Concurrent Application of ANC and THM to assess the $^{13}$C($\alpha$, $n$)$^{16}$O Absolute Cross Section at Astrophysical Energies and Possible Consequences for Neutron Production in Low-mass AGB Stars

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Abstract

The $^{13}$C($\alpha$, $n$)$^{16}$O reaction is considered to be the main neutron source responsible for the production of heavy nuclides (from Sr to Bi) through slow $n$-capture nucleosynthesis ($s$-process) at low temperatures during the asymptotic giant branch phase of low-mass stars ($\lesssim$3–4 $M_\odot$, or LMSs). In recent years, several direct and indirect measurements have been carried out to determine the cross section at the energies of astrophysical interest (around 190 ± 40 keV). However, they yield inconsistent results that cause a highly uncertain reaction rate and affect the neutron release in LMSs. In this work we have combined 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 factor. With these, we have determined a very accurate reaction rate to be introduced into astrophysical models of $s$-process nucleosynthesis in LMSs. Calculations using this recommended rate have shown limited variations in the production of those neutron-rich nuclei (with 86 ≤ $A$ ≤ 209) that receive contribution only by slow neutron captures.

Key words: nuclear reactions, nucleosynthesis, abundances – stars: AGB and post-AGB

1. Introduction

Slow neutron captures, making up the so-called $s$-process, are responsible for the production of about 50% of nuclei heavier than iron. They take place during the He- and C-burning phases of massive stars for the production of nuclides between iron and strontrium (60 ≤ $A$ ≤ 90, Pignatari et al. 2010) and in the He-burning layers of low- and intermediate-mass asymptotic giant branch (AGB) stars for the main component (between Sr and Bi, Gallino et al. 1998).

In this paper we focus our attention on this latter astrophysical site, specifically, the theromally pulsing AGB phase of low-mass stars (LMSs,$^4$ $M_\odot$ ≲ 3–4 $M_\odot$, Busso et al. 2001; Straniero et al. 2003). During these stages, a star is characterized by a structure made of a C–O degenerate core surrounded by two shells, the inner composed of helium, and the outer hydrogen rich, burning alternatively (Iben & Renzini 1983). As shell H-burning proceeds while the He shell is inactive, the mass of the He increases and attains higher densities and temperatures. As a consequence, He-burning in the shell is temporarily activated by thermonuclear runaway flash events generating convective instabilities (or thermal pulses) thanks to sudden temperature enhancements. These stars undergo repeated mixing episodes (the so-called third dredge-up, TDU) of material below the H-burning shell, where He-burning and slow neutron captures occur, bringing the fresh material that is just produced toward the stellar surface (Busso et al. 1999; Herwig 2005; Käppeler et al. 2011). In this astrophysical scenario, the main neutron source has been identified in the $^{13}$C($\alpha$, $n$)$^{16}$O reaction that is activated in radiative conditions during the quiet phases between two subsequent thermal instabilities at a temperature of about 0.9 × 10$^8$ K (Gallino et al. 1988). A second neutron exposure is due to $^{22}$Ne($\alpha$, $n$)$^{25}$Mg reaction during the convective instabilities of the helium shell providing more intense neutron fluxes. However, this is only marginally activated because of the typically low temperature of only about 2.5 × 10$^8$ K of stars less massive than 3 $M_\odot$ (Straniero et al. 1995).

The typical neutron densities for the $s$-process in LMSs provided by the $^{13}$C($\alpha$, $n$)$^{16}$O reaction are about 10$^6$–10$^8$ n cm$^{-3}$. Existing direct measurements, collected in the European Compilation of Reactions Rates for Nuclear Astrophysics (NACRE) by Angulo et al. (1999) and the subsequent updated version by Xu et al. (2013) (hereafter NACRE II), stop at a lowest value of about 280 keV (Drotleff et al. 1993), whereas the region of astrophysical interest, the so-called Gamow window (Rolfs & Rodney 1988; Iliadis 2007), corresponds to about 150–230 keV at a temperature of 10$^8$ K. At low temperature, the main uncertainty source is represented by a resonance near the $\alpha$-threshold that corresponds to the 1/2$^+$ excited state of $^{12}$O. The most recent works (Heil et al. 2008; Guo et al. 2012; La Cognata et al. 2012, 2013; Xu et al. 2013; Avila et al. 2015) in the literature are oriented toward a substantial lowering of the reaction rate with respect to the rate suggested by NACRE (Hale 1997), because it is believed that the role of the resonance mentioned above was overestimated in the past (Heil et al. 2008). In this scenario, the $^{13}$C($\alpha$, $n$)$^{16}$O reaction plays a crucial role in determining the neutron production and the timescale of $^{13}$C burning at a given temperature, and it influences the possibility of a complete exhaustion of the fuel during the radiative phase (Cristallo et al. 2011). For these reasons, its efficiency is still a matter of debate that aims at reducing the uncertainty, which can reach about 300% in the most interesting astrophysical region (Angulo et al. 1999; Johnson et al. 2006).

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$^4$ We consider the limit between low- and intermediate-mass stars to be the mass of those stars whose temperatures are too low to activate the CNO cycle at the base of the convective envelope (hot bottom burning), and the $^{22}$Ne($\alpha$, $n$)$^{25}$Mg (see the discussion later in this section) neutron source is always only partially activated because only low temperatures are reached.
Moreover, the $^{13}$C($\alpha$, $n$)$^{16}$O reaction is also activated in other different astrophysical sites (Jorissen & Arnold 1989), such as at the C-burning in massive stars; at the beginning of He-burning phase; and in the case of a proton injection in He-rich layers (e.g., central He flash in a star less massive than $2 M_\odot$; for a late convective instability in nuclei of planetary nebulae at the beginning of Wolf–Rayet, type N, phase showing little hydrogen and nitrogen enhancement at the stellar surface in certain massive mass-losing stars; and accretion of H-rich material on a white dwarf in a binary system). The analysis of consequences of the $^{13}$C($\alpha$, $n$)$^{16}$O reaction in these conditions is beyond the primary purpose of this article, but it is highly desirable.

After a brief presentation of the currently available measurements for the $^{13}$C($\alpha$, $n$)$^{16}$O reaction cross section (Section 2), we present in Section 3 a new approach that starts from indirect experimental data to constrain the absolute normalization factor of direct measurements at high energies. The astrophysical factor is calculated and compared (Section 4) with the most recent works in the literature, also focusing on the electron screening effect (Section 5). In Section 6 we determine the recommended reaction rate for the $^{13}$C($\alpha$, $n$)$^{16}$O reaction to be used in the astrophysical scenarios outlined above. In particular, here we evaluate possible consequences on the s-process nucleosynthesis.

2. Current State

Because the $^{13}$C($\alpha$, $n$)$^{16}$O reaction is relevant as the main neutron source for the s-process in LMSs, during the last decades several measurements of its cross section have been performed covering different energy ranges. One of the most commonly adopted rate was that or the one presented in Angulo et al. (1999), which takes experimental cross sections into account that were determined in previous works by Sekharan et al. (1967), Davids (1968), Bair & Haas (1973), Drotleff et al. (1993), and Brune et al. (1993). An unprecedented accuracy of 4% was later reached by Harissopulos et al. (2005), triggered by the need to reliably subtract the background in the observation of geo-neutrinos (e.g., in the KamLAND detector, Araki et al. 2005). One of the most recent works on the $^{13}$C($\alpha$, $n$)$^{16}$O reaction by Heil et al. (2008) combines a high-accuracy cross-section measurement down to about 300 keV with an extensive multichannel R-matrix fitting of all cross-section data for the channels that feed the $^{17}$O states that contribute to the $^{13}$C($\alpha$, $n$)$^{16}$O reaction in the energy range below about 500 keV.

