\text{Tsum}} \rangle \approx 80 \text{ MeV/c}$ in correspondence with the Goldhaber statistical model. So, it can be assigned to the average transverse momentum carried away by neutrons. For the ${}^9\text{Be}$ coherent dissociation through the ${}^8\text{Be}$ 0^+ and 2^+ states there is no differences in the values $\langle P_{\text{Tsum}} \rangle$, which points to a “cold fragmentation” mechanism. The whole complex of these observations may serve as an evidence of the simultaneous presence of the ${}^8\text{Be}$ 0^+ and 2^+ states with similar weights in the ground state of the nucleus ${}^9\text{Be}$.

Charge topology of “white” stars

Channel	^{12}C	^{11}C	^{10}C	^9C
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 %)



NTE exposure by ^{10}C beam

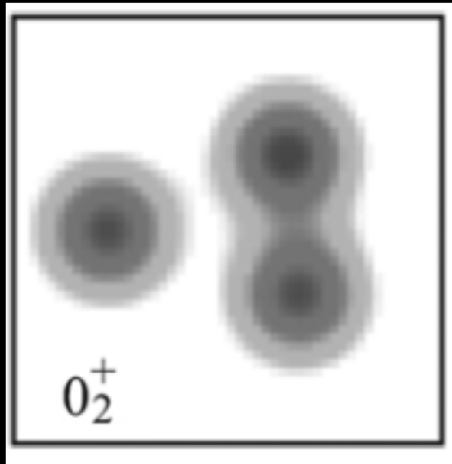


ON NUCLEAR REACTIONS OCCURRING IN VERY HOT STARS. I. THE SYNTHESIS OF ELEMENTS FROM CARBON TO NICKEL

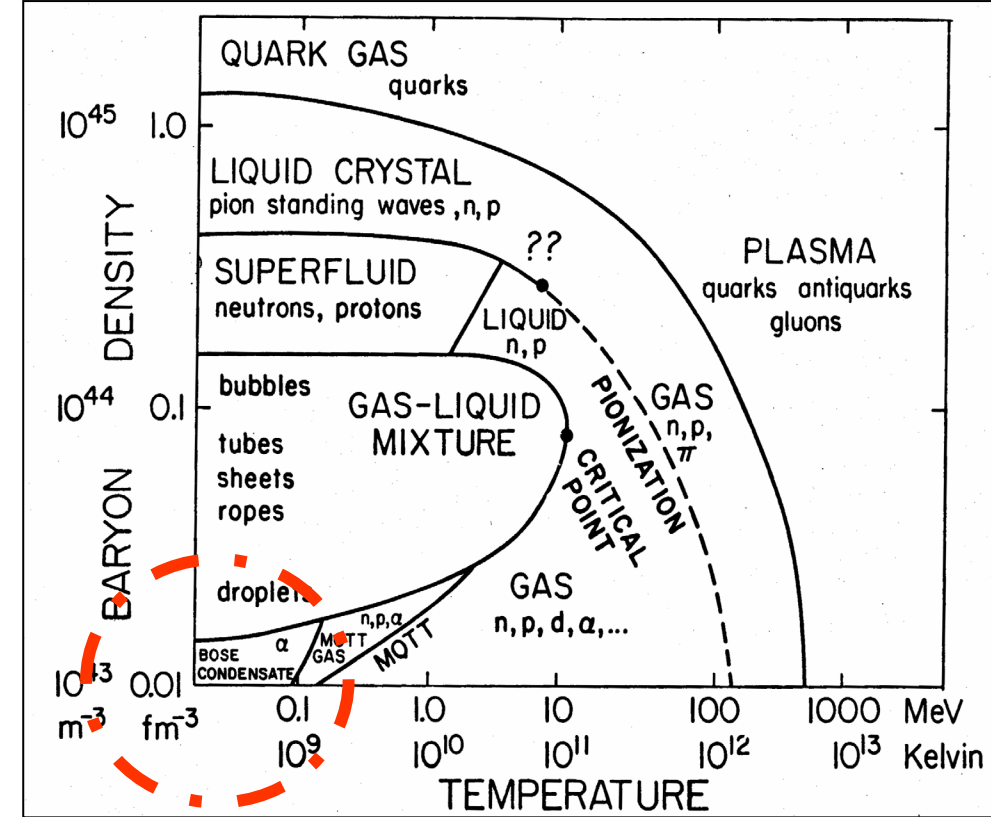
F. HOYLE*

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

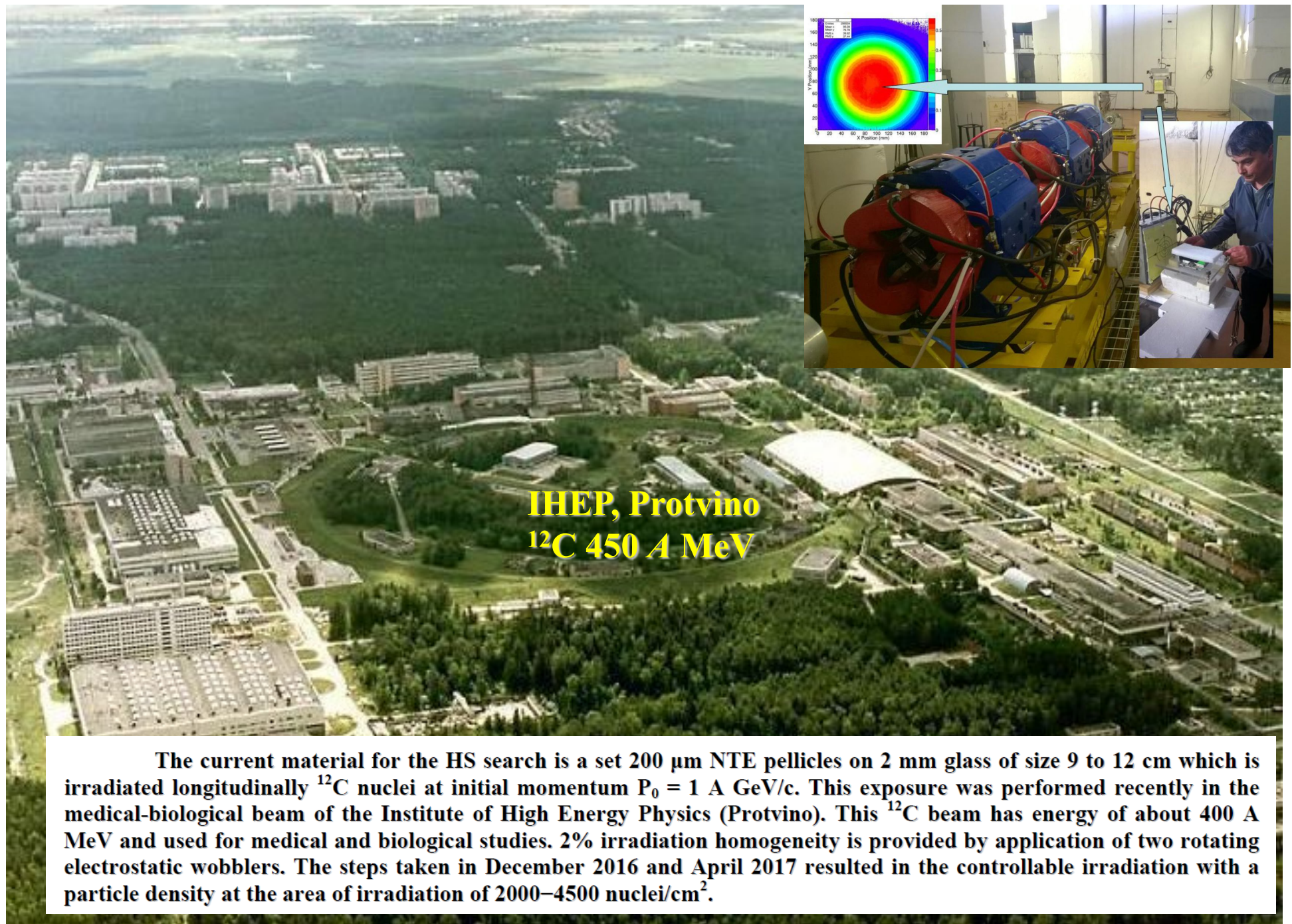
Received December 22, 1953



E_x in ^{12}C (MeV \pm keV)	$J^\pi; T$	$\Gamma_{c.m.}$ (keV)	Decay
14.08	4^+		
13.35	(2^-)		
12.71	1^+		
11.83	2^-		
10.84	1^-		
10.3	(0^+)		
9.641	3^-		
7.6542	0^+		
4.4389	2^+	$(10.8 \pm 0.6) \times 10^{-6}$	γ
7.6542 \pm 0.15	$0^+; 0$	$(8.5 \pm 1.0) \times 10^{-8}$	γ, π, α

