Synthesis of neutron-rich nuclei at the NICA complex.

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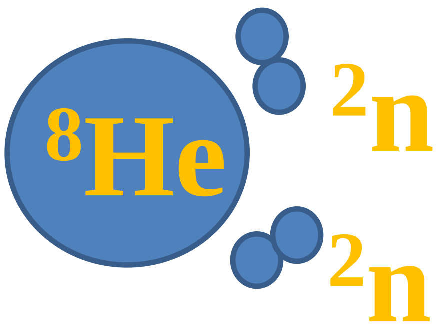
Yu.Oganessian, D.Sakulin, E Syresin , et al.

^{12}He makes it possible to study the structure of neutron-excess nuclei.

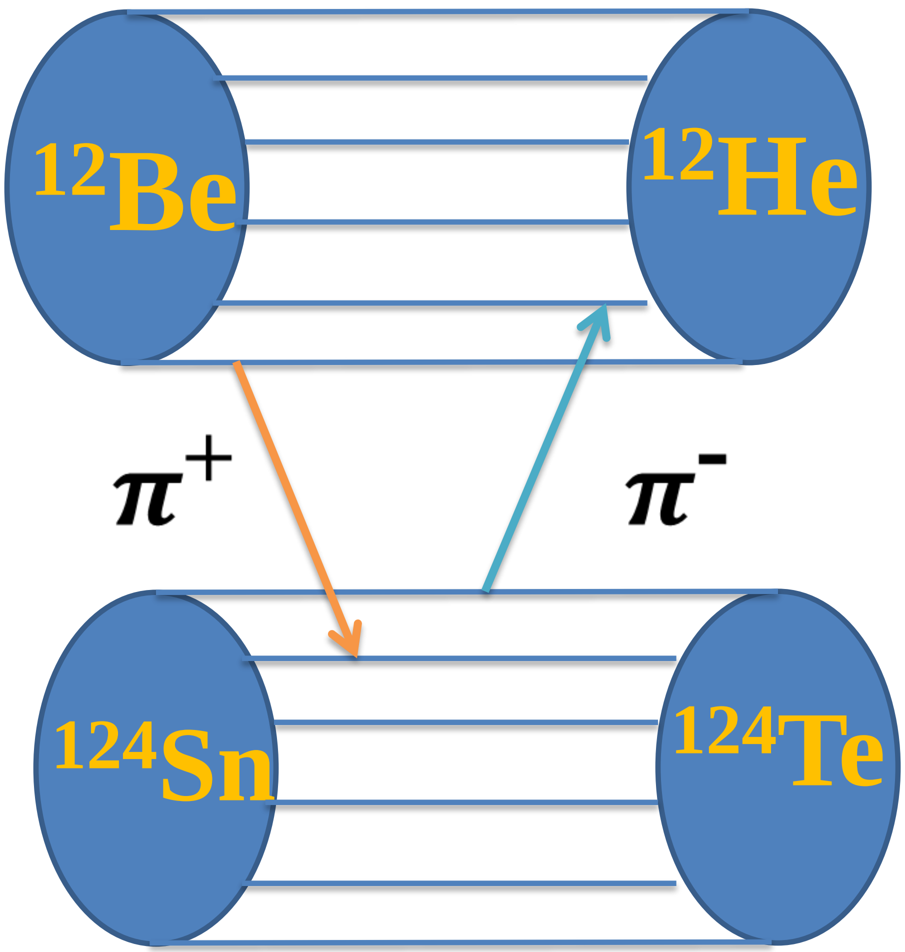
$$^{12}He \rightarrow {}^{8}He + 4n$$

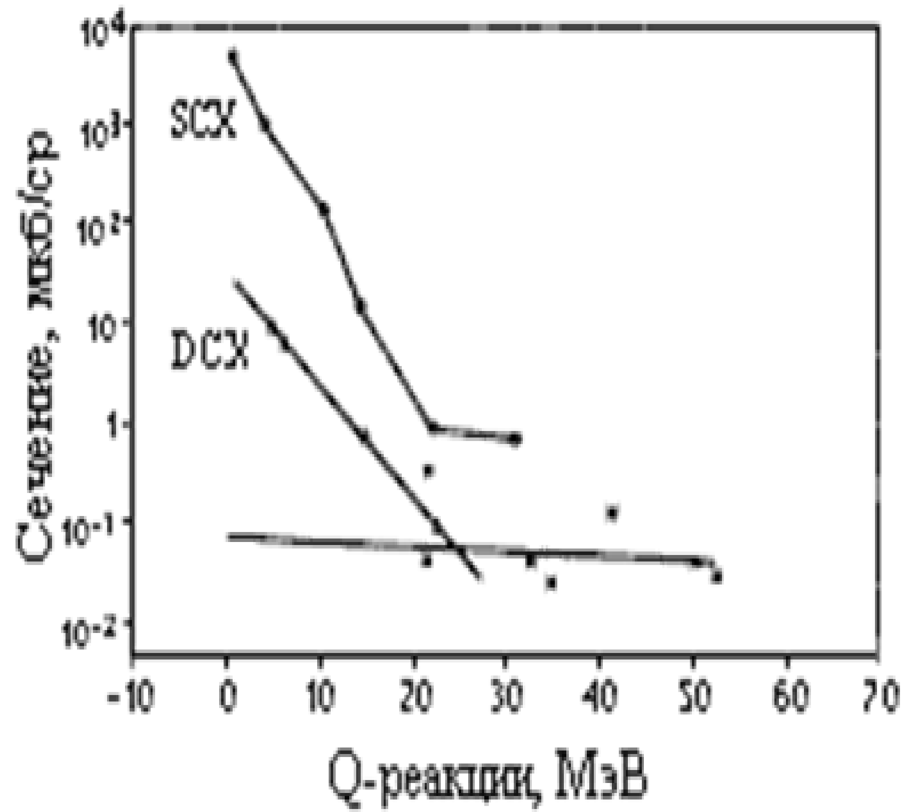


$$^{12}He \rightarrow {}^{8}He + {}^{2}n + {}^{2}n$$

$$^{12}He \rightarrow {}^{8}He + {}^{4}n$$

The probability of ^{12}**He** synthesis is determined only by the **z/n** ratio and the difference in binding energies of the parent and daughter nuclei.





http://nuclphys.sinp.msu.ru/exotic/e02.html

Формирование ^{12}He на пучке ^{12}Be в реакции двойной перезарядки $^{12}Be(\pi^+, \pi^-)^{12}He$

$^{12}Be + {}^{124}Sn \rightarrow {}^{12}He + {}^{124}Te$ (Q=24.5 MeV)

The reaction should give a greater output for the beam intensity $10^9\ c^{-1}$

$\sigma(dcx) \approx 1.0\mu b/str$

Targ=1.0 g/cm^2

$$I = 10^{-8} I_b$$

Beam intensity for ^{12}Be It must be at least $I_b > 10^3 c^{-1}$ $t = 10^6 c$

27 h/ev.

Energy balance of the charge exchange reaction

$^{11}Li + ^{11}B \rightarrow ^{10}He + ^{12}C$

$^{11}Li \rightarrow ^{10}He$

$^{11}B \rightarrow ^{12}C$

Q=-0.37 MeV

$^{11}Li + ^{11}B \rightarrow ^{12}He + ^{10}C$

$^{11}Li \rightarrow ^{12}He$

$^{11}B \rightarrow ^{10}C$

Q=32.9 MeV

Reaction cross sections

$\sigma(^{10}He) \approx 10 mb/str$

$\sigma(^{12}He) \approx 0.1 \mu b/str$

$^{12}Be + ^{11}B \rightarrow ^{12}He + ^{11}N$ (Q=24.5 MeV)

$\sigma(dcx) \approx 1.0 \mu b/str$

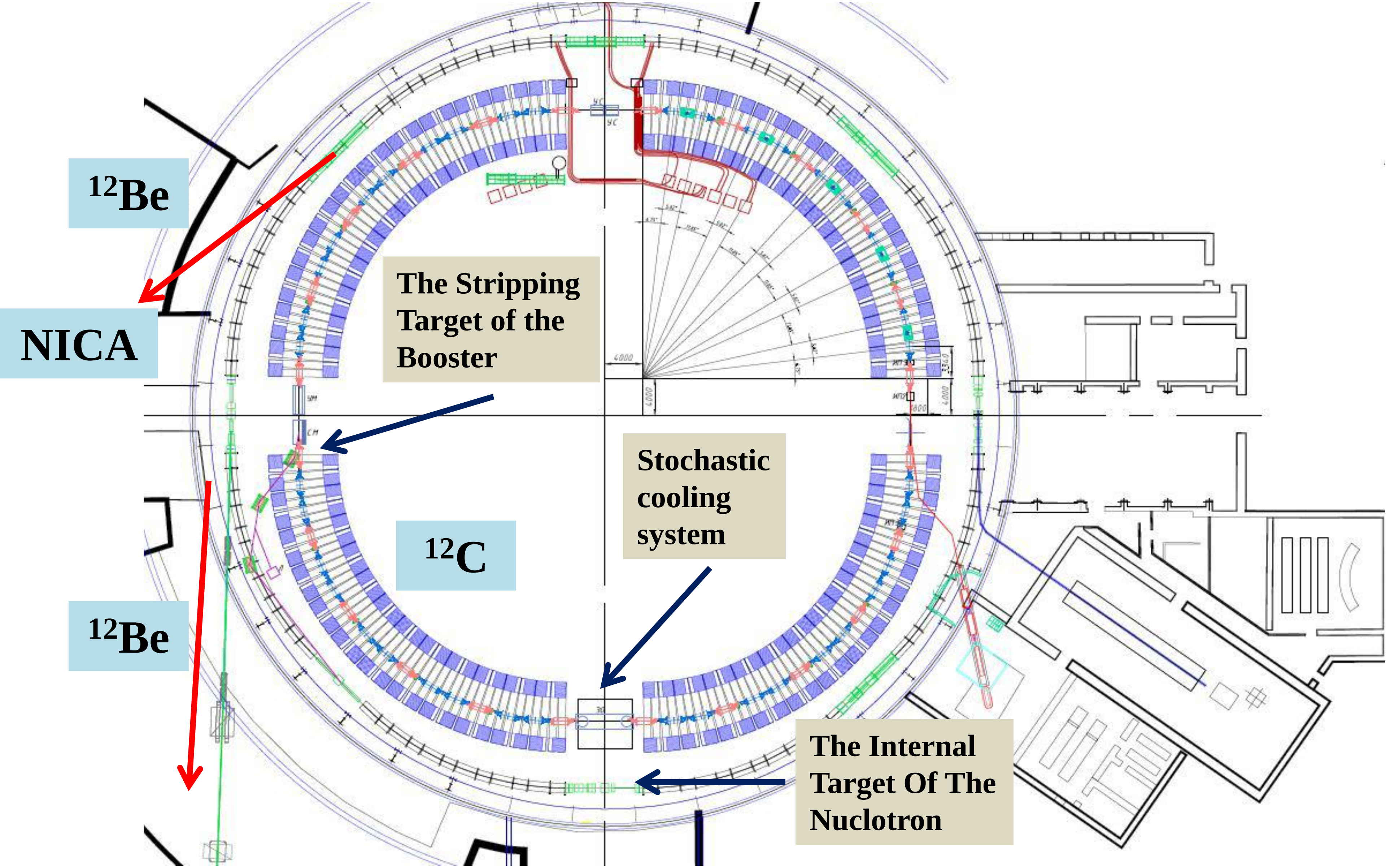
Formation of a ^{12}Be beam on a nuclotron in a double-charge reaction on the inner target of a booster or nuclotron.

$$^{12}C + ^{124}Sn \rightarrow ^{124}Te + ^{12}Be \quad (Q=22.8\ MeV)$$

σ(dcx)≈1.0μb/str $\quad$ $I_{beam} = 3\cdot10^9\ A/q^2 = 3\cdot10^9 \cdot 11/25 = 1.3\cdot10^9$ **ions/cycle**

The maximum beam intensity is ^{12}Be during multi-turn interaction with the target

