



XXIV International Baldin Seminar
on High Energy Physics Problems
Relativistic Nuclear Physics & Quantum Chromodynamics

September 17 - 22, 2018, Dubna, Russia

Observation of the Hoyle state in dissociation of relativistic ^{12}C nuclei in nuclear track emulsion

Andrei Zaitcev

(LHEP, JINR)

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

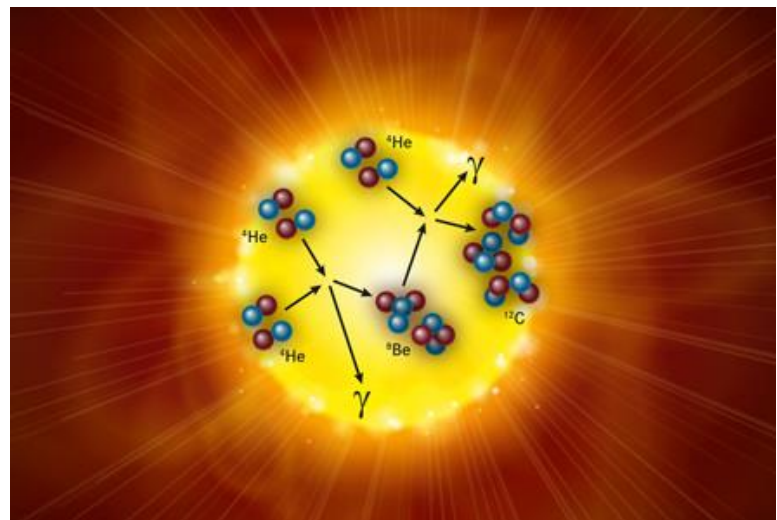
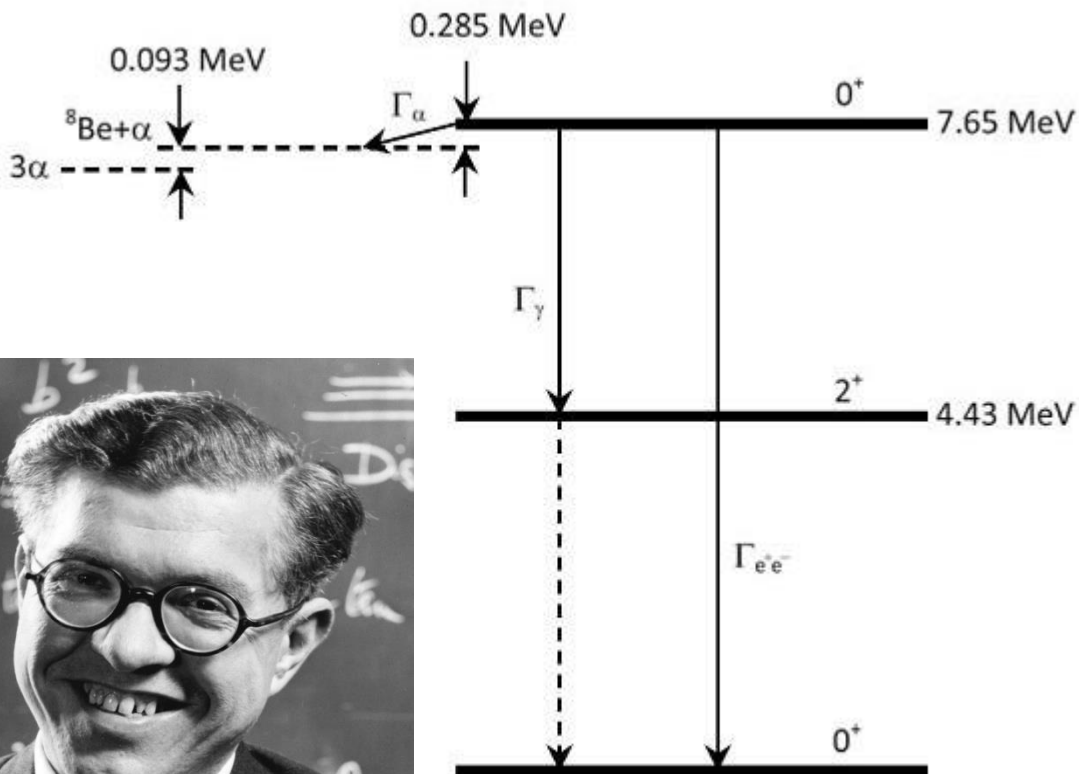
F. HOYLE*

MOUNT WILSON AND PALOMAR OBSERVATORIES

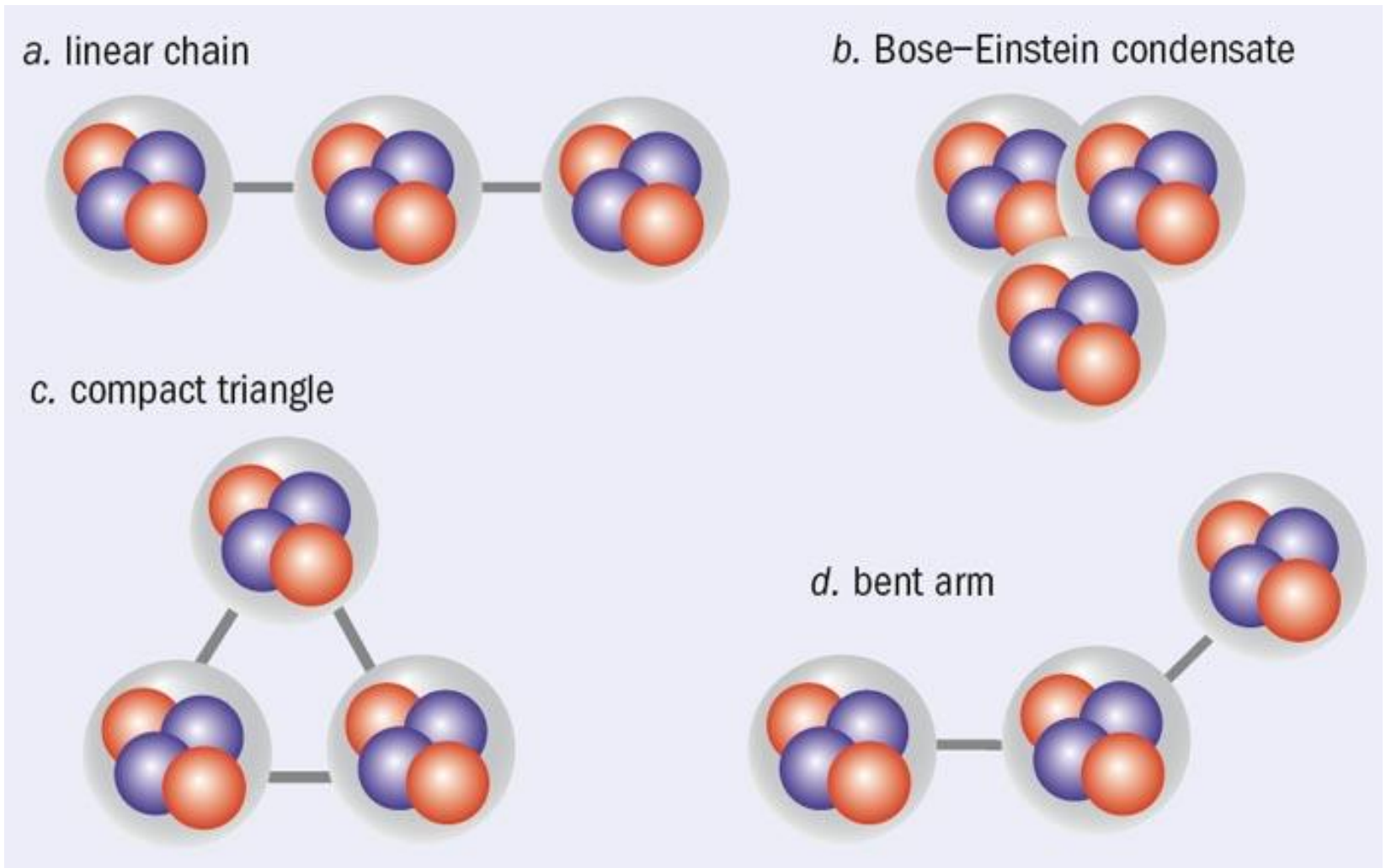
CARNEGIE INSTITUTION OF WASHINGTON

CALIFORNIA INSTITUTE OF TECHNOLOGY

Received December 22, 1953



Structure of the Hoyle state



RMS radii (fm) of ^{12}C (HS) nucleus, predicted by various theoretical works

3.47	3.38	3.27	4.31	3.83	3.53	3.22	2.9	2.4
------	------	------	------	------	------	------	-----	-----

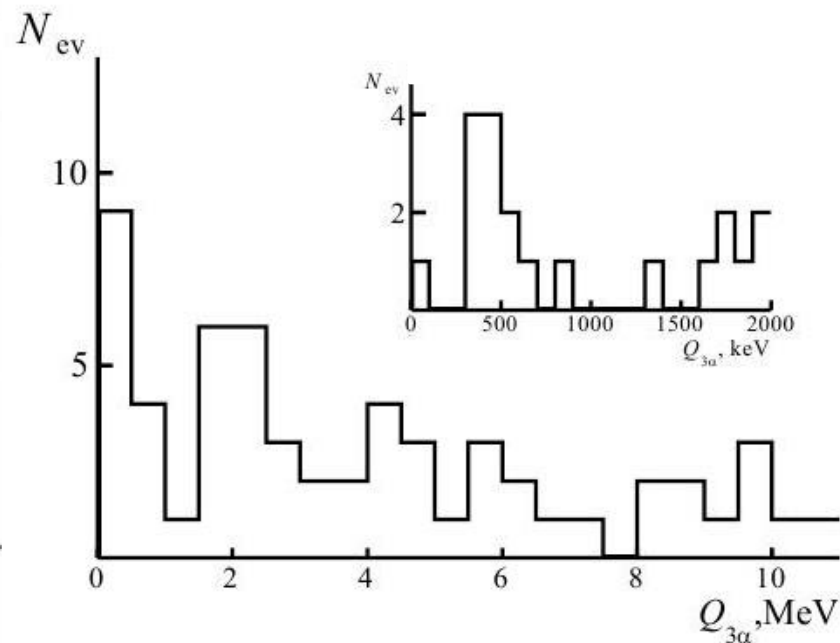
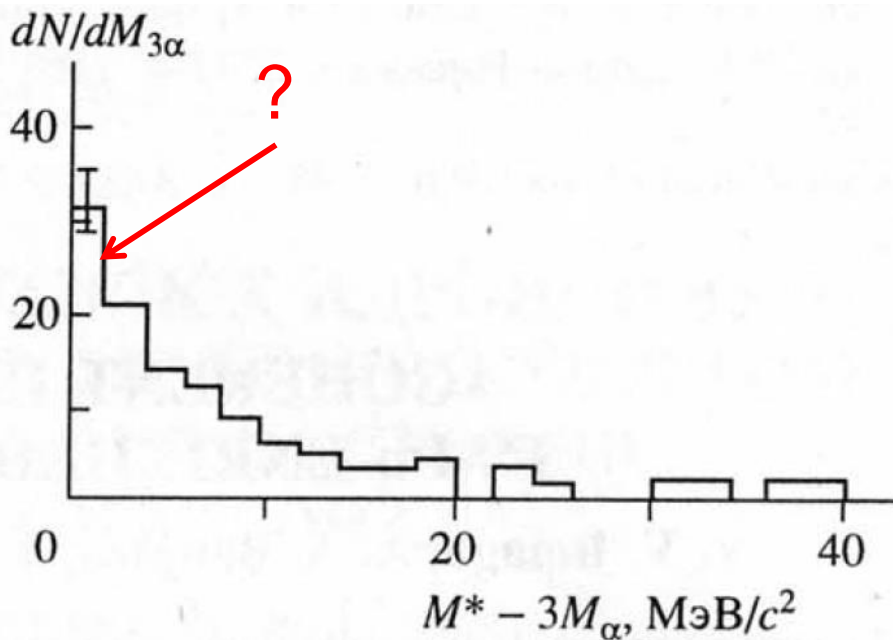
КОГЕРЕНТНАЯ ДИССОЦИАЦИЯ $^{12}\text{C} \rightarrow 3\alpha$ ПРИ 4.5А ГэВ/с НА ЯДРАХ ЭМУЛЬСИИ, ОБОГАЩЕННОЙ СВИНЦОМ

