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PHYSICS OF ELEMENTARY PARTICLES AND ATOMIC NUCLEI. EXPERIMENT

Astrophysical S-factor of $T(^4He, \gamma)^7Li$ Reaction at E_{cm} = 15.7 keV

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Abstract—The astrophysical S-factor of the reaction $T(^4He, \gamma)^7Li$ is measured for the first time at the center of mass energy E_{cm} = 15.7 keV, lower than the energy range of the Standard Big Bang Nucleosynthesis (SBBN) model. The experiment is performed on a Hall pulsed accelerator (TPU, Tomsk). An acceleration pulse length of 10 μs allows one to suppress the background of cosmic radiation and the ambient medium by five orders of magnitude. A beam intensity of ~ 5×10^{14} $^4He^+$ ions per pulse allows one to measure an extremely low reaction yield. The yield of γ-quanta with the energies E_γ^0 = 2483.7 keV and E_γ^1 = 2006.1 keV is registered by NaI(Tl) detectors with the efficiency $\varepsilon = 0.331 \pm 0.026$. A method for direct measurement of the background from the chain of reactions $T(^4He, ^4He)T \to T(T, 2n)X \to (n, \gamma)$ and/or $(n, n'\gamma)$ which ends by neutron activation of materials surrounding the target is proposed and implemented in this study. The value of the astrophysical S-factor of the reaction $T(^4He, \gamma)^7Li$ $S_{\alpha t}(E_{cm} = 15.7\text{ keV}) = 0.091 \pm 0.032$ keV b provides the choice from the set of experimental data for the astrophysical $S_{\alpha t}$-factor in favor of experimental data [4] with $S_{\alpha t}(E_{cm} = 0) = 0.1067 \pm 0.0064$ keV b.

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STATEMENT OF THE PROBLEM

In the "cosmological lithium" problem, the puzzle with lithium-7 is that its abundance (as compared to that of hydrogen), measured by means of observational astronomy, $^7Li/H = (1.58 \pm 0.31) \times 10^{-10}$, is smaller by almost a factor of three than the result of calculation using the standard Big Bang Nucleosynthesis model (SBBN), $^7Li/H = (4.68 \pm 0.67) \times 10^{-10}$ [1, 2]. It is assumed that the main reaction of ^7Li production in the primary nucleosynthesis epoch is $^3He(^4He, \gamma)^7Be$, with the transformation of ^7Be into ^7Li via β^+ decay. The second important reaction is $T(^4He, \gamma)^7Li$ [2]. The results of experiments at accelerators yielding data on cross sections and astrophysical S-factors of the processes [3] should serve as an experimental proof of calculations using the BBN model. At present, however, there is no experimental proof of calculations based on the SBBN model, which discredits the Big Bang model or requires "nonstandard physics" [2]. It was demonstrated in [4] that the reaction $T(^4He, \gamma)^7Li$ is the defining one for ^7Li production in the energy range in the center of mass system $30 < E_{cm} < 150$ keV. Direct measurements of the S-factor for the reaction $T(^4He, \gamma)^7Li$ were performed in four experiments [4–7]. The two other results were obtained in indirect experiments using the method of Coulomb dissociation of ^7Li nucleus in αt channel in the field of a heavy nucleus [8, 9]. All these results are shown in Fig. 1.

A large spread of the values of S-factors is observed, and there are few points for energies <100 keV. The objective of our experiment is to measure the cross section and the S-factor of the reaction $T(^4He, \gamma)^7Li$ for the energy of $^4He^+$ ions E_α = 39 keV in the laboratory system (E_{cm} = 16.7 keV). This is the maximum energy that can be obtained using a Hall accelerator. In our opinion, experimental values of the cross section and the S-factor for the minimum energy of ^4He-^3H interaction would provide more precise information on the S-factor of the reaction $T(^4He, \gamma)^7Li$ [10].

FORMULATION OF EXPERIMENT

The differential cross section of the reaction $T(^4He, \gamma)^7Li$ in the considered energy range of ^4He ions is practically isotropic, i.e., independent of the γ-quanta emission angle [4]; therefore, the "thick target" method applied earlier [11–13] can be used for determining the total reaction cross section.

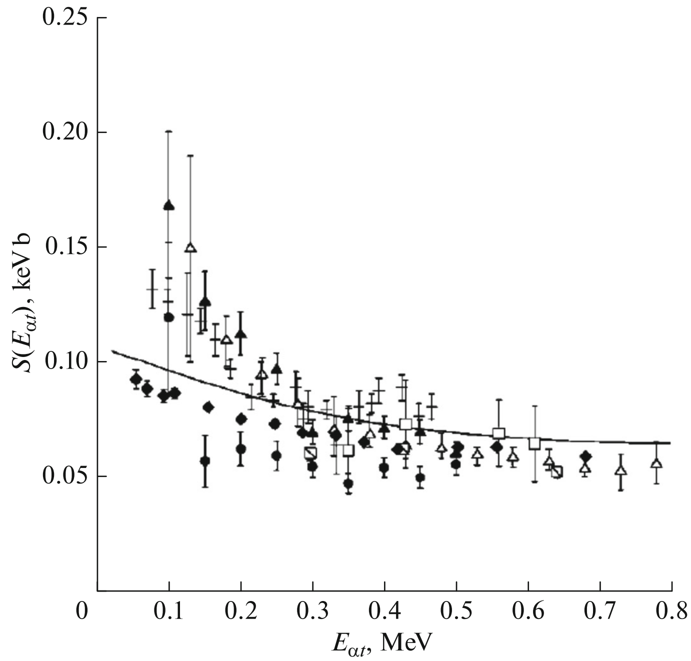

Fig. 1. (Figure 26c from [9] is used.) S-factor of the reaction $T(^4He, \gamma)^7Li$ as a function of the collision energy of $^4He^+$ ions and tritium nuclei in the center of mass system. Solid line shows calculation [9]. Results of direct measurements: (squares) [5], (strike-through squares) [6], (crosses) [7], and (solid diamonds) [4]. Results of indirect measurements: (open triangles) [8] and (solid triangles) and (solid circles), two data sets from [9].

