ISSN 1063-7761, Journal of Experimental and Theoretical Physics, 2011, Vol. 112, No. 6, pp. 952–960. © Pleiades Publishing, Inc., 2011.
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NUCLEI, PARTICLES, FIELDS, GRAVITATION, AND ASTROPHYSICS

Nuclear Reactions in the $Pd/PdO:D_x$ and $Ti/TiO_2:D_x$ Systems Excited by Ionizing Radiation

I. P. Chernov[a], A. S. Rusetskii[b], D. N. Krasnov[a], V. V. Larionov[a], B. F. Lyakhov[c], E. I. Saunin[c], Yu. I. Tyurin[a], and Yu. P. Cherdantsev[a]

[a] *National Research Tomsk Polytechnic University, Tomsk, 634050 Russia*

[b] *Lebedev Physical Institute, Russian Academy of Sciences, Leninskii pr. 53, Moscow, 119991 Russia*
e-mail: rusets@lebedev.ru

[c] *Frumkin Institute of Physical Chemistry and Electrochemistry, Russian Academy of Sciences, Leninskii pr. 31, Moscow, 119991 Russia*

Received October 18, 2010

Abstract—The yield of the products of nuclear reactions from deuterated palladium and titanium irradiated by an electron beam and X rays has been studied. Charged particles have been detected by CR-39 track detectors, which are not sensitive to electronic noise, electrons, and X-ray photons. To identify the type of particles and to estimate their energy, three detectors covered by aluminum and copper foils of various thicknesses have been used. It has been established with reliable statistics that 30-keV electrons and X rays initiate the synthesis of deuterons in the $Pd/PdO:D_x$ and $Ti/TiO_2:D_x$ systems with the yield of 3-MeV protons.

DOI: 10.1134/S1063776111050104

1. INTRODUCTION

It was shown in [1–3] that deuterium D (hydrogen H) atoms in metals can accumulate the energy of ionizing radiation (accelerated electrons and X rays); as a result, a deuterium (hydrogen) subsystem is transferred to an excited state and the energy of deuterium (hydrogen) atoms in it becomes an order of magnitude higher than the energy of matrix atoms. This is confirmed by the following experimental facts:

intense migration and yield of hydrogen isotopes from metals irradiated at room temperature and lower,

yield of hydrogen (deuterium) atoms from the entire sample irradiated by a focused electron beam (the diameter of the beam is much smaller than the size of the target),

yield of hydrogen (deuterium) atoms from the entire surface of the sample even when only a small part of the sample is irradiated; this fact indicates that irradiated atoms acquire energy enough to overcome the barrier on the surface of metals (higher than 1 eV).

It is known that accelerated electrons and X rays lose energy in a solid due primarily to the excitation of its electronic subsystem. The lifetime of these excitations in metals is very short, about 10^{-15} s. How does the electronic subsystem in PdD_x transfer the absorbed energy to hydrogen (deuterium) atoms throughout the crystal? This question was answered when studying the evolution of the electronic structure and the excitation spectrum of metals saturated with hydrogen to various extents.

Ab initio investigation of the electronic structure and spectrum of collective electronic excitations in Pd and PdH_x was performed in [4, 5], where it was found that bonding and antibonding states of PdH_x are local, indicating that oscillations of the electron density, which correspond to the dominant plasma oscillations, are localized near hydrogen atoms. Furthermore, hydrogen appeared to significantly reduce the frequency of plasma oscillations of the valence charge density of the metal. For this reason, the main part of the energy of ionizing radiation penetrating into the crystal is absorbed due to the excitation of plasmons, which ensure an efficient mechanism of energy transmission throughout the sample; the energy is predominantly localized near hydrogen atoms.

The energy that can be acquired by irradiated deuterium atoms was not determined; in particular, it was unclear whether it is enough to initiate nuclear reactions. The possibility of the initiation of nuclear reactions in a $Pd/PdO:D_x$ target irradiated by 30-keV electrons with a current of 300 nA was studied in [5], where it was revealed that irradiation initiates the yield of 3-MeV protons. In this work, we confirm the previous experimental results, investigate the yield of the products of nuclear reactions from $Pd/PdO:D_x$ as a function of the electron current density, and study nuclear processes in the $Ti/TiO_2:D_x$ system that are stimulated by an electron beam and X rays.

2. EXPERIMENTAL PROCEDURE

Charged particles were detected by CR-39 track detectors (RadTrak), which were manufactured by the

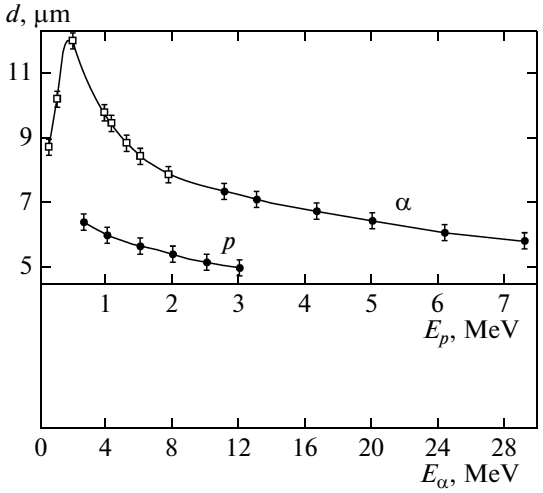

Fig. 1. Diameters of the tracks of (*p*) protons and (α) α particles versus their energies in the CR-39 detector after 7-h etching in a 6*M* NaOH solution at a temperature of 70°C.