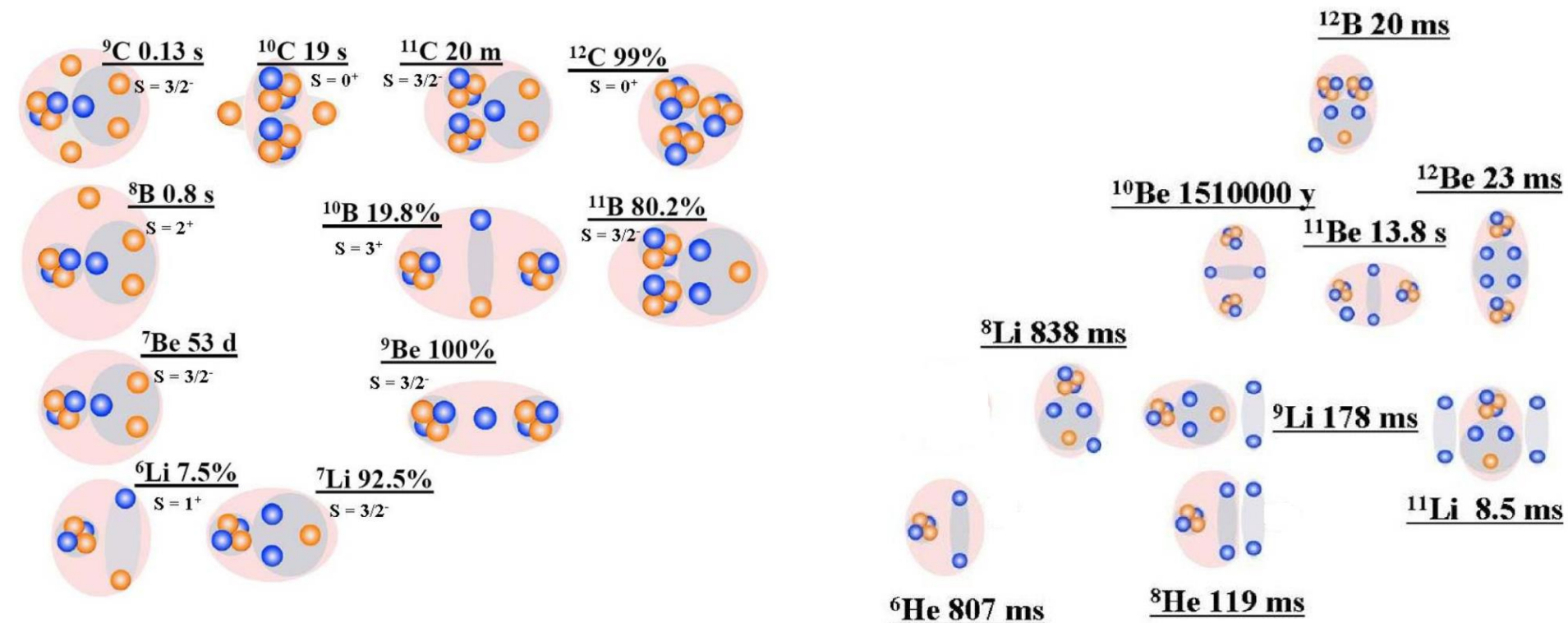
© 1995 г. В. В. Белага, А. А. Бенджаза¹⁾, В. В. Русакова, Дж. А. Саломов²⁾, Г. М. Чернов

Объединенный институт ядерных исследований, Дубна, Россия

Поступила в редакцию 16.05.94 г.; после доработки 06.03.95 г.

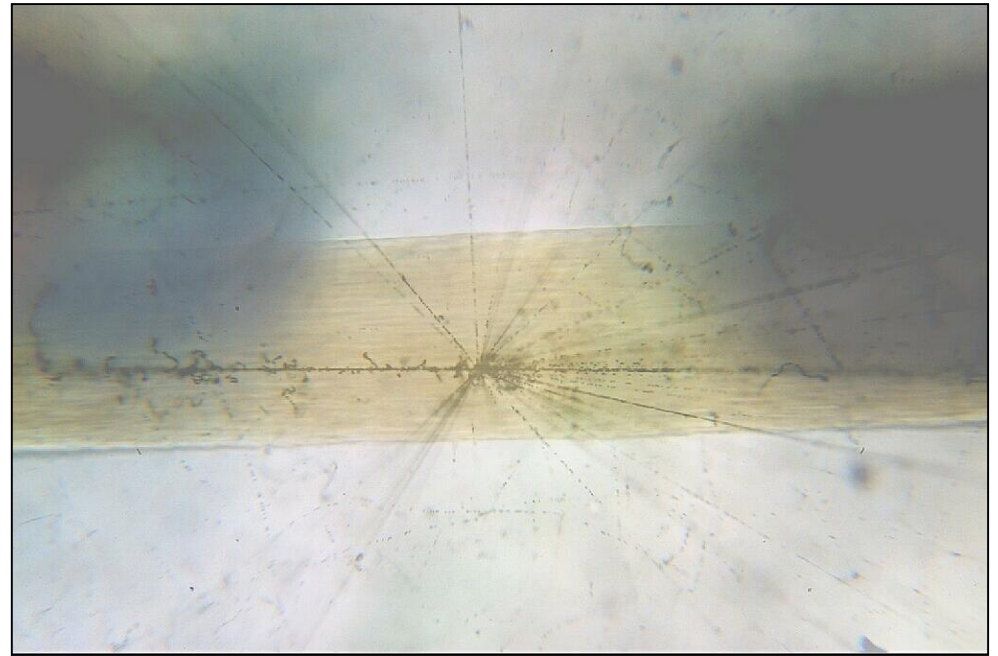
Изучались распределения по поперечным импульсам и корреляционные характеристики релятивистских α -частиц из реакции когерентной диссоциации ядра углерода на три α -частицы при $p_0 = 4.5\text{А ГэВ/с}$ в эмульсии, обогащенной свинцом. Проведен сравнительный анализ данных, полученных в обычных и обогащенных свинцом эмульсионных стопках. Показано, что статистическая модель быстрой фрагментации не описывает импульсные и корреляционные характеристики α -частиц в с.ц.и. ядра углерода. Оценена распадная температура ядра ^{12}C , которая слабо зависит от массы ядра-мишени. Показано, что фрагментирующее ядро углерода приобретает в соударении угловой момент.





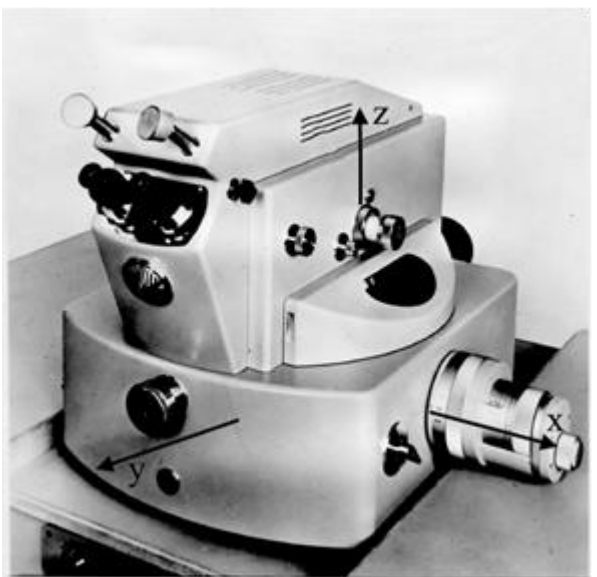
Earlier observations were made in NTE exposures with the nuclei ${}^{12}\text{C}$, ${}^{16}\text{O}$, ${}^{22}\text{Ne}$, ${}^6\text{Li}$ and ${}^7\text{Li}$ and were carried out at the JINR Synchrotron in the 70-90s. Within the *BECQUEREL Project* the peripheral interactions were analyzed in NTE exposed to the following set of nuclei: ${}^6\text{He}$, ${}^7,{}^9\text{Be}$, ${}^8,{}^{10},{}^{11}\text{B}$, ${}^9,{}^{10},{}^{11}\text{C}$ and ${}^{12},{}^{14}\text{N}$. These experimental results allow to present a comprehensive picture of clustering for a family of nuclei at the beginning of the isotope table.

Photo emulsion technique



The project is based on the method of nuclear track emulsions (NTE) providing **unrivaled spatial resolution (0.5 μm)** and a sensitivity range for measuring tracks of charged particles, starting with highly ionizing short-range ions and up to singly-charged relativistic particles. The use of NTE in newly created beams of relativistic nuclei accelerators makes it possible to make analysis that can not to be reach by electronic detection methods. The accuracy and completeness of the measurement of the angles of emission of fragments generated in peripheral interactions of relativistic nuclei provides unique opportunities for studying the nucleon clustering of light nuclei.

Angular measurements

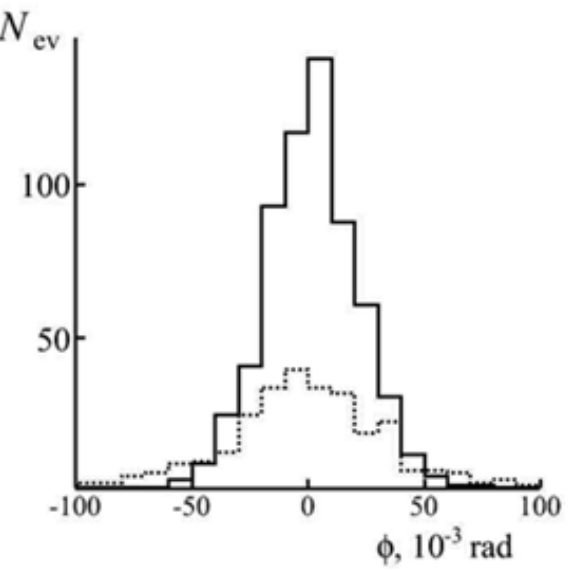
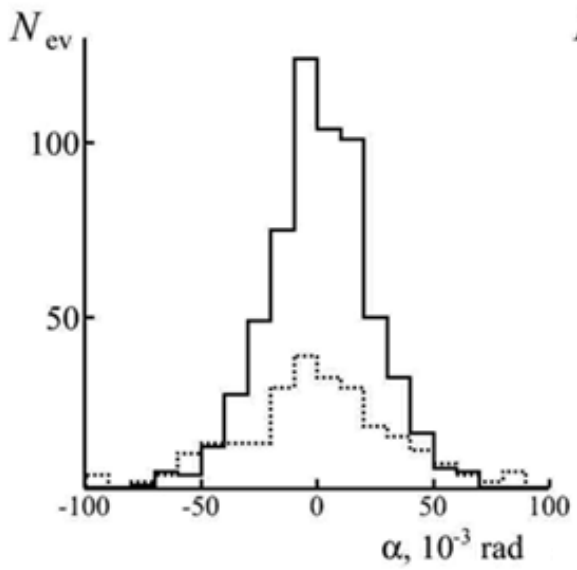


Microscope KSM-1 for measurement of angle emission of charge fragments

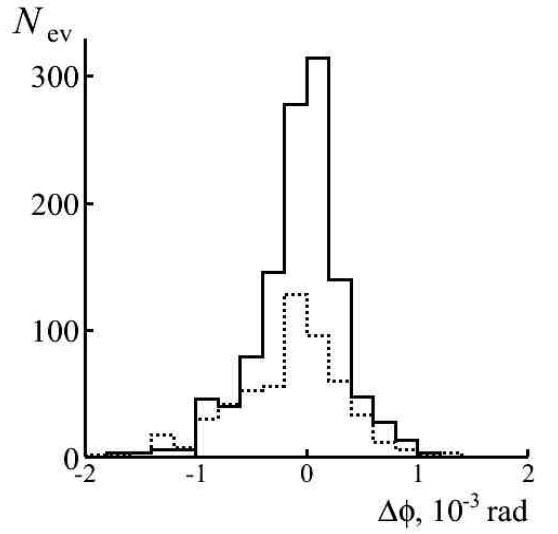
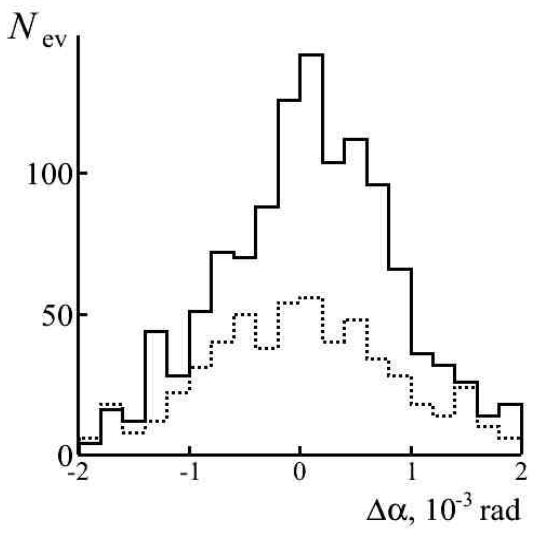
Fragments of a relativistic nucleus are contained in a narrow cone of the polar angle θ , which is