However, many experimental difficulties exist (e.g., Coulomb suppression, electron screening effect, and a different absolute value) when performing a direct measurement at the energies relevant for astrophysics. In this context, two characteristics are evident for direct data concerning the astrophysical factor of the $^{13}$C($\alpha$, $n$)$^{16}$O reaction: (i) the very high uncertainties due to the prohibitively small reaction cross section in the low-energy region; (ii) data by Davids (1968), Drotleff et al. (1993), and Heil et al. (2008) appear to be consistent with each other, but they are different from data reported by Bair & Haas (1973) especially for an issue connected to resolution, which concerns the height of the resonances above 500 keV. At the same time, measurements of Kellogg et al. (1989) and Harissopulos et al. (2005) are in agreement, but they are considerably lower in absolute value than those mentioned above.

Moreover, since direct measurements stop immediately at the edge of the Gamow window, several experiments using indirect methods (determining the spectroscopic factor and/or the asymptotic normalization coefficient, ANC, for the $1/2^+$ level of $^{17}$O near threshold) have been performed to determine the cross section of this neutron source in the energy region relevant for astrophysics. Kubono et al. (2003) measured the $^{13}$C($^4$Li, $d$)$^{17}$O transfer reaction, which suggested a very small spectroscopic factor $\mathcal{S}_n = 0.01$, which was then reanalyzed by Keeley et al. (2003). This reanalyzed value indicated a considerably stronger contribution, about a factor of 40 larger, depending on the theoretical approach. The first determination of the ANC for the $^{13}$C($\alpha$, $n$)$^{16}$O reaction was performed by Johnson et al. (2006) using the $^4$Li($^{13}$C, $d$) $^{17}$O sub-Coulomb $\alpha$-transfer reaction. The authors obtained a value of the squared Coulomb-modified ANC $(C_{\alpha}^2)^{17}$O($1/2^+$)$^2 = 0.89 \pm 0.23$ fm$^{-1}$. This result, appearing to be inconsistent with the emerging scenario of the $^{13}$C($\alpha$, $n$)$^{16}$O reaction, was recently revisited by Avila et al. (2015). In both cases, the $\alpha$-transfer $^4$Li($^{13}$C, $d$) $^{17}$O reaction was performed with a 8 MeV $^{12}$C beam in inverse kinematics to achieve the lowest possible energy in the center-of-mass system. Taking target deterioration into account, the squared Coulomb-modified ANC becomes $3.6 \pm 0.7$ fm$^{-1}$, a factor of four larger than the value suggested in the first analysis of the same measurement.

Pellegriti et al. (2008) and Guo et al. (2012) also determined the spectroscopic factor, $S = 0.29 \pm 0.11$ and 0.37 $\pm 0.12$, and the ANC $(C_{\alpha}^2)^{17}$O($1/2^+$)$^2 = 4.5 \pm 2.2$ fm$^{-1}$ and 4.0 $\pm 1.1$ fm$^{-1}$, respectively. This shows that independent ANC experiments, using different transfer reactions and theoretical approaches, seem to indicate values for $C^2$ in the range 0.89–4.5 fm$^{-1}$ (see Table 1), where the very low value suggested by Johnson et al. (2006), as already explained above, was recently revised in Avila et al. (2015).

The experiment performed by applying the indirect Trojan horse method (hereafter THM, Spitaleri et al. 2011) at the Tandem-LINAC facility of the Florida State University deserves a separate discussion because it extends over a broad energy range between $-0.3$ and 1.2 MeV. This means that negative $E_{\text{cm}}$, and the region covered by direct measurements are both explored in a single measurement. The $^4$Li($^3$Li, $n^0$)O$d$ reaction was studied in quasi-free kinematic conditions (the deuteron inside the $^3$Li beam is considered as a spectator to the three-body reaction) in order to deduce the astrophysical $S(E)$ factor of the $^{13}$C($\alpha$, $n$)$^{16}$O reaction free of Coulomb suppression and electron screening effects. Two peaks at positive $E_{\text{cm}}$ were used to normalized direct measurements, while the ANC was extracted for the resonance below the $\alpha$ emission threshold. The normalization of indirect data to direct measurements represents the most crucial and sensible phase of THM off-line analysis using an energy region covered by both types of experiments. This procedure strongly depends on the uncertainties that affect direct measurements, and it often represents the higher source of error for the THM astrophysical factor. The observable partial width $\Gamma_{1/2^+}$ of the $-3$ keV resonance was obtained from the $R$-matrix fit of the same $S$-factor, yielding a value of $107$ $\pm$ $5_{\text{stat}} ^{+9}_{-5_{\text{norm}}}$ keV, which is higher than the value obtained in our preliminary analysis (La Cognata et al. 2012) $\Gamma_{1/2^+} = 83_{-12} ^{+9}$ keV. The new result is slightly lower than the value commonly adopted in the literature, $124 \pm 12$ keV (Tilley et al. 1993), and lower than the value reported in Heil et al. (2008), 158 keV. As mentioned before, the THM approach
Table 1

| Reference                     | $\Gamma_n$ (keV) | ANC (fm$^{-1}$) |
|-------------------------------|------------------|-----------------|
| Fowler et al. (1973)          | 124              | ...             |
| Tilley et al. (1993)          | 124 ± 12         | ...             |
| Sayer (2000)                  | 162.37           | ...             |
| Johnson et al. (2006)         | 124 ± 12         | 0.89 ± 0.23     |
| Pellegriti et al. (2008)      | 124 ± 8          | 4.5 ± 2.2       |
| Heil et al. (2008)            | 158.1            | ...             |
| La Cognata et al. (2012)      | 83.12$^{0.9}_{-0.4}$ | 6.7 ± 0.9     |
| Guo et al. (2012)             | 124              | 4.0 ± 1.1       |
| La Cognata et al. (2013)      | 107 ± 5$_{+50}^{+8}$ | 7.7 ± 0.3$_{+11}^{+16}$ |
| Faestermann et al. (2015)$^a$ | 136 ± 5          | ...             |
| Avila et al. (2015)           | ...              | 3.6 ± 0.7       |

Note.

$^a$ These values are also used in this paper (see Section 3).

allowed us to also extract the Coulomb-modified ANC $C_n^{\text{16O}(1/2^+)}$ of the $-3$ keV resonance from the same data sets (at odds with other direct and indirect measurements) from the half of energy shell (HOES) $R$-matrix fitting of the THM data. Then, it was the first time that THM was used to extract the ANC of a subthreshold resonance. In detail, we obtained the $(C_n^{\text{16O}(1/2^+)})^2 = 7.7±0.3_{+1.6}^{−1.5}\text{norm},$ fm$^{-1},$ as just diffusely discussed in Mukhamedzhanov & Tribble (1999) and La Cognata et al. (2012). The resulting ANC, obtained with the complete THM data set, is in agreement with our preliminary value 6.7$^{+0.9}_{−0.6}$ fm$^{-1},$ within the uncertainties.

