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ANOMALOUS ENHANCEMENT OF DD-REACTION, ALPHA-EMISSION AND X–RAY GENERATION IN THE HIGH-CURRENT PULSING DEUTERIUM GLOW-DISCHARGE WITH Ti-CATHODE AT THE VOLTAGES RANGING FROM 0.8-2.5 kV

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ABSTRACT

Using electronic noiseless solid state plastic track (CR-39) and Al_2O_3:C thermo-luminescent (TLD) detectors, the yields of charged particles (DD-reaction products and long-range α-particles) and X-ray photons are studied in the pulsing-periodic deuterium glow discharge with Ti-cathode at low discharge voltage (ranging of 0.8-2.5 kV) and high current density (300 – 600 mA/cm^2). Analysis of DD-proton yields versus accelerating voltages, allowed to estimate the deuteron screening potential value U_S at the deuteron energy range of $0.8 < E_d < 2.45$ keV. It was found that in this energy range the effective screening potential would be as high as $U_S = 620 \pm 140$ eV.

1, INTRODUCTION

Earlier it was established that high-current deuterium glow discharge (GD) with some metal cathodes, operating at relatively low voltage ranging from 0.8-2.0 kV, generates DD-reaction products and intensive soft X-rays [1]. It was shown that using stable voltage applied to GD it is possible, in principle, to study the dependence of DD-reaction product yield on the deuteron energy. At the same time, to this date the actual DD - cross - section vs. deuteron energy was measured only at E_d (lab) ≥ 2.5 keV on high-current low voltage accelerators [2-4]. Unfortunately, the experiments with these accelerators for metal targets are limited by deuteron energy $E_d > 2.0$ keV due to drastic decrease of beam current following the E_d decrease. That is why, the DD reaction cross-section at lower deuteron energy is still approximated by Bosch & Halle S-factor function, which was built up empirically taking into account cross-section data at E_d(lab.) > 5.0 keV. Meanwhile, the knowledge of DD-reaction yield at essentially lower energies Ed is strongly desirable to confirm Cold Fusion phenomena in deuterated solids as well as for astrophysical purposes. In this connection, regardless of some negative peculiarities of GD (in particular, higher deuteron energy spread compared to accelerator), utilization of high-current deuterium GD (300<I<500 mA) to study DD-reaction cross-section at very low deuteron energies may allow estimate yields of DD-reaction even at $E_d < 1.0$ keV.

In the present paper we carried out a systematic study of DD-reaction and X-ray yields in the pulse high-current GD and showed that this technique can actually be used to estimation DD-reaction cross-section at lowest E_d down to 0.8 keV. We also showed that generation of charged particles from conventional DD-reaction (3.0 MeV protons) is accompanied by long-range alpha-particles emission.

2, EXPERIMENTAL TECHNIQUE

Principal diagram of Glow discharge used is described elsewhere [1,5]. The discharge operates at deuterium pressure ranging from 3.0 – 10.0 tor. Square -shape pulses with the duration τ =200–400 μs, the short arise time (~1 μs) and pulse repetition frequency of 50 kHz were applied to the gap between cathode and anode (x~ 5.0 mm) to drive this GD. In the stable regime being used, the changes in a discharge voltage did not exceed ± 10 %. Stabilization of current and voltage pulses is reached due to accurate pressure support by continuous deuterium pumping out during the discharge operation. The amplitude of the input power density in the pulsing regime, with respect to the bombarded layer is comparable with deuteron stopping power in the cathode and ranged from 100-1,000 MW/cm^3. Measurements of target temperature showed that at any 0.8-2.5 kV voltage used in applied pulse current regime (when effective discharge power $W_{eff} \geq 40$ W), the effective temperature of T-surface is close to its melting point T_m=1950 K. That is why, these GD runs are accompanied by melting and sputtering of the cathode surface.

The 99.9 % purity annealed 100 μm thick Ti-foil was served as a cathode. To allow radiation detection, 7 small diameter holes were drilled in the massive movable Mo anode. In order to detect charged particles and X-ray emissions during GD operation, the plastic track CR-39 and Al_2O_3-TLD detectors located at the opposite side of Mo-anode were employed.