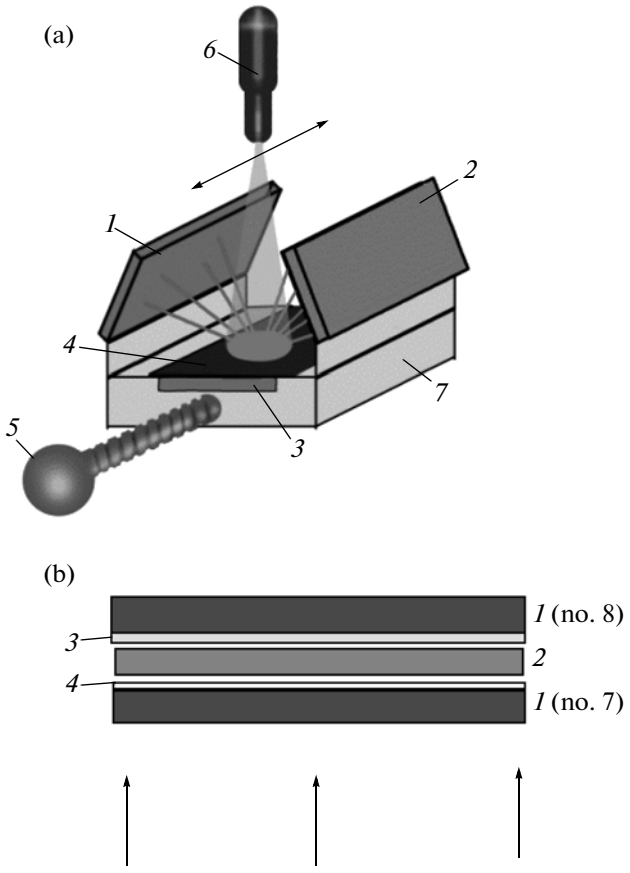

Fig. 2. Layout of the experiment with (a) electrons (*1–3* are the CR-39 detectors, *4* is the sample, *5* is the manipulator, *6* is the electron gun, and *7* is the substrate) and (b) X rays (*1* are the CR-39 detectors, *2* is the sample, *3* is the 25-μm copper layer, *4* is the 11-μm aluminum layer, and the arrows show the direction of the X-ray beam).

Landauer/Fukuvi Company (United States). To identify the type of particles and to estimate their energy, two or three detectors covered by aluminum and copper foils of various thicknesses were used. The track detectors were preliminarily calibrated using a Van der Graaf accelerator (proton energy 0.65–3.0 MeV), a cyclotron (alpha-particle energy 10–30 MeV), and standard alpha sources. Figure 1 shows the calibration curves and the energy dependence of the proton and alpha-particle track diameters *d* determined after the etching of the track detector in a 6*M* NaOH solution at a temperature of 70°C. The track diameters 5.0–6.6 μm correspond to protons with energies $E_p = 1$–3 MeV. Proton tracks can be separated from the tracks of alpha particles with energies $E_\alpha < 20$ MeV, whose diameters are 7.0–12 μm. Measuring the sizes of the tracks in the detectors and using tabular data, it is possible to certainly determine the type of particles and their energy at the time of the emission from the sample.

By the thermal oxidation of a Pd foil (a purity of 99.95% and a thickness of 50 μm), 2.5 × 1-cm Pd/PdO:D_x samples were prepared. As a result, a 20-nm PdO oxide film is formed on the foil surface [6]. Then, the samples were deuterated by means of electrolyze in a 0.3 *M* LiOD solution in D_2O with a Pt anode at the current density $j = 10$ mA/cm^2 and a temperature of about 279 K in a cell with separated cathode and anode spaces. The samples deuterated to a degree of $x = D/Pd \approx 0.73$ were washed in heavy water, cooled by liquid nitrogen to a temperature of $T = 77$ K, and were mounted during 1 min in a holder opposite to the fixed CR-39 detectors (see Fig. 2a).

By means of electrolytic deuteration from a 1*M* D_2SO_4 solution in D_2O at a current density of 30 mA/cm^2, 3 × 1-cm Ti/TiO_2:D_x samples were prepared from a 300-μm titanium foil with a 100-nm TiO_2 oxide layer. Subsequent weighting showed that the weight of deuterium introduced in each sample during 24-h electrolyze was 0.25 mg, which ensured the average deuteration degree $x = D/Ti = 0.1$ to a depth of 3 μm.

To study the action of electrons on the yield of the products of the DD synthesis, the samples and detectors were placed to a vacuum chamber ($P = 10^{-6}$ mm Hg) of a scanning electron microscope, the energy of electrons was 30 keV, the current density was 0.53 and 2.1 μA/cm^2, and the diameter of the spot was 6 mm (see Fig. 2a). Two detectors were mounted above the open surface of the sample (at an angle of 60°), and detectors *1* (*4*) and *2* (*5*) were covered by the 11-μm Al and 25-μm Cu foils, respectively. The distance between the center of the electron spot on the sample and the detectors was 12 mm. Detector *3* (*6*) covered by a 33-μm Al foil was in contact with the opposite side of a Pd/PdO:D_x or Ti/TiO_2:D_x sample; this side of the sample was not irradiated by the electron beam (the ordinary numbers of the detectors for the Ti/TiO_2:D_x samples are given in the parentheses).

Proton fluxes from the Pd/PdO:D_x and Ti/TiO_2:D_x samples irradiated by electrons and X rays

Detector no.	Sample	Irradiation type	Coating thickness, μm	Detection efficiency, %	N_p, $p/(s\ cm^2\ 4\pi\ sr)$
1	Pd/PdO:D_x	Electrons	11 (Al)	2.6	$(1.1 \pm 0.1) \times 10^{-3}$*
2	Pd/PdO:D_x	Electrons	25 (Cu)	2.6	$(1.1 \pm 0.1) \times 10^{-3}$*
3	Pd/PdO:D_x	Electrons	33 (Al)	13	$(7.2 \pm 1.6) \times 10^{-4}$
4	Ti/TiO_2:D_x	Electrons	11 (Al)	2.6	$(8.4 \pm 1.5) \times 10^{-4}$*
5	Ti/TiO_2:D_x	Electrons	25 (Cu)	2.6	$(8.4 \pm 1.5) \times 10^{-4}$*
6	Ti/TiO_2:D_x	Electrons	33 (Al)	13	0
7	Ti/TiO_2:D_x	X rays	11 (Al)	13	$(1.5 \pm 0.3) \times 10^{-2}$
8	Ti/TiO_2:D_x	X rays	25 (Cu)	13	$(3.8 \pm 0.4) \times 10^{-2}$

* The flux averaged over the data from two detectors.