estimated as:

$$\sin \theta = \frac{p_{fr}}{p_0}$$



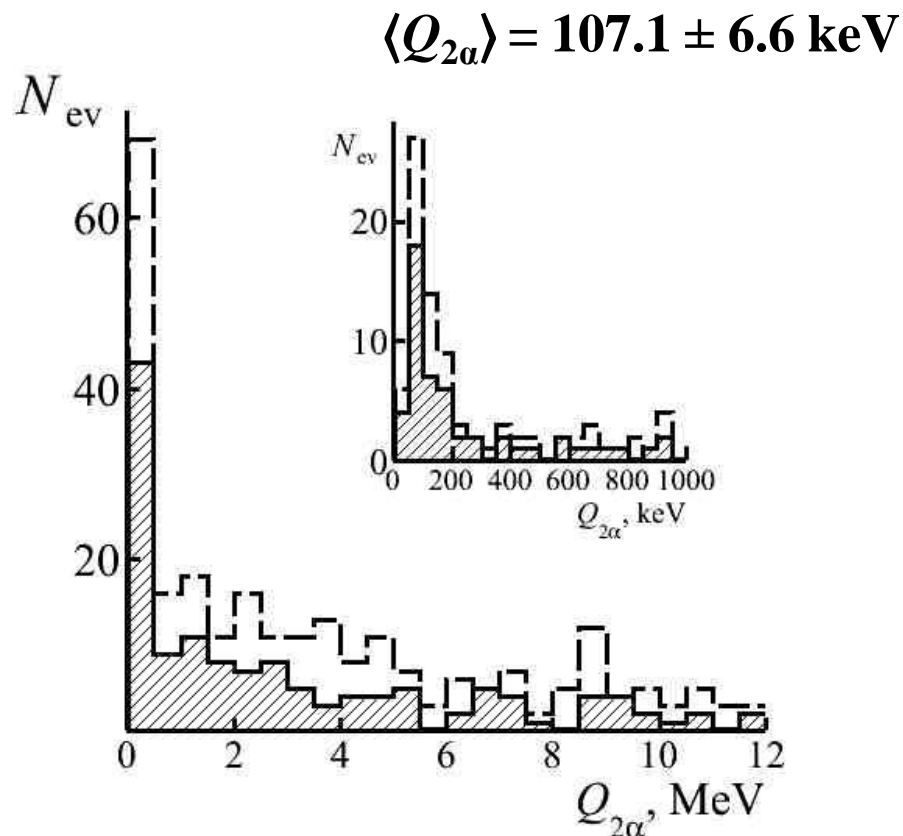
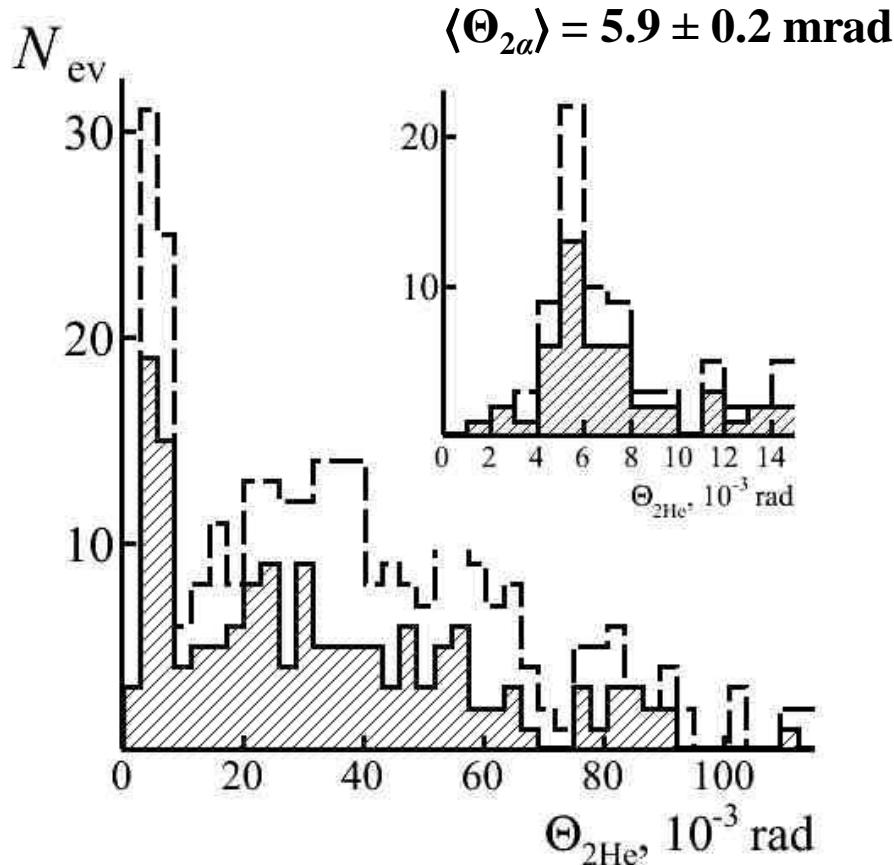
Distributions of fragments He (solid) and H (dotted) over dip (α) and planar (ϕ) angles in events $^{10}\text{B} \rightarrow 2\text{He} + \text{H}$



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

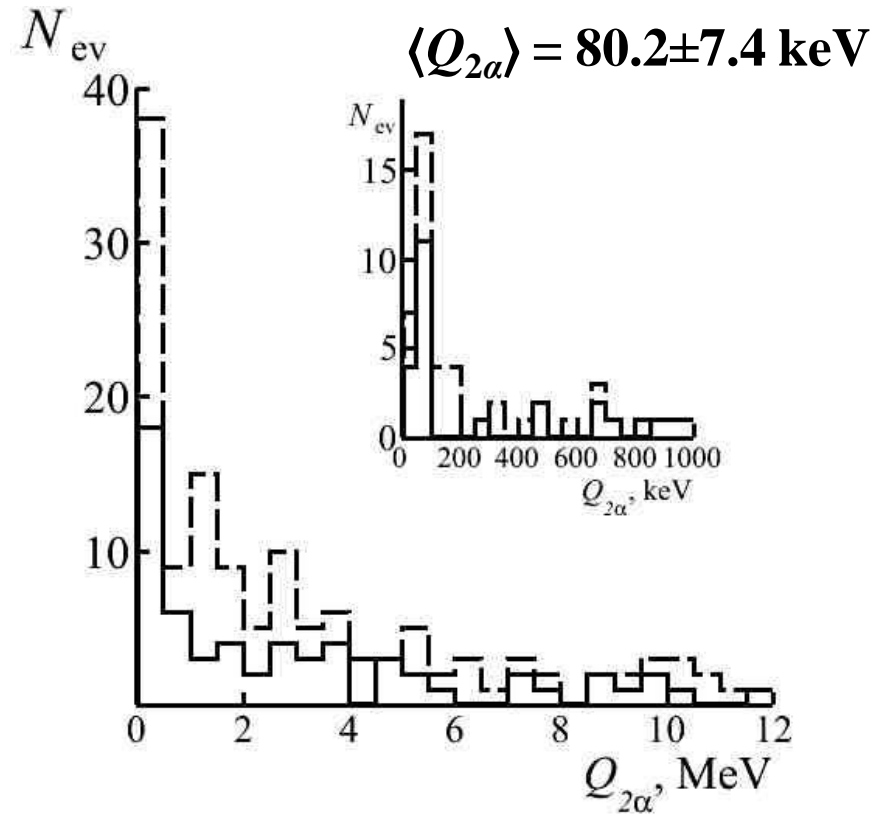
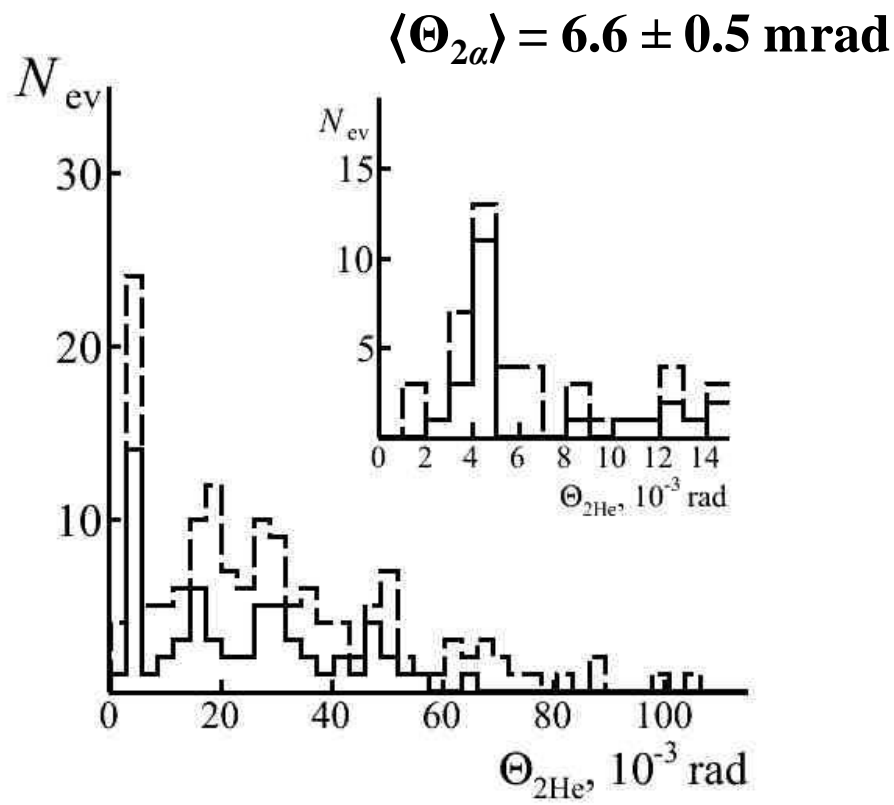
Reconstruction of decays by invariant mass

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



$^{10}\text{B} \rightarrow 2\text{He} + \text{H} \quad (1 \text{ A GeV}/c)$

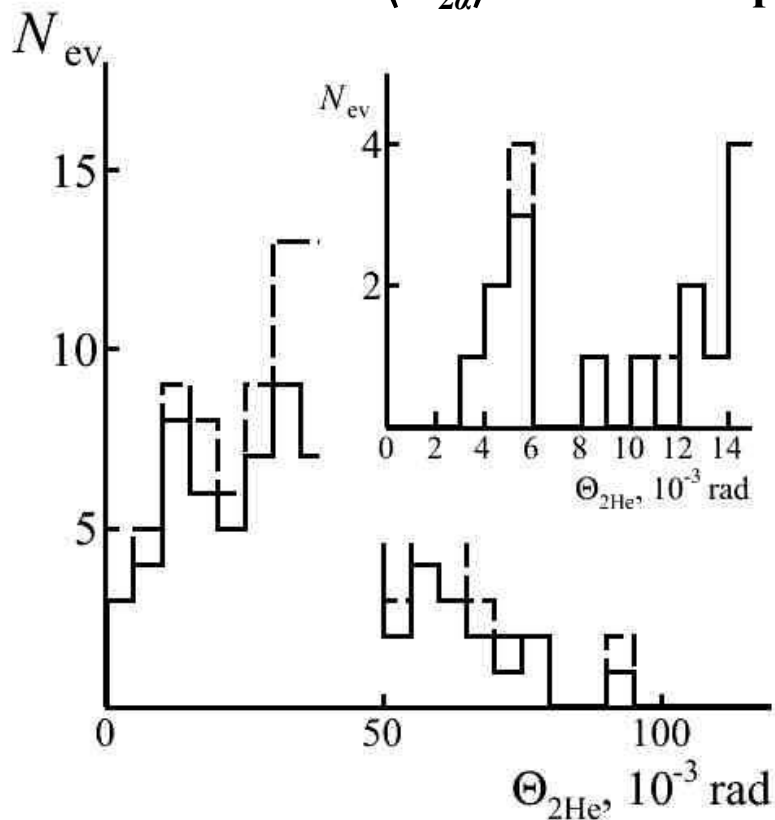
24% decays of $^8\text{Be}_{g.s.}$



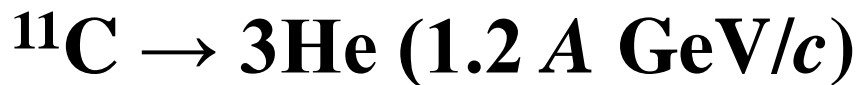
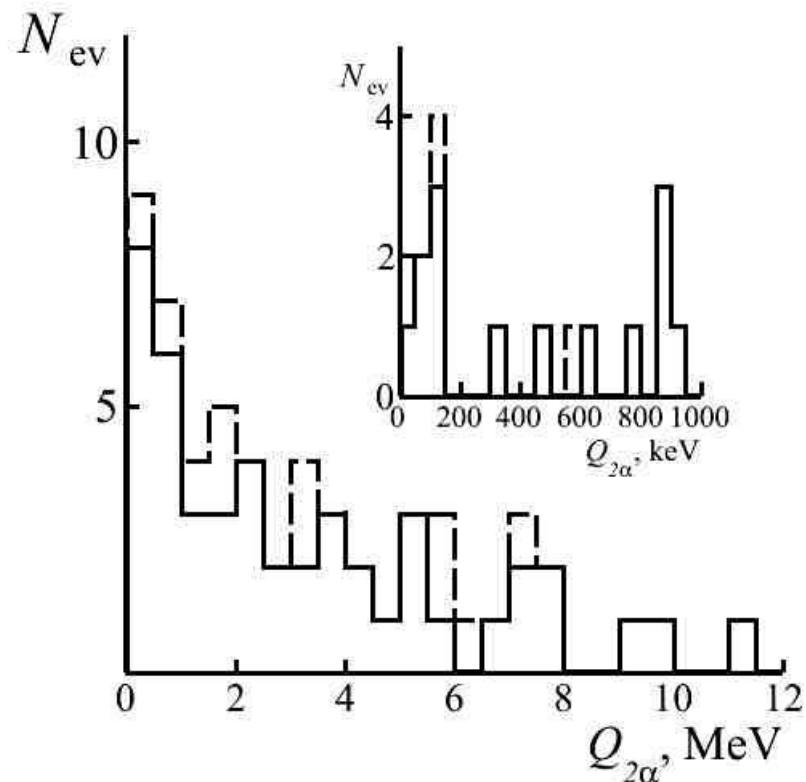
$^{11}\text{C} \rightarrow 2\text{He} + 2\text{H} \text{ (1.2 A GeV/c)}$

