Asymptotic normalization coefficients for $\alpha + {}^{12}C$ synthesis and the S factor for ${}^{12}C(\alpha, \gamma){}^{16}O$ radiative capture

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Background: The ${}^{12}C(\alpha, \gamma){}^{16}O$ reaction, determining the survival of carbon in red giants, is of interest for nuclear reaction theory and nuclear astrophysics. A specific feature of the ${}^{16}O$ nuclear structure is the presence of two subthreshold bound states, (6.92 MeV, 2^+) and (7.12 MeV, 1^-), that dominate the behavior of the low-energy S factor. The strength of these subthreshold states is determined by their asymptotic normalization coefficients (ANCs), which need to be known with high accuracy.
Purpose: The objective of this research is to examine how the subthreshold and ground-state ANCs impact the low-energy S factor, especially at the key astrophysical energy of 300 keV.
Method: The S factors are calculated within the framework of the R-matrix method using the AZURE2 code.
Results: Our total S factor takes into account the $E1$ and $E2$ transitions to the ground state of ${}^{16}O$ including the interference of the subthreshold and higher resonances, which also interfere with the corresponding direct captures, and cascade radiative captures to the ground state of ${}^{16}O$ through four subthreshold states: 0_2^+, 3^-, 2^+, and 1^-. To evaluate the impact of subthreshold ANCs on the low-energy S factor, we employ two sets of the ANCs. The first selection, which offers higher ANC values, is attained through the extrapolation process [Blokhintsev *et al.*, Eur. Phys. J. A **59**, 162 (2023)]. The set with low ANC values was employed by deBoer *et al.* [Rev. Mod. Phys. **89**, 035007 (2017)]. A detailed comparison of the S factors at the most effective astrophysical energy of 300 keV is provided, along with an investigation into how the ground-state ANC affects this S factor.
Conclusion: The contribution to the total $E1$ and $E2$ S factors from the corresponding subthreshold resonances at 300 keV are (71–74)% and (102–103)%, respectively. The correlation of the uncertainties of the subthreshold ANCs with the $E1$ and $E2$ $S(300\,\text{keV})$ factors is found. The $E1$ transition of the subthreshold resonance 1^- does not depend on the ground-state ANC but interferes constructively with a broad (9.585 MeV; 1^-) resonance giving (for the present subthreshold ANC) an additional 26% contribution to the total $E1$ $S(300\,\text{keV})$ factor. Interference of the $E2$ transition through the subthreshold resonance 2^+ with direct capture is almost negligible for small ground-state ANC of 58 $\text{fm}^{-1/2}$. However, its interference with direct capture for higher ground-state ANC of 337 $\text{fm}^{-1/2}$ is significant and destructive, contributing -27%. The low-energy $S_{E2}(300\,\text{keV})$ factor experiences a smaller increase when both subthfreshold and the ground-state ANCs rise together due to their anticorrelation, compared to when only the subthreshold ANCs increase.

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I. INTRODUCTION

The ${}^{12}C/{}^{16}O$ ratio in red giant stars has been attracting substantial scientific attention for a long time [1,2]. While ${}^{12}C$ is formed via the triple-α fusion, ${}^{16}O$ is the result of the ${}^{12}C(\alpha, \gamma){}^{16}O$ radiative capture reaction, which determines the survival of carbon. Numerous attempts to obtain the astrophysical factor of the ${}^{12}C(\alpha, \gamma){}^{16}O$ reaction, both experimental and theoretical, have been made for almost 50 years (see Refs. [1–18] and references therein). The latest comprehensive and thorough review of the state of the art has been presented in Ref. [2].

The main goal of the research is to obtain the astrophysical S factor for the ${}^{12}C(\alpha, \gamma){}^{16}O$ radiative capture in the Gamow window with the most effective astrophysical α-${}^{12}C$ relative kinetic energy energy $E = 300$ keV with the accuracy $<10\%$.

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