strongly depends on the deuterium mobility in the target. In metals (Ti, Au) with low deuterium mobilities and high activation energies for deuteron diffusion, the screening potentials were low (U_e = 65 ± 15 and 70 ± 10 eV, respectively). These U_e values were only two times higher than the value for a gas (D_2) target. In contrast, the screening potentials in targets (such as Pd and PdO) with high deuterium mobilities were rather high (U_e = 310 and 600 eV, respectively) [10].

Unlike the aforementioned investigations [6–10] with metal targets and low-current accelerators, Bystritsky *et al.* [12–14] studied the D(d, n)He^3 reaction yield in a deuterated polyethylene (CD_n) target using the Z-pinch technique [12]. For the deuteron energies 3.6 keV < E_{lab} < 7.8 keV, the measured neutron yield and the evaluated *S* factor showed (to within the experimental error) the absence of enhancement of the DD reaction: the D(d, n)He^3 reaction cross section in CD_n was comparable to that described using the Bosch–Halle extrapolation in the given range of deuteron energies [14]. It should be noted that the dielectric target used in [13, 14] was characterized by a low mobility of deuterium, while the energy spread of bombarding deuterons was very large as compared to that in the experiments using accelerators [6–10].

Previously, accelerators with a low (<1%) spread of deuteron energies allowed the DD reaction yield in metal targets to be studied only for E_{lab} > 2.5 keV. Further decrease in the accelerating voltage leads to insurmountable difficulties in maintaining a sufficiently high beam current density, which makes impossible measurement of the DD reaction yield within an acceptable period of time because of an extremely low yield. At the same time, investigations of the DD reaction yield and cross section at low deuteron energies (below 1 keV) is of considerable interest from the standpoint of astrophysical processes of star evolution [15] and controlled thermonuclear reactions, in particular, the cross sections of a hot deuterium plasma interaction with a reactor wall [16].

An alternative possibility for studying the DD reaction yield at deuteron energies below 1 keV is offered by the experiments with a high-current pulsed discharge in deuterium. The results of previous experiments [17] showed that pulsed glow discharge makes it possible to obtain ions with the energies within 0.8–2.5 keV and current densities within 300–600 mA/cm^2 at a deuterium pressure of 1–10 Torr. The current density used fore the bombardment of the cathode (target) surface in glow discharge is three orders of magnitude higher than that accessible using accelerators. Preliminary estimates show that high-current bombardment of the cathode with deuterium ions in glow discharge can provide for detection of the DD reaction products even at $E \leq 1$ keV for exposures not exceeding several tens of hours (in the case of exponential growth of the DD reaction enhancement factor at low energies). Moreover, this bombardment may initiate the X-ray emission (accompanying the DD reaction initiation in a metal lattice with high solubility of hydrogen [18]), which has never been detected in the experiments using accelerators because of insufficiently high deuteron beam current density.

This paper presents the results of our systematic investigation of the DD reaction yield and X-ray emission in a titanium (Ti) cathode bombarded with deuterons of very low energies (0.8 keV < E_d < 2.45 keV) in a high-current pulsed glow discharge. The thick target yield (Ti cathode) showed evidence for a very high DD reaction enhancement described by screening potential U_e = 610 ± 150 eV. At E_d = 1.0 keV, the DD-reaction rate is nine orders of magnitude higher than that calculated by standard extrapolation [11] of the DD-reaction cross section.

2. EXPERIMENT

The yields of charged particles and X-ray quanta from a DD reaction were studied in a vacuum chamber where glow discharge was initiated at various voltages and currents. Figure 1 shows a schematic diagram of the experimental setup and the arrangement of detectors. The distance between the mobile Mo anode and the replaceable Ti cathode was 4–5 mm. The cathode was made of a 0.01-cm-thick cold rolled foil (99.95% Ti) and had an area of 0.64 cm^2). In order to eliminate overheating of the electrodes, thus reducing their sputtering rate and prolonging work life, the hollow cathode and anode holders were cooled from inside by a flow of distilled water. In order to prevent arc discharge formation at high current densities, the cathode and anode holders were covered by Teflon.

Rectangular voltage and current pulses with a short front (below 1 μs) and a duration of 200–400 μs were generated with a frequency of 3 kHz. The pulse parameters were monitored with the aid of a two-channel 100-MHz storage oscilloscope. A power supply source provided stable glow discharge at deuterium concentrations within 2–9 Torr. It was found that continuous leveling of the pressure during the glow discharge operation suppressed uncontrolled current and voltage fluctuations, thus stabilizing the discharge conditions. Under conditions of quasi-stable glow discharge, the average deuteron energy in the laboratory frame (E_{lab} = *eV*, where *e* is the electron charge) corresponds with high precision to the applied voltage *V*. Indeed, a low (<10^{-5}) degree of deuterium ionization in glow discharge makes the "maxwellization" effects (generating high-energy deuterons at the "tail" of the energy distribution) insignificant [19], so that the average deuteron energy is close to the nominal discharge voltage. The spread of the average deuteron energy, which is an analog of the particle energy spread in an accelerator) in our case did not exceed ±15% of the nominal value and

