D15-2002-200

MEASUREMENT OF THE ASTROPHYSICAL *S*-FACTOR IN *dd* INTERACTION AT ULTRALOW DEUTERON COLLISION ENERGIES USING THE INVERSE *Z*-PINCH

Submitted to «Ядерная физика»

Vyach. M. Bystritsky, V. V. Gerasimov, A. R. Krylov, S. S. Parzhitski, F. M. Pen’kov, O. M. Shvyryaev, V. A. Stolupin, G. N. Dudkin[1], B. A. Nechaev[1], V. M. Padalko[1], J. Wozniak[2], G. A. Mesyats[3], Vit. M. Bystritskii[4], V. I. Makhrin[5], N. A. Ratakhin[5]

---

[1] Research Institute of Nuclear Physics at the Tomsk State University, Tomsk, Russia

[2] Department of Physics and Nuclear Techniques, University of Mining and Metallurgy, Cracow, Poland

[3] Institute of Electrophysics, Yekaterinburg, Russia

[4] University of California, Irvine, USA

[5] Institute of High-Current Electronics, Tomsk, Russia

1 Introduction

The importance of studying reactions between light nuclei in the ultralow energy range is emphasized in many papers [1-7] for this may allow a possibility of verifying fundamental symmetries in strong interactions [1-4] and solving some astrophysical problems [5-7].

However, it is very difficult to carry out such research at classical accelerators because cross sections for nuclear reactions in the ultralow energy range are extremely small.

A new method for investigation of nuclear reactions by using radially converging powerful fluxes of ions generated in the course of liner plasma implosion (formation of a direct Z-pinch) was proposed in [7-10].

This method allowed the effective cross sections for the dd reaction

$$d + d \rightarrow {}^3He + n(2,5MeV) \tag{1}$$

and the astrophysical S-factor to be estimated for the first time in the deuteron collision energy range 1.8 ÷ 2.3 keV [10-16] (see Fig. 1).

It is of interest to study nuclear reactions between light nuclei at higher deuteron collision energies (3 ÷ 7 keV) because these studies will make it possible not only to measure the dd reaction cross sections in the above energy range for the first time but also to compare them correctly with the calculations and the experimental results at collision energies 6 ÷ 7 keV [17,18].

For these investigations we proposed a method based on inverse Z-pinch formation [19].

The inverse Z-pinch scheme has a few advantages over the direct Z-pinch configuration:

(a) the density of the incident plasma flux decreases;

(b) the processes of the electrodynamic liner acceleration and liner-target interaction are better discriminated in time;

(c) the method of measuring the energy distribution of accelerated liner ions with optical detectors, which detect radiation from the liner in the course of its acceleration, becomes technically much simpler.

Characteristics of the deuterium liner accelerated to $(2.8 \div 7.2)\cdot 10^7$ cm/s were first experimentally investigated within the inverse Z-pinch scheme in [19].

The results of investigating the inverse Z-pinch formation [19-21] indicate that the proposed method can be used to study nuclear reactions in the ultralow energy range.

Another point is worth mentioning. To use a liner plasma for precise investigation of nuclear reactions (measurement of cross sections, astrophysical S-factors), one should know the energy distribution of accelerated liner ions and the liner-target interaction model because the cross sections of the reactions in question are sharply dependent on the particle collision energy in the entrance channel.

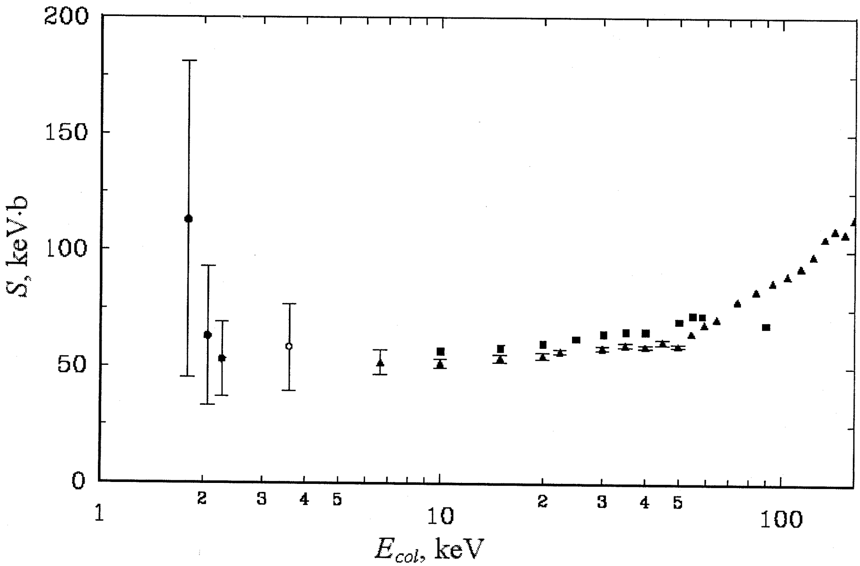

Figure 1: Astrophysical S-factor for dd reactions as a function of the deuteron collision energy – solid circles, solid triangles, and solid squares are the data from [16], [17], and [18] respectively; the circle is the result of the present paper

In this connection an investigation [21] was carried out to develop a method for measuring the energy distribution of accelerated deuterons in experiments on the study of the dd reaction by using the inverse Z-pinch scheme.

