Investigation of the interaction of ion beams and X-ray quanta with deuterated crystal structures at the HELIS facility

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Report outline

1. Investigation of nuclear fusion reactions at low energies on accelerators (brief review)
2. Brief description of the HELIS installation
3. Overview of the work performed on the HELIS installation
4. Results obtained in 2017-2018
5. Plans for future experiments
6. Conclusion

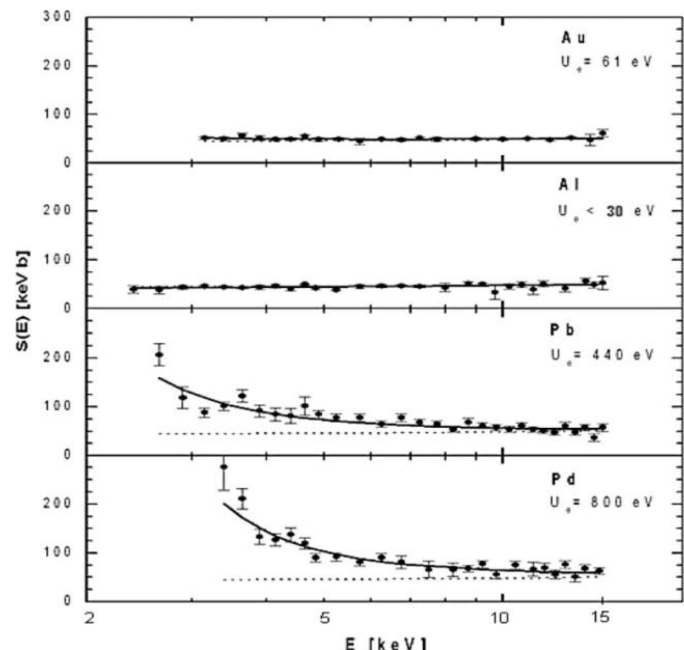
Investigation of nuclear fusion reactions at low energies at accelerators

The LUNA collaboration investigated the yields of DD-fusion nuclear reactions at energies <10 keV and beam currents <50 μA

1. **Electron screening in d(d,t)p for deuterated metals and the periodic table**
   Physics Letters B 547 (2002) 193
   F. Raiola, P. Migliardi, L. Gang, C. Bonomo, G. Gyürky, R. Bonetti, C. Broggini, N.E.Christensen, P. Corvisiero, J. Cruz, A. D'Onofrio, Z. Fülöp, G. Gervino, L. Gialanella, A.P. Jesus, M. Junker,K. Langanke, P. Prati, V. Roca, C. Rolfs, M. Romano, E. Somorjai, F. Strieder, A. Svane, F. Terrasi, J. Winter

2. **Enhanced electron screening in d(d,t)p for deuterated metals**
   European Physical Journal A19 (2004) 283
   F. Raiola, L. Gang, C. Bonomo, G. Gyürky, M. Aliotta, H.-W. Becker, R. Bonetti, C. Broggini, P. Corvisiero, A. D'Onofrio, Z. Fülöp, G. Gervino, L. Gialanella, M. Junker, P. Prati, V. Roca, C. Rolfs, M. Romano, E. Somorjai, F. Strieder, F. Terrasi, G. Fiorentini, K. Langanke, J. Winter

The electron screening effect in the d(d, p)t reaction has been studied for 29 deuterated metals and 5 deuterated insulators/semiconductors. As compared to measurements performed with a gaseous D_2 target, a large effect has been observed in the metals V, Nb, Ta, Cr, Mo, W , Mn, Re, Fe, Ru, Co, Rh, Ir, Ni, Pd, Pt , Zn, Cd, Sn, Pb. An explanation of this apparently novel feature of the periodic table is missing



ANOMALOUSLY ENHANCED D(d,p)T REACTION IN Pd AND PdO OBSERVED AT VERY LOW BOMBARDING ENERGIES

JETP Lett. 1998. V. 68, P. 785

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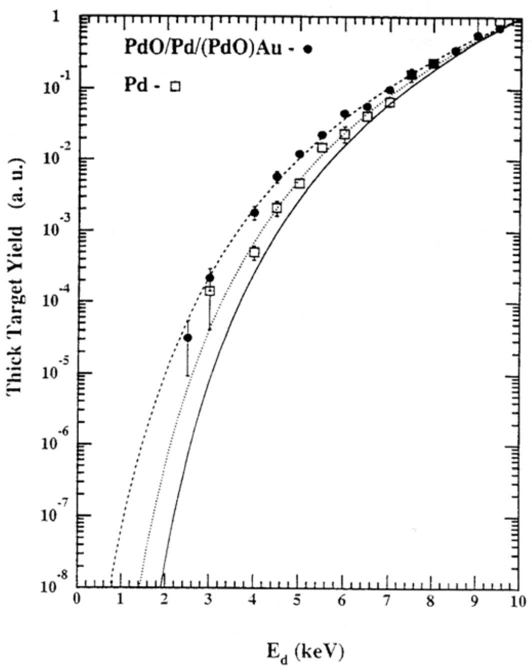
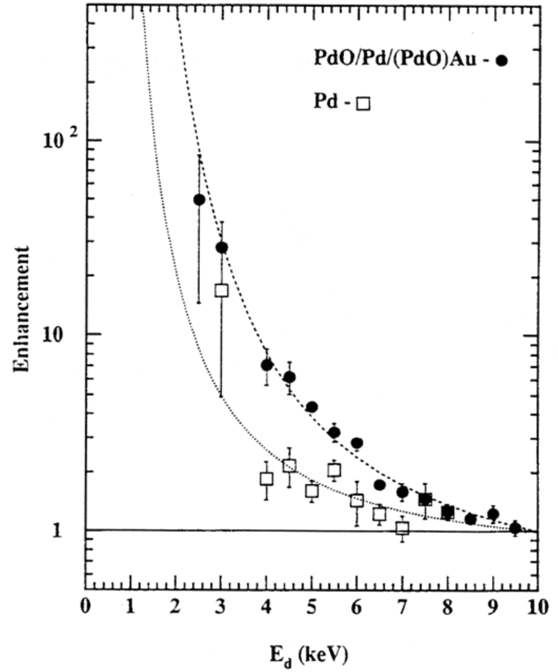


Thick target yields of the D(d,p)T reactions in Pd (squares) and PdO (circles).



Observed enhancement of the thick target yields of the D(d,p)T reactions in Pd (squares) and PdO (circles). The solid curve is a calculated one without any enhancement. The dotted and dashed curves are those with the screening potential Ue = 250 and 600 eV, respectively.