The γ-quanta energy E_γ also weakly depends on the emission angle. The γ-quanta energy for the reaction $T(^4He, \gamma)^7Li$ was determined using the formula

$$E_\gamma = Q + E \pm \Delta E_{\mathrm{Dop}} - E_{\mathrm{rec}}, \qquad (1)$$

where $Q = (m_{\mathrm{T}} + m_\alpha - m_{\mathrm{Li\text{-}7}})c^2 = 2467.0$ keV is the reaction energy; $\Delta E_{\mathrm{Dop}} = \frac{v}{c} E_\gamma \cos\theta \approx 4.5$ keV is the Doppler line broadening $E_{\mathrm{rec}} = \frac{E_\gamma^2}{2(m_{\mathrm{Li\text{-}7}})c^2} \approx 0.2$ keV is the energy of the recoil nucleus ^{7}Li; $E = E_\alpha \frac{m_{\mathrm{T}}}{m_{\mathrm{T}} + m_\alpha}$ is the collision energy of helium ions and tritons in the center of mass system; m_{T}, m_α, $m_{\mathrm{Li\text{-}7}}$ are the masses of tritium, helium, and lithium nuclei, respectively; $\cos\theta$ is the angle between the γ-quanta and the ^{7}Li nucleus directions; and E_α is the kinetic energy of helium ions.

Three types of γ-quanta are produced in the reaction $T(^4He, \gamma)^7Li$: $E_\gamma^0, E_\gamma^1, E_\gamma^2$.

1. With a probability of ~60%, the reaction goes via the ground state $\frac{3^-}{2}$ of the nucleus ^{7}Li. In this case, γ-quanta with the energy $E_\gamma^0 = 2483.7 \pm 4.5$ keV are produced; they are registered by γ-quanta detectors and, as a result, the energy spectrum of registered events contains three peaks: the peak of total absorption of the energy of these γ-quanta and two peaks corresponding to incomplete absorption of the γ-quanta energy in the crystal of the γ-quanta detector as one or two annihilation γ-quanta with an energy of 0.511 MeV escape. The first peak corresponds to the energy loss of the γ-quanta with the energy $E_\gamma^0 = 2483.7 \pm 4.5$ keV deposited in the crystal of the γ-detector, the second peak corresponds to the energy $E_{\gamma 1}^0 = 1972.7$ keV, and the third peak corresponds to the energy $E_{\gamma 2}^0 = 1461.7$ keV.

2. With a probability of ~40% the reaction $T(^4He, \gamma)^7Li^*$ goes via the first excited state $\frac{1^-}{2}$ of the nucleus ^{7}Li. The energy of the first excited state $\frac{1^-}{2}$ of the nucleus $^7Li^*$ $E_\gamma^2 = 477.6$ keV. In this case, γ-quanta with the energy $E_\gamma^1 = 2006.1 \pm 4.1$ keV are produced and the corresponding total absorption peak appears in the energy spectrum, along with the peaks of incomplete absorption with the emission of the first and second 0.511 MeV annihilation γ-quanta with peak energies $E_{\gamma 1}^1 = 1495.1$ keV, $E_{\gamma 2}^1 = 984.1$ keV.

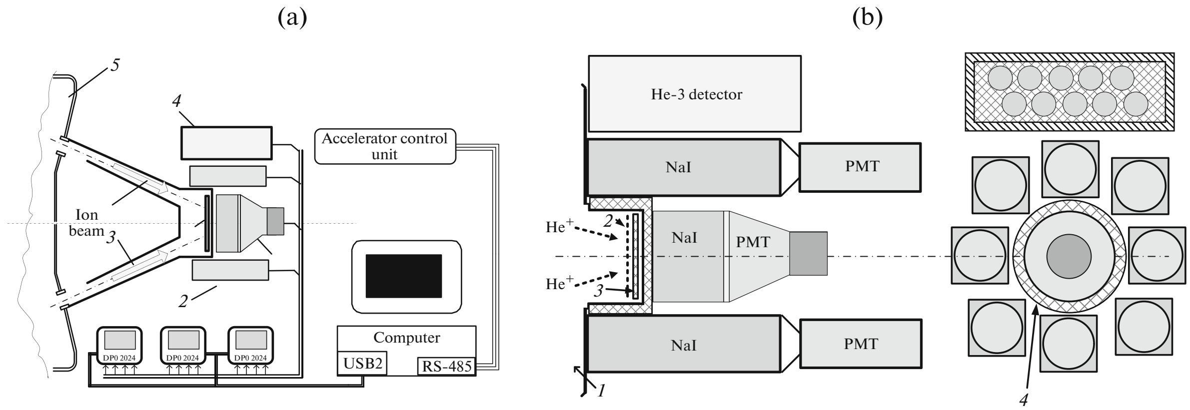

Fig. 2. (a) Schematic diagram of the experiment: (*1*) target from titanium tritide TiT, (*2*, *3*) NaI(Tl) γ-detectors, (*4*) ^{3}He neutron detectors, and (*5*) Hall ion accelerator. (b) Detector layout: (*1*) Hall ion accelerator, (*2*) grid, (*3*) TiT target, and (*4*) additional shielding of the detectors; PMT is the photoelectron multiplier.

3. Moreover, the γ-quanta with the energy $E_\gamma^2 = 477.6$ keV corresponding to the transition $\frac{1^-}{2} \to \frac{3^-}{2}$ is emitted isotropically simultaneously with the γ-quanta with the energy E_γ^1.

The reaction T(^{4}He, γ)^{7}Li was studied at the pulsed plasma Hall accelerator for the energy of $^4He^+$ ions equal to $E_\alpha = 39$ keV (the collision energy of helium ions with tritium atoms in the center of mass system is $E_{cm} = 16.7$ keV) using the facility shown in Figs. 2a and 2b.

The Hall accelerator is described in detail in [14]. The measurement chamber of the accelerator is pumped out using the turbomolecular and cryogenic pumps. The working vacuum in the measurement chamber is $<10^{-7}$ mm Hg. Online monitoring of sorption (desorption) on the target is performed using quartz scales with a frequency resolution of ~1 Hz (sensitivity 10^{-2} μg/Hz). The applied method for determining the surface purity provided online monitoring of the quality of vacuum pumping system in the measurement chamber of the accelerator and the accelerating ion diode volume for finding and eliminating the factors that contribute to the surface contamination due to the presence of residual gases.

The number of accelerated $^4He^+$ ions hitting the titanium tritide target was ~5×10^{14} per pulse. The duration of the acceleration pulse was 10 μs, which allowed one to suppress recording background events determined by cosmic radiation and natural radioactivity of the ambient medium by a factor of 10^5. The specific features of the high voltage accelerator equipment operation (high voltage capacity charging and discharging), operation of the γ-quanta registration system, and the registration system of accelerated ion beam parameters (digital oscilloscopes) lead to the following measurement procedure. First, an acceleration pulse with a duration of 10 μs was supplied (the yields of the reaction γ-quanta and neutrons and the beam parameters were measured during this pulse); then, 6 s later, the cosmic radiation background and radioactivity of the materials around the detectors were measured in 10 μs without an accelerating voltage followed by the charging of the high voltage capacity. The measurement cycle was 14.28 s (pulse repetition rate 0.07 Hz). Thus, background events alone were accumulated, along with events from the detectors, during the acceleration time in the experiment.