That methodological investigation was carried out with a deuterium liner and a deuterated polyethylene target and involved a few shots (by a shot is meant a single operation of the high-current accelerator). The present paper reports the results of analyzing the experimental information gained in these shots (S-factor and dd reaction cross sections).

2 Measurement method

Experimental determination of the astrophysical S-factor is based on measurement of the neutron yield from reaction (1) and parametrization of the dependence of the dd reaction cross section on the deuteron collision energy

$$\sigma(E) = \frac{S(E)}{E} e^{-2\pi\eta}, \qquad (2)$$

$$2\pi\eta = 2\pi\frac{(Ze)^2}{\hbar V} = 31,29\left(\frac{1}{E}\right)^{1/2},$$

where η is the Sommerfeld parameter, Ze is the deuteron charge, E is the center-of-mass deuteron collision energy (in keV), V is the velocity of the relative deuteron motion.

As was found in [22], the total yield of detected neutrons N_n^{exp} from reaction (1) can be represented as

$$N_n^{exp} = N_d n_t \varepsilon_n \overline{S(E)} \int_0^\infty e^{-2\pi\eta} D(E)dE \int_E^\infty f(E')dE', \tag{3}$$

where the average S-factor value is given by the expression

$$\overline{S(E)} = \int_E S(E)P(E)dE \tag{4}$$

corresponding to distribution function

$$P(E) = \frac{e^{-2\pi\eta}D(E)\int_E^\infty f(E')dE'}{\int_0^\infty e^{-2\pi\eta}D(E)dE\int_E^\infty f(E')dE'}, \tag{5}$$

$$D(E) = -\frac{1}{E}\frac{dx}{dE}.$$

In addition, energies average over the distribution functions $f(E)$ and $P(E)$

$$\overline{E} = \int_E Ef(E)dE, \tag{6}$$

$$E_{col} = \int_E EP(E)dE. \tag{7}$$

will be used below. Here $f(E)$ is the energy distribution function of the liner deuterons incident upon the target; $P(E)$ is the differential deuteron collision energy distribution function of the probability for yield of neutrons from reaction (1) normalized to unity; ε_n is the detection efficiency for 2.5-MeV neutrons; $\overline{E}$ is the average deuteron collision energy corresponding to the distribution function $f(E)$; N_d is the number of deuterons incident upon the target; n_t is the deuteron density in the target; $dE/dx = -(\pi n_t e^4)L/2E$ is the specific Coulomb energy loss of liner deuterons because of their collisions with target deuterons [23]; e is the elementary electric charge; L is the Coulomb logarithm for the deuterium plasma conforming to the experimental conditions [23]; E_{col} is the average deuteron collision energy determined by the function $P(E)$.

Reaction cross section parametrization (2) assumes that the Coulomb potential corresponds to interaction of bare deuterons.

In addition, the following is worth mentioning:

1) expression (3) was derived with allowance made for the energy spread of incident deuterons and Coulomb energy loss at their interaction with the target;

2) further replacement $\overline{S(E)} \rightarrow S(E_{col})$ is assumed in the energy interval determined by the deuteron energy spread and Coulomb energy loss.

This is because the S-factor is a slightly varying function in the given deuteron collision energy interval.

Thus, measuring the neutron yield from the dd fusion reaction and the energy distribution of incident deuterons in a particular shot, one can find by (3) the average value of the S-factor for the dd reaction. This value corresponds to the average deuteron collision energy E_{col} determined by the distribution function $P(E)$. Note that for finding $\overline{S(E)}$ from (3) one should also know the total number of incident deuterons N_d and the neutron detection efficiency ε_n of the experimental setup.

The quantity N_d can be found by calculation within the zero-dimensional model of the inverse Z-pinch formation dynamics with using the data obtained with magnetic dB/dt probes. The detection efficiency for 2.5-MeV neutrons can be found both experimentally with using standard ^{252}Cf, Po-Be sources of neutrons and by the Monte Carlo calculation. As to n_t, its values fully depends on the procedure used to apply deuterated polyethylene on the target backing.

3 Experiment

The experiment was carried out with the pulsed high-current accelerator SGM (generator current I = 950 kA, high-voltage pulse duration $\tau = 80$ ns [24]) at the Institute of High-Current Electronics. The experimental setup consisting of a high-current generator, a load module, and detecting and diagnostic equipment is schematically shown in Fig. 2.

The initial deuterium liner was formed with a fast electromagnetic valve and a supersonic Laval nozzle. The average liner radius was 15 mm. A current-intercepting structure (CIS) in the form of a squirrel cage of radius 45 mm made of rods 1 mm in diameter was installed on the way of the radially diverging plasma shell. The CIS installation radius determines the liner acceleration path. The current through the liner was measured with the Rogovsky coils.

Three light detectors LD1, LD2, and LD3 were installed behind the CIS along the radius in the direction of the liner's motion away from the axis. The distance between the CIS and LD1, LD1 and LD2, and LD2 and LD3 was 50 mm. Each light detector consisted of a collimator, a quartz light guide, and fast photomultiplier.

The target was placed around the liner. It was a cylindrical copper shell with a radius of 185 mm and with a length of 40 mm. The inner surface of the target was coated with a CD_2 layer 0.25 mm thick.

Fast neutrons were detected by a time-of-flight method with using the plastic scintillator detector D1 (d = 10 cm, l = 20 cm).