Europhys. Lett., **54 (4), pp. 449–455 (2001)**

Enhancement of the electron screening effect for d + d fusion reactions in metallic environments

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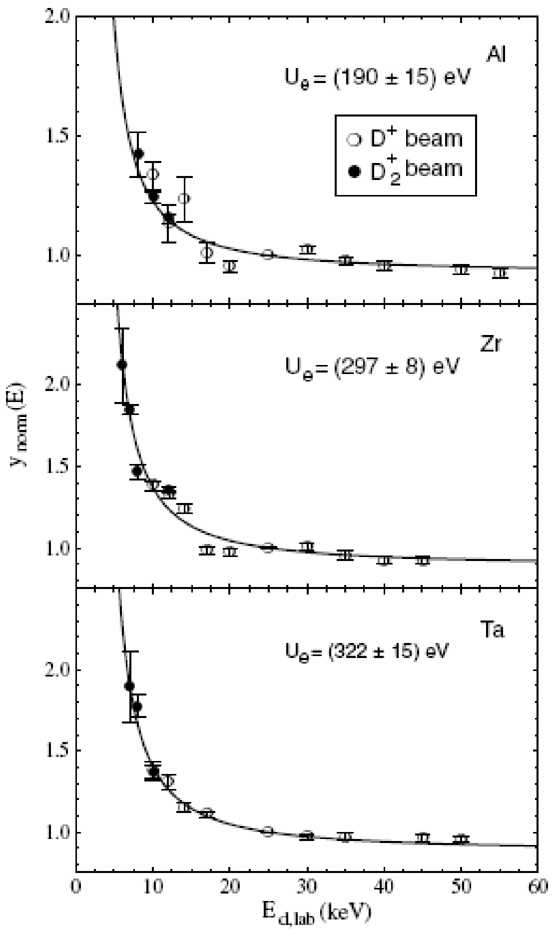


Enhancement of the thick-target yields
for three different metals:
(Al, Zr, Ta)

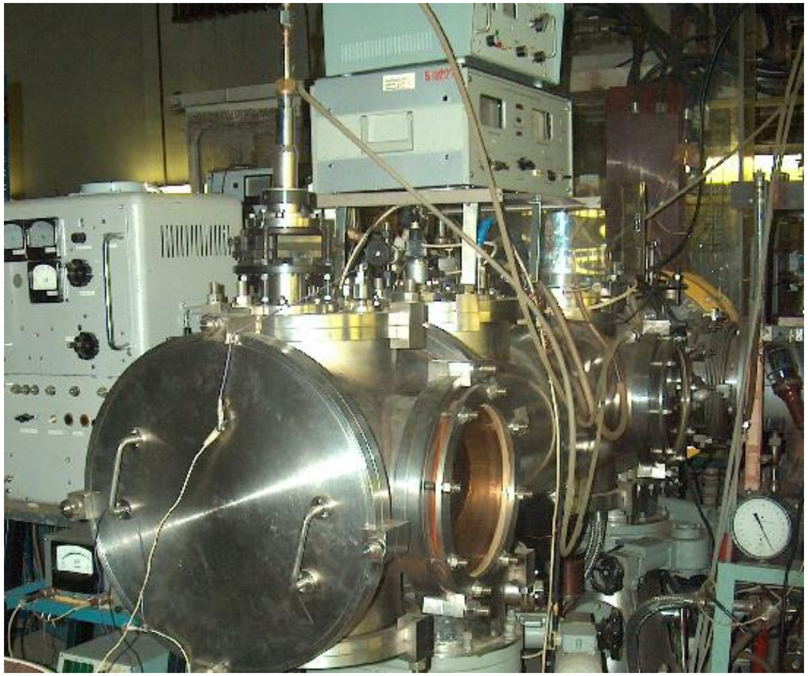
The HELIS facility

The **HELIS** developed at the **Lebedev Physical Institute** and designed for a wide spectrum of experiments:

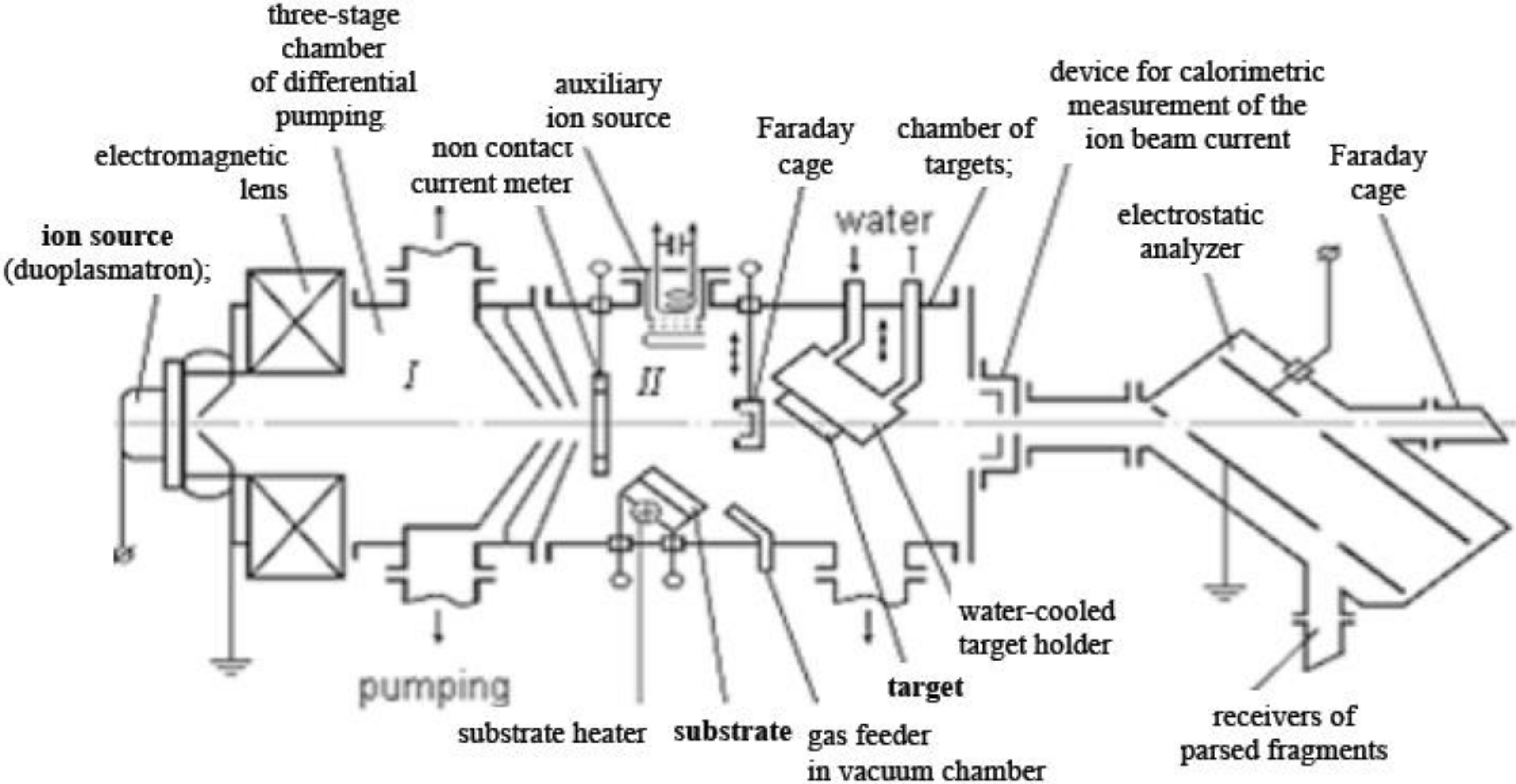
- study of collisions of light nuclei with energies of tens of keV,
- study of elementary and collective processes in ion-beam plasma,
- study of ion beam interaction with various materials, modification of their surface,
- fabrication of thin-film coatings by ion-beam sputtering.

