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INVESTIGATION OF TEMPERATURE DEPENDENCE OF NEUTRON YIELD AND ELECTRON SCREENING POTENTIAL FOR THE $d(d,\, n)^3$He REACTION PROCEEDING IN DEUTERIDES ZrD_2 AND TiD_2

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Исследование температурной зависимости выхода нейтронов и потенциалов электронного экранирования для реакции $d(d,n)^3$He, протекающей в дейтеридах ZrD_2 и TiD_2

Исследуется температурная зависимость фактора усиления dd-реакции, протекающей в TiD_2 и ZrD_2. Эксперименты проводились на импульсном ионном ускорителе Холла (ИЯФ, Политехнический университет, Томск, Россия) в интервале энергий дейтронов $7{,}0 \div 12{,}0$ кэВ и в области температур от 20 до 200 °C. Найденные значения потенциалов электронной экранировки для dd-реакции, протекающей в TiD_2 и ZrD_2, свидетельствуют о том, что факторы усиления данной реакции не зависят от температуры указанных мишеней в диапазоне $20 \div 200$ °C. Полученный нами результат противоречит выводам работ коллаборации LUNA.

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Investigation of Temperature Dependence of Neutron Yield and Electron Screening Potential for the $d(d,n)^3$He Reaction Proceeding in Deuterides ZrD_2 and TiD_2

The temperature dependence of the enhancement factor for the dd reaction proceeding in TiD_2 and ZrD_2 is investigated. The experiments were carried out at the Hall pulsed ion accelerator (INP, Polytechnical University, Tomsk, Russia) in the deuteron energy interval $7.0 \div 12.0$ keV and at temperatures ranging from 20 to 200 °C. The values obtained for the electron screening potentials indicate that the dd-reaction enhancement factor does not depend on the target temperature in the range of $20 \div 200$ °C. This result contradicts the conclusions drawn by the LUNA Collaboration from their work.

The investigation has been performed at the Dzhelepov Laboratory of Nuclear Problems, JINR.

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1. INTRODUCTION

Study of reactions between light nuclei (pd, dd, $d\,^3$He, $d\,^6$Li) in the ultralow energy range ($\sim$keV) is of great interest from the point of view of both nuclear physics and nuclear astrophysics [1–8]. Investigation of stellar cycle reactions between light nuclei will make it possible to describe correctly the picture of initial nucleosynthesis and stellar nucleosynthesis. These studies are utterly important for construction of the stellar burning processes and evolution.

Cross sections for reactions between light nuclei at low collision energies are determined by the Coulomb penetration factor [9, 10] $\sim \exp(-2\pi\eta)/\sqrt{E}$, the $1/\sqrt{E}$ law, and the astrophysical factor $S_b(E)$ weakly-dependent on collision energy [11]:

$$\sigma_b(E) = \frac{S_b(E)}{E}\exp(-2\pi\eta), \quad 2\pi\eta = 31.29 Z_1 Z_2 \sqrt{\frac{\mu}{E}}, \tag{1}$$

where η is the Sommerfeld parameter; E is the particle collision energy in the reaction entrance channel, keV; Z_1, Z_2, and μ are the charges and reduced mass of the interacting nuclei, a.m.u.; $S_b(E)$ is the astrophysical S-factor for the reaction between bare nuclei at the collision energy E [12–14].

In the late 1980s a lot of experimental works were published [15–31], reporting results that indicated a considerable increase in cross sections for reactions between light nuclei in the ultralow energy region as compared with the cross-section values calculated by formula (1):

$$dd \to {}^3\mathrm{He}(0.8\ \mathrm{MeV}) + n(2.5\ \mathrm{MeV}), \tag{2a}$$

$$dd \to t\,(1.03\ \mathrm{MeV}) + p\,(3.0\ \mathrm{MeV}), \tag{2b}$$

$$d\,^3\mathrm{He} \to p(14.7\ \mathrm{MeV}) + {}^4\mathrm{He}(3.7\ \mathrm{MeV}), \tag{3}$$

$$d\,^3\mathrm{He} \to {}^5\mathrm{Li} + \gamma\,(16.4\ \mathrm{MeV}), \tag{4}$$

$$d\,^6\mathrm{Li} \to 2\alpha. \tag{5}$$

The increase in intensity of fusion reactions is very similar to the increase in rate of nuclear reactions in the interior of the Sun [32] due to the Debye screening of the Coulomb potential, when the interaction potential of two Coulomb centers

with the charges eZ_1 and eZ_2 separated by a distance R in plasma is represented as

$$U(R) = \frac{e^2 Z_1 Z_2}{R} \exp\left(-R/R_{\rm D}\right). \tag{6}$$

Here e is the elementary charge, and $R_{\rm D}$ is the Debye radius, which in the case of electron screening is written as

$$R_{\rm D} = \sqrt{\frac{k_{\rm B} T}{4\pi e^2 n_e}}, \tag{7}$$

where $k_{\rm B}$ is the Boltzmann constant, n_e is the electron density, and T is the temperature of free electrons.

Since at distances R substantially smaller than the Debye radius the screening potential (6) differs from the Coulomb potential by the constant $e^2 Z_1 Z_2 / R_{\rm D}$

$$U(R) = \frac{e^2 Z_1 Z_2}{R} - \frac{e^2 Z_1 Z_2}{R_{\rm D}} \equiv \frac{e^2 Z_1 Z_2}{R} - U_e, \tag{8}$$

it is convenient to describe the screening energy by the screening potential $U_e = e^2 Z_1 Z_2 / R_{\rm D}$, introduced in [33], to describe screening of interacting nuclei by atomic electrons. This shift of the potential energy by a constant is equivalent to an increase in kinetic energy of nuclear collision by the same constant, and the influence of the screening effect on the nuclear reaction cross sections $\sigma(E)$ will be expressed in terms of the reaction cross section $\sigma_b(E)$ for interaction of bare nuclei by a simple relation $\sigma(E) = \sigma_b(E + U_e)$ [33].

