



Research Article

# Detection of Abnormal Quantity of Hydrogen upon Electrical Explosion of Titanium Foil in a Liquid

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## Abstract

Experimental studies of pulse electrical explosion of thin titanium foils in water, with discharge power of  $\sim 0.2$  GW are described. Production of a considerable amount of molecular hydrogen is revealed whose origin cannot be explained either by water decomposition or by known chemical reactions. A nuclear mechanism for the formation of the observed molecular hydrogen upon electric explosion is hypothesized. Emphasis is laid on some measurements confirming the hypothesis.

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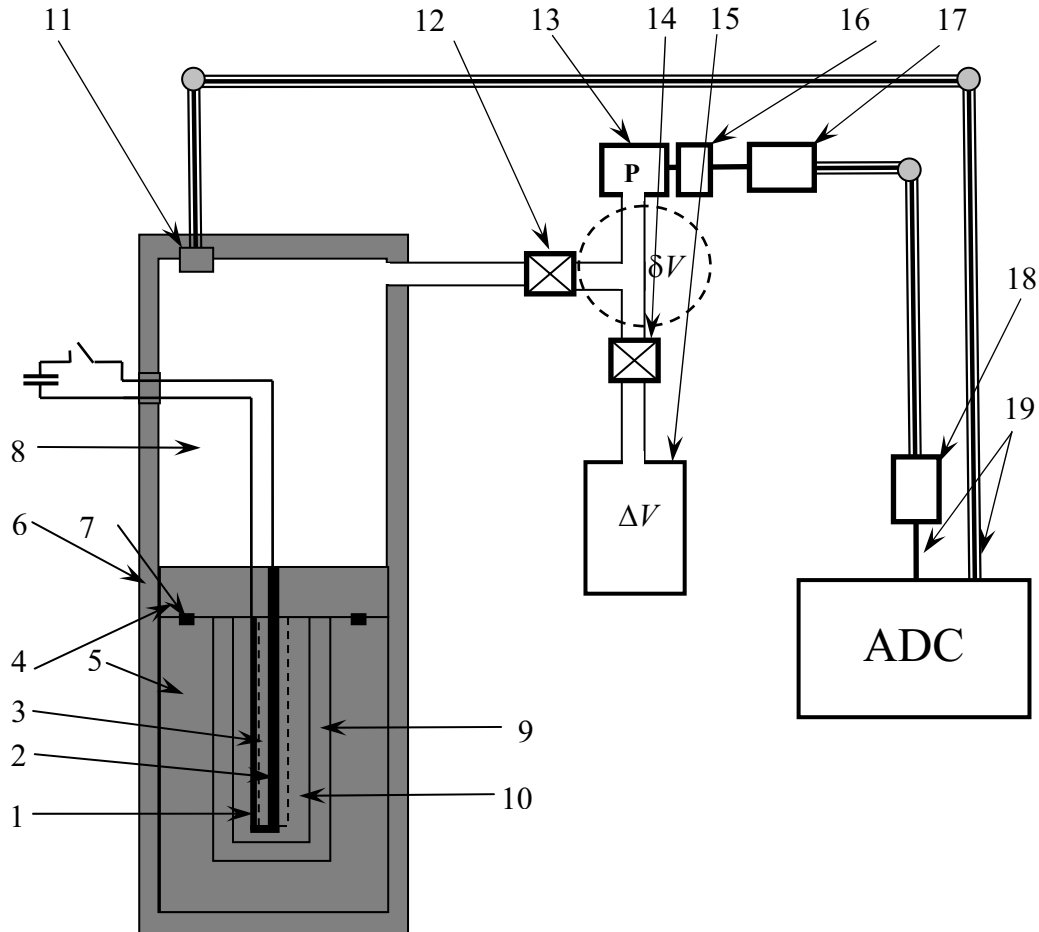
## 1. Introduction

It has long been known that high-current electrical explosions of metal wires in liquid produce strong magnetic fields ( $H \sim 1$  MGs) and high pulse pressures ( $P \sim 10^5$  atm) [1,2]. Meanwhile, there is no doubt that such strong external fields can significantly change the probability of nuclear decays and even the conditions of nuclear stability [3].

In this connection, in our previous works we studied the electric explosions of metal foils in uranium salt solutions [4, 5] in order to detect experimentally the effect of ionization and strong magnetic fields on the change in the  $\beta$ -decay periods. During these experiments we studied the gas phase of such electric explosions (i.e., the gases resulting from these explosions). The analysis of the gas mixtures showed an abnormally high content of hydrogen. A thorough

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**Figure 1.** Schematic drawing of experimental setup. (1) Titanium foil; (2) Titanium electrode; (3) Insulator; (4) Lid; (5) Interior of the explosion chamber; (6) Stainless steel frame; (7) Sealing; (8) Gas-collecting chamber; (9) Disposable beaker; (10) Liquid; (11) Piezoelectric total pressure sensor; (12) Valve; (13) Polarographic sensor DV-16 of hydrogen partial pressure; (14) Valve; (15) Calibrated gas-collecting volume; (16) Signal amplifier; (17) Voltage–frequency signal transducer; (18) Frequency–voltage signal transducer; (19) Cable.

investigation of this phenomenon required more than 500 experiments and took about 4 years. The results of this research are outlined in the present paper.