The main part of the HELIS is an ion accelerator allowing generation of continuous ion beams with a current up to 50 mA and energies up to 50keV.

Ion beam current (for protons (p) at 50 keV)	≤50 mA
Energy range	10 -:- 50 keV
Energy spread	10 -:-100 eV
Reduced emittance	$2{\cdot}10^{-5}$ -:- $5{\cdot}10^{-5}$ cm·rad



A schematic diagram of the HELIS facility



Experiments with D-beam on D-enriched target

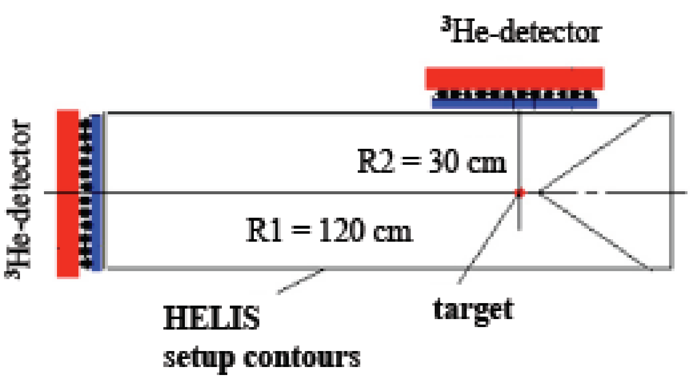
Nowadays, at HELIS, **we study nuclear reactions** in the interactions of the **deuterium beam** with **deuterium-enriched fixed targets.** In these experiments **we use polycrystalline deuterium-enriched targets of Ti, Pd and CVD diamond.**

The products of the DD-reactions

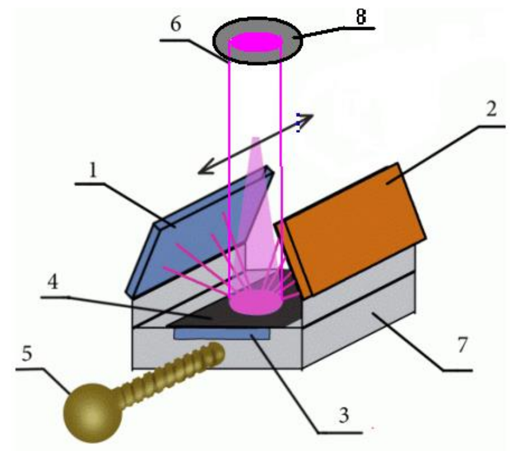
$$d+d \rightarrow \mathbf{p}\ (3\,\text{MeV}) + T(1\,\text{MeV}), \quad (1)$$

$$d+d \rightarrow \mathbf{n}\ (2.45\ \text{MeV}) + {}^{3}He(0.8\ \text{MeV}) \quad (2)$$

(**neutrons and protons**) were detected using a **multichannel neutron detector based on ^{3}He-filled counters** and a **CR-39 track detector**.



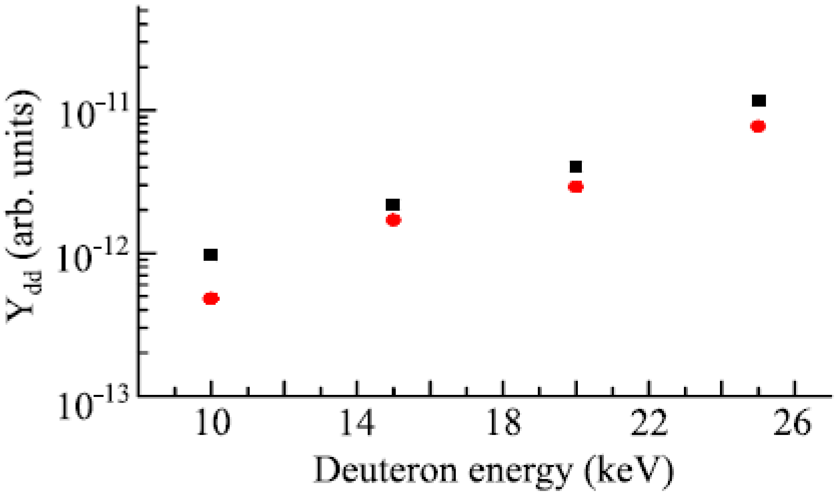
The layout of the **^{3}He-detector in the HELIS setup**



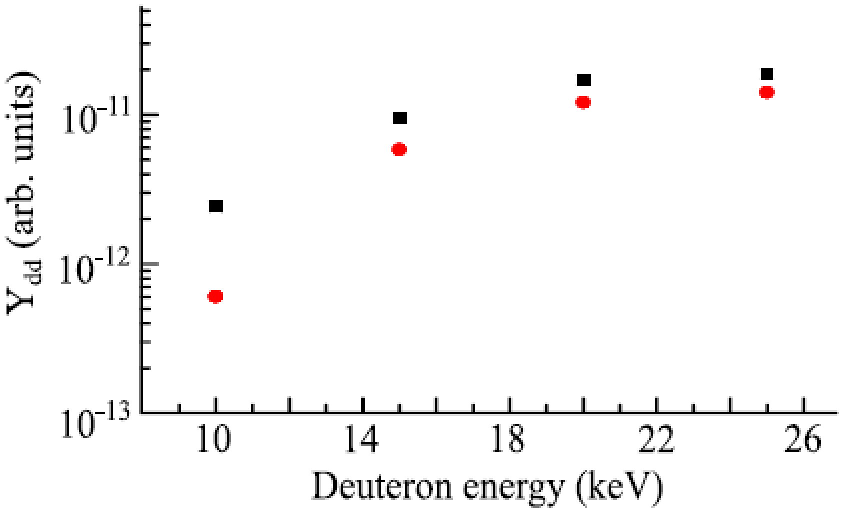
The layout of **the target and track detectors** in the ion beam in the HELIS installation. 1, 2, 3 - track detectors CR-39 with different coatings; 4 - target; 5 - the manipulator; 6 - ion beam; 7 - steel substrate; 8 - aperture

HELIS experimental data

Dependence of DD-reaction product yield using Ti/TiO2:Dx (a) and the Pd/PdO:Dx (b) structures on the deuteron energy in the range of 10–25 keV