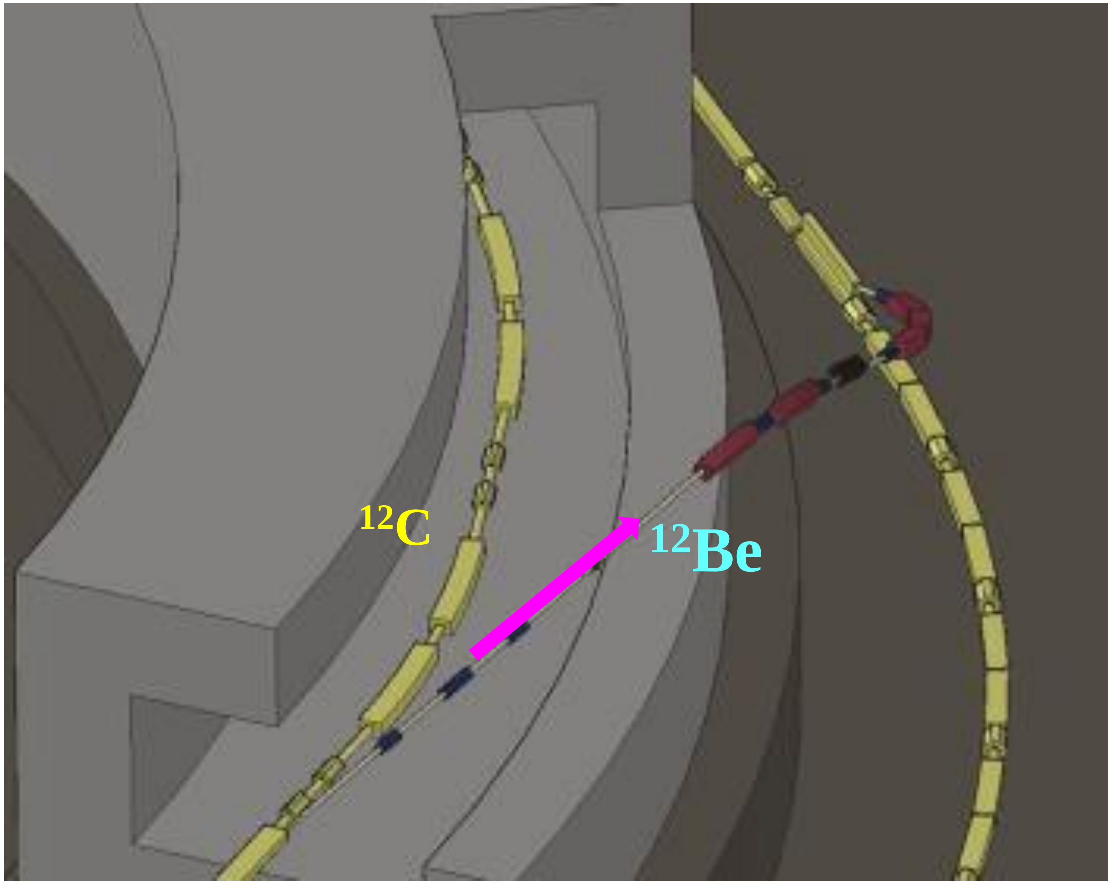
$$1.3\cdot10^9 \cdot 10^{-6} \approx 10^3 \text{ ионов}(^{12}Be)/\text{цикл.}$$


12Be
NICA
The Stripping Target of the Booster
12C
12Be
Stochastic cooling system
The Internal Target Of The Nuclotron

Beam output from the booster

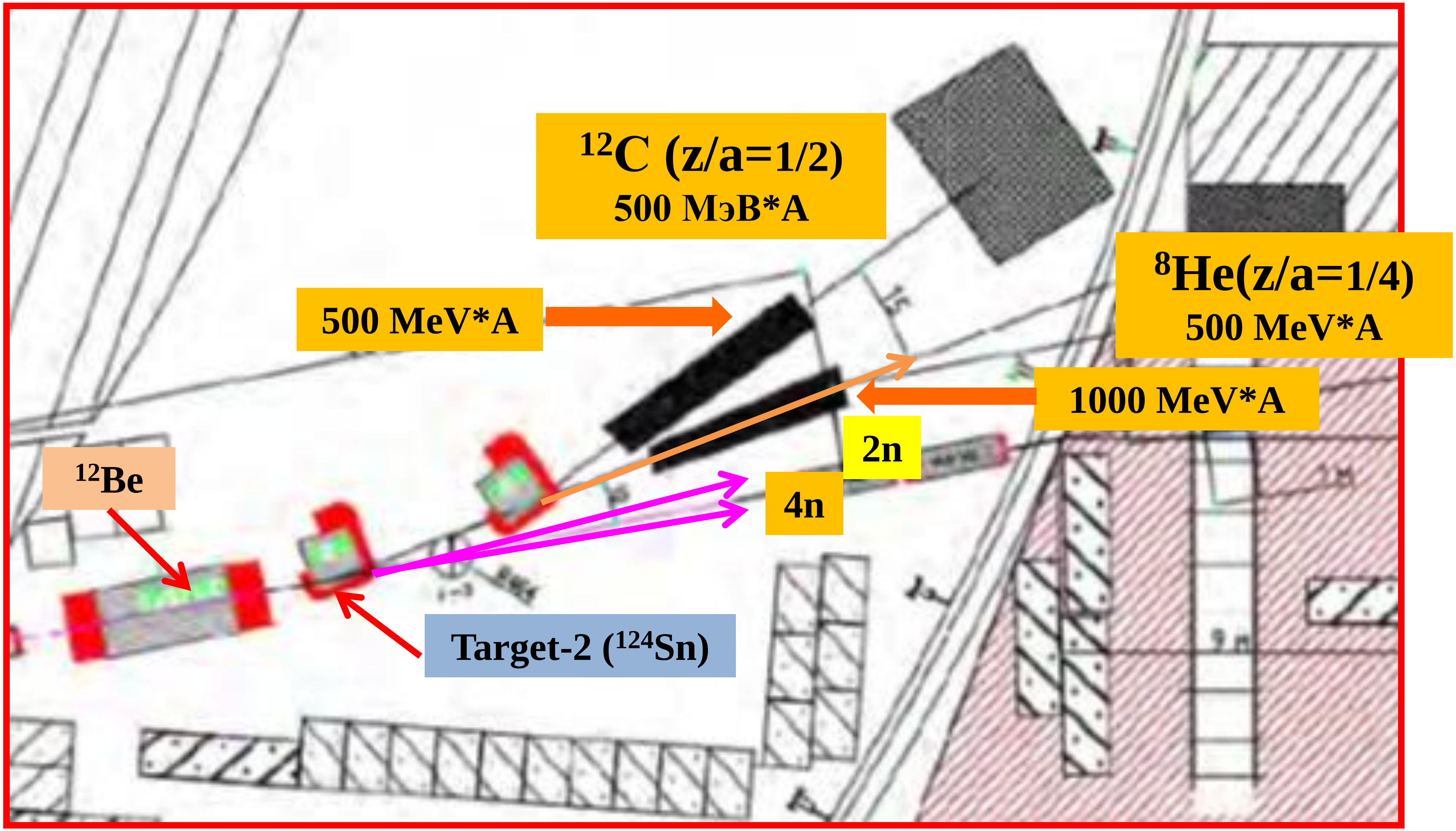
Setting up the complex for $^{12}C^{4+}$ Z/A=1/3

Syntesis ^{12}Be by beam $^{12}C^{6+}$ → ^{12}Be Z/A=4/12=1/3
Z/A=1/2




Mounted foils on the comb of the stripping station.

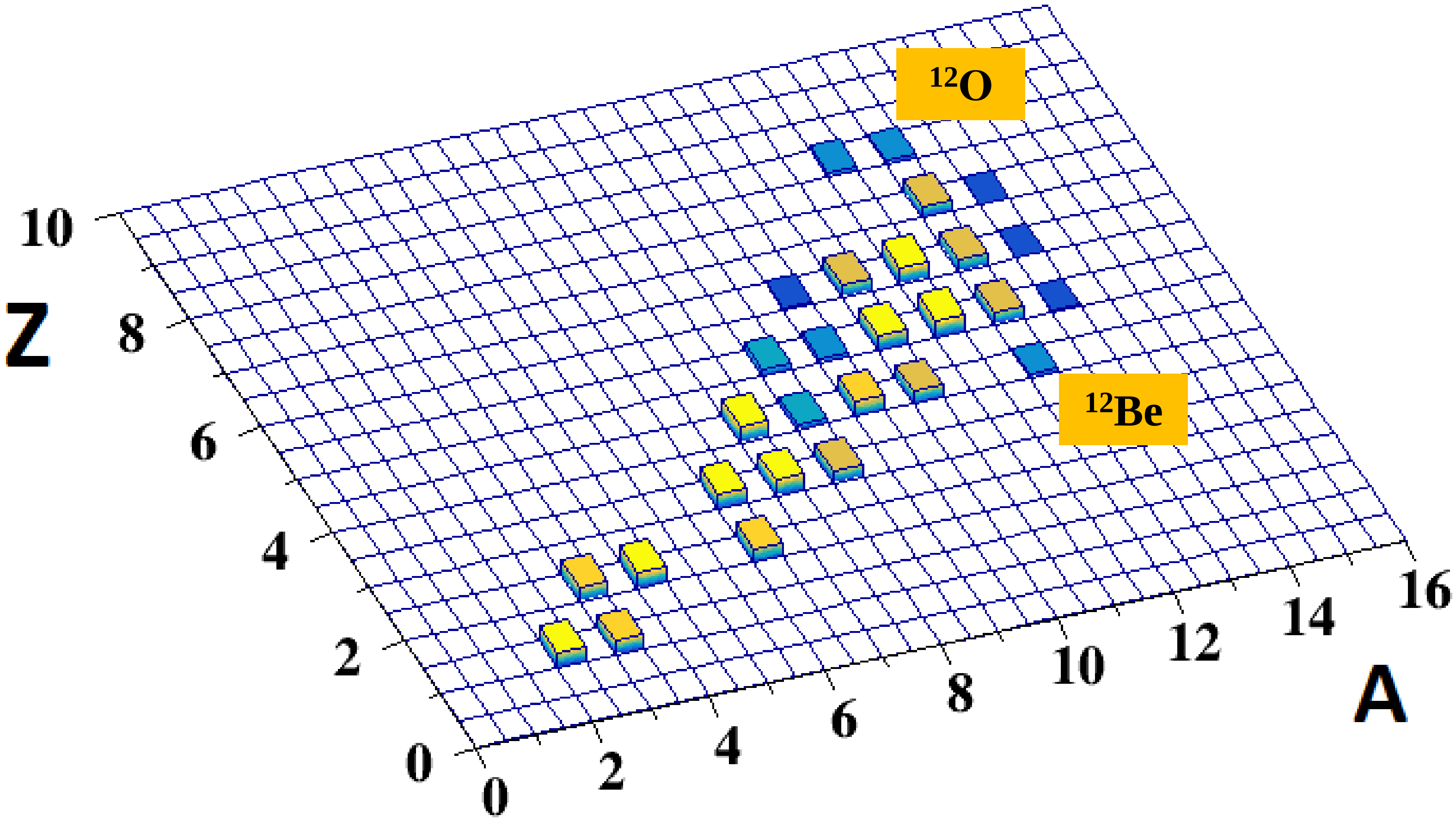
Registration of ^{12}He by decay products of ^{8}He +4n
^{8}He - magnetic spectrometer + dE/dx



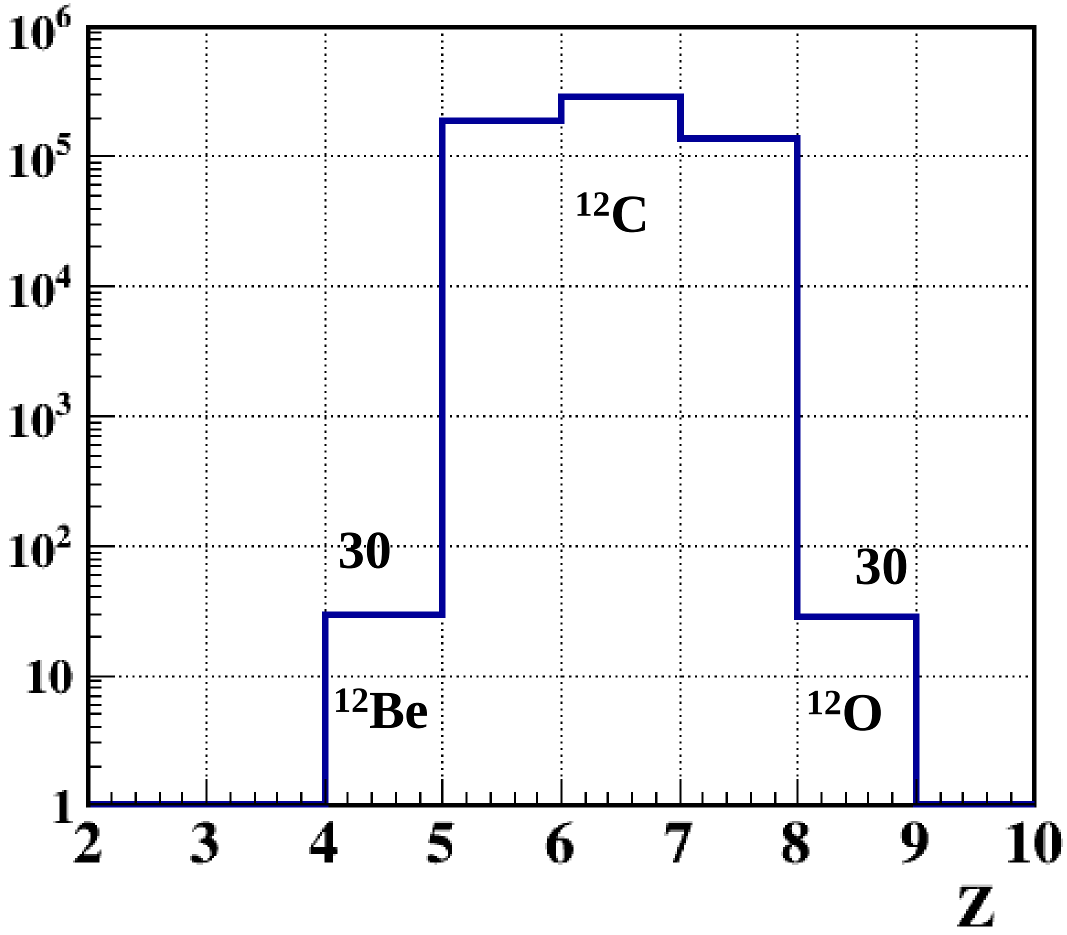
Simulation of the reaction by DCM-QGSM-SMM