## 2. Description of the Experimental Setup

The experimental setup consisted of two (2) capacitor banks with  $C = 2.5 \times 10^{-3}$  F each. One bank was charged to +4.8 kV and the second one was charged to –4.8 kV (relative to the ground potential). Under maximum voltage, the energy reserve of the setup was  $W \sim 50$  kJ. Two vacuum solid-state spark-gaps of trigatron type were used as commutators; they were ignited by specially designed devices. The current pulse of each bank lasted for  $T \sim 120 \mu\text{s}$  and its amplitude was about  $I_0 \sim 120$  kA. The electric pulse was transported from each bank through four coaxial

cables with the inductance  $L = 0.4 \mu\text{H}$ . The current was measured by coaxial shunts and the voltage was measured by a divider, which were described in detail previously (together with oscillogram data of the electrical current and voltage) [4,5]. Analog oscillographs and high-speed analog-to-digital transformers connected to computers were used to record the electric signals. The recording equipment was located in a shielding room at a  $\sim 40$  m distance to avoid electromagnetic disturbance.

In this experimental series, each bank worked to its own electrical load which was a titanium foil 1 (Fig. 1) resistance-welded to a bulk titanium electrode 2. Figure 1 shows one of the two explosion chambers where a Teflon insulator 3 was mounted between the bulk electrode and the foil and, hence, the welded foil served as a cable armoring short-circuited to the cable central core. The electrodes were fixed to the dielectric insulator 4 as shown in the figure, which was made either of polyethylene or Teflon depending on the experimental purpose. Simultaneously, this insulator served as a packing element for the explosion chamber. The amount of the titanium foil (loading) varied in different experiments from one to four stripes, each being  $\Delta = 50 \mu\text{m}$  thick, 1 cm wide and  $L = 4.0$  cm long. The weight of each stripe was  $m = (90 \pm 5) \times 10^{-3}$  g.

The interior of the explosion chamber 5 was made of polyethylene (or Teflon) and placed in the lower part of a firm body made of stainless steel 6, which provided tightness in all experiments. All the sealing elements were made of nonhydrogenous materials. The tightness of the explosion chamber itself was provided by sealing 7 of the lid 4. The power input was through the upper part of the metallic container, which served also as a  $V = 3.125$  l gas-collecting chamber 8. The gas-collecting chamber was required as the attempts to hold the gases back in the explosion chamber failed, resulting only in the mechanical destruction of the explosion chamber.

The interior of the explosion chamber 5 contained a disposable Teflon (or polyethylene) beaker 9 filled with liquid 10. The central electrode bearing the foil welded to it was immersed in the liquid. At the instant of electric explosion, beaker 9 was subjected to the greatest mechanical deformation. Teflon beakers were even mechanically destroyed. Therefore, the use of this construction element significantly increased the service life of the basic part 5 of the explosion chamber. The volume of the liquid (in the main part of the experiments) was  $v \sim 18 \text{ cm}^3$ . The liquids used were either de-ionized doubly distilled water or certified heavy water 99.8% ( $\text{D}_2\text{O}$ ).

At the instant of electric explosion, the pressure in the chamber rapidly increased and the resulting gas broke through the sealing 7 into the gas collecting chamber 8. A pressure sensor 11 was located in the upper part of the gas collector, and also a branch pipe connected through valve 12 to the partial hydrogen pressure sensor 13 and through valve 14 to the calibrated gas collecting volume 15 ( $\Delta V = 250 \text{ cm}^3$ ) whose function will be discussed below. Before installation, the gas collecting volume had been evacuated down to the  $2 \times 10^{-2}$  Torr pressure. The gas collecting chamber had been evacuated before the electric explosion down to a pressure of several Torr, purged with argon several times, and then filled with high-purity argon until the pressure was  $P = 1.5$  atm. This procedure minimized the influence of atmospheric gases on the results of measurements.

### 3. Procedure of Measurements

We used both standard procedures (solid-state laser mass spectrometry, gas chromatography, gas mass spectroscopy, electron microscopy) and methods specially developed for this particular experiment (measuring the relative hydrogen content, optical method, and a procedure for producing calibration H/D gas mixtures).

#### 3.1. Procedure of hydrogen partial pressure measurements

Since the results of measuring the amount of produced hydrogen are of great importance for the present research, this method will be analyzed most thoroughly. The method involved the following measuring instruments: a hydrogen partial pressure sensor, a total pressure sensor, a block of electronics, an analog-to-digital converter (ADC), and a

computer. A polarographic DV-16 sensor (produced by the JSC “Insovt”, St.-Petersburg) [6] was used as a partial hydrogen pressure sensor. The sensor operation was based on the linear dependence of the diffusion current running in the polarographic cell on the partial pressure of electrolyte-dissolved hydrogen. Our tests showed that the sensor response function depended on two parameters: the hydrogen partial pressure  $P_H$  and the total pressure  $P_0$  in the mixture. Note that in the pressure range  $1 \text{ atm} < P_0 < 2.5 \text{ atm}$ , the dependence  $U_{PH} = f(P_0)$  was not strong, but a special calibration procedure was needed to increase the accuracy of measurements.

The experimental conditions required the transfer of information on the measured parameter by a considerable distance (by more than 30 m), which resulted in overlapping between noise and the useful signal. Furthermore, at the instant of electric explosion, high-voltage discharges are very likely to get onto the hydrogen sensor circuits. With the use of galvanic coupling in the direct current, this can cause failure of the entire measurement system. The problem was solved by converting the measured voltage into frequency. The error (nonlinearity) in the signal voltage-to-frequency conversion was  $\pm 0.03\%$ , the error (nonlinearity) of the reverse (frequency-to-voltage) conversion being  $\pm 0.06\%$ , which is much less than the hydrogen meter basic error of  $\pm 1.5\%$ .

