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

O D Dalkarov[1], M A Negodaev[1*], A S Rusetskii[1+], A S Chepurnov[2], M A Kirsanov[3], I A Kishin[1,4], A S Kubankin[1,4], I A Kudryashov[2], D A Selivanova[3]

[1] P.N. Lebedev Physical Institute Russian Academy of Sciences, Leninskiy Prospekt 53, Moscow, 119991, Russia
[2] Skobeltsyn Institute of Nuclear Physics, Lomonosov Moscow State University, Leninskie gory, GSP-1, Moscow, 119991, Russia
[3] National Research Nuclear University MEPhI (Moscow Engineering Physics Institute), Kashirskoe highway 31, Moscow, 115409, Russia
[4] Laboratory of Radiation Physics, Belgorod National Research University, Koroleva St. 2a, Belgorod, 308034, Russia

E-mail: [*]negodaev@lebedev.ru, [+]rusets@lebedev.ru

Abstract. The results of studies of the interaction of ion beams and X-ray quanta with deuterated crystal structures at the HELIS facility (LPI) are presented. Results on research of DD-reactions in deuterated crystal structures at deuteron energies 10 - 25 keV show significant enhancement effect. It is shown that the effect of the beams of ions Ne^+ and H^+ at energies in the range of 10 - 25 keV and a beam of X-radiation of 20 - 30 keV for deuterated target leads to stimulation of DD-reaction. For the target of CVD-diamond it is showed that the orientation of the sample with respect to the deuteron beam affects the neutron yield. Targets (deuterated CVD diamond, palladium, zirconium and titanium) were irradiated with both ion beams and X-ray quanta using an X-ray tube with an energy of up to 30 keV. Analysis of X-ray fluorescence spectra from deuterated targets of CVD diamond and palladium revealed "additional" peaks that are not identified by any of the characteristic radiation lines. Their appearance cannot be connected with any known element, as well as with diffraction processes.

1. Investigation of nuclear fusion reactions at low energies on accelerators

Measuring the cross sections for nuclear fusion reactions at low energies is of considerable interest, both for the creation of new generation power plants and for understanding the processes occurring inside stars. For this purpose, high-current accelerators HELIS [1] and LUNA-1 [2] were created. A series of works by the LUNA collaboration showed significant effects of enhancing the yield of the ^{3}He (^{3}He, 2p) ^{4}He reaction at energies in the Gamow peak [3, 4]. The authors attributed this to the screening effect of ions by plasma electrons, which makes it easier to overcome the Coulomb barrier in the synthesis of nuclei and increases the yield of the reaction. In [5], the effects of amplification of the DD reaction on Al, Zr, Ta targets were shown. The LUNA collaboration has done a series of studies on the yields of the DD reaction in various materials [6, 7]. It was shown that the effects of enhancement strongly depend on the elemental composition of the target. A little earlier, in the nuclear center Sendai (Japan), work was carried out to study the amplification of the yields of the DD reaction at energies below 10 keV [8, 9]. Maximum amplification effects were obtained on Pd and PdO / Pd / PdO / Au targets. This paper presents the results of studies of low-energy nuclear reactions at the HELIS facility.

2. Brief description of the HELIS installation

Installation HELIS [10], created in the P.N. Physical Institute of the Russian Academy of Sciences, allows to obtain continuous ion beams with currents up to 50 mA and energies up to 50 keV and is intended for carrying out a wide range of experiments, such as studying collisions of light nuclei with energies of tens of keV, studying elementary and collective processes in an ion-beam plasma, studying the interaction of an ion beam with various materials, modifying their surfaces and obtaining thin-film coatings by the method of ion-beam spraying. The main part of the GELIS installation is an ion accelerator, which includes: 1) an ion source (duoplasmatron) with equipment that provides its power supply; 2) an ion beam focusing system; 3) vacuum system; 4) diagnostic equipment for measuring the current and energy of the ion beam.