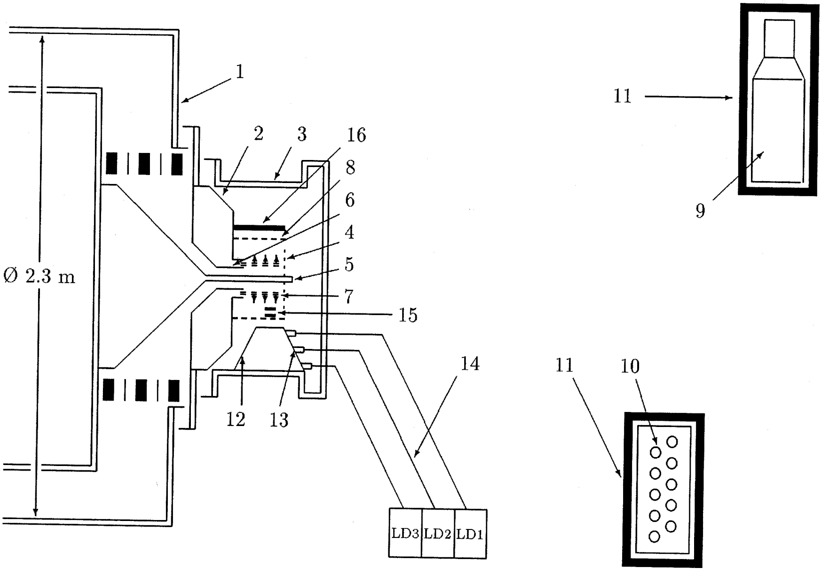

Figure 2: Experimental setup – (1) high-current generator, (2) accelerator load module, (3) measuring chamber, (4) grid cathode, (5) return conductor, (6) supersonic Laval nozzle, (7) liner, (8), current-intercepting structure, (9) scintillator detector D1, (10) thermal-neutron detector D2, (11) Pb shielding, (12) light-protecting cone, (13) collimators, (14) light guides, (15) magnetic dB/dt probes, (16) CD_2 target; the electromagnetic valve is not shown

The total flux of neutrons emitted at interaction of the deuterium liner with the target was measured by thermal-neutron detector D2. It consisted of 10 proportional BF_3 counters enclosed in polyethylene moderator. The detectors D1 and D2 were installed at the respective distances 410 and 277 cm from the liner axis. They were shielded with 5 cm of Pb to suppress the effect of powerful X-ray radiation and bremssstrahlung on them. The neutron detection efficiency was $4.5 \cdot 10^{-6}$ for D1 and $4.0 \cdot 10^{-6}$ for D2.

Pulses from the three light detectors and the neutron scintillator spectrometer arrived at the inputs of the TEKTRONIX oscilloscopes. The high-voltage generator current pulse was a "Trigger" signal.

The experimental setup is described in more detail in [19-21].

Table 1 presents the CD_2 target and deuterium liner parameters in shots 1 and 2.

Table 1: Experimental conditions

Shot No	E^p, keV	$\overline{E}$, keV	m, μg/cm	l, cm	N_d, 10^{18}	n_t, 10^{22} cm^{-3}	d_l^{in}, mm	d_l^{ex}, mm	r_t, mm	t, mm	N_n^{cal}
1	2.24	2.52	6.2	2	3.72	8.0	30	32	185	0.25	15.5
2	1.20	1.42	5.3	2	3.18	8.0	30	32	185	0.25	0.077

$\overline{E}$, E^p are the average and the most probable center-of-mass deuteron energies corresponding to the distribution function $f(E)$, m is the liner mass per unit length, l is the liner length, n_t is the density of target atoms, d_l^{in} is the internal diameter of the liner, d_l^{ex} is the external diameter of the liner, r_t is the target arrangement radius, t is target thickness, N_n^{cal} is the yield of detected neutrons calculated by (3) with the S-factor equal to 53.8 keV·b [18]

The liner mass was found by using the zero-dimensional model of liner motion and the information on the current through the liner and the instants of appearance of signals from the magnetic dB/dt probes detecting passage of the liner current shell through them. Liner acceleration was monitored with two dB/dt probes placed at the radii of 23 and 34 mm.

The mass of the liner and its velocity over the radius at which the CIS was placed were taken to be such that the calculated times of arrival of the liner at the positions of the magnetic dB/dt probes coincided with their real readings within the measurement error.

4 Analysis of the results

The energy distribution of liner ions incident on the target was measured by means of recording optical radiation of the liner (H_α and H_β lines) moving radially away from the axis.

The times of appearance of signals from the light detectors (placed at certain distances from the CIS) and the durations of these signals (dictated by the duration of the light pulse) are related to the distance from the CIS by the equation

$$\Delta t = 16,15 \frac{L_d}{\sqrt{(E^p)_{ls}}} \frac{(\Delta E)_{ls}}{(E^p)_{ls}}, \tag{8}$$

where Δt(ns) is the full width at half-maximum of the light pulse from the detector placed at the distance L_d(cm) from the CIS (it is assumed that after the liner reaches the CIS, its further motion is free motion of the currentless shell); $(E^p)_{ls}$ is the most probable energy of liner ions in lab system (in keV); $(\Delta E)_{ls}$ is the total width of deuteron energy distribution in lab system (in keV) at the distance L_d from the CIS.