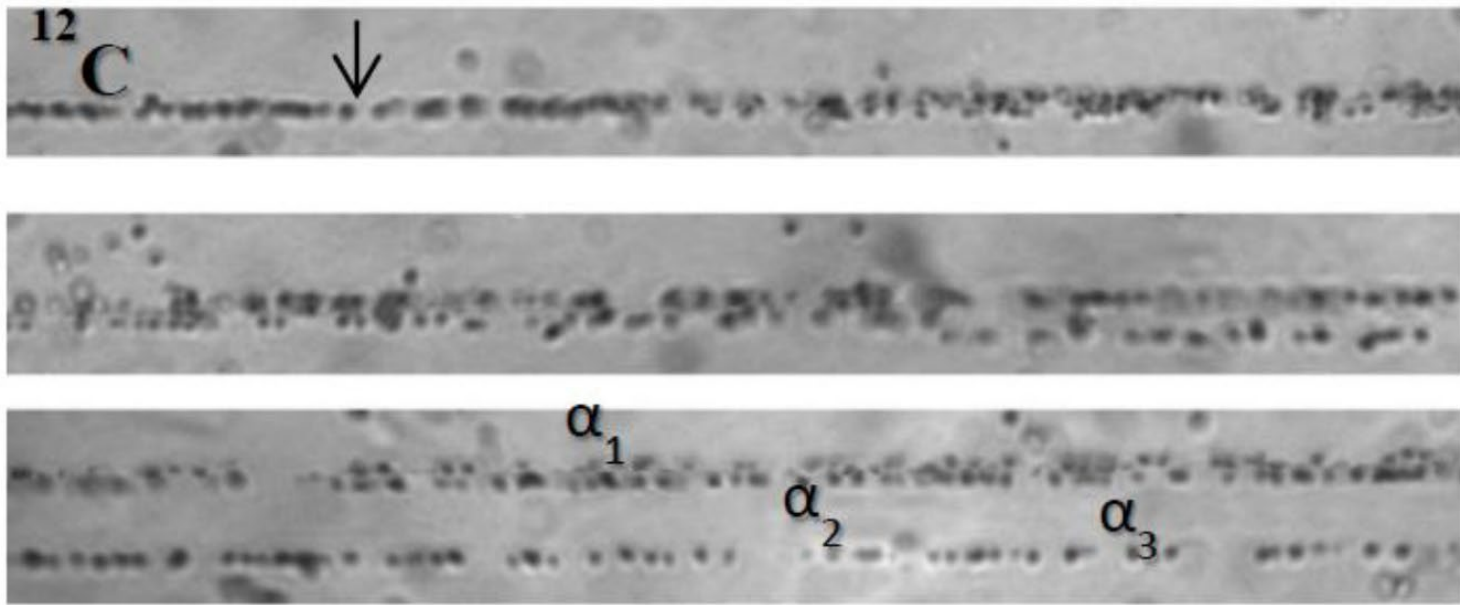


The second excited state of the ^{12}C nucleus is named after the astrophysicist F. Hoyle who postulated its existence to explain the prevalence of the ^{12}C isotope. Following an accurate prediction of the HS energy it was experimentally confirmed that the ^{12}C nucleus has the excited state located 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.

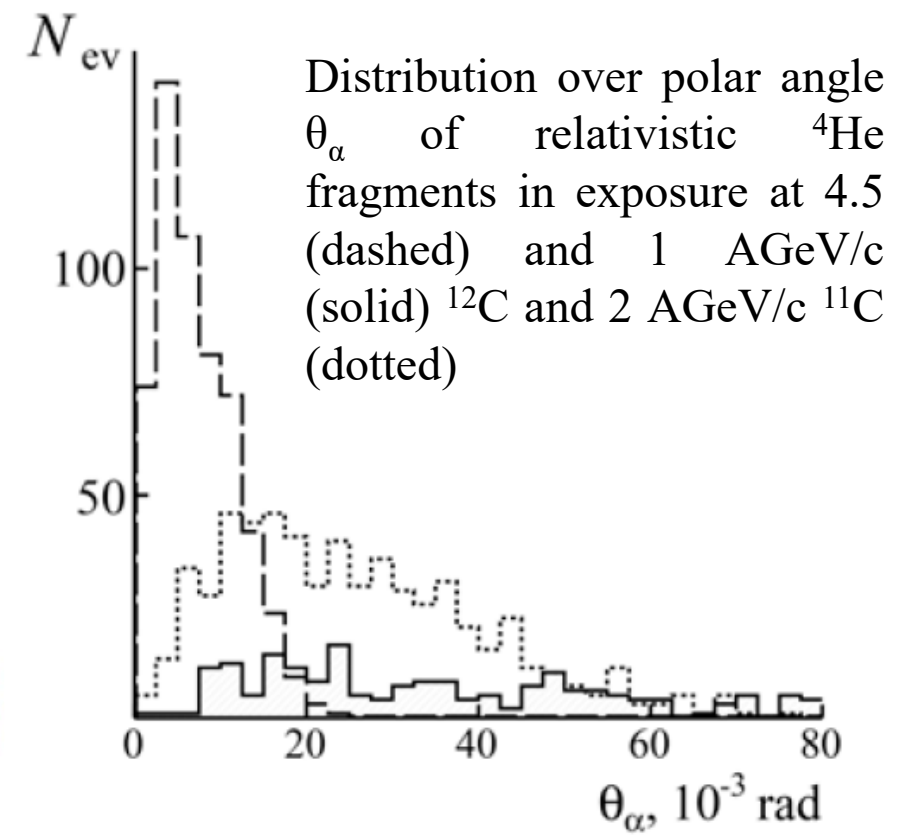


IHEP, Protvino
 ^{12}C 450 A MeV

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/cm².



Consecutive frames of coherent dissociation $^{12}\text{C} \rightarrow 3\alpha$ at $1 A \text{ GeV}/c$ ("white" star); arrow indicate interaction vertex; grain sizes are about $0.5 \mu\text{m}$. 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 $^{12}\text{C} \rightarrow 3\alpha$ events, including 36 "white" stars, are found and measured in exposure at IHEP (Protvino).



Main results:

