# Investigation of neutron generation upon irradiation of deuterated crystalline structures with an electron beam

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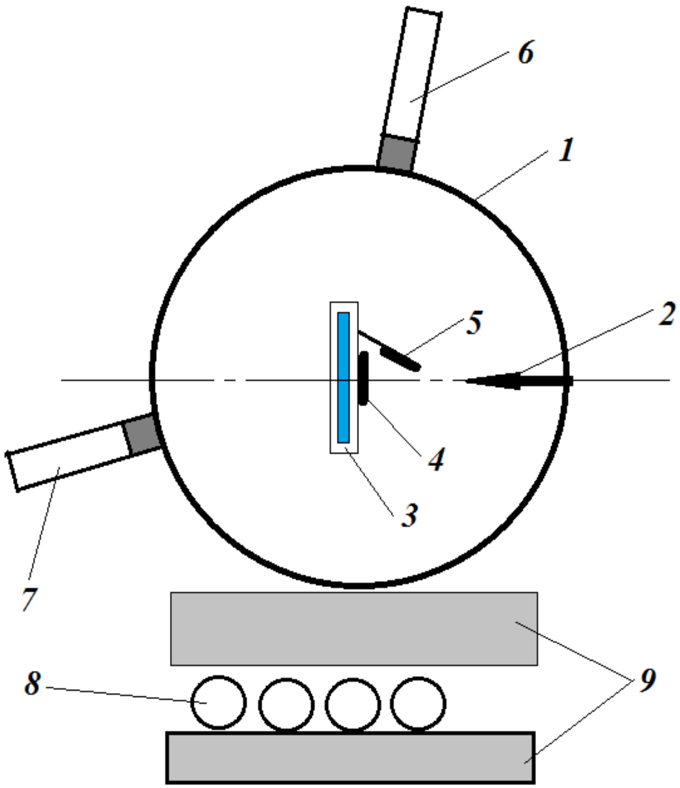
# Introduction

Previous works reported on the possibility of initiating nuclear fusion reactions in solid-state deuterated materials by various external radiation (X-rays, ion and electron beams). So earlier we observed the products of nuclear DD-fusion (protons and neutrons under the action of X-ray quanta with energies of 20-30 keV on deuterated crystal structures of palladium, titanium and CVD-diamond. In this work, we investigated the possibility of generating neutrons (products of nuclear DD fusion) in crystalline deuterated targets by an electron beam with an energy of 20–40 keV. This approach assumes the combined action of both electrons and bremsstrahlung X-ray quanta on the target. The DD fusion reactions were studied

$d + d \rightarrow n\ (2.45\ MeV) + {}^{3}He\ (0.8\ MeV)$ (1)

$d + d \rightarrow p\ (3\ MeV) + T\ (1\ MeV)$ (2)

# Experimental technique




Layout of the target and detectors.

1 - wall of the vacuum chamber, 2 - electron beam, 3 - target holder, 4 - target, 5 - CR-39 track detector, 6 and 7 - scintillation detectors with PMT, 8 - He-3 counters, 9 - polyethylene neutron moderators

# The research was carried out on the basis of an electron gun of the NRU "BelSU" with the following parameters:

1. accelerating voltage - 10–100 kV;
2. beam current - 1–500 μA;
3. emission current - up to 0.8 mA;
4. beam divergence on the target – 0.5°;
5. beam current stability - no worse than 1%;
6. the spread in the electron beam energy is no more than 0.1%.

In our work, we had the following irradiation regimes. Beam energy - 20-40 keV, current - 100-170 μA. The beam diameter on the target was 3 or 6 mm. The target was moved across the beam to reduce the radiation load on the surface.

# Neutron detection methods

1. The CR-39 track detector made it possible to detect both charged particles emitted from the target and neutrons (through recoil protons and decay reactions). The coating of the detectors (44 μm Al) made it possible to avoid irradiation of the detector by scattered electrons. The detection efficiency of fast neutrons by recoil protons with a Cf-252 source was measured as $\eta_{n1} \sim 6\ 10^{-5}$.
2. A neutron detector based on four SNM-18 counters filled with He-3 gas and equipped with a polyethylene moderator was designed to register thermal neutrons. The detection efficiency – $\eta_{n2} \sim 5\ 10^{-3}$
3. Scintillation detectors based on a p-terphenyl crystal (diameter - 2.5 cm, height - 2.5 cm) with a photomultiplier were intended for registration of fast neutrons. Digital analysis of scintillation detector pulses separates signals from neutrons and gamma quanta. The detection efficiency of fast neutrons with an energy of 2.5 MeV with a scintillation detector was measured with an ING-07D generator. Taking into account the geometric factor, the efficiency to DD-neutron was $\eta_{n3} \sim 2\ 10^{-4}$

