Orientation effect of the neutron yield in deuterated Pd target bombarded by deuterium ion beam

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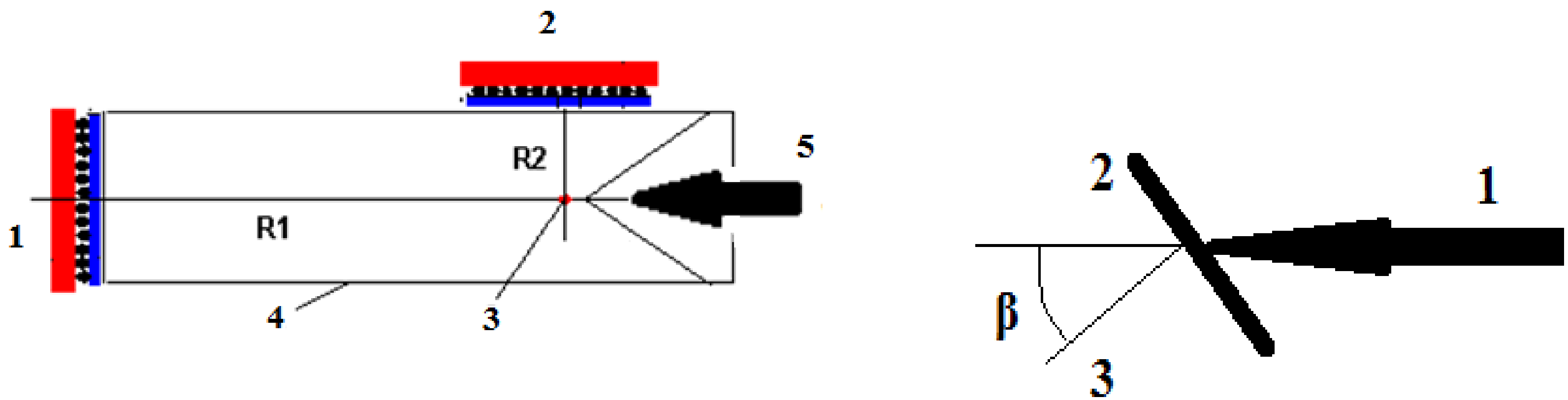
Anisotropy of DD-reaction yield

In our previous investigations of DD-reaction in the crystal targets (Pd, Ti), an anisotropy was observed: the neutron flux along the beam direction was higher than that in the transverse direction.

Particularly large anisotropy was observed using a polycrystalline CVD diamond target.

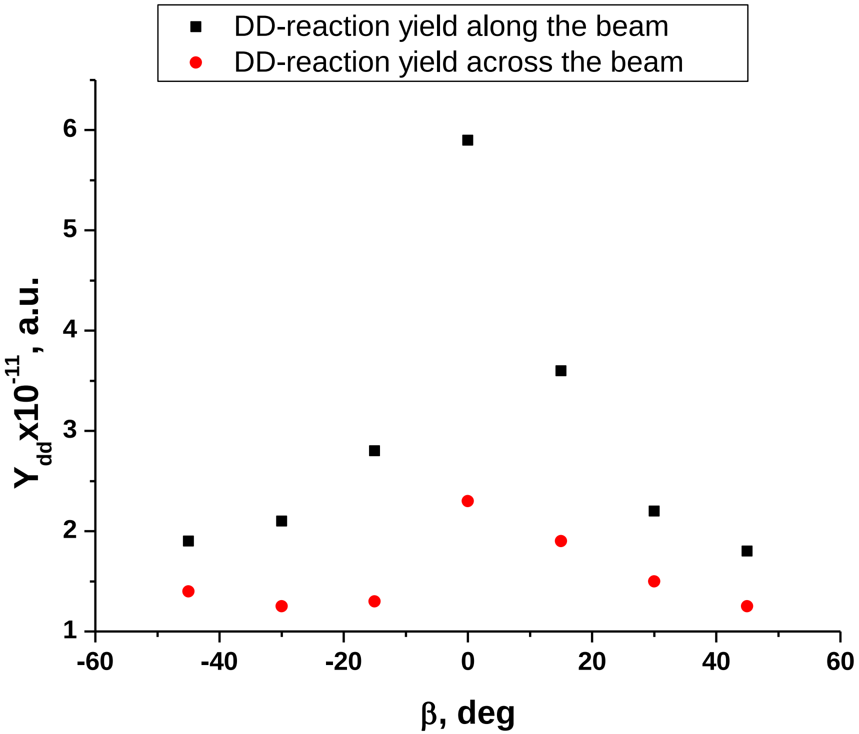
Left panel: the ^3He detector setup at HELIS, representing the first (1) and the second (2) ^3He-counter groups with radii R=85 cm and R=38 cm, respectively. The target is placed at (3) inside the HELIS beam pipe (4). The ion beam direction is indicated by (5). Right panel: The beam scattering angle beta: the beam is indicated by (1), the target is shown by (2), the normal to the target surface (3).