A SIEMENS SITRANS P Serie Z, Typ 7MF 1564 piezoelectric sensor was used to measure the total gas mixture pressure in the chamber. The electric signal  $U_{P_0}$  from the sensor was taken directly to the AD converter. The linearity of the sensor, along with the whole tract, was verified by a standard manometer. The calibration showed that the measuring system was linear with good approximation up to  $\sim 0.1\%$ , which is even higher than guaranteed by the manufacturer.

After an electric explosion of foil, the pressure in the gas-collecting chamber became  $P_0 \sim 2 \text{ atm}$  and was measured by pressure sensor 11 (Fig. 1). At the instant of “shot”, valve 12 was shut off, which was dictated by service characteristics of the hydrogen sensor. This sensor lost operability upon both a sharp pressure jump and forevacuum evacuation. The valve 14 was also closed, thus separating the calibrated volume 15 from the chamber working volume. The use of the calibrated volume 15 is needed within this method because the air present between valves 12, 14 and pressure sensor 13 (see Fig. 1) cannot be pumped out of the “dead space”  $\delta V \sim 18 \text{ cm}^3$ . Thus, the dead space  $\delta V$  turned out to be filled with air at atmospheric pressure. Therefore, after valve 12 was opened and  $\delta V$  was thus combined with the main space, the partial gas pressures started to slowly equalize due to the rather slow diffusion through the membrane. This resulted in a long time required for establishing the equilibrium between the measured gas volume  $V_0$  and the hydrogen sensor. As a consequence, the time required for the one measurement was too long.

The measuring procedure was as follows. To reduce the time it took for hydrogen pressure sensor to be equilibrated, valve 14 was opened and the gas was “pressed” into the volume  $\delta V$ . In this case, the stationary mode was established in the hydrogen partial pressure sensor within only  $\sim 30 \text{ min}$ .

Next, the valve to the hydrogen-pressure sensor was closed (step 2), and the calibration volume and the hydrogen sensor were detached. The calibrated volume was again pumped out to  $10^{-2} \text{ Torr}$ , and then the partial pressure was measured several times.

Assuming the process to be isothermal, we can readily write the relations between the pressures of the  $i$  and  $i + 1$  iteration steps:

$$\begin{aligned} P_0^i &= P_0^{i+1} \left( \frac{V_0 + \Delta V}{V_0} \right) + \frac{\delta V}{V_0} (P_0^{i+1} - P_a), \\ P_H^i &= P_H^{i+1} \left( \frac{V_0 + \Delta V + \delta V}{V_0} \right), \end{aligned} \quad (1)$$

where  $P$  is pressure in atmospheres and  $P_a = 1 \text{ atm}$  is atmospheric pressure.

Since at each step the relative hydrogen content depends on the initial relative hydrogen content  $\gamma^0$  and the known

volumes

$$\gamma^{i+1} = \frac{P_H^{i+1}}{P_0^{i+1}} = \gamma^i \left( 1 + \frac{P_a \delta V}{P_0^i V_0} \right)^{-1}, \quad (2)$$

we obtain  $n$  measurements of one and the same quantity  $\gamma^0$ . The advantage of such a method lies in the decrease, due to averaging, of the measurement error caused by the weak dependence of the readings of the hydrogen partial pressure sensor on the total gas-mixture pressure  $P_0$ . To make sure that the method works well, we prepared a calibration mixture (83% Ar + 17% H<sub>2</sub>). The hydrogen concentration was measured by the above-described method with a no less than one percent error.

To make certain that the elaborated method of hydrogen percentage measurement is linear in the concentration range of interest, we prepared (Ar + H<sub>2</sub>) mixtures of different concentrations. The calibration mixture composition was determined using a gas chromatograph. We found that within the range  $5\% < \gamma < 30\%$ , the response function was linear depending on  $\gamma$ .

Our method also made it possible to measure slow variations of relative hydrogen content during several days. The method is insensitive to the replacement of H<sub>2</sub> by D<sub>2</sub> or HD.

### 3.2. Procedure of chromatographic analysis

Gas chromatography was used, on the one hand, to verify the abovedescribed method for determining the specific hydrogen content in the gas mixture under study and, on the other hand, to perform a qualitative and quantitative analysis of the gas mixture. We used an LCM-80 gas chromatograph, which had three sorption columns. The analysis was carried out at a temperature of 40°C in isothermal mode. The analyzed mixture components were detected by a detector based on the thermal conductivity of separate gas-mixture components. The quantitative composition of the gas mixture was calculated by the absolute calibration method from chromatographic peak areas (for gaseous components CH<sub>4</sub>, C<sub>2</sub>H<sub>4</sub>, C<sub>2</sub>H<sub>2</sub>, and CO<sub>2</sub>).

Standard gas mixtures were used for calibration with respect to hydrogen, nitrogen, and CO. We either made calibration the same day as the gas samples were tested or used the calibration of the previous analysis. The method did not permit measurement of hydrogen isotopic distribution.

