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Methods of studying the composition of the low-energy ion beams and the surface of deuterated-metal targets

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Abstract. To study the reactions between the light nuclei (dd, pd, d^3He, d^4He) with ultralow collision energies, there is a need to obtain the high-precision experimental results on the purity of the target surface saturated with the hydrogen isotopes (protium, deuterium) and on the number and composition of the accelerated particles falling on the target. To solve this problem, a method has been developed and tested for operational testing the quality of the vacuum system and the cleaning of the metal target surface saturated with deuterium. The paper also presents the measurement results for the true flow of the accelerated ions and neutrals of hydrogen (deuterium), using a multigrid electrostatic energy analyzer. The values of the ion and neutral components of the accelerated particle flow were received for the Hall ion source. The values of the secondary electron emission coefficients were determined for a number of the metal targets (Cu, Ti, Ta, Zr) in the range of the accelerated ion energies of 3–12 keV.

1. Introduction

The modern models of nuclear astrophysics assume that the rates of nuclear reactions between the light nuclei in the stars are increased due to screening the charges of interacting nuclei by negatively charged electrons. Screening the charges at low energies is equivalent to an increase in the kinetic energy of interacting light nuclei by a small quantity U_e that is called the potential of screening [1, 2]. To verify this theoretical assumption, the fusion reactions are studied using the metal targets saturated with deuterium. This is caused by the presence of quasi-free electrons in metals, similar to quasi-free electrons in stellar plasma. To provide the required methodological purity of the experiment for studies of the electron screening effect, the reactions $d(d,p)^3H$ or $d(d,n)^3He$ are usually selected.

The comparison of the results concerning the studies of the mechanisms for proceeding the *dd* - reactions in metals saturated with deuterium [3–12] has shown that some results differ from other results and the results of calculations obtained using the traditional models of nuclear physics [13, 14]. In particular, this statement refers to the results received for the ZrD_2 and TiD_2 targets.

The calculations show that this difference may be connected with the presence of a parasitic adsorbed layer on the surface of the target. Therefore, to analyze the experimental data, there is a need to take into account the ionization losses of the deuteron energy in the adsorbed layer before the introduction of deuterons into the "pure" layer of the deuterated metal.

The layered Auger-spectrometric studies have shown that carbon is the basis of the adsorbed layer deposited in the operating vacuum of $2 \cdot 10^{-7}$ mm Mercury in our experiments. In addition, the surface of the target is significantly contaminated by carbon even in the ultra-high vacuum ($\sim 10^{-9}$ mm Mercury), using the magnetic separation of accelerated ions in the studies of the $d(d,p)^3H$ reactions conducted by other authors [12]. Numerous studies (within the international project ITER) with the

use of various techniques have shown that the films deposited in tokamaks and various discharges in the presence of hydrogen (including our conditions) are hydrogenated carbon with a weakly ordered structure.

In vacuum, the sources of carbon films are all carbon-containing materials and residual gases contacting with plasma or the beams of accelerated particles. Moreover, the ratio of deuterium and carbon particles in the films may reach a value of D/C = 2 [15, 16]. In the experiments, in real time, the composition and thickness of the films can not be controlled. Consequently, it is necessary to clean the target surface.

This paper presents the results of the study concerning the rate of the material deposition on the surface of the quartz plate (without heating) for different operation conditions of the setup and the experimental results demonstrating the complex effect of the temperature and accelerated deuterium ions on the surface of the target. Quartz of the crystal resonator in the device "Micron – 5" and the titanium film (TiD_2) saturated with deuterium and deposited on the substrate were used as the targets.

In addition, to study the reactions between the light nuclei (dd, pd, d^3He, d^6Li,..) with ultralow collision energies, there is a need to obtain the high-precision experimental results on the number of the accelerated particles falling on the target. To solve this problem, we developed and tested a method for measuring the true flow of the accelerated ions and neutrals of hydrogen (deuterium), using a multigrid electrostatic energy analyzer.

2. Controlling the mass thickness of the adsorbed layer on the target surface

The measurements were carried out in a vacuum chamber of the setup [17] used for the study of nuclear reactions dd, pd, etc. during the interaction of the deuterium (hydrogen) ions accelerated up to the energy of 6 – 12 keV with a metal target preliminary saturated with deuterium.

The plate of the quartz resonator was placed in a vacuum chamber where the target was mounted. The frequency of the quartz resonator was measured consistently for the different operating conditions of the setup with simultaneous controlling the temperature.