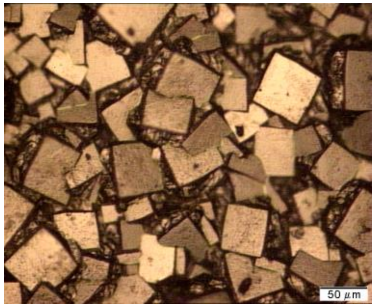


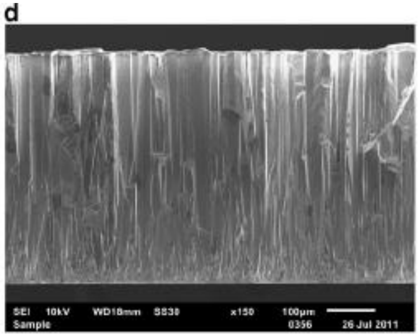
The relative yield of the DD reaction $Y_{dd} = n_n/(S \times I_d)$,

where n_n - longitudinal or transverse neutron flux, S - irradiated area of the target and I_d - the ion beam current.

The neutron yield obtained with the CVD-diamond sample as a function of the angle between the beam and the target plane norm, measured longitudinally (black squares) and transverse (red diamonds) directions with respect to the ion beam. Ion beam with the energy of E_d=20 keV and the current of 50-60 μA.

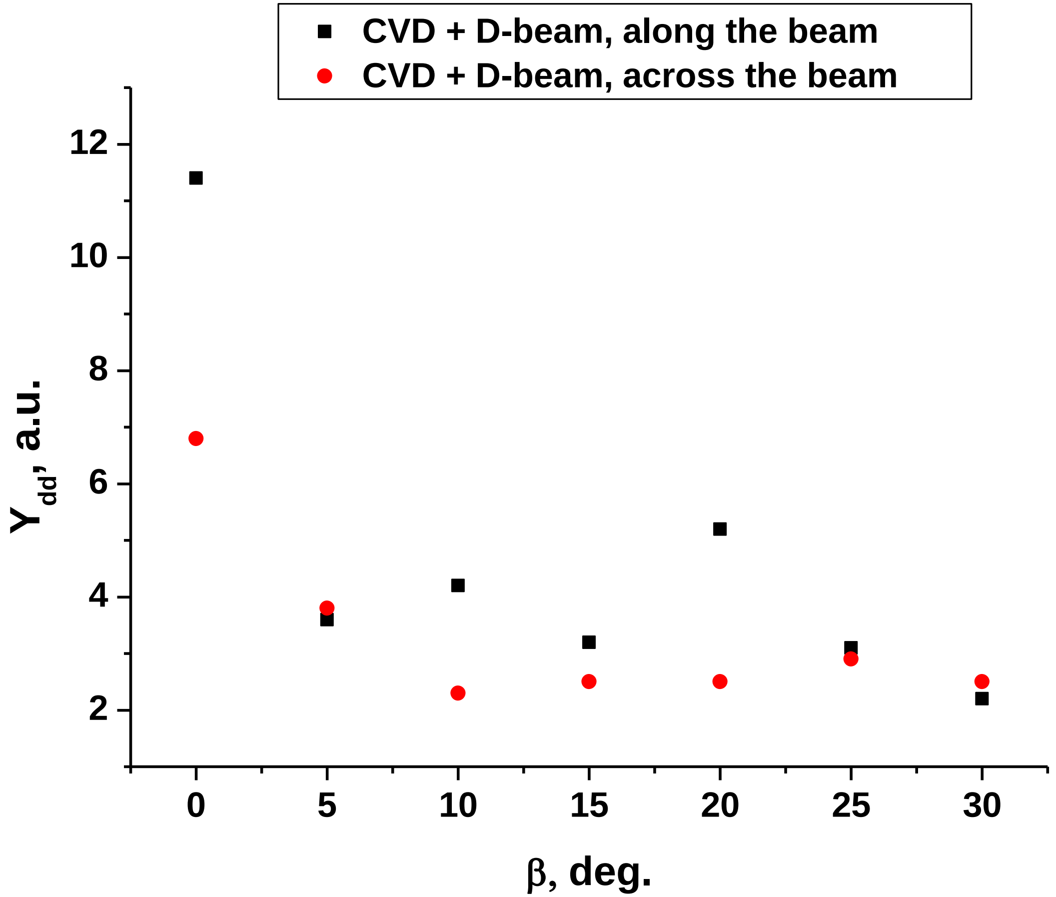






A.V. Bagulya, O.D. Dalkarov, M.A. Negodaev, A.S. Rusetskii, A.P. Chubenko, V.G. Ralchenko, A.P. Bolshakov, Channeling effect in polycrystalline deuterium-saturated CVD diamond target bombarded by deuterium ion beam, 6-th International Conference ***Channeling 2014 - Charged & Neutral Particles Channeling Phenomena*** (Capri-Naples, Italy) on October 5-10, 2014; Nuclear Instruments and Methods in Physics Research B 355 (2015) 340 - 343