The energy spread of the beam of $^4He^+$ ions is FWHM ≈ 19.9% [15]. The energy distribution of $^4He^+$ ions hitting the target was measured using an electrostatic multigrid spectrometer of charged particles. The electrostatic energy analyzer placed before the target in a special experiment [15] was used for determining the number of fast neutral particles and the coefficient of secondary ion–electron emission of the target material. The following result was obtained: the upper bound of relative content of fast neutral particles in the accelerated ion flux is <2.1%, with the probability $P = 0.95$. The number of $^4He^+$ ions interacting with the target in each pulse was determined by integration of target current (3). For suppressing the electron emission from the target, a metal grid (2) with a transparency of 93% was installed at a distance of 1 cm before the target and a potential of −150 V was applied to it; see Fig. 2b.

The reaction T(^{4}He, γ)^{7}Li was studied using titanium tritide (TiT) targets. The technology of target manufacture was as follows: a magnetron was used to deposit a titanium layer with a thickness of about 1.5–2 μm on a molybdenum substrate (with a diameter of 97 mm); then this substrate was placed into a Sieverts apparatus where the titanium layer was saturated by tritium to the required stoichiometry. Two TiT targets were manufactured in 2015. The triton density distribution along the target depth was measured using elas-

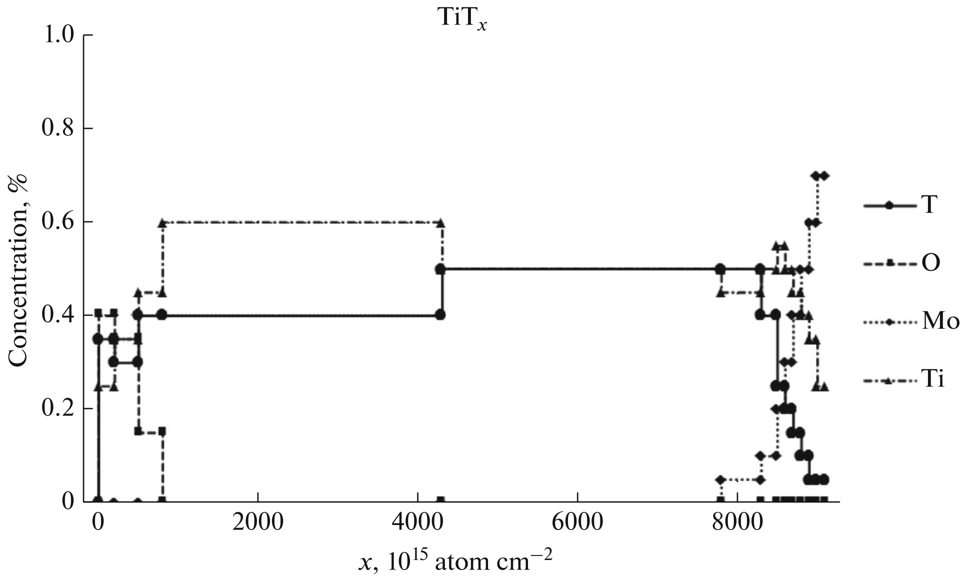

Fig. 3. Concentration of tritium and admixtures along the TiT target depth.

tic recoil detection (ERD) with a 2.3 MeV α particle beam produced by the Van de Graaff accelerator (JINR, Dubna). Simultaneously with recoil tritons, α particles scattered on target nuclei to the back hemisphere were also detected (Rutherford backward scattering (RBS) method) [16]. Combined analysis of ERD and RBS spectra allows one to determine the distribution of tritons and admixture atoms as a function of depth into the target with high precision. The results of the target studies are shown in Fig. 3.

The homogeneity of titanium layer saturation with tritium over the area and depth of the target with a diameter of 97 mm was studied using electron fluorescence analysis. The target was scanned along the surface by a collimated semiconductor silicon detector with a 25-μm-thick beryllium input window. Characteristic X ray lines $K_{\alpha 1}$, $K_{\beta 1}$ of titanium atoms with the energies $Er = 4.51$, 4.93 keV, which appear in titanium under the action of β^- particles from tritium decay, were registered. The inhomogeneity of saturation with tritium of the titanium layer does not exceed 7%. Figure 4 shows the spectrum of characteristic X rays from TiT target together with the calibration X ray spectrum of an ^{241}Am source.

The neutron detector based on ^{3}He counters shown in Fig. 2 is designated for measuring background neutrons. The main source of the neutron background in an investigation of the reaction $T(^4He, \gamma)^7Li$ is elastic scattering of $^4He^+$ ions on tritium atoms with energy transfer to tritium nuclei and subsequent reactions of the interaction of tritium nuclei with tritium nuclei of the target,

$$T(t, nn)^4He, \quad Q = 11.33 \text{ MeV}, \qquad (2)$$

$$T(t, n_1)^5He^*, \quad Q = 9.24 \text{ MeV}, \qquad (3)$$

$$T(t, n_0)^5He, \quad Q = 10.4 \text{ MeV}. \qquad (4)$$

Time-correlated pairs of neutrons are produced in these reactions. The neutron detector represents an array of ten counters in the form of tubes with a diameter of 3 cm and a length of 50 cm filled by the $^3He + Ar + CO_2$ mixture at 4 atm and placed in a polyethylene moderator. The detector dimensions are 15 × 30 × 54 cm. The array of 10 ^{3}He counters was situated in a double aluminum casing for reducing electromagnetic noise. The efficiency of neutron registration emitted by an AmBe source using the ^{3}He detector is 15%. The characteristic feature of such detectors is their weak sensitivity to γ-quanta.

The γ-quanta from the reaction were registered using eight scintillation detectors based on NaI(Tl) crystals (100 × 100 × 400 mm) situated around the titanium tritide (TiT) target and the ninth NaI(Tl) detector (diameter 150 mm, thickness 100 mm) attached to the rear side of the target chamber at a distance of 3 cm from the target. Signals from NaI(Tl) detectors were AD-converted using the memory oscilloscopes Tektronix DPO 2024. The energy resolution and registration efficiency of the detectors for the γ-quanta energy $E_\gamma = 2.484$ MeV were determined using a ^{232}Th γ-quanta source and calculation with a Monte Carlo code. Figure 5 shows show the γ-quanta energy spectrum obtained at one of the detectors from the ^{232}Th source. The energy resolution of the detector (FWHM) for $E_\gamma = 2.614$ MeV was $\Delta E = 5.1\%$. The registration efficiency for γ-quanta with this energy by the system of nine NaI(Tl) detectors was determined by moving the ^{232}Th source to the center of the tritium target; it was equal to $\varepsilon = 0.28$ for the registration threshold $E_\gamma = 1.9$ MeV. Since in this experiment it was impossible to separate the yields of the reaction