3. Overview of the work performed on the HELIS facility

In recent years, a series of studies have been carried out at HELIS to study the yields of DD reactions in deuterated crystal structures at deuteron energies of 10–25 keV, as well as to stimulate the DD reaction with ion beams [10–16]. The targets were deuterated structures of palladium [10, 12], titanium [11, 13, 14], CVD diamond [15]. To detect DD reaction products:

$$d + d \rightarrow p\ (3\ \mathrm{MeV}) + T\ (1\ \mathrm{MeV}) \qquad (1)$$

$$d + d \rightarrow n\ (2.45\ \mathrm{MeV}) + {}^{3}\mathrm{He}\ (0.8\ \mathrm{MeV}) \qquad (2)$$

a multichannel neutron detector based on counters with He-3 filling and a CR-39 track detector was used. The location of the detectors and targets on the HELIS installation is shown in figure 1. The procedure for detectors calibration is described in [14].

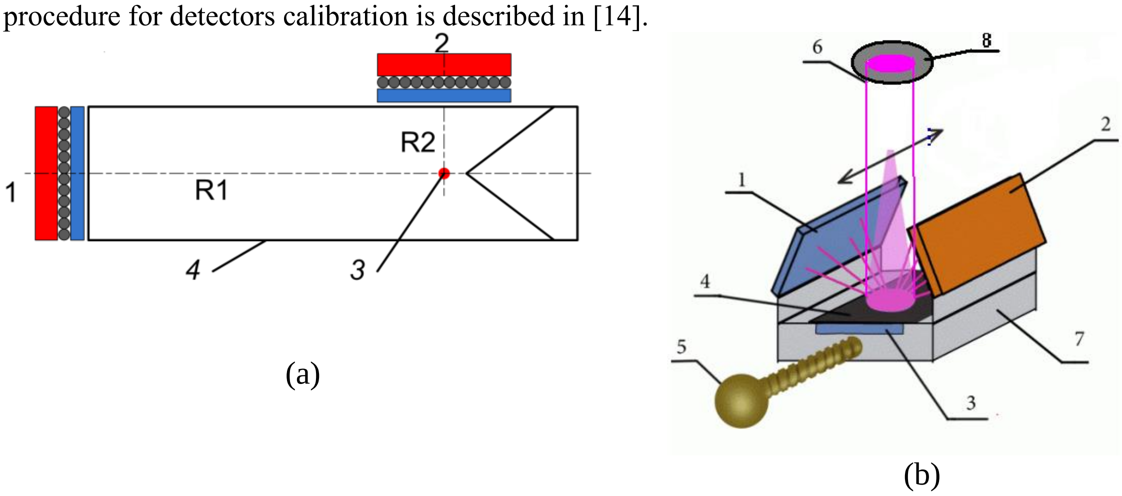

Figure 1. (a) The layout of the He-3 detector on the HELIS installation. 1 and 2 - two positions of the ^{3}He detector (R1 = 120 cm, R2 = 30 cm), 3 - the location of the target, 4 - contours of the HELIS installation. (b) The layout of the target and track detectors in the ion beam in the GELIS setup. 1, 2, 3 - track detectors CR-39 with different coatings; 4 - target; 5 - the manipulator; 6 - ion beam; 7 - steel substrate; 8 - diaphragm.

To calculate the output of the DD reaction from a thick target bombarded with deuterons, we used the procedure described in [10].

The dependence of the DD reaction yield from Pd/PdO:D_x and Ti/ TiO_2:D_x targets on the deuteron energy is shown in figure 2. It also shows the values of the yields of the DD reaction, calculated for the given experimental conditions. Figure 2 shows that the experimental yields of the DD reaction from the targets significantly exceed the calculated values. So, with E_d = 10 keV for Ti/ TiO_2:D_x and Pd/PdO:D_x targets, the experimental yields are 2 and 4 times more calculated than, respectively.