23% decays of $^8\text{Be}_{g.s.}$

$$\langle \Theta_{2\alpha} \rangle = 5.3 \pm 0.5 \text{ мрад}$$

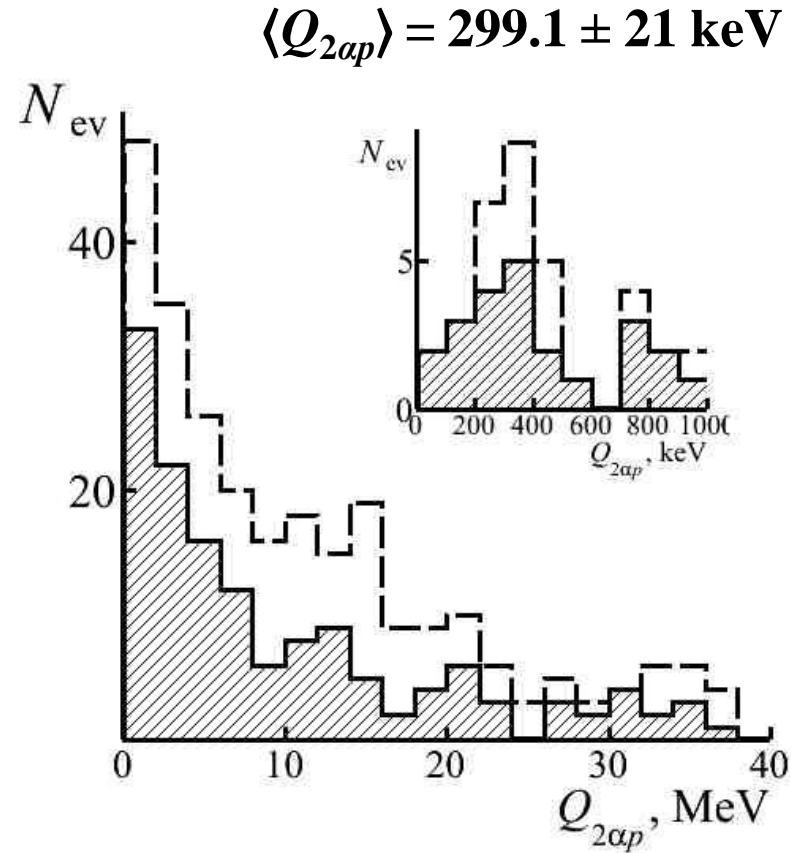
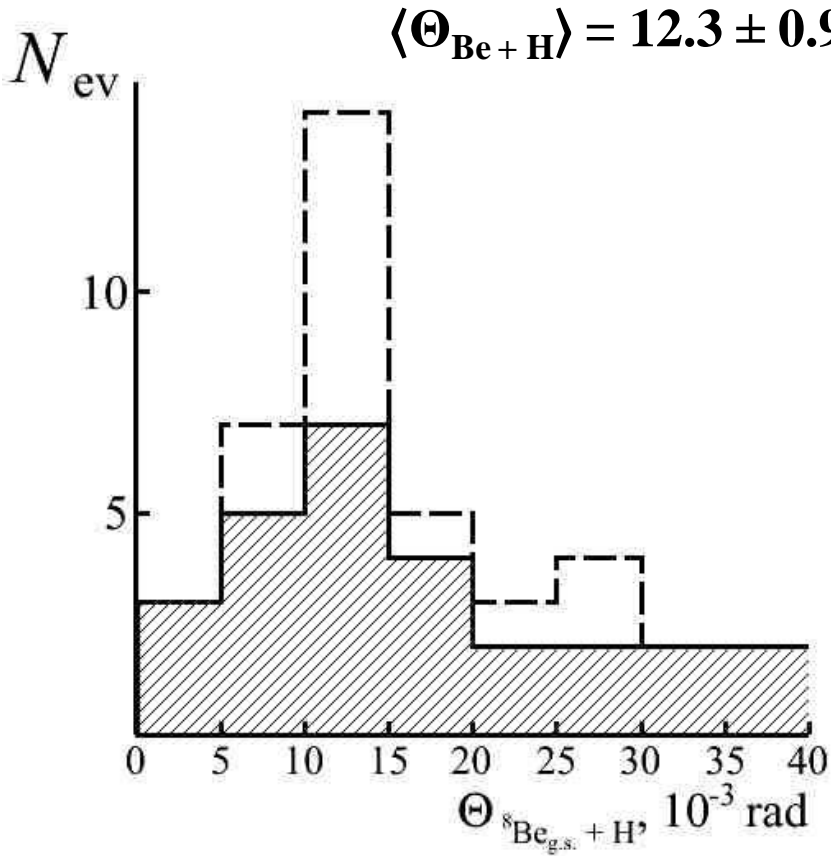


$$\langle Q_{2\alpha} \rangle = 97.1 \pm 9.1 \text{ кэВ}$$



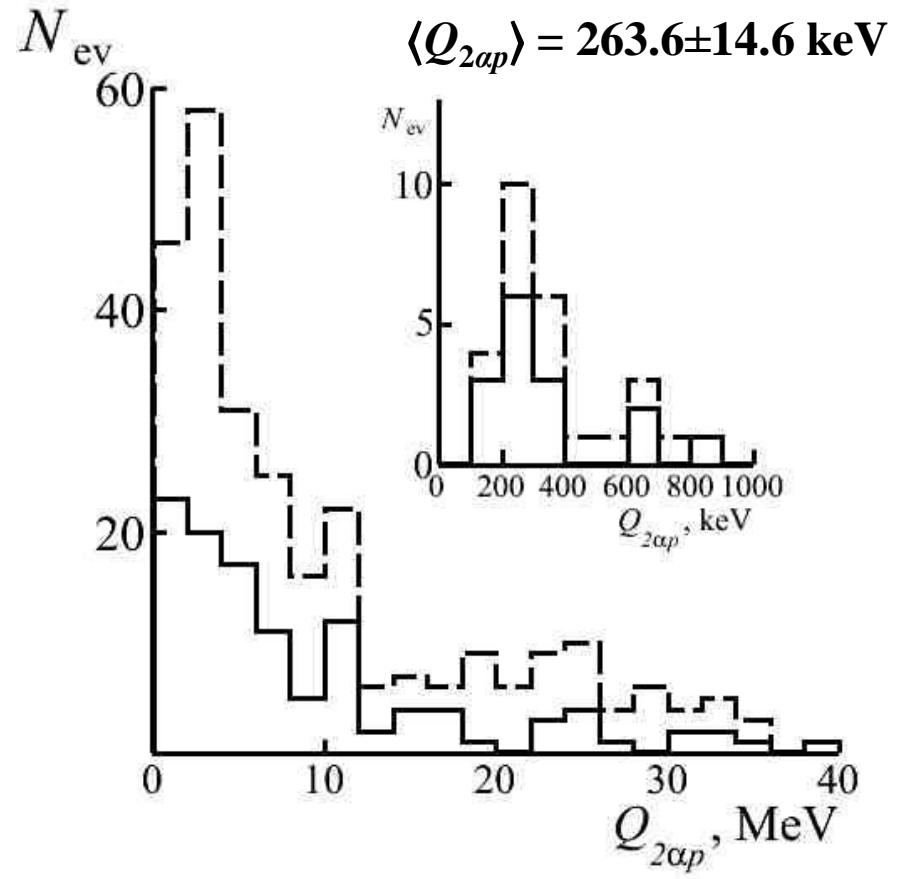
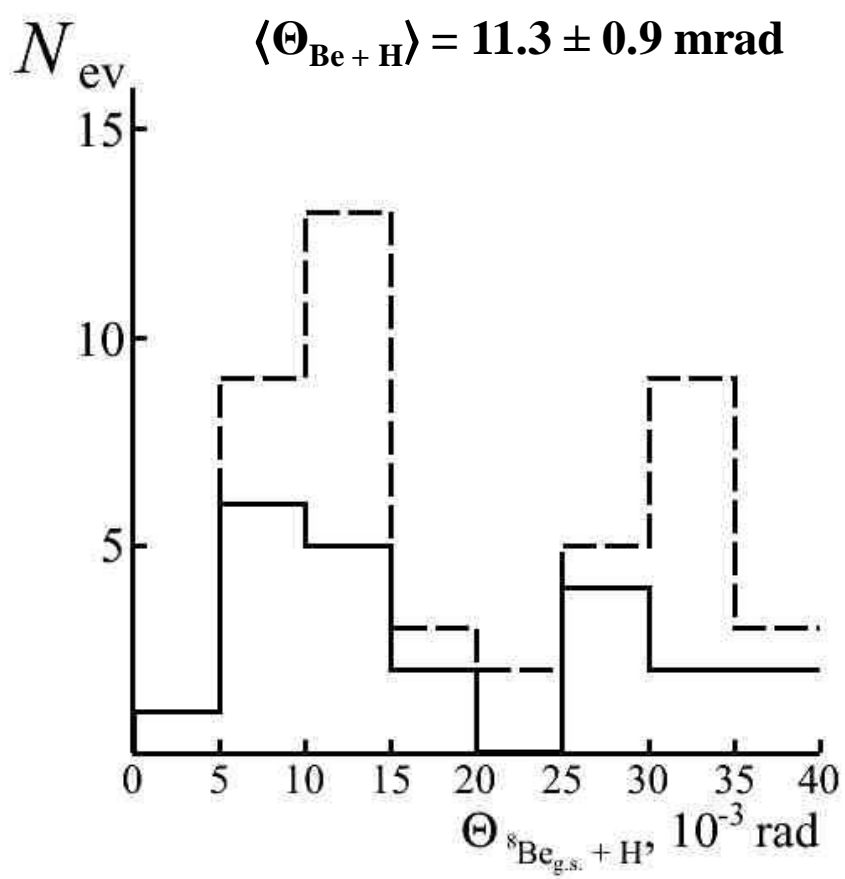
19% decays of $^8\text{Be}_{g.s.}$

$$Q_{2\alpha+p} = \sqrt{[2 \cdot m_\alpha^2 + m_p^2 + 2 \cdot \sum (E_i \cdot E_j - p_i \cdot p_j)]} - 2 \cdot m_\alpha - m_p$$