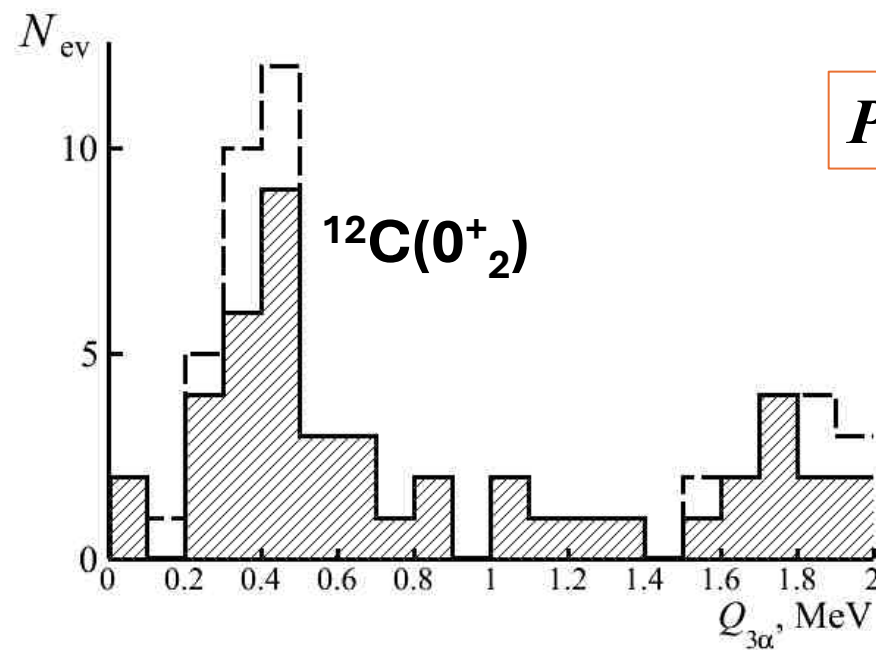
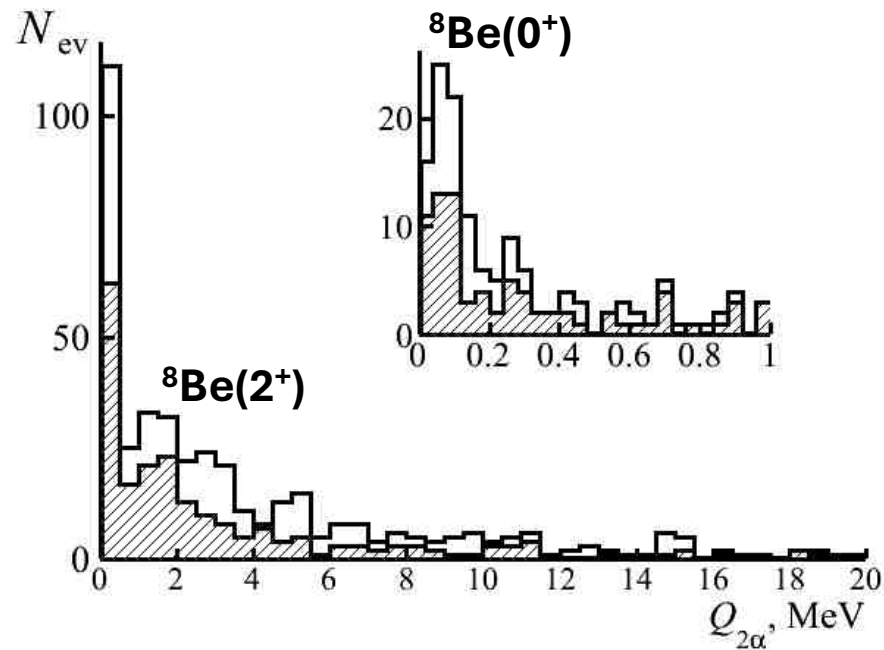
The $Q_{2\alpha}$ distributions obtained on a basis of angular measurements of events $^{12}\text{C} \rightarrow 3\alpha$ at two values P_0 are presented jointly. The region $Q_{2\alpha} < 200$ keV contains a peak pressed to the origin which corresponds to decays of ^8Be .



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. According to the “soft” condition $Q_{3\alpha} < 1$ MeV the contribution of HS is estimated to be about 10–15% in both exposures.

Nuclear track emulsion in search for the Hoyle-state in dissociation of relativistic ^{12}C nuclei[☆]

D.A. Artemenkov^a, V. Bradnova^a, G.I. Britvich^b, E. Firu^c, M. Haiduc^c, V.A. Kalinin^b, S.P. Kharlamov^d, N.K. Kornegrutsa^a, M. Yu Kostin^b, A.V. Maksimov^b, E. Mitseva^{a,e}, A. Neagu^c, V.A. Pikalov^b, M.K. Polkovnikov^b, V.V. Rusakova^a, R. Stanoeva^{e,f}, A.A. Zaitsev^{a,d}, P.I. Zarubin^{a,d,*}, I.G. Zarubina^a



$$P_1 \approx P_0$$

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

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

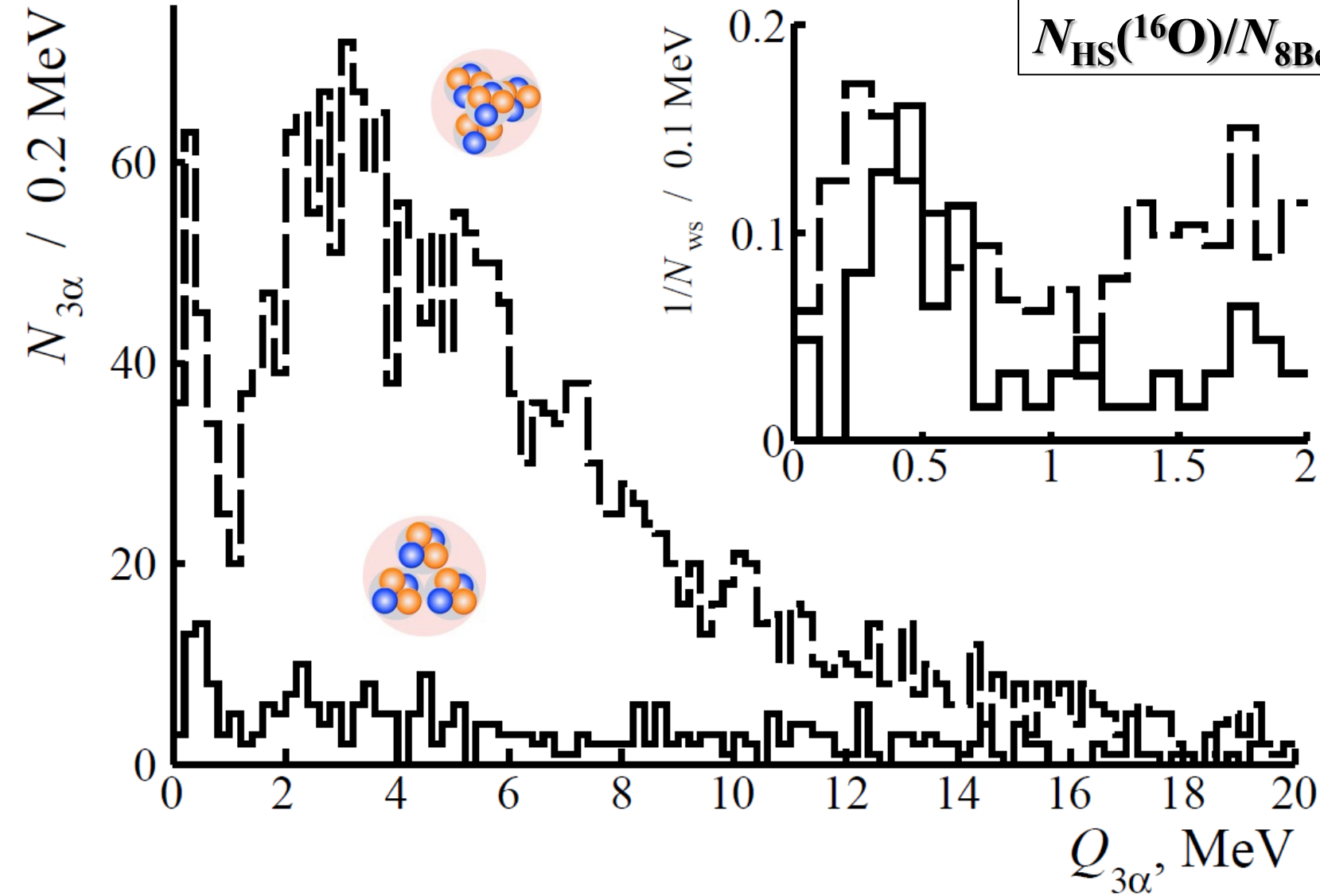
$$P_z = P_0 \cdot A \cdot \sin(\alpha)$$