Moreover, a new calculation of the $^{13}\text{C}(\alpha, n)^{16}\text{O}$ reaction rate is available in the updated version of NACRE compilation (NACRE II, Xu et al. 2013). In addition to the data previously described in Angulo et al. (1999), it contains the direct measurements of Harissopulos et al. (2005) and Heil et al. (2008) to extend the energy range up to $E_{\text{c.m.}} \sim 6$ MeV and indirect measurements (Keeley et al. 2003; Kubono et al. 2003; Pellegriti et al. 2008; Guo et al. 2012; La Cognata et al. 2012) to take the contribution of the state near the $\alpha$-threshold into account. At low temperature, the ensuing reaction rate is significantly reduced with respect to their previous determination (Angulo et al. 1999) because of the choice of a very steep $S$-factor assumed for the $1/2^+\text{ }$resonance contributions. However, the corresponding uncertainties are very high, up to $+36\%$ and $−28\%$ around 0.09 GK, and they are connected to the normalization procedure between NACRE II calculation and direct data. This fact clearly called for further investigations of the absolute value of the astrophysical $S$-factor.

The ANC value by Avila et al. (2015), which is the most precise calculation to date, is now compatible with results of Pellegriti et al. (2008) and Guo et al. (2012), but a discrepancy is still evident (see Figure 4 in Avila et al. 2015, and Table 1 for a detailed comparison between several works present in literature) with the two measurements performed by applying the THM (La Cognata et al. 2012, 2013), pointing at some issue that is worth investigating to supply a reliable reaction rate for astrophysical applications. Understanding this discrepancy is one of the reasons that motivated this work, which aims to propose a consistent description of the $^{13}\text{C}(\alpha, n)^{16}\text{O}$ reaction. As we discussed above, the main issue affecting THM measurement is the normalization procedure to direct data at high energies.

In a recent work (Faestermann et al. 2015), levels of $^{17}\text{O}$ close to the $^{13}\text{C} + \alpha$ threshold were studied by investigating the $^{19}\text{F}(d, \alpha)^{17}\text{O}$ reaction to measure their excitation energies and widths with high accuracy because they are astrophysically important. The new results recommended in Faestermann et al. (2015) for the $1/2^+$ state are $E^* = 6.5634 ± 0.0031$ MeV and $\Gamma = 0.136 ± 0.005$ MeV, which significantly improves the uncertainties and modifies the values assumed before. The new excitation energy is 7.4 keV higher than the adopted value (Tilley et al. 1993), while the threshold value is almost unchanged, and it is considered to be at 6.359 MeV. As a first consequence, the $1/2^+$ level of $^{17}\text{O}$ is now centered at about $4.7 ± 3$ keV above the threshold. This state can no longer be considered a subthreshold resonance, but it is now more properly called threshold resonance.

In order to form an idea of the ambiguous situation concerning the $1/2^+$ state, a series of the neutron-reduced width in the literature is listed in Table 1. The spread for possible $\Gamma_n$ values is wide and ranges between 83 and 162 keV; a clear solution still remains to be found. For all these reasons, the contribution to the astrophysical factor of the broad resonance located near the $^{13}\text{C}(\alpha, n)^{16}\text{O}$ threshold still remains matter of debate, and we address this issue in the next sections. In this context, the THM represented an alternative and complementary approach for distinguishing among previous experiments that were performed via indirect techniques and showed incompatible results for the $^{13}\text{C}(\alpha, n)^{16}\text{O}$ reaction. Moreover, the value of ANC, for which there now seems to exist a converging value around 4 fm$^{-1},$ together with the THM data could represent a promising starting point to constrain the absolute normalization value by culling this value from the several direct data present in literature.

Our goal is to overturn the present paradigm in the application of indirect approaches. We make synergetic use of THM and ANC to assess the absolute normalization of direct data at high energies, which greatly reduces the systematic errors that affect the reaction rate.

3. Reanalysis of THM Data

The two most recent papers (Avila et al. 2015; Faestermann et al. 2015) presented in the previous section described the $1/2^+$ excited state of $^{17}\text{O}$ near the $^{13}\text{C} + \alpha$ threshold with high accuracy, with crucial consequences for the current scenario outlined in La Cognata et al. (2013) for the astrophysical factor of the $^{13}\text{C}(\alpha, n)^{16}\text{O}$ reaction. A reanalysis of the data obtained through THM therefore becomes necessary in order to (i) verify any variation of the ANC value as a consequence of the changed resonance energy and width of the $1/2^+$ level near the $^{13}\text{C} + \alpha$ threshold and (ii) use the ANC and THM data with the aim to validate direct measurements.

From a theoretical point of view, we cannot extract the ANC value from THM data as has been done for the first time in La Cognata et al. (2012) and then in La Cognata et al. (2013) because, as claimed by Faestermann et al. (2015), the resonant state mentioned above is not a subthreshold resonance, but it is centered at 4.7 keV. This means that an extension of the technique is required in order to obtain the $C_n^{\text{16O}(1/2^+)}$ in the positive energy region. As we demonstrate in the Appendix, this is possible considering Equation (2) for captures to unbound states. This formula was used to calculate the ANC starting from the reduced width extracted from THM data (La Cognata et al. 2013) and from the resonance energy determined.
by Faestermann et al. (2015); a very high value of about $12.1^{+1.9}_{-1.6}$ fm$^{-1}$ is retrieved, which significantly departs from the values in the literature: see the third column of Table 1 for a comparison with other calculations in the past. Because THM data require to be anchored to direct measurements at higher energies in order to obtain absolute values, the uncertainty affecting direct data in the normalization region could be the cause of the discrepancy between ANC calculated from THM (La Cognata et al. 2012, 2013) and the ANC values measured by transfer reactions (Pellegriti et al. 2008; Guo et al. 2012; Avila et al. 2015). Since very accurate values of ANC have recently become available, we choose to reverse the usual normalization procedure that has characterized THM experiments and adopt the $(C)^2$ of the literature by scaling the THM data to the threshold resonance. In this way, it will be possible to assess the correct normalization of direct data using THM.

Second, the neutron-reduced width of Faestermann et al. (2015) is greater than the width shown in La Cognata et al. (2013), where authors obtained $\Gamma_n = 107 \pm 5_{\text{stat}}^{+9}_{-5_{\text{norm}}}$ assuming a different location, $E_{\text{cm}} = -3$ keV for the $1/2^+$ state. In particular, experiments performed via the THM do not provide an accurate measure of the position for resonances because the typical value of the energy resolution prevents us from distinguishing between the two scenarios described above. On the other hand, Avila et al. (2015) provided the most precise value for ANC, but it is considerably lower than the value suggested by the previous analysis of THM measurement.

In this context, we decide to assume the most precise value for the ANC given by Avila et al. (2015) and to calculate the reduced width $\gamma$ by applying Equation (2). On the other hand, in order to constrain the neutron partial width $\Gamma_n$, we use the precise evaluation of Faestermann et al. (2015), so that both $\gamma$ and $\Gamma_n$ are defined at the beginning of our approach. These values are used in the next section with the aim to determine the normalization factor in order to establish a connection between THM indirect data and direct measurements.