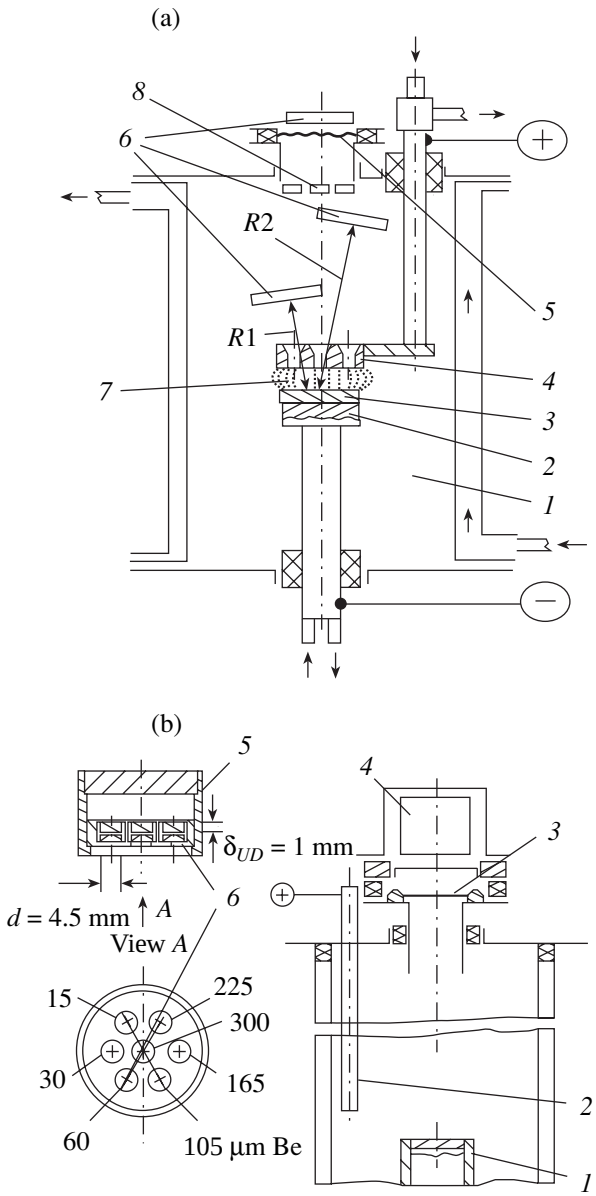

Fig. 1. (a) Schematic diagram of the glow discharge setup: (*1*) vacuum chamber; (*2*) cathode holder; (*3*) cathode; (*4*) anode; (*5*) Be window; (*6*) CR-39 detectors; (*7*) glow discharge region; (*8*) thermoluminescent detectors (TLDs) with 15- to 300-μm-thick Be filters. (b) Schematic diagram of the experiments with open cathode: (view *A*) TLDs with Be filters of different thickness; (*1*) cathode; (*2*) anode; (*3*) Be filters; (*4*) TLDs or pinhole camera; (*5*) metal holder of detectors; (*6*) 15- to 300-μm-thick Be filters.

was mostly determined by the residual pressure instability in the discharge chamber.

The current (I) and voltage (V) measurements in glow discharge at a constant pressure showed that the I–U curves were linear [19, 20] in the range of I = 100–300 mA and U = 800–2000 V (Fig. 2). The proportionality of current and voltage provides a convincing evidence for the absence of "arc" effects (capable of distorting the deuteron spectrum) in glow discharge. In

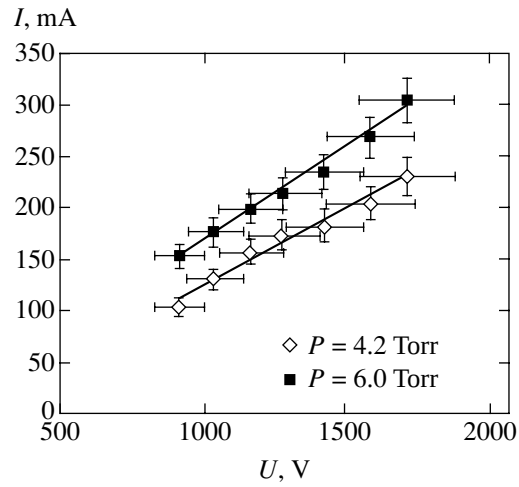

Fig. 2. Current-voltage curves of a glow discharge with Ti cathode in deuterium at a pressure of 4.2 and 6.0 Torr.

order to provide for the maximum DD reaction yield, we selected the maximum current at a given pressure, so as to maintain a preset voltage according to the I–V curve.

The results of temperature measurements performed using thermoresistors pressed against the rear side of the cathode showed that the cathode temperature was increased by 50–100 K over discharge operation [21]. However, these measurements do not provide correct estimates of the temperature of a near-surface layer of the cathode: examination of the cathode showed evidence of the material melting over the entire surface even at a minimum electric power (100 W/cm^2) applied to the discharge. In connection with this, below we will assume the maximum temperature in the near-surface layer of the cathode (with a thickness on the order of the range of bombarding deuterons in the cathode material) to be equal to the melting temperature of titanium.

In order to suppress spurious electromagnetic signals induced by the discharge, which are capable of significantly distorting the measured output signals, we did not use surface-barrier Si detectors (typically employed in experiments [6–10]). The DD reaction products were detected with the aid of plastic track detectors of the CR-39 type (Fukuvi Chemical Industry, Japan), which are insensitive to electromagnetic fields. These detectors were arranged in the discharge chamber behind the anode (in which seven holes were made) at a distance of 3 cm from the cathode surface (Fig. 1a). Measurements performed under analogous conditions of discharge in hydrogen (replacing deuterium) were used for determining the background level.

