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MEASUREMENT OF ASTROPHYSICAL S-FACTORS AND ELECTRON SCREENING POTENTIALS FOR $d(d,n)^3$He REACTION IN ZrD_2, TiD_2, D_2O AND CD_2 TARGETS IN THE ULTRALOW ENERGY REGION USING PLASMA ACCELERATORS

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Измерение астрофизических S-факторов и потенциалов электронного экранирования для $d(d,n)^3$He-реакции в ZrD_2-, TiD_2-, D_2O- и CD_2-мишенях при ультранизких энергиях, с использованием плазменных ускорителей

Настоящая работа посвящена изучению влияния эффекта электронного экранирования на скорость протекания $d(d,n)^3$He-реакции в диапазоне ультранизких энергий столкновения дейтронов в полиэтилене CD_2, замороженной тяжелой воде (D_2O) и дейтеридах ZrD_2 и TiD_2. Мишени из ZrD_2 и TiD_2 были изготовлены методом магнетронного распыления циркония и титана в среде дейтерия. Эксперименты проводились с использованием сильноточных импульсных плазменных ускорителей с формированием инверсного Z-пинча (ИСЭ РАН, Россия) и импульсного плазменного ускорителя Холла (ИЯФ при ТПУ, Россия). Регистрация нейтронов из dd-реакции с энергией 2,5 МэВ осуществлялась восемью сцинтилляционными спектрометрами на основе пластика. В результате анализа экспериментальных данных в диапазоне энергий столкновения дейтронов 2–7 кэВ получены энергетические зависимости астрофизического S-фактора для dd-реакции, а также определены значения потенциалов электронного экранирования U_e взаимодействующих дейтронов в указанных выше мишенях: $U_e(CD_2) \leqslant 40$ эВ; $U_e(D_2O) \leqslant 26$ эВ; $U_e(ZrD_2) = (157 \pm 43)$ эВ; $U_e(TiD_2) = (125 \pm 34)$ эВ. В опыте с мишенью из D_2O найдено значение S-фактора при энергии столкновения дейтронов, равной нулю: $S_b(\mathrm{O}) = (58{,}6 \pm 3{,}6)$ кэВ · б.

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Measurement of Astrophysical S-Factors and Electron Screening Potentials for $d(d,n)^3$He Reaction in ZrD_2, TiD_2, D_2O and CD_2 Targets in the Ultralow Energy Region Using Plasma Accelerators

The present paper is devoted to study of electron screening effect influence on the rate of $d(d,n)^3$He reaction in the ultralow deuteron collision energy range in the deuterated polyethylene (CD_2), frozen heavy water (D_2O) and deuterated metals (ZrD_2 and TiD_2). The ZrD_2 and TiD_2 targets were fabricated via magnetron sputtering of titanium and zirconium in gas (deuterium) environment. The experiments have been carried out using high-current plasma pulsed accelerator with forming of inverse Z-pinch (HCEI, RAS, Russia) and pulsed Hall plasma accelerator (NPI at TPU, Russia). The detection of neutrons with an energy of 2.5 MeV from dd reaction was done with eight plastic scintillation spectrometers. As a result of the experiments, the energy dependences of astrophysical S-factor for the dd reaction in the deuteron collision energy range of 2–7 keV and the values of the electron screening potential U_e of interacting deuterons have been measured for the targets indicated above: $U_e(CD_2) \leqslant 40$ eV; $U_e(D_2O) \leqslant 26$ eV; $U_e(ZrD_2) = (157 \pm 43)$ eV; $U_e(TiD_2) = (125 \pm 34)$ eV. The value of astrophysical S-factor, corresponding to the deuteron collision energy equal to zero, in the experiments with D_2O target is found: $S_b(0) = (58.6 \pm 3.6)$ keV · b (D_2O). The paper compares our results with results of other available published experimental and calculated data.

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 in ultralow energy region ($\sim$ keV)

$$dd \begin{array}{l} \rightarrow {}^3\mathrm{He}(0.8\ \mathrm{MeV}) + n(2.5\ \mathrm{MeV}), \quad (1a) \\ \rightarrow p(3.0\mathrm{MeV}) + t(1.03\mathrm{MeV}), \quad (1b) \end{array}$$

$$pd \rightarrow {}^3\mathrm{He} + \gamma(5.5\ \mathrm{MeV}), \quad (2)$$

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

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

$$d^6\mathrm{Li} \rightarrow 2\alpha(22.4\ \mathrm{MeV}) \quad (5)$$

is of a great interest due to possibility of: verification of fundamental symmetries in strong interaction (charge and isotopic invariance of nuclear forces) [1, 2]; acquisition of information on contribution and structure of exchange meson currents [3, 4], contribution of which to interaction in the ultralow energy region becomes significant (e.g., in case of radiative capture of protons by deuterons and tritons: $p + d \rightarrow {}^3\mathrm{He} + \gamma$; $p + t \rightarrow {}^4\mathrm{He} + \gamma$); acquisition of information for microscopic description of nucleon–nucleon interaction; testing of theoretical articles dedicated to three-body tasks solution based on modern representation of nucleon–nucleon interaction potential within the bounds of realistic two-body, two-body plus three-body forces [5]. Concerning astrophysics, there is a need for the reliable experimental information on parameters of all general processes, included in hydrogen and carbon cycles, that occurs in the stars with ultralow energy of nuclei interaction [6–8].

It is assumed in the modern star models that, at the high level of the star matter density reached in the process of the star evolution, the rate of the nuclear reactions increases, due to the screening of positively charged nuclei by negatively charged electrons. Electron screening (ES) results in the effective decrease of Coulomb barrier and thus in the increase of the nuclear reaction rate [9–11].