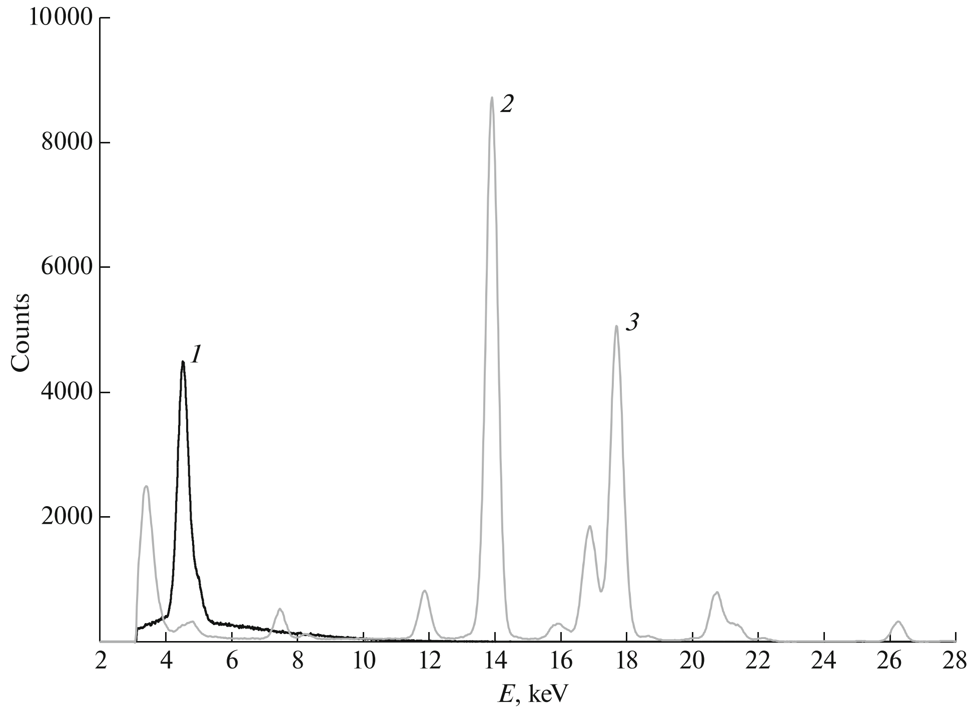

Fig. 4. Characteristic X-ray spectrum of TiT target and ^{241}Am spectrum: (*1*) unresolved $K_{\alpha 1}$, $K_{\beta 1}$ lines of Ti, $Er = 4.51$, 4.93 keV; (*2*, *3*) X-ray lines of ^{241}Am.

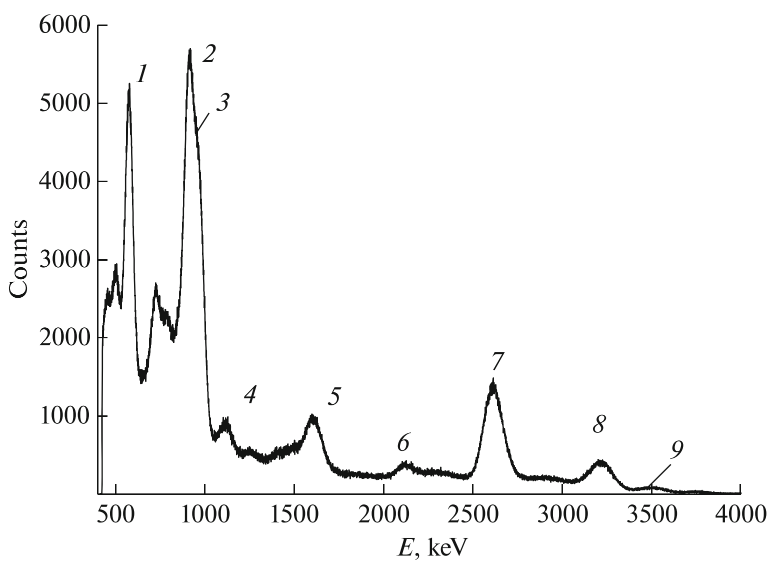

Fig. 5. The γ-quanta energy spectrum from ^{232}Th. The γ-quanta lines correspond to the following decay chain: ^{232}Th... → ^{228}Th... → ^{208}Tl → ^{208}Pb [17]: (*1*) $E_\gamma = 583.19$ MeV, (*2*) $E_\gamma = 911.2$ MeV, (*3*) $E_\gamma = 968.97$ MeV, (*4*) $E_\gamma = 1115.97$ MeV, (*5*) $E_\gamma = 1592.5$ MeV, (*6*) $E_\gamma = 2103.5$ MeV (peak corresponding to emission of one annihilation γ-quanta with an energy of 0.511 MeV in registration of $E_\gamma = 2614.5$ MeV), (*7*) $E_\gamma = 2614.5$ MeV, (*8*) $E_\gamma = 3197.7$ MeV (peak summing the energies of the following γ-quanta: ^{208}Tl $E_\gamma = 583.19$ MeV and $E_\gamma = 2614.5$ MeV), and (*9*) $E_\gamma = 3476.6$ MeV.

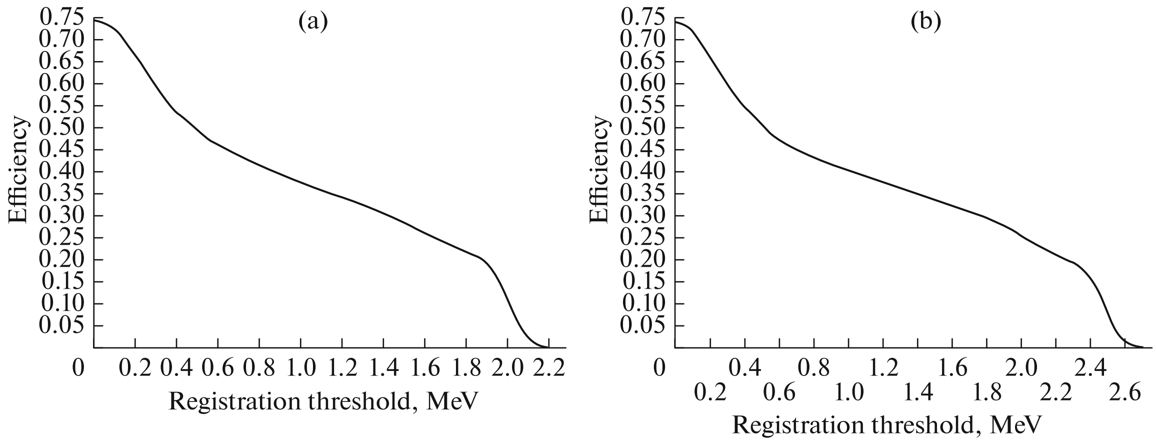

Fig. 6. (a) Registration efficiency of γ-quanta with the energy $E_\gamma = 2.006$ MeV as a function of the registration threshold. (b) Registration efficiency of γ-quanta with the energy $E_\gamma = 2.484$ MeV as a function of the registration threshold.