When studying the action of X rays, the Ti/TiO_2:D_x samples were irradiated on an X-ray unit with a tungsten cathode (voltage $U = 120$ kV and current $I = 5$ mA) in air and were placed between two detectors *7* and *8* covered by the 11-μm Al and 25-μm Cu foils, respectively (see Fig. 2b). After exposure, the samples were etched for 7 h in the 6*M* NaOH solution at a temperature of 70°C.

The distributions of the tracks in the detectors were analyzed at the Lebedev Physical Institute, Russian Academy of Sciences on the automated measurement facility PAVICOM [7]. Only "circular" tracks (normal incidence or with the deviation from the normal incidence less than 10°) were taken into account in the distributions. Under these conditions, the total efficiency was $\varepsilon = 2.6\%$ for detectors *1*, *2*, *4*, and *5* and $\varepsilon \approx 13\%$ for detectors *3* and *6*–*8*.

3. EXPERIMENTAL RESULTS AND THEIR DISCUSSION

Analysis of the tacks in a background detector, which was located in the vacuum chamber of the microscope far from the samples, shows that the spectrum has no statistically significant maxima in the track diameter range of 4–6 μm; the same result was obtained for the Pd/PdO:H_x and Ti/TiO_2:H_x samples irradiated by electrons for a long time.

In this work, we report the results obtained in five runs of the measurement of the yield of the products of the DD synthesis in the Pd/PdO:D_x samples irradiated by electrons; each run continued three months. In four runs, the average current density of the electron beam was about 0.53 μA/cm^2 and the exposure time was about 1100 min per run. The results were well repeatable and the total yields of protons in all runs coincide with each other with a high accuracy. Taking into account the efficiency of the detection, the yield rate of 3-MeV protons from the sample side irradiated by electrons averaged over the data of detectors *1* and *2* was $N_p = (1.1 \pm 0.1) \times 10^{-3}\ p/(s\ cm^2 \times 4\pi\ sr)$, whereas the yield rate from the opposite side of the sample was $N_p = (7.2 \pm 1.6) \times 10^{-4}\ p/(s\ cm^2 \times 4\pi\ sr)$, which is one and a half lower than that from the irradiated side (see table). The electron flux density in the fifth run was increased by a factor of 4 and was 2.1 μA/cm^2 and the yield rate of 3-MeV protons averaged over the data of detectors *1* and *2* was doubled.

The total distribution histograms of the charged particle tracks in detectors *1*–*3* under electron irradiation for the total exposure time (7020 min) are shown in Fig. 3. Statistically significant maxima are observed in detector *1* in the track diameter range of 5.2–5.4 μm and in detector *2* in the track diameter range of 5.8–6.4 μm (see Figs. 3a, 3b); according to calibration, they correspond to protons with the energies of 2.5–2.75 and 1.2–1.3 MeV, respectively. These energies are expected when 3-MeV protons pass through the 11-μm aluminum film in detector *1* and through the 25-μm copper film in detector *2* [8]. It is worth noting that 3-MeV protons are also emitted from the opposite side of the sample (detector *3*, Fig. 3c), i.e., from the side that is not subjected to the action of electrons (the mean free path of 30-keV electrons in Pd is several micrometers, whereas the thickness of the sample is 50 μm). The spectrum of the tracks in detector *3* has a maximum at a track diameter of 5.6 μm. This diameter corresponds to protons with an energy of $E_p \approx 2.0$ MeV, which appear when 3-MeV protons from the DD reaction pass through the 33-μm aluminum filter. The yield of 3-MeV protons from the opposite side of the sample indicates that deuterium atoms acquire energy not only in the region of the direct action of the beam incident on the sample, but also throughout the sample volume. This fact confirms the plasmon mechanism of the excitation of the deuterium subsystem in metals by ionizing radiation [3, 4].

Figure 4 shows the reconstructed integral energy spectrum of protons that were emitted from the Pd/PdO:D_x sample irradiated for 7020 min and were