$^{12}C + ^{124}Sn \rightarrow ^{124}Te + ^{12}Be$ (Q=22.8 MeV)

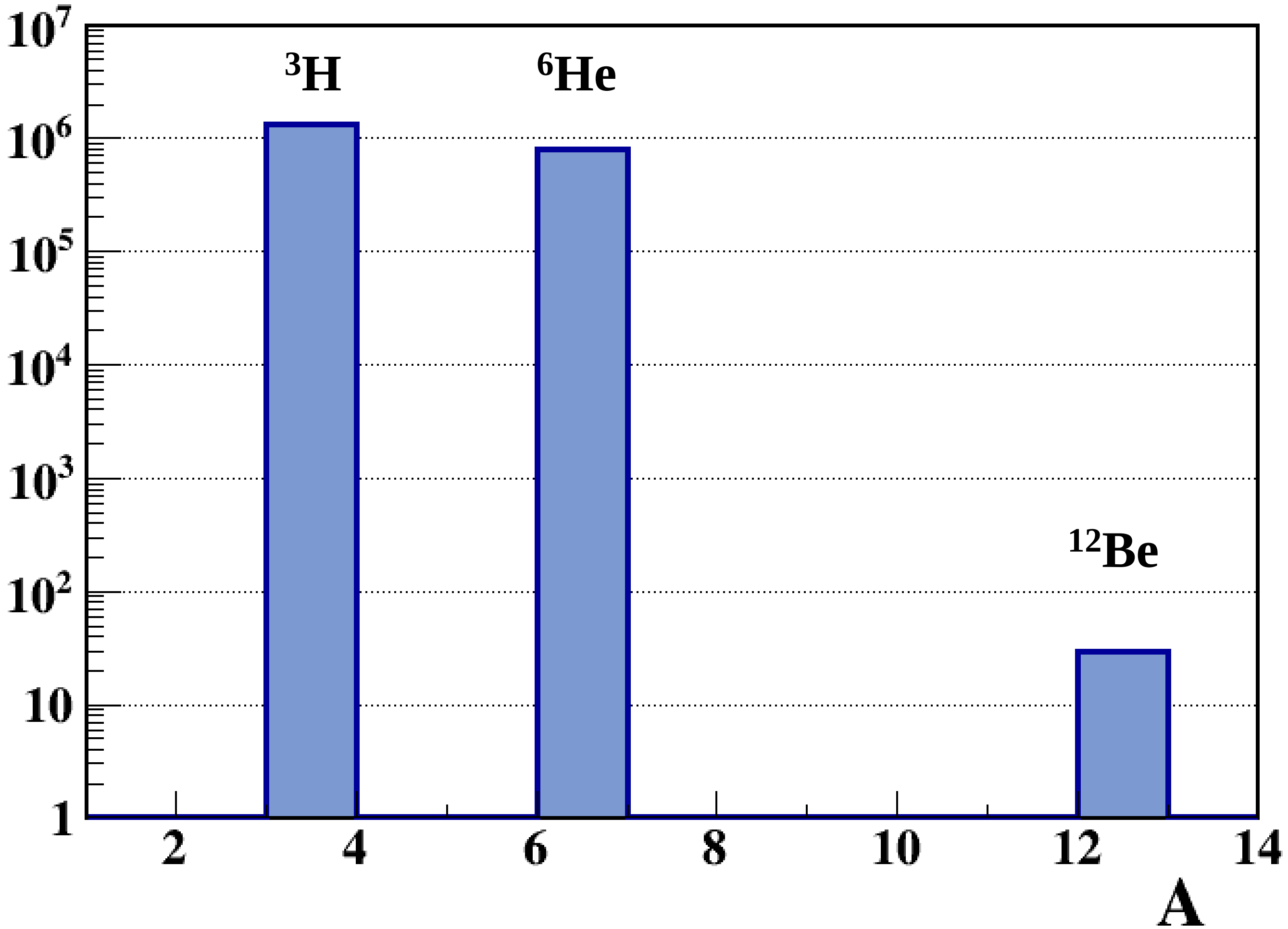
Beam energy 500 MэВ*A



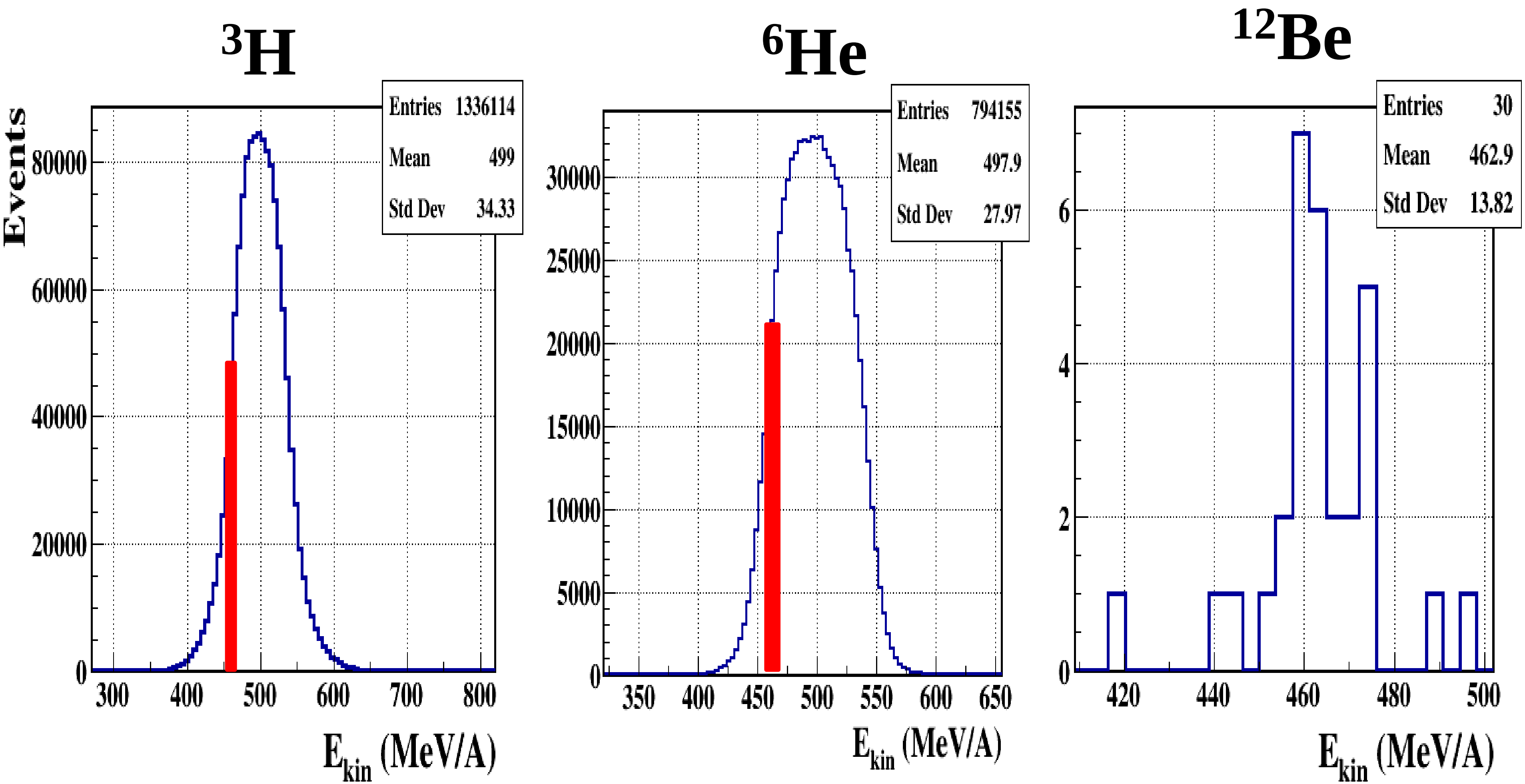
The yield of fragments in the reaction $^{12}C + {}^{124}Sn \rightarrow X$ for A=12 and 10^7 interactions.

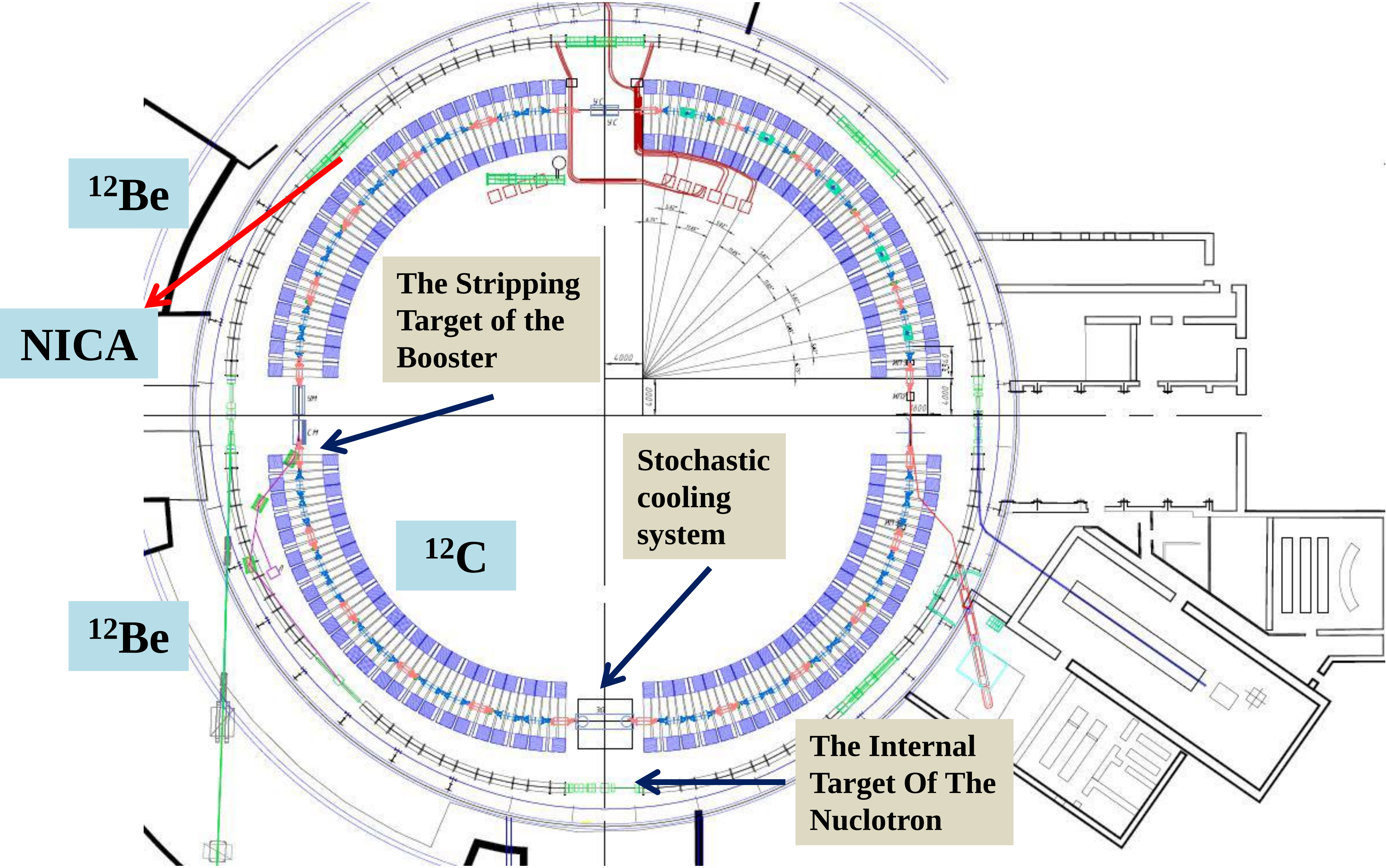


Separation of fragments in the reaction $^{12}C + ^{124}Sn \rightarrow X$ for Z/A=1/3 and 10^7 interactions.



