Cross section of the $^{13}C(\alpha,n)^{16}O$ reaction at low energies

G. F. Ciani$^{1,2,3}$, L. Csedreki$^{2,3}$, J. Balibrea-Correa$^{4,5}$, A. Best$^{4,5}$

for the LUNA collaboration

1 Institute for Nuclear Research (Atomki), PO Box 51, 4001 Debrecen, Hungary
2 Gran Sasso Science Institute, Viale F. Crispi 7, 67100 L’Aquila, Italy
3 Istituto Nazionale di Fisica Nucleare Laboratori Nazionali del Gran Sasso (LNGS), Via G. Acitelli 22, 67100 Assergi, Italy
4 Università degli Studi di Napoli “Federico II”, Dipartimento di Fisica “E. Pancini”, Via Cintia 21, 80126 Napoli, Italy
5 Istituto Nazionale di Fisica Nucleare, Sezione di Napoli, Via Cintia 21, 80126 Napoli, Italy

E-mail: giovanni.ciani@lngs.infn.it

Abstract. The $^{13}C(\alpha,n)^{16}O$ reaction is the main neutron source for the $s$-process in low mass AGB stars. Although several direct measurements have been performed, no dataset reaches the Gamow window (140-250 keV) due to the exponential drop of the cross section $\sigma(E)$ with decreasing energy. The reaction rate becomes so low that the strong cosmic background would become predominant.

In order to measure the $^{13}C(\alpha,n)^{16}O$ cross section at low energies, a double effort has been performed, namely to suppress the background in the setup and to keep under control the target modification under an intense stable beam provided by the LUNA accelerator (100-200 $\mu$A). These measurements were carried out in deep underground laboratories of Laboratori Nazionali del Gran Sasso (LNGS) in the framework of the LUNA experiment. Preliminary results are reported in this contribution.

1. State of the art

The $^{13}C(\alpha,n)^{16}O$ reaction ($Q=2.215$ MeV) is the major neutron source for the main component of the $s$-process in low mass AGB stars, whose temperature of interest is about $1-2\cdot10^8$ K. This corresponds to a Gamow window between 140 and 250 keV, below the Coulomb potential energy of the reaction.

In the last 25 years, several direct measurements of this reaction cross section have been performed [1, 2, 3, 4]. The astrophysical S(E)-factor, is shown in Figure 1. The lowest energy point has been measured by Drotleff et al. [2] with an uncertainty of 50%.

In addition, the reaction mechanism at low energies includes also the contribution of the high energy tail of a near-threshold resonance at $E_R = -3\pm8$ keV (the resonance energy in the center-of-mass system), corresponding to $E_x = 6.356$ MeV state in $^{17}O$. 
Cross section measurement of the $^{13}\text{C}(\alpha, n)^{16}\text{O}$ reaction at low energies

In Figure 1 the main dataset from direct measurement are compared. The red and the green curves indicate the R Matrix extrapolation performed by Heil, considering and omitting the subthreshold resonance, respectively. As one can see the two curves differ almost by one order of magnitude in the astrophysical energy region (violet bar).

The extrapolation at lower energies can be improved only by the extension of experimental cross section data towards the Gamow-window with moderated and fully controlled uncertainties. Another way to solve the problem are indirect measurements: the Trojan Horse Method (THM)[5] or the Asymptotic Normalization Coefficient (ANC)[6] have been used to measure the $^{13}\text{C}(\alpha, n)^{16}\text{O}$ reaction, but these techniques need a normalization with respect to direct data, so approach the Gamow Window with a direct measurement has a crucial importance.

In this framework the LUNA collaboration’s goal is the approach of the Gamow window with an overall uncertainty of about 10%, requested to improve the stellar evolution models [7].

2. The experimental setup at LUNA

The Laboratory for Underground Nuclear Astrophysics (LUNA) collaboration takes advantage from the low background environment of Underground Laboratori Nazionali Del Gran Sasso (LNGS). Thanks to 1400 m of rocks (3500 m.w.e) the cosmic background is reduced by 6 orders of magnitude for muons and by three orders of magnitude for neutrons [8].

