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Determining the $^{13}C(\alpha, n)^{16}O$ absolute cross section through the concurrent application of ANC and THM and astrophysical consequences for the s-process in AGB-LMSs

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Abstract. The $^{13}C(\alpha, n)^{16}O$ reaction is considered to be the most important neutron source for the s-process main component in low-mass asymptotic giant branch stars. No direct experimental data exist at very low energies and measurements performed through direct techniques show inconsistent results, mostly in their absolute values. In this context, we reversed the usual normalization procedure combining two indirect approaches, the asymptotic normalization coefficient and the Trojan Horse Method, to unambiguously determine the absolute value of the $^{13}C(\alpha, n)^{16}O$ astrophysical $S(E)$-factor in the most relevant energy-region for astrophysics. Adopting the new reaction rate for the n-source in the NEWTON s-process nucleosynthesis code, astrophysical calculations show only limited variations, less than 1%, for those nuclei whose production is considered to be totally due to slow neutron captures.

1 Introduction

The s-process main component, responsible for the synthesis of neutron-rich nuclei with $86 \leq A \leq 209$, is produced during the asymptotic giant branch (AGB) phase of low-mass stars (LMSs) through a series of subsequent n-captures and β-decays [1]. In this astrophysical environment, the main neutron source is considered to be the $^{13}C(\alpha, n)^{16}O$ reaction providing n-densities of the order of $10^6 - 10^8$ cm^{-3} at typical energies of 8 keV in radiative conditions. However, the cross section of the $^{13}C(\alpha, n)^{16}O$ reaction still remains uncertain in the Gamow window (140 − 230 keV) because of the contribution of a broad resonance, corresponding to the $1/2^+$ excited state of ^{17}O, close to the α-threshold. Several experiments adopting both direct and indirect techniques have been performed in the last decades to determine the $^{13}C(\alpha, n)^{16}O$ cross section at the energies of astrophysical interest. In particular, the ASFIN (AStroFIsica Nucleare) group of LNS (Catania, Italy) performed an experiment at the Florida State University (USA), adopting the indirect Trojan Horse Method (or THM, see [2] for more details). The $^{13}C(^6Li, n^{16}O)d$ reaction was measured in quasi-free kinematical conditions using a 7.82 MeV ^6Li beam. In this way, d is spectator to the $^{13}C(\alpha, n)^{16}O$ process and it can be extracted at astrophysical energies free of Coulomb suppression and the electron screening effect [3, 4].

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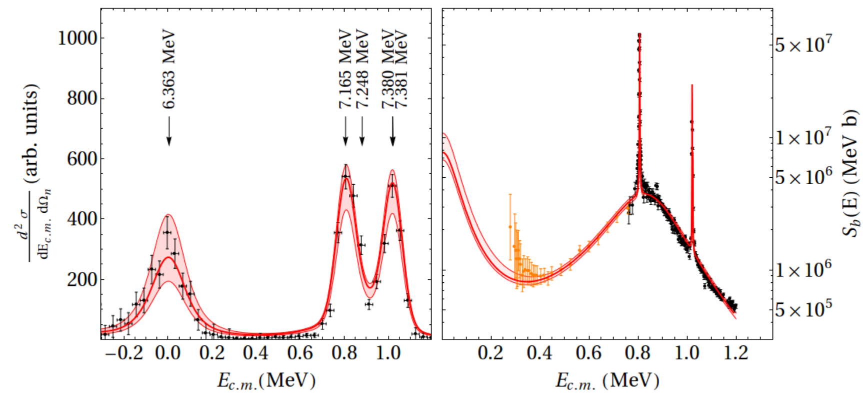

Figure 1. *Left panel* – New HOES (Half-Of-Energy-Shell) R-matrix fit (red shaded area) superimiposed on THM data (black points). *Right panel* – R-matrix $S(E)$-factor (red shaded region) superimposed on direct data from [7] and [8] (orange and black points, respectively). The red bands in each panel account for both statistical and normalization uncertainties.

Moreover, direct measurements in the literature cover only energies down to 300 keV and they are also affected by large systematic errors due to the spread in absolute values even at high energies [5], while indirect data crucially depend by the normalization procedure to direct ones in an energy region covered by both types of experiments. In this context, we have reversed the usual normalization procedure combining two indirect approaches, the asymptotic normalization coefficient (ANC) and the THM [6], to unambiguously determine the absolute value of the ^{13}C$(\alpha, \mathrm{n})^{16}$O astrophysical factor.