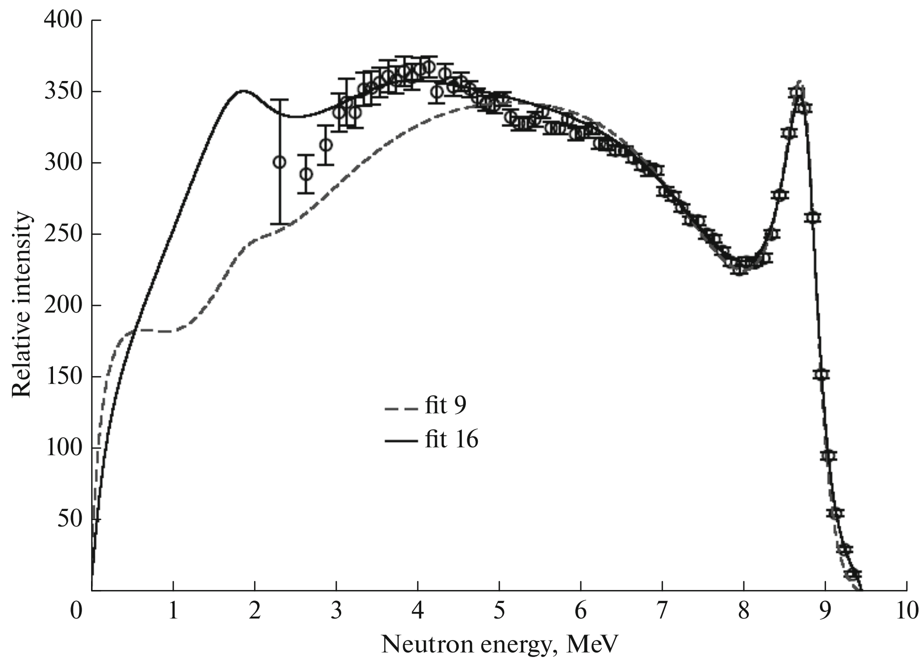

Fig. 7. (Fig. 8 from [18] is used). Neutron energy spectrum from reactions (2)–(4). Neutron yields from reactions (2)–(4) are related as 70 : 20 : 10, respectively [19].

$T(^4He, \gamma)^7Li$ with the ^7Li nucleus in the ground ($E_\gamma = 2.484$ MeV) and excited ($E_\gamma = 2.006$ MeV) states, we calculated to determine the averaged registration efficiency for the total yield.

Figures 6a and 6b show the results of calculation for the registration efficiency of γ-quanta with the energies $E_\gamma = 2.484$ MeV and $E_\gamma = 2.006$ MeV depending on the registration threshold.

Then the averaged registration efficiency for the reaction $T(^4He, \gamma)^7Li$ going via the ^7Li nucleus in the excited ($E_\gamma = 2.006$ MeV) and ground ($E_\gamma = 2.484$ MeV) states (with account for the fact that the probability of the process with excitation makes 40% of the total probability of this process [4]) was found to be equal to $\varepsilon = 0.331 \pm 0.026$ for the registration threshold $E_\gamma = 1.4$ MeV. Here, we took into account that for γ-quanta with the energy $E_\gamma = 2.006$ MeV the energy spectrum contains the emission peak of the first γ-quanta with the energy $E_\gamma = 2.006–0.511$ MeV = 1.495 MeV.

An extremely low cross section of the reaction $T(^4He, \gamma)^7Li$ in this energy region requires thorough analysis of all background reactions and their minimization. The main sources of the background are reac-

Background parameters. The γ-quanta energies and corresponding reactions

E_γ, keV	Reaction	E_γ, keV	Reaction	E_γ, keV	Reaction
1408	^{54}Fe(n, $n'\gamma$)^{54}Fe	1726	^{207}Pb(n, $n'\gamma$)^{207}Pb	2093	^{207}Pb(n, $n'\gamma$)^{207}Pb
1434	^{52}Cr(n, $n'\gamma$)^{52}Cr	1770	^{207}Pb(n, $n'\gamma$)^{207}Pb	2212	^{27}Al(n, $n'\gamma$)^{27}Al
1467	^{206}Pb(n, $n'\gamma$)^{206}Pb	1778	^{27}Al(n,γ)^{27}Al	2223	^{1}H(n, γ)^{2}H
1636	^{23}Na(n, $n'\gamma$)^{23}*Na*	1810	^{56}Fe(n, $n'\gamma$)^{56}Fe	2615	^{208}Pb(n, $n'\gamma$)^{208}Pb
1720	^{27}Al(n, $n'\gamma$)^{27}Al	1844	^{206}Pb(n, $n'\gamma$)^{206}Pb	2982	^{27}Al(n, $n'\gamma$)^{27}Al

tions (2)–(4) and, when two time-correlated neutrons are produced, neutron interaction with materials around the target via the reactions (n, γ) or (n, $n'\gamma$) and the production of γ-quanta with energies in the sought-after energy range, E_γ = 1.4–2.8 MeV.

The sources of background γ-quanta were analyzed using data [20–25], as well as our results [13]. The γ-quanta detection system of our facility designated for investigating radiative capture reactions consists of eight NaI(Tl) detectors with dimensions of 10 × 10 × 40 cm^3 [11–13] and the ninth NaI(Tl) detector (diameter 150 mm, thickness 100 mm). The mass of all γ-quanta detectors is ~117 kg; the partial masses of iodine, sodium, and thallium are 98.7, 17.8 and 0.5 kg, respectively. The following problem was formulated: to determine and compare the background level due to reactions with fast and slow neutrons with the surrounding materials (including those of NaI(Tl) detectors). If the background contribution from slow neutrons is smaller than that from fast neutrons, it was reasonable to slow down neutrons with the energies E_n = 0.5–9.5 MeV from the *tt* fusion reaction to thermal energies before they hit the NaI(Tl) detectors. For this purpose, we performed two experiments with neutron sources: fast neutrons, AmBe, and thermal neutrons, ^{252}Cf in a polyethylene moderator [13]. The sources irradiated a NaI(Tl) crystal (diameter 80 mm, length 80 mm) installed on the HPGe detector. It turned out that the main source of Compton background are γ-quanta (E_γ = 2223.1 keV) from the reaction of neutron radiative capture on hydrogen of the polyethylene moderator [13]. These γ-quanta are responsible for high Compton background in the studied energy region. The table 1 gives data on the reactions in which background γ-quanta with energies in the considered range, E_γ = 1.4–2.8 MeV, are produced.