The neutron yield obtained with the CVD-diamond sample as a function of the angle between the beam and the target plane norm, measured longitudinally (black squares) and transverse (red diamonds) directions with respect to the ion beam. Ion beam with the energy of E_d=21.4 keV and the current of 200 μA.



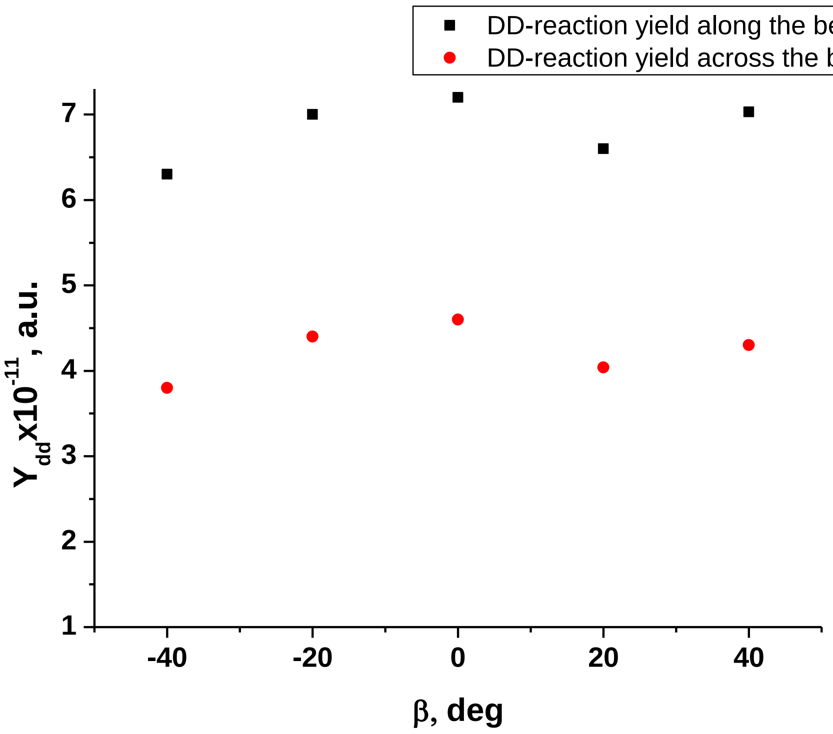
Pd/PdO:D_x Sample preparation

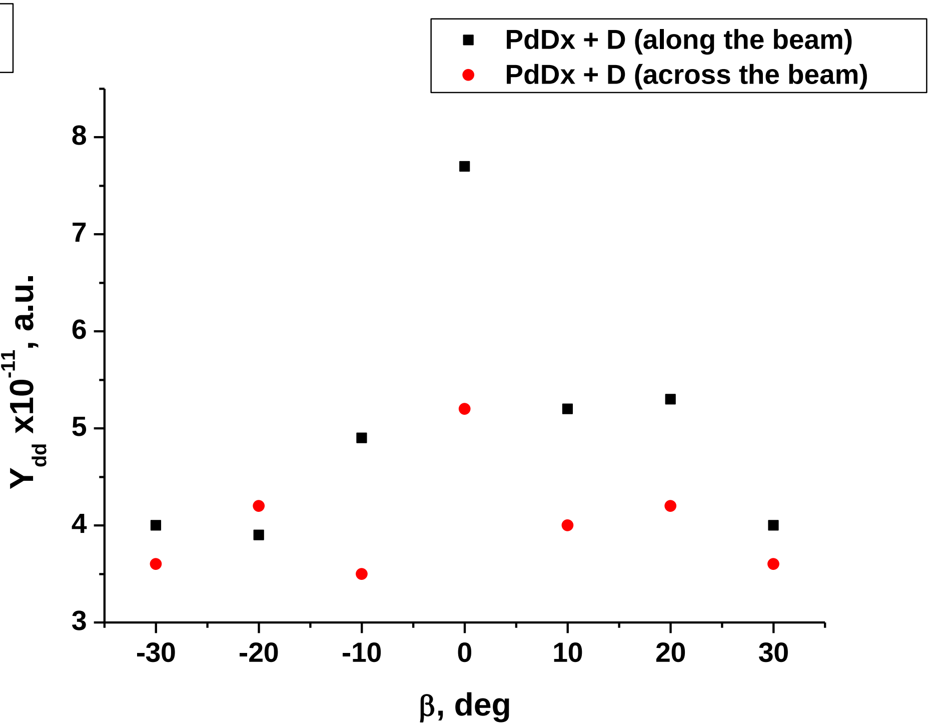
- The PdO/Pd/PdO samples have been prepared by thermal oxidation from Pd cold-rolled foil (99.95 % purity) of 50 μm thick with dimensions S = 30 x 10 mm^2.
- Electrochemical loading in 0.3M-LiOD solution in D_2O with Pt anode; j = 10 mA/cm^2. x =D/Pd ~ 0.73 (about 40 min required).
- The samples have been rinsed in pure D_2O
- The samples then were rapidly mounted (during ~1 min) in sample holder in front of detectors set and irradiated by D+ ion beam