Journal of Physics: Conference Series **1390** (2019) 012002 doi:10.1088/1742-6596/1390/1/012002

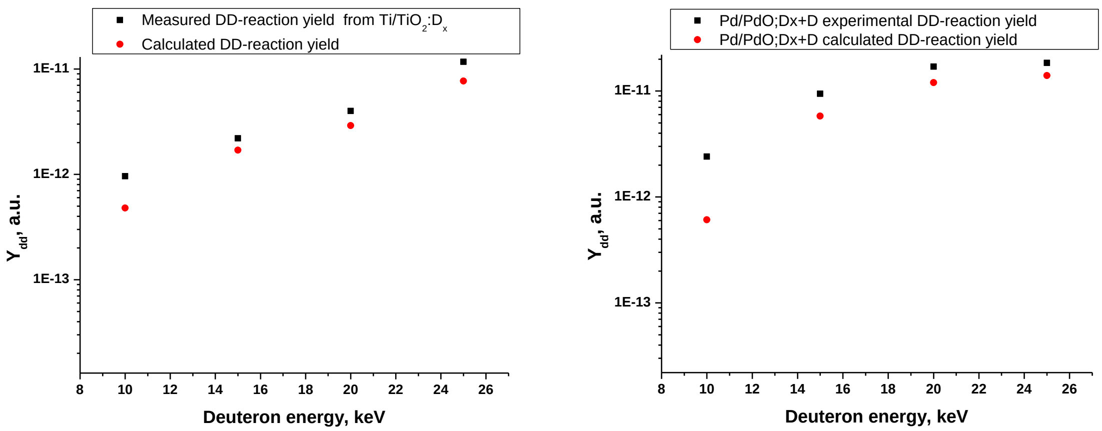

Figure 2. The dependence of the yields of the DD reaction from the Pd/PdO:D_x target (right) and Ti/TiO_2:D_x (left) on the beam energy D^+. ■ is the measured yield of the DD reaction through the beam, ● is the yield of the DD reaction calculated for the given energy.

The possibility of stimulating the yields of DD reactions from Pd/PdO:D_x and Ti/TiO_2:D_x structures with beams of H^+ and Ne^+ ions in the energy range 10 - 25 keV was also investigated [12-14]. The scheme of the experiment is similar to the one with the D^+ ion beam (figure 1). The yield of protons and neutrons of the products of DD reactions (1) and (2) under the action of an ion beam on a previously deuterated target was studied. Figure 3 shows the results of measurements of the neutron flux by the ^{3}He detector under the action of the H^+ and Ne^+ beams on the Ti/TiO_2:D_x target. Background measurements were performed with similar beams on a Cu target. From figure 3, it can be seen that when a beam is applied to a Ti/TiO_2:D_x target, the neutron detector reads above the background values. The CR-39 track detectors also showed the presence of proton emission from deuterated targets of irradiated ions (see figure 4). The position of the leftmost peak in figure 4 shows the presence of tracks from protons with an initial energy of 3 MeV (products of the DD reaction). Similar results were obtained with the Pd/PdO:D_x target. The average flux of DD neutrons stimulated by the beam reached a value of ~ 10^2 s^{-1} into 4π sr.

It is also observed, that some crystalline structures and the orientation of the sample with respect to the beam has an impact on the neutron yield [15]. The neutron yield in the DD-reaction at the deuterium enriched CVD diamond is measured as a function of the beam incident angle. The highest yield is recorded for the CVD diamond target, oriented perpendicular to the deuteron beam. Simulation of the passage of a deuterium ion beam in diamond crystals confirmed the influence of the crystal structure on the neutron yield [16]. A similar effect was observed for samples of deuterated palladium with pore structure on the surface. For homogeneous structures without selected directions, this effect was not observed.

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 cannot be associated with any of the known elements [17]. 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. 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. Therefore, these are not diffraction peaks. It was also shown that “additional peaks” are not “escape peaks “. Thus, the question of the nature of “additional” peaks in X-ray spectra from crystalline targets when they are irradiated with a beam of X-ray quanta remains open. The effect was not observed for targets with a homogeneous structure (Ti, Cu).