Thus, the study of background conditions yielded the following conclusion: the following materials should not be used (or should be minimally used) in the experimental facility: lead, aluminum, polyethylene, and iron.

EXPERIMENTAL RESULTS

The first runs of the γ-yield measurement for the reaction T(^{4}He, γ)^{7}Li demonstrated the presence of a considerable background. Typical oscilligrams of the accelerator current pulse and pulses from the NaI(Tl) detectors are shown in Fig. 8a.

For reducing the background load of the detectors by fast neutrons from reactions (2)–(4), additional shielding was installed between the detectors and the target (*4*, in Fig. 2b); the schematic diagram of this shielding is shown in Fig. 9.

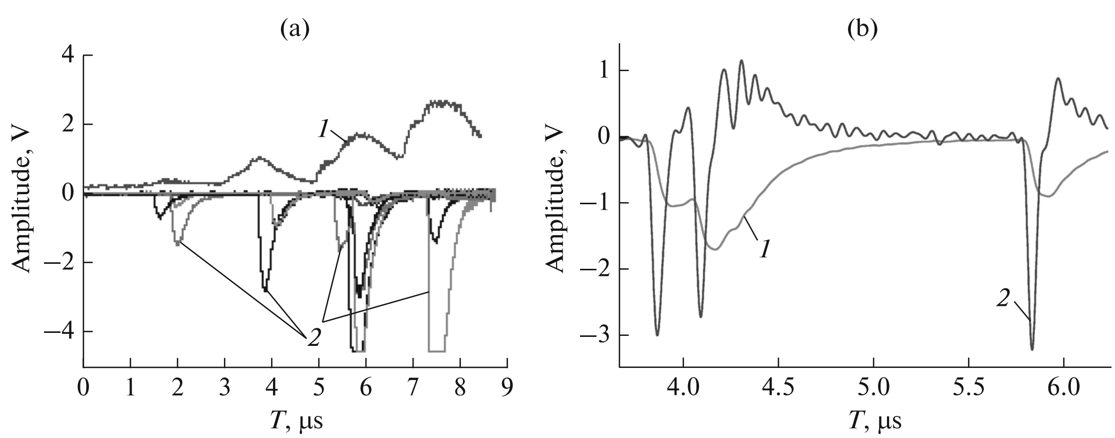

Fig. 8. (a) (*1*) Oscillograms of accelerator current pulses; (*2*) oscillograms of pulses from NaI(Tl) detectors. (b) Oscillogram of signals from NaI detector (fragment): (*1*) oscillogram of original signal and (*2*) oscillogram of differentiated signal.

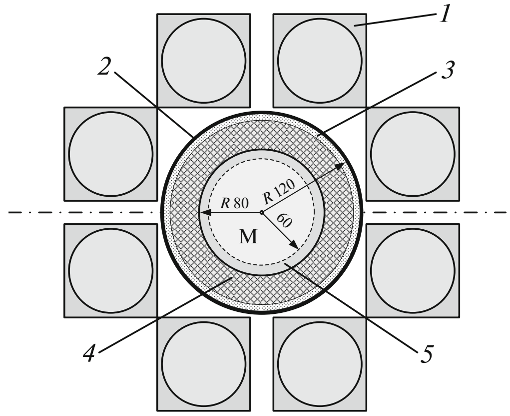

Fig. 9. Schematic diagram of additional shielding of NaI(Tl) detectors from neutrons: (*1*) NaI(Tl) detectors, (*2*) cadmium layer (cylinder with a wall thickness of 0.5 mm), (*3*) boron nitride layer (5-mm-thick powder layer), and (*4*) D_2O layer (35-mm-thick heavy water layer); M is the TiT target.

The calculation yielded the reduction of the fast neutron flux by a factor of 2.2. The experiment using the monitor neutron detector demonstrated the reduction of the neutron flux by a factor of 2.1.

An additional problem in processing experimental results occurs due to pulse overlapping (Figs. 8a, 8b). The pulse overlapping results in the fact that the code for oscillogram processing interprets two pulses as one pulse with large amplitude, which results in a considerable distortion of event energy distribution. In order to eliminate this problem, we developed an online code for rejecting overlapping pulses. The signal oscillogram registered by a digital oscilloscope is first smoothed by a Gaussian filter (Fig. 8b, curve *1*) with the parameters providing the best amplitude resolution of the γ-quanta spectrum. The smoothed oscillogram is differentiated (Fig. 8b, curve *2*), which allows one to separate overlapping γ-quanta pulses. The amplitude spectrum constructed based on the differentiated signal has worse amplitude resolution, but provides almost complete discrimination of overlapping in our experimental conditions. The energy resolution of the detector (FWHM) for $E_\gamma = 2.614$ MeV is equal to $\Delta E = 6.5\%$, unlike $\Delta E = 5.1\%$ obtained before digital differentiation of the signal. Moreover, the code allows one to discriminate time-correlated (with an accuracy of 10 ns) two or more γ-quanta with energies exceeding the energy threshold $E_\gamma = 0.9$ MeV, which appear in the accelerator pulse. These γ-quanta appear due to the interaction of time-correlated neutrons with the materials surrounding the target, including the materials of the NaI(Tl) detectors. The reactions of radiative capture (n, γ) or inelastic scattering $(n, n'\gamma)$ are characterized by times of order of 10^{-12}–10^{-14} s. The probability of appearance of correlated γ-quanta from the reaction $T(^4He, \gamma)^7Li$ in one accelerator pulse is small. It can be a random time coincidence (in an interval of 10 ns) of γ-quanta with the energies $E_\gamma^0 = 2483.7$ keV and $E_\gamma^1 = 2006.1$ keV. Time-correlated γ-quanta with the energies $E_\gamma^1 = 2006.1$ keV and $E_\gamma^2 = 477.6$ keV are not discriminated, since $E_\gamma^2 = 477.6$ keV is below the registration threshold. In evaluations, we used the Gamov formula for the cross section in the nonresonance energy region, $E_{\text{Gamov}} = 6735$ keV is the Gamov energy for the reaction $T(^4He, \gamma)^7Li$, and the fact that an average of $\sim 5 \times 10^{14}$ $^4He^+$ ions hit the tritium target in one accelerator pulse.

$$\sigma_{\alpha t}(E) = \frac{S_{\alpha t}(E)}{E}\exp\left(-\frac{82.067}{\sqrt{E}}\right). \quad (5)$$

Here, $S_{\alpha t}(E) = 0.1$ keV b is the averaged S-factor; $E = 16.7$ keV is the reaction energy in the center of mass system.