As is evident, in under-barrier reactions even a small shift of the initial energy can result in a considerable increase in the reaction cross section. In view of weak dependence of the astrophysical S-factor on nuclear collision energy, this increase, expressed by the factor f, is determined by the Coulomb penetration factor [33]:

$$\begin{gathered} \sigma(E) = \sigma_b(E = U_e) = \sigma_b(E) f(E), \\ f = \frac{E}{E + U_e} \exp\left(-2\pi\eta(E + U_e) + 2\pi\eta(E)\right) \\ \text{at} \quad E \gg U_e, \quad f(E) \approx \exp\left(\frac{\pi\eta(E) U_e}{E}\right), \end{gathered} \tag{9}$$

which can be appreciably large in the deep under-barrier energy region ($2\pi\eta(E) \gg 1$). Naturally, according to (1), this enhancement can also refer to the S-factor:

$$S = S_b f. \tag{10}$$

It is worth noting that in [18, 20–27, 34, 35], where the dd reaction proceeding in metal deuterides was studied, it was also found out that dd-reaction enhancement

factor f and accordingly the electron screening potential (ESP) depended on the period in the periodic table of chemical elements, target temperature, and degree of saturation of the target by deuterium [18, 20–27, 34, 35]. A comparison of the results of those works with one another and with calculations within the traditional atomic-physics model [21, 27, 36, 37] reveals considerable disagreement.

If the temperature of the medium is much lower than the ionization energy of atoms, the screening effect arises only from atomic electrons [15]. For example, for fast particles, when the Born approximation is valid, the screening is defined by undistorted wave function of the target atom. In the case of the dd-collision the effective potential of the Coulomb interaction of the deuteron with the deuterium atom can be represented as a potential averaged over the hydrogen atom wave functions $\Psi(\mathbf{r})$:

$$U\left(R\right) = \left\langle \Psi\left(\mathbf{r}\right)\right| \frac{e^2}{R} - \frac{e^2}{\left|\mathbf{R}-\mathbf{r}\right|} \left|\Psi\left(\mathbf{r}\right)\right\rangle = \left(\frac{e^2}{R} + \frac{e^2}{a_b}\right) \exp\left(-\frac{2R}{a_b}\right), \qquad (11)$$

where a_b is the Bohr radius. At small distances the effective interaction (12) is also shifted away from the Coulomb interaction by a constant:

$$U\left(R\right) = \frac{e^2}{R} - \frac{e^2}{a_b} \equiv \frac{e^2}{R} - U_e, \quad U_e = \frac{e^2}{a_b}. \qquad (12)$$

Thus, the Born screening potential for all hydrogen isotopes is 27.2 eV. This value is very close to the screening potential values for the dd reaction obtained in the experiments with the gaseous deuterium target $U_e = 25 \pm 5$ eV (reaction (2b)) [18], heavy water (D_2O) and deuterated polyethylene targets $U_e \leqslant 26$ eV and $U_e \leqslant 40$ eV [38] (for reaction (2a)), respectively.

In collisions of slow deuterons, when their relative motion velocity is smaller than the velocity of the orbital electrons of the target atoms, the electron charge density is well described by adiabatic equations, and the limiting correction to the Coulomb interaction of nuclei [15] is equal to the difference in binding energy between the united atomic ion with one electron (in our case the binding energy of the $^4He^+$ ion) and the target atom $\varepsilon_{\rm H}$, that is, $U_e = 3$, $\varepsilon_{\rm H} = 40.8$ eV. Actually, it is the adiabatic approach that determines the limit of possible screening for the state of target atoms when the deformation of the electron surrounding of the atoms is small (normal conditions).

The results of [22, 23] indicate a considerable excess of the ESP over the adiabatic limit for deuterides of metals (except metals from groups 3 and 4 of the periodic table) while for insulators, semiconductors, and elements of the lanthanum group the ESP values are no larger than the adiabatic limit. Moreover, in [22, 23] the relation between the screening potential and the density of conduction electrons is pointed out.

To verify the plasma model of screening for the dd reaction, the temperature dependence of the ESP for deuterium-saturated Pt, Co, and Ti was investigated

Electron screening potentials U_e(ZrD) and U_e(TiD) for the deuterated targets ZrD and TiD

Target	Temperature, °C	Stoichiometry	Experimental U_e, eV	Theoretical U_e, eV
ZrD	20	$ZrD_{1.1}$	$\leqslant 40$ [22]	
	200	$ZrD_{0.13}$	205 ± 70 [23]	
	20	ZrD_2	297 ± 8 [21]	112 [21, 27]
	20	ZrD_2	157 ± 43 [41]	
	20	ZrD_2	319 ± 3 [27]	
TiD	-88	$TiD_{3.76}$	66 ± 15 [20]	
	-10	$TiD_{2.1}$	$\leqslant 30$ [34]	
	20	$TiD_{1.3}$	$\leqslant 30$ [22]	100 [21, 27]
	20	TiD_2	125 ± 34 [41]	
	50	$TiD_{1.1}$	$\leqslant 50$ [23]	
	100	$TiD_{0.26}$	250 ± 40 [23]	
	150	$TiD_{0.23}$	295 ± 40 [23]	
	200	$TiD_{0.20}$	290 ± 60 [23]	

in [23, 39]. The measured temperature dependences of the ESP for platinum and cobalt deuterides turned out to be $T^{-1/2}$, which agreed with Debye's plasma model describing the dd reaction in the above deuterides [23, 39]. As to titanium deuteride, the investigation of the ESP-temperature relation for it in the range from –10 to 200 °C [23, 39] indicates an increase in the ESP beginning with the temperature of 50 °C (see the Table). This result does not agree with Debye's plasma model.