$^{10}\text{B} \rightarrow 2\text{He}+\text{H}$

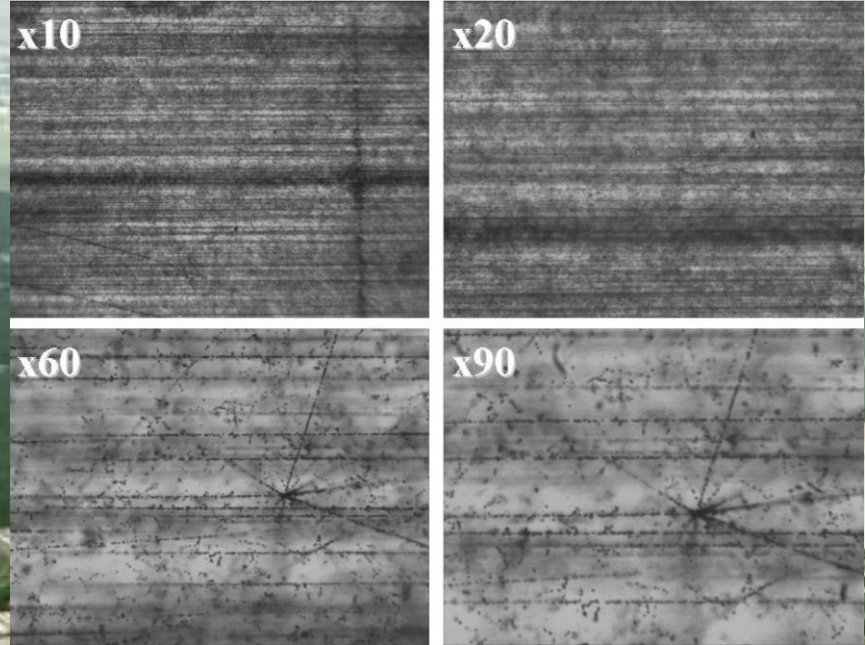
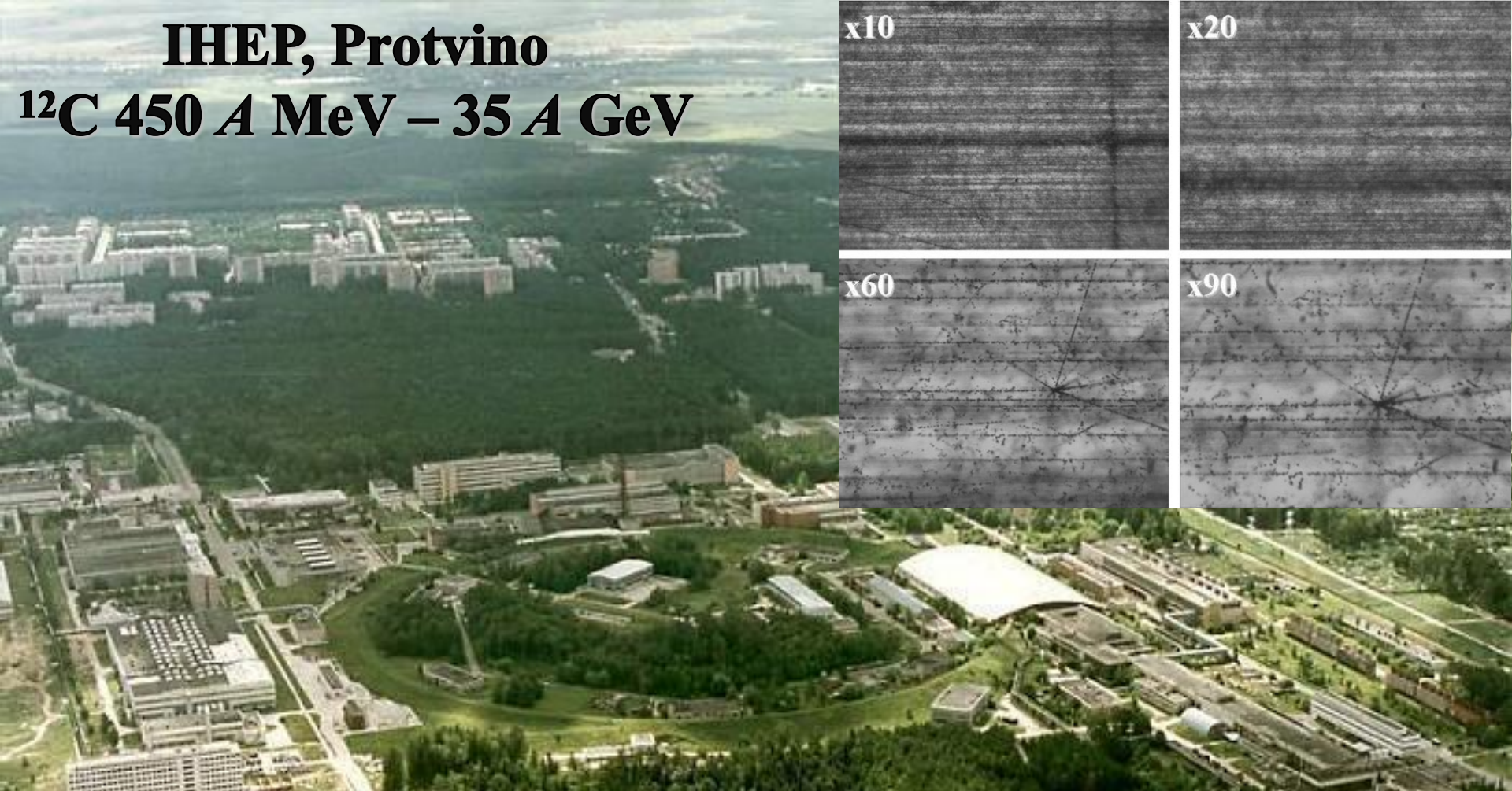
10% decays $^9\text{B}_{g.s.}$



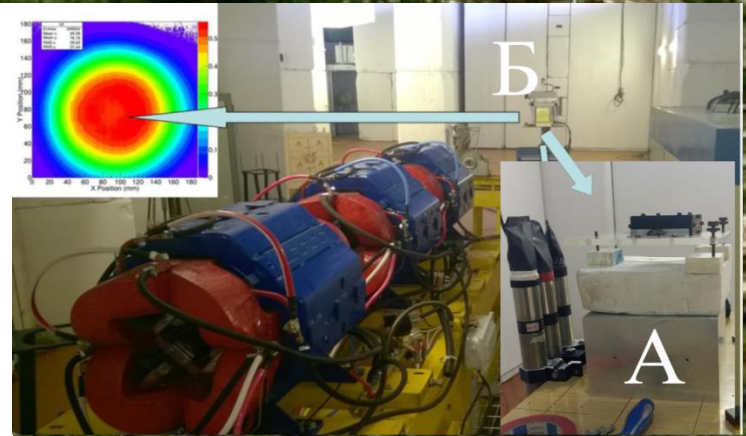
24 decays (15%) of ${}^9\text{B}_{g.s.}$

IHEP, Protvino

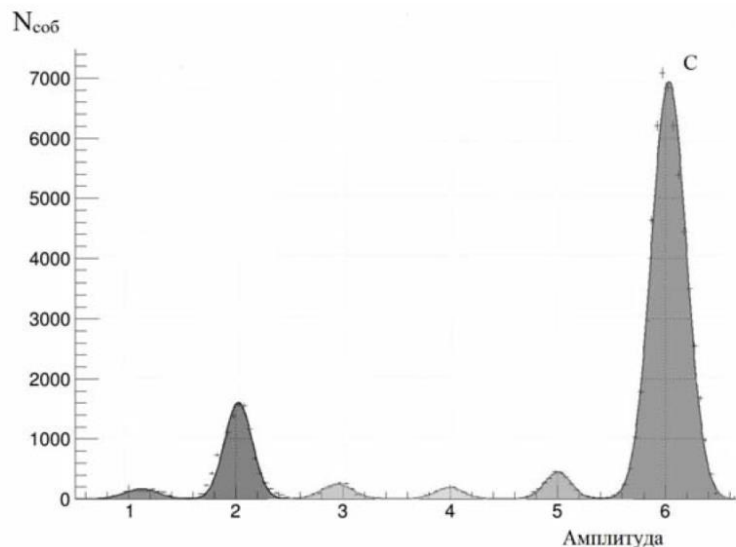
^{12}C 450 A MeV – 35 A GeV



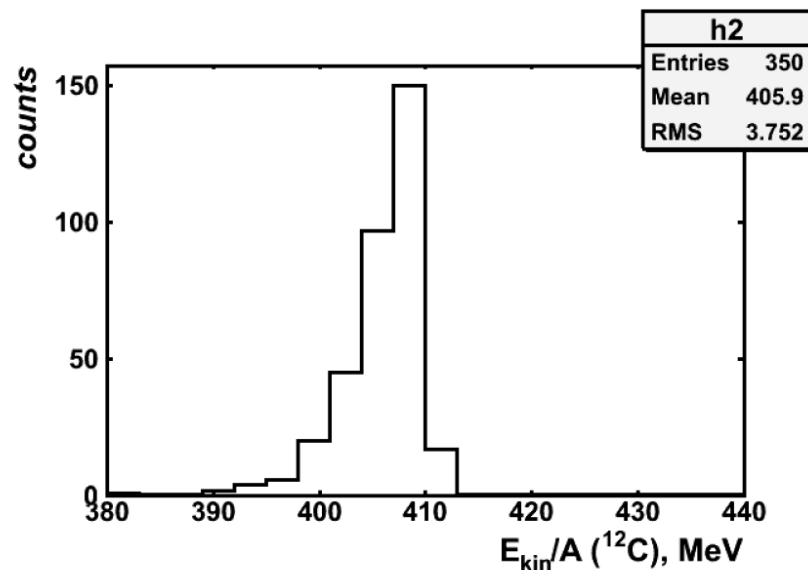
A medical beam of ^{12}C nuclei in IHEP, used at the initial stage, ensures the required uniformity of irradiation. It has an energy corresponding to the maximum of the cross section of electromagnetic dissociation. Its working intensity, which is not less than 10^8 nuclei per cycle, must be at least reduced 10^3 times to avoid overexposure and to provide beam monitoring. The solution of this problem is not simple, since high intensity provides feedback for the tuning of the accelerator.



Мероприятия, осуществленные в декабре 2016 г., позволили контролируемым образом облучить слои ЯЭ толщиной 500 мкм. Производство таких слоев возобновлено компанией “Славич” (г. Переславль Залесский). Для обеспечения плотности частиц в месте облучения 2000-4500 ядер/см² был изменен режим медленного вывода, снижена эффективность вывода, точка облучения ЯЭ перенесена дополнительно на 8 метров по направлению пучка, длительность вывода сокращена с 600 до 400 мс.



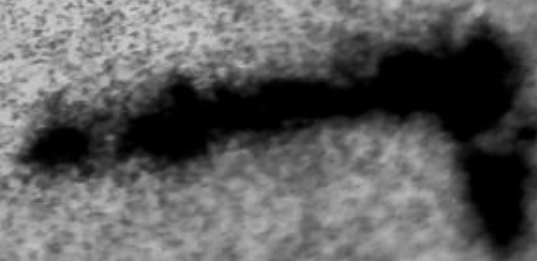
Состав пучка ядер углерода медицинского канала У-70 в месте облучения ядерной эмульсии