# Targets for irradiation

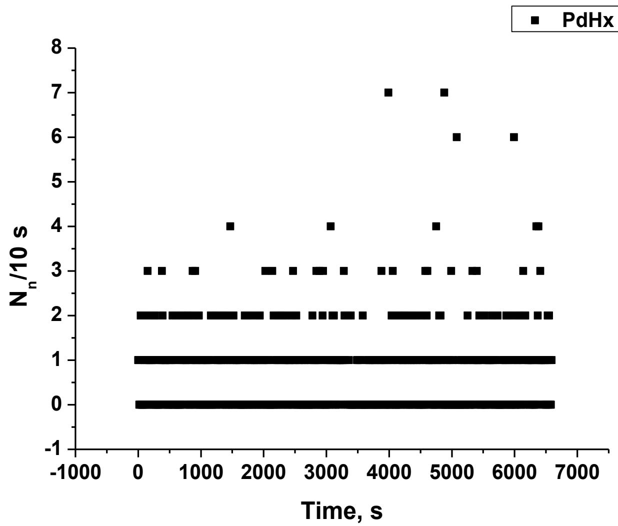
Deuterated targets made of palladium and textured CVD diamond were used in the experiment. Targets made of copper, aluminum (target holder substrate) or those saturated with hydrogen under similar conditions were used as background.

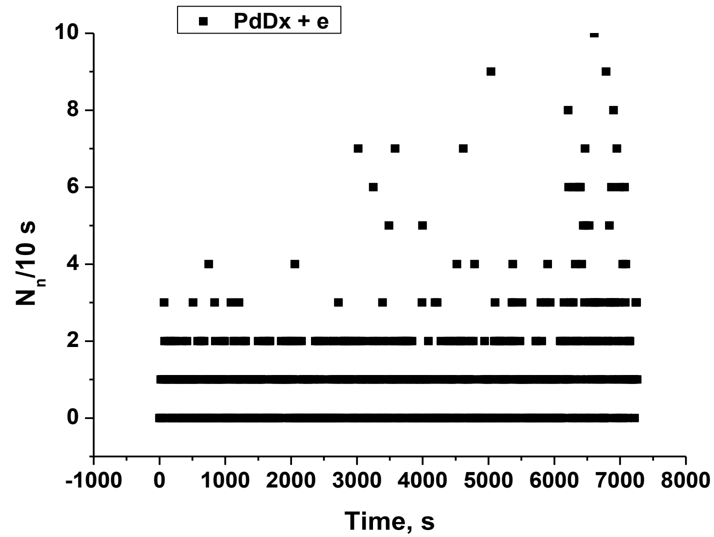
Samples of Pd / PdO: $D_x$ 2.5 - 1 $cm^2$ and 2 - 4 $cm^2$ were prepared by thermal oxidation of Pd foil (99.95% purity, 50 and 40 µm thick). As a result, a PdO oxide film ~ 50 nm thick is formed on the foil surface. We also used palladium samples without oxide film 2.5 - 1 $cm^2$ in size and 500 µm thick. Then the samples were saturated with deuterium by electrolysis in a 0.3M solution of LiOD in $D_2O$ with a Pt anode at a current density $j = 20$ mA / $cm^2$. After saturation with deuterium to the degree $x = D / Pd \sim 0.4$-$0.6$, the samples were washed in heavy water and cooled with liquid nitrogen to a temperature of $T = 77$ K (cooling the sample to the temperature of liquid nitrogen is necessary to slow down the release of deuterium in order to study the effect of ionizing radiation on the desorption process ).

The deuterated structure of textured CVD diamond was saturated by electrolysis in a 0.3 M LiOD solution in $D_2O$ with a Pt anode. The samples were used as a cathode. Then the samples were washed in heavy water and cooled with liquid nitrogen to a temperature of $T = 77$ K.

The control of the amount of deuterium released from the samples after irradiation was carried out by weighing them. The maximum amount of deuterium in the sample can be estimated as $4.3\ 10^{21}$, and the amount of deuterium released after irradiation (mobile deuterium involved in the process) as $\sim 10^{21}$.

