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Measurement of sub threshold resonance contributions to fusion reactions: the case of the ^{13}C$(\alpha,n)^{16}$O astrophysical neutron source

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Abstract. The ^{13}C$(\alpha,n)^{16}$O reaction is the neutron source for the main component of the s-process. It is is active inside the helium-burning shell of asymptotic giant branch stars, at temperatures $\lesssim 10^8$ K. In this temperature region, corresponding to an energy interval of $140-230$ keV, the ^{13}C$(\alpha,n)^{16}$O cross section is dominated by the -3 keV sub-threshold resonance due to the 6.356 MeV level in ^{17}O. Direct measurements could not establish its contribution owing to the Coulomb barrier between interacting nuclei, strongly reducing the cross section at astrophysical energies. Similarly, indirect measurements and extrapolations yielded inconsistent results, calling for further investigations. The Trojan Horse Method was applied to the ^{13}C$(^6$Li$,n^{16}$O$)d$ quasi-free reaction to access the low as well as the negative energy region of the ^{13}C$(\alpha,n)^{16}$O reaction. By using the generalized R-matrix approach, the asymptotic normalization coefficient $(\tilde{C}^{^{17}\mathrm{O}(1/2^+)}_{\alpha^{13}\mathrm{C}})^2$ of the 6.356 MeV level was deduced. For the first time, the Trojan Horse Method and the asymptotic normalization coefficient were used in synergy. Our indirect approach lead to $(\tilde{C}^{^{17}\mathrm{O}(1/2^+)}_{\alpha^{13}\mathrm{C}})^2 = 7.7^{+1.6}_{-1.5}$ fm^{-1}, slightly larger than the values in the literature, determining a ^{13}C$(\alpha,n)^{16}$O reaction rate slightly larger than the one in the literature at temperatures lower than 10^8 K, with enhanced accuracy.

1 Introduction

The origin of the chemical elements has been subject of quantitative studies since modern physics was born. Regarding heavy nuclides having $90 \lesssim \mathrm{A} \lesssim 208$, a major nucleosynthesis site has been identified as low-mass ($\lesssim 3\mathrm{M}_\odot$), thermally pulsing asymptotic giant branch (AGB) stars [1], responsible for the production of heavy elements along the valley of stability through slow neutron captures (s-process) [3]. In more details, this is usually referred to as main s-process component, because the relatively low neutron fluxes (on the order of 10^5 to 10^{11} neutrons per cm^2 per second), causes the neutron accretion rate to be slower than the β-decay rate. Each thermal pulse on the AGB provides favorable conditions for the convective dredge-up of material after the end of the flash-burning in the He shell [9]. Dredge-up brings nucleosynthesis products from combined H- and He-shell burning to the surface; moreover, partial mixing at the interface between the convective and radiative regions admixes protons with ^{12}C-rich material. Protons mixed downwards are quickly captured by carbon nuclei, eventually leading to the formation of the so-called ^{13}C pocket [2]. Then, ^{13}C nuclei give up their excess neutrons to heavier nuclei through the ^{13}C$(\alpha,n)^{16}$O reaction. This process is considered as the main neutron supply providing for the neutron flux necessary to build up heavy elements from iron-peak seed nuclei.

In the He-burning shell, temperatures vary between 10^7 and 0.9×10^8 K during the time that the H-shell is the major nuclear source in the star, while temperatures can reach to 3×10^8 K during the He-burning phase [4]. At 0.9×10^8 K, the energy range where the ^{13}C$(\alpha,n)^{16}$O reaction is most effective, the so-called Gamow window [5], is within $\sim 140-230$ keV. At such small energies the Coulomb barrier exponentially reduces the fusion cross section σ leading to values as small as 10^{-11} barn at the Gamow energies [6]. Such small values are very difficult to measure as the signal-to-noise ratio rapidly approaches zero. Extrapolation, supported by nuclear theory such as the R-matrix [7], has been used to determine the cross section values at astrophysical energies. To this purpose, the astrophysical $S(E)$-factor has been introduced [8] to have a more reliable extrapolation at astrophysical energies:

$$S(E) = E\,\sigma(E)\exp(2\pi\eta)\,, \tag{1}$$

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where $\exp(2\pi\eta)$ is the reciprocal of the Coulomb barrier penetration factor for s-wave and center-of-mass energies much smaller than the Coulomb barrier (Gamow factor) and η the Sommerfeld parameter. The astrophysical S-factor varies less rapidly with energy than the cross sections at low energies, as Coulomb effects are partially compensated for by the $\exp(2\pi\eta)$ factor, reducing the uncertainty introduced by extrapolation.

In the $^{13}C(\alpha,n)^{16}O$ case, extrapolation is complicated by the occurrence of a sub threshold resonance at -3 keV due to the 6.356 MeV level of ^{17}O, causing an increase of the astrophysical factor as E draws closer to zero. Furthermore, at such low energies atomic electrons shield nuclear charges resulting in an enhancement of the $S(E)$-factor right at astrophysical energies [8]. Since electron screening modifies the low-energy trend of $S(E)$ by a factor of less than 1.2 below 300 keV [11], systematic errors might be introduced by the extrapolation procedure if electron screening is not properly accounted for. In fact, the experimentally observed electron screening enhancement of the cross section turns out to be systematically larger than what present-day atomic models predict [10]. Therefore, alternative approaches have been introduced to independently assess the low-energy $S(E)$-factor using indirect methods. In particular, since its trend is essentially governed by the 6.356 MeV ^{17}O state, the measurement of this resonance parameters has allowed for the calculation of the $S(E)$-factor beyond the energy region explored by means of direct experiments. In particular, the measurement of the asymptotic normalization coefficient (ANC) [12] and of the spectroscopic factor have proved very effective to size the contribution to the $S(E)$-factor of the -3 keV peak.

In Table 1 we give the astrophysical S-factors evaluated at 100 keV, that is, at the lower energy edge of the Gamow window, by different authors and we specify as well the approaches adopted by each of them. In detail, in Refs. [6, 15] an extrapolation of direct data using the R-matrix fitting of existing data was performed, the first work using a very large number of data sets (including, for instance, the time-reversed reaction and the elastic scattering). Refs. [13, 14] report theoretical calculation using the microscopic cluster approach while Refs. [16–18] focus on the measurement of the ANC or of the spectroscopic factor to constrain the 6.356 MeV state and provide a more accurate R-matrix. However, Table 1 clearly shows a large dispersion of the $S(E)$-factor at astrophysical energies, suggesting the possible existence of systematic errors determining the scatter of $S(100\,\text{keV})$. Therefore, new and improved measurements are necessary to pin down the $^{13}C(\alpha,n)^{16}O$ $S(E)$-factor and calculate a reliable reaction rate for astrophysical applications.

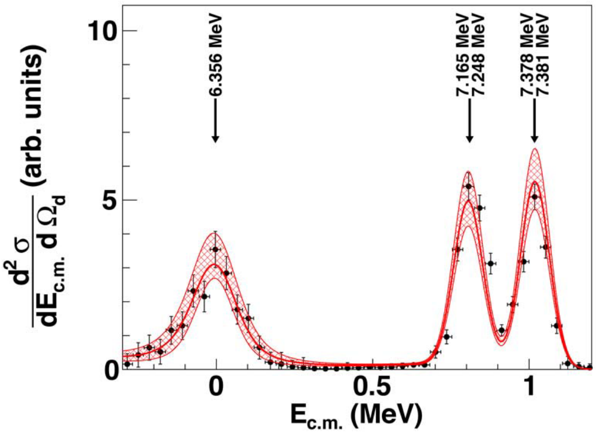

Figure 1. THM cross section of the $^{13}C(^6Li,n^{16}O)d$ quasi-free reaction (red dots) as a function of the $\alpha - {}^{13}C$ relative energy ($E_{c.m.}$). The blue band highlights the modified R-matrix fit of the THM data. The uncertainty range includes statistical and normalization errors. The arrows mark the resonances occurring in the energy window spanned in the present work.