The CR-9 track detectors employed for detecting charged particles produced in the course of the D(d, p)T reaction were calibrated (Fig. 3) using standard α particle sources (E_α = 2.0–7.7 MeV), a cyclotron beam (E_α = 8.0–30.0 MeV), and a proton beam of the Van de Graaff accelerator (E_p = 0.5–3.0 MeV) of the

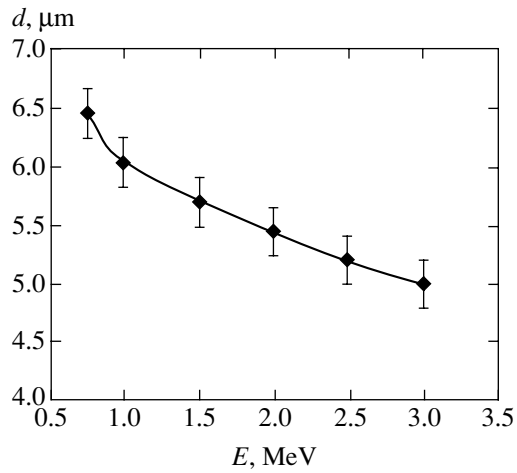

Fig. 3. Calibration curve of proton track diameter *d* versus particle energy *E* for CR-39 detectors.

Institute of Nuclear Physics (Moscow State University). After exposure, the detectors were etched in 6 M aqueous NaOH solution for 7 h at 70°C. The tracks ware examined and their diameters measured using an optical microscope equipped with a digital video camera.

In order to eliminate the action of discharge plasma and sputtered cathode particles on the detector surface, the detectors were screened with a 11-μm-thick Al foil. This foil transmits 3-MeV protons and absorbs 1-MeV tritons from the D(d, p)T reaction. The results of our measurements showed that the tracks due to 3-MeV protons transmitted through the foil have a diameter of about 5.2 μm. The detection efficiency of a CR-39 detector spaced by 3 cm from the cathode is determined primarily by the geometric factor. Taking into account the total area of holes in the anode, the geometric efficiency of 3-MeV proton detection was estimated at $\varepsilon_p = 5.6 \times 10^{-3}$.

The average energy and intensity of X-ray quanta emitted from the cathode surface were evaluated using Al_2O_3-based thermoluminescent detectors (TLDs) and a set of beryllium (Be) filters with thicknesses from 15 to 300 μm (2.8–55.5 mg/cm^2). These TLDs measured the absorbed radiation dose. Seven TLDs (each with a diameter of 5 mm) were arranged outside the discharge zone, at a distance of 7 cm from the anode. In a separate experiment performed in order to determine spatial position of the source of X-ray quanta in the discharge, the anode was shifted 20 mm away from the cathode and the TLD or a pinhole camera was positioned immediately in front of the cathode (Fig. 1b). The TLDs were calibrated using a standard ^{137}Cs source. The TLD signal readout and construction of the glow curves were performed using a special device based on a picosecond processor (Harshaw Co.).

The time correlation of X-ray emission and discharge current pulses were studied using a 17-mm-diam plastic (PMMA) scintillator and an FEU-85 photoelectron multiplier. These experiments were performed at a pressure of 4.2 Torr and a current of 250 mA. A positive image of the X-ray emitting zone was obtained with a pinhole camera using an X-ray-sensitive film.

The experiments devoted to the detection of charged particles were performed in a glow discharge operating at a voltage of 0.8–2.45 kV and a current of 240–450 mA. The duration of each exposure at a certain fixed discharge voltage was about 7 h. Preliminary experiments with CR-39 detectors covered by aluminum (Al) and polyethylene (PE) films of various thicknesses showed a statistically significant number of the 3-MeV proton tracks, which was dependent on the discharge voltage and current. Figure 4 presents typical distributions of the proton track diameters *d* in the detector covered by films of different thicknesses in a glow discharge in deuterium and hydrogen at U = 1.25 kV and I = 240 mA. As can be seen from these data, the track diameter strongly depends on the coating thickness, in accordance with the energy losses for 3-MeV protons [22] generated during operation of the glow discharge. In the presence of 11-μm-thick Al foil, the distribution peak is at d = 5.2 μm corresponding to E_p = 2.85 MeV (Fig. 4a). When the coating thickness was increased to 33 μm (Al foil) and 60 μm PE film, the peak shifts to d = 6.8 μm (Figs. 4b). In the glow discharge with Ti cathode in hydrogen under the same conditions (voltage, current, pressure) as in deuterium, no track were observed in the interval of diameters corresponding to the 3-MeV protons.

The thick target yield of 3-MeV protons $Y_t(E_d)$ from a Ti cathode bombarded by deuterons with an energy E_d was calculated using a formula [3]

$$Y_t(E_d) = \int_0^{E_d} N_D(x)\sigma_{lab}(E)\left(\frac{dE}{dx}\right)^{-1} dE, \qquad (1)$$

where $N_D(x)$, $\sigma_{lab}(E)$, and dE/dx are the deuteron concentration in the cathode, the DD reaction cross section, and the deuteron stopping power in titanium. The cross sections at low energies were determined by using the Bosch–Halle parametrization [11]. The deuteron stopping power in Ti target was assumed to be proportional to the particle velocity, which is consistent with the data available for various targets at low deuteron energies (down to E_d = 1.0 keV) [23, 24].

The yields of 3-MeV protons observed for various discharge voltages in the 0.8–2.45 kV range were normalized to the yield at the maximum voltage (U = 2.45 kV) with allowance for the discharge power and the effective temperature at the target surface (the factors influencing variations of the deuterium concentration $N_D(x)$ in the Ti cathode). The effective concentration of deuterium in Ti was defined as $N_D(\text{eff}) = k(W, T)N_D(x)$, where T and W are the temperature and

power at the target surface, respectively. The coefficient $k(W, T)$ can be expressed as [21]

$$k(W, T) = \exp\left(-\frac{\varepsilon_d \Delta T}{k_B T_m T_0}\frac{W_m}{W_x}\right), \quad (2)$$

where k_B is the Boltzmann constant, $\varepsilon_d = 0.04$ eV is the activation energy for deuteron escape from the Ti cathode surface during discharge, $T_m = 1941$ K is the melting temperature of titanium, $T_0 = 290$ K is the initial temperature of the target, $\Delta T = T_m - T_0$, $W_m = 906.5$ W is the maximum discharge power at $E_d = E_m = 2.45$ keV, $I_m = 370$ mA, and W_x is the power at lower values of the current and voltage. The ε_d value was determined from data reported for the experiments using accelerators [9], by approximating the 3-MeV proton yield in Ti target with an Arrhenius plot [25] in the temperature interval 185–195 K at $E_d = 10$ keV (where no any DD enhancement takes place). The slope of the plot of yield versus temperature corresponds to the activation energy of the yield of deuterium from the target surface (Fig. 5).