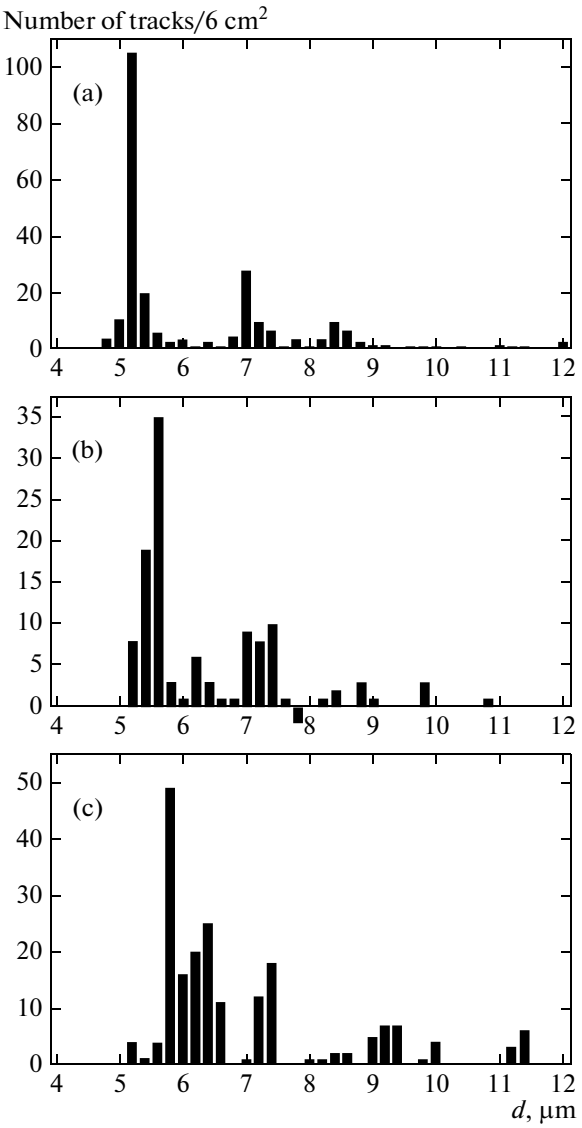

Fig. 3. Distributions of the diameters of the tracks of the charged particles that were emitted from the Pd/PdO:D_x sample irradiated by 30-keV electrons for 7020 min and were detected in detectors *1* covered by (a) 11-μm aluminum, (b) 25-μm copper, and (c) 33-μm aluminum foils. The difference between the front (directed toward the sample) and back (background) sides of the detector is shown.

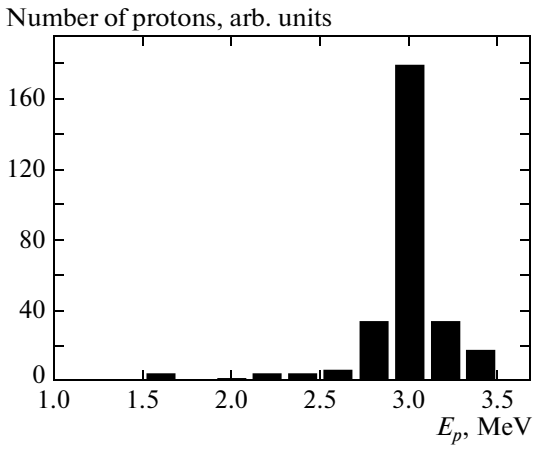

Fig. 4. Reconstructed energy spectrum of protons that were emitted from the Pd/PdO:D_x sample irradiated by 30 keV electrons for 7020 min and were detected by detectors *1–3*.

detected by detectors *1–3*. The yield of 3-MeV protons was observed with reliable statistics in three independent detectors, certainly indicating the DD synthesis in the Pd/PdO:D_x samples irradiated by the electron beam.

The results of the investigation of the action of accelerated electrons and X rays on the Ti/TiO_2:D_x sample are shown in Figs. 5–8. Figure 5 shows the distributions of the track diameters in detectors *4* and *5* after 2200-min irradiation by 30-keV electrons with a current density of 0.53 μA. The main peak in the distributions is observed in the range of 5.0–6.6 μm; it is shifted rightward with an increase in the covering thickness. According to calibration, this peak can be identified as a signal from 3-MeV protons. Detector *6* located on the nonirradiated side of the sample does not detect excess over background.

Figure 6 shows the distributions of the track diameters for detectors *7* and *8*, which were in contact with the Ti/TiO_2:D_x sample irradiated by X rays (I = 100 mA, U = 120 kV, and an irradiation time of 240 min). Background distributions from the back sides of the operating detectors are also shown for comparison. According to calibration, the leftmost peak in the distributions corresponds to protons with an initial energy of 3 MeV.

The reconstructed integral energy spectra of protons in these experiments with the electron and X-ray beams are shown in Figs. 7a and 7b, respectively. It is also noteworthy that the distributions shown in Figs. 5 and 6 contain not only proton peaks in the range of 5.0–6.6 μm, but also peaks corresponding to diameters larger than 7.0 μm, i.e., to α particles of various energies according to calibration. It is seen in Fig. 7, accelerated electrons and X rays on the Ti/TiO_2:D_x sample stimulate the yield of 3-MeV protons, similar to electron irradiation of the Pd/PdO:D_x samples.

It is worth noting that the yield of protons predominantly with an energy of 3 MeV from both the irradiated and nonirradiated sides of the sample. The emission of protons from the opposite side of the Ti/TiO_2:D_x sample was not observed, likely because plasmons cannot reach this side in view of the large thickness (300 μm) of this sample. Therefore, nuclear processes occur predominantly in the surface region of the sample apparently at the Pd–PdO and Ti–TiO_2 interfaces. One of the causes of this property is an increased concentration of deuterium at the metal–insulator interface, because radiation-induced diffusion of deuterium in metals is much faster than that in