In this connection, it is undoubtedly interesting to verify the experimental result [23, 39] indicating the temperature dependence of the ESP for the dd reaction in some metal deuterides, in particular TiD. The results of this verification will allow an unambiguous answer to the question of whether Debye's plasma model is capable of explaining the nature of the electron screening effect.

The purpose of this work was to investigate temperature dependences of the neutron yields from the dd reaction, electron screening potentials, dependences of the astrophysical S-factors on the deuteron collision energies in zirconium and titanium deuterides in stable phase states [42] at temperatures ranging from 20 to 200 °C.

The choice of the additional zirconium deuteride target was dictated by the necessity to obtain more detailed information on the electron screening mechanism for the dd reaction in the deuterides of the metals (TiD_2, ZrD_2) belonging to the same group in the periodic table. It should be mentioned that the results of our earlier experiments [38, 41] on measurement of the astrophysical S-factors and electron screening potentials for the dd reaction occurring in ZrD_2 and TiD_2 at

the target temperature of 20 °C are in conflict with the results of the experiments with both zirconium deuteride [21, 22, 27] and titanium deuteride [22] (see the Table).

The experiments in question will allow not only a comparison of our results for the ZrD_2 and TiD_2 targets with the results available in the literature but also an unambiguous answer to the question of whether Debye's model describes our experimental results.

2. MEASUREMENT METHOD

The experimental determination of the astrophysical S-factors for the $d(d,n)^3$He reaction is based on the measurement of the neutron yield in reaction (2a) and parameterization (1), which represents cross-section dependence on the deuteron collision energy:

$$N_n^{\exp} = N_d \varepsilon_n \int\limits_0^\infty F(E)dE \int\limits_0^\infty n_t(x) \frac{e^{-2\pi\eta} S(E')}{E'} dx, \tag{13}$$

here $F(E)$ is the energy distribution function for incident deuterons; E is the dd collision energy (in c.m. system); ε_n is the neutron detection efficiency; $n_t(x)$ is the deuteron density in the target at the depth x; $S(E')$ is the astrophysical S-factor for the dd reaction at the deuteron collision energy E'; $E' = E'(E,x)$ is the c.m.s. energy of the incident and target deuteron collision at the target depth x; N_d is the number of the deuterons incident on the target.

Without considering the electron screening effect, the experimental values of the astrophysical S-factors for the dd reaction in the TiD_2 and ZrD_2 targets corresponding to specified average values of deuteron collision energies could be defined as follows [43–51]:

$$\overline{S(E)} = \frac{N_n^{\exp}}{N_d \varepsilon_n \int\limits_0^\infty F(E)dE \int\limits_0^\infty n_t(x) \dfrac{e^{-2\pi\eta}}{E'(E,\ x)} dx}, \tag{14}$$

here $\overline{S(E)} \approx S(\overline{E})$ is the value of the astrophysical S-factor averaged over the deuteron collision energy.

The average deuteron collision energy $\overline{E} = \int\limits_0^\infty EP(E)dE$ is defined by the normalized-to-unity distribution function $P(E)$, which represents the distribution function of the probability for neutron detection in the dd reaction, over the

deuteron collision energy:

$$P(E') = \frac{e^{-2\pi\eta} D(E') \int\limits_{E'}^{\infty} n_t(x(E,\, E'))F(E)dE}{\int\limits_{0}^{\infty} e^{-2\pi\eta} D(E')dE' \int\limits_{E'}^{\infty} n_t(x(E,\, E'))F(E)dE}, \tag{15}$$

where $n_t(x(E, E'))$ is the deuteron density in the target at the depth x, where the c.m.s. energy of the incident and target deuteron collision is $E' = E'(E, x)$; $D(E') = -\dfrac{1}{E'}\dfrac{dx}{dE'}$ is the specific Coulomb energy losses of beam deuterons caused by collisions with target deuterons.

To determine the ES potential of interacting deuterons in different deuterated substances, the expression $S(E') = S_b(E')f$ (Eq. 10) should be substituted into approximating expression (13) for the experimental neutron yield of the dd reaction.

In turn, expressions for the dd-reaction enhancement factor (9) and for $S_b(E')$ should be substituted into (10). The values of $S_b(E')$ are found from the R-matrix cross sections for the $d(d,n)^3$He reaction by Eq. (1) using the approximation by the polynomial [12]:

$$S_b(E) = A_1 + E(A_2 + E(A_3 + E(A_4 + EA_5))), \tag{16}$$

where $A_1, \ldots, A_5$ are parameters [12]:

$$A_1 = (5.3701 \cdot 10^1)\ \text{keV} \cdot \text{b}; \quad A_2 = (3.3027 \cdot 10^{-1})\ \text{b};$$
$$A_3 = (-1.2706 \cdot 10^{-4})\ \text{b/keV}; \quad A_4 = (2.9327 \cdot 10^{-8})\ \text{b/keV}^2;$$
$$A_5 = (-2.5151 \cdot 10^{-12})\ \text{b/keV}^3.$$

As is clear in the latter case, the only variable parameter is the potential of electron screening of the interacting deuterons U_e in different targets.

3. EXPERIMENTAL PROCEDURE

The $d(d,n)^3$He reaction in the deuterated metals Ti and Zr was experimentally studied using the plasma high-current Hall ion accelerator [45–47, 51] at the National Scientific Research Polytechnical University (Tomsk, Russia).

