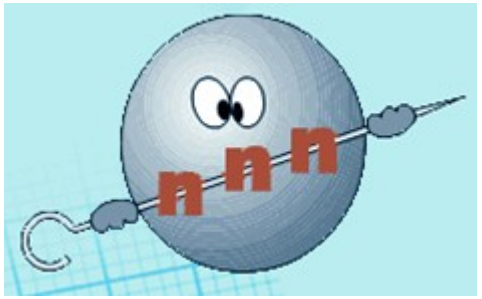


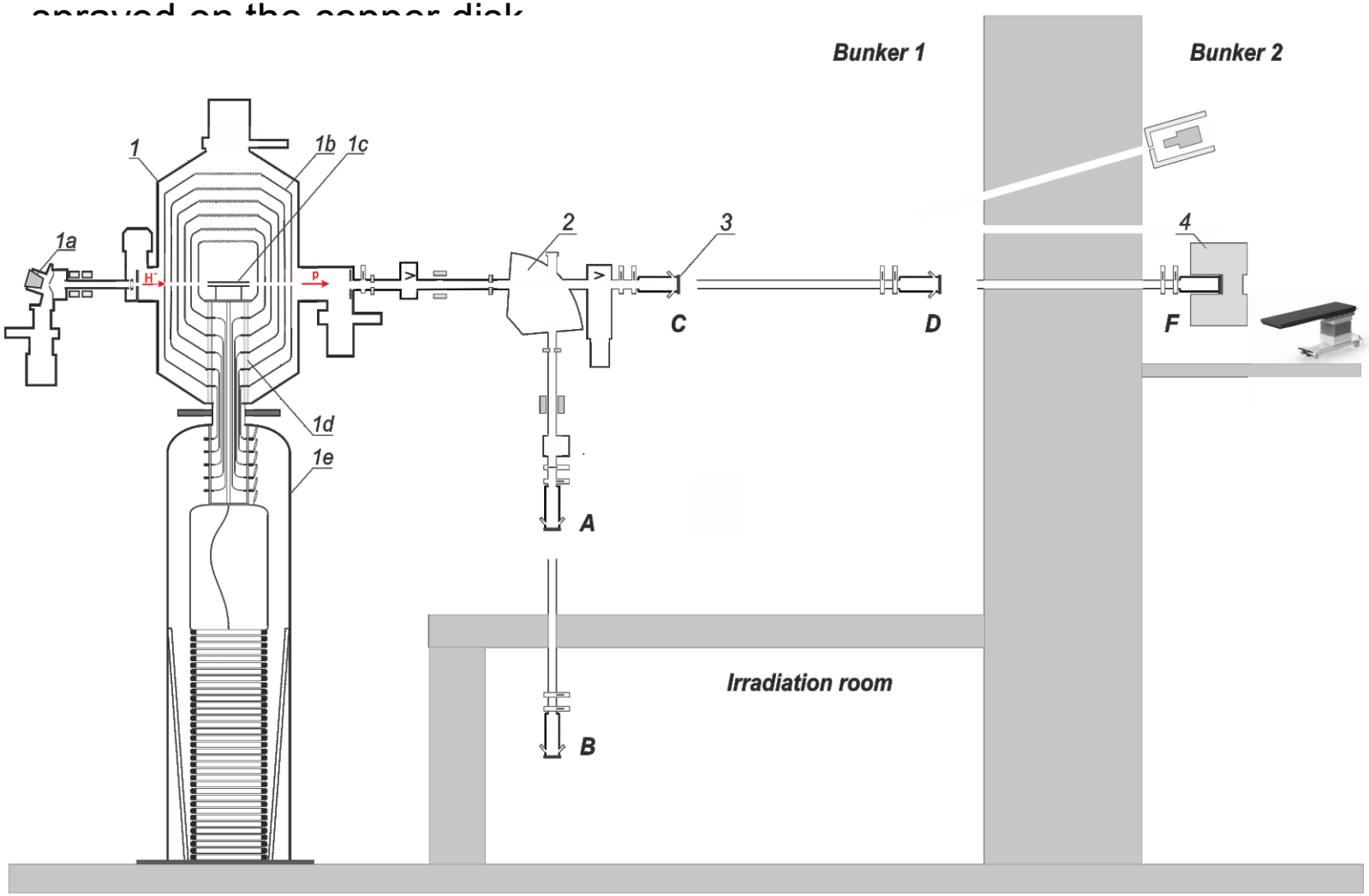
Measurement of cross sections for nuclear reactions of interaction of protons and deuterons with lithium at ion energies 0.4 – 2.2 MeV

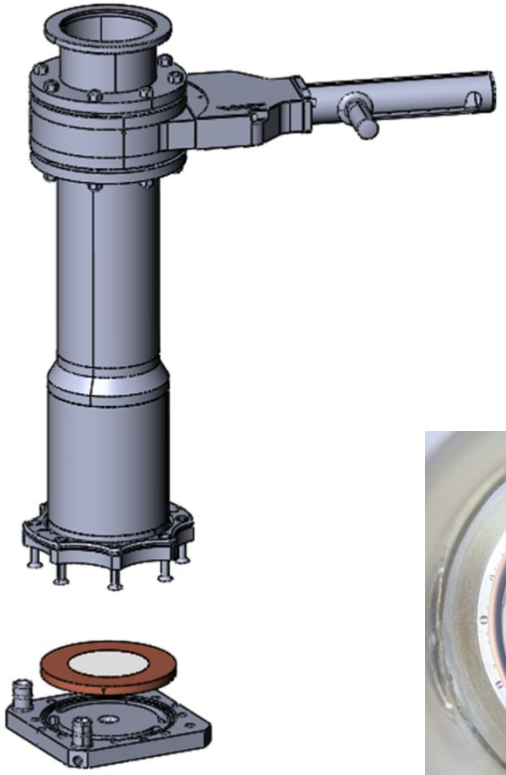
Marina Bikchurina, PhD student, Budker INP

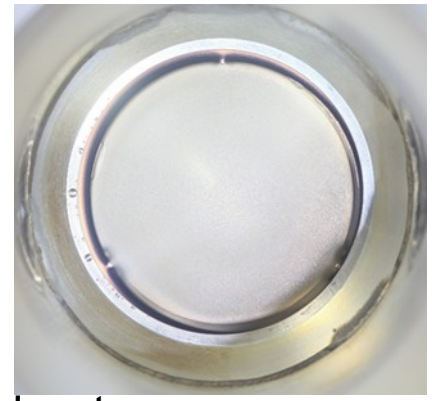
Scientific supervisor: Prof. Sergey Taskaev

I. Scheme of High flux neutron source

The VITA is used to provide dc proton/deuteron beam with an energy within a range of **0.3–2.3 MeV** with current from **1 nA to 10 mA**. The target is a copper disk with a thin layer of crystalline density lithium was thermal sprayed on the copper disk.