In case of interaction between «bare» nuclei (without ES) the cross section of the considered reaction in the ultralow energy region could be represented as a product of Gamov barrier factor, due to the Coulomb repulsing of particles in the entrance channel, and astrophysical S-factor for the reaction [8, 9, 12–15]:

$$\sigma_b(E) = \frac{S_b(E)}{(E)} \exp(-2\pi\eta), \quad 2\pi\eta = 31.29 Z_1 Z_2 (\mu/E)^{1/2} \tag{6}$$

here η — Sommerfeld parameter; E — incident particles collision energy of reaction entrance channel in the c.m. system; Z_1, Z_2, μ — incident particles charges and reduced mass in a.e.m., respectively; $S_b(E)$ — astrophysical S-factor for the reaction between «bare» nuclei at the collision energy E.

At present there are experimental data substantiating relative increase of dd-reaction cross section that occurs in deuterium-filled targets (gas targets and deuterated metals) as well as in some dielectrics and insulators at deuteron collision energies of 1.6–10 keV [9, 16–25]. ES effect was also observed and taken into account when studying d^3He and d^6Li reactions [17, 26–29] at deuterons and helium (lithium) collision energies of 2–13.8 keV (10.0–65.0 keV for d^6Li reaction). In particular, the effect of ES is taken into account to extract correctly the parameters of a wide 2^+ resonance of the compound nucleus, which contributes to the cross section of d^6Li reactions at low energies [29].

Accounting for the existence of ES effect, Eqs. (6), which are valid for «bare» deuteron interaction description, could be transformed to

$$\sigma_{\rm scr} = \sigma_b f, \tag{7}$$

$$S_{\rm scr} = S_b f, \tag{8}$$

here f is the factor of enhancement rate of dd reaction caused by the ES of interacting deuterons.

Taking into account ES of nuclei charges, the cross section of the reaction $\sigma_{\rm scr}(E)$ could be written [9, 26, 28] as follows:

$$\sigma_{\rm scr}(E) = \frac{S_b(E)}{E + U_e} \exp(-2\pi\eta(E + U_e)), \tag{9}$$

here U_e is the screening energy.

Therefore, the enhancement factor of a reaction between light nuclei in ultralow collision energy region

$$f = \frac{E}{E + U_e} \exp(-2\pi\eta(E + U_e) + 2\pi\eta(E)), \tag{10}$$

even at $U_e \ll E$,

$$f \approx \exp(\pi\eta(E) U_e / E) \tag{11}$$

can achieve a great magnitude.

Study of the ES effect for the dd reaction has been carried out in a more detailed way and with a wide variety of target materials compared with that for d^3He and d^6Li reactions. It is due to the fact that the yields of the $d(d,p)t$ and $d(d,n)^3$He reactions in the ultralow deuteron collision energy region (2–10 keV) substantially exceed respective yields in the d^3He and d^6Li reactions. This gives the opportunity not only to determine values of astrophysical S-factors and ES potentials with high confidence level for both dd-reaction channels, but also to carry out the correct comparison of these values with the results of theoretical calculations.

The results of the $d(d,p)t$-reaction study fulfilled up to the present time confirm the existence of the correlation between ES effect and periodicity of the chemical elements of the target material, as well as the degree of target saturation by deuterium and the target temperature [16, 18–25, 30–31]. At the same time, the experiments on dd reaction in metallic targets [18–25, 30–31] show a divergence between the results as well as with the calculations based on traditional models of atomic physics [10, 19]. Particularly this statement relates to the results of experiments with dd reaction in ZrD [19–21, 25] and TiD [18, 20, 21] targets (see table). The table represents the compilation of measured ES potentials in respective metallic targets.

Electron screening potentials for deuterated targets ZrD and TiD

Target	Temperature, °C	Solubility of deuterium	Experimental U_e, eV	Theoretical U_e, eV
ZrD	20	$ZrD_{1.1}$	$\leqslant 40$ [20]	
	200	$ZrD_{0.13}$	205 ± 70 [21]	
	20	ZrD_2	297 ± 8 [19]	112 [19]
	20	ZrD_2	319 ± 3 [25]	
TiD	–88	$TiD_{3.76}$	66 ± 15 [18]	
	20	$TiD_{1.3}$	$\leqslant 30$ [20]	100 [19]
	50	$TiD_{1.1}$	$\leqslant 50$ [21]	
	100	$TiD_{0.26}$	250 ± 40 [21]	
	150	$TiD_{0.23}$	295 ± 40 [21]	

For clarification of the nature of such a divergence between the results of various studies (see table), we have performed the experimental study of $d(d,n)^3$He reaction in the ultralow deuteron energy region (4–15 keV), using TiD_2 and ZrD_2 targets at the temperature 293 K. The results of these experiments are presented below in the Sect. 4.3. Besides, to obtain a quantitative information on ES potential of n^3He channel in dd reaction occurring in dielectrics (deuterated polyethylene CD_2 and frozen heavy water D_2O), we performed reanalysis of previous experiments carried out with targets of these materials [32–36]. The results of this analysis are presented in Sects. 4.1. and 4.2.

2. METHOD OF MEASUREMENT

The experimental determination of the astrophysical S-factors and effective cross section for $d(d,n)^3$He reaction is based on the measurement of the neutron yield in the reaction (1a) and parameterization (6) which represents cross section dependence on deuteron collision energy. Method of determination of ES potentials in different targets is based on measuring the neutron yields dependence on deuteron collision energy and then its fitting by analytical expression (12) that includes parameterization of dd-reaction cross section with and without ES effect including (see Eqs. (6), (7), and (10)).