The experimental setup (Fig. 1) comprised the pulsed plasma Hall accelerator (PHA) with closed electron current that allowed acceleration of H^+, D^+, and $^3He^+$ plasma ions in the energy range $2 \div 15$ keV; scintillation detectors to detect 2.5 MeV neutrons from the dd reaction; two types of solid targets, one of zirconium deuteride and the other of titanium deuteride, with a system of their warming within the range from 20 to 200 °C; diagnostics equipment to monitor

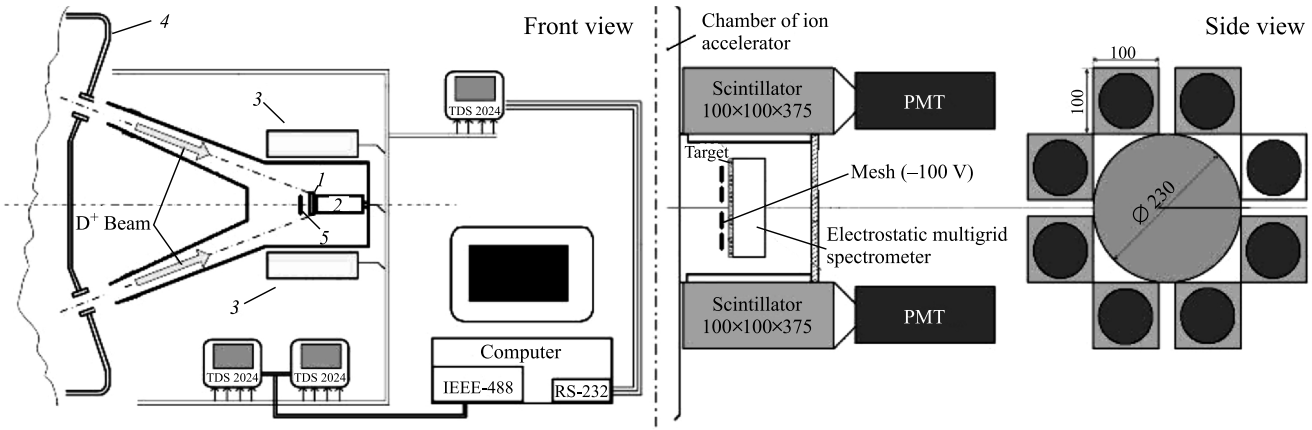

Fig. 1. Experimental setup: *1* — deuterium target; *2* — electrostatic multigrid spectrometer; *3* — plastic scintillation detectors, *4* — PHA, *5* — mesh

parameters of the deuteron beam incident of the target; and the system for monitoring the state of the target in the course of measurements.

A distinctive feature of the acceleration process in the Hall accelerator designed and built by us is conservation of quasi-neutrality of the accelerating ion layer due to sharply limited transverse mobility of magnetized electrons in the magnetic field [52, 53]. Under these conditions ion current density limitations by the space charge are removed and the limiting values of the ion current are governed by induction of the external magnetic field.

This method for production of intensive ion beams is characterized by stability of the acceleration process because the necessary level and zero lag of ion emission are provided by the external induction plasma source with pulsed gas bleed-in.

The design of the PHA provides the possibility of measuring parameters of the ion flow incident on the target (including energy distribution of ions) during the experiments [54, 55]. The main characteristics and advantages of the HA are the following: the plasma density is $(1 \div 2) \cdot 10^{13}$ cm^{-3}, which corresponds to the ion saturation current $\sim (1 \div 3)$ A/cm^2; electrodeless inductive discharge in the gas provides a low level of impurities; the HA provides control in a wide range of plasma parameters with respective ion current density up to ($\leqslant 1$ A/cm^2); the type of the filling gas could be easily changed for generating plasma of different ion species.

The targets were shaped as discs 97 mm in diameter and 2 mm thick, made of stainless steel with surface layers of Zr and Ti deuterides of average thickness 1.2 microns deposited by reactive DC magnetron sputtering (ALCATEL SCM650) of zirconium and titanium in the deuterium environment. The ultimate vacuum was less than $5{\cdot}10^{-7}$ Torr with liquid nitrogen shielding. The discharge gas was a mixture of D_2 and Ar (D_2/Ar ratio was 1:1) at the total pressure $1.5{\cdot}10^{-2}$ Torr.

The duration of the pulse of the accelerated deuteron flow generated by the Hall ion source was ~ 10 μs, the pulse repetition rate was $\sim 5 \cdot 10^{-2}$ Hz, and the integral number of deuterons in the pulse was $\sim 10^{14}$.

To determine the actual flow of the accelerated deuterons which hit the target, it is necessary to have information about the secondary electron emission from the target under the action of deuterons and neutrals formed via charge exchange of D ions on the residual gas in the measuring chamber of the accelerator during their transport from the PHA to the target. To suppress the emission of electrons from the target, a mesh with transparency of 93% was placed in front of the target at the distance of 1 cm and held at the potential $U_m = -100$ V. We developed methods for measuring the coefficient of secondary electron emission and determining the total number of accelerated particles (ions and neutrals) incident on the target. In addition to these measurements, the knowledge of the composition of accelerated particles is necessary to correct interpretation of the experimental data. These measurements were carried out in experiments with the time-of-flight technique.

In those experiments a number of important parameters of the accelerated flow of particles impinging on the target were measured: the efficiency of transporting the flow of accelerated particles from the exit of the PHA to the location of the target (base ~ 105 mm) in the angular span of $0 \div 20°$; the energy distribution function of the deuterons in the flow [53, 54]. The experimental results indicate that the fraction of the molecular D ions in the accelerated flow is negligible ($\leqslant 1\%$), while the neutrals produced in the charge exchange on the residual gas in the measuring chamber of the accelerator during their transport to the target make up $10 \div 15\%$, depending on the experimental conditions (the composition of the plasma source in the PHA, the partial pressure of the residual gas in the measuring chamber of the accelerator, where the ZrD_2 and TiD_2 targets were located).