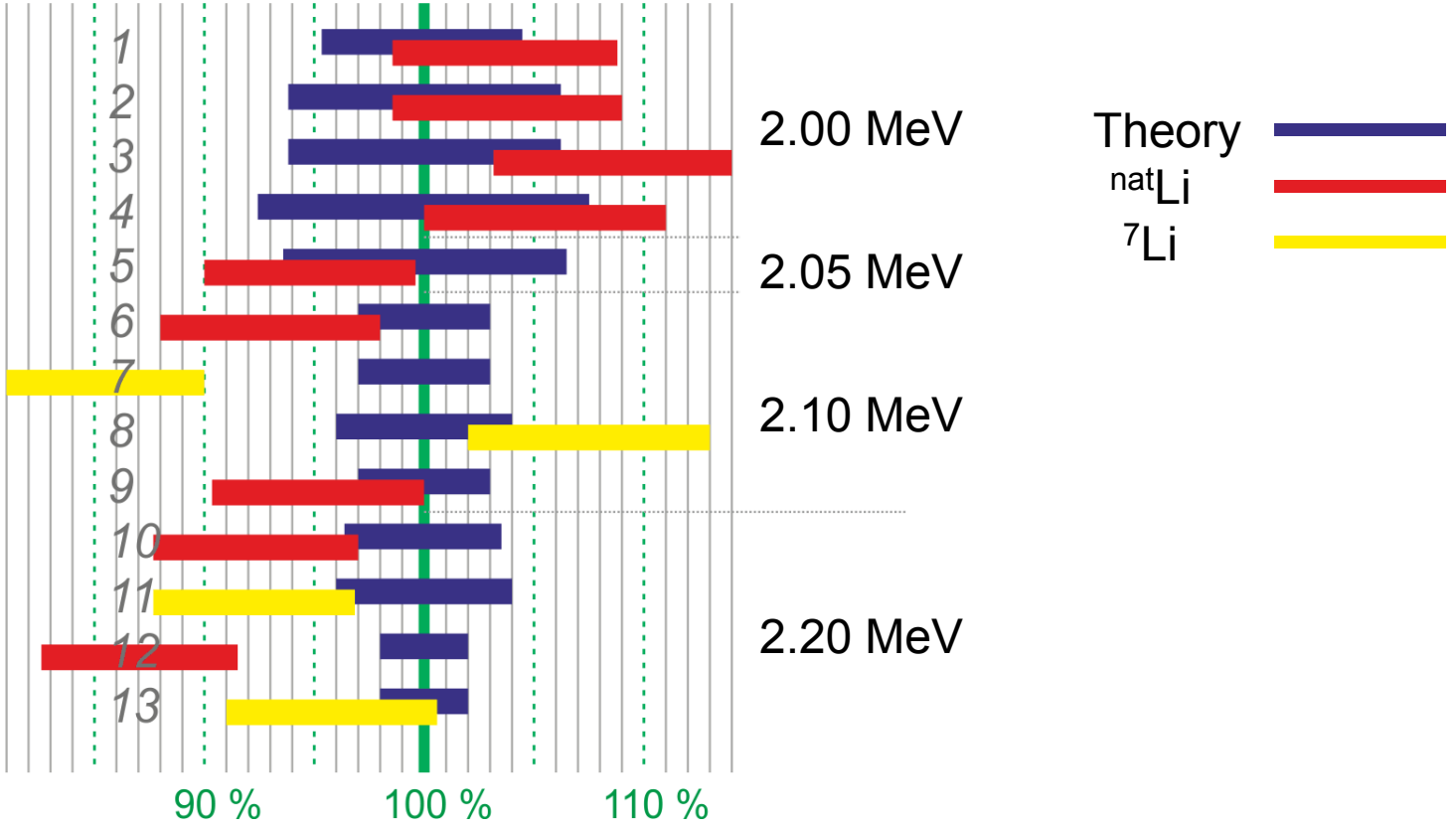




-insulated tandem accelerator;
magnet;
arget ^{7}**Li(p,), ^{7}Li(d,);**
ıaping assembly.
target is placed in the 5 possible positions

Nuclear reaction cross sections σ and particle yield Y:

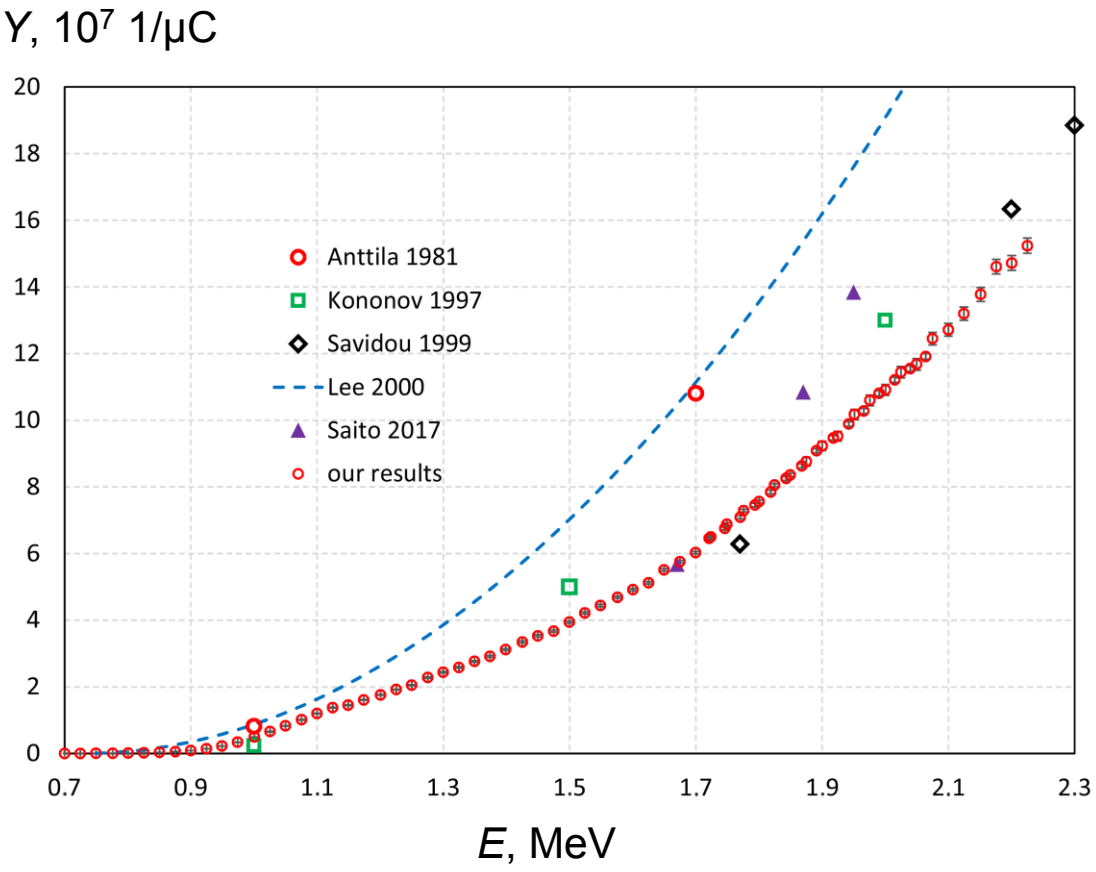
- **n** **^{7}Li(p,n)^{7}Be** M. Bikchurina *et al*. *The measurement of the neutron yield* … Biology 10 (2021)
- γ ^{7}Li(p,p'γ)^{7}Li S. Taskaev *et al*. *Measurement of the ^{7}Li(p,p'γ)^{7}Li* … NIM B 502 (2021) 85-94
- α ^{7}Li(p,α)α D. Kasatov *et al*. *The measurement of the ^{7}Li(p,α)α* … NIM B (2022)



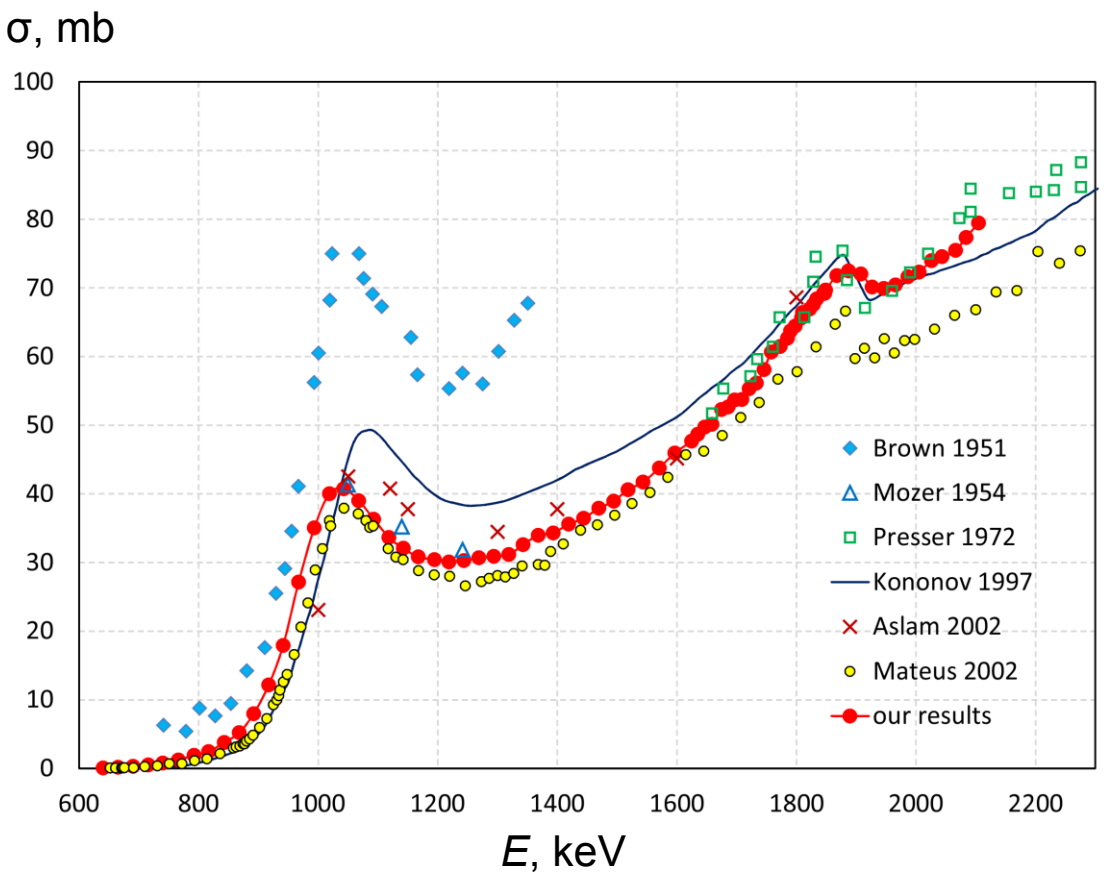
Comparison of measured neutron yield with theoretical

Nuclear reaction cross sections σ and particle yield Y:

- n ^{7}Li(p,n)^{7}Be — M. Bikchurina *et al. The measurement of the neutron yield* … Biology 10 (2021)
- γ **^{7}Li(p,p'γ)^{7}Li** — S. Taskaev *et al. Measurement of the ^{7}Li(p,p'γ)^{7}Li* … NIM B 502 (2021) 85-94
- α ^{7}Li(p,α)α — D. Kasatov *et al. The measurement of the ^{7}Li(p,α)α* … NIM B (2022)



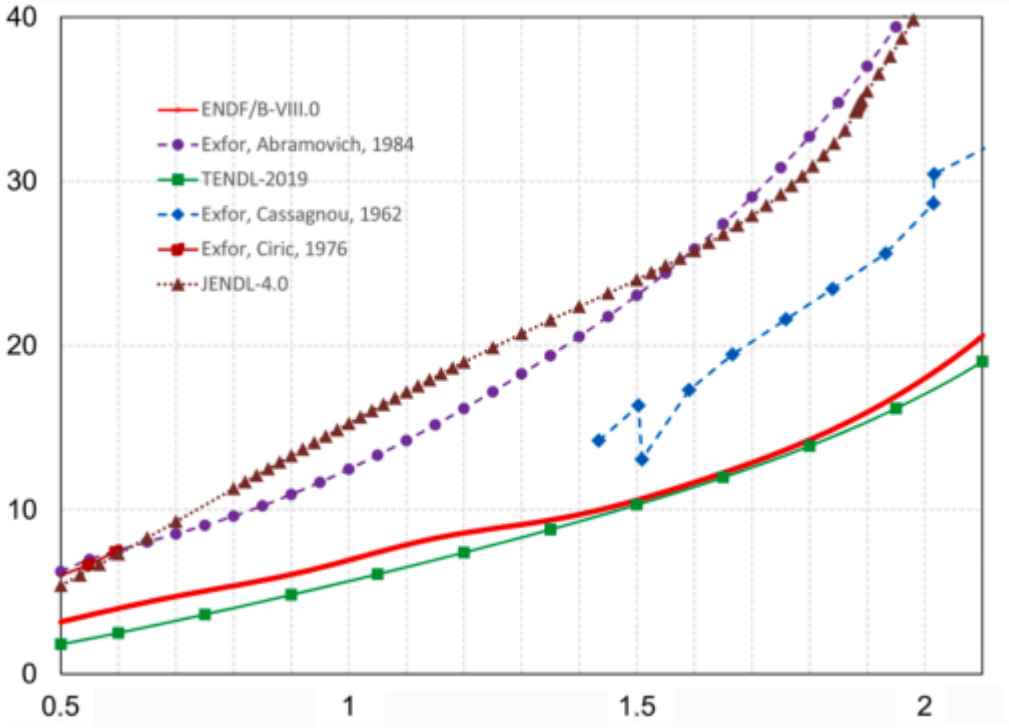
478 keV photon yield from a thick lithium target



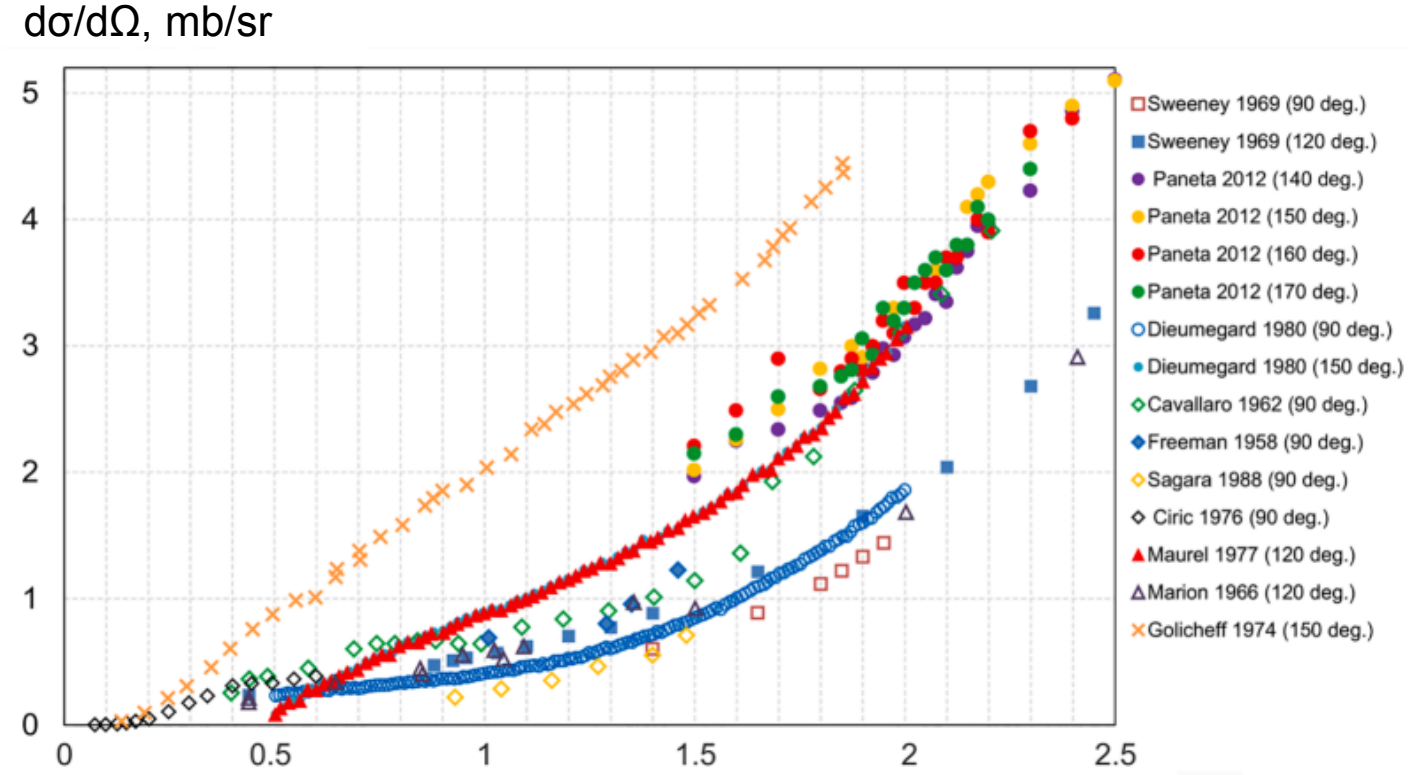
^{7}Li(p,p'γ)^{7}Li reaction cross-section

Nuclear reaction cross sections σ and particle yield Y:

- n $^{7}Li(p,n)^{7}Be$ M. Bikchurina *et al*. *The measurement of the neutron yield* … Biology 10 (2021)
- γ $^{7}Li(p,p'\gamma)^{7}Li$ S. Taskaev *et al*. *Measurement of the* $^{7}Li(p,p'\gamma)^{7}Li$ … NIM B 502 (2021) 85-94
- α **$^{7}Li(p,\alpha)\alpha$** M. Bikchurina *et al. The measurement of the* $^{7}Li(p,\alpha)\alpha$ … NIM B (2022)



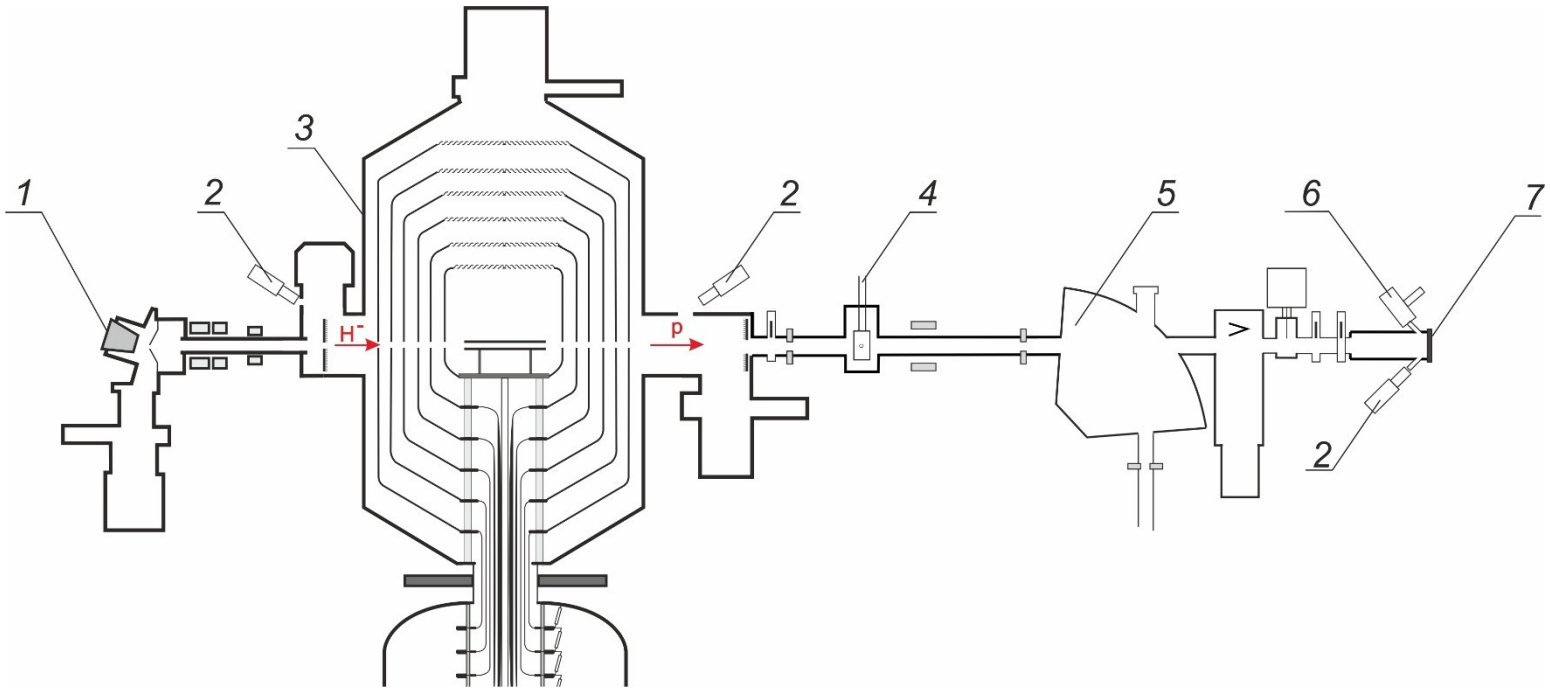
$^{7}Li(p,\alpha)^{4}He$ reaction cross-section