TiD_x sample preparation

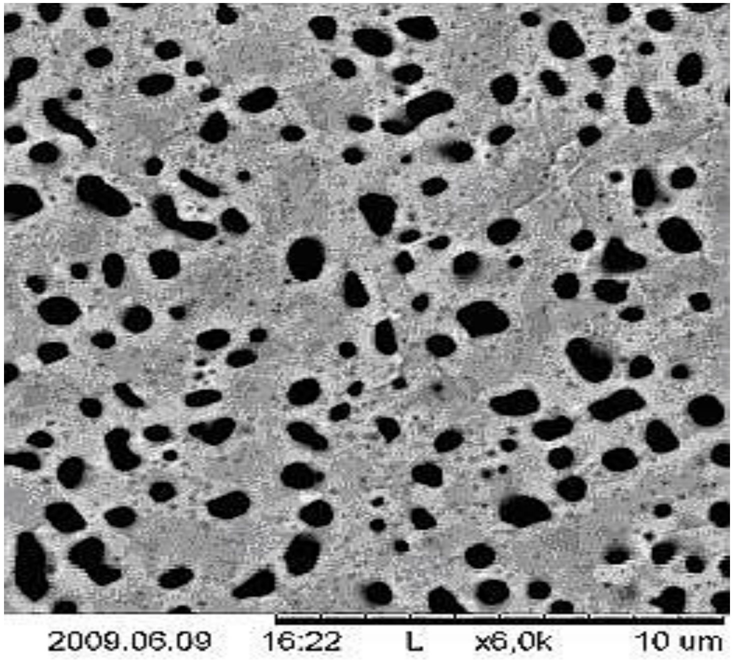
- The Ti foils of 30, 55 and 300 μm thick have been loaded in 0.2M solution of D_2SO_4 in D_2O during t = 36 h at J = 10 mA/cm^2, in order to dissolve the TiO_2 oxide layer at the Ti-surface and to provide D-penetration.
- The average loading (x = D/Ti = 0.1 at depth of ~1 μm) has been determined by weight balance.
- Saturation of the sample can be carried out long before irradiation because the compound is absolutely stable at T = 300 K.

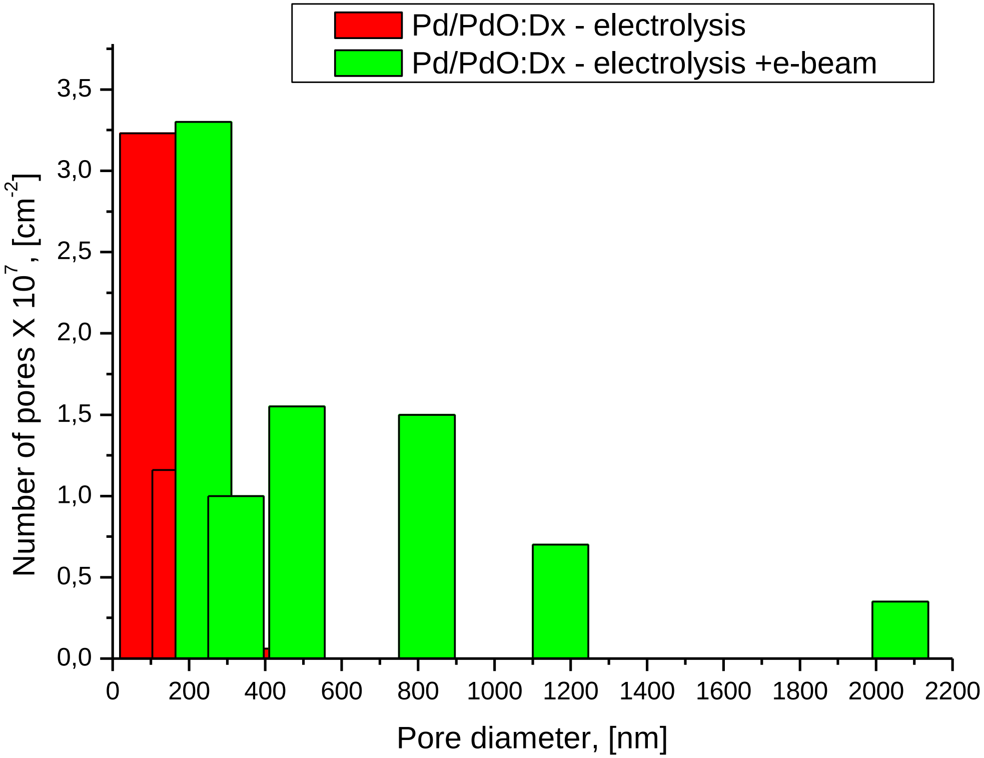
The dependence of the neutron yield from the samples Ti / TiO_2: D_X (left) and Pd / PdO: D_x (right) on the angle β between the deuteron beam and the normal to the plane of the target. (▪ - along the beam, ● - across the beam). The energy of the beam - E_d = 20 keV, current - 40 μA