Thus, broadening of light signals with increasing distance between the liner and the CIS characterizes the corresponding liner ion energy spread.

Note that changing-over from the time dependence of the liner light intensity measured by the detectors LD1 – LD3 to the energy distribution of liner ions is based on some assumptions concerning motion dynamics of an expanding liner plasma (deuterium liner).

One of the major assumptions is that thermodynamic equilibrium is established between ions and excited neutrals in the expanding plasma and its stable acceleration takes place[1].

By way of example, Fig. 3 displays oscillograms of signals from the light detectors LD2 and LD3 in shot with deuterium target (shot 1).

Table 2 presents results of processing oscillograms of LD2 and LD3 pulses in shots 1 and 2.

Figure 4 displays deuteron energy distributions $f(E)$ and $P(E)$ measured in shot 1 and corresponding to the time distributions in Fig. 3.

For finish processing of the experimental data the energy distributions $f(E)$ and $P(E)$ (see Fig. 3 and 4) found by averaging the corresponding distributions obtained with the detectors LD2 and LD3 were used for shots 1 and 2.

In Fig. 5 deuteron energy distributions $f(E)$ and $P(E)$ measured in shot 2 are displayed for illustration and comparison with results of the analysis of the data from shot 1 with the CD_2 target.

The astrophysical S-factor was found by formula (3) with the deuteron energy distribution $f(E)$ averaged over the LD2 and LD3 data and the measured yield of detected neutrons N_n^{exp} substituted into it.

The yield of detected neutrons was found as follows.

Figure 6 displays the oscillogram of the neutron spectrometer signals in shot 1. The right and left arrows indicate the limits of the time interval within which detection of neutrons from the dd reaction is possible. These limits are dictated by the energy distribution $f(E)$ of accelerated deuterons incident upon the target: the right limit corresponds to liner deuteron energy E^p - $2\sigma_E$ and the left limit to E^p + $2\sigma_E$, where σ_E is the root-mean-square deviation of the deuteron collision energy over the distribution $f(E)$.

The middle arrow corresponds to the most probable initial deuteron energy E^p for the distribution $f(E)$.

As is evident from Fig. 6, in this time interval there are two distinct neutron peaks caused by detection of neutrons from reaction (1) in shot 1. Note that these peaks result from time overlap of individual events of neutron detection by the scintillation spectrometer D1.

---

[1] As shown in [21], the assumptions mentioned hold if the liner is accelerated in the inverse Z-pinch scheme at distances larger than 10 cm from the CIS. Therefore, oscillograms of pulses from the detectors LD2 and LD3 are dealt with in what follows.

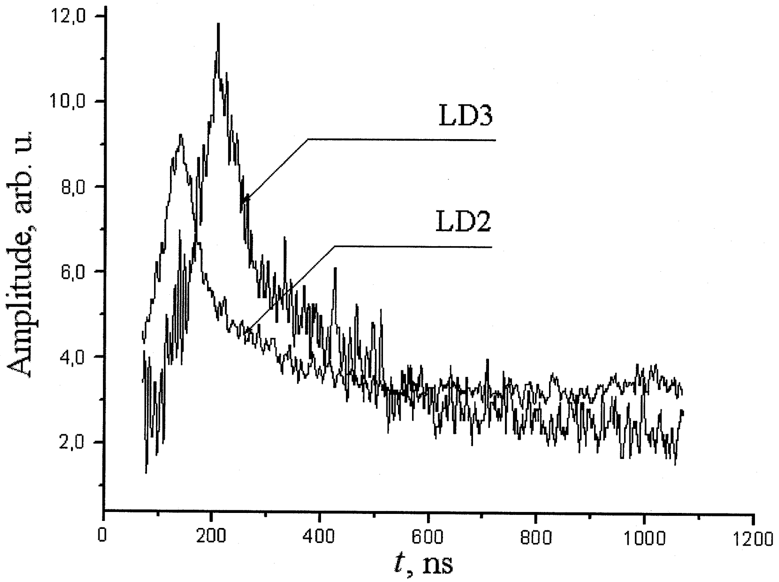

Figure 3: Oscillogram of signals from the light detectors LD2 and LD3 in shot 1

Table 2: Results of analyzing LD2 and LD3 oscillograms

Shot No	T_3-T_2 ns	$(\mathrm{FWHM})^t$ LD2, ns	$(\mathrm{FWHM})^t$ LD3, ns	V_d, 10^7cm/s	E^p, keV	$(\mathrm{FWHM})^E$ LD2, keV	$(\mathrm{FWHM})^E$ LD3, keV
1	69	49.2	84.4	7.1	2.24	1.62	1.86
2	98.6	55.2	139	5.07	1.20	0.90	1.39

T_2 and T_3 are the times of signals appearing at the output of the detectors LD2 and LD3 respectively; $(\mathrm{FWHM})^t$ LD2 and $(\mathrm{FWHM})^t$ LD3 are the full widths at half-maximum of the LD2 and LD3 pulses respectively; V_d is the deuteron velocity in the lab system found from the time shift of the positions of the LD2 and LD3 pulse vertices; E^p is the most probable center-of-mass deuteron energy corresponding to the velocity V_d; $(\mathrm{FWHM})^E$ LD2 and $(\mathrm{FWHM})^E$ LD3 are the full widths at half-maximum of the deuteron energy distributions derived for the LD2 and LD3 through changing over from time distributions to energy distributions by formula (8)