$^{7}Li(p,\alpha)^{4}He$ differential reaction cross section

III. Measurement of the ^{7}Li(p,α)^{4}He reaction cross section

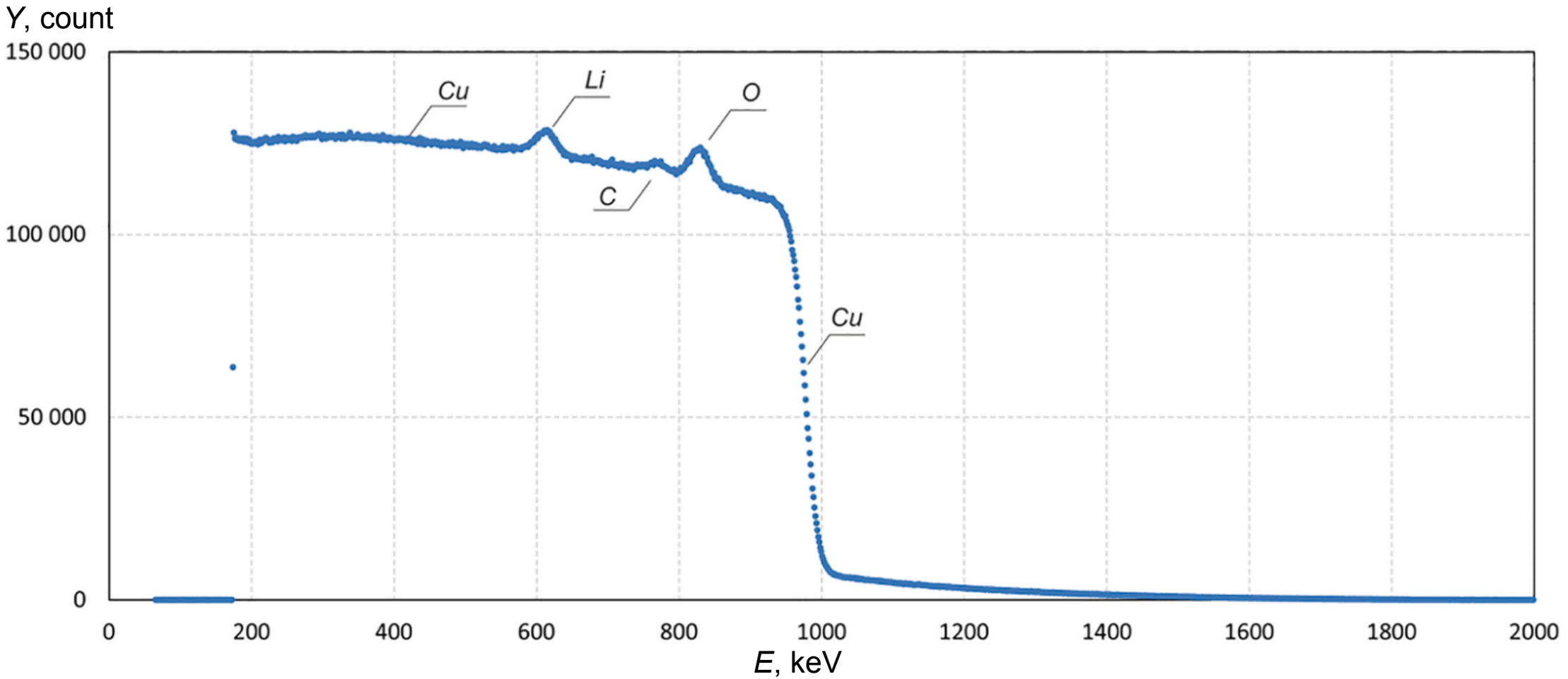
Proton energy: 0.6 – 2 MeV (± 0.1 %)
Current: 1.5 μA (± 0.4 %)
Beam diameter: 10 mm



1. Ion source
2. Cameras
3. Vacuum-insulated tandem accelerator
4. Aperture
5. Bending magnet
6. α-spectrometer
7. Lithium target

III. Measurement of the ^{7}Li(p,α)^{4}He reaction cross section

- Simulation of the back-reflected proton spectrum in the SIMNRA program. l = **0.42** ± 0.02 μm, l_{imp} ~ 2.5 nm
- Measuring the mass of lithium on a scale (1.5 mg ~ **0.5 μm**). Overdisperses ~ 99.9% lithium

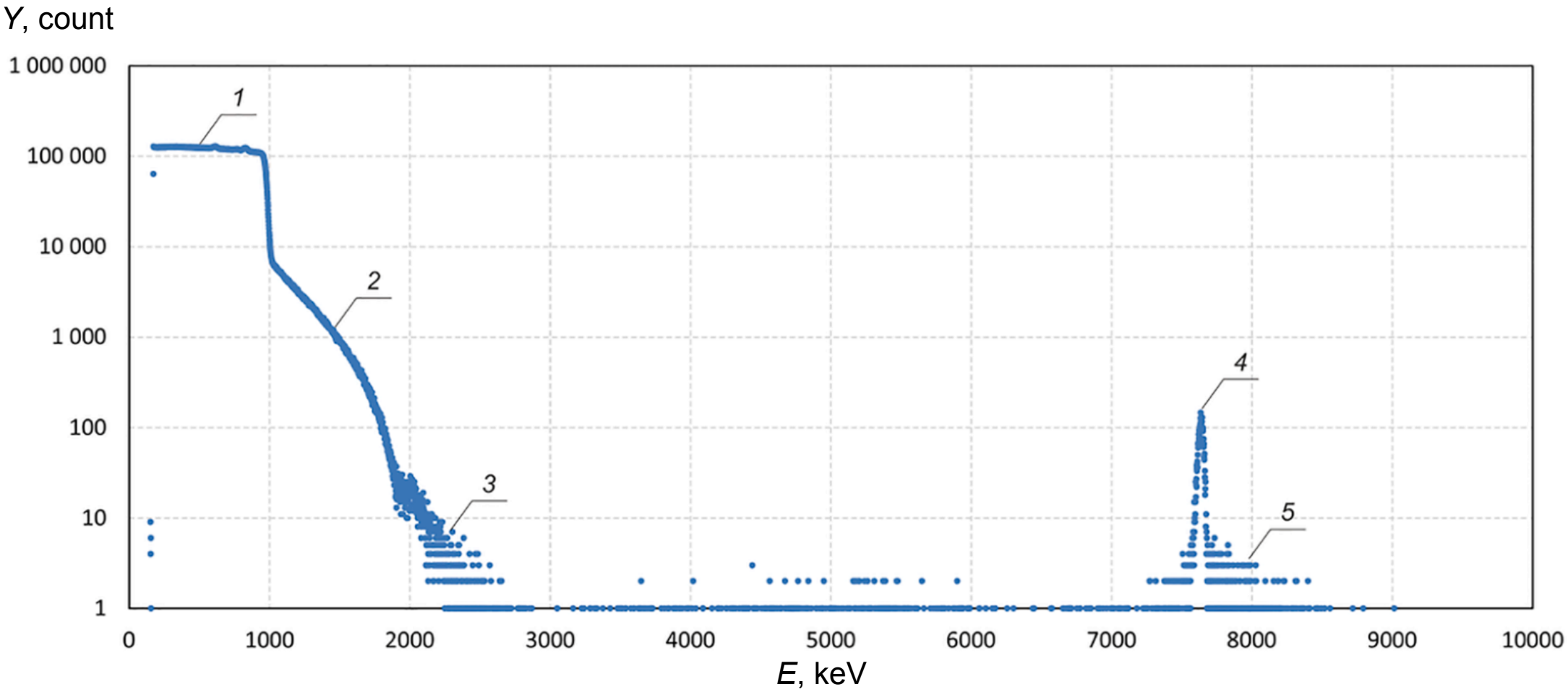


Spectrum of charged particles recorded by the α-spectrometer at the proton energy of 1 MeV:
Cu, Li, C, and O – back-reflected protons from copper, lithium, carbon, and oxygen atoms.