Furthermore, the LUNA accelerator provides an intense ($< I > = 200 \mu A$) stable alpha beam in the energy range $50 < E_\alpha < 400$ keV [9, 10] on a solid state target or on
Cross section measurement of the $^{13}$C($\alpha$, n)$^{16}$O reaction at low energies

a windowless gas target system[11]. The experimental setup used for this measurement is based on 18 $^3$He counters with low intrinsic background arranged in two rings (6 in the inner ring, 12 in the outer ring) concentric with respect to the target chamber. The counters are embedded in a polyethylene moderator. All the setup is shielded by a 2 inches layer of borated polyethylene absorber to further reduce the environmental background [12]. The setup is designed to allow the opening of the moderator and to insert a High-Purity Germanium (HPGe) detector in close geometry. The usage of the gamma detector is described later. The alpha particle intrinsic background, coming from impurities of uranium and thorium in the counter cases, was reduced using stainless steel counters instead of standard aluminium ones. The reduction of one order of magnitude is evident in Figure 2, between the blue and the red spectrum, measured in the LNGS with stainless steel and aluminium counters, respectively. The black spectrum is measured in a surface lab with a stainless steel counter.

Figure 2. Comparison of LNGS neutron background measured with two different $^3$He counters. Blue spectrum refers to the stainless steel, while the red spectrum to aluminum.

Raw preamplifier signals from detectors were acquired with Caen V1724 digitizers and a further background reduction was obtained rejecting alpha signals with a pulse shape discrimination analysis [13]. This permitted to have an overall background of about 1 count/h in the setup, 4 orders of magnitude lower than previous experiments performed in surface laboratories. In order to dissipate the power deposited within the beam spot size (about 2 cm$^2$), the $^{13}$C targets were directly water-cooled and a LN$_2$ cold trap was installed to prevent carbon build-up on the target surface.

3. Target characterization and monitoring

$^{13}$C targets used during the measurement at LUNA have been produced evaporating $^{13}$C isotopically enriched at 99% on tantalum backing using the evaporator installed
Cross section measurement of the $^{13}\text{C}(\alpha,n)^{16}\text{O}$ reaction at low energies

at the nuclear institute of research Atomki (Debrecen, Hungary). An extensive target characterization was performed through Nuclear Resonant Reaction Analysis (NRRA) of the $^{13}\text{C}(p,\gamma)^{14}\text{N}$ reaction at 1.75 MeV at the Tandetron accelerator installed at Atomki in order to check stoichiometry, density and depth profile immediately after the evaporation[14].

The monitoring of these quantities mentioned is crucial also during the cross section measurement performed at LUNA, where the NRRA technique is not applicable, due to the lack of resonances in the available energy range. For this reason, a new method of analysis was developed.

Data taking at LUNA consisted in long $\alpha$-beam runs with accumulated charges of $\approx 10^2$ C per run, interspersed by short proton-beam runs with moderator opened and HPGe detector in close geometry, with typical accumulated charges of 0.2 C at most. During the last mentioned proton run, the target degradation can be checked observing the direct capture de-excitation to the ground state peak of $^{13}\text{C}(p,\gamma)^{14}\text{N}$ reaction with the HPGe detector. The shape of this peak is due to the slowdown of beam projectiles going deeper and deeper in the target: the number of $\gamma$-rays emitted per unit of charge is proportional to the cross section $\sigma(E)$ and to the inverse of stopping power $\epsilon(E)$. These quantities are both energy dependent. Consequently, in each bin of the acquired spectra, the number of counts detected, mimic the energy dependence of the $\sigma(E)$ and $\epsilon(E)$. In particular we assume that with the alpha beam impinging the target, implants inactive nuclei in the target increasing the stopping power and consequently decreasing the yield of the $^{13}\text{C}(p,\gamma)^{14}\text{N}$ reaction. Setting the effective stopping power as a free parameter in the fit, it is possible to quantify its modification as a function of the accumulate charge. Further details can be found in a paper in submission[15]. The data taking was carried out alternating acquisition of $^{13}\text{C}(p,\gamma)^{14}\text{N}$ spectrum for the fit of the $\gamma$-peak and the $^{13}\text{C}(\alpha,n)^{16}\text{O}$ for the cross section evaluation. Proton beam runs were all performed at the same reference energy, $E_p = 310$ keV. The effective stopping power evaluated during two proton runs was interpolated and used as average value during the alpha run between them. This obtained value was used to properly correct the $^{13}\text{C}(\alpha,n)^{16}\text{O}$ experimental yield, which is proportional to the cross section reaction. The importance of this correction is shown in Figure 3. The yield for individual alpha beam irradiations at beam energy of 400 keV is plotted before (red circles) and after (blue crosses) the degradation correction. The straight lines indicate the weighted average of corresponding data.

