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Analysis of astrophysical ^{30}Si$(n,\gamma)^{31}$Si reaction via the asymptotic normalization coefficient method

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This study investigates the ^{30}Si$(n,\gamma)^{31}$Si astrophysical reaction using the Asymptotic Normalization Coefficient (ANC) method. The squared neutron asymptotic normalization coefficients (ANCs), for the virtual decay ^{31}Si $\rightarrow$ ^{30}Si + n are extracted by reanalyzing the existing angular distributions of the ^{30}Si$(d,p)^{31}$Si reaction at 12.5 MeV. Both the Distorted Wave Born Approximation (DWBA) and Adiabatic Distorted Wave Approximation (ADWA) models are applied to refine the analysis. The results show improved ANC values compared to previous DWBA calculations. The squared neutron asymptotic normalization coefficient (ANC), for the ground state is found to be $32.49 \pm 6\,\mathrm{fm}^{-1}$ with DWBA and $31.45 \pm 6\,\mathrm{fm}^{-1}$ with ADWA. Additionally, the direct capture (DC) reaction rate was calculated and compared with previous work. The results show good agreement with the literature, with minor deviations at higher temperatures, highlighting the importance of the DC process in the ^{30}Si$(n,\gamma)^{31}$Si reaction. This work emphasizes the crucial role of neutron capture reactions in the formation of the weak s-process component in stars and provides new insights into reaction rates and cross-sections.

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Astrophysical importance of the ^{30}Si$(n,\gamma)^{31}$Si reaction. The ^{30}Si$(n,\gamma)^{31}$Si reaction plays a crucial role in the weak s-process, contributing to the synthesis of heavier nuclei during carbon and neon burning phases in massive stars [1, 2]. Neutron captures on ^{30}Si affect silicon isotopic abundances and impact galactic chemical evolution models [3]. Presolar SiC grains extracted from meteorites exhibit isotopic ratios that reflect the nucleosynthesis of the s-process [4, 5]. These data provide valuable constraints on stellar models. In particular, AGB star simulations [6] support a reduced neutron capture cross section for ^{30}Si as proposed by Guber et al. [7], who demonstrated the absence of the previously assumed 2.235 keV resonance. This finding implies that the direct capture (DC) component could play a more significant role than previously thought, reinforcing the need for updated reaction rate calculations.

DWBA and ADWA calculations. To investigate the structure of ^{31}Si, we reanalyzed the ^{30}Si$(d,p)^{31}$Si reaction at $E_d = 12.5$ MeV [8] using the Distorted Wave Born Approximation (DWBA) [9] and the Adiabatic Distorted Wave Approximation (ADWA) [10, 11]. Although DWBA is widely used for transfer reactions, it does not account for deuteron breakup, which can influence the peripheral nature of the reaction. ADWA incorporates this effect, offering a more accurate treatment, especially at low energies. Angular distributions for the ground and first excited states of ^{31}Si were calculated and compared with the experimental data. The good agreement achieved using both DWBA and ADWA confirms the appropriateness of the adopted optical model parameters and reinforces confidence in the extracted nuclear structure information. The similarity between the results from DWBA and ADWA further suggests that the reaction is peripheral and that the influence of deuteron breakup is limited in this case. This justifies the use of either method for extracting Asymptotic Normalization Coefficients (ANCs).

ANC method and extracted values. The Asymptotic Normalization Coefficient (ANC) method provides a powerful tool to determine nuclear overlap functions in the asymptotic region, where the nuclear potential vanishes and only long-range forces act [12]. This makes the ANC approach particularly well suited for indirect studies of capture reactions, especially when

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the reaction is peripheral. In this work, neutron ANCs were extracted for the virtual decay $^{31}\mathrm{Si} \to {}^{30}\mathrm{Si} + n$ by fitting the angular distributions of the $^{30}\mathrm{Si}(d,p)^{31}\mathrm{Si}$ reaction using DWBA and ADWA. For the ground state ($J^\pi = 3/2^+$), the squared ANC values were $C^2 = 32.49 \pm 6\ \mathrm{fm}^{-1}$ (DWBA) and $31.45 \pm 6\,\mathrm{fm}^{-1}$ (ADWA). For the first excited state at $E_x = 0.752\,\mathrm{MeV}$ ($J^\pi = 1/2^+$), the values were significantly lower: $C^2 = 3.12 \pm 0.4\,\mathrm{fm}^{-1}$ (DWBA) and $2.85 \pm 0.4\,\mathrm{fm}^{-1}$ (ADWA). The consistency between the DWBA and ADWA results confirms the peripheral character of the transfer reaction and the robustness of the extracted ANC values. These values serve as reliable input for calculating the DC component of the $^{30}\mathrm{Si}(n,\gamma)^{31}\mathrm{Si}$ reaction rate.

DC reaction rate calculation. To determine the $^{30}\mathrm{Si}(n,\gamma)^{31}\mathrm{Si}$ reaction rate at astrophysical energies, we employed a potential model calculation [13] normalized to the extracted ANC values. Because the reaction is peripheral at low energies, the capture cross section depends mainly on the asymptotic part of the nuclear overlap function, making the ANC method ideal for calculating the DC component in a model-independent way. The capture cross sections were computed by folding the overlap function with the neutron wave function, and the resulting rates were obtained by convolution with a Maxwell–Boltzmann distribution. The calculated reaction rates show good agreement with existing MACS data [14], particularly at low stellar temperatures ($T_9 < 0.5$), where DC dominates over potential resonant contributions [13]. The calculated DC reaction rates are in good agreement with the literature. The comparison of reaction rates obtained in this work and from the literature is shown in Fig. 1.

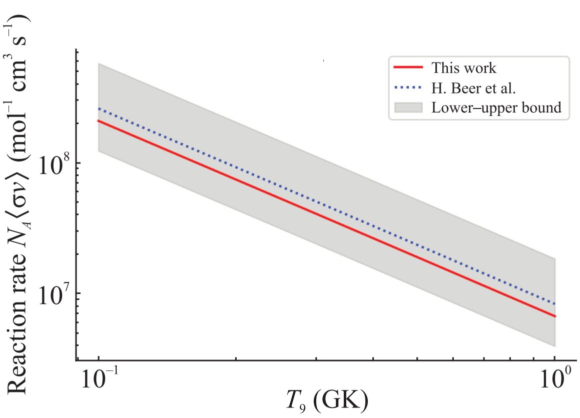

Fig. 1. (Color online) Comparison of reaction rates for $^{30}\mathrm{Si}(n,\gamma)$. The red solid line represents the results of this work, the blue dotted line corresponds to [14], and the gray shaded area indicates the uncertainty range

Conclusion. This study demonstrates the effectiveness of the ANC method, combined with DWBA and ADWA, in reliably extracting nuclear structure information relevant to neutron capture processes. The consistent ANC values derived for the ground and first excited states of $^{31}\mathrm{Si}$ validate the peripheral nature of the $^{30}\mathrm{Si}(d,p)^{31}\mathrm{Si}$ reaction and justify their use in DC cross section calculations.

The resulting $^{30}\mathrm{Si}(n,\gamma)^{31}\mathrm{Si}$ reaction rates support previous findings at low stellar temperatures and provide improved constraints for stellar nucleosynthesis models. These findings highlight the role of $^{30}\mathrm{Si}$ in the weak s-process and emphasize the importance of indirect methods in modern nuclear astrophysics.

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