Energy distribution for products.

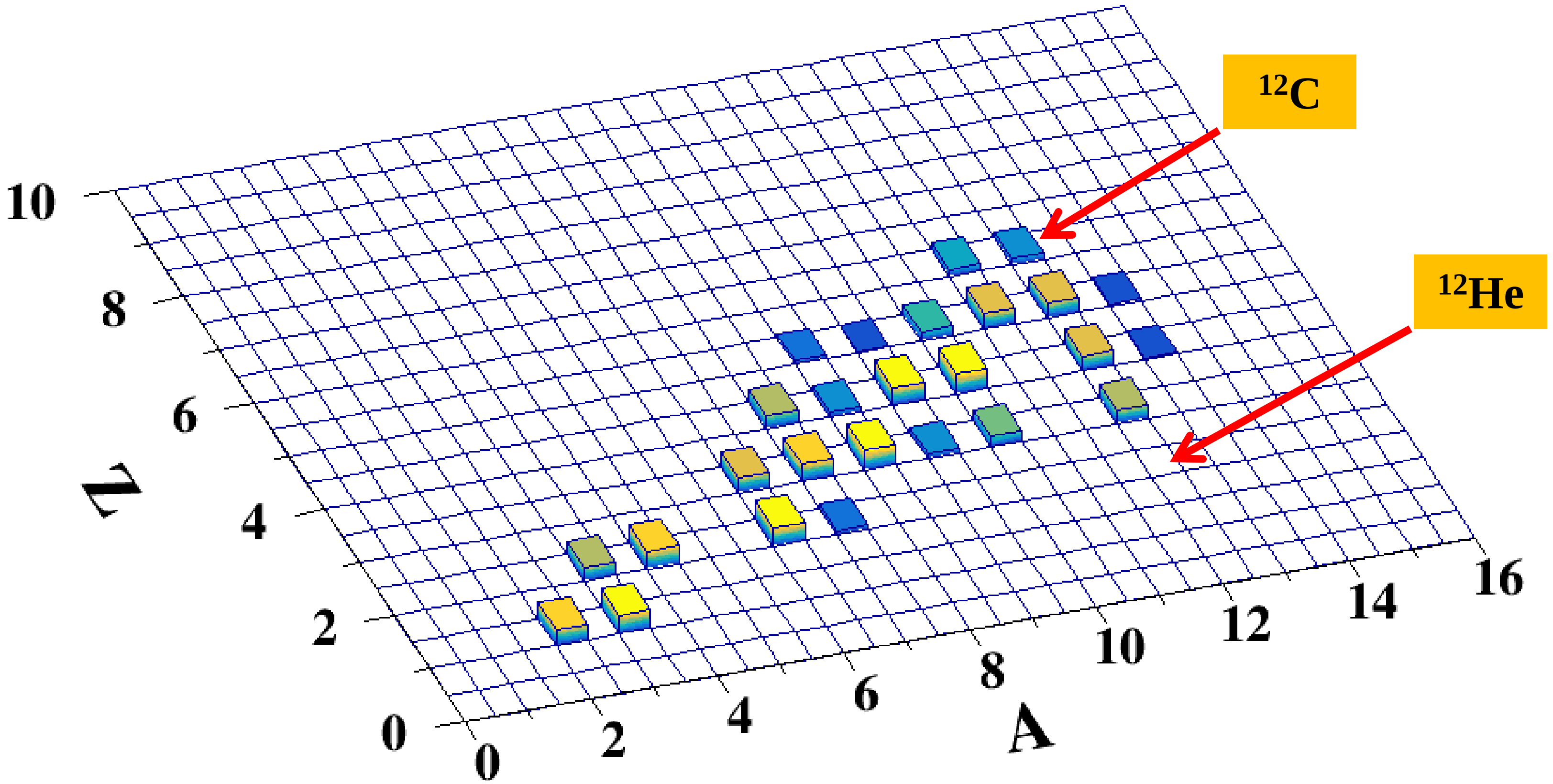



^{12}Be
NICA
The Stripping Target of the Booster
Stochastic cooling system
^{12}C
^{12}Be
The Internal Target Of The Nuclotron

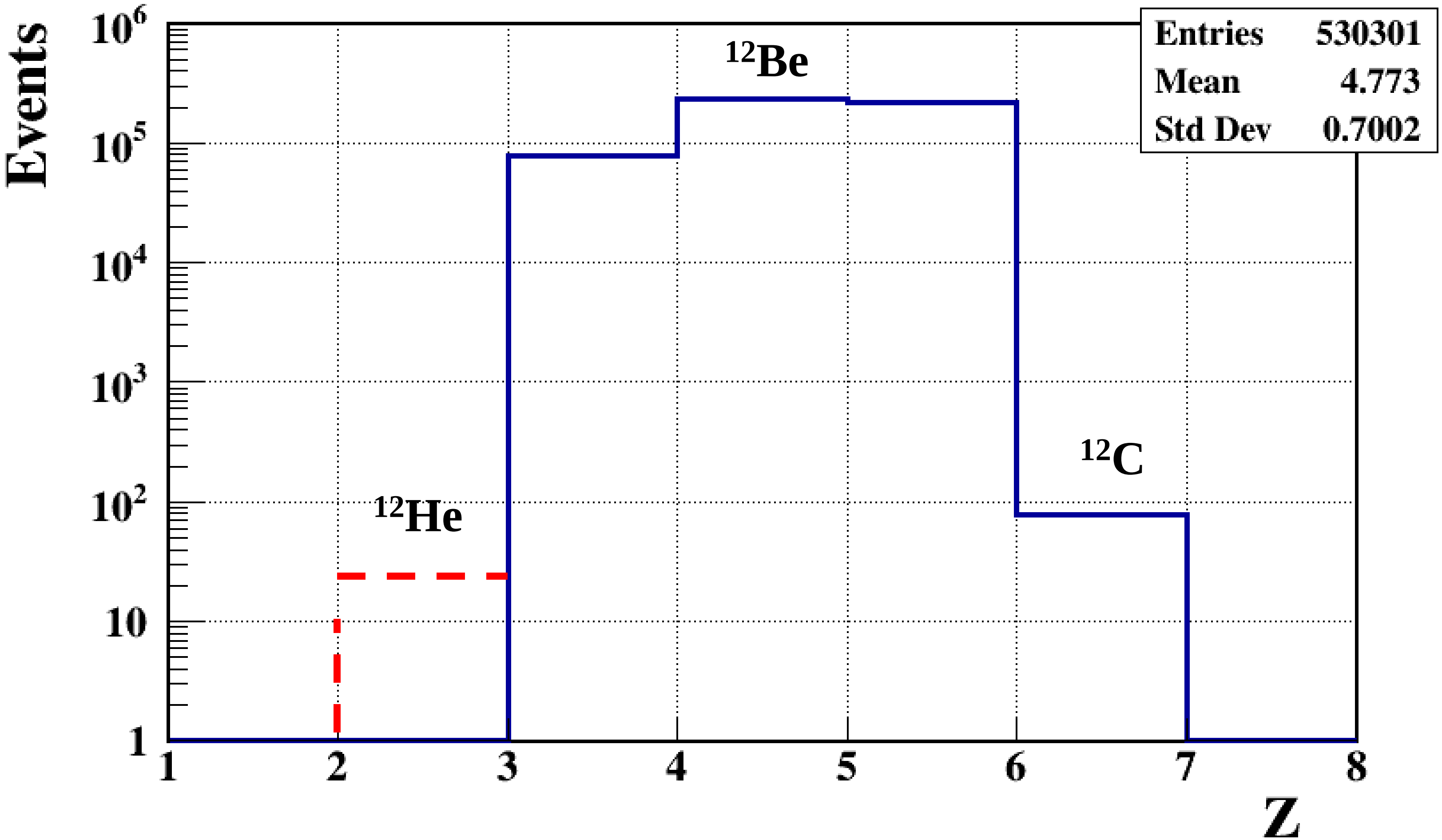
Simulation for the reaction

$^{12}Be + ^{124}Sn \rightarrow ^{124}Te + ^{12}He$ (Q=24.5 MeV)