3. EXPERIMENTAL RESULTS

The results of measurements using CR-39 detectors covered by 11-μm-thick Al foil showed a statistically significant number of 3-MeV proton tracks, which was dependent on the discharge voltage and current. Figure 6 presents a typical distribution of the track diameter for two discharge voltages (U = 2175 and 805 V) and the same current (I = 250 mA). A peak of the 3-MeV proton track diameter at d = 5.2 μm well agrees with the results of calibration (Fig. 2) and the preliminary measurements at U = 1.25 kV (Fig. 4).

The total set of data presented in Table 1 includes the numbers of tracks at various values of the current and voltage with allowance of the correction factor k calculated using formula (2). As the deuteron energy decreases from 2.45 to 0.8 keV, the 3-MeV proton yield drops by 3 orders in magnitude (with allowance for the normalization factor k). Calculated without the correction for k, the yield decreases by only one order in magnitude (Table 1, fourth column). This difference is related to the fact that the concentration of deuterium in Ti al low voltages (and discharge powers) is much higher than that at U = 2.45 kV because the effective temperature in the near-surface cathode layer is proportional to the discharge power.

Figure 7 shows the experimental yields of the D(d, p)T reaction in Ti as functions of the deuteron energy E_d in the range from 0.8 to 2.45 keV. Before the normalization using the coefficient k (Fig. 7a), the dependence of the 3-MeV proton yield on the discharge voltage has a more pronounced exponential character as compared to that expected taking into account the behavior of the cross section at low energies. After the

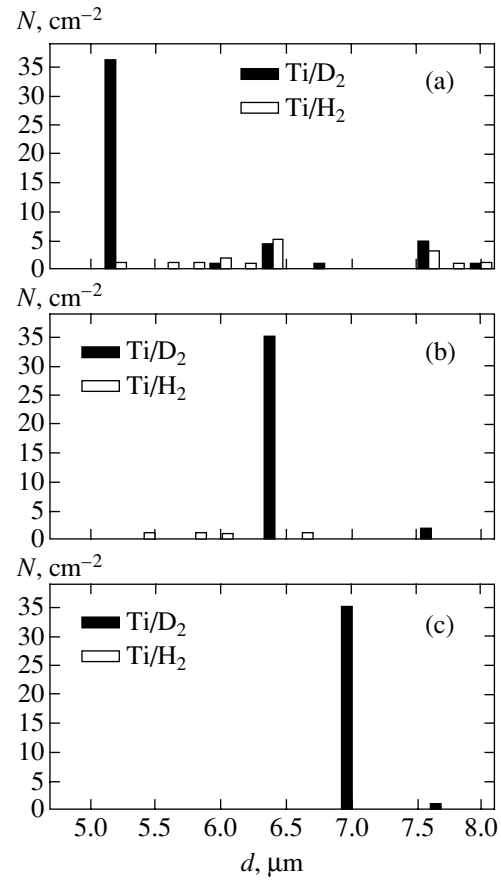

Fig. 4. Proton track diameter distributions in CR-39 detectors for glow discharge in deuterium and hydrogen (pressure, 6 Torr; U = 1.25 kV; I = 240 mA; exposure time, 7 h; cathode–detector distance, R = 3 cm): (a) detector covered with 11-μm-thick Al foil (the peak at d = 5.2 μm corresponds to protons with E_p = 3 MeV; energy losses in the foil are $\Delta E = 0.2 \pm 0.1$ MeV); (b) detector covered with 11-μm-thick Al foil and 60-μm-thick PE film (the peak at d = 6.4 μm corresponds to protons with E_p = 3 MeV; energy losses in the foil are $\Delta E = 1.1 \pm 0.2$ MeV); (c) detector covered with 33-μm-thick Al foil and 60-μm-thick PE film (the peak at d = 6.8 μm corresponds to protons with E_p = 3 MeV; energy losses in the foil are $\Delta E = 2.5 \pm 0.2$ MeV).

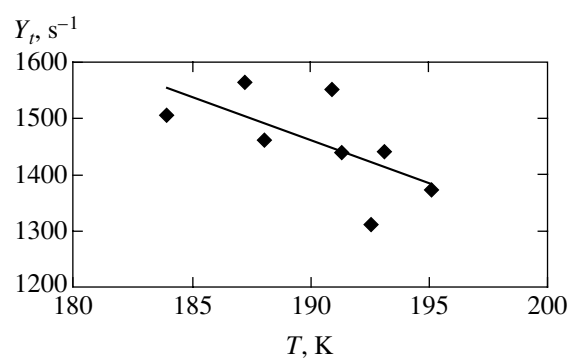

Fig. 5. Normalized proton yield versus temperature for a Ti target bombarded in an accelerator with deuterons at E_d = 10.0 keV and I = 60–100 μA [9]. Solid line corresponds to the Arrhenius function.