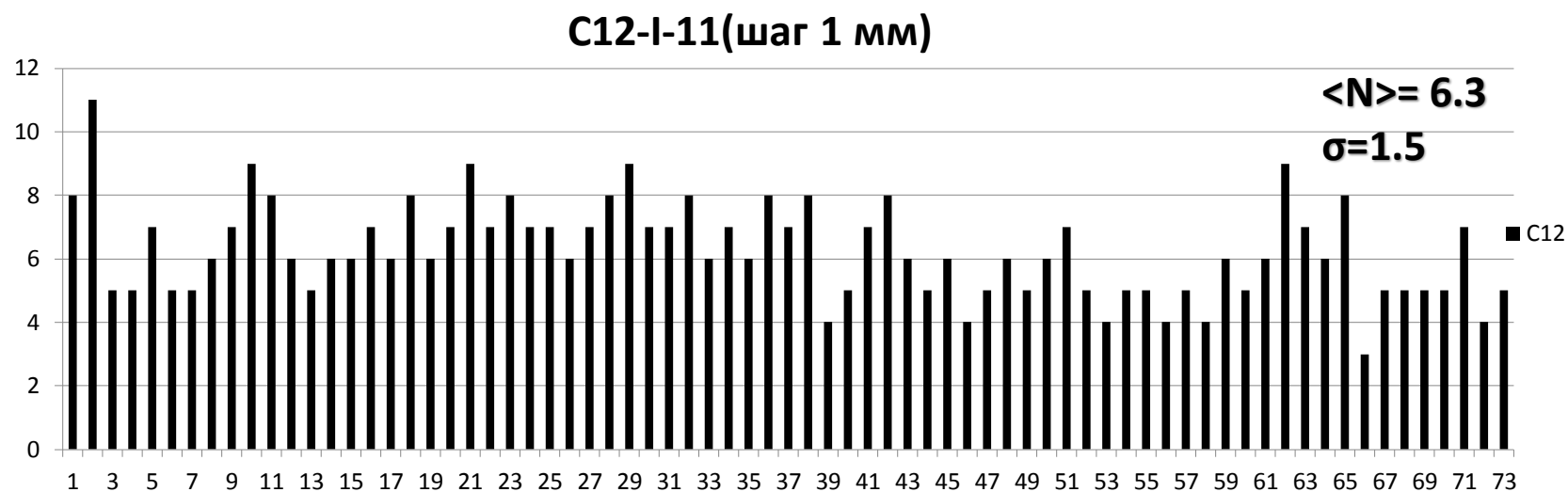
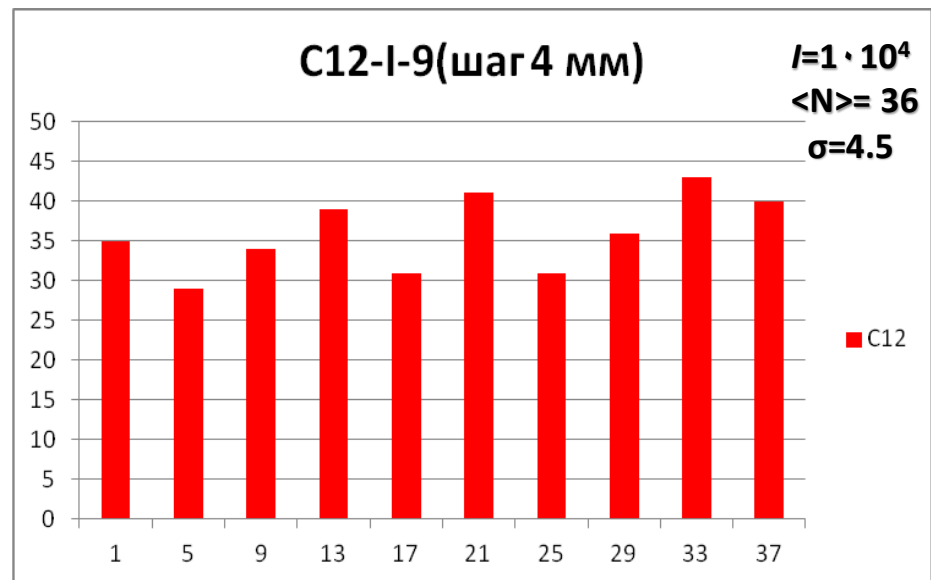
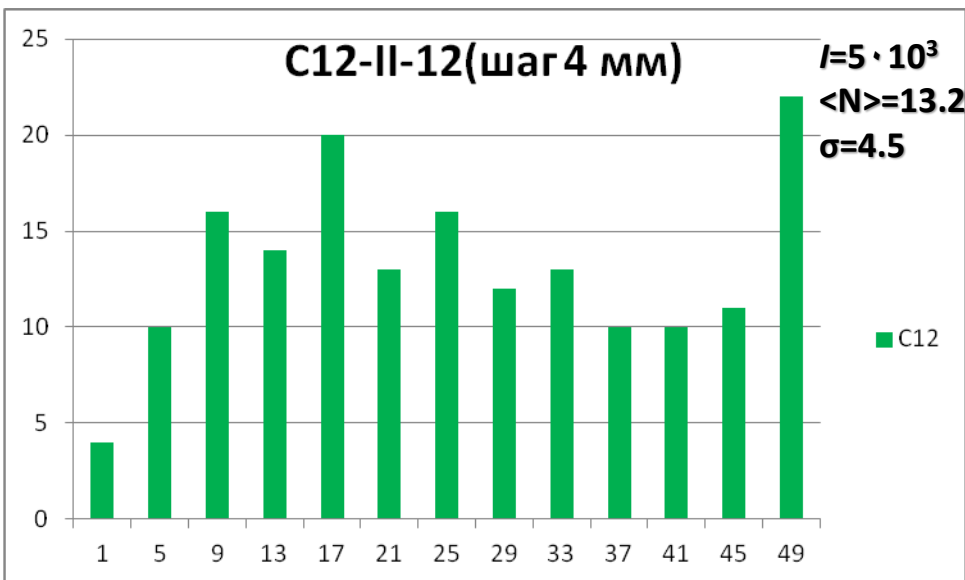
Моделирование прохождения ¹²C по каналу

Для контроля облучения ядерных эмульсий были использованы три счётчика: на основе сцинтилляторов производства ИФВЭ (пластический полистирольный типа СЦ-301) размером 10×10 мм² с толщиной 1 мм и ФЭУ-85. При облучении стопки слоев ЯЭ устанавливались перед счётчиками. На рис. 6. представлен состав пучка ядер углерода медицинского канала У-70 в месте облучения ЯЭ. Доля ядер с зарядом 6 составила около 78%, 5 – 2%, 4 – 2%, 3 – 2%, 2 – 14%, 1 – 2%. Такая смесь является ожидаемым следствием отсутствия вакуумного ионопровода и сепарирующих магнитов. Этот факт не затрудняет отбор “белых” звезд. Напротив, возникает возможность попутных калибровок по заряду и многократному рассеянию.