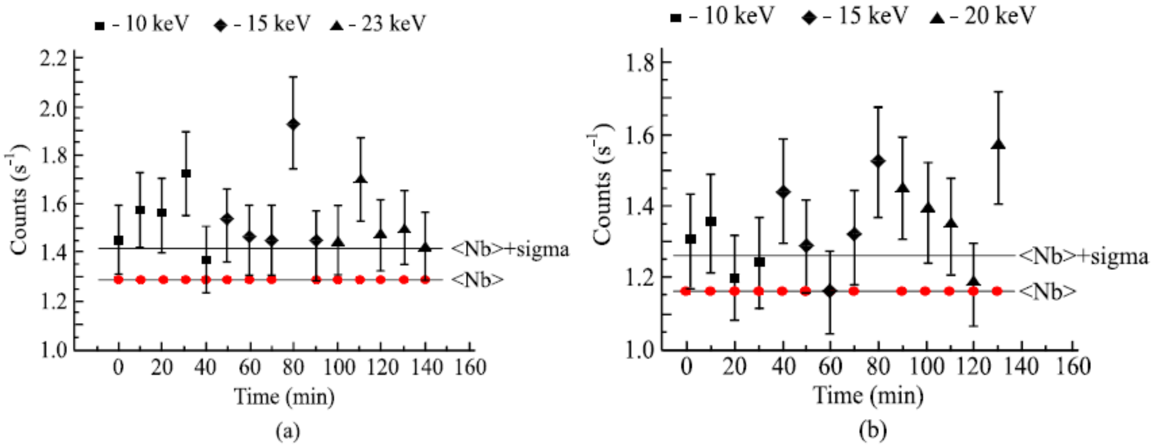

Figure 3. The count of the neutron detector ^{3}He (■, ♦, ▲). (a) Target - Ti/TiO$_2$:D$_x$ 300 μm, beam - H + (10, 15, 23 keV), (b) Target - Ti/TiO$_2$:D$_x$ 300 μm, beam - Ne + (10, 15, 20 keV). The average background <Nb> (●) is measured with a Cu target.

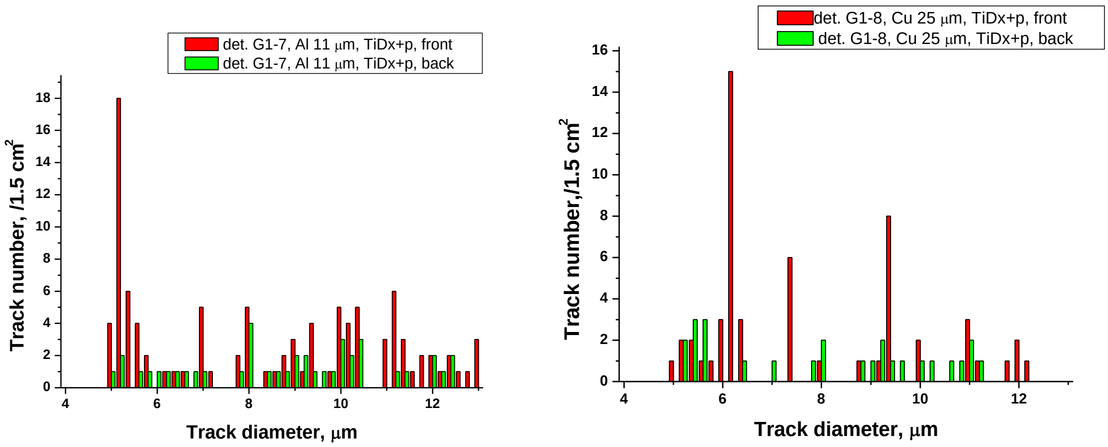

Figure 4. Distributions of track diameters on the CR-39 detectors with a coating of 11 μm Al (left) and 25 μm Cu (right) located above the - Ti/TiO$_2$:D$_x$ sample irradiated by a 23-keV proton beam. Readings from front (dark columns) and back (bright columns) sides of detector.