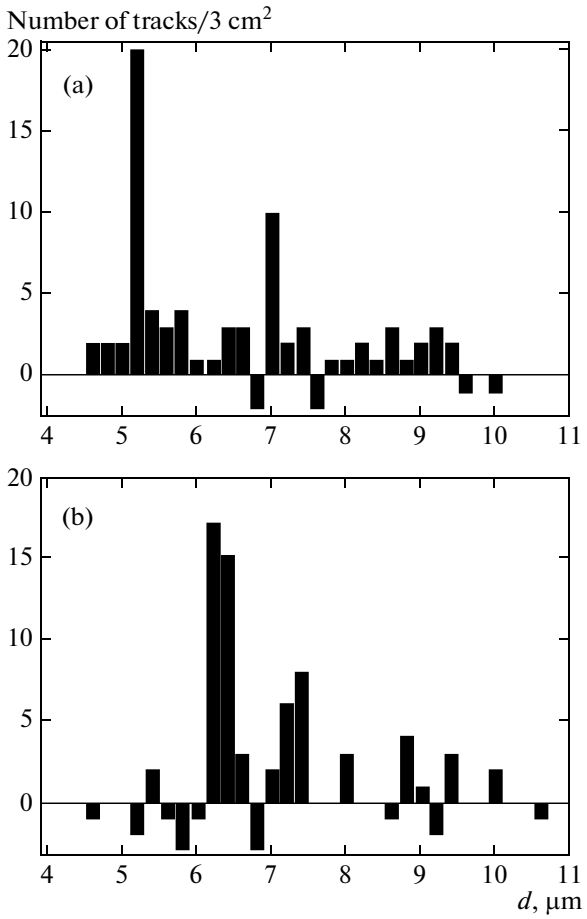

Fig. 5. Distributions of the diameters of the tracks of the charged particles that were emitted from the Ti/TiO_2:D_x sample irradiated by 30-keV electrons for 2200 min and were detected in detectors *4* covered by (a) 11-μm aluminum and (b) 25-μm copper foils. The difference between the front (directed toward the sample) and back (background) sides of the detector is shown.

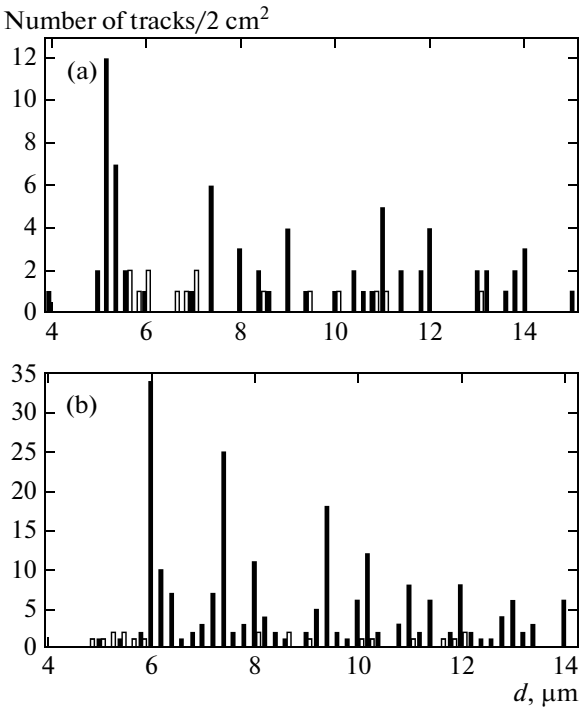

Fig. 6. Distributions of the diameters of the tracks of the charged particles that were emitted from the Ti/TiO_2:D_x sample irradiated by X rays for 240 min and were detected in detectors *7* and *8* covered by (a) 11-μm aluminum and (b) 25-μm copper foils, respectively. The distributions from the back (background) sides of the detectors are shown by the open columns for comparison.

metal oxide. Another possible cause is that the energy of deuterium atoms at the interface is higher than that in the bulk in view of the features of the plasmon mechanism of the acceleration of atoms. The interference of plasmons appearing in the bulk and on the surface of the sample can lead to an increase in the amplitude of oscillations of the electron density and thereby to the appearance of an electric field, where deuterium atoms can acquire energy enough for their fusion.

The table presents the proton fluxes from the Pd/PdO:D_x and Ti/TiO_2:D_x samples irradiated by the electron beam and X rays. It is seen in the table that the fluxes of 3-MeV protons from the Pd/PdO:D_x and Ti/TiO_2:D_x samples irradiated by 30-keV electrons are approximately identical. The yield of protons from the Ti/TiO_2:D_x sample irradiated by X rays is an order of magnitude higher than that from the same sample irradiated by electrons. This is primarily due to the fact that the power of X rays is much higher than the power of the electron beam and also due likely to the fact that X rays act on the entire sample, whereas electrons act only on its thin surface layer. It is also seen that the flux of 3-MeV protons detected by detector *8*, whose front side is directed against the beam, is larger than that detected by detector *7*, whose front side is directed along the beam, by a factor of 2.5. Thus, there is strong anisotropy in the fluxes of particles emitted from the sample along and against the X-ray beam (particle flux along the beam is larger).

The yield of the products of the DD reactions from the Pd/PdO:D_x and Ti/TiO_2:D_x was estimated by the following formula using the method described in detail in [9]:

$$Y_{DD} = J_D N_{eff}(T) \int_0^{E_d} dE f(E) \sigma_{DD}(E) \frac{dx}{dE}. \quad (1)$$

Here, J_D is the current density of deuterium ions; the effective concentration of deuterium on the surface at the temperature T is given by the expression

$$N_{eff}(T) = N_0 \exp(-\varepsilon_D \Delta T / k_B T T_0),$$

where N_0 is the concentration of deuterium at $T_0 =$ 290 K and ε_D is the energy of the activation of the emission of a deuterium atom from the surface; k_B is the Boltzmann constant; $f(E)$ is the gain factor; σ_{DD} is

the cross section for the DD reaction without amplification; and dE/dx is the stopping power of deuterium ions in the target [10].

The gain factor is determined as

$$f(E) = \frac{Y_{\exp}(E)}{T_{\mathrm{BH}}(E)} = \exp\left[\pi\eta(E)\frac{U_e}{E}\right], \qquad (2)$$

where $Y_{\exp}(E)$ is the experimental yield of the protons from the DD reaction, $Y_{\mathrm{BH}}(E)$ is the yield at the same energy determined according to the Bosch–Halle extrapolation [11], $2\pi\eta = 31.29Z^2\sqrt{\mu/E}$ is the Sommerfeld parameter, and Z, μ, and E are the charge number, reduced mass, and energy of the deuterium ion.

The screening potential U_e was estimated by the semiempirical formula [12]

$$U_e = (T/T_0)^{-1/2}(a\ln y + b), \qquad (3)$$

where $a = 145.3$ and $b = 71.2$ are the numerical constants, $y = ky_0(J_D/J_0)$, $y_0 =$ Pd/D at $T_0 = 290$ K, and $J_0 = 0.03$ mA/cm^2.