### 3.3. Procedure of solid-state laser mass spectrometry

We used laser mass spectrometry here only to determine the oxidation state of the titanium powder formed from the foil as a result of explosion. This information was necessary for the correct account of the amount of oxygen absorbed by titanium. In other words, the method was aimed at determining the  $n$  value in the TiO <sub>$n$</sub>  formula in each experiment. In addition, we were interested in the isotopic distribution of titanium contained in the powder. Therefore, to determine the element and isotope compositions of the liquid and metal foil remainders, we chose laser mass-spectrometry which, given sufficient sensitivity ( $10^{-4} - 10^{-5}$  at.%), shows an error of 10–15% in determining the amount of trace impurities.

The validity of the measurements was permanently checked through both the standard alloy samples and certified geological samples.

### 3.4. Procedure of gas mass spectrometry

Gas mass spectrometry was also needed for two purposes. First, it duplicated the gas chromatographer measurements, and therefore, when extracted from the same removable containers and already measured on the gas chromatograph, the gas was examined using the gas mass spectrometer. Second, this method was very important for finding the isotopic

distribution of hydrogen atoms in the gas mixture due to electric explosion in experiments with liquid represented by heavy water.

The method rested upon a time-of-flight quadrupole unipolar MMC-1A mass-spectrometer described in greater detail in [7], which allowed determination of components with atomic mass of 1–400. The test with standard gas mixtures showed that this method operated within a 5% error in the entire mass range of interest. In some cases, to check correctness of measurement correlations for the second, third and fourth masses ( $H_2$ , HD,  $D_2$ ) we used a gas mass spectrometer with magnetic focusing. The obtained results showed good agreement. Masses above 44 ( $CO_2$ ) were not observed in the tested gas samples to within 5% precision.

### 3.5. Spectral analysis

Optical spectroscopy was chosen as a duplicate method for a qualitative elemental analysis and semi-quantitative isotopic analysis of hydrogen. For this purpose, a special setup was designed. This setup made it possible to obtain and investigate the radiation spectrum of high-frequency discharge occurring in the gas flow. In order to avoid “pollutions” of an investigated optical spectrum by “impurity” hydrogen, vacuum rubber seals were only used where gas containers were attached to the analytical system and also where the setup was connected to the forevacuum pump.

For the same purpose liquid nitrogen traps, which froze out vapors from water-containing liquids were placed upstream and downstream of the discharge area. These liquids are normally contained in forevacuum pump oil, the vacuumvalve lubricant, and can get into the gas volume when a gas sample is taken from the experimental setup. To avoid accumulation in the high-frequency discharge area of impurities, which could be due to microcracks and vessel degassing, the discharge was implemented in a stream of the analyzed gasses. The maximum pressure of the remaining gas in the setup space was nearly  $10^{-3}$  Torr, while the gas flow pressure during the discharge was  $\sim 3.0$  Torr. We shall see below that these measures sufficed to avoid alien impurities in the gas under investigation.

The gas was excited in a gas tube with a high-frequency Tesla generator. The occurring optical radiation was gathered by a quartz objective and focused on 1:1 scale onto the slit of a spectrograph with the diffraction grating (PGS-2). Dispersion of the device in the area under study was  $7.3 \text{ \AA/mm}$ . All of the experimental procedures are described in more details in [8].

## 4. Experimental Results

### 4.1. Basic results

As has been said above, the ionized gas is produced at the instant of foil electric explosion and breaks through the seals from the explosion chamber to the prechamber. For constant parameters of the experiment, namely, load mass, foil type, explosion chamber geometry, type of liquid, current, etc., the pressure jump was by one and the same value. For example, for the Ti load mass  $m_{Ti} = 180 \text{ mg}$ , the pressure jump was  $\Delta P = 0.42 \pm 0.04 \text{ atm}$  which, when converted to the chamber volume, made up  $\Delta N = 3.4 \times 10^{22}$  atoms. At first glance, this result may seem to be absolutely natural because it is common knowledge that an electric charge running through water must generate hydrogen and oxygen. But it should be taken into account that an electric charge stored in a capacitor bank amounted to  $Q \sim 11 \text{ C}$  and the Faraday number is  $F \sim 96\,500 \text{ C/mol}$ .

Note that the reproducibility of the effect in these experiments depends on many factors which at first glance may seem insignificant. However, it took us about two years to attain satisfactory reproducibility of the results.

As has already been noted, when the capacitor bank was actuated, the currents and voltages under electric load and the signals from the piezoelectric pressure sensor were recorded. The signal from the pressure sensor branched consistently and then was digitized through two different analog-to-digital converters (ADC). The signal digitization frequency was  $\nu = 0.2 \text{ MHz}$  for the first (“fast”) ADC signal and  $\nu = 10 \text{ Hz}$  for the second (“slow”) ADC. Typical