The D current at the exit of the PHA was measured using the Rogowski coil with a passive RC integrator. The current density distribution of the ions incident on the surface of the deuterium target was measured by a linear set of collimated Faraday cups placed along the target radius. This diagnostics provided information in each pulse of the PHA on the radial distribution of the D current density over the target surface. The area of the D beam cross section in the target plane was $\sim$73.9 cm^2. The energy distribution of the D ions incident on the target was measured with the multigrid electrostatic energy spectrometer located behind the target in line with the ion flow [53, 54]. Figure 2 illustrates the integral and differential energy spectra of the deuterons which hit the ZrD_2 target in the experiment on the study of the dd reaction. The energy spread of the D beam in the energy range of $4 \div 15$ keV amounted to $14 \div 16\%$.

The in-depth distributions of the concentrations of the base elements and impurities in the targets of zirconium, titanium and tantalum deuterides were measured by the ERD (Elastic Recoil Detections) and RBS (Rutherford Backscattering Spectrometry) methods using the helium ion beam with the energy of

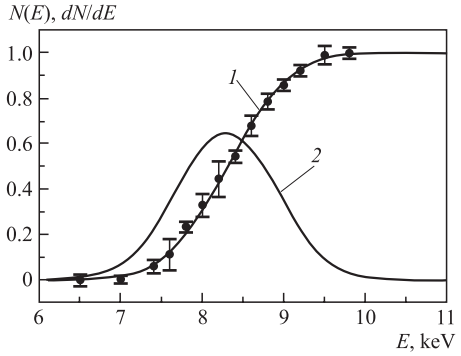

Fig. 2. Energy spectra of deuterons incident on the target: *1* — integral spectrum, *2* — differential spectrum

2.297 MeV [56–58] and by the method of level-by-level analysis of ZrD and TiD targets using the Auger electron spectroscopy [59].

Neutrons with the energy 2.5 MeV from the $d(d,n)^3$He reaction were detected by eight counters based on plastic scintillators, $100 \times 100 \times 375$ mm in size, placed around the measuring chamber of the accelerator (see Fig. 1). The neutron detection efficiency was calculated by the Monte Carlo simulation using the results of calibration of the detectors with the standard sources of neutrons (^{252}Cf, ^{239}Pu) and gamma rays (^{137}Cs, ^{60}Co, ^{224}Th). The relative neutron detection efficiency at the experimental energy threshold of recoil proton detection (160 ± 6) keV was found to be (0.230 ± 0.013). The given estimate of the efficiency is a summation of the statistical deviation, the geometry error in determining the distance and the location of the neutron detectors with respect to the target; the error in the measurement of the radial distribution of the impinging beam deuterons over the target; the error in determining the threshold amplitude of the neutron detection system; the errors in the cross-section values for the interactions of 2.5 MeV neutrons with different substances located between the target and the neutron detectors, and also with the plastic scintillator.

The experimental setup is described in detail in [38, 41, 45–47, 51, 54, 55].

4. ANALYSIS OF EXPERIMENTAL DATA

To measure the dependence of the astrophysical S-factors for the dd reaction on the collision energy of the deuterons in the targets of ZrD_2 and TiD_2 and calculate the respective electron screening potentials (ESPs), it is needed to have correct information on distribution of deuterons along the target depth. The measurements of the in-depth deuterium concentration distributions obtained by the ERD and RBS methods [56–58] in zirconium and titanium deuterides showed the uniform distribution with the ratios $x = N_{\rm D}/N_{\rm Zr(Ti)} \approx 2.0$, where $N_{\rm D}$, $N_{\rm Ti}$, and $N_{\rm Zr}$ are the concentrations of the D, Zr, and Ti atoms, respectively.

In addition to the ERD and RBS methods, we used the level-by-level analysis of the ZrD and TiD targets based on the Auger electron spectroscopy [59] to determine more precisely the surface layer composition of the targets, including the «parasitic» film formed on it due to the presence of the residual gas ($< 5 \cdot 10^{-7}$ Torr) in the chamber of the accelerator and to find the total thickness of the zirconium and titanium deuteride layers. The Auger spectrometer with the energy resolution of 0.1% included an electron source that forms the probing e-beam with the energy 3 keV, 1 mm in diameter, and an analyzer of electrons. For sputtering the sample surface, an argon ion beam 0.5 mm in diameter was used. Its axis was tilted at an angle of 70° relative to the normal to the surface of the sample.

The Auger analysis gives information on the in-depth atomic concentration distribution of zirconium, titanium, carbon, nitrogen, and oxygen in the layers of

metal deuterides with thickness of $(500 \div 600) \cdot 10^{-7}$ cm and in the «parasitic» layer with thickness of $(1 \div 2) \cdot 10^{-7}$ cm (this method of analysis is not sensitive to hydrogen isotopes). The results of the Auger measurements must be taken into account in the calculation of the respective energy loss of the deuterons during their passage through this «parasitic» film in front of the ZrD_2 and TiD_2 layers. According to our experimental data, the «parasitic» layer of organic material (CNO) at the surface subjected to vacuum cleaning was about $10^{-7} \div 2 \cdot 10^{-7}$ cm thick, which did not introduce a significant error in the interpretation of the measured yield of neutrons from the dd reaction in the calculation of the astrophysical S-factor and ES for the dd reaction.