The expression that represents experimentally measured neutron yield for dd reaction reads as follows:

$$N_n^{\exp} = N_d \varepsilon_n \int\limits_0^\infty F(E)dE \int\limits_0^\infty n_t(x) \frac{\mathrm{e}^{-2\pi\eta} S(E')}{E'} dx, \qquad (12)$$

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

Without including electron screening effect the experimental values of astrophysical S-factors for dd reaction in TiD_2, ZrD_2, D_2O and CD_2 targets, corresponding to specified average values of deuteron collision energies, could be defined as follows [32–35]:

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

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

To determine the values of the ES potential of interacting deuterons in the different deuterated substances the expression $S(E') = S_b(E')f$ (Eq. (8)) should be substituted into the approximating expression (12) for dd-reaction experimental neutron yield and the values of $S_b(E')$ are calculated from R-matrix cross sections for $d(d,n)^3$He reaction with Eq. (6) using approximation by the Pade polynonial (13):

$$S_b(E) = A_1 + E(A_2 + E(A_3 + E(A_4 + EA_5))), \qquad (14)$$

where $A_1 = 5.3701 \cdot 10^1$ keV·b; $A_2 = 3.3027 \cdot 10^{-1}$ b; $A_3 = -1.2706 \times$ $\times\, 10^{-4}$ b/keV; $A_4 = 2.9327 \cdot 10^{-8}$ b/keV^2; $A_5 = -2.5151 \cdot 10^{-12}$ b/keV^3.

As is clear in the last case, the only variable parameter is ES potential of interacting deuterons U_e in the different target.

3. EXPERIMENTAL TECHNIQUE

The experiments on $d(d,n)^3$He-reaction research were carried out using plasma high-current accelerator (I = 950 kA, τ = 80 ns) with Z-pinch forming at the Institute of High Current Electronics of RAS (Tomsk, Russia) [32, 33, 37–39] and Hall ion accelerator [34–36] at the Nuclear Physics Institute of Tomsk Polytechnic University (Tomsk, Russia).

The following text provides a brief description, in chronological order, of experiments on $d(d,n)^3$He-raction research at the previously named accelerators.

Experimental setup based on Z-pinch technology [32, 33, 37–39] included:

a) pulsed voltage generator;

b) load module;

c) diagnostics for measuring parameters of Z-pinch formation dynamics (magnetic dB/dt probe and bolometer);

d) detectors for measurement of optical plasma radiation and ion collectors for measurement of the energy distribution of the ions in the expanding liner;

e) deuterated target, gamma rays and neutron detectors.

The scheme of Z-pinch experimental setup is shown in Fig. 1.

The initial deuterium liner has been formed using fast electromagnetic valve and supersonic Laval nozzle.

A current-intercepting structure in the shape of a circular squirrel cage was installed on the way of the radially diverging plasma envelope. The radius of the calculated cage position defined the length of the liner acceleration. The current in the liner was measured with Rogowski coil. The optical radiation detectors LD1, LD2 and LD3 were located behind CIS at various radial distances from the axis. Optical radiation detectors represented assemblies of a collimator, quartz light guide and a photoelectron multiplier. The target has a shape of a cylinder surrounding liner with its inner surface coated by a CD_2 layer of 0.25 mm thickness. Fast neutrons from dd reaction were detected by a spectrometer D1 based on plastic scintillator and time-of-flight method.

Measuring of the total neutron flux, emitted from the target during deuterium (D)-liner interaction with the target, has been performed with thermal neutron detectors. Thermal neutron detector represented an assembly of 10 proportional ^{3}He counters, encased in the polyethylene moderator. For reducing x-ray and bremsstrahlung radiation impact on D1 and D2 detectors, they have been shielded with Pb layer of 5 cm thickness. The liner acceleration process has been controlled using two dB/dt probes, established at radii of 23 and 34 cm. Mass of the liner was calculated with a zero-dimensional model of the liner plus additional experimental information on the liner current dynamics, as well as dynamics of the moments of passage

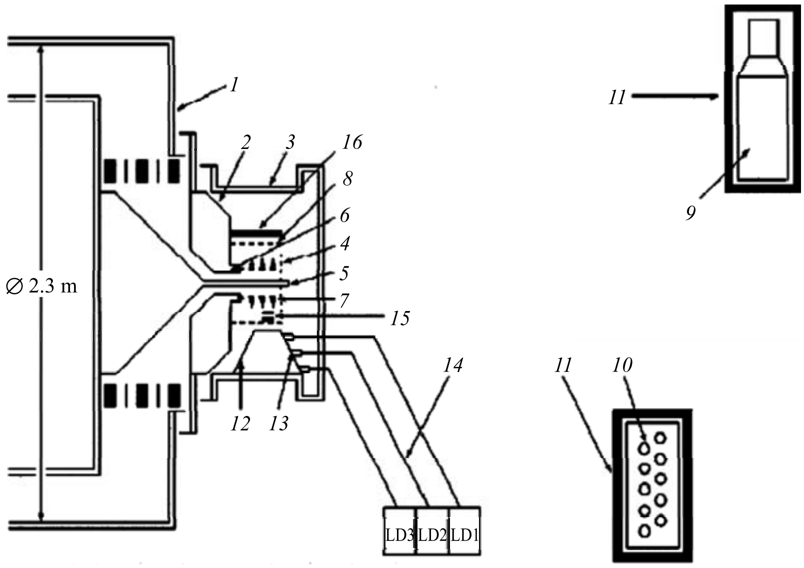

Fig. 1. Scheme of experimental setup: *1* — high-current generator; *2* — accelerator load unit; *3* — measuring chamber; *4* — grid cathode; *5* — reverse-current conductor; *6* — supersonic Laval nozzle; *7* — liner; *8* — current-intercepting rods; *9* — scintillation detector (D1); *10* — thermal-neutron detector (D2); *11* — Pb protective shield; *12* — light cone; *13* — collimators; *14* — fibers; *15* — dB/dt magnetic probes; *16* — deuterated polyethylene target

B probes of the current carrying envelope. The measurement of the energy flux density in the radially expanding plasma in the inverse Z-pinch was done with the precision foil bolometer.