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

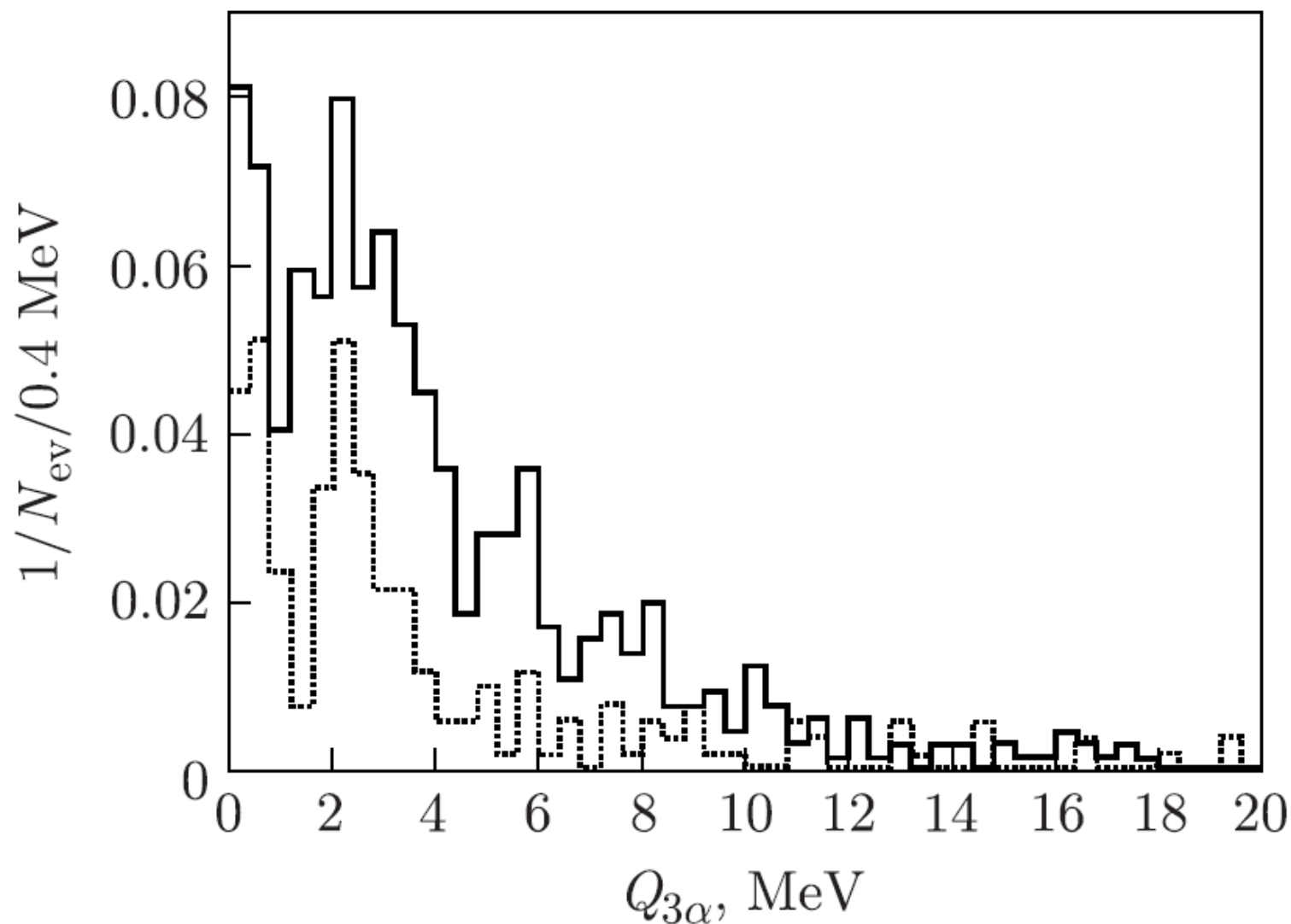
$$\Theta_{12} = \frac{P_{x1} \cdot P_{x2} + P_{y1} \cdot P_{y2} + P_{z1} \cdot P_{z2}}{P_1 \cdot P_2}$$

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

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



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



<u>10.847</u>	<u>1⁻; 0</u>
<u>10.3</u>	<u>(0⁺); 0</u>
<u>9.87</u>	<u>2⁺; 0</u>
9.641	3 ⁻ ; 0
7.654	0 ⁺ ; 0
4.4398	2 ⁺ ; 0
	0 ⁺ ; 0

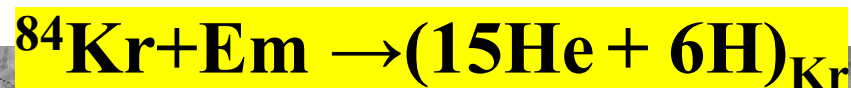
^{12}C

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

A.A. Zaitsev^{a,b,*}, D.A. Artemenkov^a, V.V. Glagolev^a, M.M. Chernyavsky^b, N.G. Peresadko^b, V.V. Rusakova^a, P.I. Zarubin^{a,b}

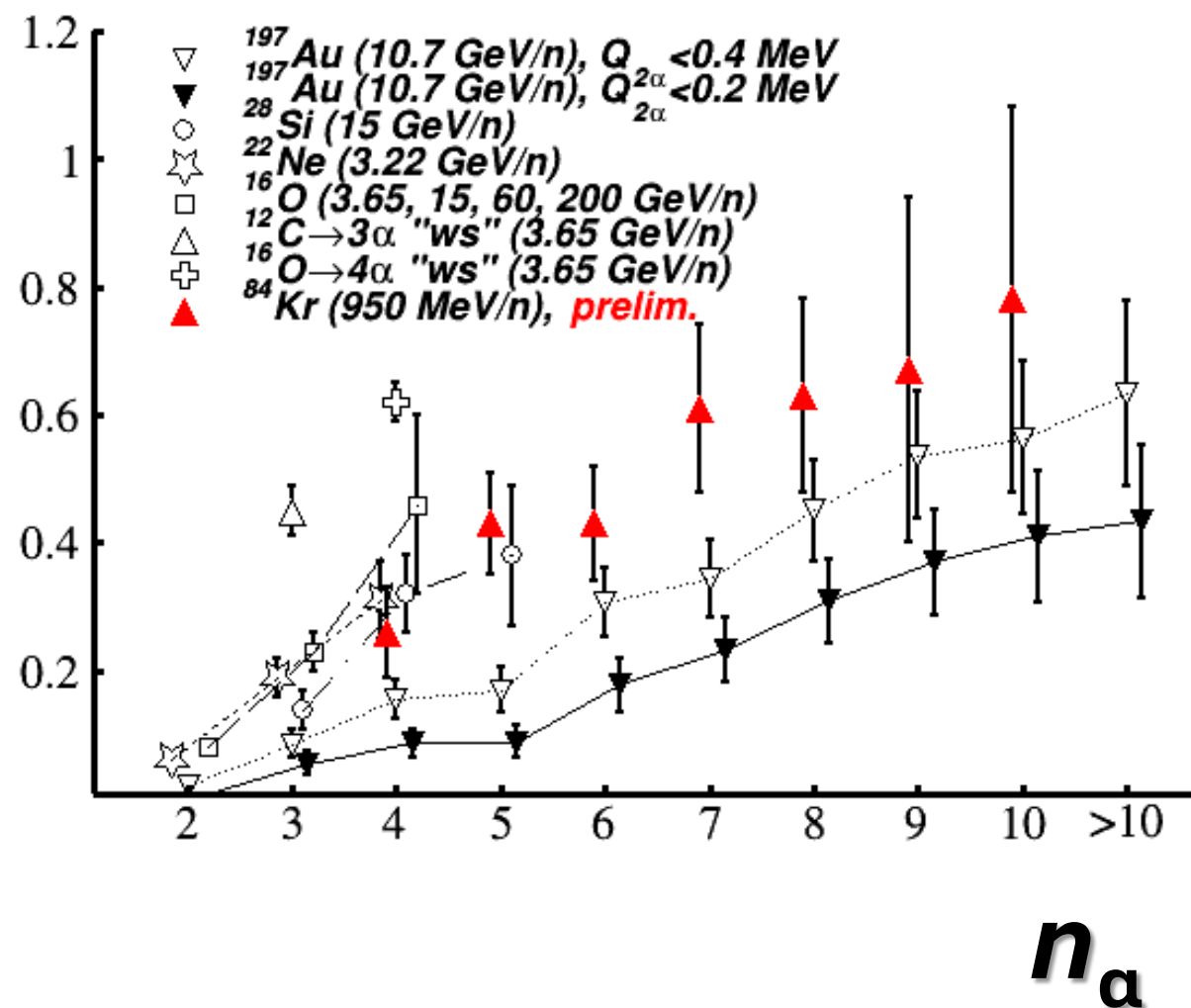
^a Joint Institute for Nuclear Research, Dubna 141980, Russia

^b Lebedev Physical Institute, Russian Academy of Sciences, Moscow 119991, Russia



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.