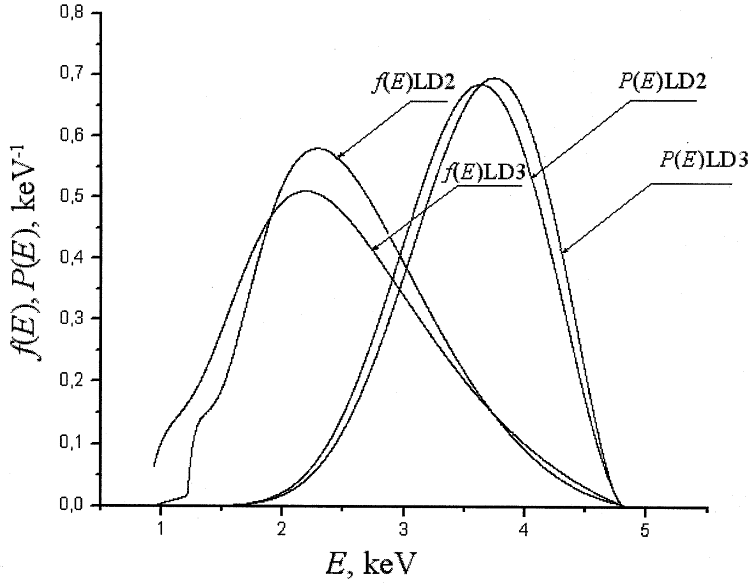

Figure 4: Liner deuteron energy distributions $f(E)$ and $P(E)$ measured in shot 1 with the light detectors LD2 and LD3

Therefore, there arises a problem of finding the average number of detected dd fusion neutrons from the shape of the spectrometer D1 signal resulting from pile-up of a few pulses from individual neutron detection events.

To solve the problem, we analyzed the shape of the signals from the neutron spectrometer exposed to γ quanta and neutrons from standard sources (^{137}Cs, ^{60}Co, Po-Be, ^{252}Cf, Pu-Be) with varying intensity. The plastic scintillator light output due to γ quanta and recoil protons[2] coupling in the energy range corresponding to the maximum recoil proton energy 2.5 MeV was used. Using the Monte Carlo method and taking into account the shape of the neutron spectrometer scintillation pulse and the time distribution of the neutron radiation intensity, we found the average number of detected neutrons in the time interval shown in Fig. 6: $N_n^{exp} = 18.2 \pm 3.6$ (see Table 3). The astrophysical S-factor value was derived by substituting the experimental neutron yield N_n^{exp} of reaction (1) into (3). It came out to $S(E_{col}{=}3.69$ keV$) = 58.2 \pm 18.1$ keV·b (see Table 3).

As to dd reaction cross sections, we calculated them by (2) with the above-found S-factor for the deuteron collision energies

$$E_{col} + \sigma_{P(E)},\ E_{col},\ E_{col} - \sigma_{P(E)}$$

---

[2] Fast neutrons are detected by the plastic scintillator through detecting recoil protons arising from elastic np scattering.

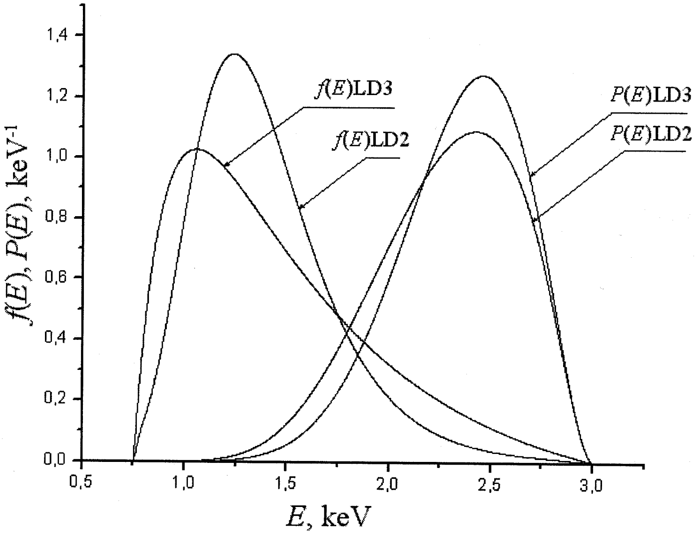

Figure 5: Liner deuteron energy distributions $f(E)$ and $P(E)$ measured in shot 2 with the light detectors LD2 and LD3

Table 3: Experimental data analysis results

a) Experiment

Shot No	E^p, keV	$\overline{E}$, keV	E_{col}, keV	$E^p_{P(E)}$, keV	$\sigma_{P(E)}$, keV	N_n^{exp}	$S(E_{col})$, keV·b	$\Delta S(E_{col})$, keV·b
1	2.24	2.52	3.69	3.56	0.57	18.2±3.6	58.2	18.1
2	1.20	1.42	2.45	2.33	0.34	-	-	-

b) Calculations

Shot No	N_n^{cal}	$\sigma^n_{dd}(E_{col})$, cm^2	$\sigma^n_{dd}(E_{col}+\sigma_{P(E)})$, cm^2	$\sigma^n_{dd}(E_{col}-\sigma_{P(E)})$, cm^2
1	15.5	$1.33\cdot10^{-30}$	$3.55\cdot10^{-30}$	$3.84\cdot10^{-31}$
2	0.077	$4.24\cdot10^{-32}$	$1.31\cdot10^{-31}$	$1.04\cdot10^{-32}$