This conclusion follows from the fact that the energy loss of deuterons incident on the ZrD_2 and TiD_2 targets during the passage through the «parasitic» layer

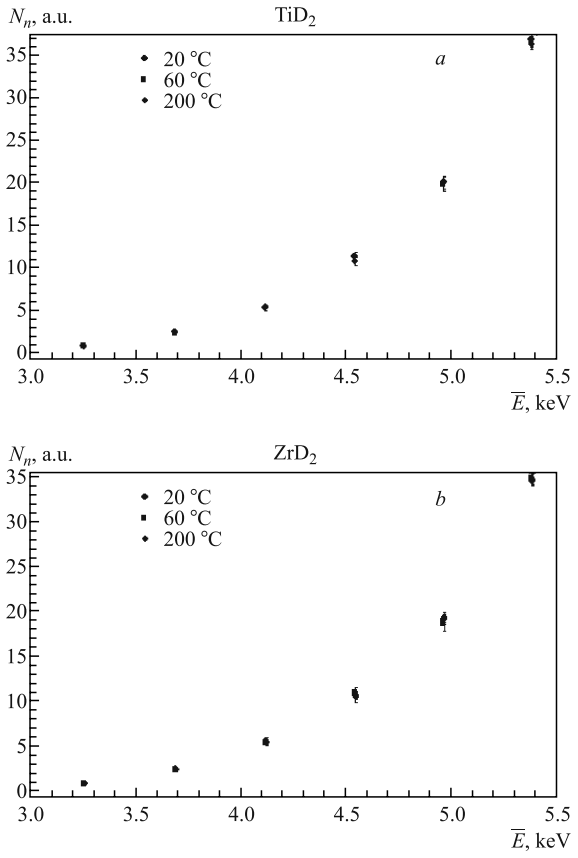

Fig. 3. Neutron yields as a function of the average deuteron collision energy in the center-of-mass system at the temperatures 20, 60, and 200 °C: *a*) TiD_2 target; *b*) ZrD_2 target

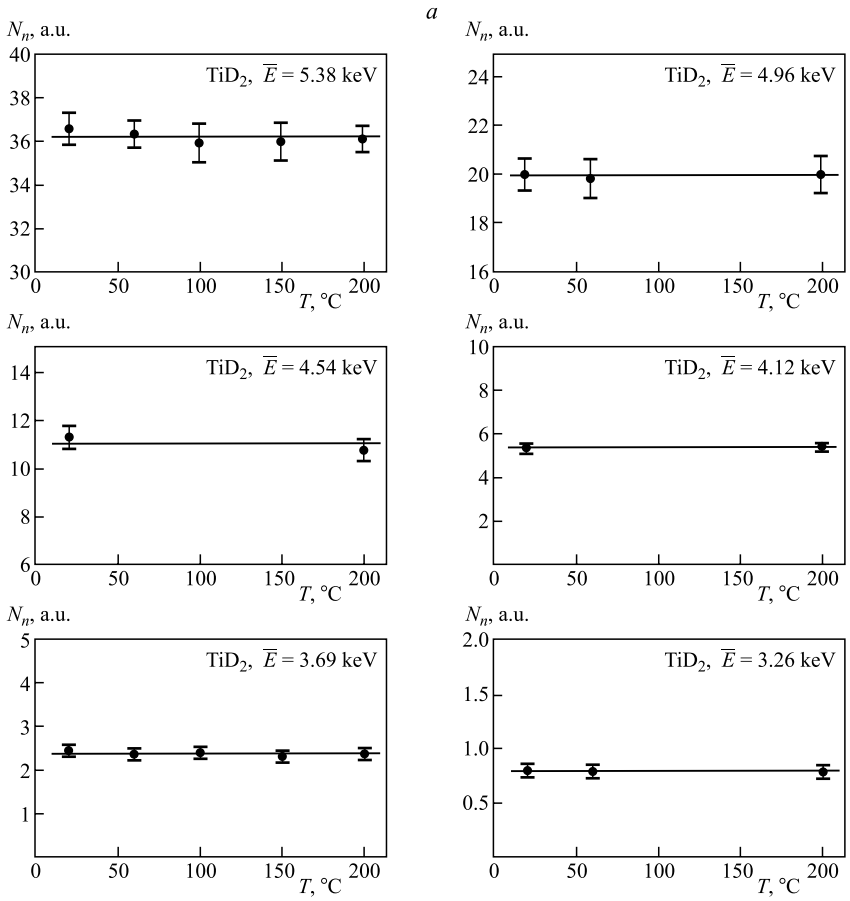

Fig. 4*a*. Dependence of the relative experimental neutron yields on the temperature of TiD_2 target for different average deuteron collision energies in the center-of-mass system. The solid curve is the result of averaging

was extremely small and practically did not change the initial energy distribution of the deuterons.

The Auger results together with the results of the joint analysis of the ERD and RBS spectra were used in the final calculation of the in-depth distributions of deuterons in the layers of titanium and zirconium deuterides.

The combination of three methods (ERD, RBS and the Auger spectroscopy) for the final calculation of the in-depth distribution of deuterons in the layers of titanium and zirconium deuterides deposited on the substrate was a well-justified methodological approach. It provided reliable unambiguous information on the in-depth distribution of the deuteron concentration up to two microns and elemental