(a)



(b)

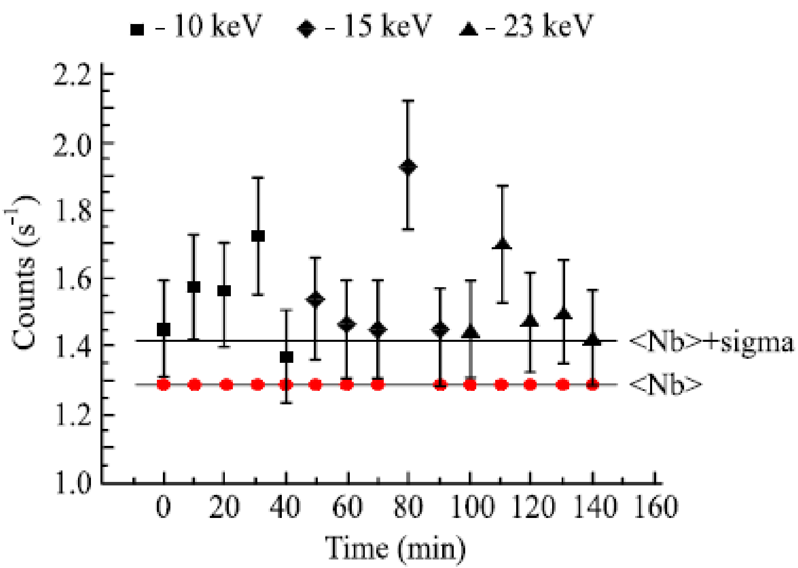
deuteron energy, E_d, keV	10	15	20	25
enhancement factor, f	2	1.3	1.4	1.2

deuteron energy, E_d, keV	10	15	20	25
enhancement factor, f	4	1.6	1.4	1.3

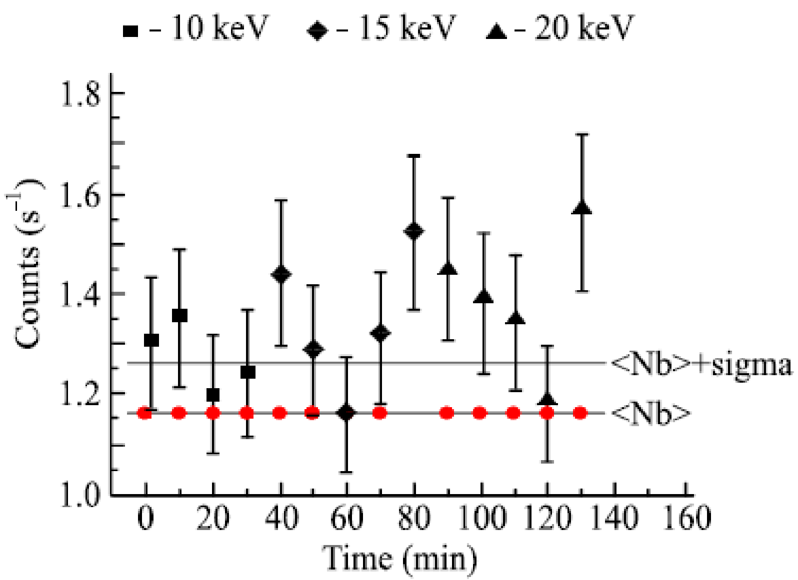
Significant amplification effects in comparison with theoretical extrapolation observed. The effect strongly depends on the current density of the deuteron beam.

HELIS experimental data

In our **experiments**, **we observed** that the **irradiation of deuterated crystals** of Pd or Ti **targets by p or Ne+ beams** with energy of ~10 keV **lead to stimulation** of yield of DD reaction



(a)



(b)

Counting rate of the ^{3}He-neutron detector (squares, diamonds, triangles).

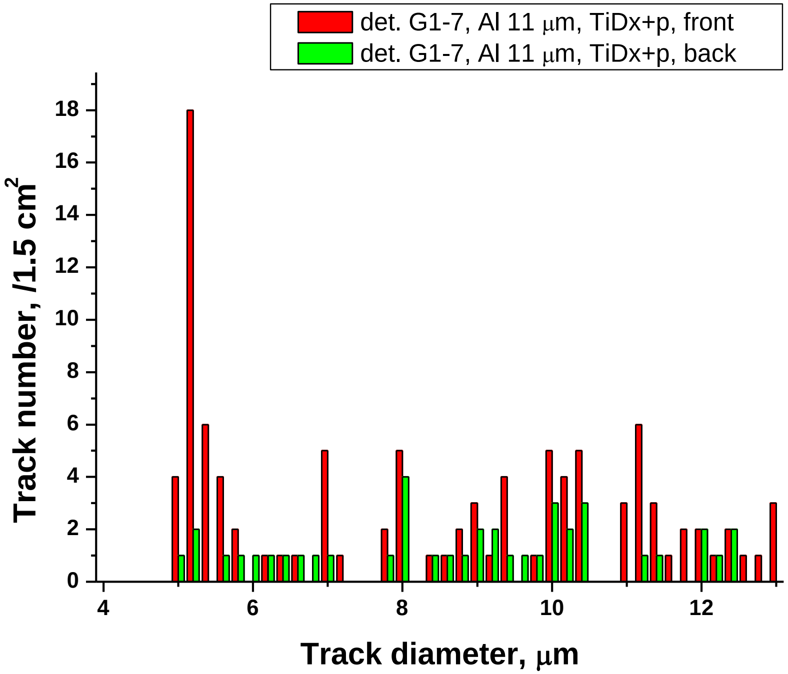
(a) Ti/TiO2:Dx target 300 μm thick and H+ beam (10, 15, 23 keV),

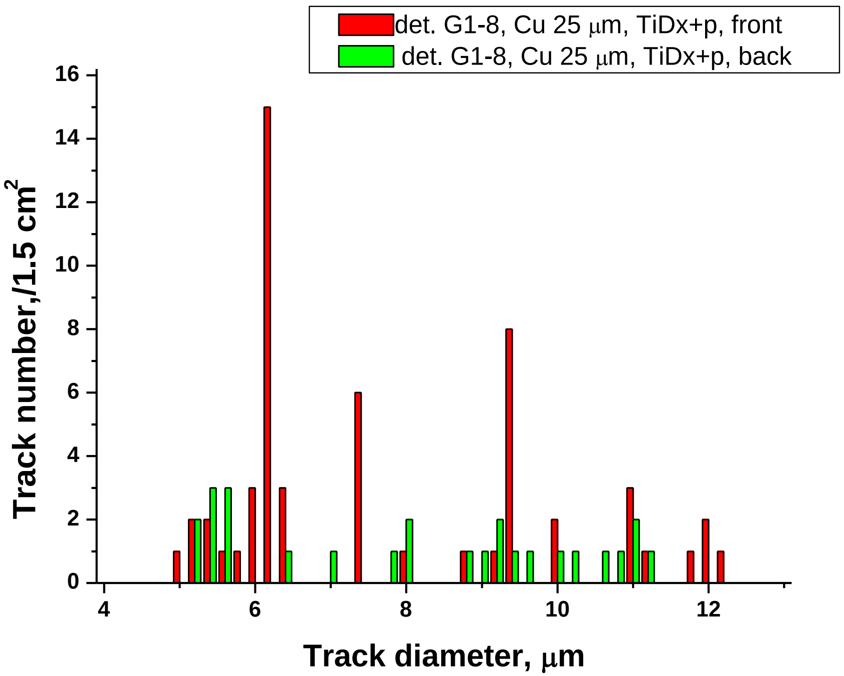
(b) Ti/TiO2:Dx target 300 μm thick and Ne+ beam (10, 15, 20 keV).