In particular, we now wish to verify possible changes when we assume these new parameters in the calculation of the astrophysical factor for the $^{13}\text{C}(\alpha, n)^{16}\text{O}$ reaction starting from the THM measurements of La Cognata et al. (2013), and at the same time, we wish to identify which direct data sets better agrees with the indirect data obtained via THM.

### 3.1. A New Normalization Procedure for THM Experiments

As anticipated in the previous sections, we aim to use THM data to give information on the absolute value of the $S(E)$-factor for the $^{13}\text{C}(\alpha, n)^{16}\text{O}$ reaction, making it possible to distinguish between the several series of direct experimental data in the literature that were obtained with different techniques, degrees of accuracy, and which cover various energy regions. The HOES $d^2\sigma/dE_{\text{cm}}d\Omega_d$ cross section, obtained through the THM technique, is at present expressed in arbitrary units, making it necessary to introduce of a normalization factor representing the only free parameter to match the modified $R$-matrix calculation with indirect data, where available. For these reasons, the THM is not considered an alternative, but a complementary approach with respect to direct measurements. As has been shown in several works (La Cognata et al. 2011, 2012), normalization can be achieved by extending the indirect measurement to an energy region where directly measured resonances are available, fixing the reduced widths to match the values in the literature and determining a scaling factor between direct and THM data. However, this procedure often represents the largest source of uncertainty for the indirect $S$-factor, also because large uncertainties often affect the direct astrophysical factor at normalization energies, for instance, in the case of the $^{13}\text{C}(\alpha, n)^{16}\text{O}$ reaction.

In this context, we performed a new analysis of THM data reported in La Cognata et al. (2013) starting from the width and resonance energy reported by Faestermann et al. (2015) for the $1/2^+$ state of $^{10}\text{O}$ located near the $^{13}\text{C} + \alpha$ threshold, and using the ANC value measured by Avila et al. (2015) to constrain the normalization to the direct measurement that best fits the THM data scaled to match this ANC. In Figure 1 we present three possibilities for normalization adopting different data sets of direct experiments from the literature. The left panels show the astrophysical factor $R$-matrix fit superimposed on direct data measurements. In the first panel, (a), we have selected data from Davids (1968), Drotleff et al. (1993), and Heil et al. (2008) (represented by blue, orange, and pink solid points, respectively) that prove to be consistent with each other without the need to adopt any normalization, unlike in our previous calculations (La Cognata et al. 2012, 2013) following the idea of Heil et al. (2008). Below, panel (b) shows by means of black circles the large data set of Bair & Haas (1973), which is more extended than that of Heil et al. 2008 and La Cognata et al. 2012, 2013), while we used data by Drotleff et al. (1993) for the energy region $E_{\text{cm}} \leq 0.75$ MeV. Panel (c) displays the two data sets showing the lowest absolute values for the $^{13}\text{C}(\alpha, n)^{16}\text{O}$ astrophysical factor of the values in the literature, in particular, Harissopulos et al. (2005) (red full points) and Kellogg et al. (1989) (purple ones). In this context, direct data from Brune et al. (1993) are not shown because, as discussed in the same paper, they correspond to the cross section calculated by Kellogg et al. (1989) multiplied by a factor of 1.17, and they appear to be compatible with the other direct measurements only as a result of their large uncertainties.

The right panels of Figure 1 show the comparison between the modified $R$-matrix calculation and the $d^2\sigma/dE_{\text{cm}}d\Omega_d$ cross section determined by the THM experiment for the $^{13}\text{C}(\alpha, n)^{16}\text{O}$ reaction described in La Cognata et al. (2013). The color of the curves is the same as used for the $R$-matrix lines in the corresponding left panel to point out that the same parameters for all resonances were adopted for the on-energy-shell (or OES) and HOES calculations. In this phase, we do not consider upper and lower limits, but only the best fits are shown in each panel of Figure 1. Black solid points represent the weighted sum of two data sets obtained with different $^{13}\text{C}$ target thicknesses: specifically, 53 and 107 $\mu$g cm$^{-2}$. These two data sets were shown to be consistent with each other in La Cognata et al. (2013); they have a theoretical energy resolution (standard deviations) of 45 and 48 keV, respectively. The $d^2\sigma/dE_{\text{cm}}d\Omega_d$ clearly shows several resonances in the $^{13}\text{C} - \alpha$ relative-energy spectrum, and more details are available in the description of Figure 2.

The calculated $R$-matrix functions and the corresponding astrophysical factors agree well for all cases presented in the left panels (a), (b), and (c) as a result of fit procedure of adjusting parameters (the reduced $\gamma$ widths) of each resonance, using as initialization parameters the values reported in Heil et al. (2008). Although a similarly good agreement is reached between curves and THM indirect data in the right panels for resonances above 500 keV, panel (c) reproduces the threshold level best, with a reduced $\chi^2 = 1.65$, using only one
normalization parameter for energies between $-0.3$ and $1.2$ MeV. It is nevertheless important to specify that this result does not represent the best fit (the fit found in La Cognata et al. 2013) for the low-energy resonance, but we can note that the curve is well compatible, within the uncertainties, with the THM $d^2\sigma/dE_{cm}d\Omega_d$ cross section. In fact, the idea is to determine the absolute normalization using the most recent resonance parameters and a single normalization constant over the whole energy region, as mandated by THM theory. The resonance located at 4.7 keV appears to be lower and larger than those the one shown in La Cognata et al. (2013), which modifies the contribution attributed to this state in the most relevant astrophysical region for stellar nucleosynthesis. In the other two cases, panels (d) and (f), the threshold resonance is always underestimated by calculations, showing the need of a higher value for the ANC of the $1/2^+$ state. Therefore, we conclude that the combination of Bair & Haas (1973) and, at low energies, of Drotleff et al. (1993) data represents the only direct data set compatible with the THM S-factor and the ANC of the threshold level measured in many experiments (Pellegriti et al. 2008; Guo et al. 2012; Avila et al. 2015). In the light of this concordance scenario, we use this pool of direct measurements in the rest of the present work. Since in the energy region above $500$ keV we find parameters that differ from those adopted in La Cognata et al. (2013, 2012) and Heil et al. (2008), variations in the cross section and the astrophysical factor of the $^{13}\text{C}(\alpha, n)^{16}\text{O}$ reaction are expected, therefore we proceed to a reanalysis of the THM data to supply a new recommended reaction rate based on this internally consistent data set. A significant improvement in systematic errors is expected since the different approaches have different possible sources of systematic errors.