In order to estimate the yields of the products of the DD reaction from the Pd/PdO:D_x and Ti/TiO_2:D_x targets irradiated by electrons, we used a simplified model of the process taking into account that the desorption of deuterium stimulated by the electron beam leads to the flux of deuterium ions moving to the surface of the sample. Such a flux can be considered as a "beam" and the deuterated surface can be treated as a "target."

According to the measurements of the rate of deuterium desorption from the targets irradiated by electrons, the deuterium ion currents from the Pd/PdO:D_x and Ti/TiO_2:D_x samples were $J_{\mathrm{D}} = 0.5$ and 0.03 mA/cm^2, respectively. The concentrations of deuterium in the Pd/PdO:D_x and Ti/TiO_2:D_x samples after electrolyze were $\langle \mathrm{D/Pd}\rangle = 0.15$ and $\langle \mathrm{D/Ti}\rangle = 0.3$. The substitution of these values into Eq. (3) yields $U_e = 730 \pm 50$ eV for Pd and $U_e = 130 \pm 30$ eV for Ti in good agreement with the data obtained in the acceleration experiments [13–15].

The observed rate of the DD reaction (about $10^{-3}\,p/(\mathrm{s\,cm^2} \times 4\pi\ \mathrm{sr})$) can be reached in the Pd/PdO:D_x sample (at the screening potential $U_e = 730$ eV) only under the assumption that the average energy of desorbed deuterium ions reaches $\langle E_{\mathrm{D}}\rangle \approx 3$–4 eV. The observed yield of protons from the Ti/TiO_2:D_x target at $U_e = 130$ eV can be reached only at $\langle E_{\mathrm{D}}\rangle \approx 500$ eV.

These results can be explained by the mechanism of the acceleration of deuterium ions in the targets irradiated by electrons according to which high interatomic fields (10^7–10^8 V/cm) appear and accelerate deuterium ions to the surface, where the deuterium concentration is maximal. In combination with a possible strong electron screening, most pronounced with metals with the large mobility of deuterium, this can lead to a significant increase in the yield of the products of the DD reaction in metal deuterides even at low energy of their excitation.

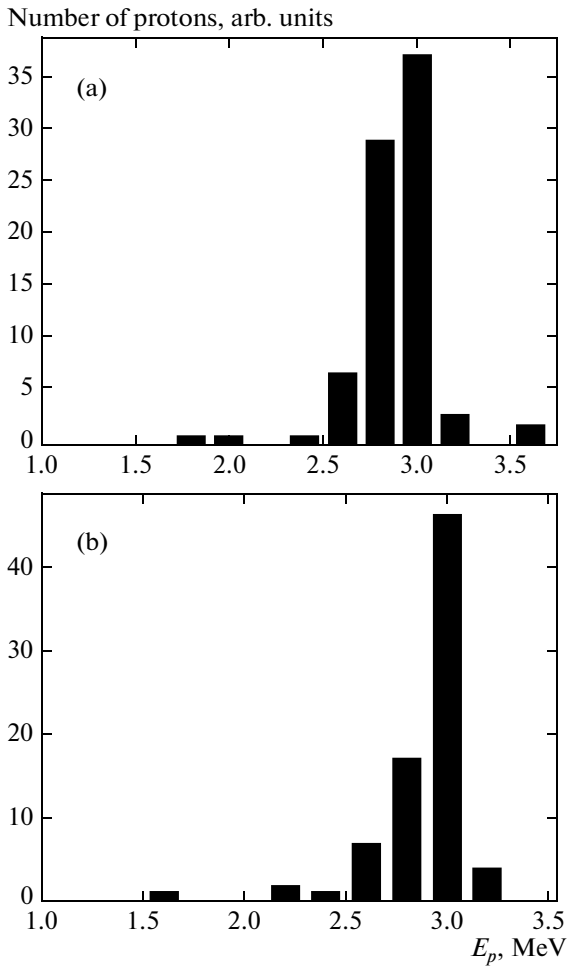

Fig. 7. Reconstructed energy spectra of protons that were emitted from the Ti/TiO_2:D_x sample irradiated by 30 keV electrons for (a) 2200 and (b) 240 min and were detected by detectors *4*, *5* and *7*, *8*, respectively.

To confirm the proposed mechanism, we analyzed changes in the structure of the surface of the samples after electron irradiation. To analyze the surface, we used the method of the Rutherford backscattering of α particles from the target nuclei and electron microscopy.

The profiles of the surfaces of the Pd/PdO:D_x and Ti/TiO_2:D_x samples obtained by the backscattering method before and after electron irradiation are shown in Figs. 8 and 9, respectively. It is seen in Fig. 8b that the thicknesses of PdO and C layers decrease strongly (from 40 to 25 nm) during 50 min after irradiation of the Pd/PdO:D_x sample. A carbon layer appears due to the annealing of palladium in the flame of an oxygen torch and stabilizes the PdO oxide layer. Remaining deuterium is localized near the PdO surface. The average rate of deuterium desorption after irradia-