The measurement of the deuteron energy distribution in the liner was done using three optical detectors LD1–LD3 and it was based on the registration of its optical radiation (H_α and H_β line) of plasma during its radial expansion from the axis.

The results of the dd experiment [32, 33] and pd experiment [40, 41] performed at the high-current plasma accelerators ($I \approx 950$ kA, $\tau = 80$ ns, and $I \approx 1.7$ MA, $\tau = 80$ ns, respectively) demonstrated, on the one hand, the promise of using liner plasma in the configuration of the inverse Z-pinch for the study of reactions between light nuclei in the field of ultralow-energy collisions, and, on the other hand, showed that the proposed technique could be of potential for nuclear diagnositics.

For the first time the characteristics of deuterium liner accelerated in the scheme of the inverse Z-pinch were studied. The values of astrophysical S-factor of dd reaction in the region of collision energy of deuterons 1.8–3.7 keV [32, 33] have been measured.

Nevertheless, the use of Z-pinch liner plasma, for measurement of characteristics of pd, dd, and d^3He reactions with a high precision still suffers from such a drawback as a low reproducibility of experimental parameters, which is endemic for high-power pulsed electronics, operating on the gigawatts power level. In our case it resulted in big statistical spread on shot-to-shot base in total number of accelerated ions in the liner, its total energy, shape of their energy distribution, which hindered analysis of the results.

Therefore, to improve the accuracy of study of nuclear reactions between light nuclei with the use of pulsed accelerators, we have designed and developed a Pulsed Hall Accelerator (PHA), operating at several orders longer pulse duration and lower power range compared with the Z-pinch technology, which allows one to accelerate the H^+, D^+ and $^3He^+$ ions in the energy range of 2–15 keV [34–36, 42, 43].

Figure 2 shows the experimental setup based on the PHA, which was used in the study of $d(d,n)^3$He reactions in the zirconium (ZrD_2) and titanium (TiD_2) deuterides, heavy water D_2O and deuterated polyethylene CD_2 targets. The experimental setup included 8 plastic scintillation detectors ($100 \times 100 \times 380$ mm) surrounding vacuum chamber of the PHA for registering 2.5 MeV neutrons from dd reaction; targets fabricated of ZrD_2, TiD_2, D_2O and CD_2; diagnostic equipment for measuring parameters of the accelerated deuterium ion beam and monitoring its conditions (Rogovsky belt, Faraday cylinders). The energy distribution of deuterium ions incident on the target was measured by the multigrid spectrometer. The radial distribution of accelerated deuteron beam was measured by an assembly of collimated Faraday cups. The PHA operated in the pulsed mode with pulse repetition rate $\sim 5 \cdot 10^{-2}$ Hz and an integral number of deuterons per pulse $\sim 10^{14}$.

Efficiency of neutron registration at a set threshold of 0.16 MeV (in units of equivalent electron energy) was 0.23. Calibration of the detectors was done with standard sources of γ rays (^{137}Cs, ^{60}Co, ^{88}Y) and neutrons (Po–Be). General description of the experimental setup is given in detail in [34–36].

In Fig. 3, as an example, the integral and differential energy spectra of deuterons which hit the ZrD_2 target in experiment on the study of dd reaction are presented. The energy spread of the D beam in the energy range of 4–15 keV made up 14–16%.

To determine the actual flow of the accelerated deuterons which hit the target, it is necessary to have information on the input of 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 a distance of 1 cm and held at the potential $U_m = -100$ V. We have developed methods of

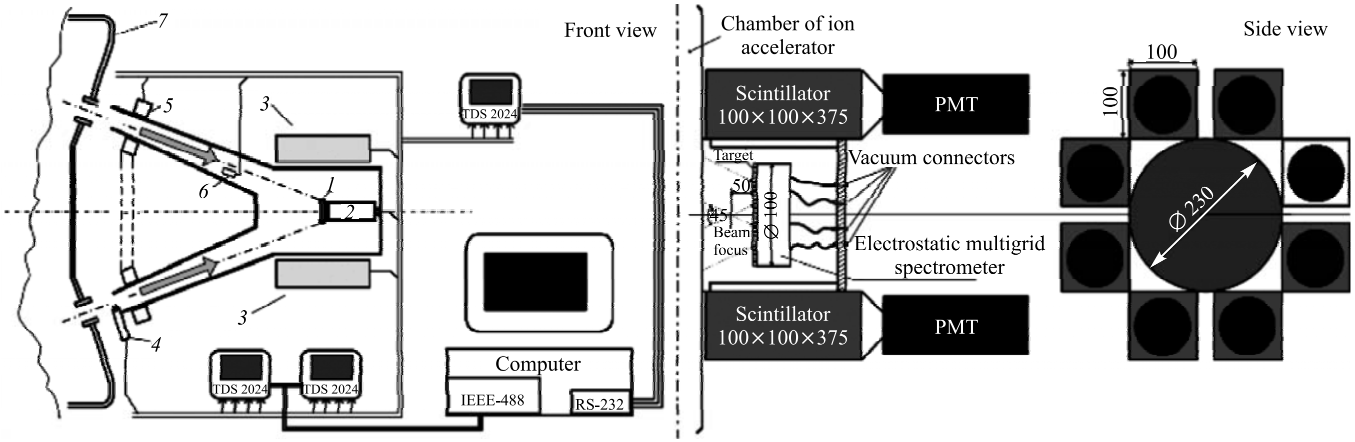

Fig. 2. Experimental setup: *1* — deuterium target; *2* — electrostatic multigrid spectrometer; *3* — plastic scintillation detectors; *4* — collimator of optical detector; *5* — Rogowski coil; *6* — Faraday cup; *7* — PHA