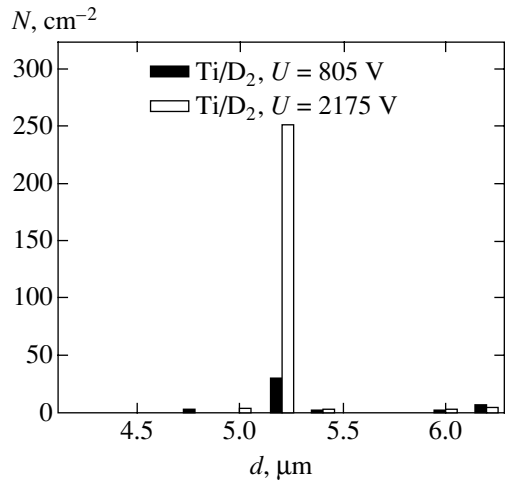

Fig. 6. Track diameter distribution for 3-MeV protons from a Ti cathode measured with a CR-39 detector for a discharge voltage of U_1= 805 and U_2 = 2175 V (I = 250 mA; exposure time, 7 h).

normalization (Fig. 7b), the curve $Y_t(E_d)$ curve exhibits a smoother behavior. This result confirms the need for normalization that takes into account the influence of random collisions (related to uncertainty in the deuterium concentration) leading to deviations of the experimental points from the exponent.

Figure 8 presents the DD proton yield Y_p at low deuteron energies normalized to that at 2.45 keV. For comparison, this figure also shows the standard yield of the D(d, p)T reaction (solid curve) calculated using the Bosch–Halle approximation [9, 10]. Even with allowance for the total error of measurements (including a systematic error and an error caused by the instability of glow discharge, amounting to ±10% in terms of the discharge voltage and current), the experimental plot of Y_p/Y(2.45 keV) lies well above the Bosch–Halle curve. This fact is clearly indicative of a large enhancement of the DD reaction in the near-surface of the target at low energies. In order to directly evaluate the DD reaction enhancement factor $f(E)$ and calculate the electron screening potential U_e in the 0.8–2.45 keV energy range, we used the formula [3]

$$f(E) = \frac{Y_p(E)}{Y_b(E)} = \exp\left[\pi\eta(E)\frac{U_e}{E}\right], \qquad (3)$$

where $Y_p(E)$ is the experimental DD proton yield in a glow discharge, $Y_b(E)$ is the yield determined for the same energy using the Bosch–Halle extrapolation, $2\pi\eta = 31.29Z^2(\mu/E)^{1/2}$ is the Sommerfeld parameter, Z is the deuteron charge (for bombardment with D^+), and μ and E are the reduced mass and energy of deuteron, respectively.

Figure 9 shows the results obtained in an accelerator (curve *1*) [10] and in a glow discharge (curve 2) with the Ti cathode (target). In the case of measurements using the accelerator for 2.5 keV < E_d < 10.0 keV, the screening potential was U_e = 65 ± 10 eV [9]. However, the screening potential evaluated from data on the reaction yield enhancement in glow discharge (Fig. 9, curve *2*) is U_e = 610 ± 150 eV. For example, the experimental DD reaction yield enhancement at E_d = 1.0 keV is almost 9 orders of magnitude greater than that pre-

Table 1. The yield of 3-MeV protons from a Ti cathode for various voltages of glow discharge in deuterium

$\langle U\rangle$, V	$\langle I\rangle$, mA	W_m, W	N (5.2 μm), cm^2	$k(W, T)$	$\langle N_p\rangle$, s^{-1}	$[\langle n/\varepsilon\rangle \pm \sigma]$, s^{-1} (in 4π sr)	Y_p, C^{-1}
805	250	201.3	30	2.2×10^{-3}	2.6×10^{-6}	$(4.7\pm1.4)\times10^{-4}$	1.9×10^{-3}
850	225	191.3	28	1.6×10^{-3}	1.8×10^{-6}	$(3.3\pm1.1)\times10^{-4}$	1.5×10^{-3}
1000	370	370	35	3.6×10^{-2}	5.0×10^{-5}	$(9.0\pm1.9)\times10^{-4}$	2.5×10^{-3}
1145	370	420	54	5.3×10^{-2}	1.1×10^{-4}	$(2.0\pm0.3)\times10^{-2}$	5.3×10^{-2}
1190	240	286	30	1.3×10^{-2}	1.6×10^{-5}	$(3.0\pm0.5)\times10^{-3}$	1.3×10^{-2}
1435	250	359	50	3.3×10^{-2}	7.0×10^{-5}	$(1.3\pm0.2)\times10^{-2}$	5.2×10^{-2}
1500	450	675	71	0.16	4.5×10^{-4}	$(8.1\pm0.5)\times10^{-2}$	1.8×10^{-1}
1647	300	495	62	8.3×10^{-2}	2.1×10^{-4}	$(4.0\pm0.5)\times10^{-2}$	1.3×10^{-1}
2000	370	740	159	1.9×10^{-1}	1.2×10^{-3}	$(2.1\pm0.02)\times10^{-1}$	5.7×10^{-1}
2175	250	544	252	1.1×10^{-1}	1.1×10^{-3}	$(2.0\pm0.02)\times10^{-1}$	8.0×10^{-1}
2450	370	906.5	317	2.7×10^{-1}	3.4×10^{-3}	$(6.1\pm0.04)\times10^{-1}$	1.65

Notes: $\langle U\rangle$, $\langle I\rangle$, and W_m are the average voltage, average current, and power of the glow discharge; N is the number density of 3-MeV proton tracks; $\langle N_p\rangle$ is the average count rate for 3-MeV protons; $\langle n/\varepsilon\rangle$ is the proton yield in a solid angle of 4π sr for a detection efficiency of $\varepsilon = 5{,}6\times10^{-3}$; Y_p is the DD proton yield per 1 C charge transferred by the deuteron current to the cathode.