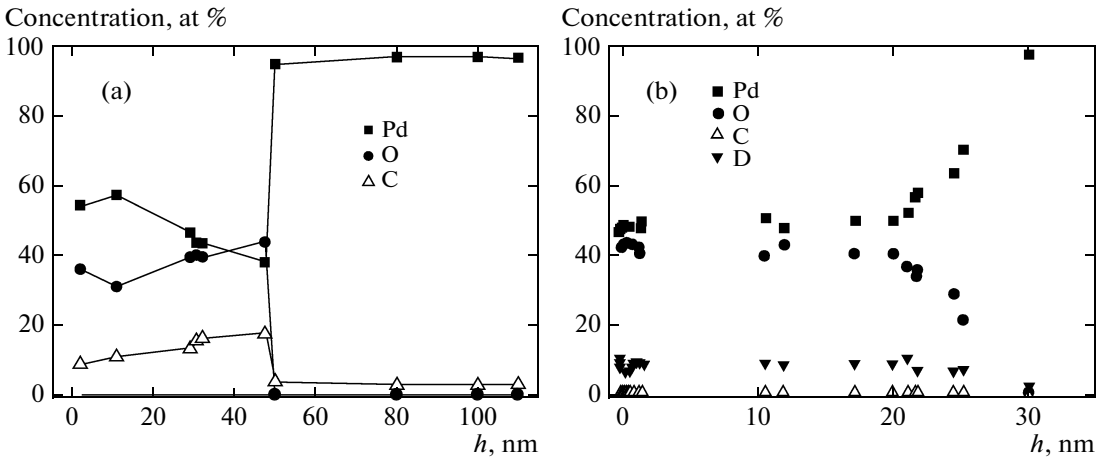

Fig. 8. Profiles of the surfaces of the Pd/PdO samples obtained by the backscattering method (a) before and (b) after deuteration and electron irradiation versus the depth h.

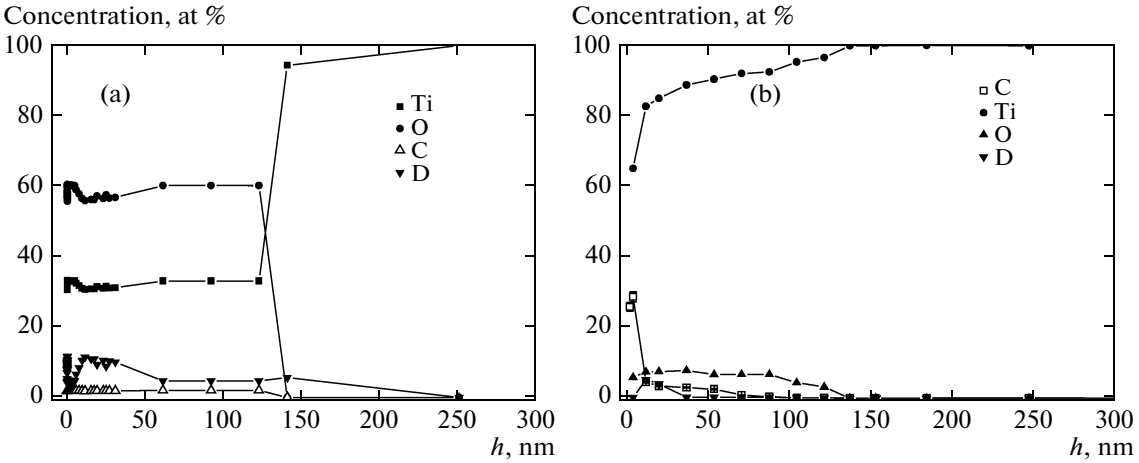

Fig. 9. Profiles of the surfaces of the $Ti/TiO_2:D_x$ samples obtained by the backscattering method (a) before and (b) after electron irradiation versus the depth h.

tion in vacuum is comparable to the desorption rate in atmosphere without irradiation, which is $(2–3) \times 10^{15}$ particles/(s cm^2). The TiO_2 oxide layer in the $Ti/TiO_2:D_x$ target before irradiation is observed at a depth up to 150 nm (see Fig. 9a). The content of oxygen in the oxide decreases after irradiation ($TiO_{0.1}$, see Fig. 9b). In this case, the depth of the oxide layer remains unchanged. Note that irradiation by X rays leads to a similar decrease in the content of oxygen on the surface. Using the backscattering data before and after irradiation of the $Ti/TiO_2:D_x$ target, we conclude that the deuterium desorption rate is about 1.5×10^4 particles/(s cm^2), which is about one twentieth of the value for the $Pd/PdO:D_x$ sample.

Figures 10 and 11 show the electron microscopy images of the $Pd/PdO:D_x$ and $Ti/TiO_2:D_x$ samples, respectively. It is seen that numerous pores with diameters 100–2000 nm appear on the Pd/PdO surface after deuteration and electron irradiation (see Fig. 10a). "Craters" with diameters 10–12 μm are also observed on the surface (see Fig. 10b). Traces of the $TiO_2 + TiC_x$ coating are seen on the surface of the $Ti/TiO_2:D_x$ sample (see Fig. 11a). Pores do not appear after electron irradiation, but the formation of craters with diameters 10–12 μm is observed (see Fig. 11b).

The reported data make it possible to arrive at the following conclusions. The presence of a thin oxide layer on the surface of the Pd foil prevents a high acceleration of deuterium ions. Indeed, since PdO is a semimetal with a significant conductivity (resistivity $\rho \approx 0.1\ \Omega$ cm), the polarization of the surface is absent. In view of the presence of numerous pores (with a length of about 50 nm), the energy of deuterium ions can be increased due to channeling. The high kinetic energy of deuterium ions in the case of the Ti/TiO_2 surface with a thick oxide layer (about 150 nm) can be