b

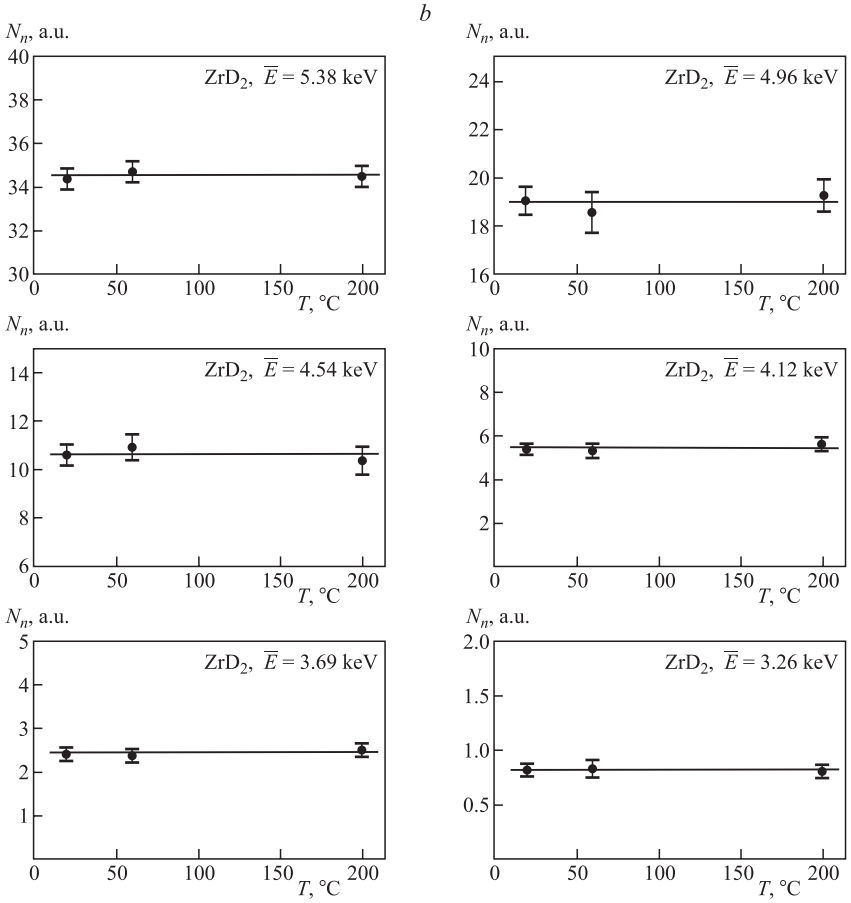

Fig. 4*b*. Dependence of the relative experimental neutron yields on the temperature of ZrD_2 target for different average deuteron collision energies in the center-of-mass system. The solid curve is the result of averaging

composition of the organic film formed at the surface of the target. The latter was important for correct processing of the data obtained in the study of dd reactions in the ultralow energy range.

We measured the dependence of the neutron yields from the $d(d,n)^3$He reaction on the average deuteron collision energy $\bar{E}$ in the range of $3.3 \div 5.4$ keV using ZrD_2 and TiD_2 targets in the temperature range $20 \div 200\,^\circ$C. By way of example, Fig. 3 shows dependences of the neutron yields from the dd reaction on the deuteron collision energy measured in the TiD_2 and ZrD_2 targets at the temperatures 20, 60, and 200 °C.

Figure 4 shows dependences of the neutron yields from the dd reaction (in relative units) on the temperature of the TiD_2 and ZrD_2 targets for different average deuteron collision energies in the center-of-mass system. As is evident, the experimental results shown in Figs. 3 and 4 indicate within the statistical experimental errors that the neutron yield from the dd reaction in titanium and zirconium deuterides does not depend on the temperature in the range of average deuteron collision energies from 3.3 to 5.4 keV. Considering (14), the results obtained allow the conclusion that the values of the astrophysical S-factors corresponding to the same average deuteron collision energies in the range $3.3 \div 5.4$ keV do not depend on the temperature of titanium and zirconium deuterides. Thus, according to (10), the dd-reaction enhancement factor f is also independent of the TiD_2 and ZrD_2 temperature, and so is (according to (9)) the electron screening potential.

Figure 5 shows dependence of the astrophysical S-factor on the average deuteron collision energy at the temperatures 20, 60, and 200 °C for the TiD_2 and ZrD_2 targets and the electron screening potentials for the dd reaction obtained by fitting the experimentally measured neutron yields for the dd reaction by expression (13) using equations (9), (10), and (16). The ESP values for both TiD_2 and ZrD_2 at the three given temperatures are seen to be in quite good agreement with the statistical measurement errors, which points to independence of the ESP from the temperatures of the deuterides. As to the absolute values of the electron screening potentials for dd reaction proceeding in TiD_2 and ZrD_2, the following is observed. The ESP for ZrD_2 is about a factor of 1.6 larger than the ESP for TiD_2.

The ESP values obtained by us for TiD_2 in the temperature range of $20 \div 200$ °C and the average deuteron collision energy range of $3.3 \div 5.4$ keV substantially differ from the results [22, 23], and the comparison of the data for ZrD_2 also shows noticeable disagreement with the results of both [22, 23] and [21] (see the Table).

As to the comparison of the results of this experiment with the calculations [21, 27], there is good agreement for TiD_2 and about a factor of 2 difference for ZrD_2.

The nature of this substantial disagreement between our results of the study of the dd reaction in titanium and zirconium deuterides and the results obtained in [21–23, 27] is still obscure.

Let us examine possible sources of systematic errors in the experiment. The main sources of these errors can be imperfect knowledge of the composition and thickness of the parasitic organic layer formed under the effect of the deuteron beam on the surface of the target at its different temperatures; imperfect knowledge of the energy distribution function of the deuterons incident on the target; and inaccurate determination of the background level at different target temperatures and different energies of the deuteron beam incident on the target. In the course of the experiment it was established by the quartz balance method (sensitivity