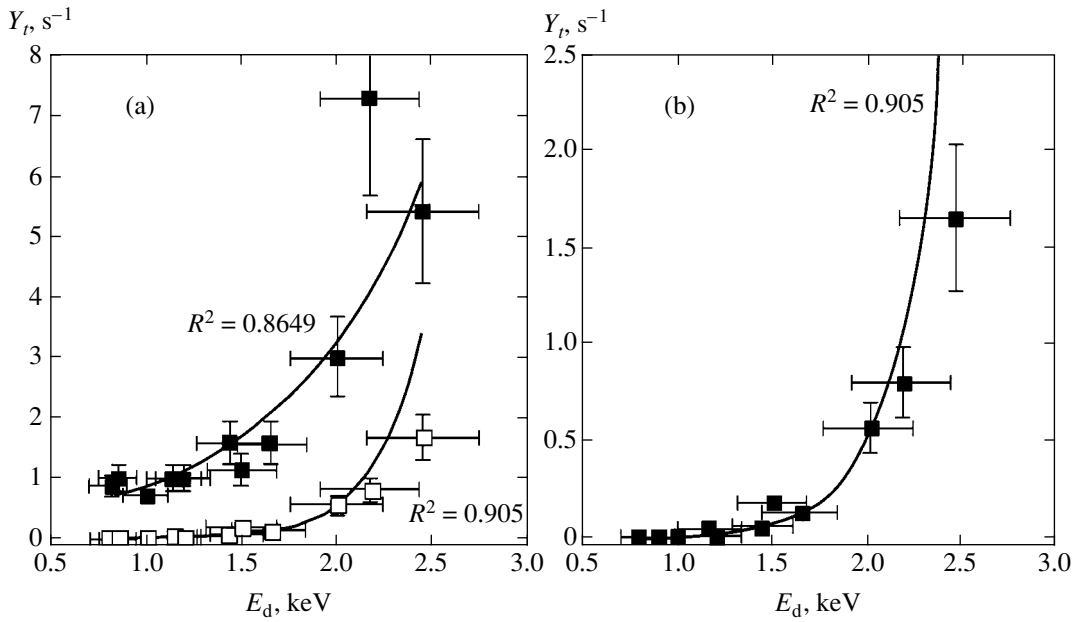

Fig. 7. The yield of 3-MeV protons from a Ti cathode: (a) nonnormalized; (b) normalized to deuterium concentration (with a normalization factor k determined using formula (2)).

dicted using the standard extrapolation of the reaction cross section to low deuteron energies.

Figure 10 presents the DD reaction yield in a glow discharge normalized to the yield measured in an accelerator at E_d = 10.0 keV (with correction of the DD proton yield for a lower effective target temperature in the accelerator as compared to that in glow discharge [9]). Similar to the situation in Fig. 8, the DD reaction yield in the glow discharge is much higher than that obtained by extrapolating to lower energy the value observed in the accelerator (for the screening potential U_e = 65 eV).

Thus, the data on the DD reaction yields in a glow discharge, corrected by normalization using the procedures analogous to those used in the experiments using accelerators [9, 10], demonstrate a much greater enhancement of the DD reaction yield at E_d < 2.45 keV as compared to that anticipated proceeding both from the theoretical extrapolation of the yield to low deu-

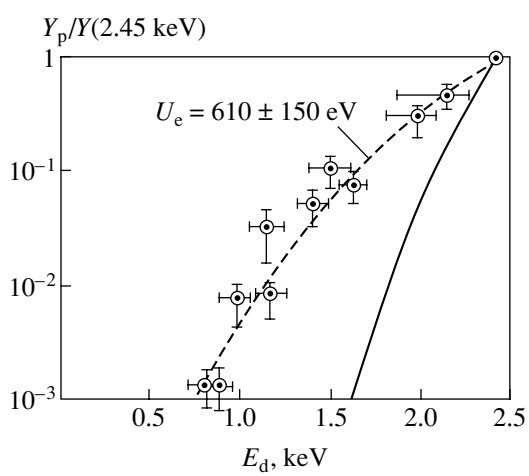

Fig. 8. The experimental yields of 3-MeV protons versus deuteron energy within 0.8 keV < E_d < 2.45 keV (normalized to the yield at E_d = 2.45 keV): Bosh–Halle approximation [11] (solid curve); DD reaction yield for a screening potential of U_e = 610 eV (dashed curve).

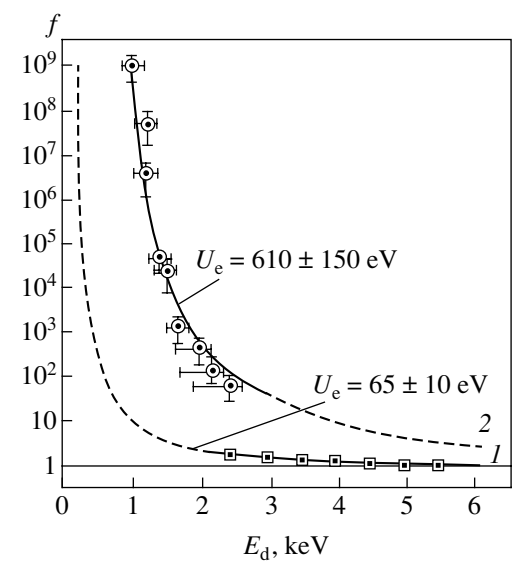

Fig. 9. Plot of the enhancement factor calculated using formula (3) versus E_d for a Ti target: (*1*) accelerator experiment [10]; (*2*) glow discharge. Solid curves correspond to the E_d intervals in which the yield was experimentally measured.