$E^p_{P(E)}$ is the most probable center-of-mass deuteron energy corresponding to the energy distribution $P(E)$; $\Delta S(E_{col})$ is the root-mean-square deviation of the astrophysical S-factor; σ^n_{dd} is the dd reaction cross section with neutron production

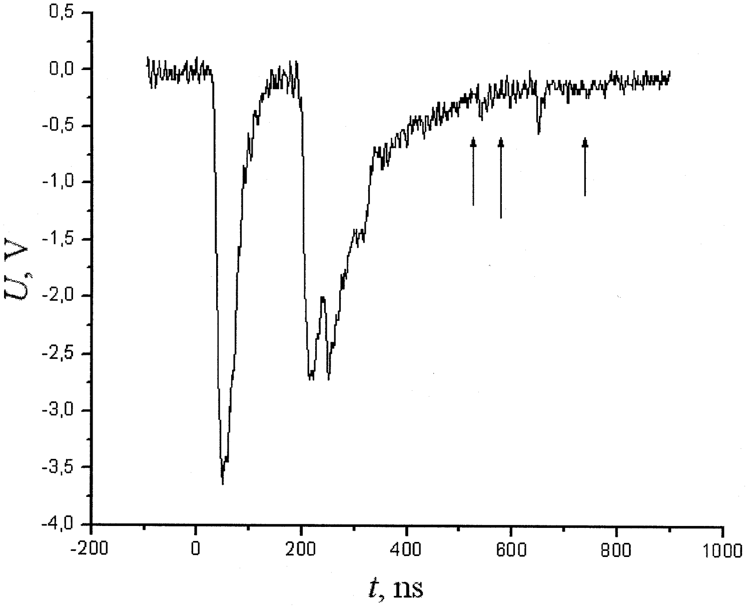

Figure 6: Oscillogram of the pulses from the scintillation neutron detector D1 in shot 1

($\sigma_{P(E)}$ is the root-mean-square deviation of the deuteron collision energy corresponding to the $P(E)$ distribution).

Table 3 presents basic characteristics of the energy distributions $f(E)$ and $P(E)$ for shots 1 and 2, measured yields of neutrons from reaction (1), astrophysical S-factors, and dd reaction cross sections.

The value of the astrophysical S-factor found by us (see Fig. 1) in shot 1 is its average corresponding to the average deuteron collision energy determined by the function $P(E)$. As is evident from Fig. 1, the measured value of the S-factor agrees within the statistical error with its expected value derived by extrapolation from the region of "higher" deuteron collision energies ($7 \div 45$ keV) to the region under consideration.

Fig. 7 displays cross sections for the neutron-yielding dd reaction at deuteron collision energies E_{col}, $E_{col} + \sigma_{P(E)}$, E_{col} - $\sigma_{P(E)}$ calculated by formula (2) with the S-factor value from [18].

As is evident from the figure, the results are quite well described by dependence (2).

As to analysis of shot 2 data, we did not observe any excess of the neutron yield over the background level. This agrees with the measured liner deuteron energy distribution in shot 2 (see Fig. 6). The expected yield of detected neutron in shot 2

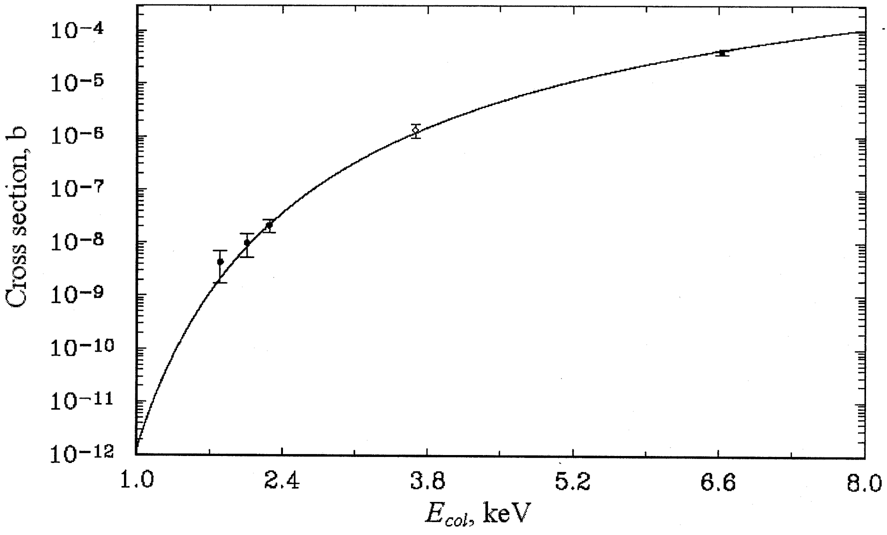

Figure 7: Dependence of the dd reaction cross section on the deuteron collision energy – the solid curve is the calculation by formula (2) with S = 53.8 keV·b [18]; solid circles and the solid square are the experimental S-factor values found in [16] and [17] respectively; the circle is the result of the present paper

($N_n \approx 2 \cdot 10^4$ into the solid angle of 4π), calculated by formula (3) with the function $f(E)$ found for this shot, turned out to be well below the neutron detection system sensitivity threshold $N_{thresh} = 5 \cdot 10^5$.