Incoming beam density of ^{12}C nuclei

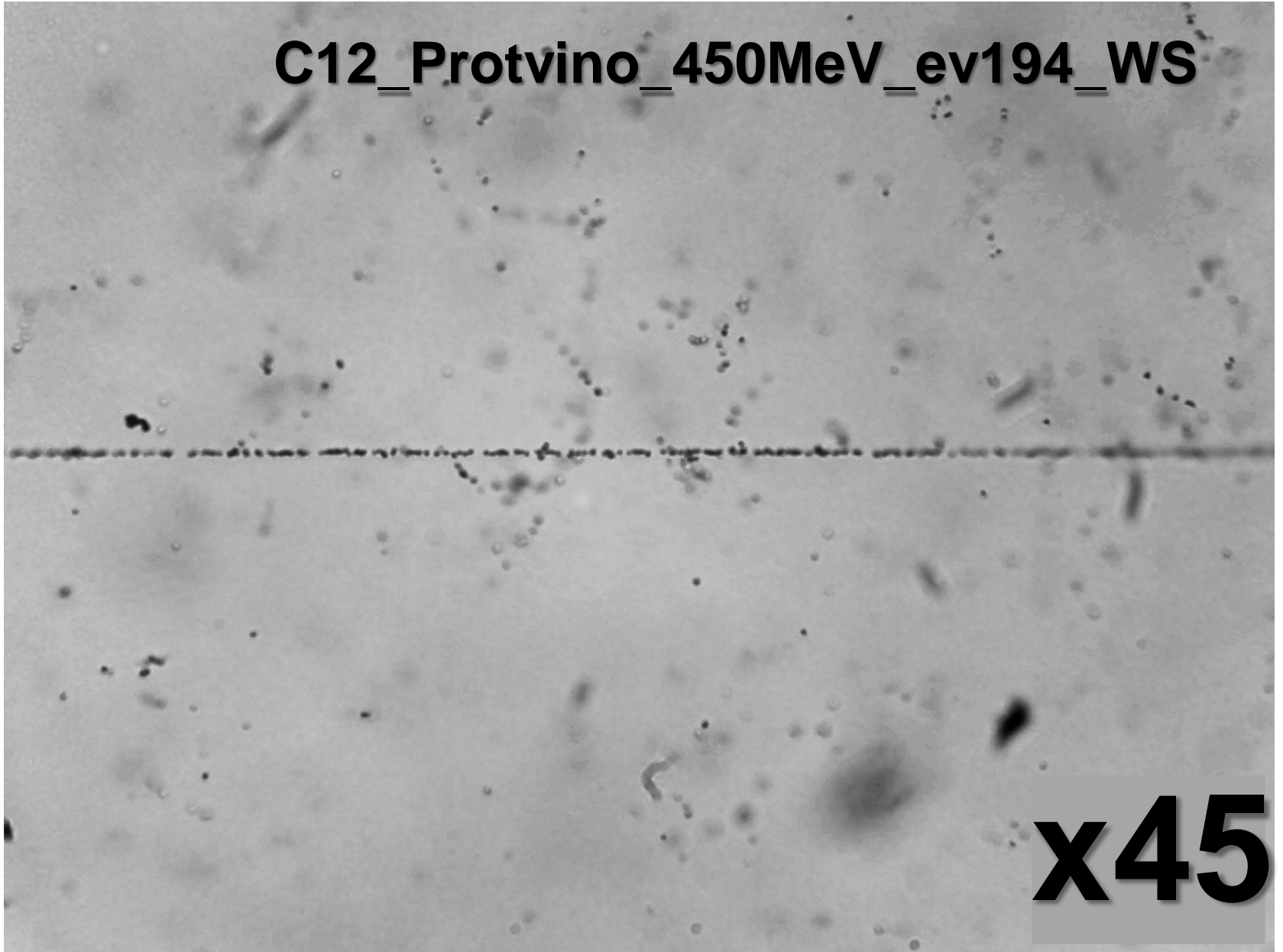


Distribution of incoming tracks of ^{12}C nuclei



Sample of event $^{12}\text{C} + Em \rightarrow 3\alpha$

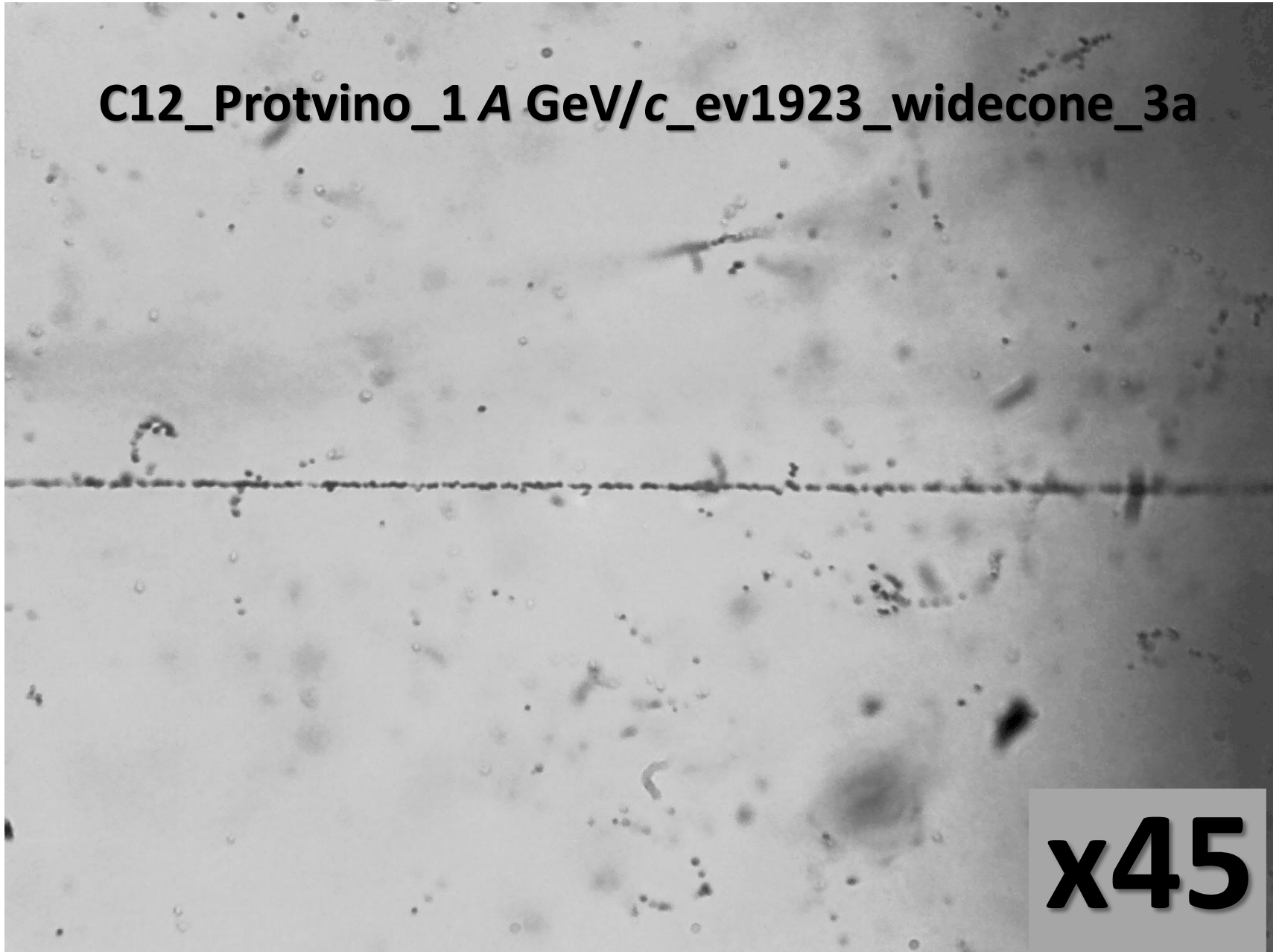
C12_Protvino_450MeV_ev194_WS



x45

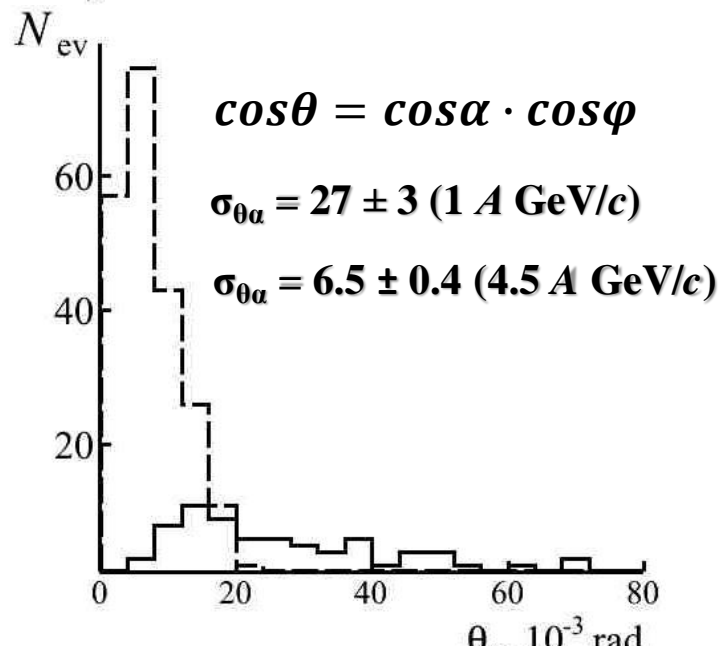
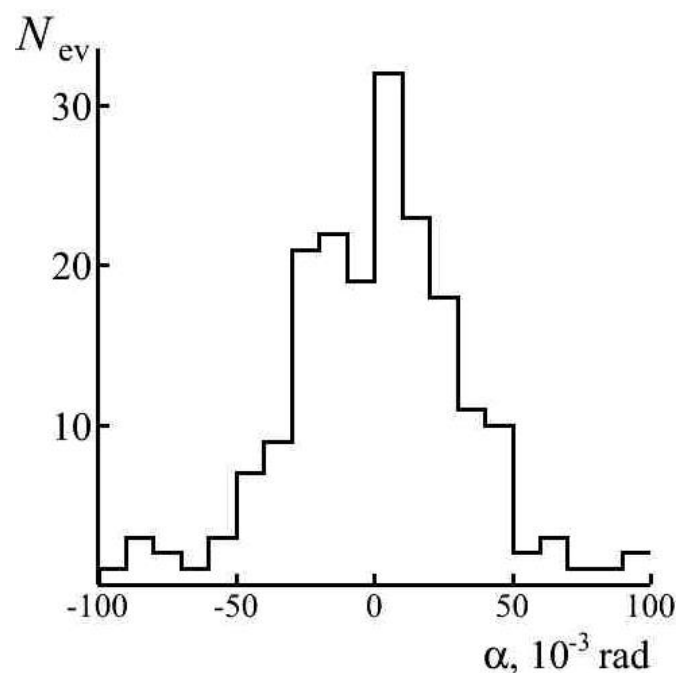
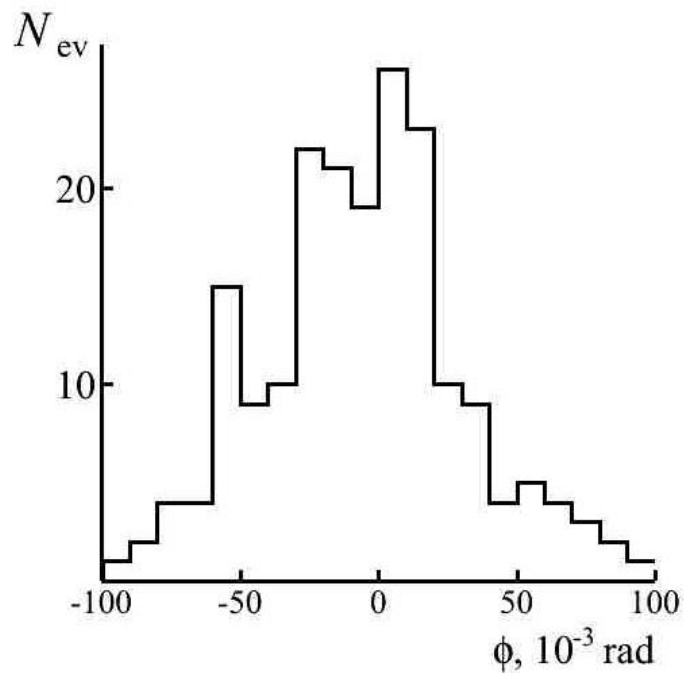
Sample of event $^{12}\text{C} + ^{12}\text{C}$

C12_Protvino_1 A GeV/c_ev1923_widecone_3a



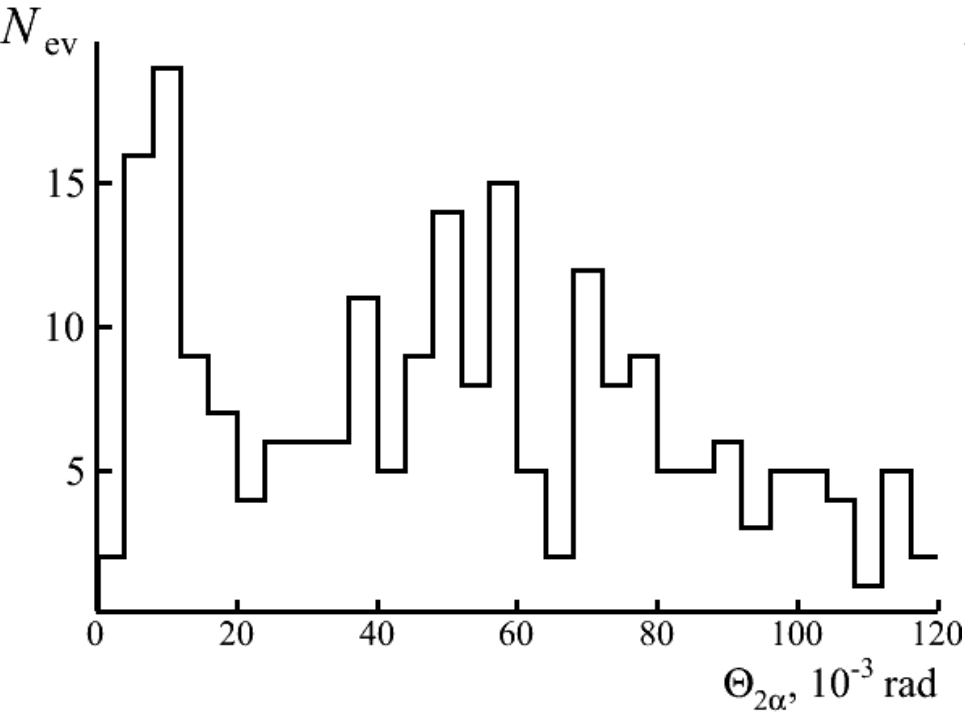
x45

Measurement of emission angles of α tracks



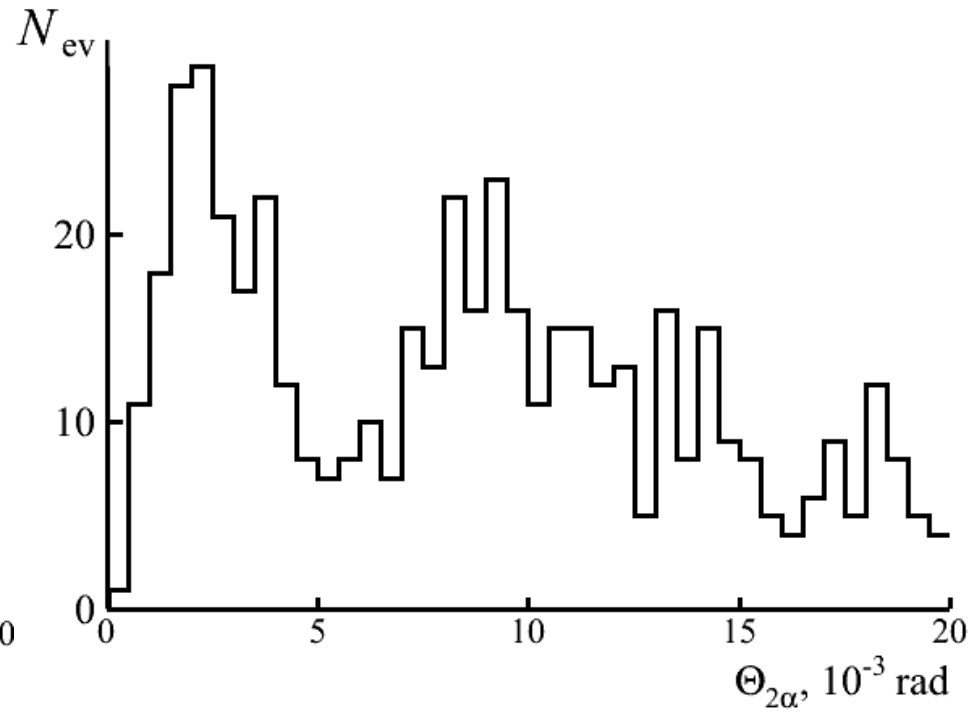
Distribution over angle between 2α -particles

1 A GeV/c



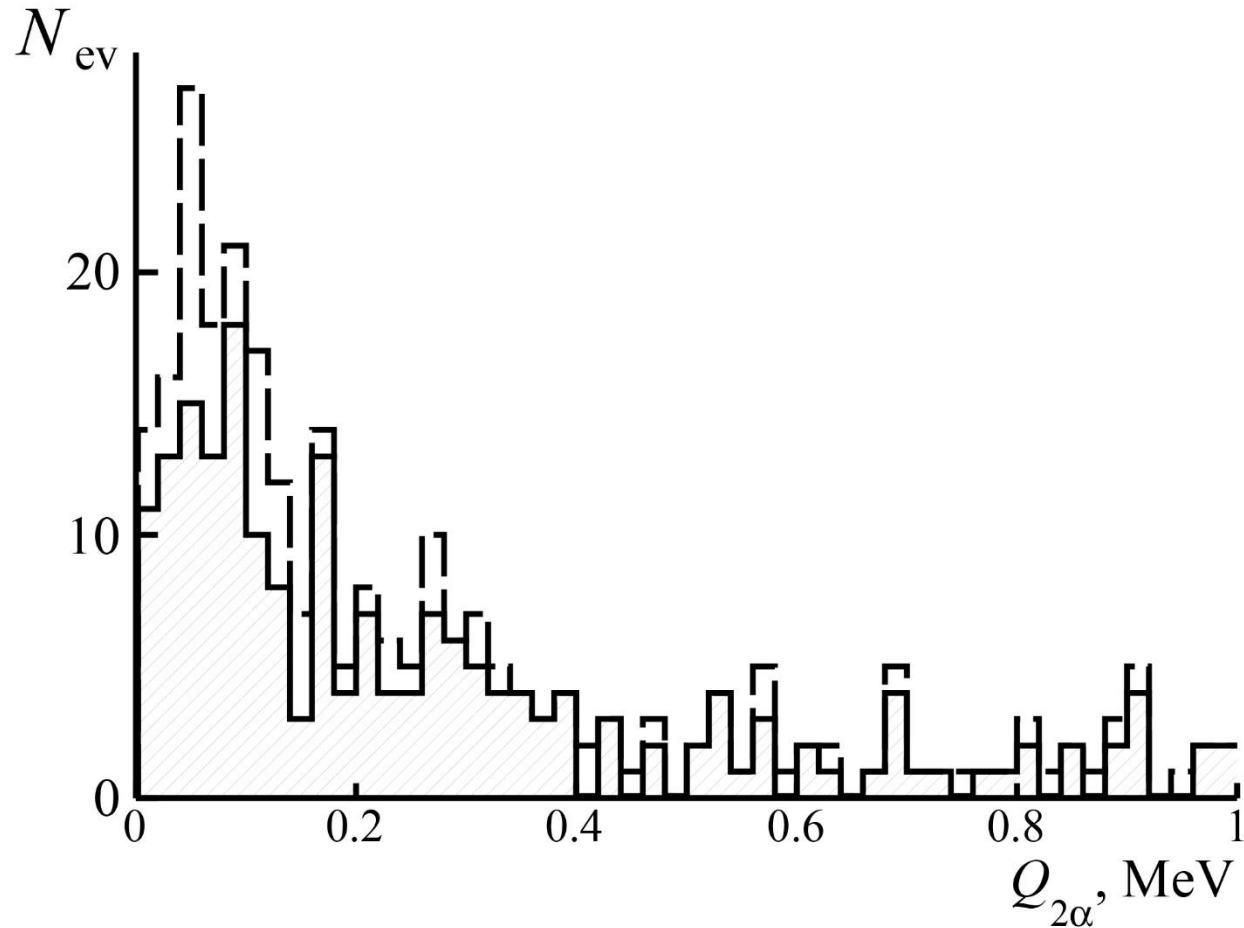
$\langle\theta_{2\alpha}\rangle (< 20 \text{ mrad}) = 11.4 \pm 0.7 (4.8)$
mrad