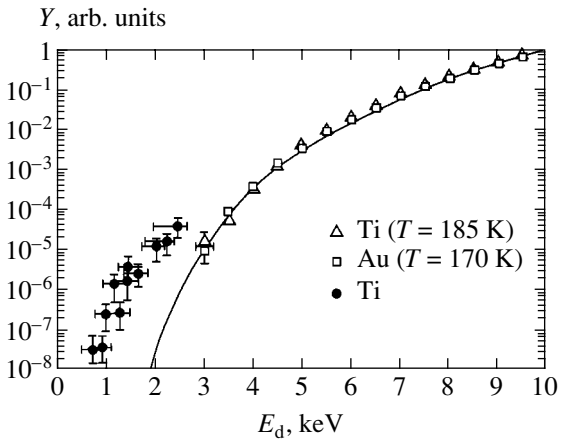

Fig. 10. Thick target yield of protons measured in glow discharge with Ti cathode (0.8 keV < E_d < 2.45 keV) and in accelerator experiments with Ti and Au targets (2.5 keV < E_d < 10 keV) [9]. All yields are normalized to the value obtained on the accelerator for E_d = 10 keV.

teron energies and from the analogous extrapolation of the yields obtained in the experiments using accelerators at E_d > 2.5 keV.

The experiments showed that the bombardment of a cathode in high-current periodic pulsed glow discharge is accompanied by the intense emission of soft X-ray quanta. In the experiments using TLDs in a glow discharge with a Ti cathode at U = 1.25 kV and I = 200 mA, we observed X-ray emission in the energy range of E_x = 1.1–1.4 keV and an intensity of I_x = 10^{13} s^{-1} in a solid angle of 4π (Fig. 11). It should be noted that the average energy of these radiation quanta is close to the energy of bombarding deuterons.

In order to determine the location of the X-ray source in the discharge, we used a setup in which the anode could be displaced relative to the cathode (Fig. 1b). In the case of a glow discharge with a "plasma" anode (i.e., with the anode shifted 20 mm away from the cathode) and the cathode open for monitoring with a pinhole camera, it was established that most X-ray quanta (>90%) are emitted predominantly from the cathode surface. A positive image of the open cathode obtained with X-ray-sensitive film (Fig. 12) represents a bright spot with dimensions corresponding to the diameter of the cathode spot.

The results of our experiments also showed that the X-ray emission pulses observed in a stationary discharge regime were strictly correlated with the current pulses. A growth in the discharge voltage and current was accompanied by substantially nonlinear growth in the yield of X-ray quanta (Fig. 13). The front of the signal from an X-ray radiation detector (based on a plastic scintillator and a photoelectron multiplier) usually coincided with the current pulse front. The X-ray intensity reaches maximum within several microseconds and then slowly decays over a period of about 200 μs.

It was found that the energy of the X-ray quanta, which was estimated using TLDs and a set of Be filters, exhibits a weak growth when the discharge voltage increases from 1.2 to 2.0 kV at a constant current of 200 mA. In order to provide for a change in the voltage at a constant current, the pressure of deuterium was varied in the interval from 2 to 9 Torr. It was found that, at U < 1.6 kV, the X-ray quantum energy E_x = 1.22 ± 0.15 keV is virtually independent of the discharge voltage. As the voltage is increased further, the X-ray quantum energy growth to reach E_x = 1.43 ± 0.17 keV.

The statement that the TLDs with Be filters detected X-ray quanta, rather than some other kind of ionizing radiation, can be confirmed by an analysis of the possible types of emission accompanying glow discharge. The TLDs employed are sensitive to X-ray and gamma

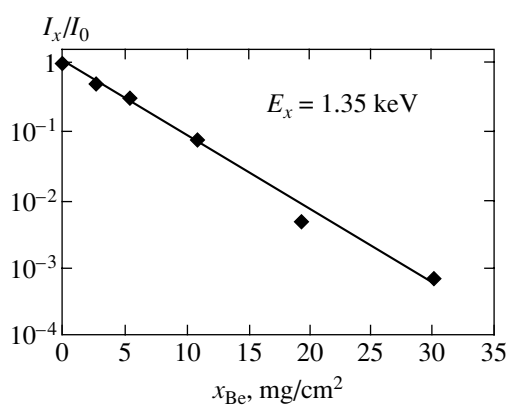

Fig. 11. Estimated energy E_x of X-ray quanta emitted from a Ti cathode in the glow discharge in deuterium (U = 1.25 kV; I = 200 mA; p = 4.4 Torr). The radiation was detected by a TLD with Be foils of variable thickness (see Fig. 1); I_x and I_0 are the X-ray intensity measured in front of and behind the filter.

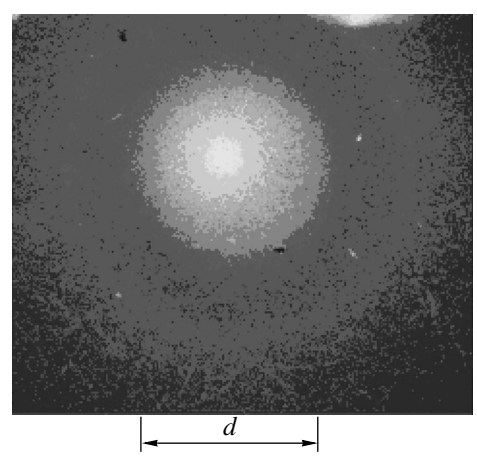

Fig. 12. A Ti cathode image obtained with X-ray film using 0.3-mm aperture pinhole camera covered by a 15-μm-thick Be foil (I = 150 mA; U = 1250 V; p = 5.3 Torr; exposure time, 1000 s).

quanta and to electrons with energies in the range from several units to several hundred of kiloelectronvolts. In the given interval of discharge voltages studied, it is unlikely that electrons can be accelerated to $E > 10$ keV. On the other hand, electrons with $E < 10$ keV are completely absorbed in a Be layer with a thickness of 15 μm. In our case, the intensity of radiation detected by TLDs exhibited a tenfold decrease only for a Be film thickness of $h > 100$ μm (Fig. 10). Therefore, we may ascertain that the radiation detected by TLDs represents only X-ray quanta, which are attenuated in Be films according to the well-known law.