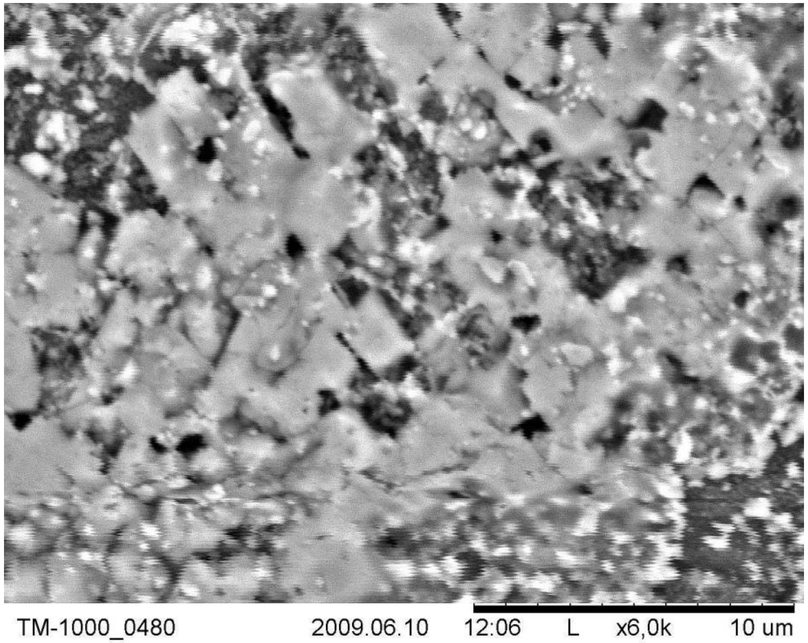


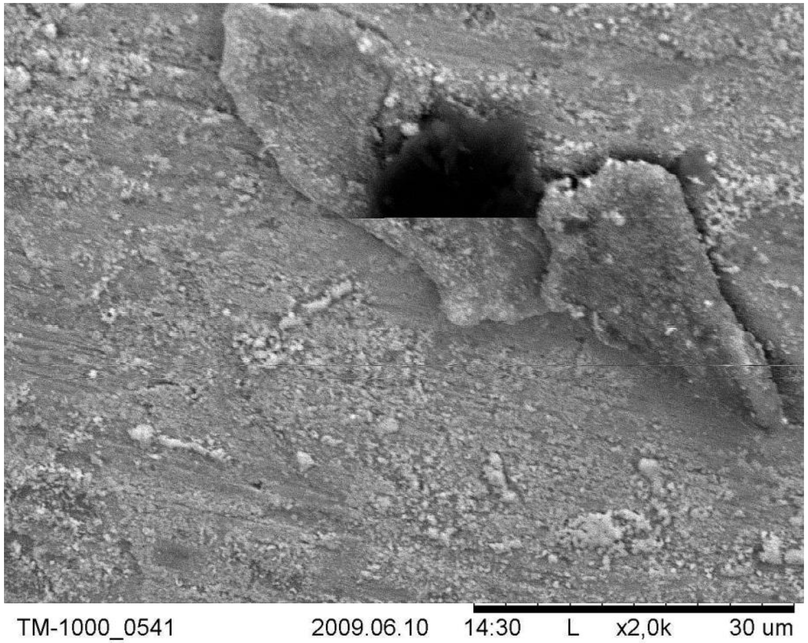
SEM Pd/PdO:D_x image (left) and pore diameter distributions in Pd/PdO:Dx (right) before and after electrolysis and e-beam irradiation.