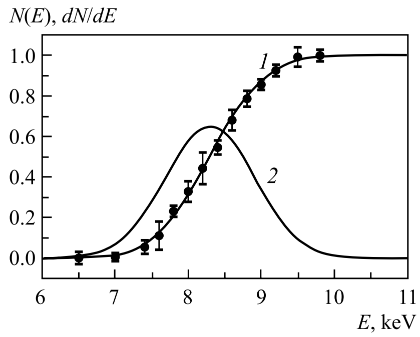

Fig. 3. Energy spectra of deuterons incident on the target: *1* — integral spectrum, *2* — differential

measuring the coefficient of secondary electron emission and determination of the full 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 for correct interpretation of the experimental data. These measurements were carried out in experiments with 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 0–20°; the energy distribution function of the deuterons in the flow. 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 residual gas in the measuring chamber of the accelerator during their transport to the target make up 10–15%, depending on the experimental conditions (the composition of the plasma source in the PHA, the partial pressure of residual gas in the measuring chamber of the accelerator, where the ZrD_2, TiD_2, D_2O and CD_2 targets were located.

4. EXPERIMENTAL DATA ANALYSIS

The digest of the analysis, based on the results of the entire data obtained so far in the experimental study of $d(d,n)^3$He reaction using Z-pinch technology (at high-current accelerators of the SGM and MIG) and the PHA, is presented in the next subsections.

4.1. CD_2 Target. Experiments on studying the $d(d,n)^3$He reactions using CD_2 targets were held both on pulsed power accelerators, the SGM and MIG [32, 33], and at the PHA [34, 36]. The disc-shaped CD_2 target was made of deuterated polyethylene 1 mm thick and 97 mm in diameter.

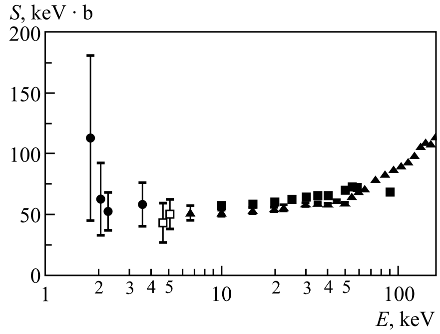

Fig. 4. Values of astrophysical S-factor for $d(d,n)^3$He reaction obtained in experiments with targets of CD_2 at different collision energies of deuterons. Filled circles and open squares — experimental values of S-factor measured in experiments using Z-pinch technology [32, 33] and Pulsed Hall Accelerator [34, 36], respectively. Filled squares and triangles — data from [42] and [43], respectively

Figure 4 shows the values of astrophysical S-factor of the $d(d,n)^3$He reaction, measured in these experiments.

The calculated upper limit of the ES potential in deuterated polyethylene for $d(d,n)^3$He reaction in CD_2 with 90% confidence level was determined as

$$U_e(\mathrm{CD_2}) \leqslant 40 \text{ eV}.$$

Comparison of our measurements of U_e values for CD_2 with the results of other studies was impossible because the latter are currently absent in the literature. The measured value of $U_e(\mathrm{CD_2})$ agrees within the measurement errors with the values of the ES potential for dd reaction, measured with targets made of insulators BeO, B, Al_2O_3, CaO_2 [20 24], which is consistent with the predictions of theoretical models.

4.2. D_2O Target. The next stage of $d(d,n)^3$He-reactions research were experimenting on the PHA with the heavy water target, D_2O [35, 36].

The D_2O target represented a 0.1 mm thick layer of frozen water, deposited on a copper disc with diameter 140 mm and thickness 1 mm, cooled by liquid nitrogen.

Figures 5 and 6 show the measured neutron yield and S-factor of the $d(d,n)^3$He reaction as function of the collision deuteron energy, obtained in a series of experiments with D_2O target.

The value of astrophysical S-factor corresponding to the deuterons collision energy equal to zero determined in our experiments with D_2O target was

$$S_b(0) = (58.6 \pm 3.6) \text{ keV} \cdot \text{b}.$$

The value of $S_b(0)$ obtained for the reaction $d(d,n)^3$He agrees within the statistical errors of measurement with the calculated values ($S_b(0) =$

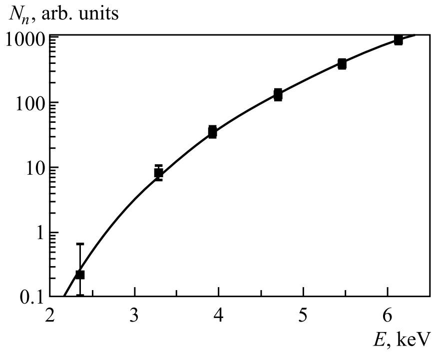

Fig. 5. Neutron yield of the dd reaction as a function of the deuteron collision energy in the experiment with the D_2O target. Solid line — calculated neutron yield, filled squares are the experimental data

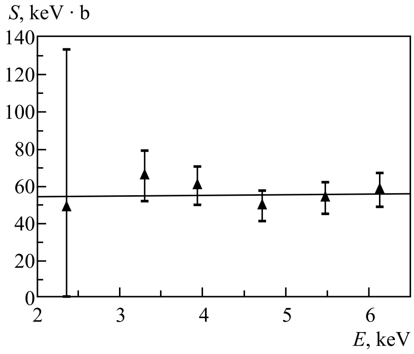

Fig. 6. The astrophysical S-factor of the dd reaction as a function of the deuteron collision energy for D_2O target. The filled triangles are the experimental data; solid line — approximation of the S-factor for the «bare» deuterons by the linear function $S_b\,(E) = S_b(0) + aE$

$= 53.7$ keV $\cdot$ b [9], 53 keV $\cdot$ b [13, 14]) and the experimental ($S_b(0) = (50.7 \pm \pm 5.0)$ keV $\cdot$ b [43], (53.8 ± 0.9) keV $\cdot$ b [42]) values of this quantity.