2 New normalization procedure from indirect to direct data

In order to define an absolute and unique value for the ^{13}C$(\alpha, \mathrm{n})^{16}$O data, we combined the recent and precise ANC calculation (3.6±0.7 fm^{-1} by [9]) and the full width for the threshold resonance (136 keV in [10]) from literature into a HOES R-matrix fit of the THM data [4] (see red curves and full symbols, respectively, in the left panel of Fig. 1). The first resonance on the left represents the $1/2^+$ excited states of ^{17}O at 6.363 MeV corresponding to 4.7 keV over the α-threshold, because this state was recently recognized by [10] to be centred at positive energies, while for long time it was considered as a sub-threshold resonance. In this way, we have to calculate the ANC of this resonance in the case of unbound states $C^2 = (-1)^{l_B} e^{\pi\eta_{aA}} e^{2i\delta^p_{l_B j_B J_B}(k_{aA(R)})} \frac{\mu_{aA}\Gamma_{aA}}{k_{aA(R)}}$, [11] where η is the Sommerfeld parameter, δ the potential (non-resonant) scattering phase shift at the real resonance relative momentum k, and Γ represents the partial width of the excited state of ^{17}O mentioned above. In this way, we obtained the γ values of the two peaks (each of them refer to two separate, but with similar central energy, resonances as shown by the four arrows in the left panel of Fig. 1) at higher energies in order to discriminate among the different direct datasets [5] and to unambiguously define (right panel of Fig. 1) the absolute value of the $S(E)$-factor. The R-matrix astrophysical factor (see the red band in right panel of Fig. 1), calculated adopting the same resonance parameters used in the corresponding left panel for the normalization procedure, shows that the measurements by [7] and [8] for the low-energy region (black and orange points, respectively) represent the only direct data set compatible with the THM $S(E)$-factor and the ANC of the $1/2^+$ state measured by [9].

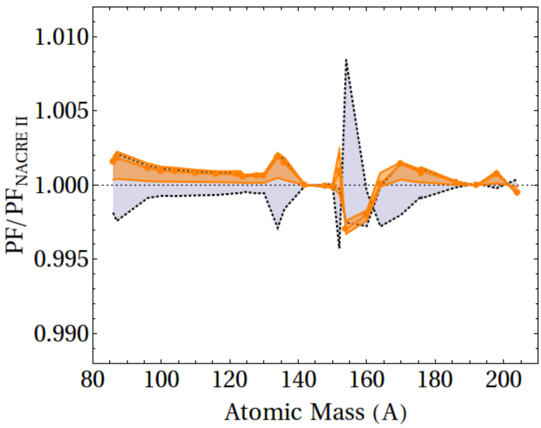

Figure 2. Production factors for the *s*-only nuclei of the main component calculated adopting the new THM rate for the $^{13}C(\alpha, n)^{16}O$ reaction (orange shaded region) or the one suggested by [5] (gray band). The horizontal dashed line, referring to predictions obtained using the recommended values of [5], is used as a reference.

3 Astrophysical consequences

Starting from the THM $S(E)$-factor described in the previous section, we calculated a very accurate reaction rate for the $^{13}C(\alpha, n)^{16}O$ neutron source and we introduced it into a code for *s*-process nucleosynthesis in AGB-LMSs [1, 12]. Because of the different normalization procedure, the reaction rate presented in this work is different, up to a factor of 1.5, with the one calculated in the precedent analysis of THM data [4]. On the contrary, it is in agreement, within errors, with the recommended value of the NACRE II compilation [5] in the most interesting temperature-region for astrophysics ($0.05 \leq T_9 \leq 0.30$), but the level of uncertainties is strongly reduced in our work. Fig. 2 shows the ratio between production factors (PF) of the main component (from Sr to Bi) *s*-only nuclei calculated by means of the NEWTON post-process code [1, 12] adopting the rate for the $^{13}C(\alpha, n)^{16}O$ reaction presented by [6] (orange band) and the one suggested in NACRE II (black shaded area [5]). In calculations of Fig. 2 we adopted a ^{13}C reservoir of about 5.0×10^{-3} $M_\odot$, as suggested by [13], assuming the case of a LMS with 1.5 $M_\odot$ and [Fe/H] = −0.15 experiencing nine thermal instabilities. In this scenario, we do not expect significant variations, less than 1%, for those isotopes which are produced exclusively by slow neutron captures.

References

[1] M. Busso, R. Gallino, G.J. Wasserburg, Ann. Rev. of Astron. and Astrophys. **37**, 239 (1999)
[2] C. Spitaleri, A.M. Mukhamedzhanov, et al., Physics of Atomic Nuclei **74**, 1725 (2011)
[3] M. La Cognata, C. Spitaleri, O. Trippella, et al., Physical Review Letters **109**, 232701 (2012)
[4] M. La Cognata, C. Spitaleri, O. Trippella, et al., Astrophys. J. **777**, 143 (2013)
[5] Y. Xu, K. Takahashi, S. Goriely, et al., Nuc. Phys. A **918**, 61 (2013), 1310.7099
[6] O. Trippella, M. La Cognata, Astrophys. J. **837**, 41 (2017), 1702.01589
[7] J.K. Bair, F.X. Haas, Phys. Rev. C **7**, 1356 (1973)
[8] H.W. Drotleff, A. Denker, H. Knee, et al., Astrophys. J. **414**, 735 (1993)
[9] M.L. Avila, G.V. Rogachev, E. Koshchiy, et al., Phys. Rev. C **91**, 048801 (2015), 1503.08743
[10] T. Faestermann, P. Mohr, R. Hertenberger, et al., Phys. Rev. C **92**, 052802 (2015), 1511.02642
[11] A.M. Mukhamedzhanov, Phys. Rev. C **86**, 044615 (2012), 1209.2158
[12] O. Trippella, M. Busso, E. Maiorca, et al., Astrophys. J. **787**, 41 (2014), 1403.6256
[13] O. Trippella, M. Busso, S. Palmerini, et al., Astrophys. J. **818**, 125 (2016), 1512.06777