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



Applications of film detectors

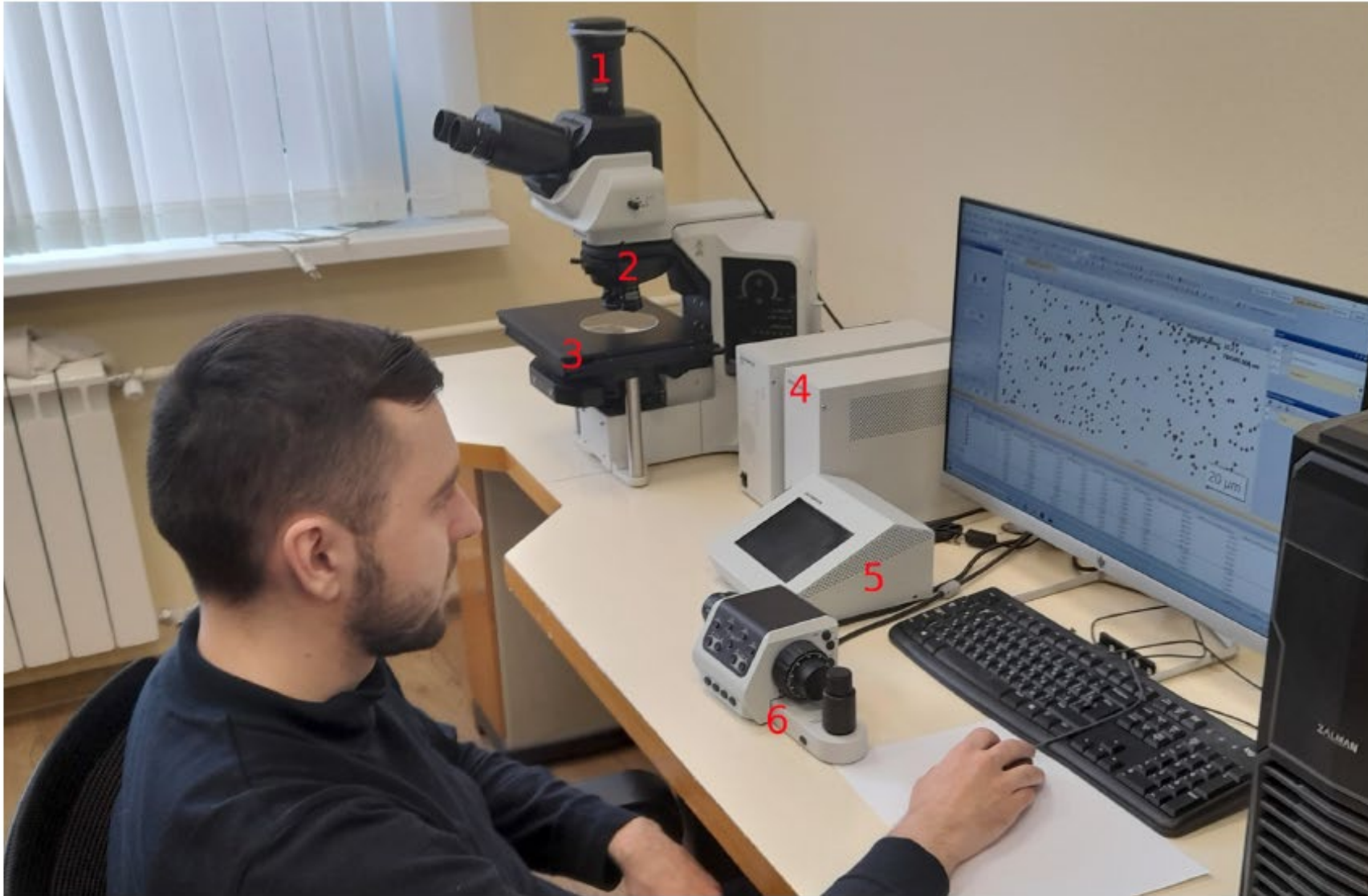
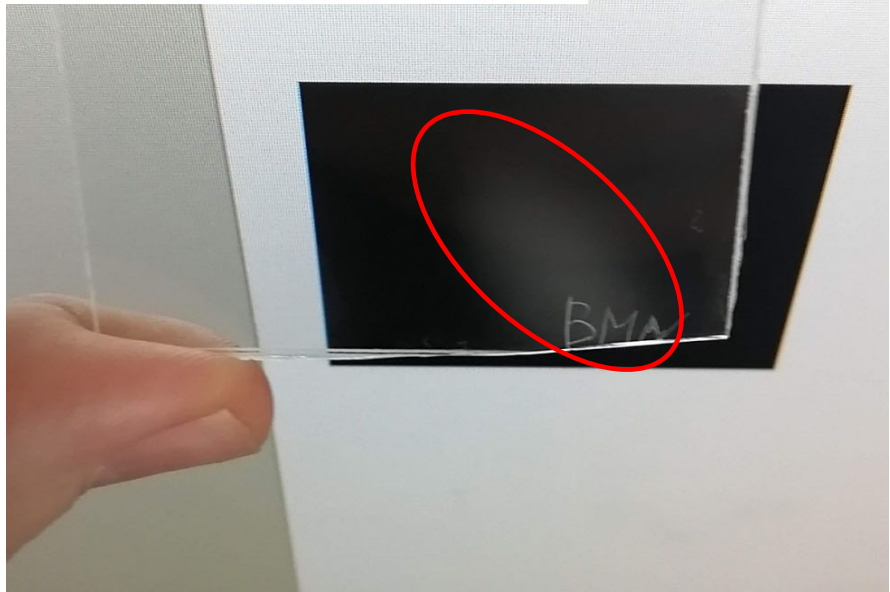
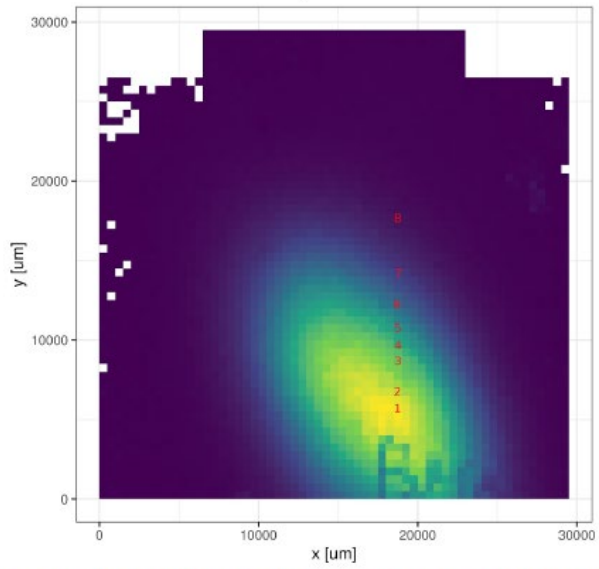
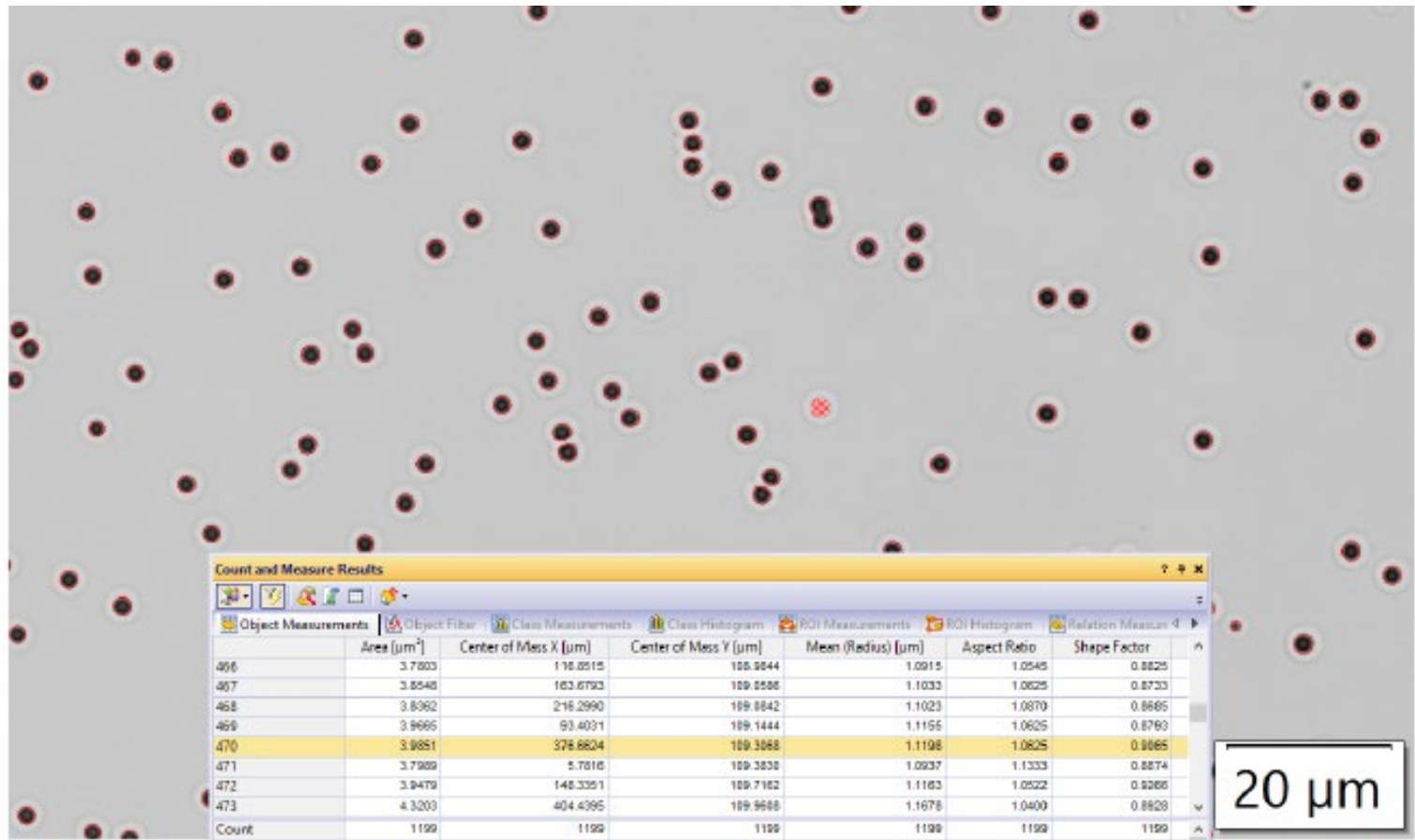