The average background ⟨*Nb*⟩ *(circles) was measured using the* Cu target.

HELIS experimental data

The distribution of the diameters of tracks on the detectors CR-39 (a beam of protons with energy of 23 keV, target - TiDx)

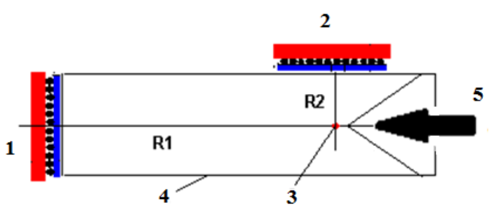


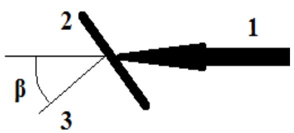


The position of the leftmost peak shows the presence of the protons tracks with initial energy 3 MeV (products of DD-reaction).

HELIS experimental data - channeling effects

The orientation of textured deuterated diamond film with respect to the D+ ion beam axis has an impact on the neutron yield. The highest yield is recorded for the diamond target, oriented perpendicular to the beam. **The possible reason for the anisotropy is the ion or the products of nuclear reactions channeling in the textured polycrystalline CVD-diamond**. The neutron yield in the DD-reaction at the deuterium enriched CVD diamond is measured as a function of the beam incident angle. It is observed, that the some crystalline structures and the orientation of the sample with respect to the beam has an impact on the neutron yield. Samples with homogeneous structure without channels on the surface do not show the dependence of the neutron yield on the orientation in the ion beam.





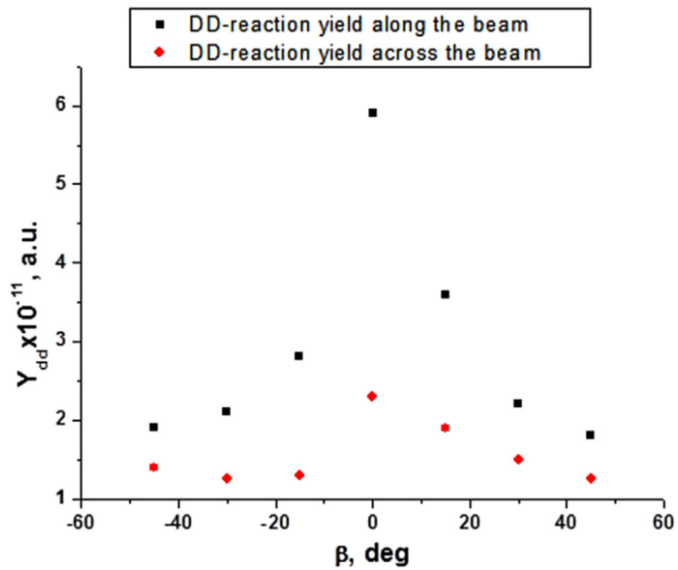
The beam incident angle β is defined as an angle between the beam direction (1) and the normal (3) to the target (2) surface.

The relative yield of the DD reaction $\mathbf{Y_{dd} = n_n/(S \times I_d)}$,

where $\mathbf{n_n}$ - longitudinal or transverse neutron flux,

S - irradiated area of the target and

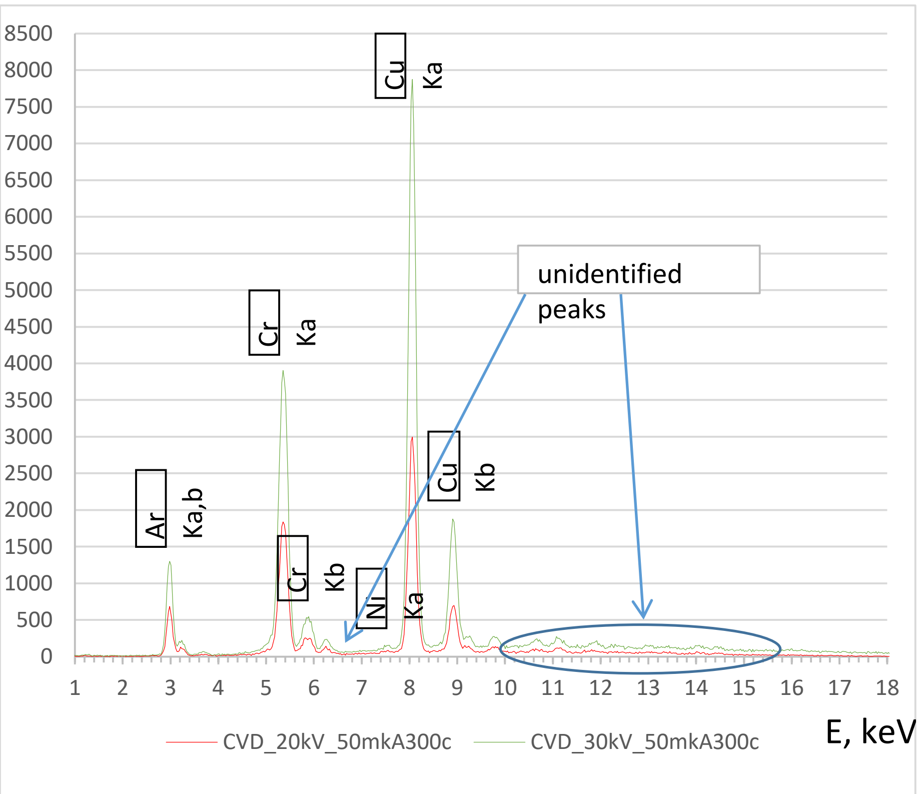
$\mathbf{I_d}$ - the ion beam current.



