EXTRAPOLATION OF THE ASTROPHYSICAL S FACTOR FOR THE $^{3}\mathrm{He}(\alpha,\gamma)^{7}\mathrm{Be}$ REACTION TO LOW ENERGIES*

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The main purpose of this work is to extrapolate the astrophysical S factor for the $^{3}\mathrm{He}(\alpha,\gamma)^{7}\mathrm{Be}$ reaction to low energies including $E = 0.0$ MeV. For this purpose, the recently measured experimental astrophysical S factor for the nuclear astrophysical $^{3}\mathrm{He}(\alpha,\gamma)^{7}\mathrm{Be}$ reaction has been analysed. The modified two-body potential approach has been used for analysing the experimental data. This method made it possible to extract precisely the values of the asymptotic normalization coefficients. New values of the asymptotic normalization coefficients for $^{3}\mathrm{He}+\alpha \to ^{7}\mathrm{Be}$ (0.0 MeV) and $^{3}\mathrm{He}+\alpha \to ^{7}\mathrm{Be}$ (0.429 MeV) with their uncertainties have been obtained. The values of the asymptotic normalization coefficients have been used for extrapolation of the astrophysical S factor to low energies within the modified two-body potential approach.

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1. Introduction

The $^{3}\mathrm{He}(\alpha,\gamma)^{7}\mathrm{Be}$ reaction plays a critical role in the production of $^{7}\mathrm{Be}$ during *pp*-chain burning in low-mass stars like our sun. The solar neutrinos are produced by electron capture on $^{7}\mathrm{Be}$ in the *pp*-II chain [1, 2]. The predicted flux of solar neutrinos from $^{7}\mathrm{Be}$ depends on $[S_{34}(0)]^{0.8}$ [3]. The uncertainty in extrapolation of the astrophysical S factors to the Gamov solar energy influences significantly the uncertainty in the predicted fluxes for solar $^{7}\mathrm{Be}$ and $^{8}\mathrm{B}$ neutrinos [1, 2].

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The experimental measurement of the astrophysical S factor of the radiative capture $^3\mathrm{He}(\alpha,\gamma)^7\mathrm{Be}$ reaction has been carried out by detecting the prompt γ-ray emitted in the reaction and detecting the γ-ray that follows the electron capture decay of ^{7}Be (activation method). In works [4–6], the S factor was measured by detecting the γ-ray that follows the electron capture decay of ^{7}Be. In [7–10], both methods were used for measuring the astrophysical S factor. In work (ERNA) [11], the activation and prompt γ-ray measurements were also carried out. The measurements of astrophysical S factors at energies of $E_{\mathrm{cm}} = 300 \div 1460$ keV were performed by detecting the prompt γ-rays from the reaction in [12]. In Ref. [13], the reaction cross sections have been measured between $E_{\mathrm{cm}} = 4.0$ and 4.4 MeV with 0.04-MeV steps by the activation technique, and one lower energy cross-section point was also determined. Nevertheless, it is still not possible to measure astrophysical S factor (or cross section) at low energies including $E = 0$.

The theoretical calculations of the S factor for the $^3\mathrm{He}(\alpha,\gamma)^7\mathrm{Be}$ reaction were performed within MTBPA [19], potential-model approach [20], potential cluster model [21] (see also [22]), *ab initio* models [23], resonating group calculation [24], and R-matrix theory [25] .

Determination of precise experimental values of the ANCs for $^3\mathrm{He}+\alpha \to ^7\mathrm{Be}$ (g.s.) and $^3\mathrm{He}+\alpha \to ^7\mathrm{Be}$ (0.429 MeV) affects the correct extrapolation of the astrophysical S-factors of the $^3\mathrm{He}(\alpha,\gamma)^7\mathrm{Be}$ reaction at solar energies. A value of ANC is extracted from the analysis of measured differential cross sections of one-particle transfer reactions and experimental astrophysical S factors. Angular distributions of transfer reactions are usually analysed via several different methods including modified distorted wave Born approximation (MDWBA) [14, 15], optical model, and coupled reaction channel (CRC) method [16, 17]. In [14], we determined the ANC values of ^{7}Be nucleus in $^3\mathrm{He}+\alpha$ channel from the analysis of the measured differential cross sections of the $^6\mathrm{Li}(^3\mathrm{He},d)^7\mathrm{Be}$ transfer reaction within the MDWBA and CRC methods. The modern experimental S factors precisely measured in Refs. [4, 7–11] for the $^3\mathrm{He}(\alpha,\gamma)^7\mathrm{Be}$ reaction were used for the determination of the ANC values in our previous work [18] within MTBPA [19].