III. Measurement of the ^{7}Li(p,α)^{4}He reaction cross section

^{7}Li(p,α)^{4}He, Q = 14.347 MeV.

E_p = 1 MeV —> E_α = 7.663 MeV;
E_p = 2 MeV —> E_α = 7.523 MeV.

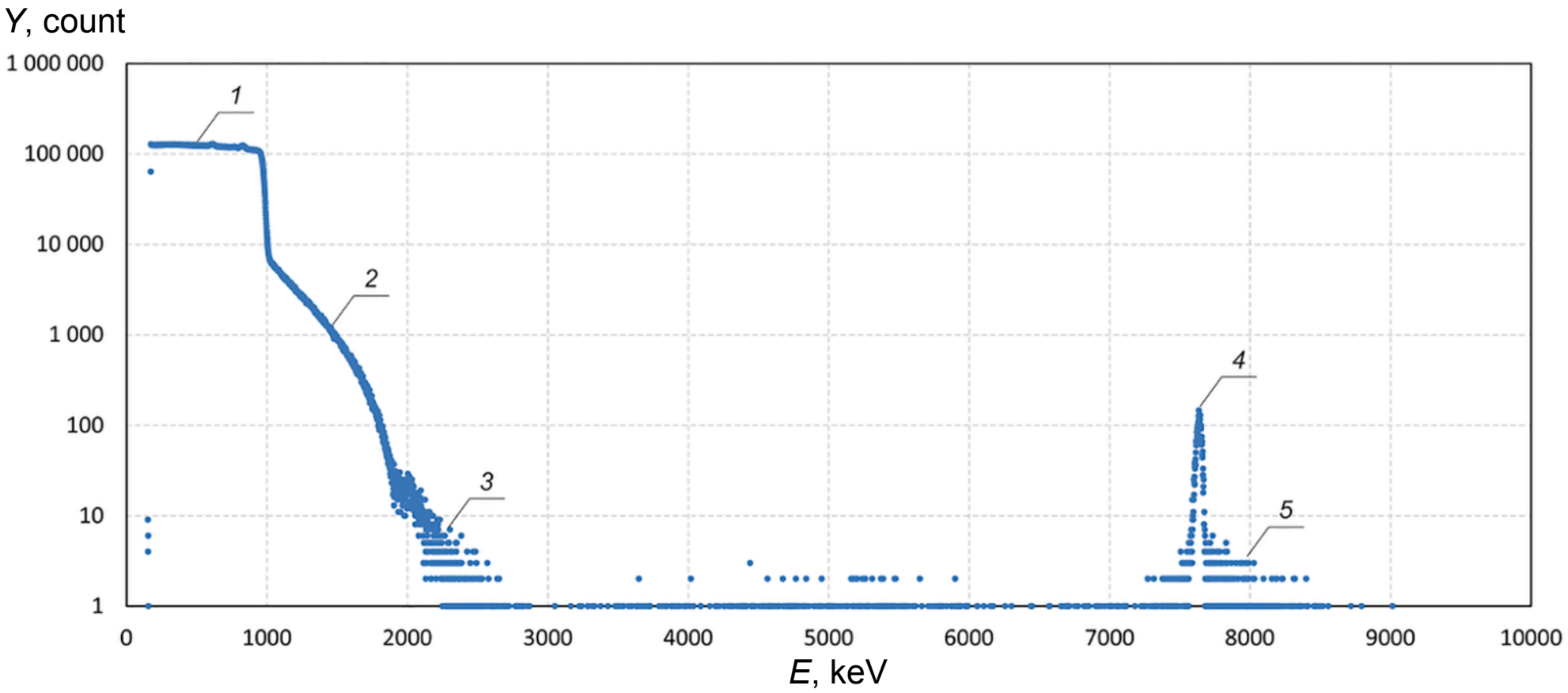


Spectrum of charged particles registered by the α-spectrometer at proton energy of 1 MeV:
1 – *3* – back-reflected protons from copper atoms (*1* – single events, *2* – double, *3* – triple),
4 – α-particles,
5 – simultaneous registration of an α-particle and a proton

- **Determination of α-particle energy**

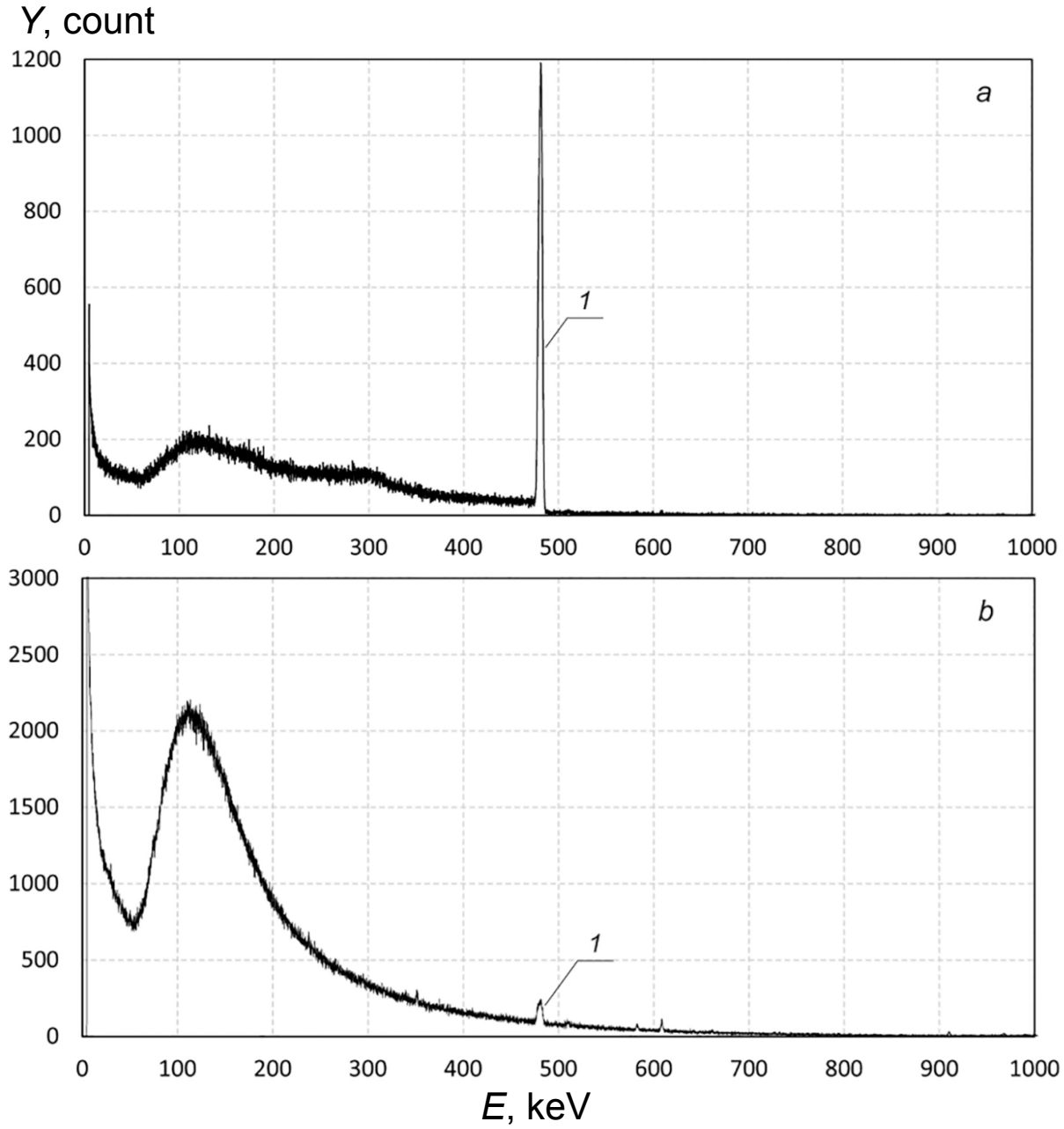
The distribution maximum is shifted by 50 – 70 keV relative to the calculated value. Ionization losses = 600 MeV/(g·cm^2)

The α-particle at **0.422 μm** lithium loses ~ 134 keV, then the average energy loss ~ 67 keV (thickness ~ 0.211 μm)



Spectrum of charged particles registered by the α-spectrometer at proton energy of 1 MeV: *1* – *3* – back-reflected protons from copper atoms (*1* – single events, *2* – double, *3* – triple), *4* – α-particles, *5* – simultaneous registration of an α-particle and a proton.