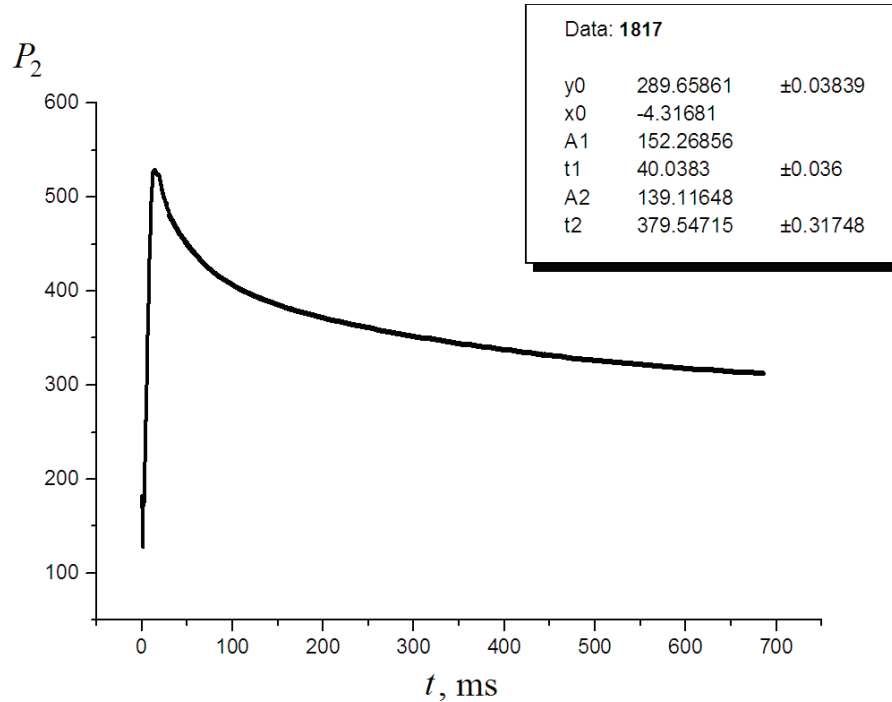


Figure 2. (a) Signal from fast ADC.

signals from both ADCs are illustrated in Fig. 2. Each of the signals is well approximated by the two exponents:

$$P(t) = y_0 + A_1 \exp\left(\frac{t - t_0}{t_1}\right) + A_2 \exp\left(\frac{t - t_0}{t_2}\right). \quad (3)$$

The characteristic exponent periods for the first signal are  $T_1 \sim 40$  ms and  $T_2 \sim 0.3$  s and for the second signal  $T_2 \sim 0.3$  s and  $T_3 \sim 3.2$  s. One can thus see that the time behavior of pressure is characterized by three time scales. This issue has not been thoroughly studied here, but we may assume the first exponent period  $T_1 \sim 40$  ms to be due to radiative cooling, the second one  $T_2 \sim 0.3$  s to be due to transition gas-dynamical processes, and the third period  $T_3 \sim 3.2$  s to result from heat conductivity. The amplification rate and the amplitude of the signal in Fig. 2 were indicative, although quite indirectly, of the gas gain intensity. And the signal from the slow ADC (Fig. 3) made it possible to control the chamber tightness after the “shot” and the hydrogen partial pressure measurement (see Fig. 3). Figure 3 shows that in 20–30 s after an electrical pulse all transition processes mainly terminate and the pressure becomes stationary.

At the early stage of our present research the main effort was directed to investigate the chemical composition of the gas formed upon a titanium foil electric explosion. Several minutes after the explosion, i.e., when the pressure and temperature in the gas-collecting chamber had already reached their stationary values, the hydrogen partial pressure in the produced gas mixture was measured by the method described above. After that, the gas was sampled to the calibrated volume and analyzed using the gas chromatograph. Table 1 presents typical data from gas chromatography. The table shows that the basic component, except the ballast gas argon, is hydrogen. One can notice the absence of oxygen beyond the method sensitivity limits.

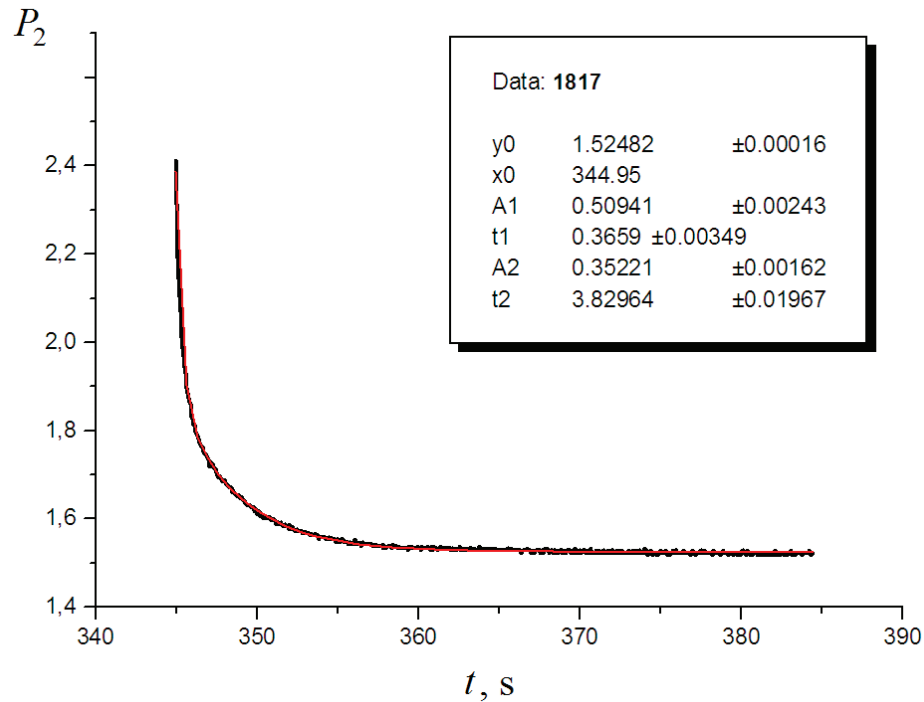


Figure 3. (b) Signal from slow ADC.