Figure 5: Olympus BX63 motorised microscope. 1) microscope camera, 2) lens revolver, 3) motorised stage, 4) microscope control units, 5) controller, 6) touch panel controller.



Увеличенное изображение облученного образца CR39, полученное с помощью микроскопа Olympus BX63. Представлена процедура автоматического анализа и счета входящих треков («дырочек») ядер Хе в плоскость детектора CR39, реализованного в фирменном программном обеспечении CellSens Olympus (демонстрационная версия).



20 µm

Фотография образца CR39, облученного в пучке ядер Хе на установке ВМ@N в 2023 г. Красным выделена область прохождения пучка.

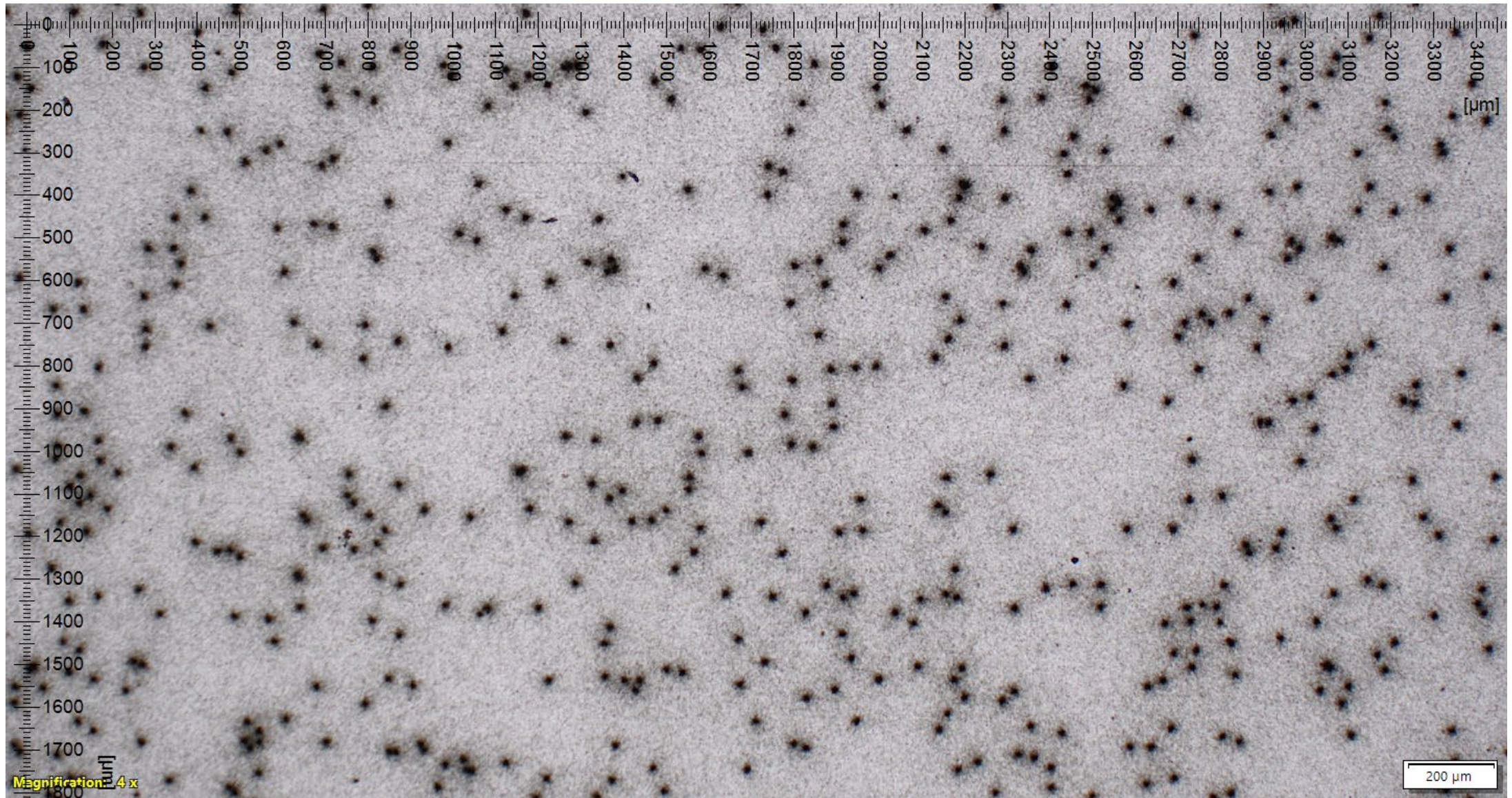


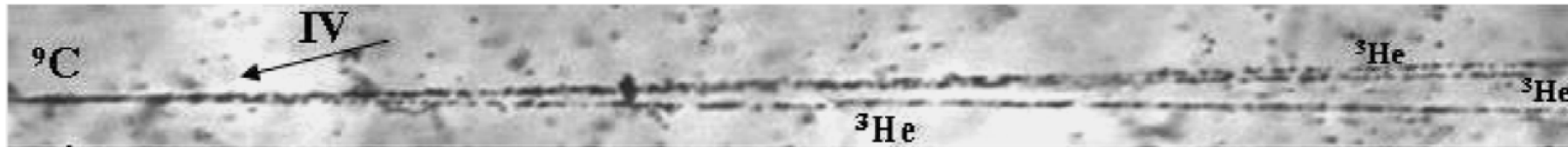
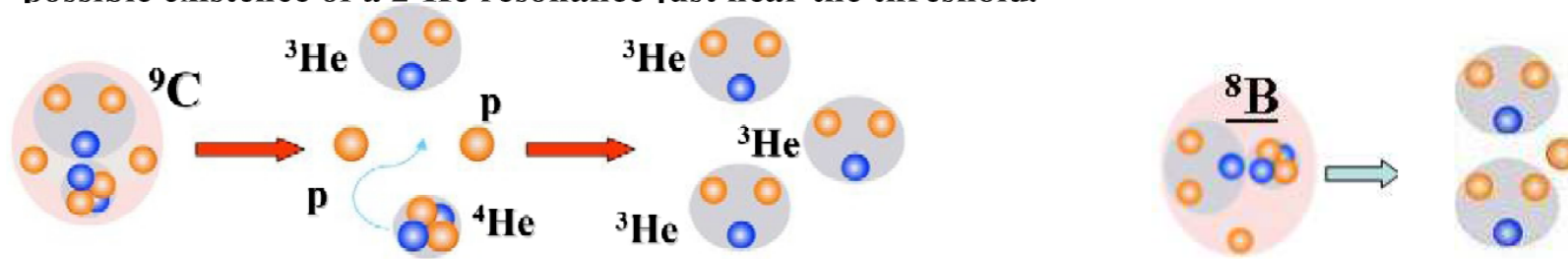
Photo at 4x magnification of a 60 μm thick layer of boron nuclear fuel irradiated with xenon-124 nuclei at 280 MeV per nucleon