III. Measurement of the ^{7}Li(p,α)^{4}He reaction cross section. Lithium thickness



Signal from the HPGe γ-spectrometer : *a* – thick layer of lithium, *b* – thin layer of lithium

- 478 keV γ-quantum yield during the ^{7}Li(p,p'γ)^{7}Li reaction

At proton energies of 1.85 MeV, γ-quantum are generated down to a depth of 128 μm in lithium

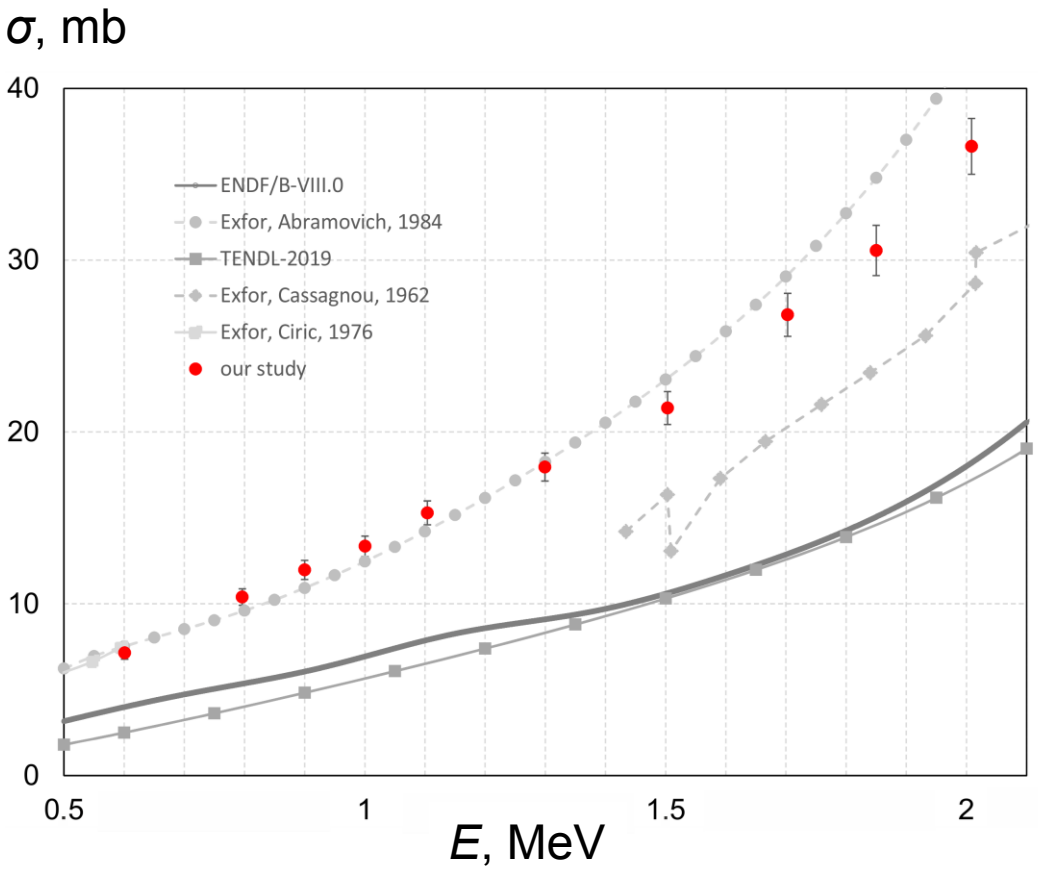
- $h\ (\mu m) = 45.698\ (\frac{Y_i}{Y_{1.85}})^2 + 56.281\ \frac{Y_i}{Y_{1.85}}$
- Ratio of signal intensities $\frac{Y_b}{Y_a} = 7.45 \cdot 10^{-3}$
- Accuracy of lithium layer thickness 3 %

l = **0.422** ± 0.013 μm

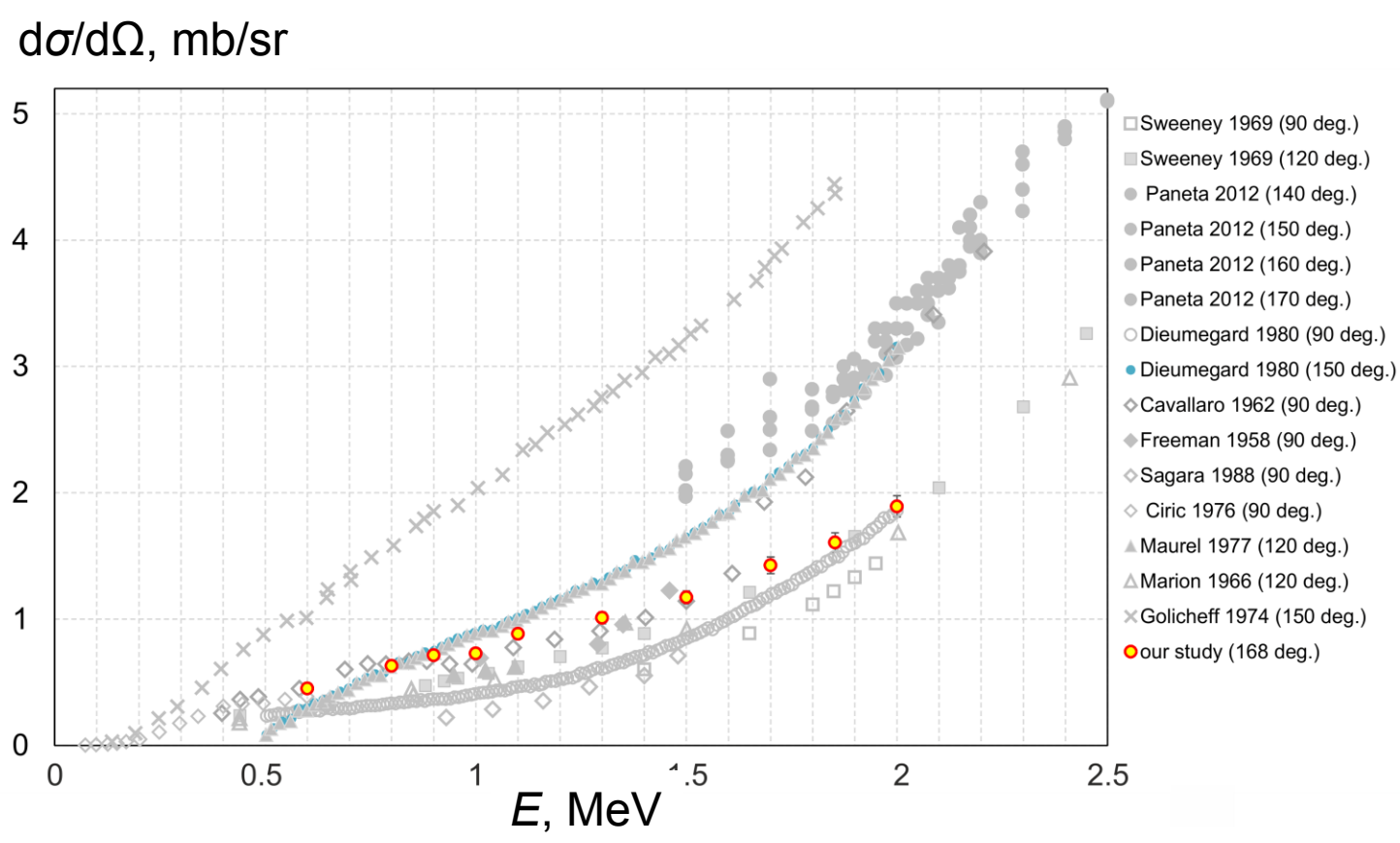
D. Kasatov, Ia. Kolesnikov, A. Koshkarev, A. Makarov, E. Sokolova, I. Shchudlo, S. Taskaev. Method for in situ measuring the thickness of a lithium layer. JINST 15 (2020) P 10006.