Table 2 gives comparison of the values of measured relative H<sub>2</sub> content in the gas mixture obtained with a gas chromatograph and a polarization sensor for one series of experiments, where Ar was also used as the ballast gas. We note that argon chemical “purity” was 99.8%. The table demonstrates good coincidence of the results obtained by two different methods. And, nevertheless, to make sure that the gas chromatograph yields a correct chemical composition

Table 1. Typical result of gas chromatograph measurements.

Element	%
H <sub>2</sub>	13.97
O <sub>2</sub>	<0.3
N <sub>2</sub>	0.6
CO	3.62
Ar	80.85
CO <sub>2</sub>	0.4
CH <sub>4</sub>	<0.02
C <sub>2</sub> H <sub>6</sub>	<0.03
C <sub>2</sub> H <sub>4</sub>	<0.04
C <sub>3</sub> H <sub>8</sub> , C <sub>3</sub> H <sub>6</sub>	<0.1
C <sub>2</sub> H <sub>2</sub>	<0.07
Σ	100



of the mixture, some of the gas samples were simultaneously analyzed using a gas mass spectrometer. The gas mass spectrometer also showed (within the method sensitivity) the absence of free oxygen.

The coincidence of the results of measurements taken within different methods implies that the anomalously large amount of hydrogen and the absence of oxygen are not due to erroneous measurements. Simple conversion of the relative hydrogen content with allowance for the chamber volume and the total pressure shows that during a pulse  $\sim 0.9$  l of hydrogen is generated (under normal conditions) in each chamber. This result is rather stable, reliable, and verified in a large number of experiments. Thus, if we assume that the registered hydrogen is a result of chemical or pyrolytic water decomposition, the question arises: where did the oxygen disappear? In other words, 0.9 l of atomic oxygen due to water decomposition must have been absorbed by the chamber surface without producing a notable amount of molecular oxygen. And as follows from Fig. 3, this mechanism must be actuated within the first seconds because after that the pressure lowering stops.

#### 4.2. Analysis of the chemical mechanism of hydrogen production

To try and examine the physical mechanism of hydrogen production, it was necessary to establish the balance in oxygen. An insignificant part of oxygen was found in the gas sample in the form of CO and CO<sub>2</sub>, and this amount of oxygen could readily be taken into account in the general balance. The reason for the absence of free oxygen could also be oxidation of the titanium electrode and exploded foil. Neither isolation of the titanium electrode from water using Teflon nor replacement of the Ti electrodes by metal electrodes possessing lower oxidability (stainless steel, cobalt, etc.) has led to observation of oxygen in the generated gas.

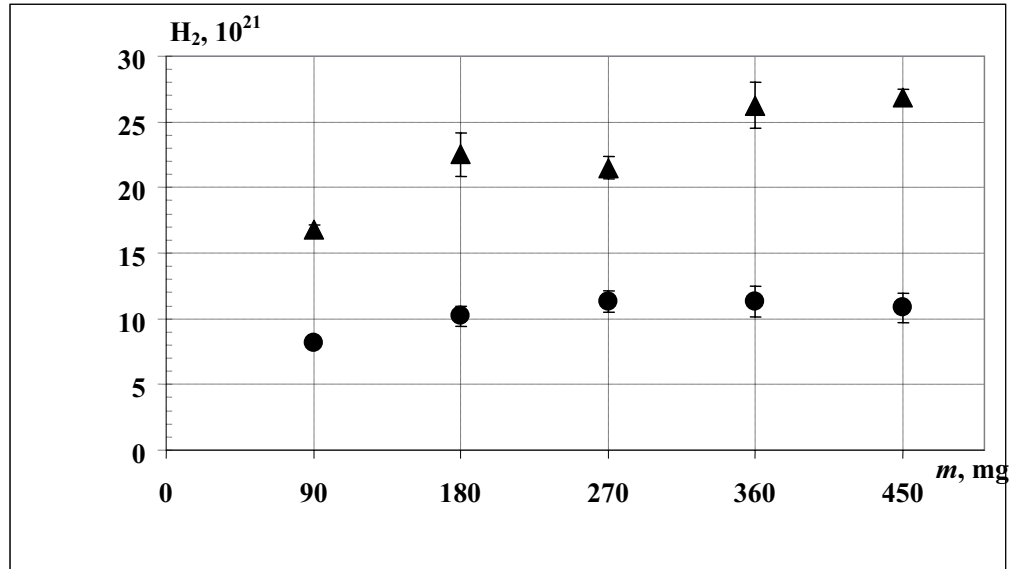
As concerns titanium foil oxidation, this channel of oxygen binding was allowed for by the solid-state mass spectrometry method. To this end, we examined the foil remainders and measured the Ti/O ratio. As a result of numerous measurements it was found that titanium was oxidized to the formula TiO<sub>n</sub> ( $n = 1.4 \pm 0.2$ ). This means that some of the Ti was oxidized to TiO<sub>2</sub> and some to TiO. It is worthy of notice that the titanium oxidation state depends on the mass of the applied load, and this fact was also taken into account in the general balance in oxygen.

For example, for the load mass  $m = 180$  mg, one mole of H<sub>2</sub>O yields  $(2.3 \pm 0.16) \times 10^{22}$  H<sub>2</sub> molecules upon electric explosion. NO<sub>2</sub> =  $(8.7 \pm 0.9) \times 10^{21}$  oxygen atoms were found in the gas samples in the form of CO and CO<sub>2</sub>. The origin of these molecules may well be explained by pyrolytic decomposition of water with subsequent formation of carbon oxides upon addition of oxygen atoms to the carbon contained, e.g., in polyethylene. When oxidized, the titanium foil binds NO<sub>2</sub> =  $(3.3 \pm 0.6) \times 10^{21}$  atoms. Hence, the oxygen balance fails almost by half, i.e., almost 0.5 . of hydrogen does not meet the corresponding oxygen atoms.