For charged particles detection (protons and high-energy alphas), purified Fukuvi Chemical plastic CR-39 track detectors were used. These detectors were calibrated by standard alpha-sources (2.0-7.7 MeV), the cyclotron alpha-beams (in the range of 8.0 – 30.0 MeV) and by proton beams ranging from 0.5-3.0 MeV using Van-DeGraaf accelerator. In accordance with proton calibration, the expected 3.0 MeV protons from conventional DD-reaction are located near 5.2 μm track diameter. To prevent the electrode material sputtering and also avoid an effect of deuterium plasma on the CR-39 surface, the detectors were covered by Al foil of 11 μm thick, which is transparent for 3.0 MeV protons and high-energy alphas.

To estimate a mean energy and an intensity of a soft Bremsstrahlung emitted during GD operation, sensitive Al_2O_3 based thermo-luminescent detectors (TLD) with a set of 15-300 μm (2.8-55.5 mg/cm2) thick Be-foils were employed. Seven TLD, 5 mm diameter each were located 70 mm from the back side of anode, outside of discharge zone. In special experiments to obtain the exact position of X-ray source in GD, Mo-anode was shifted 20 mm with respect to cathode. In this case, TLD were exposed directly against cathode surface. TLD calibration has been carried out using a standard Cs^{137} gamma source. To read out TLD and analyze TL- glove-curves, 2080 TL-Picoprocessor device of Harshow Co. was used.

Time correlation of X-ray emission with GD current pulses was studied with Photoelectron multiplier (PEM) and plastic (PMMA) scintillator (17 mm diameter). These experiments were carried out in hydrogen atmosphere with Ti-cathode at P= 4.0 torr and I=100 mA. The design and electronic characteristics of PEM and scintillator set-up is described elsewhere [5].

3, EXPERIMENTAL RESULTS.

Experiments on charged particle detection were carried out at the voltages ranging from 0.8-2.45 kV and currents varied within 100-450 mA. The duration of each experiment with corresponding discharge voltage was fixed at t = 7.0 hrs. Measurements with CR-39 track detectors covered with Al-foils showed statistically significant number of 3.0 MeV proton tracks, depending on the GD voltage and current. Typical distribution of charged particle tracks vs. their diameters for deuterium GD with U=2.0 kV and I = 370 mA is presented in Fig.2. As seen, the DD-proton emission (track diameters near 5.2 μm) is accompanied by high energy alpha particles with E = 13.5 ± 2.0 MeV (track diameter ~ 7.2μ) as well as the other particles (track diameter ~ 6.0 μm), which position in the spectra could correspond to either 1.7 MeV protons or 2.3 MeV deuterons. It should be emphasized that in contrast to proton peaks (5.2 and 6.0 μm) the intensity of alpha particle peak does not depend on discharge voltage within the range of 0.8-2.45 MeV.

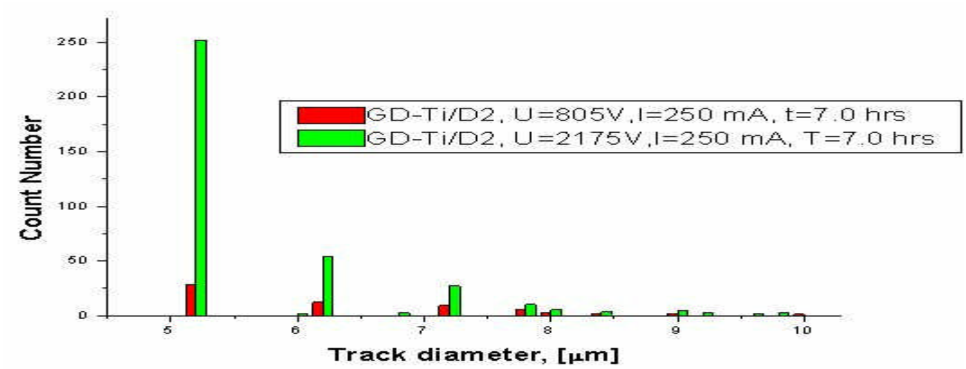

Figure 1

The yields of 3.0 MeV protons during GD-operation at different voltages are shown in **Table 1**. These yields are normalized to those at maximal voltage U=2.45 kV, taking into account discharge pulse power and effective temperature at the target surface. In such consideration the yield corrected to the applied target power and temperature counting the change in deuterium concentration in the Ti-target would be represented as follows: $Y(x) = k'(W,T)N_p(x)$, where $N_p(x)$ - is the experimentally detected 3.0 MeV proton count rate. T and W are the temperature and power at the target surface, respectively that are corresponded to the applied discharge voltage U and current I. Coefficient k can be derived as [1]:

$$\mathbf{k(W,T)} = \exp[-\frac{\varepsilon_d \Delta T}{k_B T_m T_0} * (W_m / W_x)] , \quad (1)$$

where ε_d = 0.04 eV is the activation energy of deuteron escape from the Ti surface during bombardment; T_m = 1941 K is the Ti melting point, T_0 = 290 K is the initial target temperature, $\Delta T = T_m - T_0$, W_m = 906.5 W - is a max amplitude power at E_d = eU_m = 2.45 keV and I_m = 370 mA; W_x - is a current amplitude power corresponding to any other (lower) voltage and current in GD with Ti-target. The value of ε_d was determined from the accelerator data [3] by Arrhenius plotting of 3.0 MeV proton yields for Ti-target in the temperature range of 180-195 K, at E_d=10.0 keV(with no enhancement).

Table 1

Specific 3.0 MeV proton yield at different GD voltages <U>

<U>, [V]	<I>, mA	W_m, [W]	N(5.2μm), [cm^{-2}]	k(W,T)	<N_p>, cps	<n/ε>, p/s in 4π	Y_p, [p/C]
805	250	201.3	30	2.2x10-3	2.6x10-6	4.7x10-4	1.9x10-3
850	225	191.3	28	1.6x10-3	1.8x10-6	3.3x10-4	1.5x10-3
1000	370	370	35	3.6x10-2	5.0x10-5	9.0x10-4	2.5x10-3
1145	370	420	54	5.3x10-2	1.1x10-4	2.0x10-2	5.3x10-2
1190	240	286	30	1.3x10-2	1.6x10-5	3.0x10-3	1.3x10-2
1435	250	359	50	3.3x10-2	7.0x10-5	1.3x10-2	5.2x10-2
1500	450	675	71	0.16	4.5x10-4	8.1x10-2	0.18
1647	300	495	62	8.3x10-2	2.1x10-4	4.0x10-2	0.13
2000	370	740	159	0.19	1.2x10-3	0.21	0.57
2175	250	544	252	0.11	1.1x10-3	0.20	0.80
2450	370	906.5	317	0.27	3.4x10-3	0.61	1.65

Here <U>, <I> and W_m – are the mean discharge voltage, current and amplitude power during discharge operation (t=7.0 hrs); N-is a 3.0 MeV proton track density in CR-39 detectors; <N_p> - is a mean count rate of 3.0 MeV protons; <n/ε> - is the proton yield in 4π-solid angle, taking into account efficiency $\varepsilon = 5.6x10^{-3}$ of proton detection and Y_p-is the specific proton yield per Coulomb of deuteron charge transmitted through Ti-cathode.

As shown in the Table1, the yield of DD-protons in the energy range of 2.45-0.8 keV decreases about 3 orders of magnitude, taking into account power and temperature normalization coefficient (formula 1). If coefficient k would be neglected the yield was decreased only one order of magnitude (see column N(5.2 μm)) because the deuterium concentration in Ti at lower voltage in accordance with (1) is rather higher than that at U=2.45 kV. In **Fig.2** the results of normalization of DD-proton yields Y_x at lower energies to those at E_d=2.45 keV are presented and compared to the standard DD-reaction yield behavior (solid line) calculated in accordance with Bosch & Halle DD-cross-section approximation [2-4].

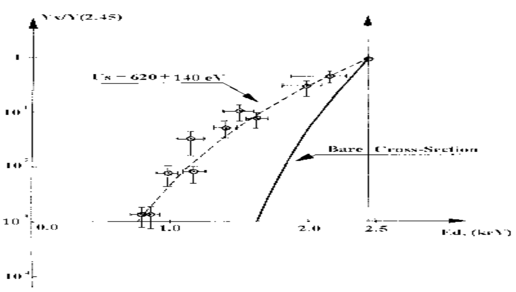

Figure 2

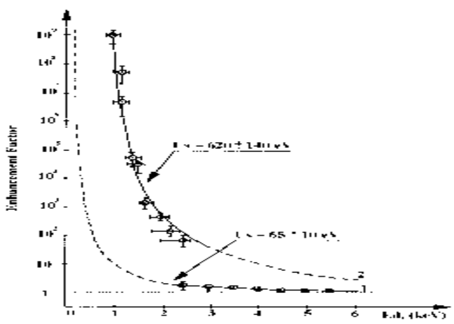

Figure 3

Even with the total error of measurements, involving as systematic errors of detection and instabilities of glow discharge (± 10 % for current and voltage) as well, the experimental $Y_p/Y(2.45)$ dependence vs. deuteron energy is significantly well above the standard B&H bare approximation curve. This fact definitely indicates presence of a large enhancement of DD-reaction at the T-cathode surface at very low deuteron energy. In order to estimate possible enhancement factor (f(E)) of DD-reaction and electron screening potential U_s during GD operation for the deuterons with the energies ranging from 0.8-2.45 keV, the enhancement formula [3] was applied:

$$f(E) = Y_p(E)/Y_b(E)=\exp[\pi\eta(E)U_s/E] \quad (2),$$

where $Y_p(E)$ – is the experimental yield of DD-protons in GD, $Y_b(E)$ – is the bare yield at the same energy determined by B&H approximation (Fig.3, curve 2); $2\pi\eta = 31.29Z^2(\mu/E)^{1/2}$ is the Sommerfeld parameter (here Z – is the charge number of deuteron in the case of D+ projectile and target, μ - is the reduced mass and

E-is the center of mass deuteron energy), respectively. The data obtained for the accelerator [3,4] (curve1) and GD experiments with Ti-target/cathode (curve 2) are shown in the **Fig.3**. In the case of the accelerator measurement with Ti-target at 2.5 < Ed < 10.0 keV the dedicated screening potential was U_s = 65 ± 10 eV [4]. However, for the glow discharge experiment, the) screening potential estimated via enhancement data (curve 2) was found to be as large as U_s=620 ± 140 eV. For instance, this experimental enhancement for GD in terms of DD-proton yield even at E_d=1.0 keV is about nine! orders of magnitude larger than that predicted with bare (B&H) cross-section (**Fig 3**, curve2). In **Fig.4** the GD yields normalized to that for 10.0 keV(taking into account power and temperature corrections of possible GD yield at E_d=10.0 keV) in the range of 0.8-2.45 keV are plotted in the diagram of accelerator yields obtained during bombardment of cooled Ti-target[3]. As in the Fig.4 the GD yields are much larger than their approximation to lower energies deduced from the accelerator data at U_s=65 eV.

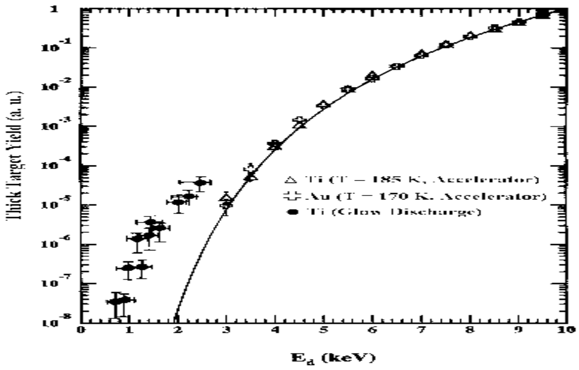

Figure 4

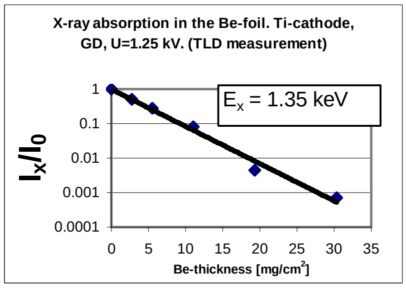

Figure 5

Thus, the GD low energy yields being treated the same way as accelerator data [2-4], exhibit larger enhancement at very low D-energy (E_d < 2.45 keV) than it was expected from the accelerator bombardment. This giant enhancement indicates that in the very low energy range of high-current projectile deuterons, the yields of DD-reaction can be essentially larger than that predicted from the standard B&H cross-section behavior.

As it was shown earlier [1], generation of DD-reaction products and alpha particles in pulse-periodic GD in deuterium/hydrogen is always accompanied by intensive emission of the soft X-ray quanta. In the experiments with TLD in GD with Ti-cathode at I=100 mA and U=1.25 kV, the intensive ($I_x \geq 10^9$ photon/s in 4π-steradian), soft X-ray emission (E_x = 1.3 –1.5 keV) was detected. Using a special movable design of the anode, allowing to change the anode position with respect to cathode we found that along with the discharge Bremsstrahlung (the brake of electrons toward the anode) generation, the essential fraction of X-ray quanta is emitted directly from the Ti-cathode surface

It is important that the mean energy of X-ray photons emitted from the cathode surface is equal or even larger than bombarding deuteron energy (**Fig.5**).