**Figure 1.** Left panels: $R$-matrix astrophysical factor calculated assuming three different direct data sets for the normalization procedure: (a) blue (Davids 1968), orange (Drotleff et al. 1993), and pink (Heil et al. 2008) symbols; (b) black (Bair & Haas 1973) and orange (Drotleff et al. 1993) for the low-energy region ($E_{cm} \leq 0.75$ MeV); (c) purple (Kellogg et al. 1989) and green (Harissopulos et al. 2005). Right panels: HOES $R$-matrix fit of the THM data presented in La Cognata et al. (2013) (solid black symbols) adopting the same resonance parameters used in the corresponding left panel. According to the $\chi^2$ value, the best choice for a normalization of THM data corresponds to panels (b) and (e).
In Figure 2 the angular integrated $d^2\sigma/dE_{\alpha,m}d\Omega_d$ cross section is displayed as full symbols, with the horizontal error bars defining the $^{13}$C$-\alpha$ relative-energy binning. The vertical error bars of experimental data account for statistical, angular integration and background-subtraction uncertainties (see La Cognata et al. 2013, for more details). The three peaks in the $^{13}$C$-\alpha$ relative-energy spectrum are clearly visible in Figure 2 in the energy range between $\sim$−300 and 1200 keV. The first resonance on the left corresponds to the $1/2^+$ excited states of $^{17}$O at 6.363 MeV (Faestermann et al. 2015), again 4.7 keV above the $\alpha$-threshold and about 7.4 keV higher than the value suggested in Tilley et al. (1993) (the small discrepancy comes from a different value of the threshold in the two works), which for a long time has been considered to be the reference paper (original evaluation by Fowler et al. 1973). Moreover, arrows in Figure 2 suggest that a priori, each of the two peaks above 500 keV refers to two separate resonances that have similar $E_\alpha$: 7.165 MeV, 7.248 MeV, 7.380 MeV, and 7.381 MeV, respectively (whose energies are taken from Faestermann et al. 2015) and were essentially confirmed by Tilley et al. 1993, considering a deviation of a few keV). The central red line shown in Figure 2 was obtained assuming the same parameters used in panels (b) and (e) of Figure 1 for all resonances. In order to comprise also the possible interference between states of $^{17}$O with the same spin-parity $J^*$, we considered the interfering effect of the $3/2^+$ subthreshold resonance at 5.931 MeV (Faestermann et al. 2015), together with the 7.248 MeV state. The upper and lower limit (delimiting the red region in Figure 2) account for the statistical uncertainties that are connected to the scatter of data points below 500 keV, and to the normalization uncertainties that are due to the fitting procedure of higher energy data. The parameters used in the calculations of this paper allow us to reproduce the observable partial width of the 4.7 keV resonance, $\Gamma^{3/2+}_n$ = 136 ± 5 keV as suggested by Faestermann et al. (2015), and the ANC value of 3.6 ± 0.7 fm$^{-1}$ as in Avila et al. (2015).
In order to provide a detailed comparison of the astrophysical factor obtained through the indirect TH approach with other determinations in the literature, Figure 4 displays only on the 60–790 keV low-energy region in the center-of-mass system, which is the most relevant for the astrophysical s-process scenario. In Figure 4 the THM $S(E)$-factor is compared only with the most recent evaluation of the $^{13}$C($\alpha$, n)$^{16}$O astrophysical factor. In particular, green and purple bands represent the S-factor by La Cognata et al. (2013), namely, the previous THM analysis, and the analysis extrapolated in Avila et al. (2015), respectively. There exists an agreement, inside the error bars, between the $S(E)$-factor in Avila et al. (2015) and the present one, in La Cognata et al. (2013) the band overestimates the new low-energy value, by a factor of 2.3 for $E_{c.m.} < 0.5$ MeV because of the different ANC value assumed in the calculation. The $S(E)$-factor by NACRE II (Xu et al. 2013) is shown by the cyan line, but there exist sam agreement with the red curves only thanks to the large uncertainties (cyan band). In particular, we can also note that their lower limit is very close to the limit reported by Harissopulos et al. (2005) and the Kellogg et al. (1989) direct data. The highest uncertainties are, in fact, located in the normalization energy region, between 0.3 and 0.7 MeV, emphasizing once again the importance to distinguish among the absolute values of different direct data sets. In this paper, we approached and tried to solve this issue shown by the NACRE II compilation, which considerably reduced the error associated with the normalization thanks to the concurrent application of ANC and THM.

5. Electron Screening

The determination of the $^{13}$C($\alpha$, n)$^{16}$O astrophysical $S(E)$-factor at very low energies by direct approaches strongly depends on the electron screening effect. Indeed, for the nuclear cross section measured in the laboratory, the projectile is usually in the form of an ion and the target is usually a neutral atom or a molecule surrounded by their electronic cloud. Following the basic idea (Assenbaum et al. 1987; Rolfs & Rodney 1988), an impinging nucleus sees no repulsive nuclear Coulomb force until it penetrates the atomic radius because of the electron cloud surrounding the target nuclei. At low beam energies, the projectile is therefore subject to a less repulsive potential because of the electron screening one $U_e$, basically the energy transfer from the atomic to nuclear degrees of freedom (Bracci et al. 1990). This results in an enhancement of the cross section relative to the value it would assume for fully ionized interacting particles. Conversely, the THM measurement is not affected by the electron screening, and it directly provides the bare-nucleus $S(E)$ factor (see red line in Figure 5). It is not possible to attain a realistic estimate of the electron screening potential from the comparison of THM $S(E)$-factor and direct data (orange point of Drotleff et al. 1993, without considering electron screening corrections) because high experimental uncertainties affect the direct data. In this context, new high-accuracy direct measurements of the low-energy astrophysical factor of the $^{13}$C($\alpha$, n)$^{16}$O can help us to better understand the electron screening effect for charged particle reactions. To estimate the electron screening effect, we have considered realistic electron-screening potentials. In detail, the green and blue lines represent the screened $S$-factor deduced by adopting the adiabatic limit ($U_e = 0.937$ keV, Bracci et al. 1990) electron screening or assuming the high value ($U_e = 2$ keV) suggested by Assenbaum et al. (1987), respectively. Since the data seem to suggest a $U_e$ value higher than the adiabatic limit, the case of $^{13}$C($\alpha$, n)$^{16}$O reaction might confirm that several measurements have demonstrated in the past, namely, that the experimental $U_e$ can be larger than the
Table 2
Table of Coefficients for the Analytical Approximation of the $^{12}$C($\alpha$, $n$)$^{16}$O Reaction Rate

| $a_i$ | 1         | 2         | 3         |
|-------|-----------|-----------|-----------|
| 1     | +0.606751 $\times 10^{-2}$ | $-0.113003 \times 10^{-2}$ | $+0.230810 \times 10^{-2}$ |
| 2     | $-0.487943 \times 10^{-2}$ | $-0.109590 \times 10^{-1}$ | $-0.675038 \times 10^{-1}$ |
| 3     | $-0.306167 \times 10^{-2}$ | $-0.733349 \times 10^{-1}$ | $-0.637515 \times 10^{-1}$ |
| $i$   | 4         | 5         | 6         | 7         |
| 4     | $-0.410653 \times 10^{-2}$ | $+0.255634 \times 10^{-2}$ | $-0.515203 \times 10^{+1}$ |
| 5     | $+0.238702 \times 10^{-4}$ | $-0.129589 \times 10^{+1}$ | $+0.169689 \times 10^{+1}$ |
| 6     | $-0.810502 \times 10^{-4}$ | $-0.669953 \times 10^{+1}$ | $-0.333333 \times 10^{+1}$ |
| 7     | $+0.383349 \times 10^{-4}$ | $+0.910751 \times 10^{+1}$ | $+0.207363 \times 10^{+1}$ |

adiabatic limit (see for instance La Cognata et al. 2005, and references therein).