Some of the most significant factors giving rise to uncertainties of the measured S-factor and dd reaction cross section values should be pointed out:

1) uncertainty of the position of the light detectors LD2 and LD3 in space with respect to the CIS: 0.5 mm;

2) inaccuracy in determination of the liner mass (and thus the number of incident deuterons) within the zero-dimensional model by analysis of the data from the magnetic dB/dt probes: 15%;

3) inaccuracy in the neutron detection efficiency of the scintillation spectrometer found by measurements with standard ^{252}Cf and Pu-Be sources and by Monte Carlo calculations: 10%;

4) inaccuracy in the number of incident liner deuterons caused by angular divergence of the radially expanding plasma flux on the way between the CIS and the CD_2 target (on the basis of bolometric investigations of the liner acceleration dynamics [21]): 5%;

5) errors in determination of the parameters of liner deuteron energy distributions arising from transformation of time distributions of signals from optical detectors LD2 and LD3 into energy distributions, the average errors in determination of E^p,

$\overline{E}$, E_{col}, $E^{p}_{P(E)}$, and the dispersions of the deuteron energy distribution functions $f(E)$ and $P(E)$ amounted to about 10%;

6) inaccurate knowledge of the ion-ion collision temperature at the determination of the liner deuteron path in a solid target, this error amount to about 7%.

Considering all the above causes of uncertainties, we found the resulting errors in the quantities of interest (see Table 3).

Finally, the following should be mentions. The results of the present experiment indicate that the use of the liner plasma in the inverse Z-pinch scheme and the proposed method for measuring the energy distribution of accelerated deuterons allow reactions between light nuclei to be investigated in the ultralow energy region, which is practically inaccessible with using classical accelerators.

With a higher generator current (and thus a larger number of accelerated liner ions), a larger number of light detectors and magnetic dB/dt probes, it will be undoubtedly possible to obtain more precise information on characteristics of nuclear reactions in a so poorly studied region of ultralow-energy collisions of strongly interacting particles.

The authors are grateful to the collaborators from the Institute of High-Current Electronics: S.A. Sorokin for fruitful discussions on dynamics of the dense Z-pinch formation and E.N. Volkov and V.A. Sinebryukhov for providing uninterruptible operation of the accelerator and for assistance in measurements.

The investigation was supported by the Russian Foundation for Basic Research (Project 00-02-17203) and the Fund of the Plenipotentiary of Poland at JINR.

References

[1] S.P. Merkuriev et al., In Intern. Proceeding of the Conf. on the Theory of Few-Body and Quark-Hadronic Systems, Dubna, D4-87-692, 1987, 6.

[2] H. Paetz gen. Schieck, Few-Body Systems **5**, 171 (1988).

[3] V.F. Kharchenko et al., Yadernaya Fizika **55**, 86 (1992) (in Russian).

[4] G.S. Chulick et. al., Nuclear Phys. **A 551**, 255 (1993).

[5] J.N. Bachall and M.N.H. Pinsonneault, Rev. Mod. Phys. **64**, 885 (1992).

[6] W.A. Fowler, Rev. Mod. Phys. **56**, 149 (1984).

[7] V.B. Belyaev, A. Bertin, Vit.M. Bystritsky et al., Nukleonika **40**, 85 (1995).

[8] V.B. Belyaev, V.M. Bystritsky, O.I. Kartavtsev et al., JINR Preprint, D15-92-324, Dubna, 1992.

[9] V.B. Belyaev, V.M. Bystritsky, V.M.Grebenyuk et al., JINR preprint D15-95-378, Dubna, 1995; Vit.M. Bystritskii et al. Albuquerque, NM, USA, 3-6 July 1995, Edited by: Baker W.L., Coperstein G. New York, NY, USA: IEEE, 1995, p. 1215.

[10] V.M. Bystritsky et al., Nukleonika **42**, 775 (1997).

[11] T.L. Bulgakov, Vit.M. Bystritskii, Vyach.M. Bystritsky et al., Yadernaya Fizika **60**, 1349 (1997) (in Russian).

[12] Vit.M. Bystritskii, V.M. Bystritsky, V.M. Grebenyuk et al., JINR Preprint D15-96-11, Dubna, 1996.

[13] T. Bulgakov, Vit.M. Bystritskii, G. Mesyats et al., In Proceeding. of 11-th Intern. Conference on High Power Particle Beams "Beams 96", Prague, Czech Republic, June 10-14, V.2, (1996) 917.

[14] V.M. Bystritsky, V.M. Grebenyuk, S.S. Parzhitski et al., Laser and Particle Beams **18**, 325 (2000).

[15] Vit.M. Bystritskii, V.M. Bystritsky, S.A. Chaikovsky et al., Phys. of Atomic Nuclei **64**, 855 (2001).

[16] V. Bystritskii, V. Bystritsky, S. Chaikovsky et al., Kerntechnik **66**, 42 (2001).

[17] A. Krauss, H.W. Becker, H.P. Trautvetter et al., Nucl. Phys. **A465**, 150 (1987).

[18] R.E. Brown and N. Jarmie, Phys.Rev. **C41**, 1391 (1990).

[19] V.M. Bystritsky, V.M. Grebenyuk, S.S. Parzhitski et al., NIM **455A**, 706 (2000).