The minimum mass contamination of the surface can be recorded at the level of $1.3 \cdot 10^{-8}$ g/cm^2 under conditions of dynamic equilibrium with the frequency resolution of the recording device 1 Hz. For carbon, about $6.5 \cdot 10^{14}$ particles/cm^2 (~ 1 monolayer) corresponds to this mass. Such a mass thickness of the adsorbed layer on the target surface is acceptable for the experiments conducted to study the influence of the electron screening in metal (saturated with deuterium) targets on the neutron yield during the $d(d,n)^3He$ reaction.

Figure 1 shows a curve that characterizes the rate of the substance desorption from the target surface during the operation of the accelerator. It follows from the figure that the rate of desorption is significantly increased by using the accelerator (t = 40 min).

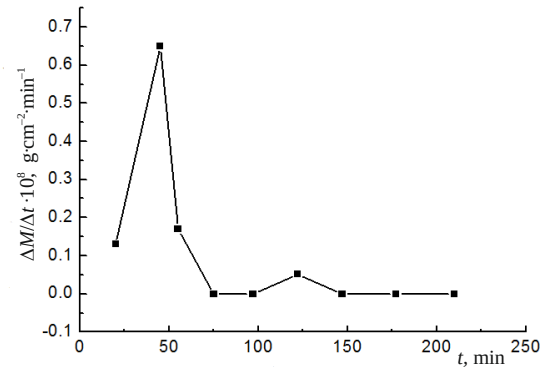

Figure 1. Rate of the substance desorption on the target surface during the experiment.

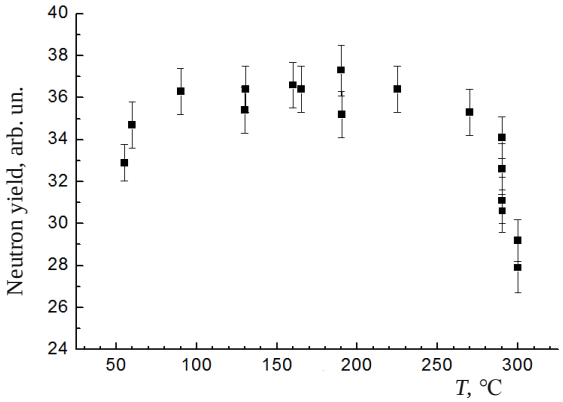

Figure 2. Yield of neutrons versus the target temperature.

The influence of the temperature factor was checked in the experiments using a titanium target saturated with deuterium (stoichiometry TiD_2). The experiments have shown (figure 2) that the neutron yield is increased during the heating of the target from the room temperature to ≤ 100 °C at the energy of the deuterons falling on the target (12 keV).

The yield of neutrons decreases during the heating of the target above 200 °C due to the decomposition TiD_2 and the subsequent separation of deuterium from the target. This assumption is consistent with the results of the study conducted by other authors and relating to the sublimation of the carbon film and the thermal desorption of deuterium implanted from titanium. [18, 19].

3. Determining the true number of the accelerated particles (ions + neutrals) falling on the metal target

To study nuclear reactions (dd, pd, and others) in the range of low-energy particle collisions, there is a need to measure the number of the accelerated particles falling on the target as accurate as possible. If the metal saturated, for example, with deuterium is used as a target, then such a target can be used as a collector for measuring the integral current of charged particles. At the same time, the current is measured on the entire target area, which is extremely important, in the case if the spatial heterogeneity and dynamic instability of the flow rule out the possibility for local measurement of the small area by using the collector.

However, in this case, to determine the true flux of the accelerated particles, it is necessary to consider the coefficient of the secondary electron emission due to the charged and fast neutral particles which fall on the target and are a substantial part of the integral flow.

In fact, fast neutrals must unavoidably be present in the flow of accelerated particles during the charge-exchange process [20]. Therefore, there is a need in the information on the number of neutrals. The fact of the neutral presence can be recorded during the secondary electron emission when the neutrals interact with the collector material.

The coefficient of secondary electron emission γ is dependent on the collector material, the energy and composition of falling particles, the purity of the collector surface, the temperature, the pressure and composition of residual gas, etc. [21–23]. Thus, it is almost impossible to select the reference values γ for the specific experimental conditions. There is a need to find a method for measuring this coefficient for the specific conditions.

In our experiments we used the capability of the grid electrostatic energy analyzer located behind the target to determine the number of fast neutrals and to control the value γ .