The χ^2-analysis gave for dd reaction in D_2O the upper boundary of ES potential value at the 90% confidence level:

$$U_e \leqslant 26 \text{ eV}.$$

Based on the value of χ^2 per freedom degree, it follows that both hypotheses for (1) existence, or (2) absence of the ES effect in the dd reaction in D_2O are relevant. To compare the obtained values of U_e in D_2O with the experimental results obtained in other studies is currently also impossible due to the absence of such data in literature. Nevertheless, the obtained value $U_e(D_2O)$ agrees with the values of ES potentials for dd reaction, measured in the targets of dielectrics and insulators [20, 24].

Based on the results presented in Figs. 4 and 6, we could conclude that even ES in CD_2 and D_2O exists, still its contribution to the value of astrophysical S-factor in these materials at ultralow energy of deuterons is small and lies within the statistical errors of measuring the neutron yield. This conclusion is substantiated by low estimated values of upper boundary for the ES potentials in CD_2 and D_2O targets.

4.3. TiD_2, ZrD_2 Targets. The experiments on measuring the ES in deuterides of zirconium and titanium were similar to the prior experiments at PHA with CD_2 and D_2O targets (Subsects. 4.1 and 4.2). The targets were of disc shape, 97 mm diameter and 2 mm thickness, fabricated of stainless steel with surface layers of Zr and Ti deuterides of average thickness 1.2 microns, deposited by magnetron sputtering of zirconium and titanium in the deuterium environment [44].

The in-depth distributions of the concentrations of the base elements and impurities in the zirconium and titanium deuterides targets were measured by the ERD (Elastic Recoil Detection) and RBS (Rutherford Backscattering Spectrometry) methods using helium ion beam with an energy of 2.297 MeV [45–47]. Results of measurements showed the uniform in-depth distributions of the deuterium concentration in zirconium and titanium targets with ratio x equal to $x = N_{\mathrm{D}}/N_{\mathrm{Zr(Ti)}} \approx 2.0$, where N_{D}, $N_{\mathrm{Zr(Ti)}}$ are concentrations of D atoms and zirconium (titanium) atoms, respectively.

In addition to the ERD and RBS methods, for more precise determination of surface layer composition of the target including «parasitic» film formed on it due to the presence of the residual gas (10^{-6} mm Hg) in the chamber of the accelerator, as well as to determine the total thickness of deuterides zirconium (titanium) layers thickness, we used the method of layering Auger electron spectroscopy [48]. Auger spectrometer with energy resolution 0.1% included electron source forming the probing e-beam with 3 keV energy, 1 mm in diameter, and analyzer of electrons. For sputtering the sample surface, an argon ion beam of diameter 0.5 mm has been used. Its axis was tilted at an angle of 70° relative to the normal to the surface of the sample.

The result of Auger analysis gives information on atomic in-depth concentrations distribution of zirconium (titanium), carbon, nitrogen, oxygen in the layer of zirconium deuteride of thickness 500–600 Å and in the «parasitic» layer (this method of analysis is not sensitive to the hydrogen isotopes). The results of Auger measurements must be taken into account when calculating the respective energy loss of the deuterons during their transition through this «parasitic» film in front of Zr(Ti) D_2 layer. According to our experimental data at the surface subjected to vacuum cleaning, «parasitic» layer consisting of organic material (CNO) was about 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 values of the astrophysical S-factor and the ES values for dd reaction.

This conclusion follows from the fact that the energy loss of deuterons incident on the target of ZrD_2 and TiD_2 during the transition of «parasitic» layer was extremely small and practically did not change the initial energy distribution of deuterons.

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

The combination of three methods (ERD, RBS and Auger spectroscopy) for final calculation of 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 2 microns and elemental 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.

Figures 7 and 8 present the measured astrophysical S-factor as a function of collision energy for dd reaction and the results of their approximation for two different target materials, ZrD_2 and TiD_2. The respective ES potentials were determined to be

$$U_e(\mathrm{ZrD_2}) = (157 \pm 43)\ \mathrm{eV}; \quad U_e(\mathrm{TiD_2}) = (125 \pm 34)\ \mathrm{eV}.$$

The found value of $U_e(\mathrm{ZrD_2})$ at the temperature of ZrD_2 $T = 20°\mathrm{C}$ considerably exceeds the value of this characteristics obtained in work [20], and it is substantially higher than the upper limit found in [20] (degree of deuterium saturation of ZrD_2 in that experiment was approximately two times lower than in the present one), and it is approximately twice lower than the value obtained in [19, 25] (see table).

The nature of such a sharp divergence between results of the present work and [19, 20, 25], as well as among results of works [19, 20, 25], remains unclear.

