THE ASYMPTOTIC NORMALIZATION COEFFICIENT FOR ^{7}Be+$p \to ^8$B AND ASTROPHYSICAL S-FACTOR FOR THE ^{7}Be$(p,\gamma)^8$B REACTION*

K.I. Tursunmakhatov

Gulistan State University, Gulistan 120100, Uzbekistan

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The main purpose of this work is to investigate the astrophysical S factor of the ^{7}Be$(p,\gamma)^8$B process at low energies. For this purpose, the new values of the asymptotic normalization coefficients for ^{7}Be $+\, p \to {}^8$B with their uncertainties have been obtained from the analysis of the directly measured experimental astrophysical S-factors of the ^{7}Be$(p,\gamma)^8$B reaction in the off-resonance energy region with the modified two-body potential approach. The weighted values of the asymptotic normalization coefficients are used for extrapolation of the astrophysical S-factor for the ^{7}Be$(p,\gamma)^8$B reaction to low energies using the modified R-matrix approach. The new parameters of the resonances are obtained.

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1. Introduction

The reaction ^{7}Be$(p,\gamma)^8$B plays a crucial role in the production of ^{8}B during *pp*-chain burning in low-mass stars such as our Sun. The solar neutrinos are formed by electron capture on ^{7}Be in the *pp*-II chain [1, 2]. The predicted flux of solar neutrinos in the standard solar model hinges on the value of the $[S_{17}/S_{17}(0)]^{10}$ ratio [3]. The uncertainty in the extrapolation of the astrophysical S-factors to the experimentally inaccessible energies influences significantly the uncertainty in the predicted fluxes for solar ^{7}Be and ^{8}B neutrinos [1, 2].

In the last decades, several direct measurements of the astrophysical S-factors of the proton capture reaction ^{7}Be$(p,\gamma)^8$B were performed (for example, see [4] and references therein). Despite so many experimental

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studies of this reaction, none of them measured the astrophysical S-factor at very low energies, including $E = 0$. Therefore, it is very important to extrapolate the astrophysical S-factor to low energies and correctly estimate the value of $S_{17}(0)$.

2. Results and discussion

The asymptotic normalization coefficient is a fundamental nuclear characteristic of bound states and plays an important role in low-energy elastic scattering, transfer, and radiative capture reactions [5]. The asymptotic normalization coefficient is usually determined from the analysis of the measured differential cross sections of the transfer reactions using the modified distorted wave Born approximation (MDWBA) [6, 7] or experimental astrophysical S-factors via the modified two-body potential approach (MTBPA) [8]. The astrophysical S-factor is expressed in terms of ANC in the modified two-body potential method (MTBPM) [7, 9]. This method includes two conditions that verify the peripheral character of the $^7\mathrm{Be}(p,\gamma)^8\mathrm{B}$ reaction in the off-resonance energy region ($E \leq 400$ keV and $1000 \leq E \leq 1200$ keV): *(i)* $R(E, b_{l_f j_f}(r_0, a)) = \text{const.}$ must be fulfilled for variation of the parameters of the Woods–Saxon potential for each fixed experimental energy E_i ($i = 1, 2, \ldots, n$). *(ii)* The ratio $C^2_{l_f j_f} = S^{\mathrm{exp}}/R(E, b_{l_f j_f}(r_0, a))$ must not depend neither on single-particle ANC $b_{l_f j_f}(r_0, a)$ nor energy E. Fulfillment of these conditions allows to determine "experimental" values of ANCs from the experimental S-factors using the relation $(C^{\mathrm{exp}}_{l_f j_f})^2 = S^{\mathrm{exp}}/R(E, b_{l_f j_f})$. In Ref. [10], the peripheral character of the $^7\mathrm{Be}(p,\gamma)^8\mathrm{B}$ reaction was checked in detail and the values of ANCs for $^7\mathrm{Be} + p \to {}^8\mathrm{B}$ were determined from the experimental data of [11] and [12] with the MTBPM. Thus, according to [10], the considered reaction is peripheral in the off-resonance energy region ($E \leq 400$ keV and $1000 \leq E \leq 1200$ keV). In this work, for extracting values of ANC, the experimental astrophysical S-factors measured at the above-mentioned energy region in Refs. [13, 14] have been analyzed with the MTBPM. The values of ANCs for $^7\mathrm{Be} + p \to {}^8\mathrm{B}$ with their uncertainties have been determined for each experimental energy E_i. The weighted mean value of these ANCs have been calculated. The determined value of ANC $C^2_{p^7\mathrm{Be}}$ (or $(C^{\mathrm{exp}}_{p^7\mathrm{Be}})^2$) at each energy and the weighted mean value of them are given in Fig. 1.