# Experimental results and their discussion




Counting a neutron detector based on four He-3 counters for 10 s. Targets - Pd / PdO: Hx (left), Pd / PdO: Dx (right). Energy 20-40 keV, current 100-170 μA

| Sample | Average count of He-3 detector, $s^{-1}$ | Average neutron flux for the He-3 detector, $s^{-1}$ to 4π sr | Percentage of exceeding the average background level <n> + 3σ % |
|---|---|---|---|
| Pd/PdO:$D_x$ | 0.10 ±0.004 | (3.8±0.15) | 4.3 |
| Pd/PdO:$H_x$ | 0.081 ± 0.003 | - | 1.2 |
| Background without beam | 0.069 ±0.003 | - | 0.4 |

# Summarized results of two scintillation detectors for similar measurement sessions

| **Target (thickness μm)** | **Beam. Energy (keV) / current (μA)** | **Sum measurement time, s** | **Number neutrons sum of readings of two detectors** | | **Average neutron count by two detectors n, $s^{-1}$ $10^{-3}$** | | **$n_n$(0.6-2.8MeV) Bg - Day background without beam $s^{-1}$ in 4π sr** |
|---|---|---|---|---|---|---|---|
| | | | 100-750 keVee | 750-1500 keVee | 100-750 keVee | 750-1500 keVee | |
| Day background without beam | - | 112560 | 199 | 19 | 1,77 ± 0,13 | 0,17 ± 0,04 | - |
| Cu(100) | 30/150* | 9600 | 15 | 0 | 1,56 ± 0,40 | 0 | 0 |
| Cu(100) | 40/100* | 10800 | 19 | 0 | 1,76 ± 0,40 | 0 | 0 |
| CVD+D (400) + converter Ti(55) | 30/150* | 13200 | 20 | 0 | 1,52 ± 0,34 | 0 | 0 |
| CVD+D (400) | 30/150* | 6000 | 10 | 0 | 1,67 ± 0,53 | 0 | 0 |
| $PdD_x$(500) | 30/150* | 35040 | 76 | 7 | 1,67 ± 0,53 | 0,20 ± 0,08 | 0,96 ± 0,52 |
| $PdD_x$(500) | 40/100* | 37200 | 83 | 8 | 1,67 ± 0,53 | 0,22 ± 0,08 | 1,12 ± 0,50 |
| $PdD_x$ (40+50) | 30/150* | 18000 | 34 | 3 | 1,89 ± 0,32 | 0,17 ± 0,10 | 0,29 ± 0,64 |
| $PdD_x$ (40+50) | 40/100* | 24000 | 55 | 4 | 2,29 ± 0,31 | 0,17 ± 0,08 | 1,26 ± 0,62 |