At the same time, the neutron emission of the products of the DD reaction (1) stimulated in deuterated targets by 20-30 keV X-ray beam was investigated (see figure 5). We used X-ray tubes with both focusing and collimation of X-ray quanta. Measurements of neutron emission were carried out by a detector based on ^{3}He counters. Background measurements were carried out without a deuterated target with the included X-ray tube irradiating the copper substrate. The results of measurement of neutron emission by a detector based on ^{3}He counters are described in detail in [18]. Comparison with background measurements shows that in the presence of a deuterated target, the mean count value of the neutron detector exceeds the background (figure 6). Taking into account the detection efficiency gives an average neutron flux of ~ 10^2 neutrons / s into 4π sr. Also, at certain points in time, the average background is exceeded by 3σ, which indicates the presence of “neutron bursts” (~ 10^4 neutrons / s into 4π sr) stimulated by X-rays. The percentage of such exceedances of the 3σ-background for deuterated targets significantly exceeds the values for the Poisson distribution, which describes the sample distribution for the background values.

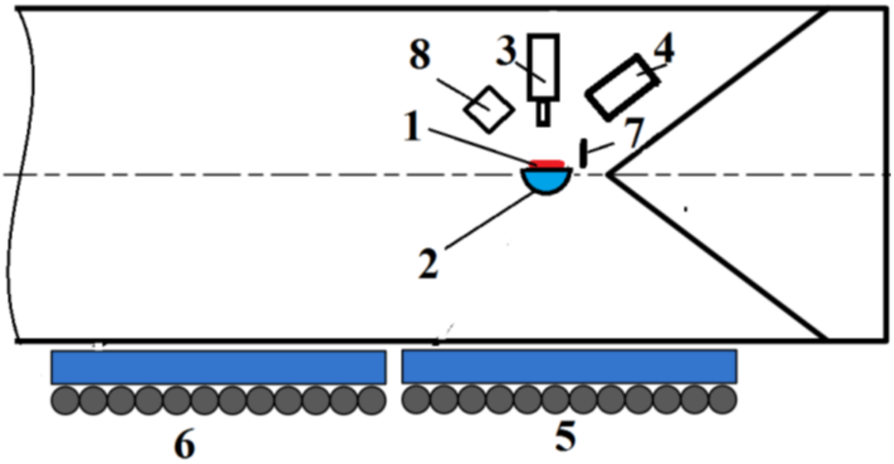

Figure 5. The scheme of experiment for irradiation of targets by X-ray beam. 1 - The target; 2 – Cu target holder; 3 – X-ray tube; 4 – SSB charged particle detector; 5, 6 - ^{3}He counter based detectors with paraffin radiator; 7 – CR-39 plastic track detector; 8 - X-ray detector

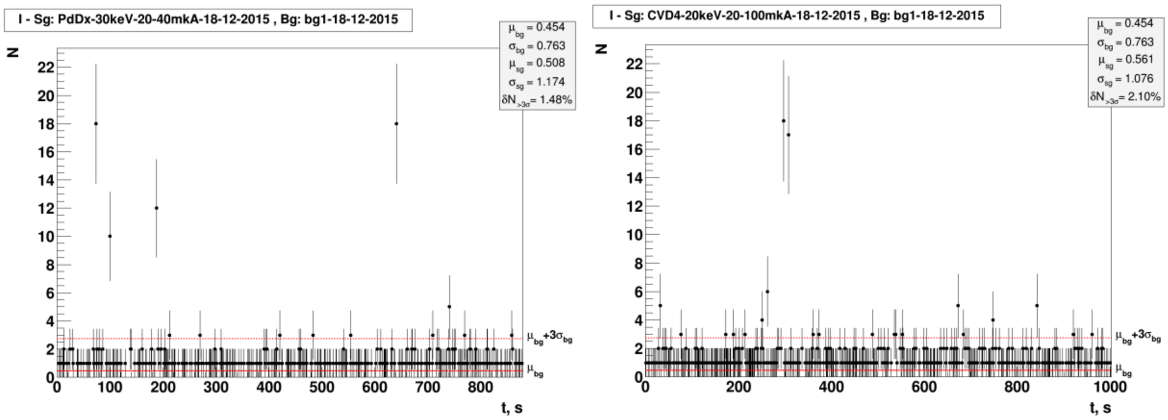

Figure 6. The total count of the neutron detector at the time of 20-30 keV X-ray irradiation of targets PdD_x (left) and deuterated CVD-diamond (right) in comparison with the mean background