6. Reaction Rate

The thermonuclear rate for the $^{12}$C($\alpha$, $n$)$^{16}$O reaction was evaluated by means of standard equations (Iliadis 2007) using the $S(E)$-factor measured through the THM devoid of electron-screening effects (see Figure 3). Table 3 contains the adopted rate with the corresponding upper and lower limits in columns two, three, and four, respectively, as a function of the temperature expressed in GK (first column). The fifth column contains the exponents of the power-ten factor that is common to the three previous columns.

The THM reaction rate can be described by the following analytical expression: $N_e\langle\sigma v\rangle = \sum_{i,j=1}^{3}a_{ij}T_9^{-1/3} + a_{3j}T_9^{-1/3} + a_{2j}T_9^{1/3} + a_{6j}T_9^{2/3} + a_{7j}\ln(T_9)$, where $T_9$ is the temperature in GK and $a_{ij}$ parameters of this expression, collected in Table 2 for the recommended $^{12}$C($\alpha$, $n$)$^{16}$O reaction rate.

Figure 6 shows the reaction rate calculated from the THM $S(E)$-factor (red central line) and compared to the reference rate (Heil et al. 2008) in the temperature range between 0.005 and 1.0 GK. The two rates are compatible almost everywhere, but the greater divergence is exactly located in the most interesting region for astrophysics, i.e., the discrepancy at $T_9 = 0.09$ is around 12%. The red band represents the corresponding statistical and normalization uncertainties on the order of $+40\%$ and $-13\%$ at lower temperature. Higher differences are expected with the reaction rate suggested in La Cognata et al. (2013) (green line), coming from the precedent analysis of THM data, because it is a factor 2.5 larger than in Heil et al. (2008) and the present work calculation at $5.0 \times 10^7$ K. The rates for $^{12}$C($\alpha$, $n$)$^{16}$O reaction by Xu et al. (2013) and Drotleff et al. (1993) are also represented (normalized to Heil et al. 2008, adopted value) in Figure 6 with a cyan shaded region and a black curve, respectively. The rate from the present work agrees within the errors with the updated NACRE II compilation (Xu et al. 2013) recommended value in the temperature range of main astrophysical interest (0.05 < $T_9$ < 0.30). The great difference consists in the level of uncertainties; the upper limits of Xu et al. (2013) is 36% higher than the corresponding recommended value, while in our case it is only 17% at about $T_9 = 0.09$; on the other hand, lower limits are 28% and 7%, respectively, which shows that our rate is more accurate by about a factor of 4. In other temperature regions, the NACRE II rates (both adopted and upper) are at most about 1.3 times higher than the rate reported here, while the lower limits are even closer to each other. On the other hand, the reaction rate reported by Drotleff et al. (1993) significantly differs from the new THM rate for temperatures higher than 0.3 GK. These differences should be evaluated in all astrophysical sites mentioned in the first section for which the activation of the $^{12}$C($\alpha$, $n$)$^{16}$O reaction is relevant.

7. Astrophysical Implications of the New Reaction Rate

The main aim of this paper is to provide a rate for the $^{12}$C($\alpha$, $n$)$^{16}$O reaction decreasing systematic errors connected to the normalization between measurements performed through indirect techniques and those direct data sets showing different absolute values. This, in fact, still represents the main source of errors also in the NACRE II compilation (Xu et al. 2013). In order to verify the impact of the new rate for the $^{12}$C($\alpha$, $n$)$^{16}$O reaction on stellar nucleosynthesis, we performed some theoretical prediction for the specific case of the s-processing in AGB-LMSs.

In this astrophysical scenario, the $^{12}$C($\alpha$, $n$)$^{16}$O is strictly connected to the amount of $^{12}$C locally produced in the He-rich region of an AGB-LMS, as a consequence of some proton penetration during the phases subsequent to the development of thermal instabilities. The abundant $^{12}$C can interact with these protons, producing fresh $^{13}$C through the reaction chain $^{12}$C($p$, $\gamma$)$^{13}$N($\beta^+\nu$)$^{13}$C. Too efficient proton captures can activate a full CN cycling, leading to the production of $^{14}$N through the reaction $^{13}$C($p$, $\gamma$)$^{14}$N. This fact is of crucial importance because $^{14}$N is a very efficient absorber for neutrons, the main $n$-poison in typical AGB star conditions, which would inhibit the captures on heavier nuclei. At this point, the star presents a $^{12}$C-pocket embedded in a He-rich environment, so that when the temperature approaches (0.9–1.0) $\times 10^8$ K, the $^{12}$C($\alpha$, $n$)$^{16}$O reaction is activated, releasing neutrons.

In most evolutionary codes this penetration is treated as a free parameter suggesting a depth down to (0.5–1) $\times 10^{-3}$ $M_\odot$ (Gallino et al. 1988; Bisterzo et al. 2010). Other mechanisms
were recently suggested to physically model the proton penetration in the He-rich region and to consequently form a C\textsubscript{13} reservoir. Battino et al. (2016) suggested gravity waves and Kelvin–Helmoltz instabilities as possible causes of proton penetration, while hydrodynamical effects induced by convective overshooting at the border of convective envelope were considered by Cristallo et al. (2011). Piersanti et al. (2013) also considered the effects due to rotation in stars, which showed that the Goldreich–Schubert–Fricke instabilities affect the formation of the C\textsubscript{13} pocket. The possibility that magnetic buoyancy represents a physical mechanism suitable to produce an extended C\textsubscript{13} reservoir (3.5–5 × 10\textsuperscript{-3} \textit{M}_\odot) with a rather flat C\textsubscript{13} distribution was investigated in Busso et al. (2007), Trippella et al. (2014), and Trippella et al. (2016). In this scenario, the H-burning reignition induces a low concentration of C\textsubscript{13} (but with a profile extending to several 10\textsuperscript{-3} \textit{M}_\odot), yielding a negligible abundance of the neutron poison \textsuperscript{14}N. The idea of a large hydrogen penetration was originally suggested to reproduce the spectroscopic observations in young open clusters by Maiorca et al. (2012), performed with new analysis methods and showing enhancements of s-element abundances with respect to the Sun. To distinguish between different scenarios for the C\textsubscript{13}-pocket formation or argue in favor of one reservoir profile with respect to another is beyond the aim of this paper. We therefore only adopted the mechanism for proton penetration suggested in Trippella et al. (2016) and performed s-process nucleosynthesis calculations with the NEWTON post-process code (Busso et al. 1999; Trippella et al. 2014, 2016), which contains a detailed network of more than 400 isotopes (from He to Bi) connected by α-, p-, and n-reactions and weak interactions, in order to assess and understand the impact of the new rate for the C\textsubscript{13}(α, n)\textsuperscript{16}O reaction.