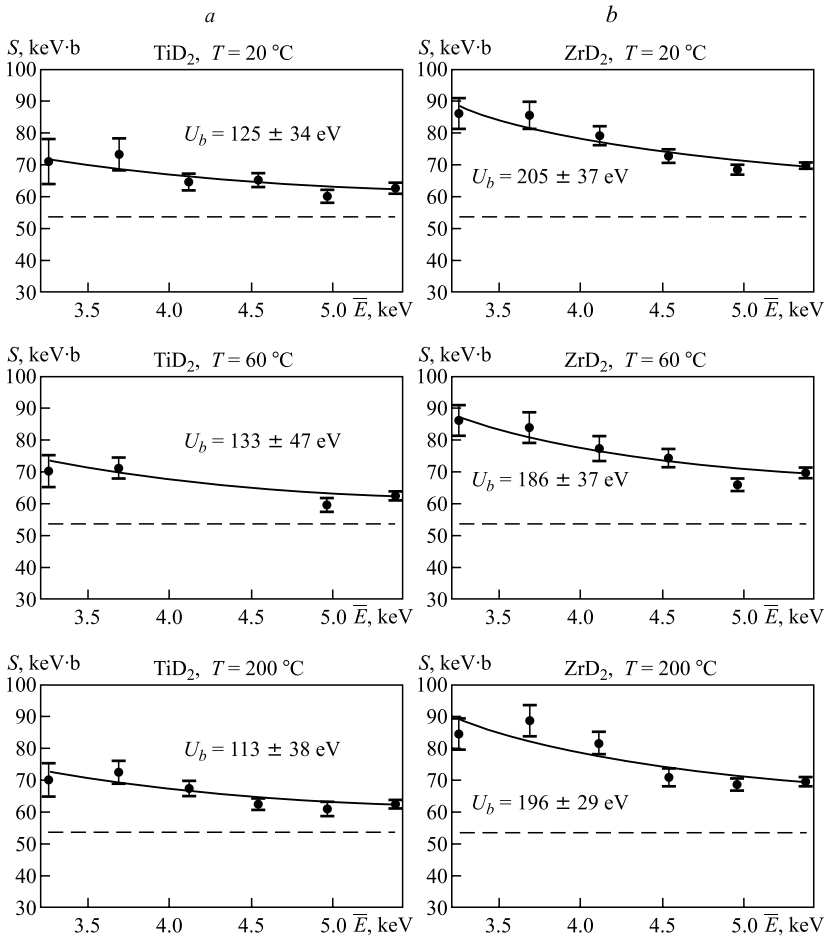

Fig. 5. Dependence of the experimental value for astrophysical S-factors on the average deuteron collision energies in the center-of-mass system at the target temperatures 20, 60, and 200 °C: *a*) TiD_2 target; *b*) ZrD_2 target. The dashed line is the calculated dependence of the dependences of the S-factor for the dd reaction in the case of interaction of bare deuterons. Solid lines are the calculated dependence of the S-factors for the dd reaction on the deuteron collision energy at the target temperatures 20, 60, and 200 °C obtained with the corresponding electron screening potentials U_e (shown directly in the plots)

$1.3 \cdot 10^{-8}$ g/cm^2) that the parasitic film of carbon, oxygen, and nitrogen atoms on the target surface was no thicker than $3.9 \cdot 10^{-7}$ g/cm^2 in the temperature range $20 \div 200$ °C. This mass thickness of the adsorbed parasitic layer (equivalent to the carbon film thickness of 2 nm) on the target surface cannot change the ratios

of neutron yields for different average deuteron collision energies at a noticeable experimental level; consequently, this experimental procedure for the study of the electron screening effect in deuterium-saturated metallic targets is appropriate.

All our results in the aggregate allow the unambiguous conclusion that there is no temperature dependence of the electron screening potential for the $d(d,n)^3$He reaction in ZrD_2 and TiD_2 in the average deuteron collision energy range $3.3 \div 5.4$ keV. This conclusion does not confirm suitability of Debye's plasma model for explaining the nature of the dd-reaction electron screening effect in deuterium-saturated metals and does not confirm the character of the dependence of the electron screening potential on the metal deuteride temperature.

5. CONCLUSIONS

Experiments on the influence of the electron screening effect (ESE) on the rate of the $d(d,n)^3$He reaction in the deuterides ZrD_2, TiD_2 in the ultralow deuteron collision energy range and temperature interval of $20 \div 200\,^\circ$C were carried on with a novel technique of high-current pulsed plasma Hall accelerator. The experimental results on the $d(d,n)^3$He reaction that we obtained so far using the pulsed ion accelerator and two different targets of metals saturated with deuterium substantiate the potential of the techniques based on pulsed high-current Hall accelerators for a detailed study of the reactions between light nuclei in the ranges of ultralow energies and temperatures.

As to comparison of our results from the experiments on dd reactions in the ZrD_2 and TiD_2 targets with other published experimental data (ZrD_2 [21, 22, 27]; TiD_2 [22, 23]), there is a significant difference the nature of which is still unclear. Some differences in the experiments on determination of potential electron screening energy for the dd reaction should be noted. First of all, the registered channel of the dd reaction in the experiments at the PHA was $d(d,n)^3$He [38, 41], and in all other studies [21, 23, 27] the registered channel was $d(d,p)t$. Second, we prepared the target for our experiment with predetermined stoichiometry by magnetron sputtering of zirconium and titanium in the ambient atmosphere of deuterium, in contrast with other laboratories [21, 23, 27], where the titanium and zirconium targets were implanted by a deuterium beam.

One important circumstance should be mentioned. The value of the electronic screening potential averaged over the temperature interval of $20 \div 200\,^\circ$C measured by us for the dd reaction in zirconium deuteride is 1.6 times higher than corresponding value for titanium deuteride.

An important result of this work is the conclusion that the ESP does not depend on temperature in the interval of $20 \div 200\,^\circ$C.

As regards the comparison of the results from this experiment on measurement of the ESP with the results of calculations, there is quite good agreement

for TiD2 and a difference of about a factor of 1.6 for ZrD_2. The nature of this disagreement is not clear as yet.

To elucidate the reasons for the existing discrepancies between the values of $U_e(ZrD_2)$ and $U_e(TiD_2)$ obtained by us and the corresponding values published in other works (ZrD_2 [21, 22, 27]; TiD_2 [22, 23]) and between the results [22, 23] and [21, 27], it is necessary to study thoroughly the dd-reaction mechanisms in a variety of target materials and wide ranges of temperature and collision energy.

In this regard, we plan to continue studying the $d(d,n)^3$He and $d(d,p)t$ reactions for determining the astrophysical S-factors and electron screening energies of interacting deuterons using the PHA and a wide range of targets made of dielectrics and metals saturated with deuterium.

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