The neutron yield obtained with the CVD-diamond sample as a function of the angle β between the beam and the target plane norm, measured longitudinally (black) and transverse (red) directions with respect to the ion beam. $\mathbf{E_d}$ **= 20 кeV, I – 50-:-60 μA**

HELIS experimental data

The "extra" peaks are present in all spectra from surface of deuterium enriched CVD diamond and Pd and it was initially identified as the diffraction peaks. These diffraction peaks should change its position when rotating the target. The effect was not observed for targets with a homogeneous structure (Ti, Cu)

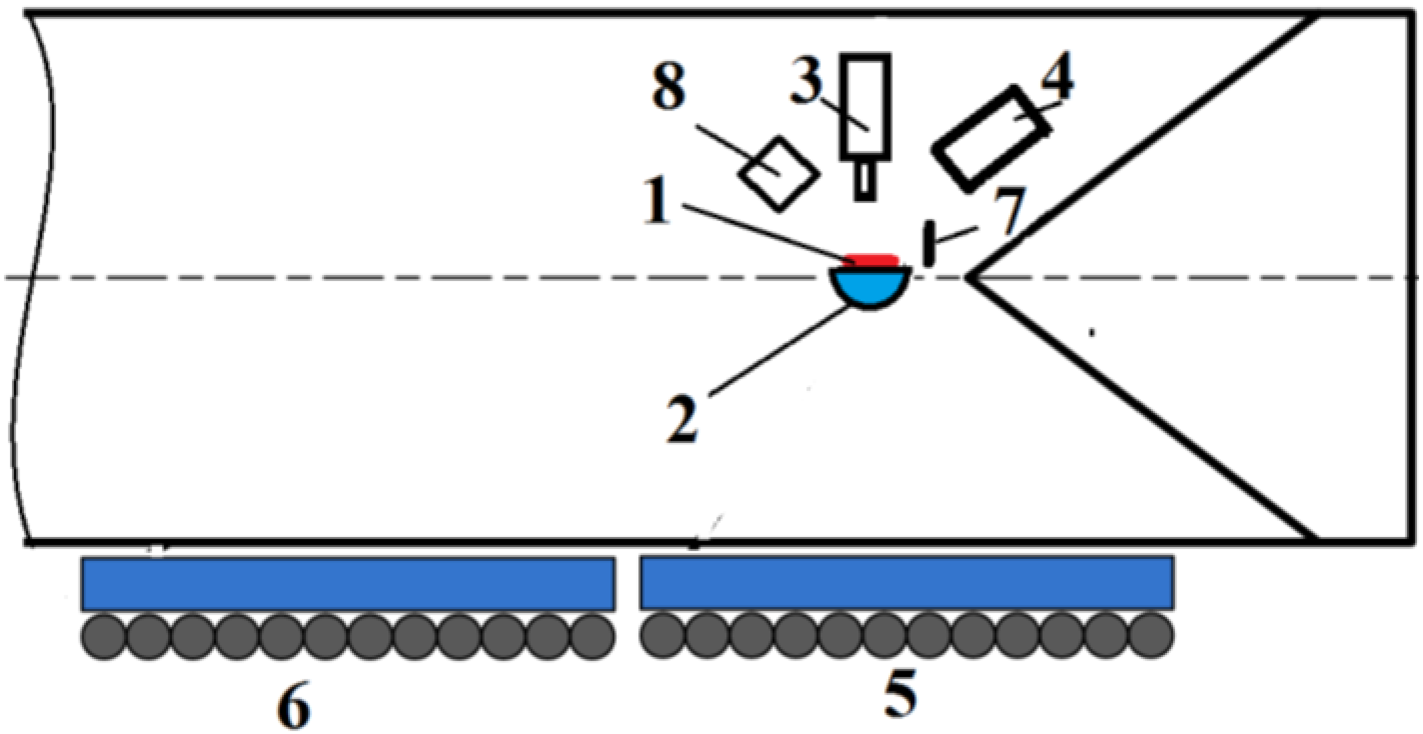


As shown by our measurements, these "extra" peaks do not change their positions in the spectrum not in the rotation of the target or detector.

Analysis of X-ray fluorescence spectra of the target bombarded by beams of ions or X-rays, allowed to find them "extra" peaks, the occurrence of which can not be associated with any of the known elements, and requires separate research.

HELIS experimental data 2017-2018

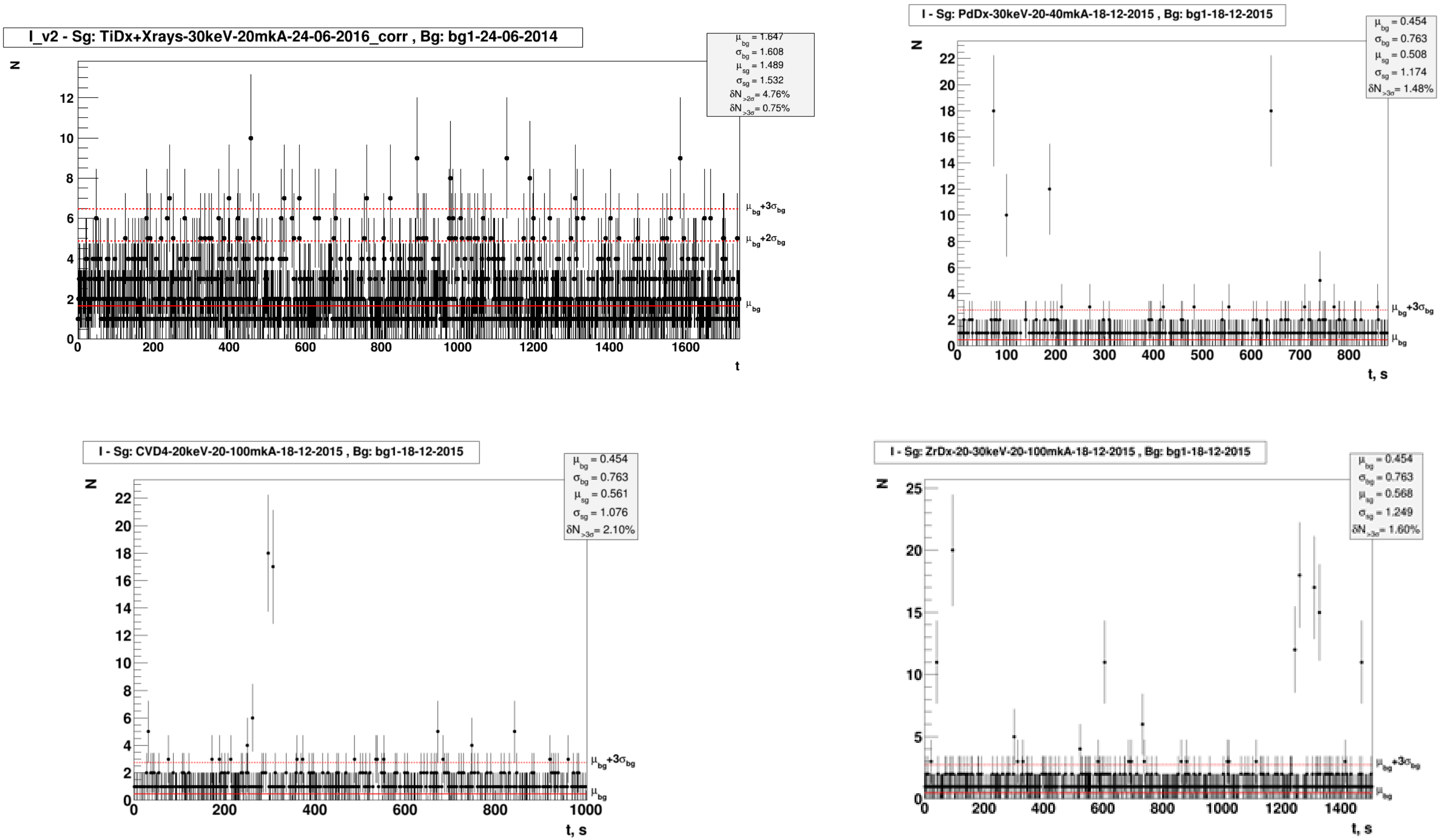
The scheme of experiment for irradiation of targets by X-ray beam