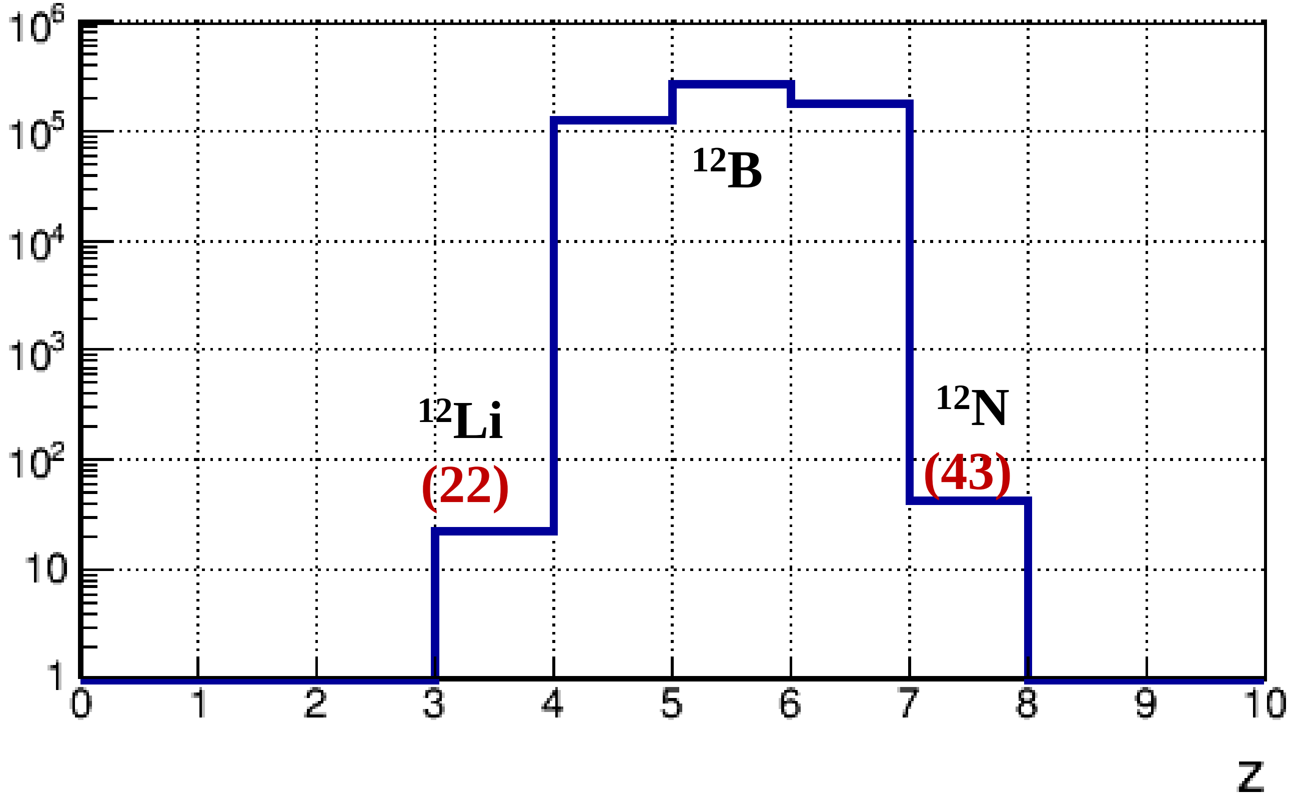
The beam energy 500 МэВ*А



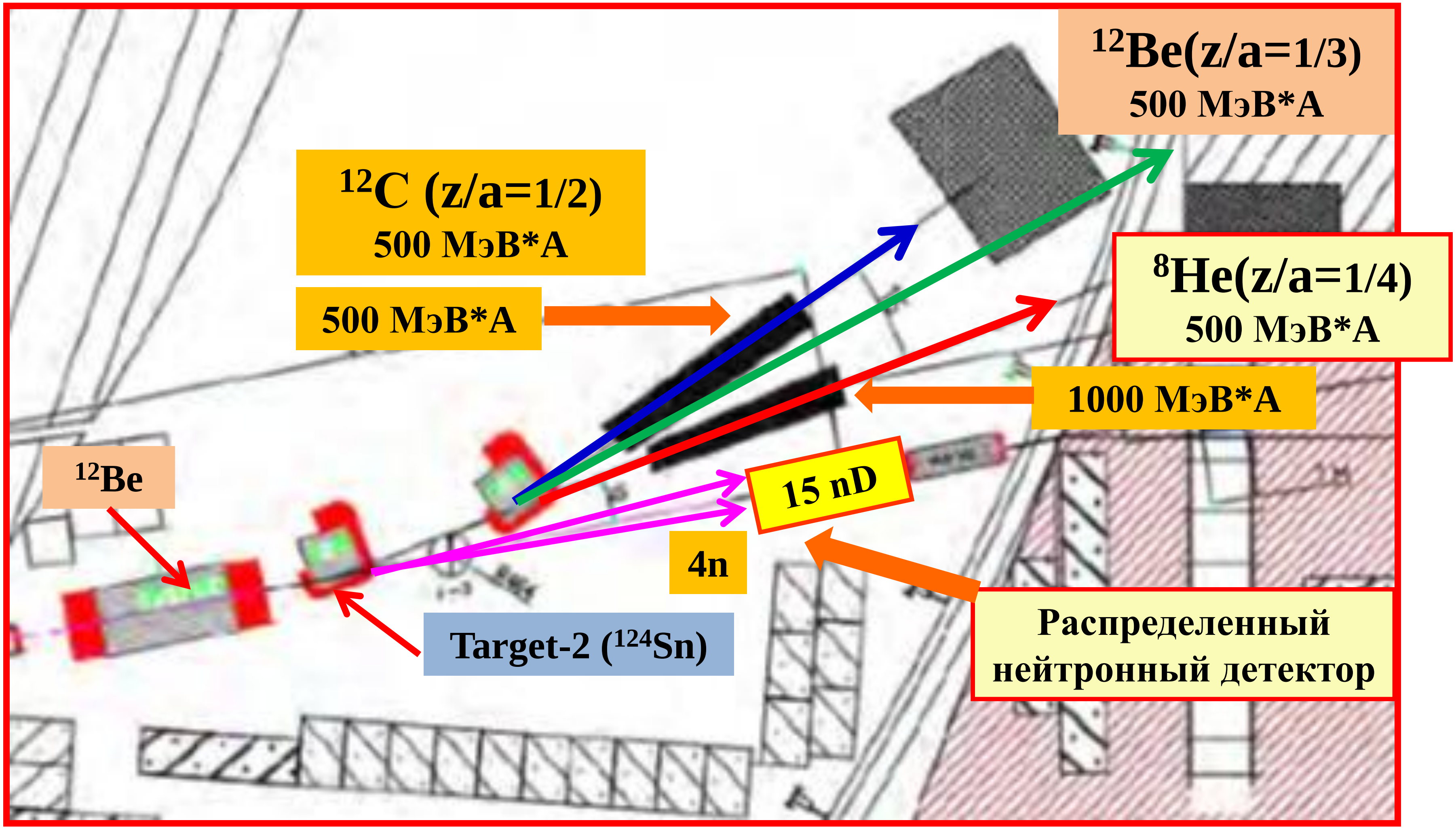
The output of fragments in the reaction $^{12}Be + ^{124}Sn \rightarrow X$ for A=12 and 10^7 interactions.



The output of fragments in the reaction $^{12}B + ^{124}Sn \rightarrow X$ for A=12 and 10^7 interactions.

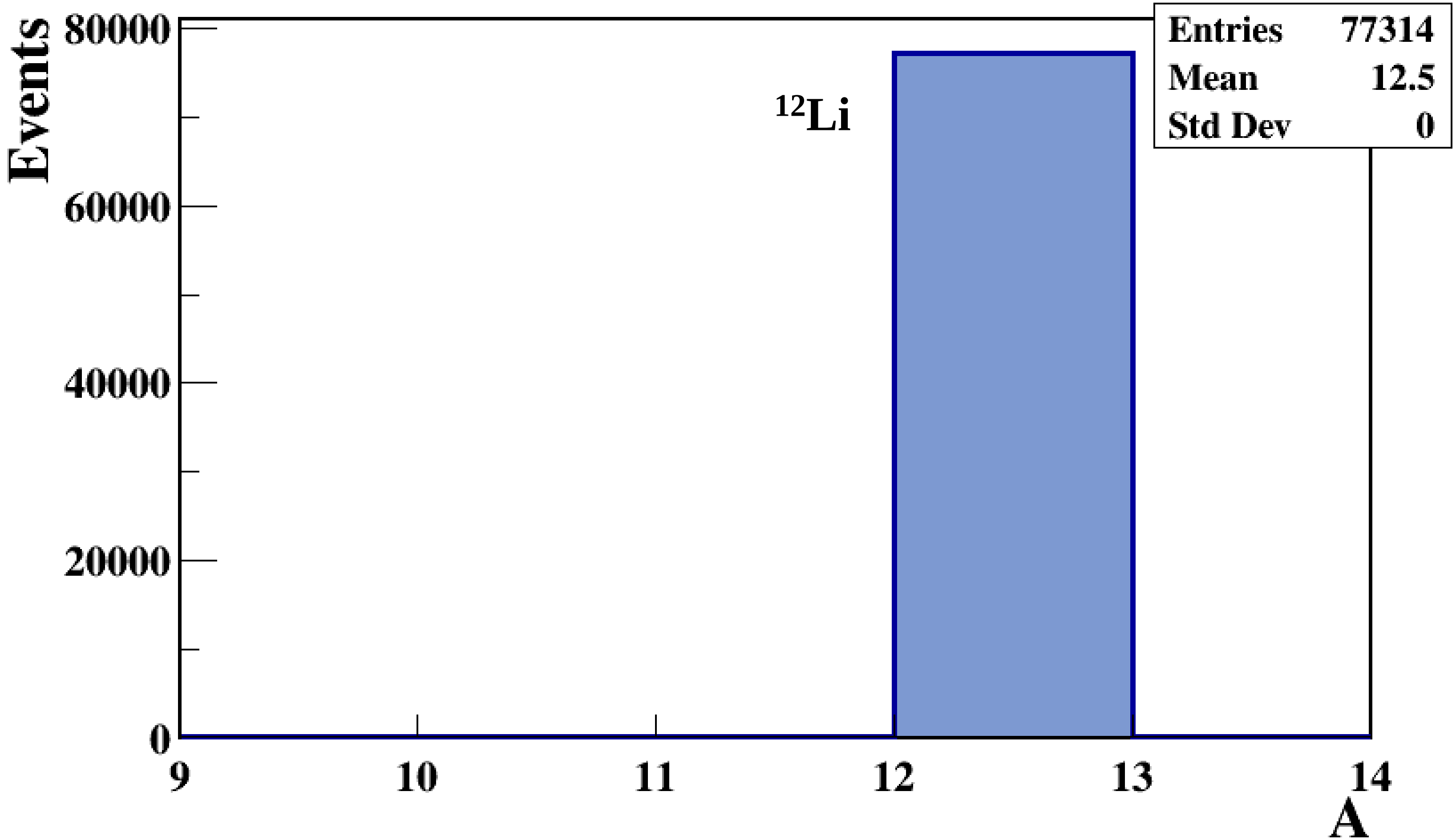


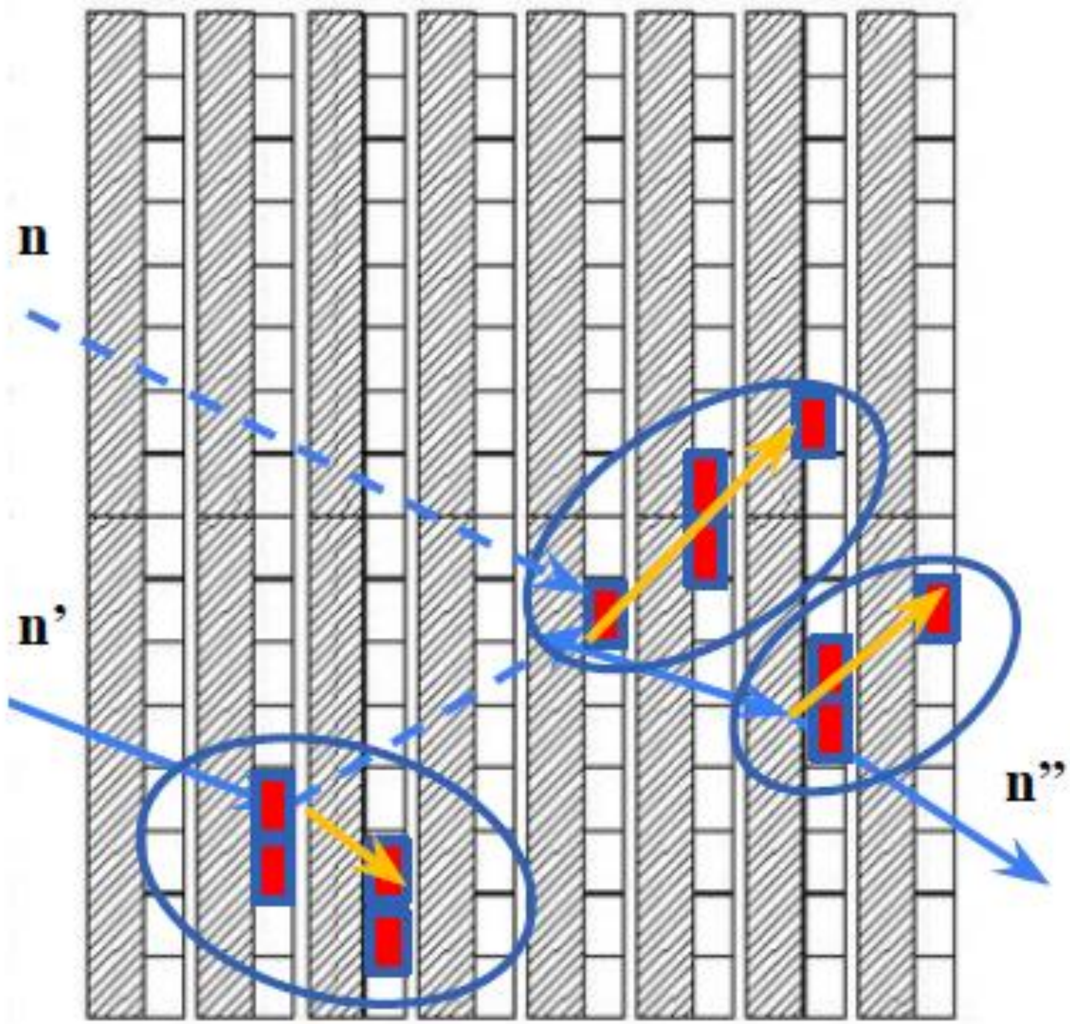
Регистрация ^{12}He по продуктам распада ^{8}He +4n
^{8}He - магнитный спектрометр + dE/dx



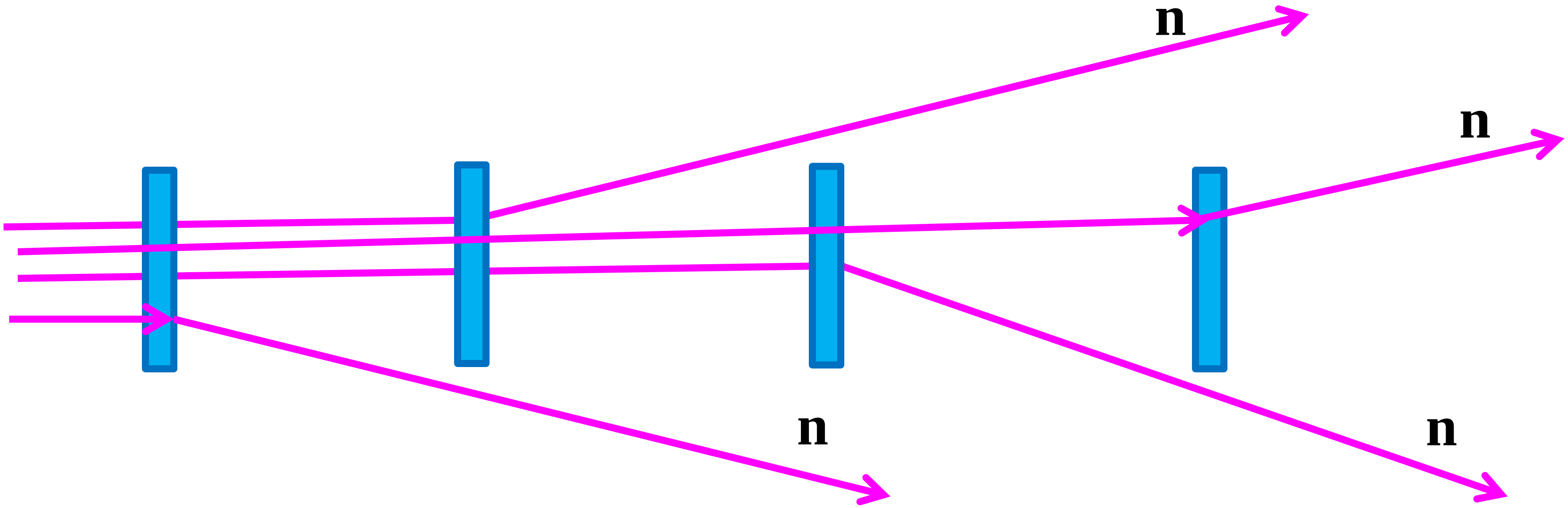
Separation of fragments in the reaction $^{12}Be + ^{124}Sn \rightarrow X$ for Z/A=1/4 and 10^7 interactions.