We have analyzed the dependence of hydrogen output on the titanium foil mass. A series of no less than seven experiments was carried out for each foil mass, and the averaged results are presented in Fig. 4. The triangular points refer to the total amount of detected hydrogen, and the round points are for hydrogen of non-chemical origin. The values of standard deviation smaller than the point size were not plotted. In view of the pulsed character of the process, the reproducibility of our experiments can be thought of as satisfactory. The figure shows that the amount of non-chemically produced hydrogen does not virtually depend on the titanium foil mass. Noteworthy is the fact that when averaged, the standard deviation values for the lower points appeared to be smaller than those for the initial measurements of the total amount of hydrogen (i.e., for the upper points). Furthermore, the number of hydrogen molecules due to a non-chemical

**Table 2.** Measured values of relative hydrogen content obtained using gas chromatography and polarization sensor for the series of experiments with loading  $m_{\text{Ti}} = 180$  mg.

No.	1830	1829	1828	1826	1825	1824	1823	1822	Average			
Polarogr.	15.76	16.89	14.2	14.0	17.9	19.5	16.8	13.4	14.4	15.6	18.5	16.1±2
Gas. chrom.	17.4	15.4	16.4	14.1	18.5	16.8	16.4	12.8	13.7	14.5	18.0	15.8±1.8



**Figure 4.** Dependence of the amount of hydrogen on the foil mass: triangles show the registered amount of hydrogen, circles show the amount of hydrogen whose origin cannot be explained by the chemical or pyrolytic mechanism of production.

mechanism is  $N = 10^{22}$  to a good accuracy irrespective of the foil mass. In other words, this mechanism is more reproducible and so-to-say “fundamental” than the foil chemical oxidation.

The imbalance in oxygen cannot, of course, be a strong argument for drawing conclusions, but it was a stimulus for seeking the mechanism of “impurity” hydrogen origin.

### 4.3. Search for “impurity” hydrogen sources

#### 4.3.1. Titanium foil

The titanium foil used in the experiments was the first to be tested as “impurity”-hydrogen generator. It is common knowledge that titanium can be saturated with hydrogen to the ratio of almost 1:1. However, most physicists unfortunately forget that this can only be achieved through titanium heating to a high temperature in hydrogen atmosphere. Although spontaneous titanium saturation with hydrogen seems to be improbable, we have nevertheless verified such a possibility experimentally.

The analysis of results of measurements of qualitative structure and quantity of gas impurity allowed asserting that:

- (1) One gram of the initial titanium foil contains  $\sim 0.2 \times 10^{19}$  molecules of  $H_2$ .
- (2) The gases contained in the initial foil are impurities located for the most part on the surface rather than in the bulk.

In more detail the results of these measurements are described in [7, 8].

Thus, the results presented imply that the experimentally observed anomalous amount of hydrogen cannot be explained by its presence in the initial foil.

**Table 3.** Dependence of the amount of hydrogen on the inner beaker diameters.

<i>D</i> (mm)	20	40	60	“Chem”
H <sub>2</sub> (%)	16.0	9.0	6.8	6.7

#### 4.3.2. Polyethylene

Polyethylene contained in the constructional elements of the explosion chamber could have been another probable source of hydrogen. To check the validity of this assumption, all the polyethylene-containing constructional elements inside the tight chamber frame were replaced by those made of Teflon. We conducted several series of experiments with all other experimental conditions (foil mass, the amount of water, ballast gas pressure, etc.) equal. The experiments gave the following result: the hydrogen content was  $(16.1 \pm 2.2)\%$  in the “polyethylene” surrounding and  $(14.0 \pm 0.6)\%$  for the “Teflon”. This showed that the polyethylene elements of the explosion chamber construction were not the source of the observed hydrogen. The small difference in the hydrogen percentage was certainly insufficient to explain the registered amount of hydrogen. Hence, even if polyethylene is the source of hydrogen, it is responsible for very small amounts. It should be noted that when made of Teflon, the disposable beaker 9 (Fig. 1) failed to withstand the high pressure caused by the electric explosion in the chamber and was destroyed, thus increasing the explosion chamber radius. And we shall see below that the diameter of the inner beaker had a very notable effect on the amount of produced hydrogen. When the entire lower part of the explosion chamber (i.e., elements 5 and 9 in Fig. 1) was made of an integral piece of Teflon (as an integral constructional element), the difference between the two series of experiments in the amount of produced hydrogen was quite insignificant.