The weighted mean value of ANC is equal to $(C^{\mathrm{exp}}_{p^7\mathrm{Be}})^2 = 0.550 \pm 0.018\ \mathrm{fm}^{-1}$. Here, $(C^{\mathrm{exp}}_{p^7\mathrm{Be}})^2 = C^2_{p^7\mathrm{Be};\,11/2} + C^2_{p^7\mathrm{Be};\,13/2} = C^2_{p^7\mathrm{Be};\,13/2}(1 + \lambda_C)$, where $\lambda_C = C^2_{p^7\mathrm{Be};\,11/2}/C^2_{p^7\mathrm{Be};\,13/2}$. Using the value of the ratio $\lambda_C = 0.125$ [10], the values of ANCs are equal to $(C^{\mathrm{exp}}_{p^7\mathrm{Be};\,13/2})^2 = 0.489 \pm 0.016\ \mathrm{fm}^{-1}$ and $(C^{\mathrm{exp}}_{p^7\mathrm{Be};\,11/2})^2 = 0.061 \pm 0.002\ \mathrm{fm}^{-1}$. The uncertainty involves the uncertainty arising due to a change of $R(E, b_{l_f j_f}(r_0, a))$ function at a variation of the free param-

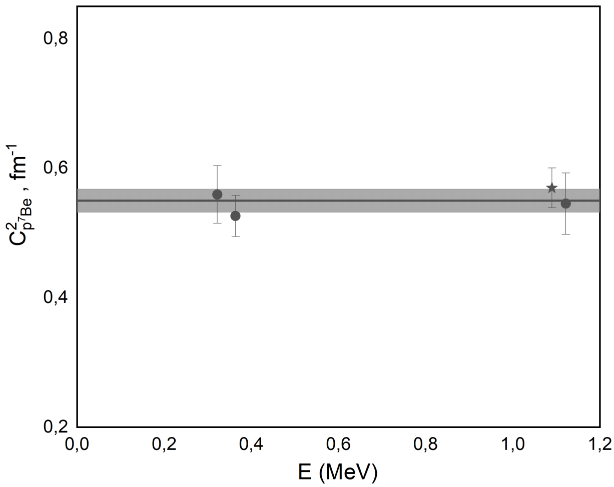

Fig. 1. The values of ANCs $C^2_{p^7\mathrm{Be}}$ for $^7\mathrm{Be}+p \to {}^8\mathrm{B}$. The full circle and full star are the value of ANC obtained from the experimental data of [14] and [13], respectively. The solid line is the weighted mean values of the experimental ANCs. The width of the band is the weighted uncertainty.

eter, where r_0 and a are the geometric parameters of the Woods–Saxon potential, and the experimental errors of the astrophysical S-factors. The astrophysical S-factor at zero energy is calculated with MTBPA using the extracted ANC value. The final result gives that the direct capture S-factor is equal to $S_{17}(0) = 20.51 \pm 0.67$ eV b. For comparison, the squared ANC $(C^{\mathrm{exp}}_{p^7\mathrm{Be}})^2$ for $^7\mathrm{Be}+p \to {}^8\mathrm{B}$, the value of S-factor $S_{17}(0)$ for the direct radiative proton capture $^7\mathrm{Be}(p,\gamma)^8\mathrm{B}$ reaction found in the present work and the recommended results of the other works are given in Table 1.

As seen from the table, the obtained value for $(C^{\mathrm{exp}}_{p^7\mathrm{Be}})^2$ is in good agreement with that recommended in Refs. [15–17]. Here, using the extracted ANC, the astrophysical S-factor for the nuclear-astrophysical reaction $^7\mathrm{Be}(p,\gamma)^8\mathrm{B}$ is calculated at low energies using the modified R-matrix approach [18], in which the direct component of the astrophysical S-factor is determined via the ANC value. The analysis was carried out taking into account the contributions from two resonances with energies E^* and spin parities level J^π $((E^*; J^\pi) = (0.774\ \mathrm{MeV}; 1^+)$ and $(2.320\ \mathrm{MeV}; 3^+))$. The proton widths used in this calculation are $\Gamma_p(E_\mathrm{R}) = 37$ keV [19] for the 1^+ resonance and $\Gamma_p(E_\mathrm{R}) = 350$ keV [20] for the 3^+ resonance. In the calculations, the γ-width of the resonances was considered as an adjustable parameter. The new parameters of the first resonance have been determined by fitting to the experimental astrophysical S-factor of the $^7\mathrm{Be}(p,\gamma)^8\mathrm{B}$ reaction, which was measured in the energy range of 367.2 keV to 812.2 keV

Table 1. The squared ANCs $(C^{\exp}_{p^7\mathrm{Be};})^2$ for $^7\mathrm{Be}+p \to {}^8\mathrm{B}$ and the values of S-factor $S_{17}(E)$ for the direct radiative proton capture $^7\mathrm{Be}(p,\gamma)^8\mathrm{B}$ reaction at energy $E = 0.0$ keV.