Figure 7 shows the ratios between production factors with respect to solar abundances of neutron-rich nuclei belonging to the s-process main component, which is considered to start at A = 86 and corresponds to nuclides of elements between strontium and bismuth in LMSs, adopting the reaction rate presented in this paper and the rate of NACRE II (Xu et al. 2013) assumed as the reference value, i.e., black and red dashed horizontal lines mean no variations between the two
Table 3

| $T_0$ (GK) | Adopted | Upper | Lower | Power of 10 | Lower than $\Delta 30$ |
|------------|---------|-------|-------|-------------|----------------------|
| 0.04       | 2.278   | 2.978 | 2.079 | -24         |                      |
| 0.05       | 1.428   | 1.843 | 1.311 | -21         |                      |
| 0.06       | 1.916   | 2.441 | 1.768 | -19         |                      |
| 0.07       | 9.515   | 11.98 | 8.826 | -18         |                      |
| 0.08       | 2.379   | 2.960 | 2.217 | -16         |                      |
| 0.09       | 3.612   | 4.444 | 3.379 | -15         |                      |
| 0.10       | 3.763   | 4.580 | 3.534 | -14         |                      |
| 0.11       | 2.926   | 3.523 | 2.756 | -13         |                      |
| 0.12       | 1.801   | 2.147 | 1.701 | -12         |                      |
| 0.13       | 9.174   | 10.83 | 8.677 | -12         |                      |
| 0.14       | 3.995   | 4.671 | 3.783 | -11         |                      |
| 0.15       | 1.525   | 1.767 | 1.446 | -10         |                      |
| 0.16       | 5.211   | 5.985 | 4.943 | -10         |                      |
| 0.18       | 4.624   | 5.227 | 4.389 | -09         |                      |
| 0.20       | 3.069   | 3.420 | 2.914 | -08         |                      |
| 0.25       | 1.434   | 1.554 | 1.362 | -06         |                      |
| 0.30       | 2.805   | 3.087 | 2.750 | -05         |                      |
| 0.35       | 3.424   | 3.621 | 3.253 | -04         |                      |
| 0.40       | 2.777   | 2.925 | 2.638 | -03         |                      |
| 0.45       | 1.675   | 1.761 | 1.591 | -02         |                      |
| 0.50       | 7.872   | 8.271 | 7.478 | -02         |                      |
| 0.60       | 9.525   | 10.00 | 9.048 | -01         |                      |
| 0.70       | 6.300   | 6.616 | 5.985 | +00         |                      |
| 0.80       | 2.727   | 2.864 | 2.591 | +01         |                      |
| 0.90       | 8.724   | 9.161 | 8.288 | +01         |                      |
| 1.00       | 2.238   | 2.350 | 2.126 | +02         |                      |

The only peculiar variations are located in the region of gadolinium isotopes of panel (a): there exists a production of $^{152}$Gd and a destruction of $^{154}$Gd, both around 5–8 parts per thousands, with the new rate with respect to the rate of Xu et al. (2013). However, the improvement in the accuracy of the predictions, as demonstrated by the shrinking of the uncertainty bands, is apparent, bespeaking the power of the approach outlined in this work.

Orange and blue curves correspond to the deeper $(5.0 \times 10^{-3} M_\odot)$ and more limited $(3.5 \times 10^{-3} M_\odot)$ proton penetration, and consequently for the extension of the $^{13}$C reservoirs suggested in Trippella et al. (2016), respectively. The blue line, corresponding to a pocket with a smaller amount of $^{13}$C, shows lower production of s-only nuclei, but variations are still on the order of few per thousands. Differences between blue and orange curves are so limited that because they are not the aim of our article, as we described before, we do not conclude in favor of one $^{13}$C reservoir with respect to the other, taking into account the present-day accuracy of observational data. We underscore that the PFs in Figure 7 are likely to be more sensible to the uncertainties affecting the reaction rate with respect to the total extension, in mass, of the two $^{13}$C pockets described above. Nonetheless, the mechanism for proton injection into the He-rich shell still represents a debated open issue that is strongly related to start-time, rate, profile, and mass of the p-penetration. The formation of $^{13}$C reservoirs is then model dependent because only fully three-dimensional magnetohydrodynamical simulations could really help in making progress in the understanding of the pocket, and different choices for the quantities mentioned above could result in higher variations for the production of s-nuclei.

The lower panels (b) and (d) of Figure 7 show the same calculations as the upper panels (a and c, respectively), but adopting a different stellar model of $3.0 M_\odot$ and one-third solar metallicity ([Fe/H] = −0.50), experiencing 11 thermal instabilities. We performed calculations for different stellar models to separate the effect of the rate by the one connected to the variation of stellar parameters. In the $3.0 M_\odot$ case, the neutrons from the $^{22}$Ne source are important and produced at a rather high neutron density, while in the lower mass models the $^{13}$C source always dominates. For the sake of simplicity, we use the same colors and symbols as before. As in previous cases, the $3.5 \times 10^{-3} M_\odot$ $^{13}$C reservoir (blue curve) shows a more limited production for the s-only nuclei than the more extended one $(5 \times 10^{-3} M_\odot$, orange line). Comparing upper (a) and (c) and lower (b) and (d) panels of Figure 7, the $3.0 M_\odot$ and one-third solar metallicity star expects higher variations for s-only nuclei up to barium (heavy s peak) with respect to the star of $1.5 M_\odot$ and almost solar metallicity.

Conversely, comparing the left (a) and (b) and right (c) and (d) panels in the same row, we can note that the $^{13}$C-pocket weakly influences the production, and variations of the production factor for s-only nuclei are smaller than those expected by changing the reference rate in the nucleosynthesis code. In particular, black and red curves, both obtained by selecting the (Xu et al. 2013) reaction rate, are very similar to each other, as well as in the case of orange and blue lines, representing the calculation performed with the $^{13}$C($\alpha$, n)$^{16}$O rate presented in this paper. In the cases discussed above, the production of the s-isotopes seems to be slightly more dependent on the reaction rate choice than the extension of $^{13}$C, stressing the importance of the well-known nuclear inputs.

scenarios. We can note from Figure 6 that in the interesting energy region for AGB-LMSs (0.8–1.0 × 10^8 K) the $^{13}$C($\alpha$, n)$^{16}$O reaction rates by Heil et al. (2008), La Cognata et al. (2013), and Xu et al. (2013) are very similar, so that s-nucleosynthesis results are expected to be almost comparable. Only isotopes that are produced exclusively by slow neutron captures (the so-called s-only nuclei), being shielded against the fast decays of the $\alpha$-process by stable isotopes, are reported in Figure 7.

Calculations in the upper panels (a) and (c) of Figure 7 refer to an LMS of 1.5 $M_\odot$ and almost solar metallicity ([Fe/H] = −0.15, assuming as reference Lodders et al. 2009), experiencing nine thermal instabilities. We considered this stellar model because Trippella et al. (2014) noted that the results of the averaging procedure on LMS models in the range between 1.5 and 3.0 $M_\odot$ are very similar to the calculations of the individual model at lower mass. This fact was the consequence of the Salpeter’s initial mass function, which favors lower masses in the weighting operation. For these reasons, this single model represents a reasonable example in order to reproduce the flat behavior of the solar distribution for s-process nuclei (Trippella et al. 2014, 2016). In Figure 7 we used bands in order to also take into account upper and lower limits of reaction rates of this paper and by Xu et al. (2013). The production factors of the selected isotopes in the He-rich region of the star show that variations are very limited and they are always lower than 1.0%, so that the effect of reaction rate of Table 3 is essentially negligible with respect to calculations obtained with the Xu et al. (2013) reaction rate.
decreasing normalization uncertainties, and determining a way to define the absolute value of the measured astrophysical factor in stellar nucleosynthesis.