For registration of protons - products of the DD reaction stimulated in deuterated targets by a beam of X-ray quanta CR-39 track detectors and silicon surface-barrier detectors were used. The detectors were coated with 11 and 44 μm of Al. Both track and surface barrier detectors showed the effect exceeding the background. Taking into account the coatings of the detectors and the distances to the target, these signals can be associated with protons from the DD reaction (2), the average flux of which can be estimated as ~ 10 s^{-1} into 4π sr. This value are in good agreement with the average proton fluxes recorded by the CR-39 detector.

4. Conclusion

The investigation of nuclear reaction in the interaction of ion beams with deuterated crystalline targets on the installation HELIS experimentally confirmed the influence of crystal lattice structure on the probability of nuclear reactions. The experiments at HELIS demonstrate the possibility of stimulation of nuclear reactions in deuterated crystal lattice under irradiation by ion and X-ray beam; 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. 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. We plane 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.

References

[1] Bagulya A V, Negodaev M A 1996 *Preprint LPI* **11** (in Russian)
[2] Greife U, Arpesella C, Barnes C A *et al.* 1994 *Nuclear Instruments Methods* A **350** 327
[3] Bonetti R, Broggini C, Campajola L *et al.* 1999 *Physical Review Letters* **82** 5205
[4] Junker M, D'Alessandro A, Zavatarelli S *et al.* 1998 *Physical Review* C **57** 2700
[5] Czerski K, Huke A, Biller A *et al.* 2001 *Europhys. Lett* **54** (4) 449
[6] Raiola F, Migliardi P, Gang L *et al.* 2002 *Physics Letters* B **547** 193
[7] Raiola F, Gang L, Bonomo C *et al.* 2004 *European Physical Journal* A **19** 283
[8] Kasagi J, Yuki H, Lipson A G *et al.* 1998 *JETP Lett.* 68 **785**
[9] Kasagi J, Yuki H, Baba T, Noda T *et al.* 2002 *Journal of the physical society of Japan* **71(**12) 2881
[10] Bagulya A V, Dalkarov O D, Negodaev M A *et al.* 2012 *Bulletin of the Lebedev Physics Institute* **39** (9) 247–253
[11] Bagulya A V, Dalkarov O D, Negodaev M A *et al.* 2012 *Bulletin of the Lebedev Physics Institute* **39** (12) 325–329
[12] Bagulya A V, Dalkarov O D, Negodaev M A *et al.* 2012 *Bulletin of the Lebedev Physics Institute* **40** (10) 282–284
[13] Bagulya A V, Dalkarov O D, Negodaev M A *et al.* 2012 *Bulletin of the Lebedev Physics Institute* **40** (11) 305–309
[14] Bagulya A V, Dalkarov O D, Negodaev M A *et al.* 2015 *Physica Scripta* **90** (7) 074051
[15] Bagulya A V, Dalkarov O D, Negodaev M A *et al.* 2015 *Nucl. Instr. and Meth*. B **355** 340
[16] Bagulya A V, Dalkarov O D, Negodaev M A *et al.* 2017 *Nucl. Instr. and Meth.* **402** 243
[17] Bagulya A V, Dalkarov O D, Negodaev M A *et al.* 2017 *Journal of Surface Investigation* **11** (1) 58-62
[18] Bagulya A V, Dalkarov O D, Negodaev M A *et al.* 2017 *Journal of Surface Investigation* **11** (1) 179-185