III. Measurement of the ^{7}Li(p,α)^{4}He reaction cross section

Angle 168°



^{7}Li(p,α)^{4}He reaction cross-section



^{7}Li(p,α)^{4}He differential reaction cross section

IV. Interaction of deuterons with lithium

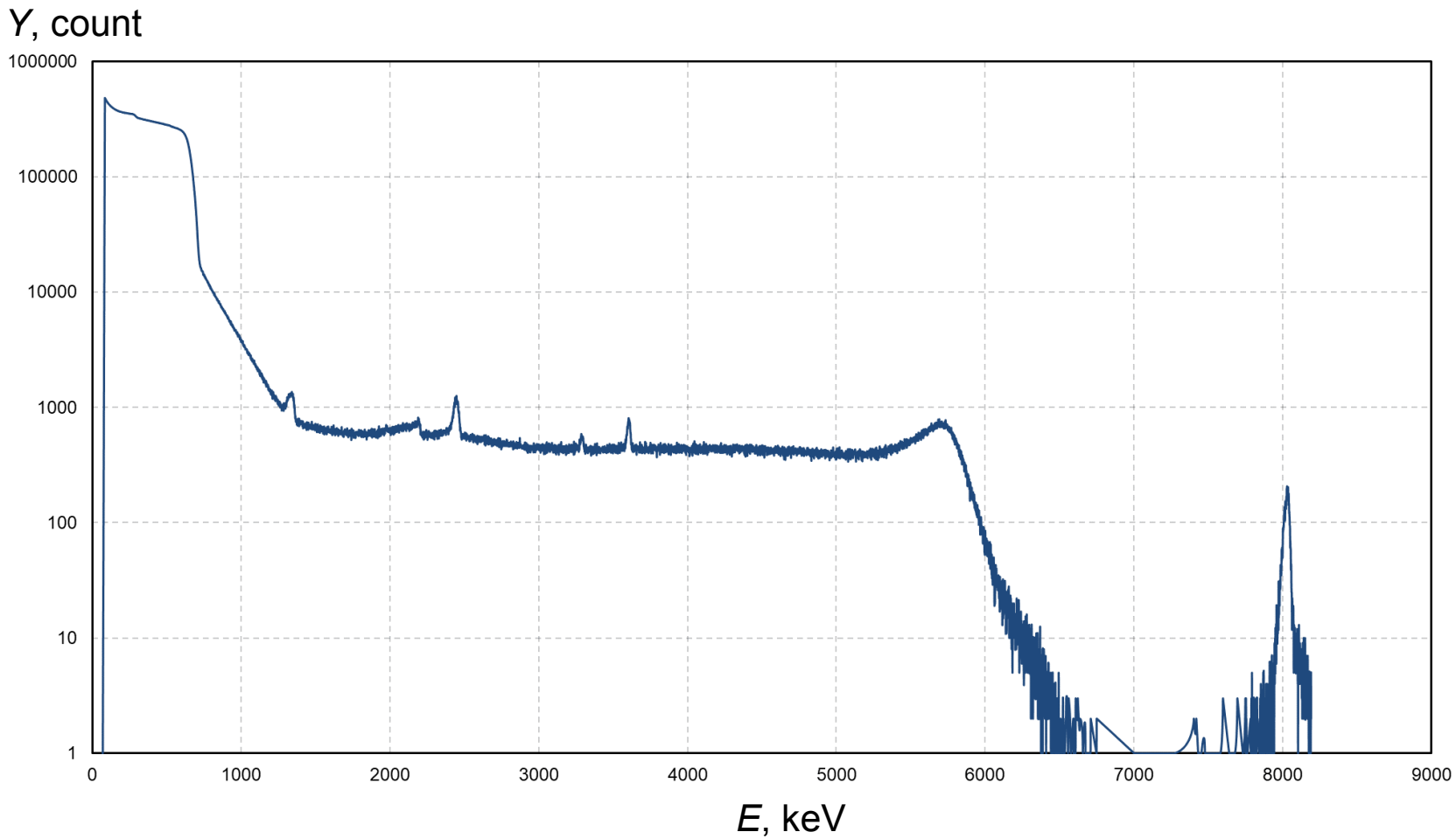
1. $^{7}Li + d = n + {}^{8}Be + 15{,}028$ MeV
2. $^{7}Li + d = n + \alpha + \alpha + 15{,}121$ МэВ
3. $^{7}Li + d = \alpha + {}^{5}He + 14{,}162$ МэВ $^{5}He = n + \alpha + 0{,}957$ МэВ
4. $^{7}Li + d = n + {}^{8}Be^{*} + 15{,}027$ МэВ

   $^{8}Be^{*} = \alpha + \alpha + 0{,}095$ МэВ
5. $^{6}Li + d = \alpha + \alpha + 22{,}38$ МэВ
6. $^{6}Li + d = n + {}^{7}Be + 3{,}385$ МэВ
7. $^{6}Li + d = p + {}^{7}Li + 5{,}028$ МэВ

   $= p + {}^{7}Li^{*} + 4{,}550$ МэВ
8. $^{6}Li + d = t + {}^{5}Li + 0{,}595$ МэВ
9. $^{6}Li + d = {}^{3}He + {}^{5}He + 0{,}840$ МэВ

   $^{5}He = n + \alpha + 0{,}957$ МэВ
10. $^{6}Li + d = {}^{3}H + p + \alpha + 2{,}6$ МэВ
11. $^{12}C + d = p + {}^{13}C + 2{,}722$ МэВ
12. $^{16}O + d = a + {}^{14}N + 3{,}110$ МэВ
13. $^{16}O + d = p + {}^{17}O + 1{,}917$ МэВ

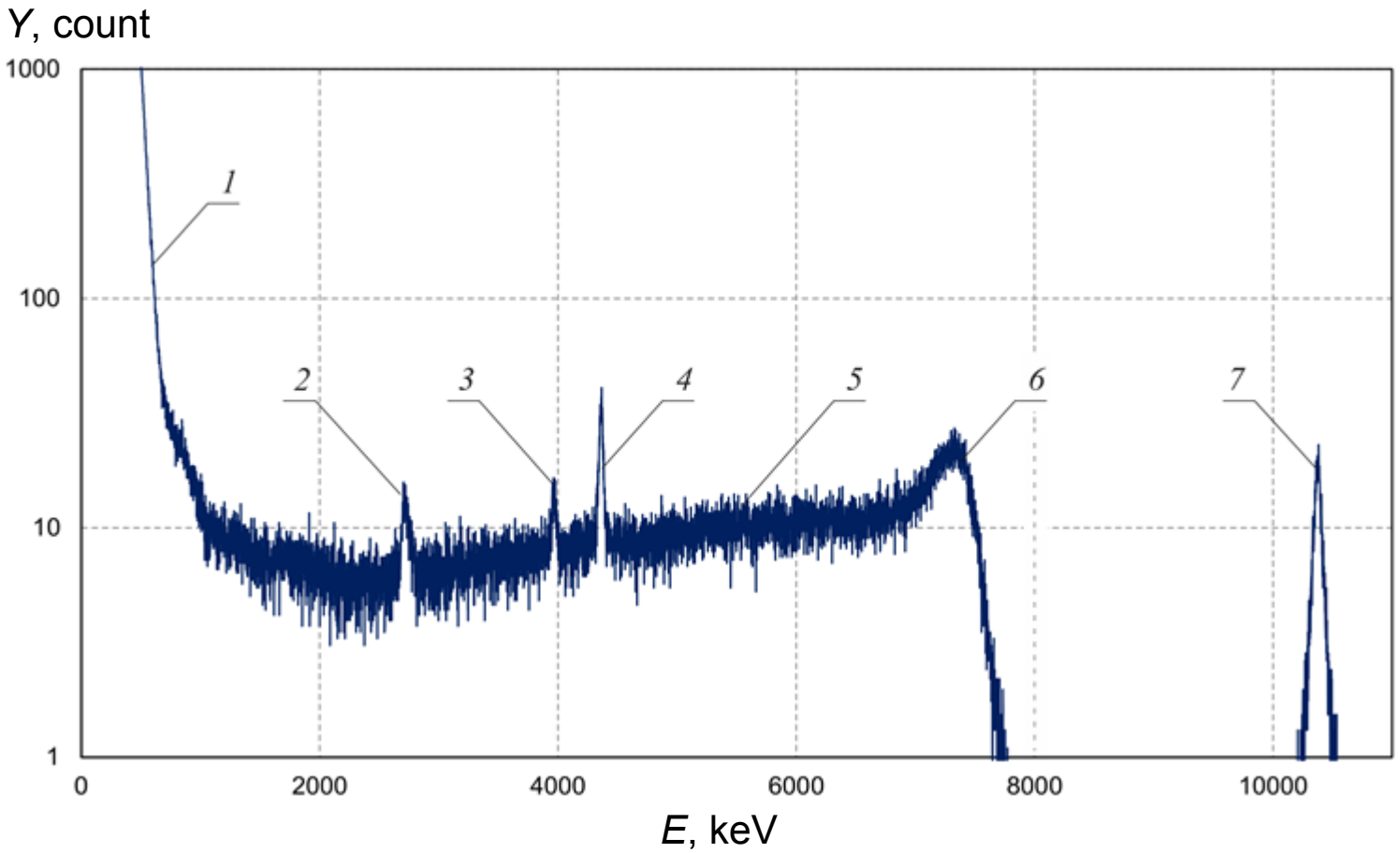
    $= p + {}^{17}O^{*} + 1{,}046$ МэВ



Energy spectrum of charged particles recorded by α-spectrometer at 135° while irradiating a lithium target with **1 MeV** deuterons