$^{12}He \rightarrow$ ^{8}He +4n



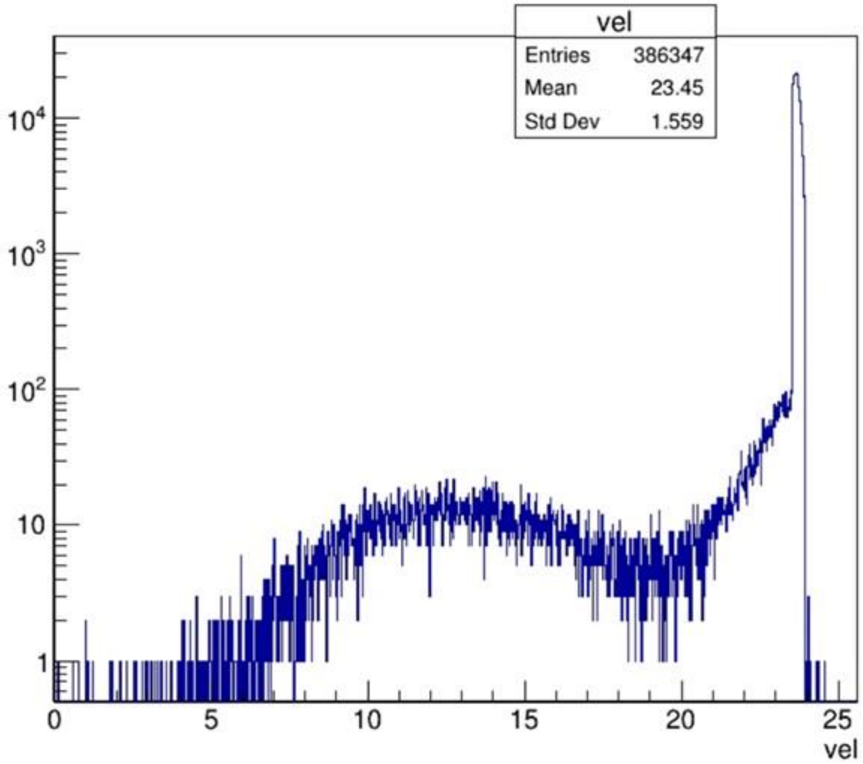

n
n'
n''

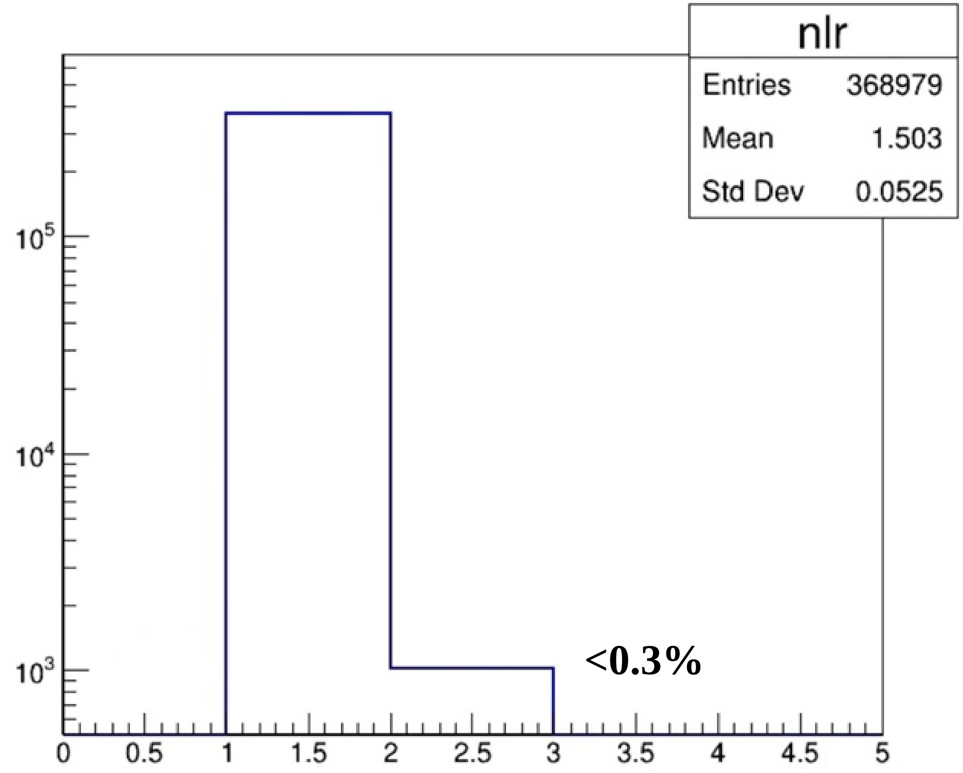
Registration of neutrons by a multilayer neutron detector. The layers are located at a distance sufficient to eliminate the interacting neutrons from the analysis.



dE_n>3MэB

The neutron velocity, reconstructed from the time of flight from the target to the detectors, and the probability of a secondary interaction of neutrons in the neutron detector.





Registration in the final state is carried out for ^{8}He and accompanying neutrons. The neutron detector is positioned at 0 degrees and consists of 15 layers of SiPM-based neutron counters and a $40x40mm^2$ scintillator. The detector area is currently being optimized by the Monte Carlo method. The neutron detector is planned to be assembled based on the prototype of the BMaN neutron detector, distributing the layers along the direction of neutron emission. In total, it is planned to use 15 blocks shown in the figure.

The distance between the layers of a neutron detector depends on the energy. For the energy of the booster 570MeV is about 1m.

T(MeV)	70	170	270	370	470	570	670	770	870	970	1070	1170	1270	1370	1470	1570
L(cm)	30	50	66	79	91	103	114	124	135	145	155	165	175	184	194	203

The time of flight from the target to the first layer of the detector based on 4.5 m, the difference in time of flight for the neutron and gamma quantum, and the separation in time of flight for a time resolution of 200ps.

TOF(ns)	41.0	28.2	23.8	21.5	20.1	19.2	18.5	18.0	17.6	17.2	17.0	16.8	16.6	16.4	16.3	16.2
t(n)-t(γ) (ns)	26.0	13.2	8.8	6.5	5.1	4.2	3.5	3.0	2.6	2.2	2.0	1.8	1.6	1.4	1.3	1.2
Nσ	130	66	44	33	26	21	17	15	13	11	10	9	8	7	6	6

The efficiency of neutron energy detection with a total thickness of scintillators = 1m (CsI) is about 75% on average.

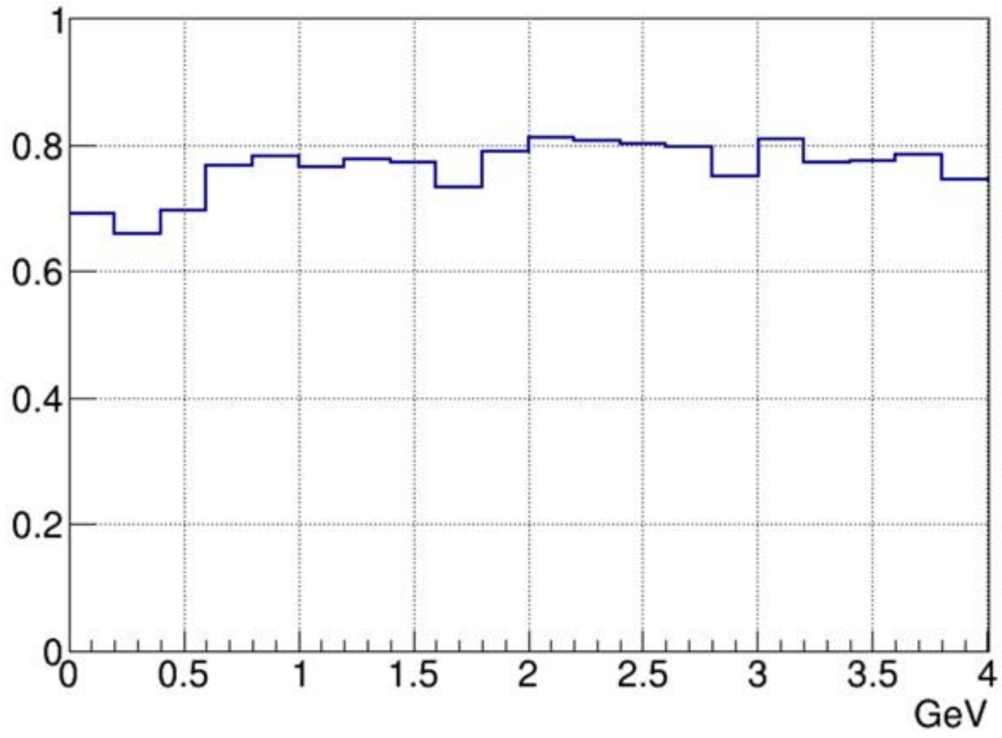
For 15 detector layers:

Registration of two neutrons is **56%.**

The probability of registration in one layer is **0.2%**

Registration of four neutrons is **31%.**

The probability of registration in one layer is **1.4%**



The final output of the reaction

Taking into account the efficiency of neutron detection, the optimistic expectation of the reaction yield is

for ^{12}He
about 10^{-2} ev/hour

Similar estimates
for ^{10}He
is about 100 ev/hour

Conclusions

- The evolution of the NICA complex makes it possible to form, separate, and use beams of short-lived neutron-reached nuclei for research.
- The existing Infrastructure makes it possible to test of the formation and separation of secondary neutron-rich nuclei and to analyze them.

Technical issues related to the project implementation

- Losses during beam transfer from the booster to the nuclotron.
- Losses during beam transportation before exiting the nuclotron.
- The primary intensity of carbon nuclei in the booster.
- The analyzing ability of the spectrometer for registration is ^{8}He.
- …

Thanks for your attention

Backup

Measured yields and released fractions (R) of lithium and beryllium isotopes from a 2 μm tantalum foil **target (~10^{-4}g/cm^2).** The measuring device used was either a Faraday cup (F), a tape station (T) associated with a β counter, or a neutron counter (N). The change in production cross section per unit mass step when moving towards the neutron drip-line was calculated for each isotope taking the ratio of yield/R to its value for the preceding isotope. The yield corrected for decay losses can be compared with the production rate calculated with Silberberg and Tsao (S&T) [6] cross sections.
Ion T1=2 Yield R _ ratio Yield/R S&T prod.