Thus, the background was reduced by another factor of four; the γ-quanta energy distribution obtained in a long run of measurements is shown in Fig. 10a.

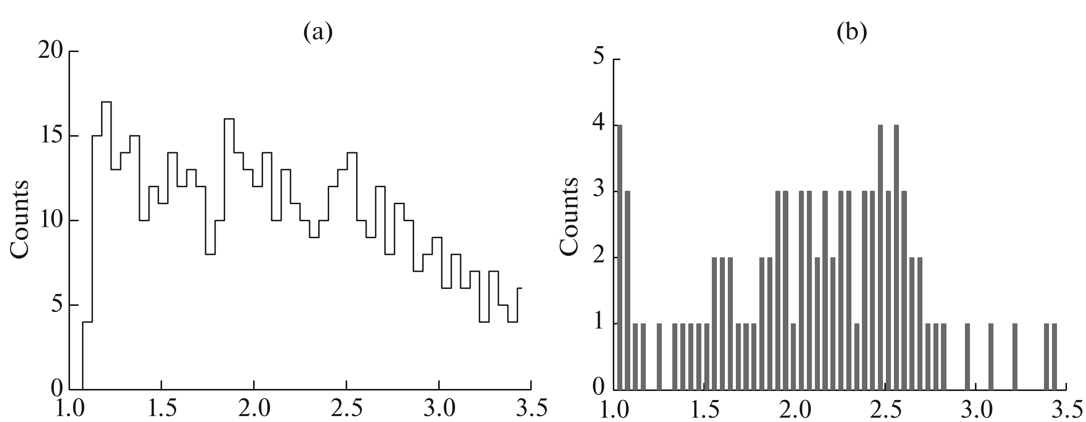

Fig. 10. (a) Experimental γ-quanta spectrum; (b) difference of γ-quanta energy spectra obtained in experiments with helium and tritium.

It can be seen from this spectrum that the applied "online" event selection means were insufficient to separate the sought process from the background. Therefore, it was decided to use the direct method of measurement and subtraction of the background due to neutron interaction with the materials surrounding the vacuum chamber in which the target and NaI(Tl) detectors were situated. The method was developed by us in investigation of the reaction ^{2}H(^{4}He, γ)^{6}Li [13]. The number of neutrons registered by the ^{3}He detector was determined in parallel with γ-quanta statistics accumulation using the NaI(Tl) detectors. Then the ^{4}He gas in the ion source was replaced by gaseous tritium (^{3}H), and the background corresponding to the reaction T(^{4}He, γ)^{7}Li was measured in a separate run. ^{3}H$^+$ ions were accelerated to 10 keV. The cross section of the reaction T(t, 2n)^{4}He at this energy is ~10^{-30} cm [26]. This energy value was chosen in order not to overload the NaI(Tl) detectors by both neutrons produced in the reaction T(t, 2n)^{4}He and γ-quanta produced in (n, γ), (n, $n'\gamma$) in the materials surrounding the target. The time of measurement of the yield for the reaction T(t, 2n)^{4}He was determined by the time of accumulation by the ^{3}He neutron detector of the neutron statistics equal to the number of neutrons registered in the run of measurement of the yield for the reaction T(^{4}He, γ)^{7}Li. Since the cross section of the reaction T(t, 2n)^{4}He is large, the background measurement time is short. The "online" event selection procedure was the same as in the measurement of the yield for the reaction T(^{4}He, γ)^{7}Li. The result in the form of the difference of the γ-quanta energy spectra obtained in the experiments with helium and tritium is shown in Fig. 10b.

EXPERIMENTAL RESULTS: DISCUSSION OF RESULTS

The experiments provided the yield of the reaction T(^{4}He, γ)^{7}Li for a collision energy of helium ions ^{4}He$^+$ with tritons ^{3}H of 16.7 keV in the center of mass system. The number of α particles that traversed the target was 1.1×10^{20}. The statistical data processing yielded the number of registered γ-quanta $N_\gamma^{\rm exp} = 71 \pm 25$. Below we denote helium ^{4}He$^+$ ions by α particles, tritium atoms ^{3}H by tritons, and the reaction T(^{4}He, γ)^{7}Li, by the αt reaction.

The experimental determination of the values of the astrophysical $S_{\alpha t}$-factor and the effective cross section of the αt reaction in the region of astrophysical energies is based on the measurement of the yield of 2.484, 2.006 MeV γ-quanta and application of parameterization for the cross section of this reaction as a function of collision energy of α particles with tritons in the form [12, 27]

$$N_\gamma^{\rm tot} = N_\alpha \varepsilon_\gamma \int_0^\infty f(E)\,dE \int_0^\infty \sigma_{\alpha t}(E')\,n(x)\left(\frac{dE'}{dx}\right)^{-1} dE'; \quad (6)$$

$$\sigma(E) = \frac{S_{\alpha t}(E)}{E}\exp\left(-\beta/\sqrt{E}\right), \quad (7)$$

in the case of the αt-reaction, $\beta = 2\pi Z_1 Z_2 \sqrt{\mu} = 3.29\, Z_1 Z_2 \sqrt{\mu}$, where $\beta/\sqrt{E}$ is the Sommerfeld parameter; Z_1, Z_2, μ are the charges of interacting particles and the reduced mass of the interacting particles in the input channel of the reaction in a.m.u., respectively; E is the collision energy in the center of mass system; $S_{\alpha t}(E)$ is the astrophysical S-factor for the αt reaction; $N_\gamma^{\rm tot}$ is the total number of registered γ-quanta; $\sigma_{\alpha t}(E)$ is the αt reaction cross section; dE/dx are the specific energy losses of α particles in the target; $n(x)$ is the triton density in the target at the depth x; $f(E)$ is the distribution function of α particles hitting the target; ε_γ is the efficiency of registration of γ-quanta from the αt reaction; and N_α is the number of α particles that traversed the target.

This parameterization of the cross section for the reaction T(^{4}He, γ)^{7}Li assumes the interaction of "bare" α particles with tritons.