Figure 3 shows the scheme of the measuring unit in the experimental setup that consists of the four-grid analyzer and the metal target with the current recording systems in the digital oscilloscope. The disc target (the area is ≈ 80 cm^2) and the part of the energy analyzer were placed in a copper screen, cooled up to – 170°C.

The cooled screen was used for the local freezing and adsorption of heavy and light hydrocarbons during the evacuation of the operating chamber. These measures were intended to reduce the contamination of the target, since the path of the accelerated deuterium particles in the target materials is < 400 nm at the energy of ~ 12 keV. The residual pressure in the chamber was maintained in the range of $1 \cdot 10^{-5} – 2 \cdot 10^{-6}$ mm Mercury.

The disk target had a hole with the area of ≈1 cm^2, through which a part of the accelerated particle flow fell on the energy analyzer.

The S_2 and S_4 grids of the energy analyzer were grounded. The breaking potential was applied to the grid S1 for cutting off the electrons. The potential cutting off the ions with the energy less U_3 was applied to the grid S_3. The values of the ballast containers C and load resistors R were selected depending on the value of the current recorded.

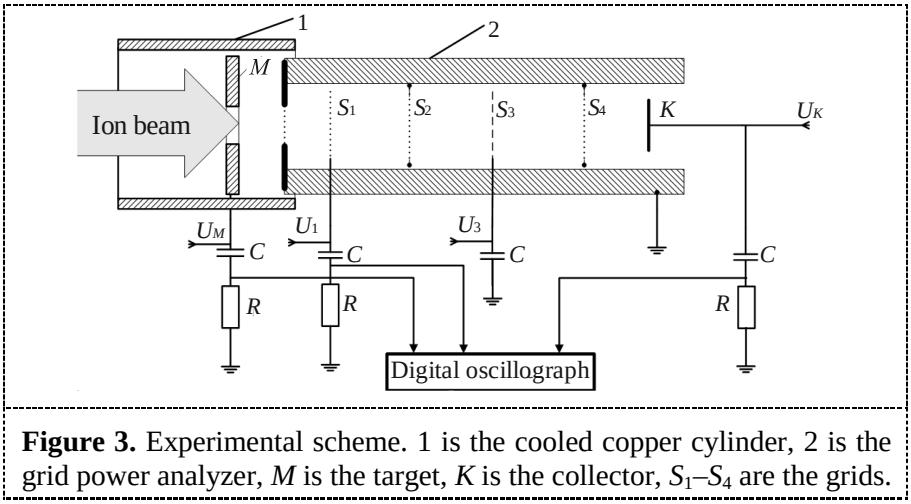

Figure 3. Experimental scheme. 1 is the cooled copper cylinder, 2 is the grid power analyzer, *M* is the target, *K* is the collector, S_1–S_4 are the grids.

A series of experiments was conducted to specify the sources (causes) of currents recorded on the target, collector and grids to develop the method for measuring the true flow of the accelerated deuterium particles.

The results of the studies have shown that a positive signal of the collector is determined by the emission of electrons subjected by fast neutrals in the presence of the cutoff voltage on the grid. The signal from the collector is almost completely suppressed after applying the displacement potential > +15 B to the collector (figure 4, oscillogram 4).

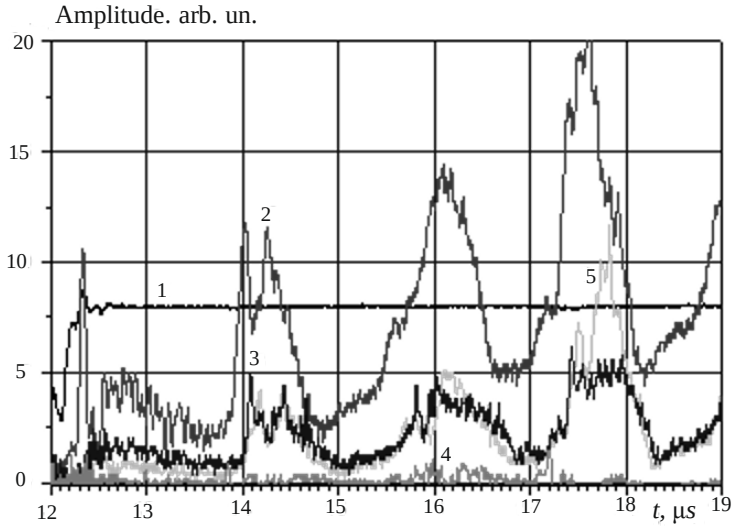

Figure 4. Oscillograms of the current and acceleration voltage. 1 is the acceleration voltage (12 kV), 2 is the target signal, 3 is the signal from the collector (displacement + 9 B), 4 is the signal from the collector (displacement +25 B), 5 is the signal from the first grid of the spectrometer.