Moreover, the new calculation presented in this paper shows a reduction of the rate for the $^{13}\text{C}(\alpha,n)^{16}\text{O}$ reaction with respect to our (La Cognata et al. 2012, 2013) or Heil et al. (2008) determinations in the region that is most interesting for astrophysics. These conditions could lead to a greater amount of unburned $^{13}\text{C}$ (Cristallo et al. 2011; Guo et al. 2012) than the previous predictions. Some $^{13}\text{C}$, survived from the interpulse stage, is engulfed in the convective shell and burns at higher temperatures, about $1.5 \times 10^8$ K, providing another neutron burst at higher densities via the $^{13}\text{C}(\alpha,n)^{16}\text{O}$ reaction itself. The percentage of $^{13}\text{C}$ depends on the metallicity and initial mass of the star. As a consequence, the activation of some s-process branchings could modify the production and/or destruction of branching-dependent isotopes. A verification of the results presented here using independent nucleosynthesis codes is highly desirable.

8. Conclusions

In this paper, we present a new approach that by overturning the usual normalization procedure strongly constrains the absolute value of the $S(E)$-factor for direct measurements starting from indirect experimental data; thus turning one of the most crucial drawbacks of indirect techniques into an advantage. This procedure can a priori be used for all those nuclear reactions of astrophysical interest that are characterized by great uncertainties at low energy and/or whose direct measurements show different absolute values for the corresponding astrophysical factor, for which ANCs of one of more resonances are measured with high accuracy.

We focused our attention on the case of the $^{13}\text{C}(\alpha,n)^{16}\text{O}$ reaction because it represents the main neutron source for AGB-LMSs, but is affected by large systematic errors that are due to the spread in absolute normalization even at high energies, as also recently confirmed by the NACRE II compilation (Xu et al. 2013). In particular, by implementing the recent and precise ANC ($3.6 \pm 0.7$ fm$^{-1}$) calculated by Avila et al. (2015) and the full width (136 $\pm$ 5 keV) of Faestermann et al. (2015) for the threshold resonance that strongly affects the $^{13}\text{C}(\alpha,n)^{16}\text{O}$ astrophysical factor in the corresponding Gamow window into a modified $R$-matrix fit of THM data, it was possible to define that the absolute normalization of direct data by Bair & Haas (1973) is the only one that defines a concordance scenario together with ANC measurements and THM data. Conversely, other data sets, Harissopulos et al. (2005) plus Kellogg et al. (1989) or the combination of Drotleff et al. (1993) with Davids (1968) and Heil et al. (2008), seem to suggest higher values for the ANC, as has recently been observed by La Cognata et al. (2012, 2013), which are not compatible with currently accepted values.

The fact that Faestermann et al. (2015) also predicted a small shift of about 7 keV toward positive $E_{\text{cm}}$ for the center of the resonance near the $\alpha$-threshold did not result in substantial changes, given the energy resolution that characterizes the THM cross section (La Cognata et al. 2013). However, as an important consequence, the procedure to calculate the ANC of the same resonance must be changed in comparison to what was previously done in La Cognata et al. (2012, 2013). As we previously discussed, the calculated value for the squared Coulomb-modified ANC ($\tilde{C}_{\alpha}^{2}(\Omega(1/2)^{+})$) is 3.6 $\pm$ 0.7 fm$^{-1}$ and then well agrees with the determinations of Avila et al. (2015) and other works (Pellegriti et al. 2008; Guo et al. 2012).

In the light of this concordance scenario, the THM cross section was fitted to determine the resonance parameters that are used to determine the astrophysical factor for the $^{13}\text{C}(\alpha,n)^{16}\text{O}$ reaction in the energy range between 0 and 1.2 MeV. The resulting $S(E)$-factor is lower than in La Cognata et al. (2013) and substantially agrees within the error bars with the values shown in Avila et al. (2015) and in Xu et al. (2013). We then calculated the recommended reaction rate by means of standard equations, providing both a tabular list and an analytical formula. Adopting the new rate suggested in the present paper as input for the NEWTON code (Trippella et al. 2014, 2016) for the s-process nucleosynthesis in LMSs, we expect only limited variations, less than few per thousand, for those nuclei whose production is considered to be totally due to slow neutron captures.

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Appendix

Evaluation of the ANC at Positive Energies

La Cognata et al. (2012, 2013) limited their discussion to the extraction of the ANC for the $^{12}\text{C}(\alpha,n)^{16}\text{O}$ reaction from THM data in the specific case of a bound state (or bs). As shown in La Cognata et al. (2013), in the case of a virtual or real decay $B \rightarrow a + A$, in the channel with relative orbital angular momentum $l_B$, total angular momentum $J_B$ of $a$, total angular momentum $J_B$ of the system $a + A$, and for subthreshold resonances, the squared ANC ($\langle C^{2}_{\alpha A} \rangle$ or $C^{2}$ for short) can be derived from the reduced width for the bs $B = (a A)$ as follows (Mukhamedzhanov 2012):

$$C^{2} = \frac{\hbar^2 W(R_{\alpha A})^2}{2\mu_{\alpha A} \gamma^2} + \int_{R_{\alpha A}}^{\infty} |W(r)|^2 dr, \quad (1)$$

where $W(R_{\alpha A}) = W^{2}_{\alpha A} - \eta_{\alpha A}^{bs} l_B + 1/2$ is the Whittaker function and $R_{\alpha A}$ is the channel radius. Moreover, $\mu_{\alpha A}$ and $\eta_{\alpha A}^{bs}$ are the reduced mass of the $a + A$ system and the Coulomb parameter for the bs, respectively. The equation above has to be modified as for bs at negative energies penetrability is zero, but the shift function can still be defined as the logarithmic derivative of the Whittaker function (Thompson & Nunes 2009).

In the case of the $^{13}\text{C}(\alpha,n)^{16}\text{O}$ reaction, the $1/2^{+}$ resonance state is close to the threshold, and the Coulomb factor cannot be neglected in defining the modified ANC ($\tilde{C}$). There is one very important reason why we cannot exclude the Coulomb factor: the renormalization does not change the reduced width, but allows us to operate with more reasonable ANCs values than the standard ones. At very low energy, in collision of charged particles, the Coulomb factor is so huge that the ANC below the threshold has a very high value $\Gamma(l_0 + 1 + \eta_{\alpha A}^{bs})$ (bs).
However, for capture to an unbound state, we have to use the following formula (Equation (7) in Mukhamedzhanov 2012):

$$C^2 = (-1)^{|L_h|} e^{2i\delta_{l_h} k_{a(A)}(l_h)} \frac{\Gamma_{aA}}{k_{a(A)}}$$

(2)

where $\delta_{l_h} k_{a(A)}(l_h)$ is the potential (nonresonance) scattering phase shift at the real resonance relative momentum $k_{a(A)}$, $\Gamma_{aA}$ represents the partial width of the excited state of $^{17}$O described above, and $\Gamma_{aA}$ is the Sommerfeld parameter. Equation (2) must be corrected by the factor $\Gamma(l_h + 1 + i\delta_{l_h})$, since the ANC for low-energy collisions of charged particle is exceedingly small.

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