1 - The target; 2 – Cu target holder; 3 – X-ray tube with lens; 4 – SSB charged particle detector; 5, 6 - He-3 counter based detectors with paraffin radiator; 7 – CR-39 plastic track detector; 8 - X-ray detector

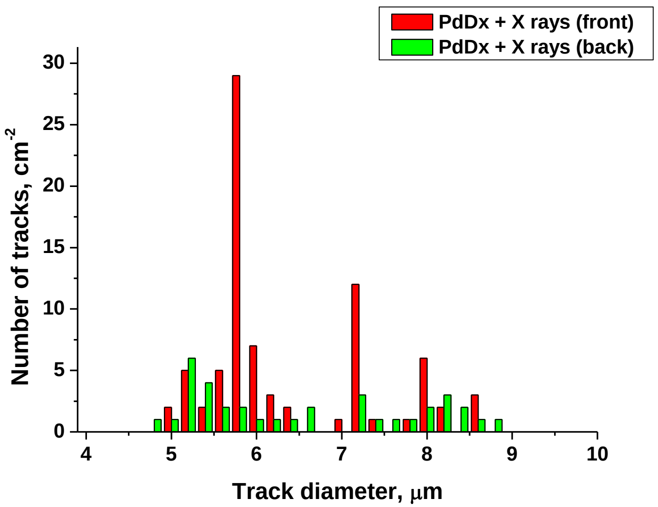
Data of neutron detector based on He-3 counters.

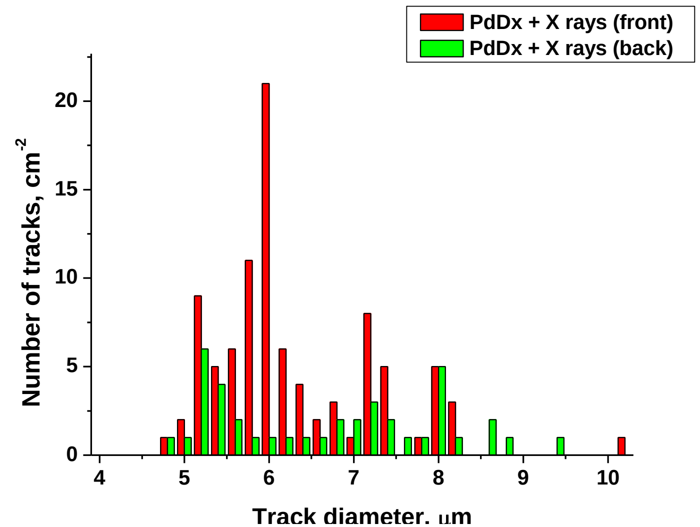
The total count of the neutron detector (Group 1) at the time of X-ray irradiation of targets TiDx (a) PdDx (b),CVD-diamond (c) and the target of $ZrD_{1.5}$ (d) in comparison with the background

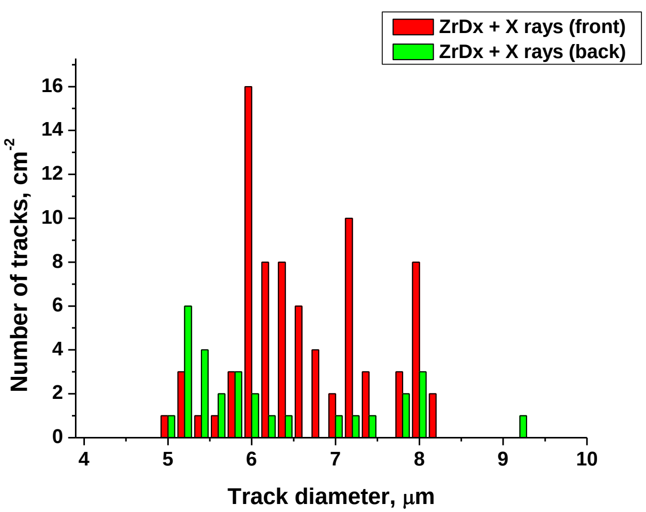


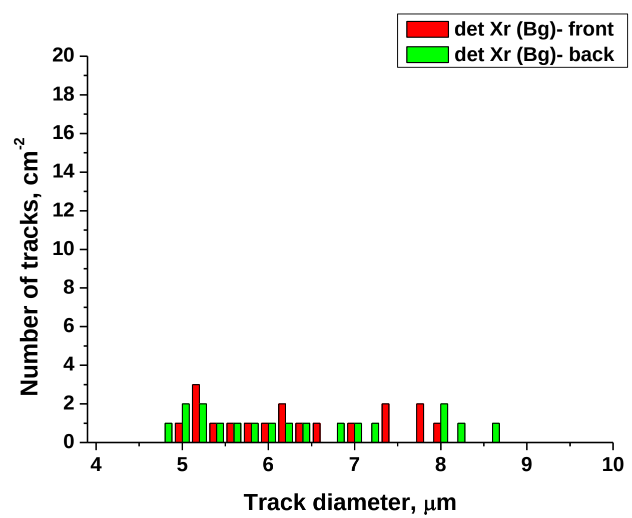
Data of CR-39 detector

The distribution of the track diameters on the front (red columns) and back (green columns) sides of detector CR-39 with a layer of Al of thickness 11 micron, with X-ray irradiation of PdDx (a), PdDxCd (b), ZrD1.5 (c) and background of the detector (d). Time of X-ray irradiation (E = 20-30 keV, I = 20-100 μA) - 3000.2000, 1200, 2000 s, respectively. Distance of detector from the target – 2 cm of air