Suppression of the positive signal after applying a relatively low positive potential of displacement to the collector of the spectrometer indicates that there are no fast deuterium ions between S_3 and S_4 (grounded).

The secondary electron emission was found not to be essential under the exposure to gamma rays and electrons. In addition, we believe that the coefficient of secondary electron emission is the same for the fast ions and neutrals of atomic deuterium, since the energy of the electrons connected with the neutrals in our range of the acceleration energy is low.

The previous studies did not reveal the accelerated particles of molecular deuterium in a flow, using the time-of-flight technique on the basis of ~ 1 m [24].

Thus, the current I^M on the metal target is caused by the flow of ions and the electrons of secondary emission

$$I^M = I^+ + \gamma \cdot (I^+ + I^0),$$

where γ is the coefficient of electron emission under the exposure to ions and neutrals, I^+ is the flow of ions, I^0 is the flow of neutral particles.

The flow of accelerated particles on the target:

$$I = I^+ + I^0.$$

The values of current integrated in the acceleration range determine the number of the corresponding particles.

The coefficient of the electron emission from the collector depends on the collector material with all other things being equal. Therefore, the collector material should be the same as the target material. Electrical copper, titanium and tantalum saturated with deuterium and deposited on the copper foil ZrD were used as the target materials (and collectors). The copper target and collector were not subjected to any pretreatment. The titanium and tantalum targets and, respectively, the collectors were subjected to evacuation and annealing during the saturation with deuterium. The zirconium target was formed by the magnetron deposition of Zr on a copper substrate in the atmosphere of deuterium.

When voltage is applied to S_3 for cutting off the ions, only neutrals fell on the collector of the energy analyzer. The positive displacement voltage on the collector was selected to suppress the electron emission (under the exposure to neutrals) under these conditions. (The positive potential "returns" the knocked-on electrons on the collector, and the collector current = 0).

Further, in the experiments, the currents were measured under different conditions, using the energy analyzer:

$I_1 = I^+ + \gamma \cdot (I^+ + I^0)$ is the collector current, the sum of currents is determined by the number of charged particles and the number of the electrons knocked-on by ions and neutrals.

$I_2 = \gamma \cdot I^0$ is the collector current determined by the number of the electrons knocked-on by neutrals from the collector.

$I_3 = I^+$ is the collector current caused by the ion current.

The currents I_1, I_2, I_3 were measured by alternating the conditions for the operation of the energy analyzer.

From here it follows (table 1):

$$\gamma = (I_1 - I_2 - I_3)/I_3.$$
$$I^+/(I^+ + I^0) = I_3/(I_3 + I_2/\gamma).$$
$$K = I^M/I = I^+/(I^+ + I^0) + \gamma.$$

Table 1. Results of measurements.

Target (collector)	Cu			Ti + D_2			Ta + D_2		
Energy of deuterium particles (keV)	γ	$I^+/(I^+ + I^0)$	K	γ	$I^+/(I^+ + I^0)$	K	γ	$I^+/(I^+ + I^0)$	K
12				1.1	0.69	1.8			
10	2	0.79	2.78	0.98	0.84	1.8	0.37	0.83	1.2
8	1.9	0.87	2.7						
6	1.92	0.9	2.9				0.45	0.87	1.3

For the target ZrD, the following values were obtained at the energy of ~7 keV: $\gamma \approx 0.17$, $I^+/(I^+ + I^0) \approx 0.64$, $K \approx 0.81$. It should be noted, that the smallest value of the ratio $I^+/(I^+ + I^0)$ was obtained for all targets at a residual chamber pressure of ~ $1 \cdot 10^{-5}$ mm Mercury.

4. Conclusion

Thus, in the experiment there is a possibility for testing the quality of the vacuum system and the different units in the setup to identify and eliminate the factors influencing on the target contamination. The results received for the combined effect on the hydrogenated carbon film on the target surface allow us to develop a procedure for operating with the titanium target saturated with deuterium.

If the target is produced from the material identical to the collector material of the energy analyzer, then the correction coefficients *K* obtained by the energy analyzer can be used for determining the true flow of the accelerated particles falling on the target.

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