At the same time, the value of $U_e(\mathrm{ZrD_2})$ found in the present experiment at temperature of a zirconium deuteride $T = 20°\mathrm{C}$ within statistical errors

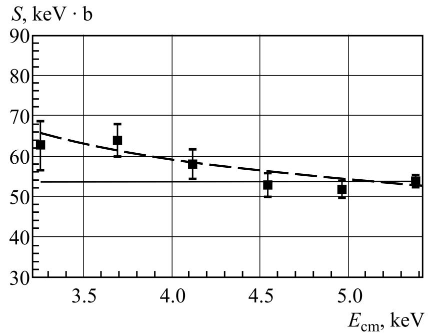

Fig. 7. The astrophysical S-factor as a function of dd-reaction energy collision in ZrD_2 target. The filled squares are the experimental data (Eq. (13)), solid line — calculated S-factor for the «bare» deuterons (Eq. (14)), dashed line — calculated S-factor for the dd reactions obtained by using Eqs. (8), (10) and (14), with $U_e(\mathrm{ZrD_2}) = 157$ eV

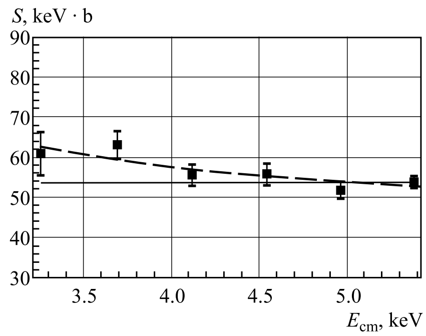

Fig. 8. The astrophysical S-factor as function of dd-reaction energy collision in TiD_2 target. The filled squares are the experimental data, solid line — calculated S-factor for the «bare» deuterons (Eq. (14)), dashed line — calculated S-factor for the dd reactions obtained by using Eqs. (8), (10) and (14) for $U_e(\mathrm{TiD_2}) = 125$ eV

concurs with the measured value of $U_e(\mathrm{ZrD_2})$ [21] at temperature $T = 200°\mathrm{C}$ (see table).

Comparing the values of $U_e(\mathrm{TiD_2})$ obtained by us and in the experiment [20] at titanium deuteride temperature $T = 20°\mathrm{C}$, we see a substantial discrepancy, and at the same time there is a rather good agreement between the result of the present work and theoretical calculation [19] (see table).

5. CONCLUSION

Experiments on influence of electron screening effect on the astrophysical S-factor of $d(d,n)^3\mathrm{He}$ reaction in the ultralow deuteron collision energy range were carried on with novel technique of high current inverse Z-pinch and pulsed Hall plasma accelerator. Up to 2001 the published data covered mainly the reaction $dd \rightarrow p + t$. For reaction channel ($dd \rightarrow {}^3\mathrm{He} + n$), the experimental data were available only for a higher energy range compared with our range (6 keV in [43]).

The experimental results of studying the $d(d,n)^3\mathrm{He}$ reaction we have obtained so far using two types of pulsed accelerators and four different targets, fabricated of dielectric (CD_2 and D_2O) and metals saturated with deuterium (ZrD_2, TiD_2), substantiate the potential of using techniques based on pulsed high current and Hall accelerators for a detailed study of the reactions between light nuclei in the range of ultralow energies.

When comparing results of our experiments on $d(d,n)^3\mathrm{He}$ reaction in dielectrics CD_2 and D_2O with other experimental data [20, 24] on the reaction $d(d,p)t$ in gaseous deuterium targets, as well as in targets fabricated of various types of insulators (BeO, B, Al_2O_3, CaO_2), there is no difference between them beyond statistical errors of measurement. As for comparing our results of experiments on dd reactions in ZrD_2 and TiD_2 targets with other published experimental data (ZrD_2 — [19, 20, 25]; TiD_2 — [20]) there is a very significant difference, the nature of which is still unclear. Some differences in the experiments on determination of ES energy for dd reaction should be noted. First of all, the registered channel of dd reaction in experiments at the PHA was $d(d,n)^3\mathrm{He}$ [34–36], and in all other studies [16, 18–25, 30, 31] the registered channel was $d(d,p)t$. In the second place, we prepared the target for the present experiment with a predetermined stoichiometry by a magnetron sputtering of zirconium and titanium in the ambient atmosphere of deuterium, as distinct from other laboratories [18–21, 25], where the titanium and zirconium targets were implanted by a deuterium beam.

It is worthy to note one more important circumstance. The values of potentials of electronic screening measured by us for dd reaction in deuterides of the titanium and zirconium at temperature $T = 20°\mathrm{C}$ are matched in respect to each other within statistical errors. This is substantiated by theoretical calculations of $U_e(\mathrm{ZrD_2})$ and $U_e(\mathrm{TiD_2})$ values [19].

To elucidate the reasons for the existing discrepancies between values of $U_e(\mathrm{ZrD_2})$ and $U_e(\mathrm{TiD_2})$ obtained by us and corresponding values published in other works ($\mathrm{ZrD_2}$ — [19, 20, 25]; $\mathrm{TiD_2}$ — [20]) as well as between results [19, 20, 25], it is necessary to obtain an unambiguous answer to the question — is there a meaningful experimental effect of the ES of interacting deuterons in metals saturated with deuterium — a more precise study of the dd-reaction mechanisms in a variety of materials, wide temperature range of targets and collision energies of deuterons is necessary.

In this regard, we plan to continue study on the $d(d,n)^3$He and $d(d,p)t$ reactions for determination of astrophysical S-factors and ES energies of interaction deuterons using the PHA and a wide range of targets dielectrics and metals saturated with deuterium.