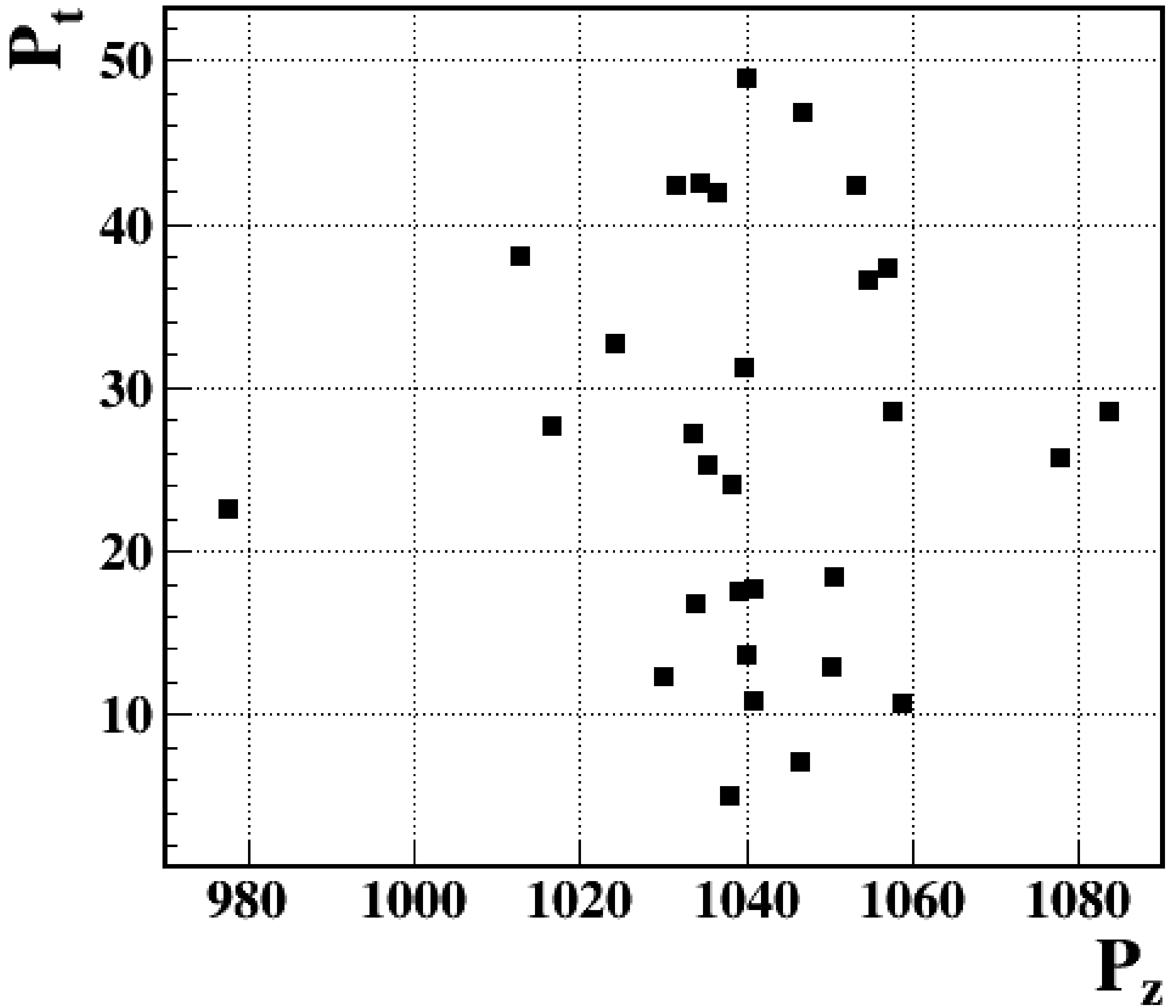
Ion (Device)	T1=2 (from [8])	Yield (1/μC)	R (%)	μ ratio A/(A-1)	Yield/R (1/ion)
	Ip=	$1.6 \cdot 10^{13}$			
7Li(F)	stable	$2.0 \cdot 10^{9}$			2,0x10-4
8Li(T)	838(6) ms	$5.8 \cdot 10^{8}$	75	1/2.6	7,7x10-5
9Li(T)	178.3(4) ms	$1.7 \cdot 10^{7}$	45	1/20	3,8x10-7
11Li(N)	8.59(14) ms	$7.0 \cdot 10^{3}$	2	1/10	3,5x10-8
9Be(F)	stable				6,3x10-5
10Be(F)	1.51(6) My	$4.9 \cdot 10^{8}$		1/1.3	4,9x10-5
11Be(T)	13.81(8) s	$3.4 \cdot 10^{6}$	82	1/100	4,1x10-7
12Be(N)	21.3(1) ms	$4.8 \cdot 10^{4}$	1,8	1/1,5	2,7x10-7
14Be(N)	4.35(17) ms	6,1	0.05	1/15	1,2x10-9

[6] R. Silberberg and C.H. Tsao, Astrophys. J. Suppl. Series No. 220(II) 25 (1973) 335.
[8] G. Audi et al., Nucl. Phys. A624 (1997) 1.

Experimental zone (report by O.V. Belov)