The correlations of X-ray bursts and GD current measured with the plastic scintillator and PEM are shown in **Fig.6**.

he X-ray pulses are strongly correlated with GD current pulses in the stationary regime. The rise of current and voltage in GD is resulted in the essentially non-linear yield of the X-ray emission. These results are in good agreement with the TLD measurement

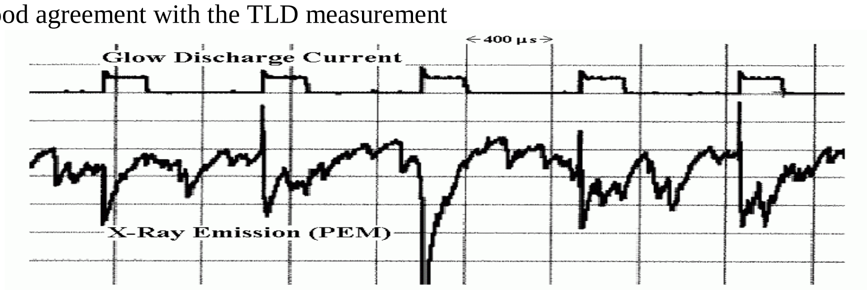

Figure 6

4, DISCUSSION AND CONCLUSIONS

In Table 2 the screening potential values dedicated from GD experiment and accelerator data, by Kasagi at al.[4] as well as the energies of inner electron shells for different metal target used are presented.

We consider that the proximity of obtained deuteron screening potentials U_s and the energy levels of inner shells of the metal targets (in particular, the L_{II} electron shell energy in Ti-atom is consistent with E_s = 620±140 eV) allow to assume some correlation between the mechanisms of deuteron screening and X-ray generation by the Ti-cathode loaded with D/H in GD. In this connection, one of possible explanation of deuteron screening in Ti assumes [3] that bombarding deuterons interact coherently with "deuterium fluid" in the subsurface layer of the Ti-cathode. This interaction would produce recoil deuterons that are able to penetrate into the inner shells of Ti-atom [6]. Such recoil deuterons can also induce the Auger-ionization and excitation of the inner shells with repopulation of liberated levels by electrons from the outer shells. The described process would be accompanied by X-ray photon emission with the energy close to that carried by projectile deuterons.

Table 2

Target/T,K	Ti*, T=186K	**Ti**** T>1000K	Au* T=180K	Yb* T=320K	Pd* T=313K	Au/Pd/PdO* T=193K
E_d,keV	10.0-2.5	2.45-0.80	10.0-3.0	10.0-3.0	10.0-2.5	10.0-2.5
U_s[eV], estimated	65±15	620±140	70±10	60±10	310±40	600±20
Level	M_I	L_{II}	O_{II}	O_I	M_V	M_{II}
E(level), eV	58.3	461	70.7	56.0	334	560

*) Accelerator measurement [4]; **) Glow discharge measurement

Indeed, assuming the excitation of L_{II} - level (461 eV) by recoiled deuteron (D_r^+) with energy E_d = 1.25 keV, caused the Auger electron emission from excited L_{II}* level and fast repopulation of this shell by the neighboring L_{III}-electron, we can suggest X-ray generation process as follows:

$$L_{II} + D_r^+ \rightarrow L_{II}^* \text{ (1762 eV)} + e^- \text{ (Auger)} + L_{III} \text{ (454 eV)} \rightarrow L_{II} + X\text{(1260 eV)},$$

here X(1260 eV) – is the emitted X-ray quantum. As a result of such interaction, the projectile deuteron could be screened inside the inner electron shell of the host-metal (U_s ~ 460 eV) and this screening effect would be accompanied by soft X-ray emission. Under GD deuteron bombardment the D-diffusion rate in Ti is much faster than in accelerator experiment due to essentially higher pulsed deuteron current (3 orders of magnitude above that for accelerator). The high fluidity of deuteron liquid in the GD case will provide quasi-elastic D-recoil with possible penetration of deuterons inside the inner Ti shells. In the accelerator case, lower fluidity of deuterons in Ti-target is caused the inelastic projectile recoil (with lower residual kinetic energy) and penetration of D_r^+ only into the M-shell (**Table 2**).

The nature of energetic alpha-particles emission (**Fig.1**, 7.2 μm maximum) is still under the study.

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