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

A.M. Mukhamedzhanov, R.J. DeBoer, B.F. Irgaziev, L.D. Blokhintsev, A.S. Kadyrov, and D.A. Savin

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. Recently, using a model-independent extrapolation method, Blokhintsev *et al.* [1] determined the ANCs for the α-particle removal taking into account three subthreshold states in ${}^{16}O$.

The goal of this work is to address four main problems elucidating the impact of the subthreshold ANCs on the low-energy S-factor. Firstly, we analyze the connection between variations of the subthreshold ANCs and the low-energy S-factor, in particular, at the most effective energy of 300 keV. Secondly, we calculate contributions to the S(300 keV)-factor from the subthreshold 1^- and 2^+ resonances, that are controlled by the subthreshold ANCs. We also evaluate the contribution of the uncertainties of the subthreshold ANCs to the budget of the S(300 keV)-factor uncertainty. Thirdly, we analyze interference of the subthreshold resonances with higher resonances and with the E1 and E2 direct captures to the ground state. Finally, we investigate a correlated effect of the subthreshold and ground-state ANCs on the low-energy S-factor and, in particular, on the S(300 keV)-factor. The S-factors are calculated within the framework of the R-matrix method using the AZURE2 code.

Our total S-factor takes into account the E1 and E2 transitions to the ground state of ${}^{16}O$ of the interfering subthreshold and higher resonances, which also interfere with the corresponding direct captures, and cascade radiative captures to the ground state of 16O through four subthreshold states: 0^+, 2^+, 3^-, 2^+ and 1^-. Since our ANCs are higher than those used by deBoer *et al.* [2], the present total S-factor at the most effective astrophysical energy of 300 keV is higher, 174 keVb versus 137 keVb of that work. 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 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 (9.585MeV; 1^-) resonance giving (for the present subthreshold ANC) an additional 26% contribution to the total E1 S(300 keV)-factor. Interference of the E2 transition through the subthreshold resonance with direct capture is almost negligible for small ground-state ANC of 58 fm−1/2. However, the interference with direct capture for higher ground-state ANC of 337 fm−1/2 is significant and destructive, contributing −27%. The interference between the E2 transition of the SR 2+ and direct capture is minimal when the ground-state ANC is small, but becomes destructive at higher ground-state ANC, resulting in a contribution of −27%. The low-energy SE2(300 keV)-factor experiences a smaller increase when both subthreshold and the ground-state ANCs rise together due to their anticorrelation, compared to when only the subthreshold ANCs increase.

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[1] L.D. Blokhintsev, A.S. Kadyrov, A.M. Mukhamedzhanov and D.A. Savin, Eur. Phys. J. A **59**, 162 (2023).
[2] R.J. DeBoer *et al.*, Rev. Mod. Phys. **89**, 035007 (2017).