EPJ Web of Conferences **66**, 07010 (2014)
DOI: 10.1051/epjconf/20146607010

Measurement of the $^{13}\mathrm{C}(\alpha, n)^{16}\mathrm{O}$ reaction at astrophysical energies using the Trojan Horse Method. Focus on the -3 keV sub-threshold resonance.

M. La Cognata[1,a], C. Spitaleri[1,2], O. Trippella[1,3], G.G. Kiss[1,4], G.V. Rogachev[5], A.M. Mukhamedzhanov[6], M. Avila[5], G.L. Guardo[1,2], E. Koshchiy[5], A. Kuchera[5], L. Lamia[2], S.M.R. Puglia[1,2], S. Romano[1,2], D. Santiago[5], and R. Spartà[1,2]

[1] *Istituto Nazionale di Fisica Nucleare, Laboratori Nazionali del Sud, Catania, Italy*
[2] *Dipartimento di Fisica e Astronomia, Università di Catania, Catania, Italy*
[3] *Istituto Nazionale di Fisica Nucleare, Sezione di Perugia, & Dipartimento di Fisica, Università di Perugia, Perugia, Italy*
[4] *Institute of Nuclear Research (ATOMKI), Debrecen, Hungary*
[5] *Department of Physics, Florida State University, Tallahassee, Florida, USA*
[6] *Cyclotron Institute, Texas A&M University, College Station, Texas, USA*

Abstract. Most of the nuclei in the mass range $90 \lesssim \mathrm{A} \lesssim 208$ are produced through the so-called *s*-process, namely through a series of neutron capture reactions on seed nuclei followed by β-decays. The $^{13}\mathrm{C}(\alpha, n)^{16}\mathrm{O}$ reaction is the neutron source for the main component of the *s*-process. It is active inside the helium-burning shell of asymptotic giant branch stars, at temperatures $\lesssim 10^8$ K, corresponding to an energy interval of $140 - 230$ keV. In this region, the astrophysical $S(E)$-factor is dominated by the -3 keV sub-threshold resonance due to the 6.356 MeV level in ^{17}O. Direct measurements could not soundly establish its contribution owing to the cross section suppression at astrophysical energies determined by the Coulomb barrier between interacting nuclei. Indirect measurements and extrapolations yielded inconsistent results, calling for further investigations. The Trojan Horse Method turns out to be very suited for the study of the $^{13}\mathrm{C}(\alpha, n)^{16}\mathrm{O}$ reaction as it allows us to access the low as well as the negative energy region, in particular in the case of resonance reactions. We have applied the Trojan Horse Method to the $^{13}\mathrm{C}(^{6}\mathrm{Li}, n^{16}\mathrm{O})d$ quasi-free reaction. By using the modified 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 has been deduced as well as the *n*-partial width, allowing to attain an unprecedented accuracy for the $^{13}\mathrm{C}(\alpha, n)^{16}\mathrm{O}$ astrophysical factor. A preliminary analysis of a partial data set has lead to $(\tilde{C}^{^{17}\mathrm{O}(1/2^+)}_{\alpha^{13}\mathrm{C}})^2 = 6.7^{+0.9}_{-0.6}$ fm^{-1}, slightly larger than the values in the literature, determining a $^{13}\mathrm{C}(\alpha, n)^{16}\mathrm{O}$ reaction rate in agreement with the most results in the literature at $\sim 10^8$ K, with enhanced accuracy thanks to this innovative approach.

[a] e-mail: lacognata@lns.infn.it

1 Introduction

Nuclei heavier than iron cannot be produced in stars by fusing lighter nuclei; instead, they are synthesized through a sequence of neutron capture reactions on seed nuclei [1]. Regarding $90 \lesssim A \lesssim 208$ nuclei, a major nucleosynthesis site has been identified in low-mass ($\lesssim 3M_\odot$) asymptotic giant branch (AGB) stars [2], where the presence of a ^{13}C pocket [3] allows for neutron production through the $^{13}C(\alpha,n)^{16}O$ reaction. The ^{13}C pocket forms after the quenching of the H-burning shell, since protons are mixed downward and quickly captured by ^{12}C nuclei, eventually leading to the formation of ^{13}C. Because of the relatively low neutron fluxes generated by the $^{13}C(\alpha,n)^{16}O$ reaction (on the order of 10^5 to 10^{11} neutrons per cm^2 per second), the neutron accretion rate is slower than the β-decay rate, thus only heavy elements along the stability valley can be produced (s-process, s for slow) [4]. At 0.9 10^8 K, a typical temperature characterizing ^{13}C-burning [5], the energy range where the $^{13}C(\alpha,n)^{16}O$ reaction is most effective, the Gamow window [1], is $\sim 100 - 270$ keV.