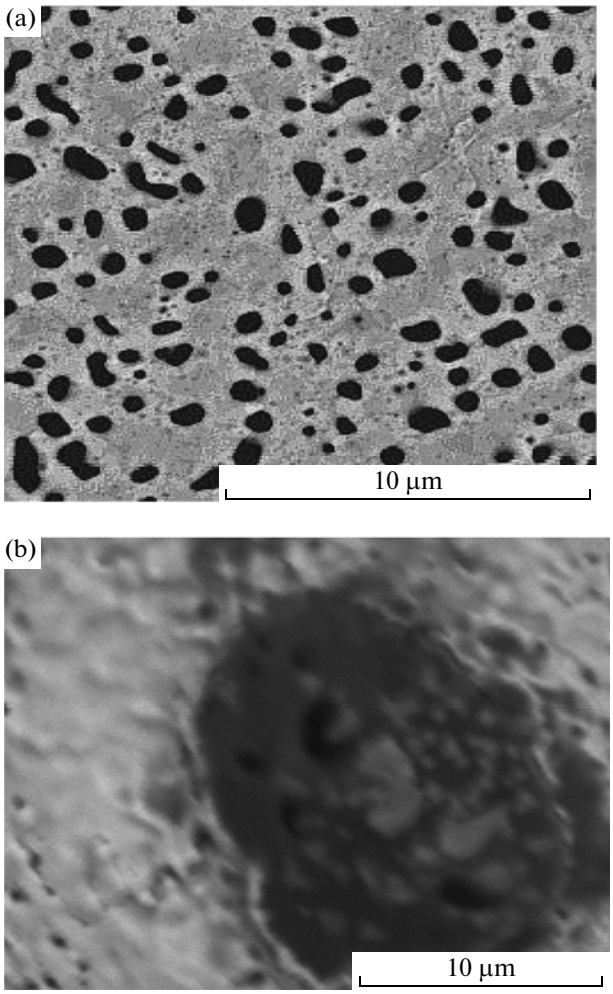

Fig. 10. Electron microscopy images of the Pd/PdO:D_x sample: (a) the Pd/PdO surface after electron irradiation and (b) a crater on the Pd/PdO surface.

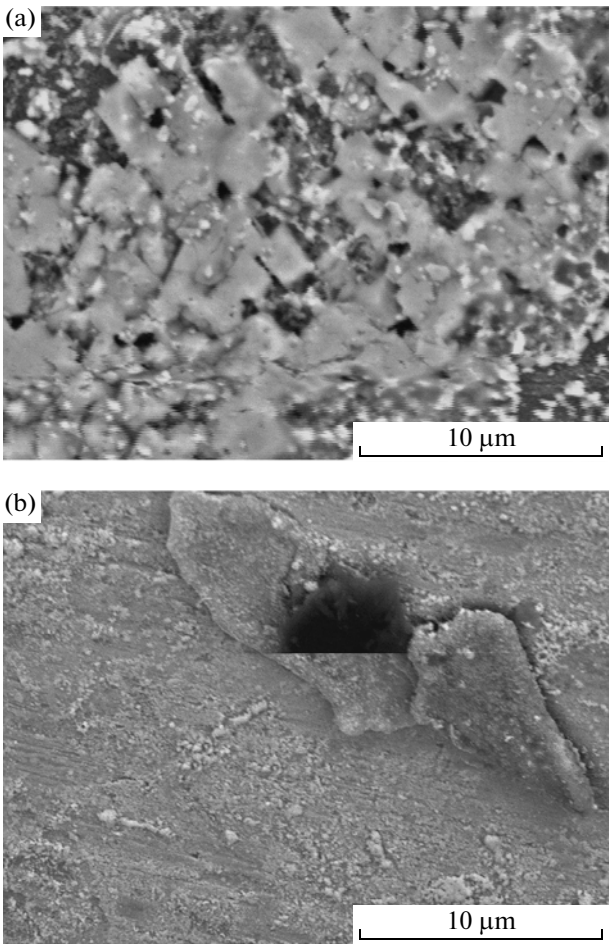

Fig. 11. Electron microscopy images of the Ti/TiO_2:D_x sample: (a) the Ti/TiO_2 surface after electron irradiation and (b) a crater on the Ti/TiO_2 surface.

reached due to acceleration in a high electric field appearing under electron irradiation. The effective acceleration energy can be estimated by the formula

$$E_D^{\text{eff}} = \varepsilon_0 + eF(TiO_2)h(TiO_2), \quad (4)$$

where $\varepsilon_0 \approx 3$ eV is the primary kinetic energy of the D^+ ion in titanium owing to the generation of plasmons, $F(TiO_2) \approx 3.3 \times 10^7$ V/cm is the electron field strength in the TiO_2 layer, and $h(TiO_2) = 1.5 \times 10^{-5}$ cm is the depth of the TiO_2 layer. In this case, the maximum acceleration energy of deuterium ions is estimated as $E_D^{\max} \approx 500$ eV.

The formation of craters with diameters 10–12 μm on the surface of the samples indicates a high energy density in these regions. In our opinion, nuclear reactions in these regions ("hot zones") are most probable.

4. CONCLUSIONS

It has been established with reliable statistics that the irradiation by accelerated electrons and X rays initiate the nuclear synthesis of deuterium ions in the Pd/PdO:D_x and Ti/TiO_2:D_x samples with the yield of 3-MeV protons. Nuclear processes occur predominantly in the surface region of the sample, most probably at the Pd–PdO and Ti–TiO_2 interfaces, where an increased concentration of deuterium atoms and a high energy of these atoms should be expected in view of the plasmon acceleration mechanism.

The complete theoretical explanation of the detected effects is still under discussion. Note that a low intensity of the observed products of the nuclear reactions prevents the direct use of the revealed effects to obtain excess energy. The effect of these synthesis processes occurring at the boundary of the first wall of an ITER-type thermonuclear reactor on the radiation resistance of these devices was analyzed in our previous work [12]. The prospect of the use of the detected effects in power engineering can be determined after

comprehensive analysis of the dependence of their intensity on the material of the target, as well as on the character and degree of its excitation.

ACKNOWLEDGMENTS

We are grateful to V.V. Sokhoreva and V.G. Mironchik (National Research Tomsk Polytechnic University) for assistance in the experiments and to O.D. Dal'karov, V.A. Ryabov, and N.G. Polukhina (Lebedev Physical Institute, Russian Academy of Sciences) for stimulating discussions.

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Translated by R. Tyapaev