Conclusion

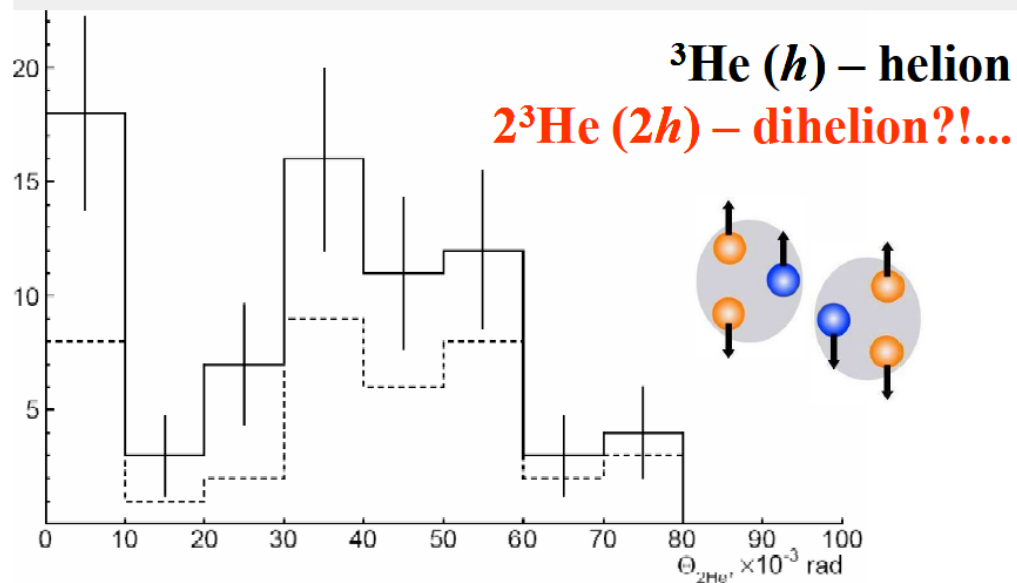
- **Productivity of the nuclear emulsion method in studies nuclear clustering and states of the lowest density and temperature is confirmed.**
- **Determination of the invariant masses from the fragment emission angles assuming conservation of momentum per nucleon of the parent nucleus allowed identifying the decays of ${}^8\text{Be}(0^+)$, ${}^8\text{Be}(2^+)$, ${}^9\text{Be}(1.7)$, ${}^9\text{B}$, ${}^6\text{Be}$, ${}^{12}\text{C}(0^+_{2})$, and ${}^{12}\text{C}(3^-)$.**
- **The observations of ${}^8\text{Be}(0^+)$ and ${}^{12}\text{C}(0^+_{2})$ 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.**

Thank you for your attention!

In the study of 2A GeV/c ${}^9\text{C}$ interactions it is found that the probability of the ${}^3\text{He}$ coherent dissociation is roughly coincides with the values for the channels with the separation of one or a pair of nucleons. Due to a significant probability of the channel ${}^9\text{C} \rightarrow {}^3\text{He}, {}^2\text{He}$ pairs with opening angles up to 10^{-2} rad are found as well as for ${}^8\text{B}$ interactions with the neutron knock out. This observation indicates the possible existence of a ${}^2\text{He}$ resonance just near the threshold.



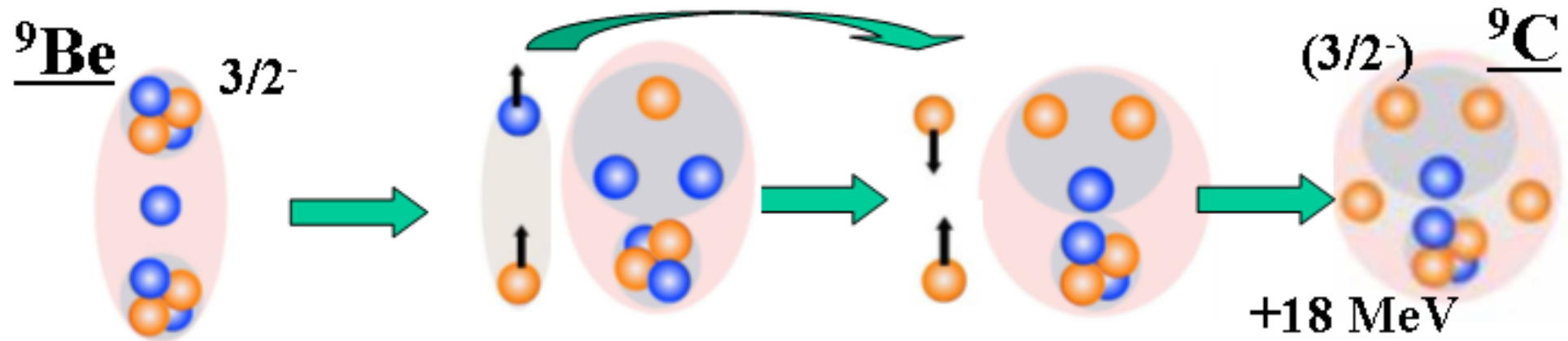
Macro photo of "white" star of ${}^9\text{C}$ dissociation to 3 ${}^3\text{He}$ nuclei in nuclear track emulsion; the interaction vertex IV is shown by the arrow.



Distribution of "white" stars N_{ws} to the charge configurations $\Sigma Z_{fr} = 6$

Z_{fr}						N_{ws}
6	5	4	3	2	1	
-	1	-	-	-	1	15
-	-	1	-	-	2	16
-	-	-	-	3	-	16
-	-	-	1	-	3	2
-	-	-	-	1	4	28
-	-	-	-	2	2	24
-	-	-	-	-	6	6