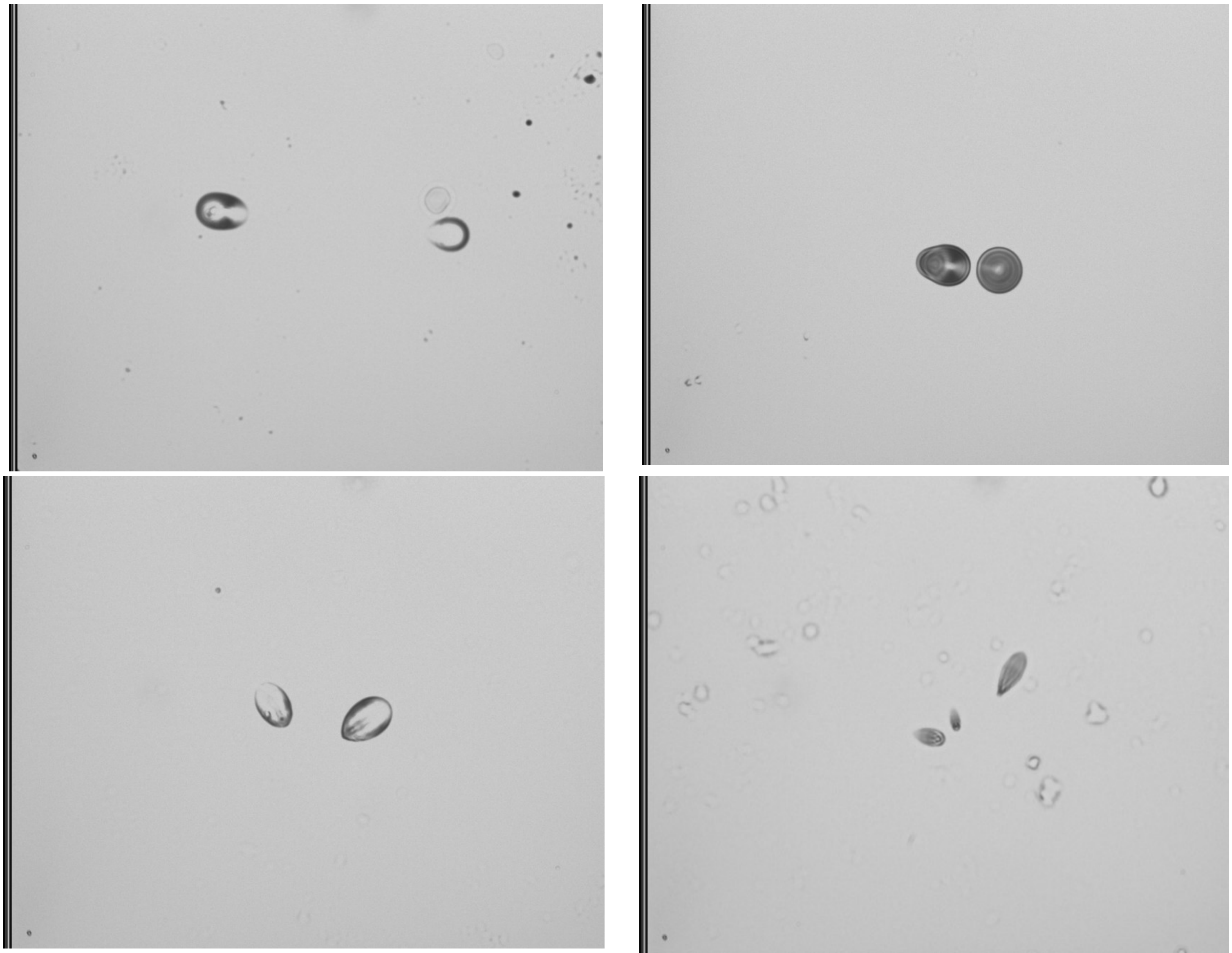
* - beam diameter - 6 mm

# Estimates of neutron fluxes using the CR-39 detector

| Detector index | Target, thickness (μm) | Number of deuterium atoms before irradiation (out of sample) | Irradiation time, s | Irradiation conditions Energy (keV) / current (μA) | Number of proton tracks on the back of the detector, $cm^{-2}$ | The number of decays of nuclei into 2 particles, $cm^{-2}$ | The number of decays of nuclei into 3 particles, $cm^{-2}$ | Neutron flux $n_n$(>0.4 MeV) $s^{-1}$ in 4π sr |
|---|---|---|---|---|---|---|---|---|
| B4-1 | $PdD_x$(500) | $4.1\ 10^{21}$ ($8\ 10^{20}$) | 26400 | 30/150* | 42 | 7 | 2 | 13±4 |
| B4-2 | CVD+D (400)+Ti (55) | $7.5\ 10^{20}$ ($7.5\ 10^{20}$) | 13200 | 30/150* | 26 | 2 | 0 | on the background level |
| B4-3 | CVD+D (400) | $7.5\ 10^{20}$ ($7.5\ 10^{20}$) | 6000 | 30/150* | 18 | 3 | 0 | on the background level |
| B4-4 | $PdD_x$(500) | $4.3\ 10^{21}$ ($9.4\ 10^{20}$) | 37200 | 40/100* | 66 | 11 | 1 | 18±5.5 |
| B4-5 | $PdD_x$(40+50) | $1.8\ 10^{21}$ ($1.2\ 10^{21}$) | 27600 | 40/100* | 56 | 11 | 1 | 20±5 |
| B4-6 | $PdD_x$ (40+50) | $1.7\ 10^{21}$ ($1.6\ 10^{21}$) | 24000 | 30/150* | 40 | 12 | 1 | 13±4 |
| B3-1 | $PdD_x$ (40) | $1.1\ 10^{21}$ ($1.1\ 10^{21}$) | 48000 | 30/150** | 60 | 10 | 2 | 9.4±3.6 |
| B3-2 | CVD+D (400) | $7.5\ 10^{20}$ ($7.5\ 10^{20}$) | 52000 | 30/150** | 32 | 10 | 1 | on the background level |
| B3-Bg1 | Cu(100), Al | - | 18600 | 30/150** | 22 | 1 | 0 | 0 |
| B4-Bg2 | Cu(100) | - | 10800 | 30/150* | 18 | 3 | 0 | 0 |
| Bg0 | Detector without irradiation | - | - | - | 15 | 1 | 0 | 0 |

* - beam diameter - 6 mm, ** - beam diameter - 3 mm

On track detectors, nuclear decays into two and three particles were found, which indicate the presence of neutrons with energies greater than 3 and 10 MeV



# Conclusions

1. Three independent methods have shown that the impact of an electron beam in the energy range of 20-40 keV initiates DD-fusion reactions in deuterated crystal structures with a neutron yield.
2. In addition to neutrons with an energy of 2.5 MeV, there are indications of the emission of neutrons with an energy of more than 3 MeV
3. Accurate quantitative estimation of neutron fluxes requires an additional joint calibration of all detectors using a DD generator.