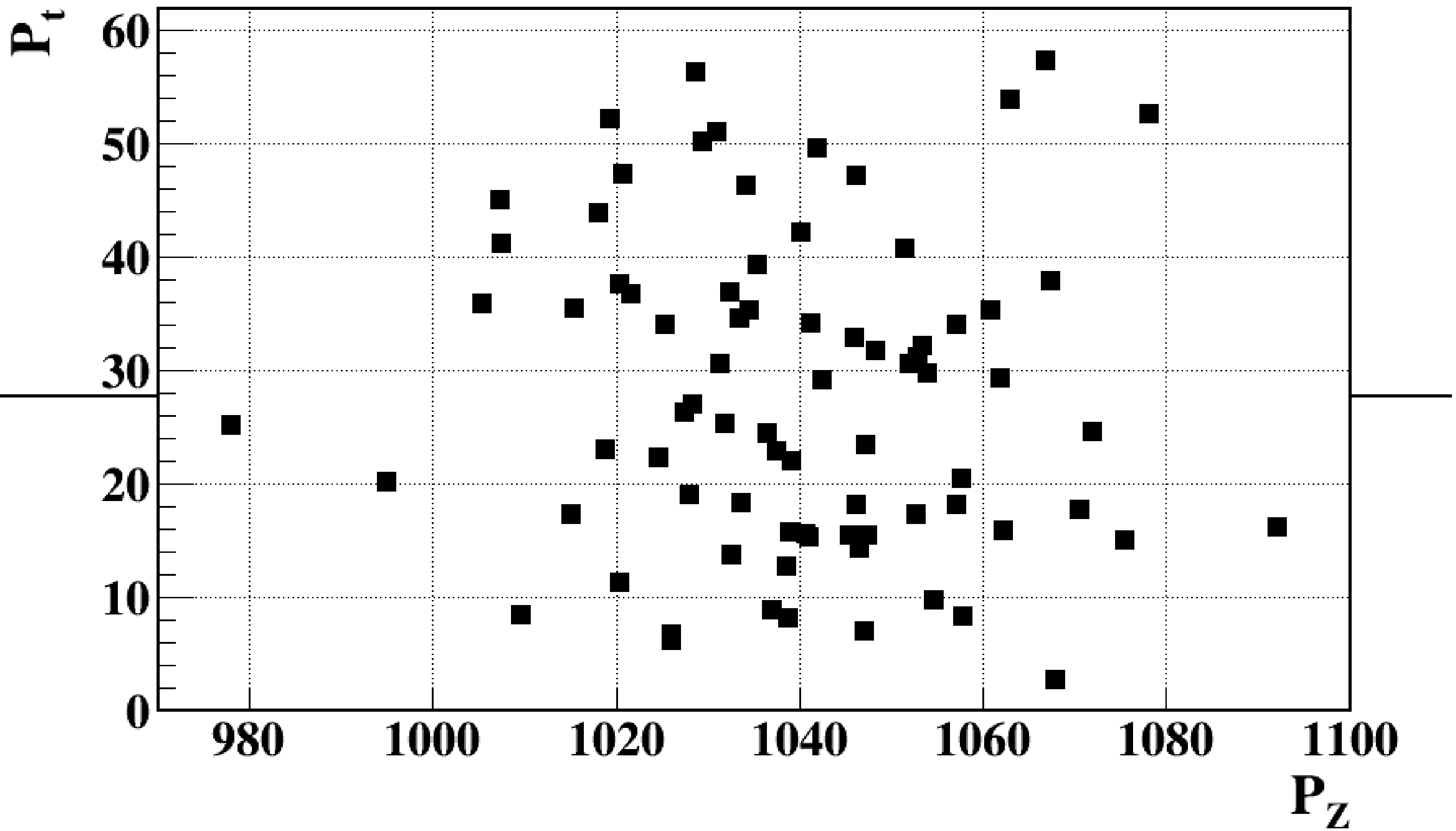
$^{12}C + ^{124}Sn \rightarrow ^{12}Be$

для 10^7 ваимодействий



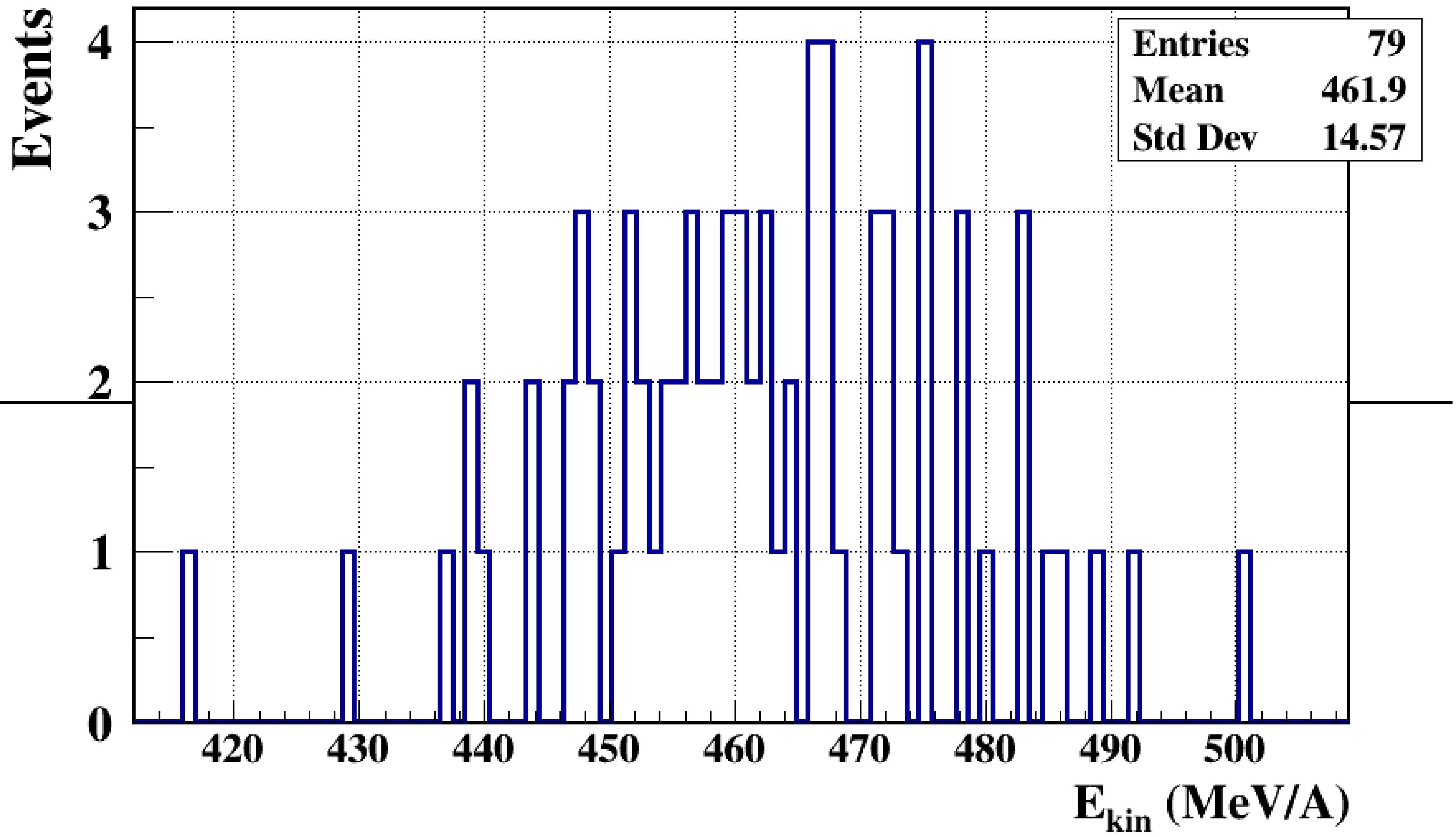
$^{12}Be + ^{124}Sn \rightarrow ^{12}C$

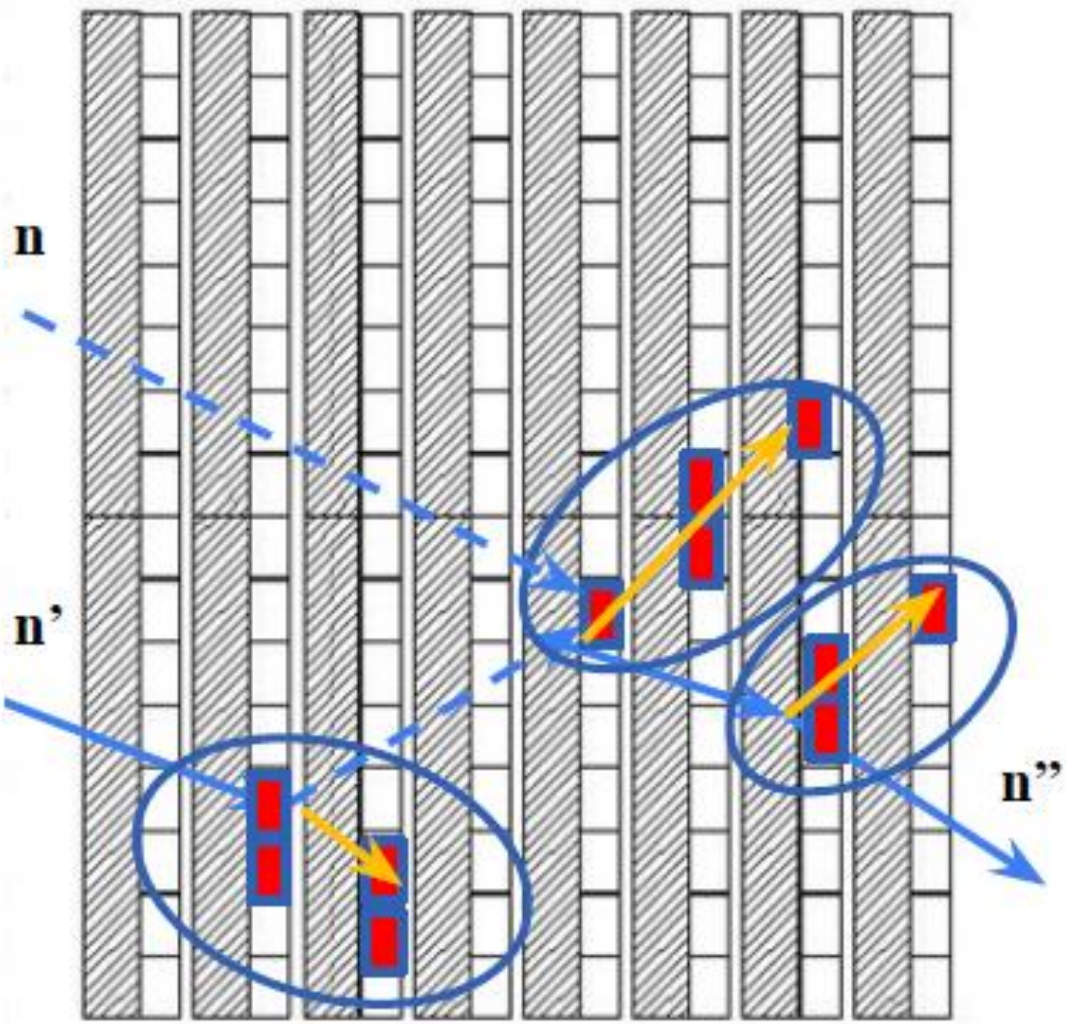
для 10^7 ваимодействий



$^{12}Be + {}^{124}Sn \rightarrow {}^{12}C$

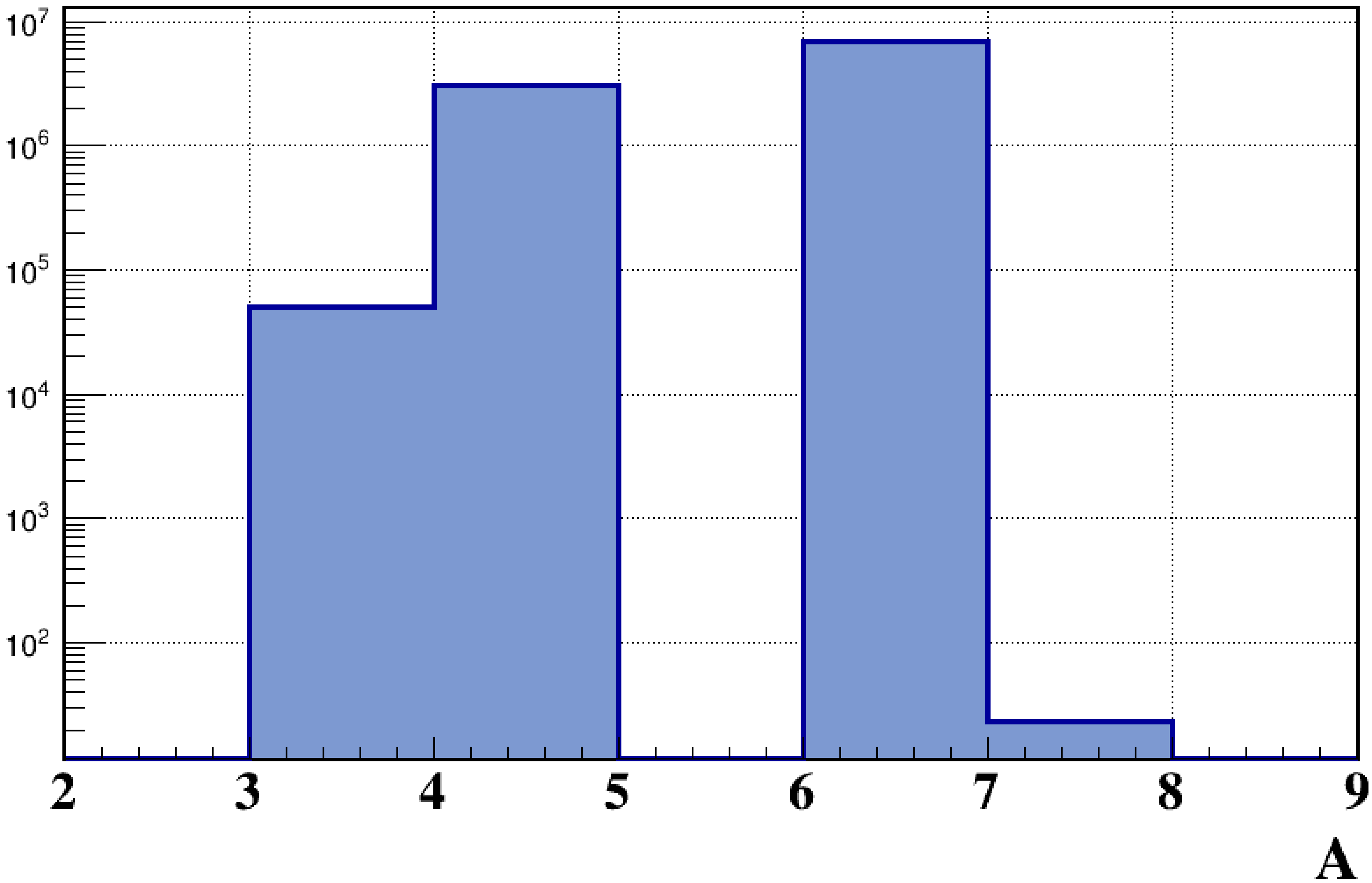
для 10^7 ваимодействий





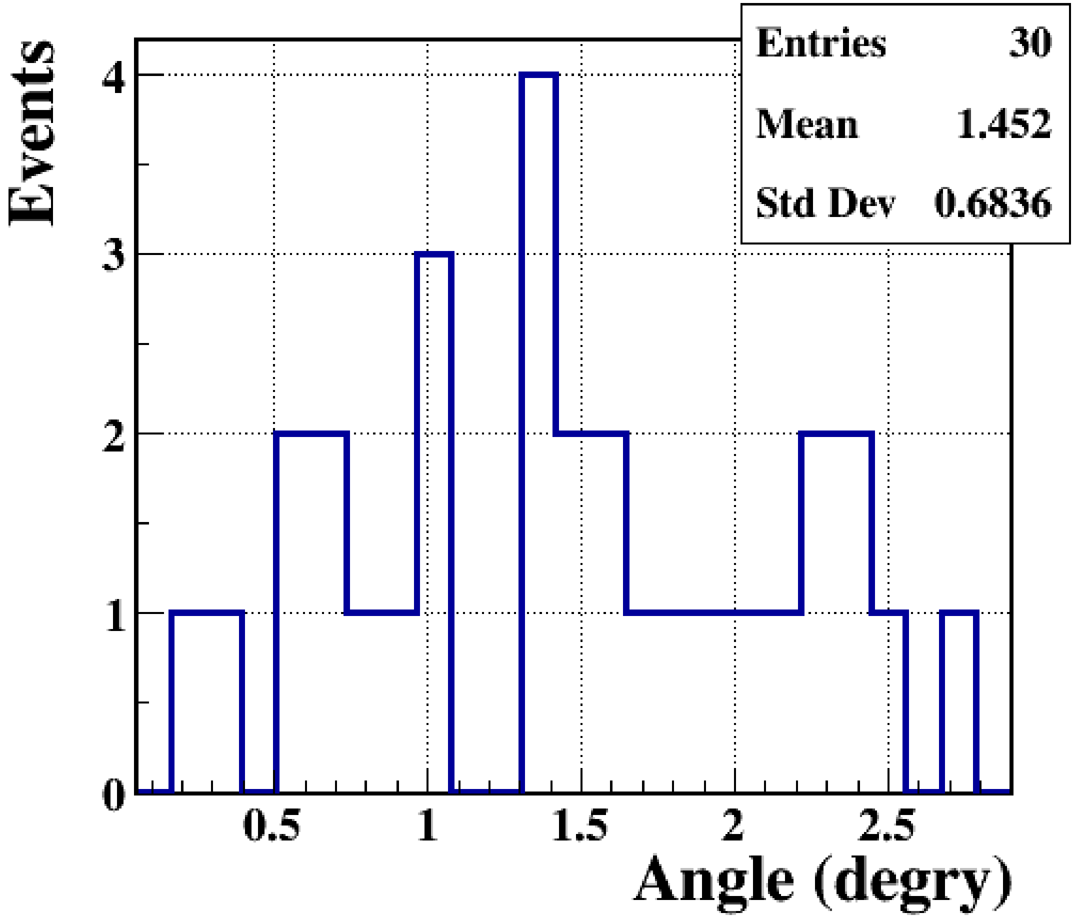
n
n’
n”

$^{12}Be + ^{124}Sn \rightarrow X\ (Z=2)$
для 10^7 ваимодействий



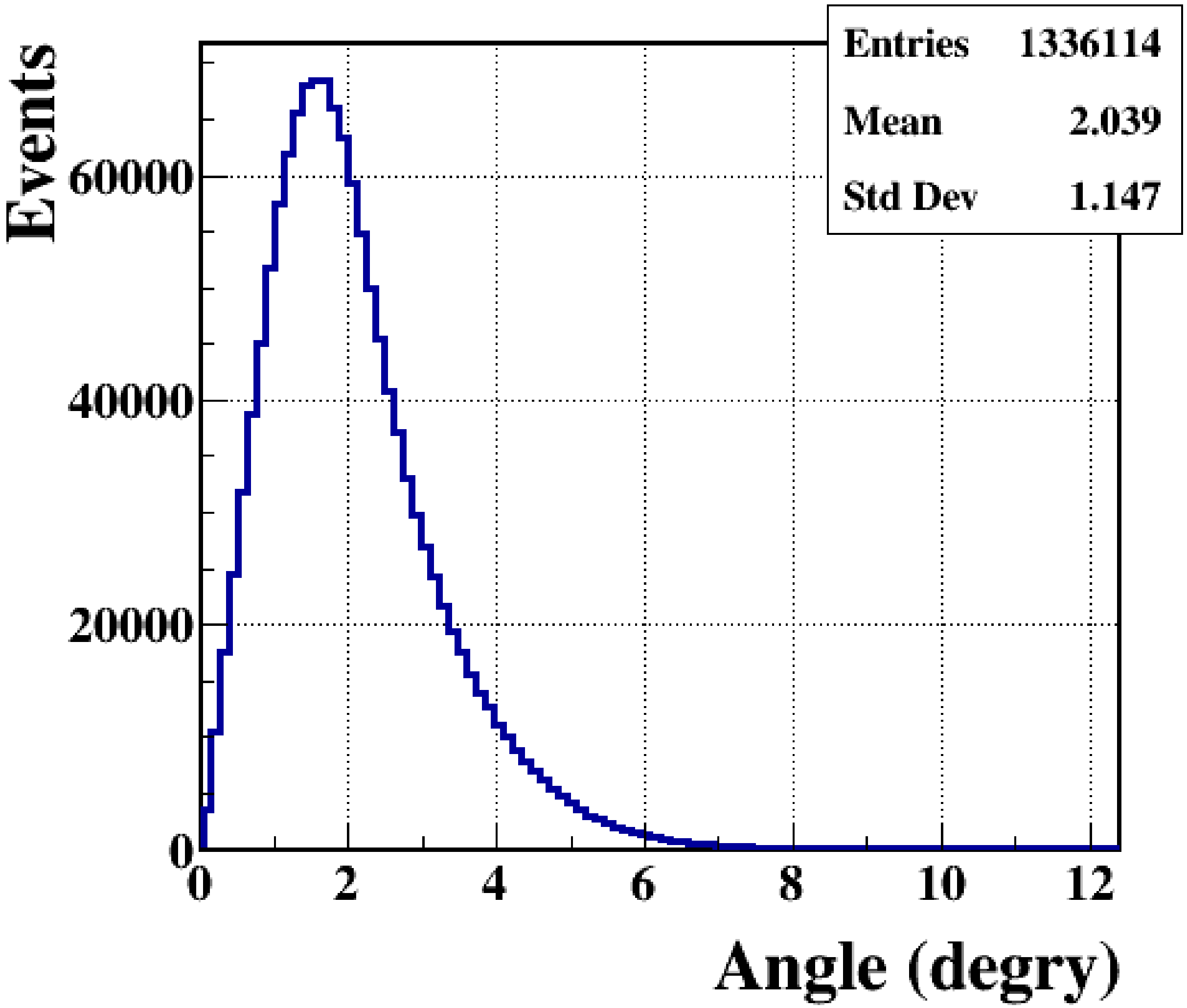
$^{12}C + ^{124}Sn \rightarrow ^{12}Be$

для 10^7 ваимодействий



$^{12}C + ^{124}Sn \rightarrow ^{3}H$

для 10^7 ваимодействий



$^{12}C + ^{124}Sn \rightarrow ^{6}He$

для 10^7 ваимодействий