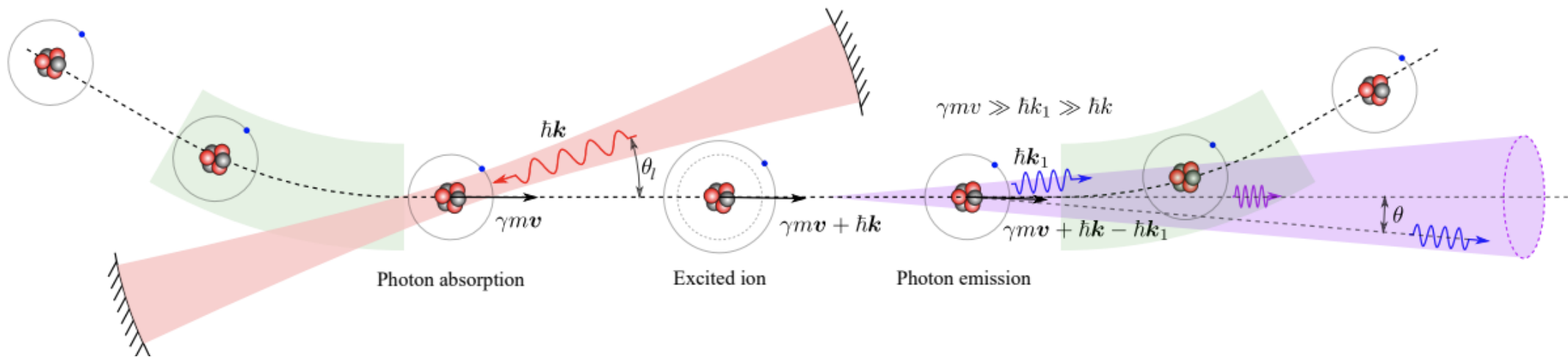
(Charge Exchange)²



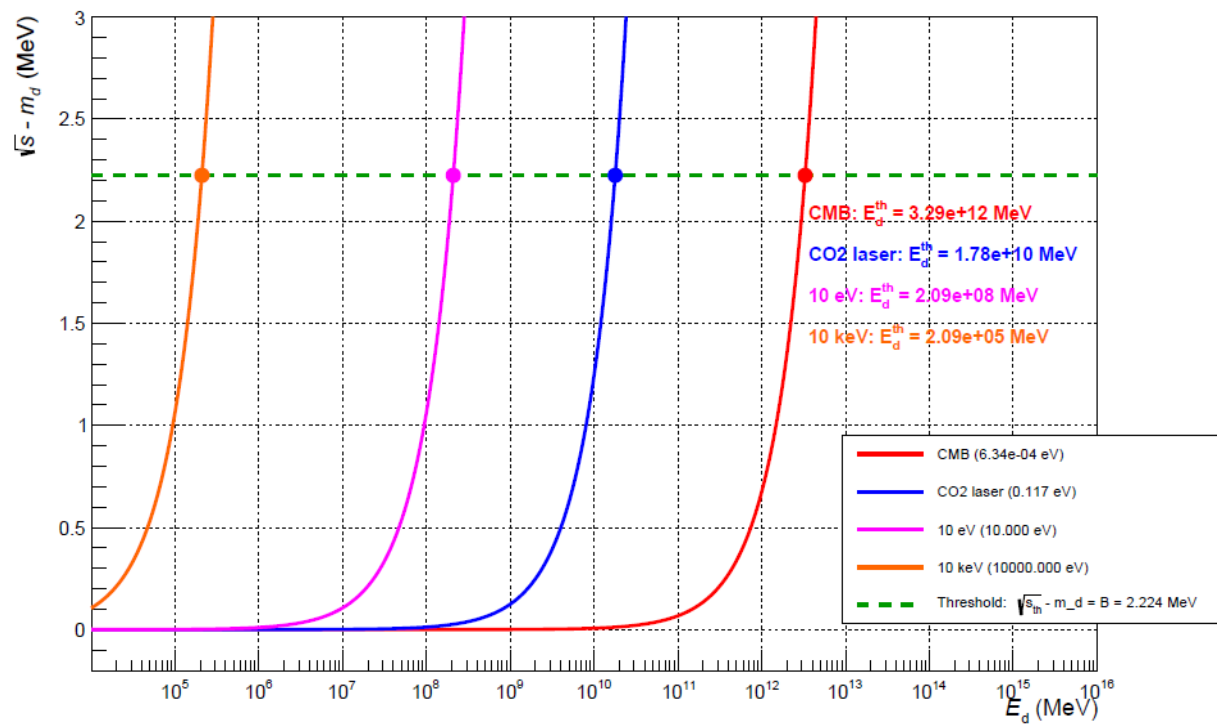
$N\Delta$ –states

The irradiation experiments are intended to investigate the double charge-exchange process ${}^9\text{Be} \rightarrow {}^9\text{C}$ and the cluster structure of proton-rich ${}^9\text{C}$ nucleus.

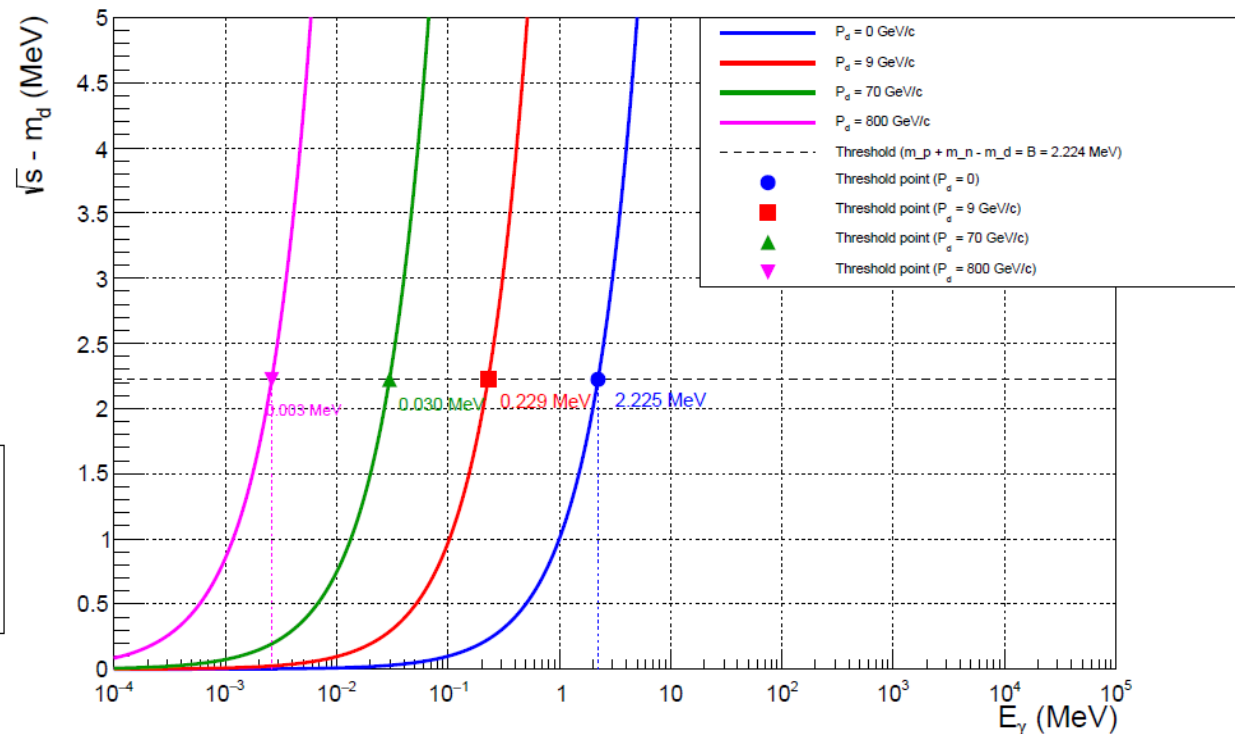
Лазер-ионный коллайдер



Head-on collision: $d + \gamma \rightarrow p + n$



$d + \gamma \rightarrow p + n$: photodisintegration threshold



Параметры Нуклотрона/НІСА: численные значения

Для $^{124}\text{Xe}^{53+}$ и перехода Lyman- α :

$$\Delta_{eg} = 31.28 \text{ кэВ}$$

$$\varepsilon_L^{\text{res}} = \frac{\Delta_{eg}}{D} = 3.1280 \text{ кэВ}$$

$$E_{\gamma,\text{max}}^{\text{res}} = D\Delta_{eg} = 312.8004 \text{ кэВ}$$

$$E_{\gamma,\text{max}}^{\text{ОКР}} = D^2\varepsilon_L^{\text{res}} = 312.8004 \text{ кэВ}$$

Параметры накопителя (оценка):

- $N_{\text{ions}} \sim 10^9$, $f_{\text{rev}} \approx 1 \text{ МГц}$
- $L_{\text{int}} \sim 2 \text{ м}$, $n_{\gamma} \sim 10^{15} \text{ см}^{-3}$

Характерный угол излучения:

$$\theta_{\text{char}} \sim \frac{1}{\gamma} = 0.1980 \text{ рад} = 11.35^\circ$$

При оценке

$$\mathcal{L} \sim N_{\text{ions}} f_{\text{rev}} n_{\gamma} L_{\text{int}}$$

получаем

$$\mathcal{L} \sim 2 \times 10^{32} \text{ см}^{-2} \text{ с}^{-1}$$

Тогда верхняя оценка темпа резонансных событий:

$$R = \mathcal{L}\sigma_{\text{max}} \sim 3.4 \times 10^{14} \text{ с}^{-1}$$