In this work, we have determined ANC values of ^{7}Be nucleus in $^3\mathrm{He}+\alpha$ channel from the experimental S factor measured in [12], and the S factors have been extrapolated using the obtained values of ANCs to low energies.

2. Results and discussion

According to MTBPM [19, 26] (see also Refs. [27, 28]), the astrophysical S factors $S_{l_f j_f}(E)$ [or $S_{aA}(E)$] for the direct radiative capture $A(a,\gamma)B$ reaction are presented in the form of

$$S_{l_f j_f}(E) = C^2_{l_f j_f} R_{l_f j_f}\left(E, b_{l_f j_f}\right) . \tag{1}$$

Here, $R_{l_f j_f} = \frac{S^{\rm sp}_{l_f j_f A}(E)}{b^2_{l_f j_f}}$ and $C^2_{l_f j_f}$ are the ANC for $a+A \to B$; $b_{l_f j_f}$ is the single-particle ANC; $l_f(j_f)$ is a relative orbital (total) angular momentum of A and a particle in the nucleus $B(a+A)$; $S^{\rm sp}_{l_f j_f}(E)$ is a single-particle astrophysical S factor. The following additional requirements [19]

$$R_{l_f j_f}\left(E, b_{l_f j_f}\right) = f(E) \tag{2}$$

and

$$C^2_{l_f j_f} = \frac{S_{l_f j_f}(E)}{R_{l_f j_f}\left(E, b_{l_f j_f}\right)} = \text{const.} \tag{3}$$

must be contemporaneously satisfied for each experimental point of energy E. The fulfillment of these conditions allows for determining the value of the ANC $(C^{\rm exp}_{l_f j_f})^2$ and its uncertainty. For obtaining the value of the ANC $(C^{\rm exp}_{l_f j_f})^2$, the directly measured astrophysical S factors $S^{\rm exp}_{aA}(E)$ are used instead of $S_{l_f j_f}(E)$ in Eq. (3).

The values of the experimental total astrophysical S factor and the experimental branching ratios $(\frac{\gamma_{429}}{\gamma_0})$ with their uncertainties in the energy region of $E = 303.4$–1452.0 keV are given in Table I in Ref. [12]. By using the experimental branching ratio one can separate the total experimental S factor measured in [12] up to the astrophysical S factor corresponding to the ground and first excited states of the residual ^{7}Be nucleus for all experimental points of energy E.

For obtaining the values of ANC for ^{3}He+$\alpha \to ^7$Be (0 MeV) and ^{3}He+$\alpha \to$ ^{7}Be (0.429 MeV), the analysis of the experimental astrophysical S factors $S^{\rm exp}_{l_f j_f}$ [or $S^{\rm exp}_{34}$] for the ^{3}He$(\alpha,\gamma)^7$Be reaction populating the ground and the first excited states [12] has been performed by using equations (1)–(3). The conditions given by equations (2) and (3) must be fulfilled for the reaction in the considering energy. These conditions for the ^{3}He$,(\alpha,\gamma)^7$Be reaction were tested in detail in a wide energy region in our previous work [18]. For each of the seventeen experimental points of E the values of the ANCs, $C^{\rm exp}_{13/2}$ for ^{3}He+$\alpha \to ^7$Be (0 MeV), and $C^{\rm exp}_{11/2}$ for ^{3}He+$\alpha \to ^7$Be (0.429 MeV) are obtained from the corresponding separated experimental astrophysical S factor [$S^{\rm exp}_{13/2}$ and $S^{\rm exp}_{13/2}$] [12] using relation (3). The results of ANCs for these experimental energy points of E are shown in Fig. 1.