Methods	$\left(C^{\exp}_{p^7\mathrm{Be};\,1\,3/2}\right)^2$	$S_{17}(0)$	Ref.
MTBPM $^7\mathrm{Be}(p,\gamma)^8\mathrm{B}$	0.550 ± 0.018	20.51 ± 0.67	present
MTBPM $^7\mathrm{Be}(p,\gamma)^8\mathrm{B}$	0.628 ± 0.017	23.4 ± 0.63	[10]
MDWBA $^7\mathrm{Be}(d,n)^8\mathrm{B}$	0.613 ± 0.06	22.8 ± 2.2	[15]
MDWBA $^{10}\mathrm{B}(^7\mathrm{Be},^8\mathrm{B})^9\mathrm{Be}$ $^{14}\mathrm{N}(^7\mathrm{Be},^8\mathrm{B})^{13}\mathrm{C}$	0.465 ± 0.041	18.2 ± 1.8	[21]
Coulomb breakup $^{58}\mathrm{Ni}(^8\mathrm{B},p^7\mathrm{Be})^{58}\mathrm{Ni}$	0.547 ± 0.027	20.8 ± 1.1	[16]
R-matrix $^7\mathrm{Be}(p,\gamma)^8\mathrm{B}$	0.518	19.4	[22]
MDWBA and charge symmetry relation $^7\mathrm{Li}(d,p)^8\mathrm{Li}$	0.57 ± 0.10	19.9 ± 3.5	[17]

in Ref. [4] using the χ^2 method. The value of the channel radius and the γ-width of the resonances are chosen to provide the minimum of χ^2. The γ width of the resonances is determined to be $\Gamma_\gamma(E_\mathrm{R}) = 13$ meV for the 1^+ resonance and $\Gamma_\gamma(E_\mathrm{R}) = 107$ meV for the 3^+ resonance. The channel radius is found to be $r_\mathrm{ch} = 3.7$ fm. The experimental data for the astrophysical S-factor for these resonances were taken from [4, 23]. The calculated and experimental astrophysical S-factors are presented in Fig. 2. The solid line is the astrophysical S-factor calculated with the modified R-matrix method using the ANC determined in this work.

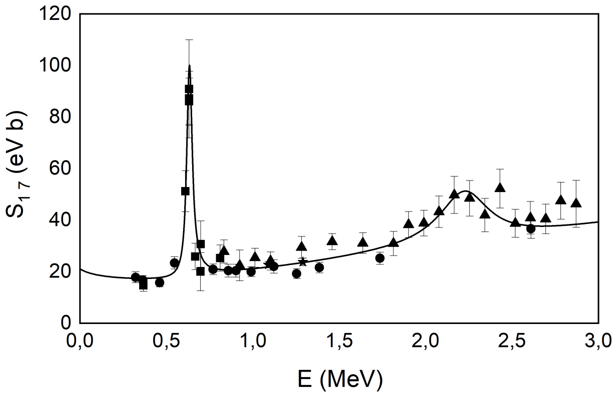

Fig. 2. Astrophysical S-factors of the $^7\mathrm{Be}(p,\gamma)^8\mathrm{B}$ reaction. The solid line is calculated astrophysical S-factor. The experimental points are taken from [13] (full star symbols), [14] (full circle symbols), [4] (full square symbols), and [23] (full triangle symbols).

3. Conclusions

The analysis of the experimental astrophysical S-factors $S_{17}^{\mathrm{exp}}(E)$ for the $^7\mathrm{Be}(p,\gamma)^8\mathrm{B}$ reaction measured in Refs. [13, 14] in the off-resonance energy region has been performed with the MTBPM [9]. The values of the ANCs for $^7\mathrm{Be}+p \to {}^8\mathrm{B}$ have been found for each of the corresponding experimental points E. New estimates for the weighted means of the ANCs with their uncertainty have been obtained. In particular, the recommended value of the astrophysical S-factor, $S_{17}(0) = 20.51 \pm 0.67$ eV b, agrees well with the results of Refs. [15–17]. The obtained ANCs were used for extrapolation of astrophysical S-factors to low energies using the modified R-matrix approach. The new values of resonance parameters are found.

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