The measurements of radiation doses I_x absorbed by TLDs for various discharge currents (100–270 mA) and voltages (1.0–1.8 kV) at a constant deuterium pressure of 6 and 4.2 Torr revealed exponential growth of I_x as a function of the effective discharge power $P^* = UIQ$, where Q is the on-off ratio for the discharge current pulses (Fig. 14). The yield of X-ray quanta at a constant pressure obeys the law

$$I_x = I_0 \exp[(\varepsilon/k_B T_m) P_x^*/P_0^*], \quad (4)$$

where $I_0 = 0.98$ and 0.725 Gy for $p = 6.0$ and 4.2 Torr, respectively; $\varepsilon = 0.04$ eV is the activation energy for deuteron escape from the Ti cathode surface (Fig. 5, formula (1)); $T_m = 1941$ K is the melting temperature of titanium; and $P_0^* \approx 6.0$ W is the minimum (threshold) effective discharge power.

The efficiency of X-ray generation (the number of quanta emitted per implanted deuteron) as a function of the discharge current also obeys an exponential dependence with the same parameters ε, T_m, and P_0^* (Fig. 15). Thus, the X-ray yield strongly depends on the deuterium concentration at the target surface at the titanium melting temperature and exhibits a tendency to growth with increasing effective cathode temperature ($T_{eff} \propto P^*$).

4. DISCUSSION OF RESULTS

The results of our experiments showed that a high-current glow discharge in deuterium at an applied voltage of 0.8–2.45 kV is characterized by significant enhancement of the DD reaction yield in a Ti cathode and is accompanied by intense X-ray emission. In contrast to the accelerator experiments [6–10], which were performed at much lower currents and higher deuteron energies and showed an enhancement of the DD reaction corresponding to an electron screening potential of $U_e \leq 65$ eV, our experiments with glow discharge gave a much higher value of $U_e = 610 \pm 150$ eV in Ti.

Let us consider the possible sources of errors in the experiments with glow discharge, which might lead to overestimation of the screening potential and enhancement factor for the DD reaction in a Ti target. As was demonstrated in earlier accelerator studies [1, 3], the

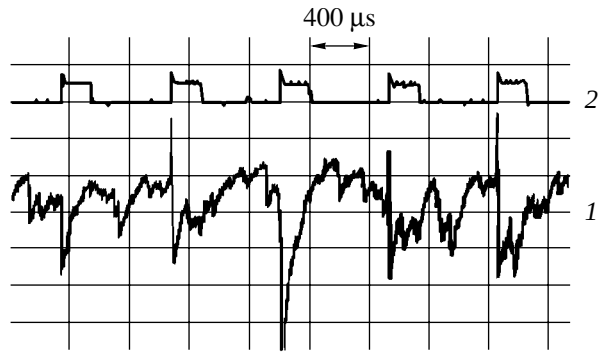

Fig. 13. Synchronized oscillograms of (*1*) X-ray emission pulses measured with the aid of a plastic scintillator and a photoelectron multiplier and (*2*) a glow discharge current ($\Delta\tau = 400$ μs) in deuterium ($U = 1.4$ kV; $I = 250$ mA; $p = 4.2$ Torr).

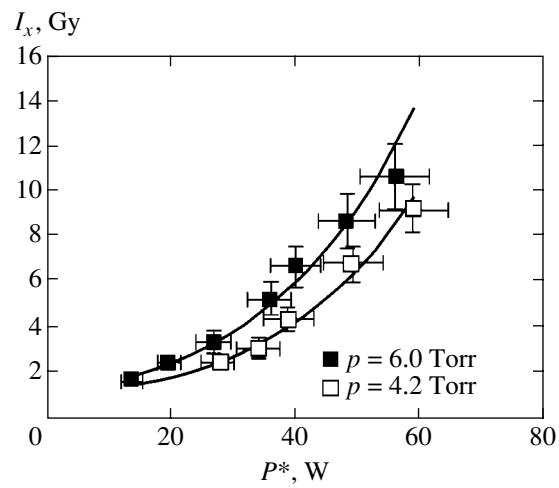

Fig. 14. Plots of the total dose of X-ray quanta emitted from a Ti cathode and detected for 6000 s by a TLD spaced by 7 cm from the cathode (with allowance for the detector efficiency) versus effective discharge power $P^* = UJQ$ ($Q = 0.15$ is the current pulse on-off ratio) for two gas pressures: $p_1 = 6.0$ Torr, and $p_2 = 4.2$ Torr.

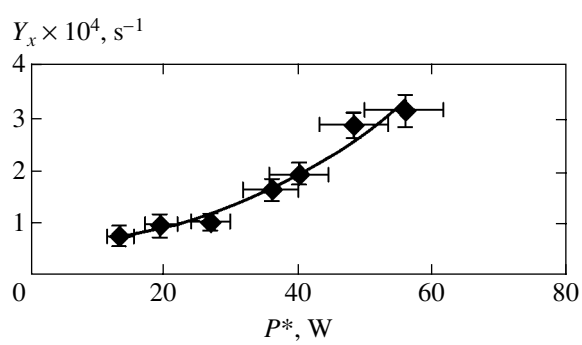

Fig. 15. Plot of the yield of X-ray quanta per deuteron versus effective discharge power P^* at a gas pressure of $p = 4.2$ Torr.