The total uncertainty of ANC for each experimental point of the energy is calculated summing in quadrature the total experimental and the theoretical uncertainties. The values of the weighted means for the ANC values for ground and first excited states obtained from all experimental data [12] are equal to $(C^{\rm exp}_{13/2})^2 = 25.18 \pm 0.82$ fm^{-1} and $(C^{\rm exp}_{13/2})^2 = 16.18 \pm 0.22$ fm^{-1}, respectively.

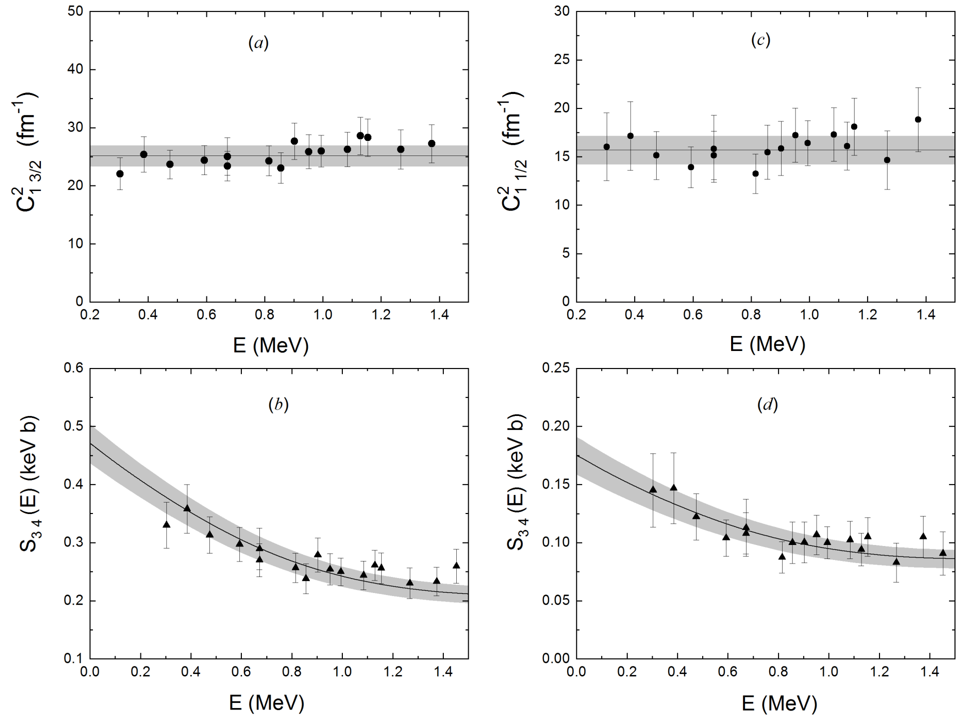

Fig. 1. The values of the ANCs, $C^2_{13/2}$ for α+^{3}He$\to$^{7}Be (g.s.) (a) and $C^2_{11/2}$ for α+^{3}He$\to$^{7}Be (0.429 MeV) (c), for each experimental energy point. The solid lines show the present results for the weighted means. In (b) [$E^* = 0$ MeV] and (d) [$E^* = 0.429$ MeV], the solid lines show the calculated astrophysical S factor within the MTBPM. The triangle symbols present the separated experimental $S_{34}^{\rm exp}(E)$ corresponding to the ground (b) and the first excited (d) states of Ref. [12]. The width of each band is the corresponding weighted uncertainty.

The corresponding weighted means of the ANCs for ^{3}He+α $\to$^{7}Be (g.s.) and ^{3}He+α $\to$^{7}Be (0.429 MeV) are used to extrapolate $S_{13/2}(E)$, $S_{11/2}(E)$ to low energies ($E \leq 25$ keV). The separated experimental [12] and calculated astrophysical S factors are presented in Figs. 1 (c) and (d). The solid lines show our calculated astrophysical S factors performed using the corresponding weighted ANC values. The weighted mean values of ANC and the total astrophysical S factor S_{34} at the energy of $E = 0$ keV are given in Table I for the comparison with the results of other works.