2 The THM measurement

For this reason we have performed a new measurement of the $^{13}C(\alpha,n)^{16}O$ at astrophysical energies. using the Trojan Horse Method (THM). This indirect method is very suited for such a study as it allows us to determine the resonance parameters even at sub threshold energies, as in the case of the 6.356 MeV ^{17}O state. A detailed discussion of the method is given in Refs. [19–22] and an exhaustive description of the experimental procedure and data analysis in the case of the $^{13}C(\alpha,n)^{16}O$ reaction study is reported in [23, 24]. Here we recall that we used a ^6Li beam of 7.82 MeV, delivered by the 9 MV tandem accelerator at the John D. Fox Superconducting Linear Accelerator Facility (Florida State University), to transfer an α-particle and populate ^{17}O levels sitting above the neutron emission threshold, in order to have $^{17}O \rightarrow ^{16}O + n$. The ^6Li beam impinged onto 99% ^{13}C enriched foils, whose thicknesses were chosen to be 53 $\mu g\,cm^{-2}$ and 107 $\mu g\,cm^{-2}$. From the measurement of the spectator deuterons and of the ^{16}O recoil energies and angles of emission, the $^{13}C - \alpha$ relative energy was reconstructed. Its spectrum, after background subtraction and integrated over the center-of-mass angular distributions is shown in Figure 1 as red dots. The given uncertainty contains statistical and normalization errors. Figure 1 demonstrates the unambiguous occurrence of the -3 keV resonance and the possibility to access not only the low-energy but also the sub threshold energy region.

The modified R-matrix approach has been used to fit the THM data and deduce the resonance parameters [23, 24]. Since the same reduced widths appear in the

Table 1. Summary of S-factors evaluated at E_{cm} = 100 keV

$S(100\,\text{keV})$ (10^6 MeV b)	Approach	Ref.
$3.3^{+1.8}_{-1.4}$	R-matrix	[6]
6.3	R-matrix	[15]
2.7	microscopic cluster approach	[13]
5.3	microscopic cluster approach	[14]
1.2 ± 0.3	ANC	[16]
3.4 ± 1.5	Spectroscopic factor	[17]
$2.5^{+0.5}_{-0.6}$	Spectroscopic factor	[18]

THM cross section and in the direct data, those extracted from THM data can be introduced into a standard R-matrix code to establish the trend of the $^{13}C(\alpha,n)^{16}O$ S-factor [19–22]. It is important to underline that the THM cross section is given in arbitrary units, thus normalization to direct data is necessary to attain absolute values. This is accomplished by spanning an energy region covered by direct data in the indirect measurement and scaling the THM cross section to the direct one, which is given in absolute units. In the case of resonance reactions, this is obtained by introducing into the modified R-matrix formula the reduced widths from the R-matrix fitting of direct data; it means that the resonance parameters, deduced from the THM cross section, are normalized to those extracted from direct data [20, 23, 24]. In the present work, normalization is performed in the $0.5 - 1.2$ MeV energy window, since four resonances are present in this interval, with well known parameters [6]. Moreover, in this region the high energy tail of the -3 keV resonance has a vanishingly small contribution, in the same way as the electron screening effect; therefore, no systematic errors on the normalization due to the -3 keV resonance or electron screening are introduced.