The Coulomb barrier exponentially dampens the 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 improve the accuracy of the extrapolation procedure:

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

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 and η the Sommerfeld parameter. The astrophysical factor has a smoother behavior than the cross section 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 determining 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 [9], systematic errors might be introduced by the extrapolation procedure if electron screening is not properly accounted for. Therefore, alternative approaches have been introduced to independently assess the low-energy $S(E)$-factor. 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 measurements. In detail, the measurement

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

Ref.	S(100 keV) (10^6 MeVb)	Approach
[6]	$3.3^{+1.8}_{-1.4}$	R-matrix
[11]	2.7	microscopic cluster approach
[12]	5.3	microscopic cluster approach
[13]	6.3	R-matrix
[14]	1.2 ± 0.3	ANC
[15]	3.4 ± 1.5	Spectroscopic factor
[16]	$2.5^{+0.5}_{-0.6}$	Spectroscopic factor

of the asymptotic normalization coefficient (ANC) [10] and of the spectroscopic factor have been undertaken to pin down the resonance top value, to calculate its contribution to the $S(E)$-factor.

Table 1 summarizes the astrophysical S-factors evaluated at 100 keV by different authors as well the approaches adopted to obtain them. 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.

2 The THM measurement

In the present work, the Trojan Horse Method (THM) has been used to investigate the $^{13}C(\alpha,n)^{16}O$ at astrophysical energies. This indirect method is very suited for such study as it allows 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. [17–20] 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 [21, 22]. Here we recall that we used a ^{6}Li 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, later decaying to $^{16}O + n$. From the measurement of the spectator deuteron 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 [21, 22]. Since the same reduced widths appear in the 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 [17–20]. 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

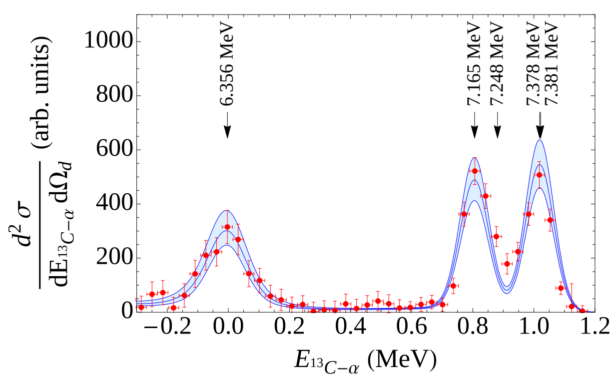

Figure 1. THM cross section of the $^{13}C(^{6}Li,n^{16}O)d$ quasi-free reaction (red dots) as a function of the α – ^{13}C relative energy. The blue band highlights the modified R-matrix fit of the THM data. The uncertainty range includes statistical and normalization errors. The arrows mark the resonances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

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 [18, 21, 22]. In the present work, normalization is performed in the 0.5 – 1.2 MeV energy window, since four resonances are present in this interval, whose parameters are well known [6]. Moreover, in this region the high energy tail of the -3 keV resonance has a vanishingly small contribution, as the electron screening effect.

A preliminary analysis of the THM experiment, based on about half of the available statistics, has lead to an ANC for the 6.356 MeV ^{17}O state $(\tilde{C}_{\alpha^{13}C}^{^{17}O(1/2^+)})^2 = 6.7^{+0.9}_{-0.6}$ fm^{-1} slightly larger than the values in the literature [14–16], determining a $^{13}C(\alpha, n)^{16}O$ S-factor at 100 keV of $4.0 \pm 0.7 \times 10^6$ MeVb. 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. [21, 22] 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 [22].

References

[1] C. Iliadis, *Nuclear Physics of Stars* (Wiley-VCH Verlag, Weinheim, 2007)
[2] B. Meyer, Annu. Rev. Astron. Astrophys. **32**, 153 (1994)
[3] R. Gallino et al., Astrophys. J. **497**, 388 (1998)
[4] F. Käppeler, R. Gallino, S. Bisterzo, and W. Aoki, Rev. Mod. Phys. **83**, 157 (2011)
[5] O. Straniero et al., Astrophys. J. **440**, L85 (1995)
[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] H.W. Drotleff et al., Astrophys. J. **414**, 735 (1993)
[10] A. M. Mukhamedzhanov et al., Phys. Rev. C **56**, 1302 (1997)
[11] P. Descouvemont, Phys. Rev. C **36**, 2206 (1987)
[12] M. Dufour and P. Descouvemont, Phys. Rev. C **72**, 015801 (2005)
[13] G. M. Hale, Nucl. Phys. A **621**, 177 (1997)
[14] E. D. Johnson et al., Phys. Rev. Lett. **97**, 192701 (2006)
[15] M. G. Pellegriti et al., Phys. Rev. C **77**, 042801 (2008)
[16] B. Guo et al., Astrophys. J. **756**, 193 (2012)
[17] M. La Cognata, C. Spitaleri, and A. M. Mukhamedzhanov, Astrophys. J. **723**, 1512 (2010)
[18] M. La Cognata et al., Astrophys. J. **739**, L54 (2011)
[19] A. M. Mukhamedzhanov et al., J. Phys. G **35**, 014016 (2008)
[20] A. M. Mukhamedzhanov, Phys. Rev. C **84**, 044616 (2011)
[21] M. La Cognata et al., Phys. Rev. Lett. **109**, 232701 (2012)
[22] M. La Cognata et al., Astrophys. J. **777**, 143 (2013)