V. Measurement of the ^{7}Li(d,), ^{6}Li(d,) reactions cross sections

E_d = 0.4 – 2.2 MeV



1 – deuterons reflected from the target

2 – reaction products ^{16}O(d,α)^{14}N

3 – ^{6}Li(d,p)^{7}Li*

4 – ^{6}Li(d,p)^{7}Li

5 – ^{7}Li(d,nα)^{4}He and decay of the resulting ^{5}He → α + n

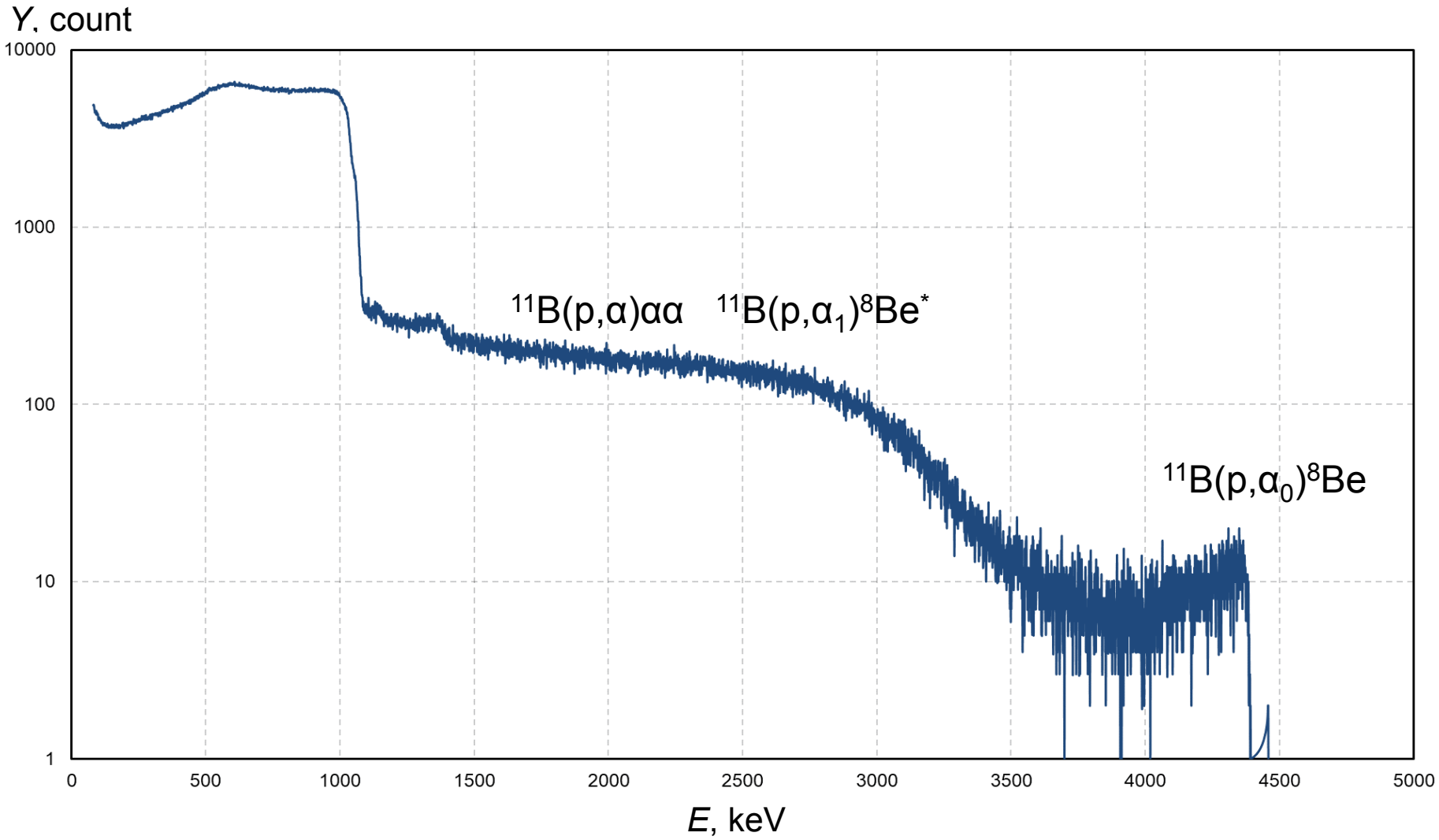
6 – ^{7}Li(d,α)^{5}He

7 – ^{6}Li(d,α)^{4}He

Energy spectrum of charged particles recorded by α-spectrometer at 135° while irradiating a lithium target with **0.4 MeV** deuterons

VI. Measurement of the $^{11}B(p,\alpha)^{8}Be$, $^{11}B(p,\alpha_1)^{8}Be^*$, $^{11}B(p,\alpha)\alpha\alpha$ reactions cross sections

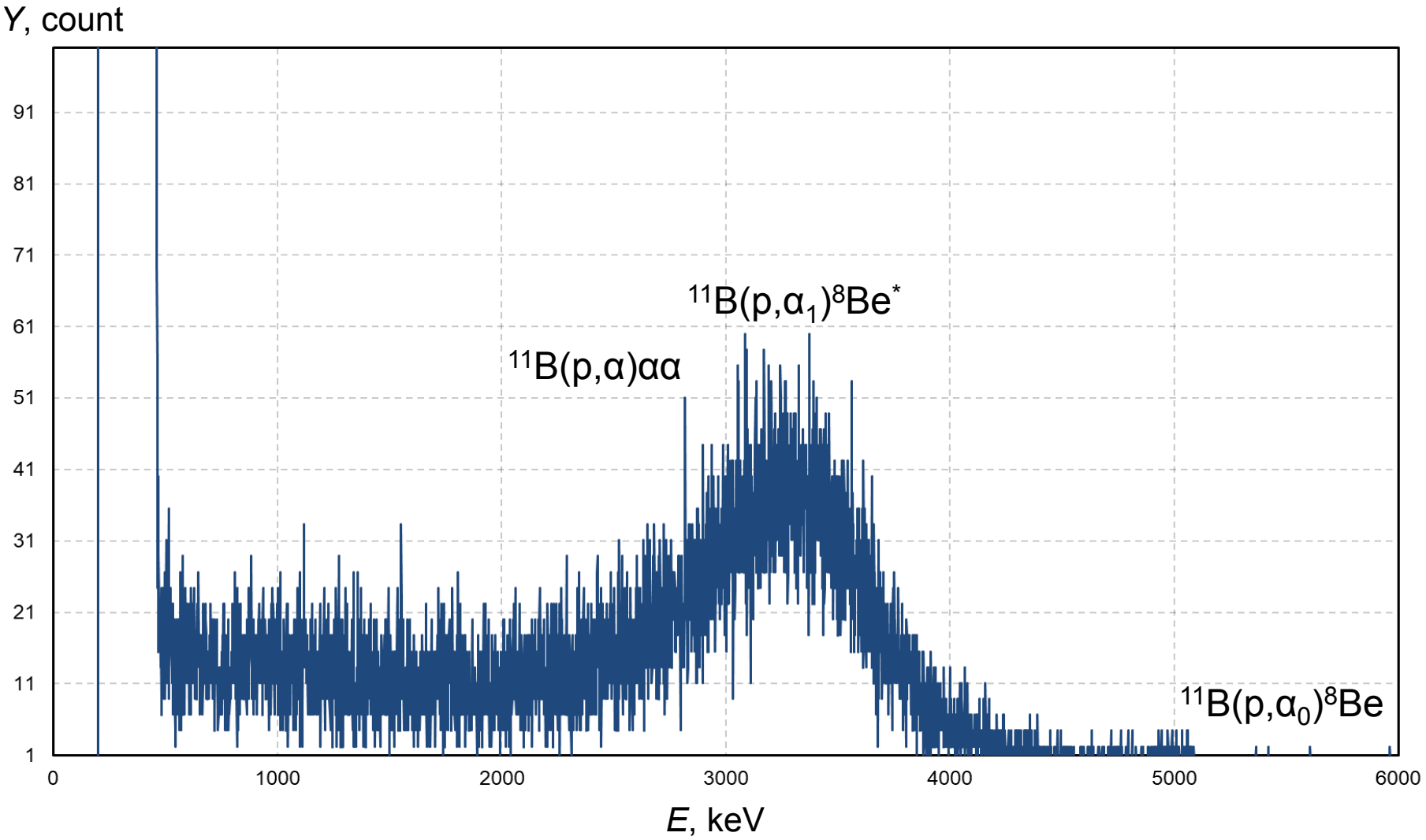
E_p = 0.4 – 2.1 MeV, Q = 8.59 MeV



Energy spectrum of charged particles recorded by α-spectrometer at 135° while irradiating a boron target with **2 MeV** protons

VI. Measurement of the $^{11}B(p,\alpha)^{8}Be$, $^{11}B(p,\alpha_1)^{8}Be^*$, $^{11}B(p,\alpha)\alpha\alpha$ reactions cross sections

E_p = 0.4 – 2.1 MeV, Q = 8.59 MeV



Energy spectrum of charged particles recorded by α-spectrometer at 135° while irradiating a boron target with **0.4 MeV** protons

Conclusion

- **^{7}Li(p,n)^{7}Be** neutron yield
- **^{7}Li(p,p'γ)^{7}Li** reaction cross section and **478 keV** photon yield
- **^{7}Li(p,α)^{4}He** reaction cross section
- **^{7}Li(d,), ^{6}Li(d,): 5** reactions cross sections
- **^{11}B(p,α)$\alpha\alpha$** to be processed
- We are open for joint researches