Taking into account the energy spread of α particles hitting the tritium target and Coulomb energy losses of α particles interacting with target atoms, the experimental values of the S-factor for the αt reaction are determined as [12, 27, 28]:

$$\overline{S_{\alpha t}(E)} = \int_E^\infty S_{\alpha t}(E)\,P(E)\,dE$$

$$= S_{\alpha t}(E_{\rm col}) = \frac{N_\gamma^{\rm exp}}{N_\alpha \varepsilon_\gamma \int_0^\infty f(E)\,dE \int_0^\infty \frac{e^{-2\pi\eta} n(x')}{E'(E,x')}dx'}, \quad (8)$$

where $2\pi\eta = \beta/\sqrt{E}$,

$$P(E) = \frac{e^{-2\pi\eta} D(E) \int_E^\infty n(x(E,E')) f(E') dE'}{\int_0^\infty e^{-2\pi\eta} D(E) dE \int_E^\infty n(x(E,E')) f(E') dE'}, \quad (9)$$

$$D(E) = -\frac{1}{E}\frac{dx}{dE}, \quad (10)$$

$$E_{\rm col} = \int_E EP(E)dE, \quad (11)$$

$$\overline{S_{\alpha t}(E)} = S_{\alpha t}(E_{\rm col}), \quad (12)$$

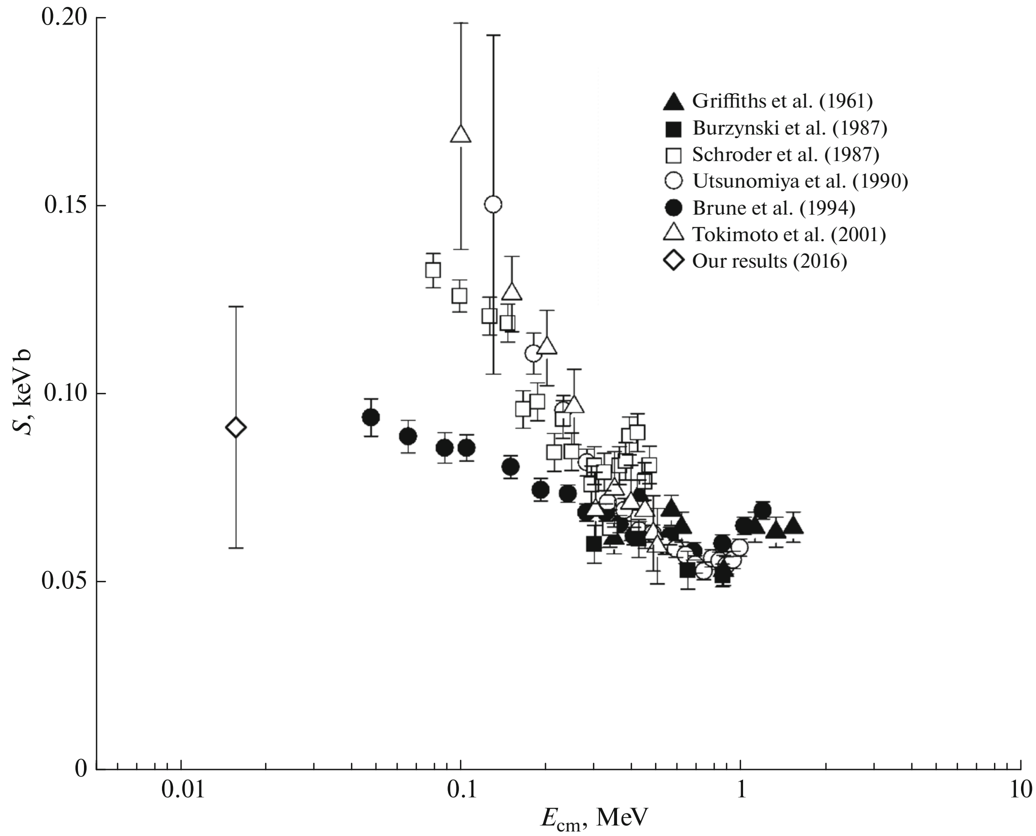

Fig. 11. Astrophysical S-factor for the reaction T(^{4}He, γ)^{7}Li. Results of direct measurements: (solid triangles) [5], (solid squares) [6], (open squares) [7], and (solid circles) [4]. Results of indirect measurements: (open circles) [8] and (open triangles) [9].

where $N_\gamma^{\exp}$ is the number of registered γ-quanta from the αt reaction, $n(x')$ is the triton density in the target at the depth x', $E'(E_{\rm cm}, x')$ is the collision energy of α particles with a triton inside the target at the depth x', $P(E)$ is the distribution function of the probability of α particle collision with tritons and subsequent registration of produced γ-quanta from the αt reaction, and $E_{\rm col}$ is the collision energy of α particles with tritons averaged over the distribution function $P(E)$.

As a result, we obtained the following value of the $S_{\alpha t}(E)$-factor:

$$S_{\alpha t}\left(E_{\rm col}=15.7\ \text{keV}\right) = \left(0.091 \pm 0.032^{(\text{stat})} \pm 0.011^{(\text{syst})}\right)\ \text{keV b}, \tag{13}$$

Here, the index (stat) denotes the statistical error and the index (syst) denotes the systematic error. The total systematic error is 12%; it is comprised of the errors in determining the γ-quanta registration efficiency (8%), the number of tritium atoms in the target (7%), and the number of ^{4}He$^+$ ions that traversed the target (5%).

Our result, together with all available experimental results on the $S_{\alpha t}$-factor, is shown in Fig. 11. Despite the fact that our result has a large error (the known difficulty in measuring the yield of a nuclear reaction in the ultralow energy region), it allows one to make certain conclusions. It can be seen that our result contradicts the results of all indirect measurements [8, 9] and one of the direct measurements [7], in which the S-factor for the zero energy of αt interaction was taken equal to $S_{\alpha t}(E = 0) = 0.14 \pm 0.02$ keV b.

In [4, 5] the following values of the S-factors were found: $S_{\alpha t}(E = 0) = 0.1067 \pm 0.0064$ keV b [4], $S_{\alpha t}(E = 0) = 0.064 \pm 0.016$ keV b [5], and our result does not contradict these studies. Theoretical calculations [29–32] yield the following values: $S_{\alpha t}(E = 0) = 0.098$ keV b [29], $S_{\alpha t}(E = 0) = 0.1$ keV b [30], $S_{\alpha t}(E = 0) = 0.1$ keV b [31], and $S_{\alpha t}(E = 0) = 0.0974$ keV b [32], which agrees well with experiment [4] and our result.

CONCLUSIONS

The experiment aimed at the measurement of $S_{\alpha t}$ factor for the reaction T(^{4}He, γ)^{7}Li at the minimum energy for the ^{3}H–^{4}He system was performed for the first time. The obtained value of the astrophysical $S_{\alpha t}$ factor at $E_{\rm cm} = E_{\rm col} = 15.7$ keV $S_{\alpha t}(E_{\rm cm} = 15.7\ \text{keV}) = 0.091 \pm 0.032$ allows one to make a choice in favor of the experimental data obtained in [4] with $S_{\alpha t}(E = 0) = 0.1067 \pm 0.0064$ keV b.

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