SEM Ti/TiO_2:D_x surface image (left). A crater on Ti/TiO_2:D_x surface after irradiation

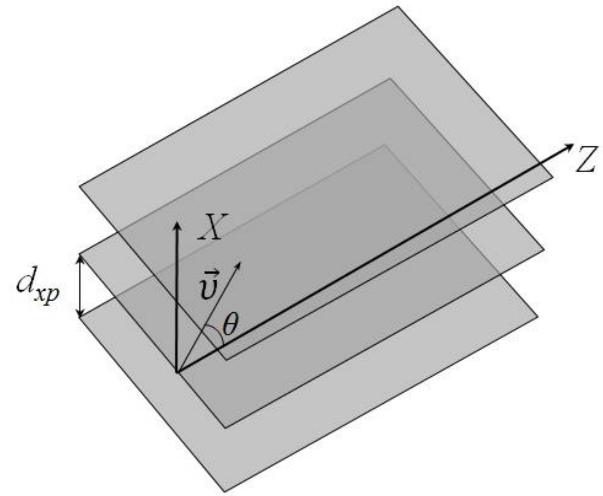




Simulation of D^+ trajectories at channeling

- Equation of motion: non-relativistic.

  Motion with constant velocity along the crystal planes (Z direction) and oscillations in X direction governed by periodic planar potential U(x), with d_{px} being a distance between planes.



- Numerical solution of equation of motion in X direction using a computer code BCM–2 (S.V.Abdrashitov, O.V.Bogdanov, K.B.Korotchenko, Yu.L.Pivovarov, E.I.Rozhkova, T.A.Tukhfatullin, Yu.L.Eikhorn, Nucl. Instrum. and Meth. B, 402 (2017) 106).