4.5 A GeV/c



$\langle\theta_{2\alpha}\rangle (< 20 \text{ mrad}) = 11.4 \pm 0.7 (4.8)$
mrad

Distribution over excitation energy of 2α system

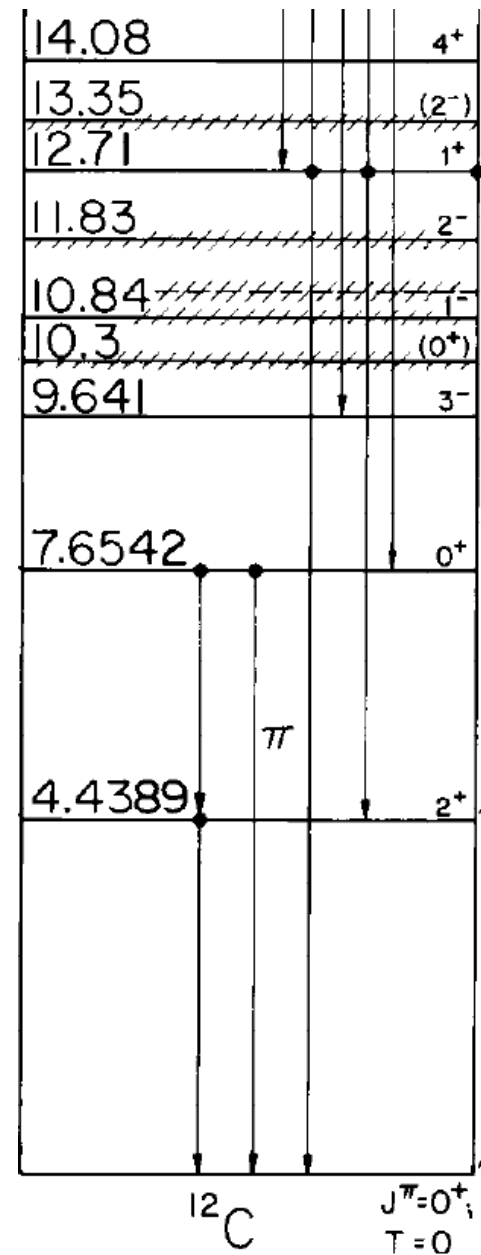
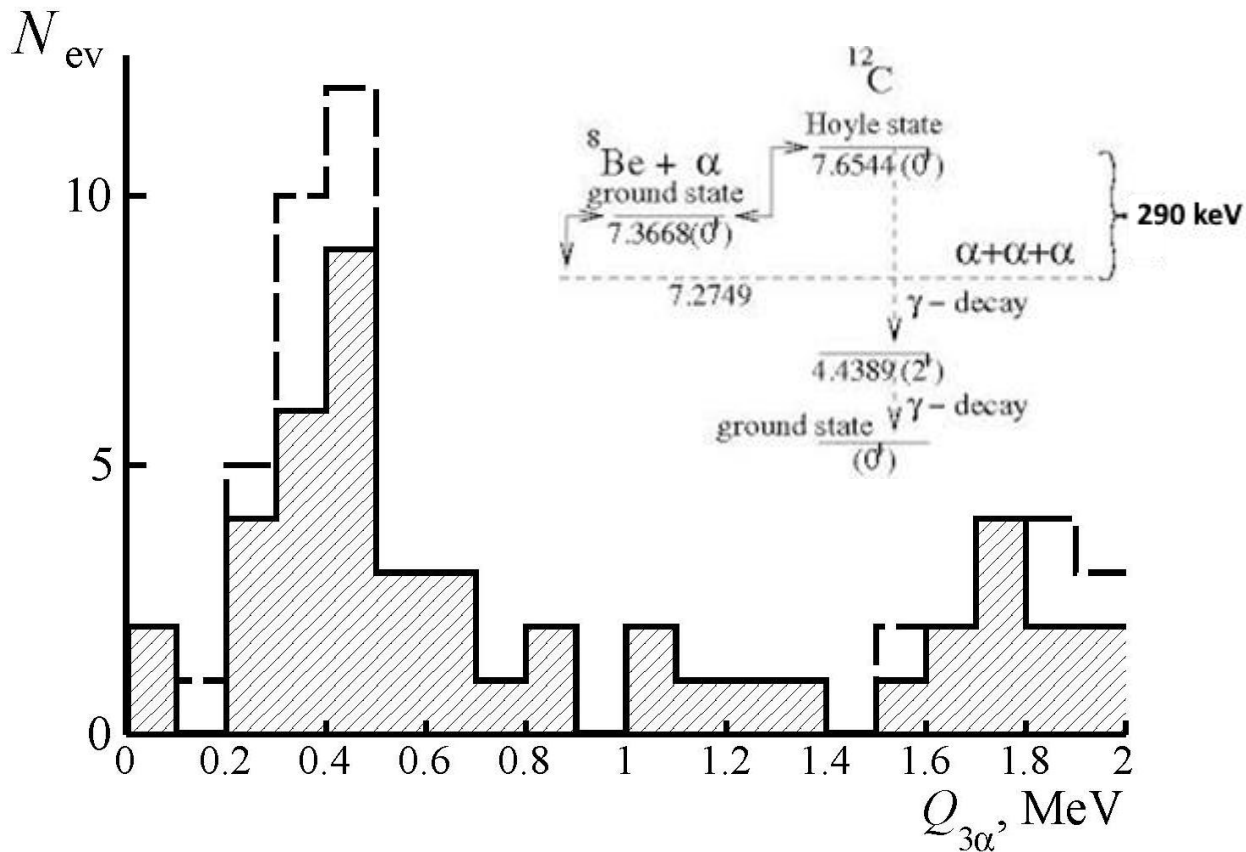


$$Q_{2\alpha} = \sqrt{2 \cdot [m_{\alpha}^2 + E_{\alpha}^2 - \vec{P}_{\alpha 1} \cdot \vec{P}_{\alpha 2}]} - 2 \cdot m_{\alpha}$$

$$\langle Q_{2\alpha} \rangle (<200 \text{ keV}) = 116 \pm 12 (75) \text{ keV}$$

Nucleus (P_0, A GeV/c)	$\langle \Theta_{2\alpha} \rangle$ (RMS), mrad ($Q_{2\alpha} < 200$ keV)	$\langle Q_{2\alpha} \rangle$ (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)
^9Be (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)
^{10}B (1.6)	5.9 ± 0.2 (1.6)	101 ± 6 (46)
^{12}C (1.0)	10.4 ± 0.5 (3.9)	107 ± 10 (79)

Distribution over invariant mass of α -triples

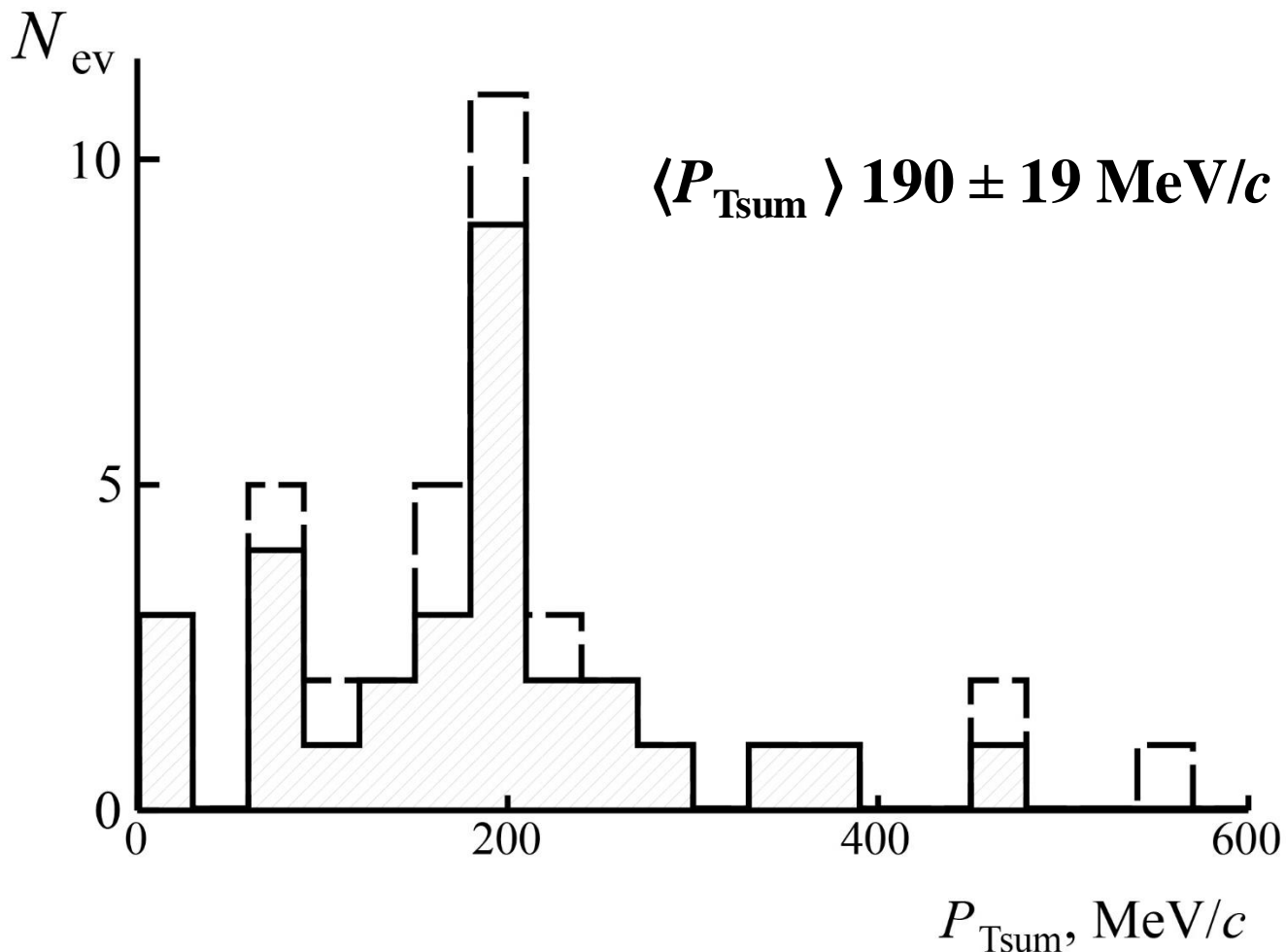


$$Q_{3\alpha} = \sqrt{3 \cdot m_{\alpha}^2 + 2 \cdot \sum_{i \neq j} (E_{\alpha i} \cdot E_{\alpha j} - \vec{P}_{\alpha i} \cdot \vec{P}_{\alpha j})} - 3 \cdot m_{\alpha}$$

$$\langle Q_{3\alpha} \rangle = 443 \pm 52 (186) \text{ keV}, P_0 4.5 \text{ A GeV}/c$$

$$\langle Q_{3\alpha} \rangle = 348 \pm 32 (75) \text{ keV}, P_0 1 \text{ A GeV}/c$$

Distribution over P_{Tsum} of 3α -particles



Distribution of α -triples of HS like decays ($Q_{3\alpha} < 1 \text{ MeV}$) over total transverse momentum $\langle P_{\text{Tsum}} \rangle$ in dissociation $^{12}\text{C} \rightarrow 3\alpha$

Conclusion

In the early 1970s, a nuclear emulsion was irradiated by ^{12}C nuclei with energy of 3.65 A GeV at the JINR Synchrophasotron. Later, stacks of layers of nuclear emulsion impregnated with lead salts were irradiated. We carried out an additional analysis of these irradiations of the nuclear emulsion. As a result, 9 events were found in which the total transverse energy of the alpha particles in the dissociating nucleus system corresponds to the excitation energy of the ^{12}C nucleus to the level of 7.65 MeV (Hoyle state).

Search for production of alpha-particle triples from the second excited state 0^+_2 of the ^{12}C nucleus in new irradiation which was carried out at accelerator complex U-70 in IHEP (Protvino) are in progress now.

In dissociation $^{12}\text{C} \rightarrow 3\alpha$ at 4.5 and $1 \text{ A GeV}/c$ in nuclear track emulsion production of the Hoyle state is identified by using approximate invariant mass representation. Contribution of HS is estimated to be about 11%.

Thank you for attention!