As seen from Table I, the weighted means of $S_{34}(0)$ obtained in the present work are in good agreement with the data sets II from [18, 29] and differ noticeably from set I from [14, 18]. The main reason for this distinction is a difference in magnitudes of the corresponding ANCs obtained from various experimental data. For comparison, the energy dependence of

TABLE I

The weighted means of the ANC values $(C^{\rm exp})^2$ for ^{3}He+$\alpha \rightarrow ^7$Be and the calculated values of $S_{34}(E)$ at the energy of $E = 0$ keV.

Methods	$\left(C^{\rm exp}_{13/2}\right)^2$	$\left(C^{\rm exp}_{11/2}\right)^2$	$S_{34}(0)$
MTBPM (present)	25.2 ± 1.8	15.7 ± 1.5	0.646 ± 0.050
MTBPM data set I [18]	24.1 ± 0.2	16.3 ± 0.2	0.628 ± 0.006
MDWBA [29]	22.9 ± 0.7	18.0 ± 0.5	0.596 ± 0.017
MTBPM data set II [18]	21.3 ± 0.3	14.6 ± 0.2	0.562 ± 0.008
MDWBA [14]	20.84 ± 1.12	12.86 ± 0.50	0.534 ± 0.025

the total astrophysical S factors calculated using ANCs found in [14, 18] and the current studies, as well as the modern precisely measured experimental astrophysical S factors, are presented in Fig. 2.

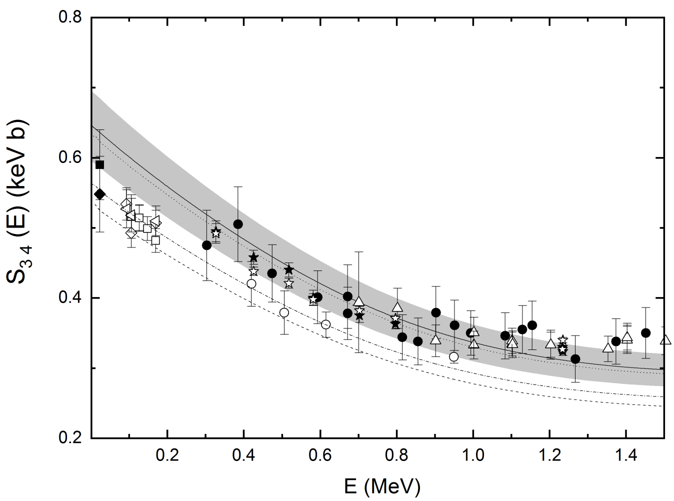

Fig. 2. The calculated and experimental astrophysical S factors for the ^{3}He$(\alpha,\gamma)^7$Be reaction. For more details, see the text.

The solid line presents a total astrophysical S factor calculated in MTBPA [19] using the ANC determined in this work. The width of the band is its weighted uncertainty. The dotted line shows the calculated astrophysical

S factor in [14], and the dashed and dash-dotted lines depict the astrophysical S factors calculated using ANCs found from data set I and data set II in [18], respectively. In Fig. 2, the filled circles present the experimental astrophysical S factors measured in [12], the empty circles — experimental data from [4], the empty triangles — experimental data taken from [11], the filled (prompt) and empty (activation) stars — experimental data given in [10]. The empty squares show the experimental S factor given in [7, 8], the empty diamonds — experimental data taken from [9], the filled squares — data from [30] and the closed diamonds — data given in [31].

3. Conclusions

In this work, we have analysed the experimental astrophysical S factors $S_{34}^{\rm exp}(E)$ for the ^{3}He$(\alpha,\gamma)^7$Be reaction measured recently in Ref. [12] at energies of $E_{\rm cm} = 300 \div 1460$ keV. The analysis has been carried out within the framework of the modified two-body potential approach MTBPA [19]. This approach made it possible to more accurately obtain the values of the ANC. The values of the ANCs for ^{3}He+$\alpha \to ^7$Be (0 MeV) and ^{3}He+$\alpha \to ^7$Be (0.429 MeV) are found for each of the corresponding experimental points of energy E. New estimates for the weighted means of the ANC values are obtained. The obtained ANCs were used for extrapolation of astrophysical S factors to low energies (including $E = 0$) within the modified two-body potential approach.

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