$$m\ddot{x} = F_x = -\frac{\partial U(x)}{\partial x}$$

$$m\ddot{z} = 0$$

$$\frac{dz}{dt} = \upsilon_z = const$$

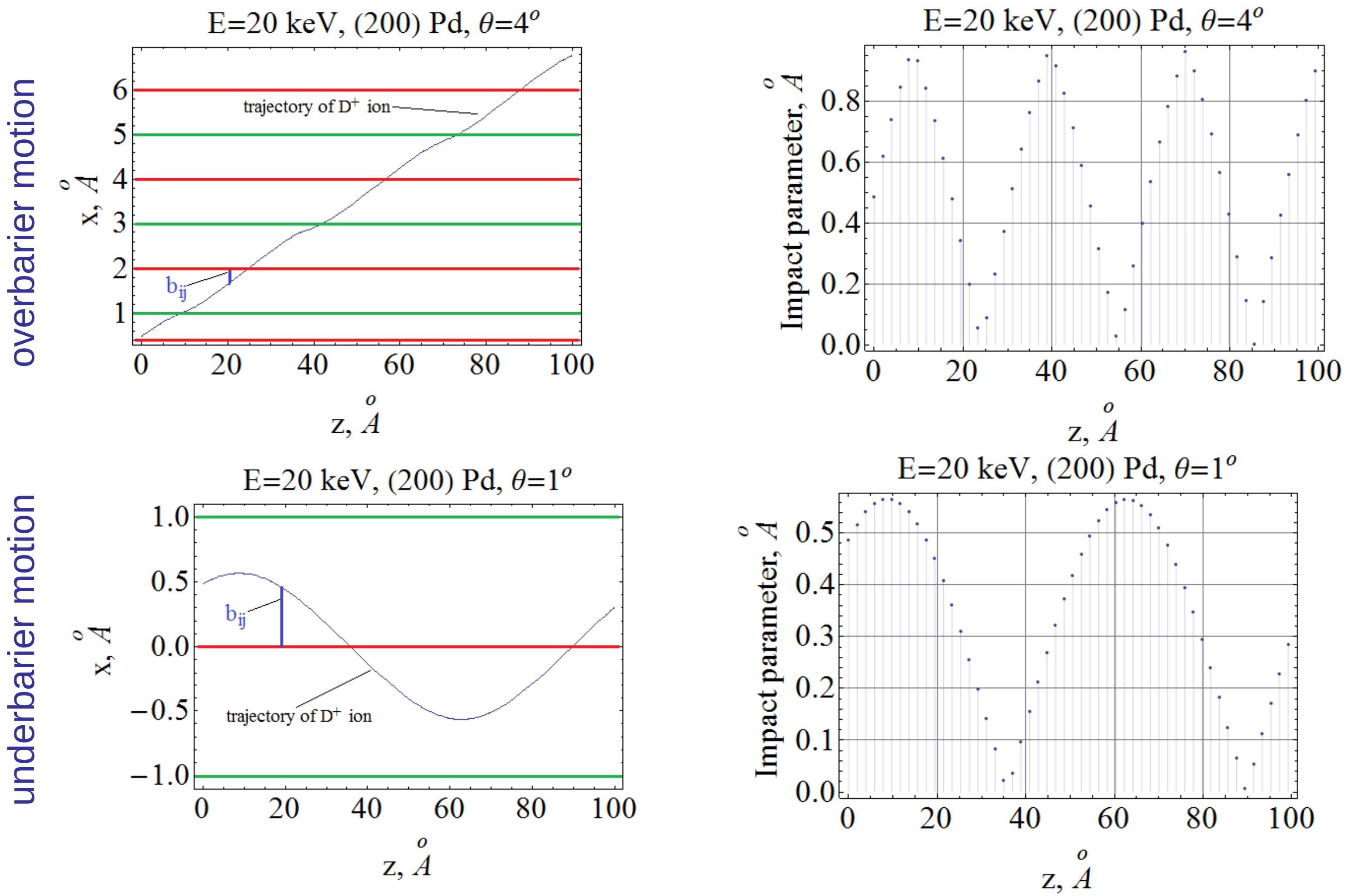
$$Initial\ condition$$

$$x(0) = x_0;$$

$$\upsilon_x(0) = \upsilon \sin(\theta)$$

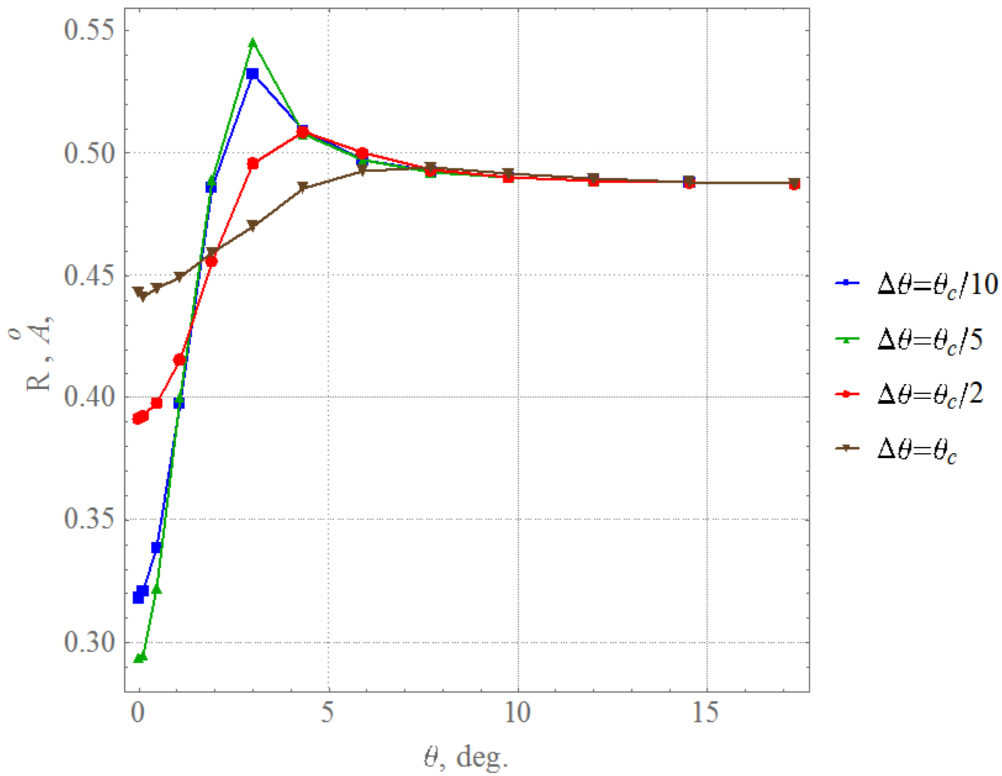
- Simulations of trajectories take into account angular divergence of the beam (for each entry points several incident angles θ are generated) and allow to calculate the channeled D^+ beam flux density which is necessary to analyze the interaction with implanted D. The incident angle θ is of order of the Lindhard critical angle.

Typical trajectories of D^+ ions at (200) channeling in Pd crystal, E=20keV



Green lines represent (200) Pd planes, red lines - D planes. b_{ij} impact parameter.