4. Preliminary results and outlook

The LUNA collaboration carried out three measurement campaigns of four month each between 2017 and 2019, using more than 100 targets. Thanks to the impressive background suppression and the novel approach to monitor target degradation, it was
Cross section measurement of the $^{13}$C($\alpha$,n)$^{16}$O reaction at low energies

![Graph 1](image1.png)

**Figure 3.** Experimental yield obtained for some of the individual irradiations at 400 keV in the laboratory system: the straight lines indicate the weighted average of the data. The yield difference between data before and after the degradation correction is about at the level of 20%.

It is possible to measure experimental yield of the $^{13}$C($\alpha$,n)$^{16}$O reaction in an energy range between 400 keV down to 305 keV in laboratory system energy, 40 keV lower than data in literature. Preliminary results are shown in Figure 4. For each data point the statistical uncertainty lower than 15% was fulfilled. Moreover, the two lowest data points are inside the Gamow window for the low mass AGB stars environment (yellow area).

![Graph 2](image2.png)

**Figure 4.** Preliminary experimental $^{13}$C($\alpha$,n)$^{16}$O yield measured at LUNA-400 as a function of the laboratory energy. Only statistical uncertainties are in the plot. The vertical green dashed curve indicates the lowest point in literature before the present work. The yellow area indicates the Gamow window region of interest.

The final analysis will be concluded within the end of 2019. The new cross section and S(E)-factor of the $^{13}$C($\alpha$,n)$^{16}$O reaction evaluated will be used to accomplish new possible astrophysical impact for the reaction.
Cross section measurement of the $^{13}\text{C}(\alpha,n)^{16}\text{O}$ reaction at low energies

Bibliography

[1] Heil, M. et al.: The $^{13}\text{C}(\alpha,n)$ reaction and its role as a neutron source for the $s$ process, Phys. Rev. C, 78, 2 (2008)
[2] Drotleff, H.W. et al.: Reaction rates of the $s$-process neutron sources $Ne_{22}(\alpha,n)Mg_{25}$ and $C13(\alpha,n)O_{16}$, Astrophys. J., 414, 2 (1993)
[3] Brune, C. R. et al.: Low-energy resonances in $^{13}\text{C}(\alpha,n)$, Phys. Rev. C, 48, 6 (1993)
[4] Harissopulos, S. et al.: Cross section of the $^{13}\text{C}(\alpha,n)^{16}\text{O}$ reaction: A background for the measurement of geo-neutrinos, Phys. Rev. C, 72, 6 (2005)
[5] La Cognata, M. et al.: On the Measurement of the $^{13}\text{C}(\alpha,n)^{16}\text{O}$ S-factor at Negative Energies and its Influence on the $s$-process, Astrophys. J., 777, 2 (2013)
[6] Mukhamedzhanov, A. et al.: Subthreshold resonances and resonances in the R-matrix method for binary reactions and in the Trojan horse method, Phys. Rev. C, 96, 2 (2017)
[7] Cristallo, S. et al.: The Importance of the $^{13}\text{C}(\alpha,n)^{16}\text{O}$ Reaction in Asymptotic Giant Branch Stars, Astrophys. J., 859, 2 (2018)
[8] Best, A. et al.: Low energy neutron background in deep underground laboratories, Nucl. Instrum. Methods Phys. Res. A, 3, 507 (2003)
[9] Formicola, A. et al.: The LUNA II 400kV accelerator, Nucl. Instrum. Methods Phys. Res. A, 3, 507 (2003)
[10] Cavanna F. et al.: Direct measurement of nuclear cross-section of astrophysical interest: Results and perspectives, International Journal of Modern Physics A, 33 (2018)
[11] Ferraro, F. et al.: A high-efficiency gas target setup for underground experiments, and redetermination of the branching ratio of the 189.5 keV Ne-22(p,γ)Na-23 resonance, Eur. Phys. J. A (2018) 54: 44
[12] Csedreki, L. et al.: Introduction of the new LUNA experimental setup for high precision measurement of the $^{13}\text{C}(\alpha,n)^{16}\text{O}$ reaction for astrophysical purposes, EPJ Web Conf. NPA 2017
[13] J. Balibrea-Correa et al.: Improved pulse shape discrimination for high pressure $^3\text{He}$ counters Nucl. Instrum. Methods Phys. Res. A, 906 (2018)
[14] Ciani, G.F. et al.: Target characterizations for direct measurement of the $^{13}\text{C}(\alpha,n)^{16}\text{O}$ reaction at LUNA 400, EPJ Web Conf. NPA 2017
[15] Ciani, G.F. et al.: A new approach to monitor $^{13}\text{C}$-targets degradation in situ for $^{13}\text{C}(\alpha,n)^{16}\text{O}$ cross-section measurements at LUNA, Submitted on Eur. Phys. J. A