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References

1. J. L. Friar, Proceedings of the International Conference on the Theory of Few Body and Quark-Hadronic System, Dubna, D4-87-692,70 (1987).
2. H. G. S. Chulick, Y. E. Kim, R. A. Rice *et al.*, Nucl. Phys. A 551, 255 (1993).
3. J. Torre and B. Goulard, Phys. Rev. C 28, 529 (1983).
4. J. L. Friar, B. F. Gibson, H. C. Jean *et al.*, Phys. Rev. Lett. 66, 1827 (1991).
5. V. F. Kharchenko, M. A. Navrotsky and P. A. Katerinchuk, Yadernaya Fizika 55, 86 (1992).
6. J. N. Bachall and M. H. Pinsonneault, Rev. Mod. Phys. 64, 1265 (1992).
7. V. B. Belyaev, A. Bertin, V. M. Bystritskii *et al.*, Nukleonika 40, 85 (1995).
8. C. E. Rolfs, W. S. Rodney, Cauldrons in the Cosmos, Chicago Press, Chicago, 1988.
9. H. J. Assenbaum, K. Langanke and C. Rolfs, Z. Phys. A 327, 461 (1987).
10. S. Ichimaru, Rev. Mod. Phys. 65, 252 (1993).
11. G. Shaviv, N. J. Shavi, Astrophys. J. 529, 1054 (2000).
12. E.G. Adelberger, S. M. Austin, J. N. Bahcall *et al.*, Rev. Mod. Phys. 70, 885 (1998).
13. H.-S. Bosch, G. M. Hale, Nuclear Fusion 32, 611 (1992) and references therein.
14. M. Rambaut, Phys. Lett. A 164, 155 (1992).
15. Theodore E. Liolios, arXive: nucle-th/0005011 v2, Sep 2000.
16. U. Greife, F. Gorris, M. Junker *et al.*, Z. Phys. A 351, 107 (1995).
17. M. Aliotta, F. Raiola, G. Gyurky *et al.*, Nucl. Phys. A 690, 790 (2001).
18. J. Kasagi, H. Yuki, T. Baba *et al.*, J. Phys. Soc. Jpn. 71, 2881 (2002).
19. K. Czerski, A. Huke, P. Heide *et al.*, Eur. Phys. J. A 27, 83 (2006).

20. F. Raiola, L. Gang, C. Bonomo *et al.*, Eur. Phys. J. A 19, 283 (2004).
21. F. Raiola, B. Burchard, Zs. Fulop *et al.*, Eur. Phys. J. A 27, 79 (2006) and references therein.
22. A. Huke, K. Czerski, P. Heide, Nucl. Instrum. Meth. B 256, 599 (2007) and references therein.
23. K. Czerski, A. Huke, P. Heide *et al.*, Europhys. Lett. 68, 363 (2004).
24. C. Bonomo, G. Fiorentini, Z. Fulop *et al.*, Nuclear Physics A 719, 37 (2003).
25. K. Czerski, A. Huke, P. Heide *et al.*, J. Phys. G: Nucl. Part. Phys. 35, 014012 (2008).
26. S. Engstler, A. Krauss, K. Neldner *et al.*, Phys. Lett. B 202, 179 (1988).
27. H. Costantini, A. Formicola, M. Junker *et al.*, Phys. Lett. B 482, 43 (2000).
28. U. Schroder *et al.*, Nucl. Instrum. Meth. In Phys. Research B 40/41, 466 (1989).
29. G. Ruprecht, K. Czerski, D. Bemmerer *et al.*, Phys. Rev. C 70, 025803 (2004).
30. F. Raiola, P. Migliardi, G. Gyurky *et al.*, Eur. Phys. J. A 13, 377 (2002).
31. K. Czerski, A. Huke, A. Biller *et al.*, Europhys. Lett. 54, 449 (2001).
32. Vit. Bystritskii, V. Bystritsky, S. A. Chaikovsky *et al.*, Kerntechnik 66, 46 (2001).
33. V. M. Bystritsky, V. V. Gerasimov, A. R. Krylov *et al.*, Phys. At. Nucl. 66, 1683 (2003).
34. V. M. Bystritsky, Vit. M. Bystritskii, L. D. Butakov *et al.*, EMIN-2006 XI International Seminar on Electromagnetic Interactions of Nuclei, 21–24 September, 2006, Institute for Nuclear Research RAS, Moscow, Russia.
35. V. M. Bystritsky, V. V. Gerasimov, A. R. Krylov *et al.*, Bulletin of the Russian Academy of Sciences: Physics. 71, 1687 (2007).
36. V. M. Bystritsky, V. V. Gerasimov, A. R. Krylov *et al.*, Eur. Phys. J. A 36, 151 (2008) and references therein.
37. V. M. Bystritsky, V. M. Grebenyuk, S. S. Parzhitski *et al.*, J. Laser and Particle Beams 18, 325 (2000).
38. Vit. M. Bystritskii, V. M. Bystritsky, G. N. Dudkin *et al.*, Zh. Tekh. Fiz. 9, 29 (2002).
39. V. M. Bystritsky, V. M. Grebenyuk, S. S. Parzhitski *et al.*, Nucl. Instrum. Meth. A 455, 706 (2000) and references therein.
40. V. M. Bystritsky, Vit. M. Bystritskii, G. N. Dudkin *et al.*, Phys. At. Nucl. 68, 1839 (2005).
41. V. M. Bystritsky, Vit. M. Bystritskii, G. N. Dudkin *et al.*, Nucl. Instrum. Meth. A 565, 864 (2006).
42. R. E. Brown, and N. Jarmie, Phys. Rev. C 41, 1391 (1990).
43. A. Krauss, H. W. Becker, H. P. Trautvetter *et al.*, Nucl. Phys. A 465, 150 (1987).
44. S. Konstantinidis, J. P. Dauchot, M. Hecq, Thin Solid Films 515, 1182 (2006).
45. A. P. Kobzev, J. Huran, D. Maczka *et al.*, Vacuum 83, S 124 (2009).
46. Wei-Kan Chu, J. W. Mayer, and M.A. Nicolet, Academic Press, New York, San Francisco, London, 1978.
47. H. Yagi, K. Tanida, K. Nishimura *et al.*, Jpn. J. Appl. Phys. 34, L577 (1995).
48. D. Briggs and M. P. Seah, Eds., Practical Surface Analysis by Auger and X-ray Photoelectron Spectroscopy, New York: Wiley, 1983.

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