Simulation results
20 keV D^+ ions channeled in (200) Pd crystal

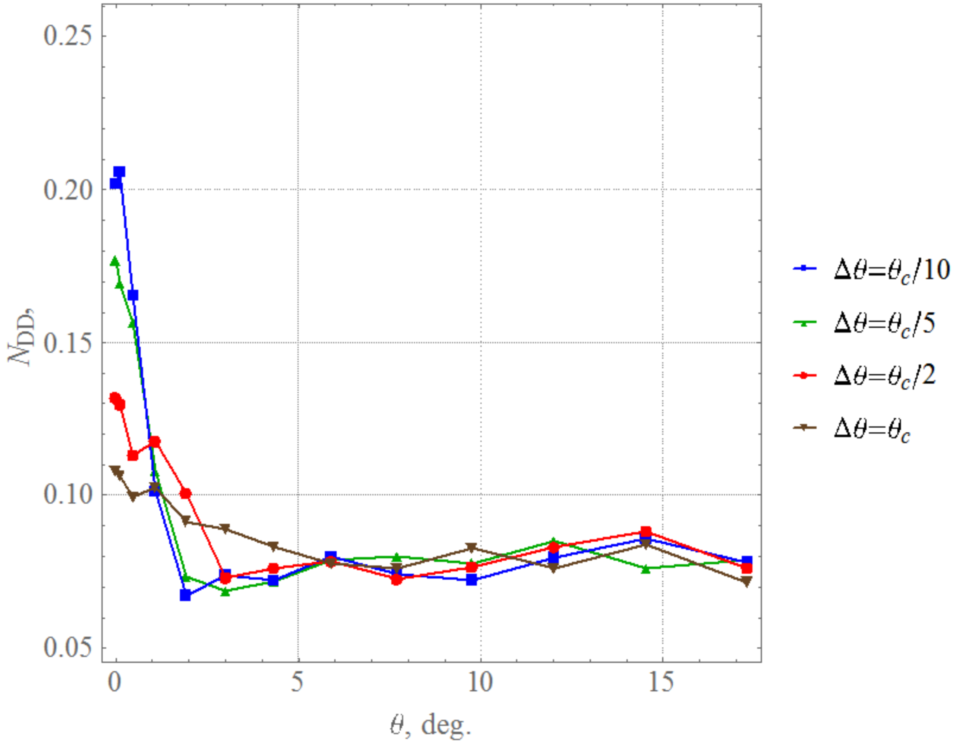


Δθ - angular divergence of the D^+ ion beam

Averaged over all trajectories impact parameter $R = \frac{\sum_{i=1}^{N_{tr}} \sum_{j=1}^{N_D} b_{ij}}{N_{tr} N_D}$

N_{tr} is the number of D^+ trajectories, N_D the number of D-atom next to which the trajectory passes, bij - impact parameter

Simulation results
20 keV D^+ ions channeled in (200) Pd crystal



$\Delta\theta$ - angular divergence of the D^+ ion beam

Part of D^+ ions with impact parameter less $3.3\ 10^{-5}$Å

$$N_{DD} = \frac{N_{tr}\left(b_{ij} < 3.3\ 10^{-5}\text{Å}\right)}{N_{tr}}$$

(θ_c =3.58° is the critical channeling angle)

Discussion

Previous work with diamond showed the presence of an orientation effect at irradiation of a textured polycrystalline diamond target (most crystallites have an orientation of (100) and its absence when working with polycrystalline target in which the crystallites are oriented chaotically.

When the Ti target is irradiated, the orientation effect is not observed.

When the Pd target is irradiated, an orientation effect is also observed, which can be caused by the presence of pores in the direction of the beam, or textured polycrystalline structure (it is known that in cold-rolled foils, crystallites have a predominant orientation).

The dependence of the neutron yield on the angle can be explained by channeling ions in the crystal structure, but this does not explain the difference in the yield neutrons along and across the direction of the beam.

Discussion

Possible reasons for orientation effect of DD-reaction yield

1. Collective processes associated with high concentration of deuterium in the certain directions;
2. The effects of channeling, leading to an increase in the effective range of ions in the direction of the channel

Conclusion 1

1. It is observed, that the some crystalline structure and the orientation of the sample with respect to the beam has an impact on the neutron yield. The highest yield is recorded with the target, oriented perpendicular to the beam.
2. Such a strong angular dependence of the neutron yield could indicate a presence of narrow channels in the sample, where the bulk of deuterium, trapped during the electrolysis, is concentrated. These channels could be created in pores on Pd surface after electrolysis and beam irradiation.
3. Another reason could be the channeling of ions in channel direction in crystal structure. Large neutron yield at the angle $\beta=0$ can be explained by increased effective range of the deuterium ions inside the channels with respect to that in the bulk of the sample.
4. Samples without channels on the surface do not show the dependence of the neutron yield on the orientation in the ion beam

Conclusion 2

1. Another reason of orientation effect could be the channeling of 20 KeV D^+ ions. Large neutron yield at the angle β=0 can be explained by increased flux density of the channeled D+ ions inside the (200) channels, where implanted D are located.
2. Orientation effect of increasing the relative probability of DD-reaction in Pd due to channeling was investigated by computer simulation. The numerically obtained trajectories allow calculate enhanced 20 KeV D^+ flux density between crystal planes at zero incident angle thus leading to increase of the neutrons yield in DD reaction.
3. Presence of channels possibly may caused further focusing of neutron wave along channel direction.
4. Qualitative agreement of the simulations with the experimental data was obtained.