[20] V.M. Bystritsky, Vit.M. Bystritskii, V.M. Grebenyuk et al., In Proceedings on 28th IEEE International Conference on Plasma Science, and 13th IEEE International Pulse Power Conference, Las Vegas, Nevada, 2001, IEEE catalog 01CH37251; PPPAS-2001, Editors: Robert Reinovsky, Mark Newton; v. 2, p. 1031-1-34.

[21] Vit.M. Bystritskii, Vyach.M. Bystritsky, V.M. Grebenyuk et al., Zhurnal Tekhnicheskoi Fiziki **9**, 29 (2002) (in Russian).

[22] V.M. Bystritsky and F.M. Pen‘kov, JINR Preprint D15-2000-293, Dubna, 2000; to be published in Phys. of Atomic Nuclei (2002).

[23] D.V. Sivukhin, Voprosy Teorii Plazmy, No. 4, p. 81, Atomizdat Moscow, 1964 (in Russian).

[24] A.V. Luchinski, V.I. Makhrin, N.A. Ratakhin et al., Izvestiya Vuzov, Seriya Fizika **38**, 52 (1995) (in Russian).

Received on October 11, 2002.

Быстрицкий Вяч. М. и др. Д15-2002-200

Измерение астрофизического S-фактора в dd-взаимодействии в области ультранизких энергий столкновения дейтронов с использованием инверсного Z-пинча

Работа посвящена измерению значений астрофизического S-фактора и сечений реакции $d + d \rightarrow {}^3\mathrm{He} + n$ в области ультранизких энергий столкновения дейтронов. Формирование потока ускоренных дейтронов, падающих на твердотельную мишень из CD_2, производилось в конфигурации инверсного Z-пинча. Лайнер в начальном состоянии представлял собой полую сверхзвуковую струю дейтерия радиусом 15 мм и длиной 20 мм. Эксперимент проводился на сильноточном импульсном ускорителе ($I = 950$ кА, $\tau = 80$ нс) Института сильноточной электроники РАН, Томск. Измерение энергетического распределения дейтронов проводилось путем анализа временных распределений интенсивности (H_α- и H_β-линий) излучения, радиально движущегося от оси лайнера, генерируемого в процессе его разгона. Регистрация данного излучения осуществлялась с помощью оптических датчиков, установленных вдоль направления разбега лайнера от его оси.

Измеренное значение астрофизического S-фактора для dd-реакции при средней энергии столкновения дейтронов $E_{\mathrm{col}} = 3{,}69$ кэВ оказалось равным $S(E_{\mathrm{col}} = 3{,}69 \text{ кэВ}) = (58{,}2 \pm 18{,}1)$ кэВ · б. Сечение dd-реакции, вычисленное с использованием найденного значения S-фактора и известной параметризации сечения реакции в виде произведения барьерного множителя и астрофизического S-фактора, составило:

$$\sigma^n_{dd}(E_{\mathrm{col}} = 3{,}69 \text{ кэВ}) = (1{,}33 \pm 0{,}41) \cdot 10^{-30} \text{ см}^2.$$

Работа выполнена в Лаборатории ядерных проблем им. В. П. Джелепова ОИЯИ.

Препринт Объединенного института ядерных исследований. Дубна, 2002

Bystritsky Vyach. M. et al. D15-2002-200

Measurement of the Astrophysical S-Factor for the dd Interaction at Ultralow Deuteron Collision Energies Using the Inverse Z-Pinch

This paper is devoted to measurement of the astrophysical S-factor and cross sections of the $d + d \rightarrow {}^3\mathrm{He} + n$ reaction at ultralow deuteron collision energies. Formation of the flow of the accelerated deuterons incident upon the CD_2 solid state target was made within the scheme of the inverse Z-pinch. The liner in the initial state was a hollow supersonic deuterium jet of radius 15 mm and length 20 mm. The experiment was carried out at the pulsed high-current accelerator ($I = 950$ kA, $\tau = 80$ ns) of the Institute of High-Current Electronics (Tomsk, Russia). Measurement of the deuteron energy distribution was performed through an analysis of the time distributions of the intensity of the liner radiation (H_α and H_β lines) generated during the liner radial moving from axis. Recording of this radiation was carried out by optical detectors placed along the direction of the liner moving from its axis.

The measured value of the astrophysical S-factor for the dd reaction at the average deuteron collision energy $E_{\mathrm{col}} = 3.69$ keV was equal to $S(E_{\mathrm{col}} = 3.69 \text{ keV}) = (58.2 \pm 18.1)$ keV · b. The dd reaction cross section calculated using the finding value of the S-factor and known representation of the reaction cross section as the product of the barrier factor and the astrophysical S-factor was

$$\sigma^n_{dd}(E_{\mathrm{col}} = 3.69 \text{ keV}) = (1.33 \pm 0.41) \cdot 10^{-30} \text{ cm}^2.$$

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

Preprint of the Joint Institute for Nuclear Research. Dubna, 2002

Макет *Т. Е. Попеко*

Подписано в печать 31.10.2002.
Формат 60 × 90/16. Бумага офсетная. Печать офсетная.
Усл. печ. л. 1,18. Уч.-изд. л. 1,77. Тираж 200 экз. Заказ № 53597.

Издательский отдел Объединенного института ядерных исследований
141980, г. Дубна, Московская обл., ул. Жолио-Кюри, 6.
E-mail: publish@pds.jinr.ru
www1.jinr.ru