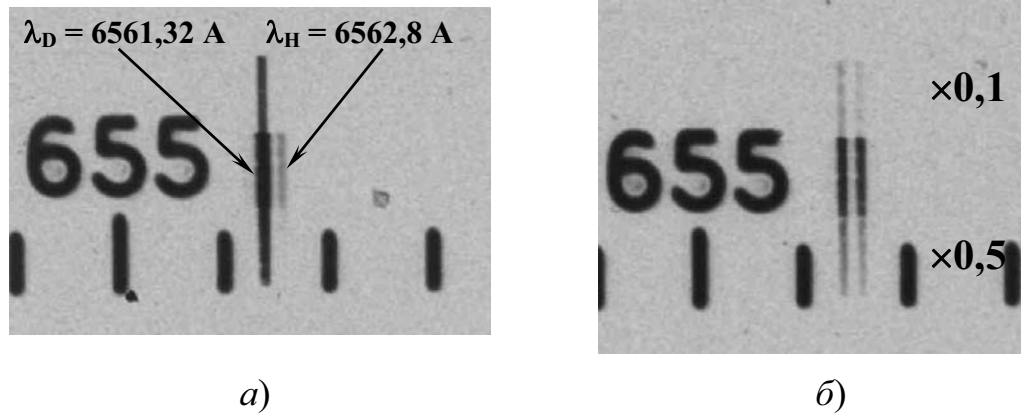
#### 4.3.3. Other sources

To finally exclude the hypothesis of “impurity” origin of hydrogen, we undertook the following series of experiments. We increased the inner beaker (9, Fig. 1) diameter, which was typically 20 mm, and accordingly the volume of doubly distilled water increased. All the other construction parts were left unchanged. Dielectric polyethylene parts were used in these experiments. The foil mass remained the same in the entire series of experiments. The percentage of produced hydrogen for different inner beaker diameters is shown in Table 3. With increasing beaker diameter the explosion chamber pressure falls, which is obviously the reason for the sharp decrease in the amount of produced hydrogen. The last column of the table shows that hydrogen percentage can be due to titanium oxidation and to allowance for CO and CO<sub>2</sub> gases. In other words, that amount of hydrogen has a clear chemical origin. All the values in the table have an almost  $\sigma_m \sim 1\%$  mean error. Table 3 shows that with an increase in the beaker diameter up to 40 mm the entire observed hydrogen can already be thought of as having a chemical origin.

All the results presented above suggest that the hydrogen produced at the moment of electric explosion is due to a process yet unknown to us, and its origin cannot be explained by the chemical or “impurity” mechanism. We believe that the observed hydrogen is of nuclear origin.

#### 4.4. Verification of the nuclear hypothesis

To verify the hypothesis, we conducted experiments using “heavy” water (D<sub>2</sub>O) instead of doubly distilled water. We used water containing 99.8% of D<sub>2</sub>O. The pressure jump and the measured hydrogen percentage differed insignificantly from the experiments with ordinary water. This circumstance suggests that at the moment of electric explosion all processes progressed almost identically in both cases. The idea of experiments with heavy water was as follows. If part of the hydrogen is of nuclear origin, it will not change upon replacement of H by D. Thus, the problem was reduced to determination in a gas sample of a relative H and D content in the produced mixture. We note that the experiments



**Figure 5.** Fragment of the optical spectrum recorded with depressions of 10% and 50%: a) control; b) experiment.

with heavy water were carried out exclusively in a Teflon explosion chamber. All the sample intakes were preliminarily pumped out carefully, and the walls were heated to exclude the presence of moisture.

To solve this problem, we used two methods, namely, optical spectrometry and gas mass spectrometry. To verify the optical method, we first prepared a gas calibration mixture containing 94% of D and 6% of H. Using the above-described optical method, we measured the ratio of intensities  $H_\alpha$  and  $D_\alpha$  as well as  $H_\beta$  and  $D_\beta$  for the calibration mixture to obtain the values of 95% of D and 5% of H.

A fragment of the calibration optical spectrum is presented in Fig. 5a. Such good agreement between the results of optical measurements with the hydrogen concentration values in the calibration mixture means that the optical setup itself contains no “impurity” hydrogen sources. So, we have made sure that the optical method is correct. Figure 5b shows, as an example, a fragment of the optical spectrum of the investigated gas mixture. The hydrogen-to-deuterium ratio measured in this experiment from the optical line ratio made up D/H–1/1. Approximately the same D to H ratio was obtained for this experiment using a gas mass analyzer:  $D_2/HD/H_2 = 0.5/0.25/0.25$ .

## 5. Discussion

- (1) We have reliably established that an electric explosion of titanium foil in water induces production of a considerable amount of molecular hydrogen ( $NH_2 \sim 2 \times 10^{22}$  molecules). The origin of about half of this amount cannot be attributed to water decomposition.
- (2) Careful search of the “impurity” hydrogen source was not crowned with success.
- (3) The authors advanced a hypothesis on the nuclear mechanism of the origin of observed molecular hydrogen and obtained some results to back up the hypothesis.

We should emphasize that by using the words “nuclear mechanism” we, of course, mean neither the nuclear fission nor the nuclear fusion mechanism, at least in their traditional sense. The temperature of plasma produced upon electric explosion is, too low (it is close to the solar corona temperature [4]), and such class of nuclear reactions is impossible in the present experiments. At the same time, on the basis of our preceding experiments [4, 9, 10] we believe that in conditions of dense low-temperature nonequilibrium plasma, an absolutely new class of nuclear reactions may proceed in the absence of strong interactions. The main difference between the hypothetic nuclear reactions and the generally known ones is the assumption concerning their collective mechanism of interaction. We should note that in plasma

physics, the role of collective interactions has long been thoroughly investigated and is beyond question, whereas in nuclear physics such a hypothesis seems to be very extravagant.

## 6. Conclusion

It is significant that although our results of relative hydrogen and deuterium content measurements seem to be reliable, in our opinion they cannot underlie the final conclusion concerning the nuclear origin of observed hydrogen. The final conclusion will require additional research. However, it is much more likely that the hydrogen described in our experiments has nuclear rather than chemical origin caused by some disregarded chemical processes.

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