The THM approach allowed us to extract the Coulomb-modified ANC $\tilde{C}_{\alpha^{13}C}^{^{17}O(1/2^+)}$ of the -3 keV resonance, from the half-off-energy-shell R-matrix fitting of the THM data [23, 25]. This is the first time that THM is used to extract the ANC of a sub threshold resonance. In detail, following the discussion in [23, 25], we obtained $(\tilde{C}_{\alpha^{13}C}^{^{17}O(1/2^+)})^2 = 7.7 \pm 0.3_{stat}\,{}^{+1.6}_{-1.5}{}_{norm}$ fm^{-1} in agreement, within the uncertainties, with our preliminary value $6.7^{+0.9}_{-0.6}$ fm^{-1}. The comparison with the ANC's for previous measurements and, where not available, the spectroscopic factors S_α for the 6.356 keV ^{17}O level indicates that our result is well consistent with the ANC deduced from the spectroscopic factor measurement by [17], and probably with the result of [18] once the increase of S_α for increasing beam energy observed by [17] is accounted for. Conversely, the present-work $(\tilde{C}_{\alpha^{13}C}^{^{17}O(1/2^+)})^2$ is significantly larger than the ANC in [16], calling for a more exhaustive investigation of the α-transfer reaction used to populate the 6.356 keV ^{17}O level, as systematic errors might be present. Using the reduced widths deduced through the Modified R-matrix approach, the $^{13}C(\alpha,n)^{16}O$ S-factor at 100 keV of $4.0 \pm 0.7 \times 10^6$ MeV b. This result agrees quite well with the largest $S(100\,\mathrm{keV})$ listed in Table 1, with an improved accuracy due to a reduced systematic uncertainty (check Refs. [23, 24] for more details). As a consequence, the reaction rate deduced from the THM S-factor is in agreement with the most results in the literature at $\sim 10^8$ K, with enhanced accuracy thanks to this innovative approach. The possible astrophysical consequences of the present work are currently under investigation [24].

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References

[1] B. Meyer, Annu. Rev. Astron. Astrophys. **32**, 153 (1994)

[2] R. Gallino *et al.*, Astrophys. J. **497**, 388 (1998)

[3] F. Käppeler, R. Gallino, S. Bisterzo, and W. Aoki, Rev. Mod. Phys. **83**, 157 (2011)

[4] O. Straniero *et al.*, Astrophys. J. **440**, L85 (1995)

[5] C. Iliadis, *Nuclear Physics of Stars* (Wiley-VCH Verlag, Weinheim, 2007)

[6] M. Heil *et al.*, Phys. Rev. C **78**, 025803 (2008)

[7] A. M. Lane and R. G. Thomas, Rev. Mod. Phys. **30**, 257 (1958)

[8] C. E. Rolfs and W. S. Rodney, *Cauldrons in the cosmos* (University of Chicago Press, Chicago, IL, 1988)

[9] F. Herwig, Annu. Rev. Astron. Astrophys. **43**, 435 (2005)

[10] M. La Cognata *et al.*, Phys. Rev. C **72**, 065802 (2005)

[11] H.W. Drotleff *et al.*, Astrophys. J. **414**, 735 (1993)

[12] A. M. Mukhamedzhanov *et al.*, Phys. Rev. C **56**, 1302 (1997)

[13] P. Descouvemont, Phys. Rev. C **36**, 2206 (1987)

[14] M. Dufour and P. Descouvemont, Phys. Rev. C **72**, 015801 (2005)

[15] G. M. Hale, Nucl. Phys. A **621**, 177 (1997)

[16] E. D. Johnson *et al.*, Phys. Rev. Lett. **97**, 192701 (2006)

[17] M. G. Pellegriti *et al.*, Phys. Rev. C **77**, 042801 (2008)

[18] B. Guo *et al.*, Astrophys. J. **756**, 193 (2012)

[19] M. La Cognata, C. Spitaleri, and A. M. Mukhamedzhanov, Astrophys. J. **723**, 1512 (2010)

[20] M. La Cognata *et al.*, Astrophys. J. **739**, L54 (2011)

[21] A. M. Mukhamedzhanov *et al.*, J. Phys. G **35**, 014016 (2008)

[22] A. M. Mukhamedzhanov, Phys. Rev. C **84**, 044616 (2011)

[23] M. La Cognata *et al.*, Phys. Rev. Lett. **109**, 232701 (2012)

[24] M. La Cognata *et al.*, Astrophys. J. **777**, 143 (2013)

[25] A. M. Mukhamedzhanov & R.E. Tribble, Phys. Rev. C **59**, 3418 (1999)