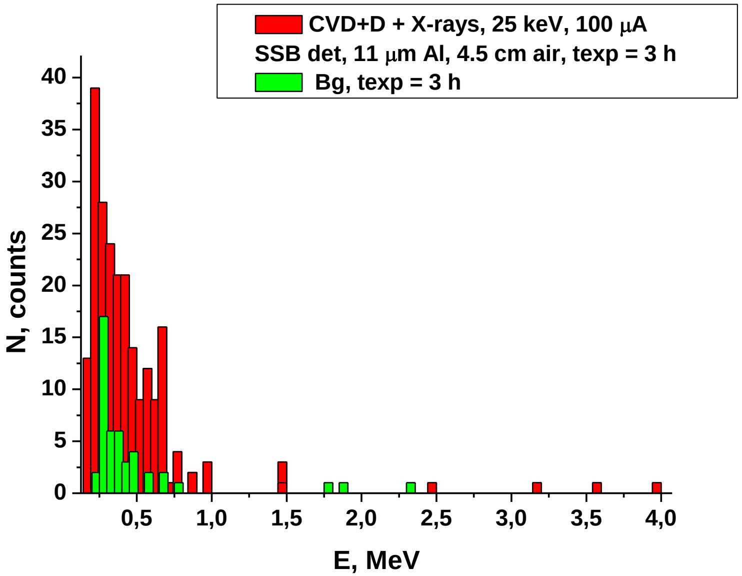


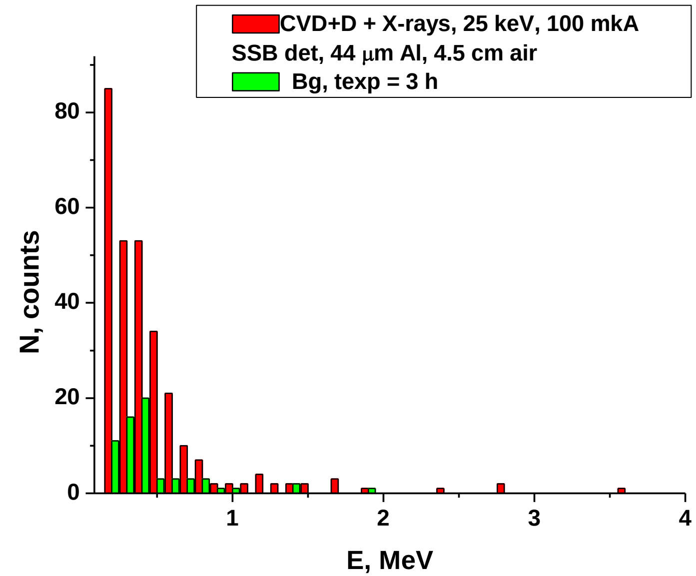


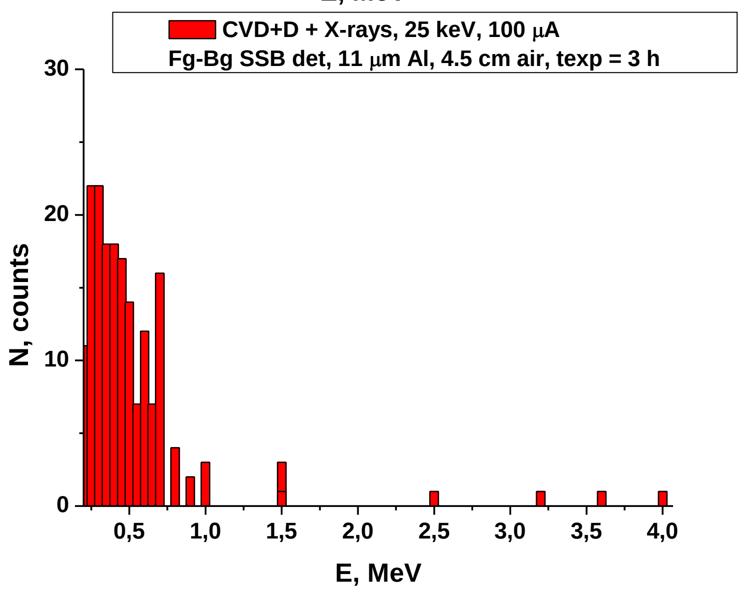


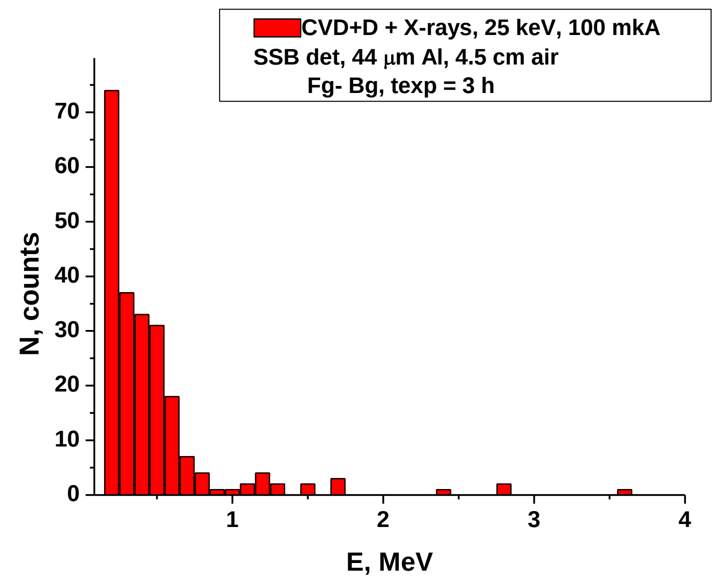
The spectrum of SSB detectors

The target CVD+D irradiated with X-rays (25 keV, 100 μA). Exposure time - 3 hours, the distance from detector to the target – 4.5 cm of air.SSB detector shielded with 11 μm Al (left), 44 μm Al (right). Average count ~ 96 / hour (<n> = 7 /s into 4π)









Plans and prospects

1. To continue the study of DD reactions at energies of 10–30 keV with the use of additional detectors of charged particles and neutrons to more accurately determine the spectral composition of the reaction products
2. Investigate the influence of the crystal structure on the yield of products of nuclear reactions for polycrystalline and single-crystal deuterated targets. The goal is to find out the effect of channeling effects on the yields of nuclear reaction products.
3. Investigate the nature of "extra" peaks in the X-ray fluorescence spectra of textured samples.
4. Measure the yields of the D + He-3, He-3 + He-3, B-11 + p nuclear reactions from various solid targets at energies of 10–30 keV using different detectors

Conclusion

1. The investigation of nuclear reaction in the interaction of ion beams with deutereted crystalline targets **on the installation HELIS** experimentally **confirmed the influence of crystal lattice structure on the probability of nuclear reactions**;

2. The experiments at HELIS demonstrate **the possibility of stimulation of nuclear reactions** in deuterated crystal lattice **under irradiation by ion and X-ray beam**;

3. The experiments at HELIS showed that, perhaps, **the channeling phenomena** in the crystal lattice **leading to an increase and anisotropy in the yield of the products of DD nuclear reactions** in the deuterium - enriched CVD diamond and Pd under irradiation by deuterium ion beam.

4. In experiments at HELIS were **observed the "extra“ (additional) peaks in the X-ray fluorescence spectra from surface** of deuterated crystals target **under irradiation by ion or X-ray beam**. These experimental observations require further studies and additional research.