Final results on the ^{13}C(α,n)^{16}O cross section at low energies at LUNA

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Abstract. It is well established that the $^{13}C(\alpha,n)^{16}O$ reaction (Q=2.215 MeV) is the major neutron source feeding the *s*-process in low mass ($1-3M_\odot$) Asymptotic Giant Branch (AGB) stars. In the last decades, several measurements have been performed. Nevertheless, no dataset reaches the Gamow window (140 keV $<E_{c.m.}<$250 keV). This is due to the exponential drop of the cross section σ(E) with decreasing energy. The consequence is that the reaction rate becomes so low that the cosmic background becomes predominant in surface laboratories.
A recent measurement was carried out in deep underground laboratory of Laboratori Nazionali del Gran Sasso (LNGS) in the framework of the LUNA experiment.
To measure the $^{13}C(\alpha,n)^{16}O$ cross section at low energies, a multiple effort has been performed to suppress the background in the setup, to maximise the detector efficiency and to keep under control the target modification under an intense stable beam provided by the LUNA accelerator ($<I>= 200\,\mu$A). Thanks to these accuracies, the $^{13}C(\alpha,n)^{16}O$ cross section was measured in the center of mass energy range 230 keV $<E_{cm}<$305 keV with a maximum 20% overall uncertainty. This allowed to constrain the reaction rate at T=0.1 GK at 15% uncertainty and to lead the way for new possible astrophysical consequences.

1 Introduction

The $^{13}C(\alpha,n)^{16}O$ reaction is the main neutron source for the *s-process* in low mass AGB stars[1]. The reaction takes place subsequently complex convective motions in the so-called 13C pocket in a stellar environment of about $1-2\cdot 10^8$ K, corresponding to a Gamow window between 140[1] and 250 keV, well below the Coulomb barrier of the reaction.

In the last 25 years, several direct cross section measurements of this reaction have been performed [2–4]. The lowest energy point, corresponding to E=265 keV, was measured by Drotleff et al. [3] with a 60% uncertainty. From the literature one can see that statistical error is mainly due to the low signal to noise ratio at low energies and a strong source of systematic uncertainty comes from the difficulty to keep under control target degradation.

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[1]all the energies are in center of mass system, unless specified otherwise

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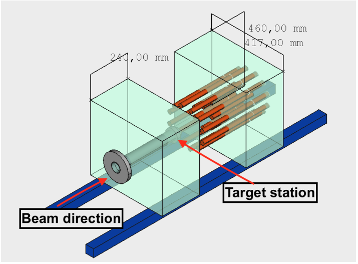
In addition, the presence of a near threshold resonance at $E_R = -3 \pm 8$ keV, corresponding to $E_x = 6.356$ MeV state in ^{17}O, influences the cross section in the Gamow window, making extrapolations from higher energies complicated.
In 2008, Heil et al. [2] performed a direct measurement and a multichannel R-matrix analysis was carried out: the S(E) factor extrapolation uncertainty in the Gamow peak is at least of 20%. A recent work by deBoer et al.[5] states that one of the main source of uncertainty for R-matrix extrapolations is due to normalisation uncertainty of the $^{13}C(\alpha,n)^{16}O$ data, directly connected to systematic uncertainties on different datasets.
In this scenario the new LUNA (Laboratory for Underground Nuclear Astrophysics) measurement, whose goal is to reach the Gamow window with a direct measurement with an overall 20% uncertainty at maximum, finds a perfect collocation that allows to constrain the reaction rate for a better development of stellar evolution.

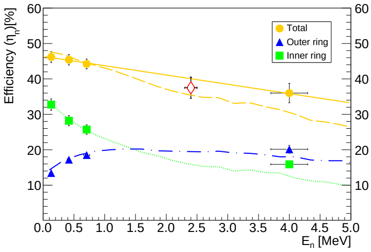
2 Experimental Setup

The LUNA experiment takes advantage from the 400 kV accelerator providing very stable proton and alpha beams in the energy range of 50 - 400 keV with a maximum on-target current up to 500 μA, with an energy resolution of 0.1 keV and a long term stability of 5 eV per hour [6].
Moreover, the deep-underground location guarantees a neutron environmental background reduction by three orders of magnitude lower than surface laboratories [7].
For the first time, the LUNA collaboration designed and installed a neutron detector array at the end of the solid target beamline.
The experimental setup used for this measurement is based on 18 ^3He 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. The whole setup is surrounded by a 2 inches borated polyethylene absorber to further reduce the environmental background [8]. Counters are arranged in two different configurations (in a vertical and a horizontal orientation) to optimize neutron detection efficiency, target handling and target cooling. Figure 1a shows the horizontal arrangement mainly used for the measurement of the lowest energy points.
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.
Moreover, a wave functions pulse shape analysis (PSD) from the raw preamplifier from detectors allowed the rejection of remaining alpha signals [9] obtaining a final background in the whole setup of about 1 count/hours, more that two orders of magnitude lower than previous experiments in surface laboratories.
The moderator was designed with the aim to open it and insert a High-Purity Germanium (HPGe) detector in close geometry for the target monitoring as explained later.
The efficiency maximization for both experimental setups was achieved by Monte Carlo simulation based on a Geant4 code. Two different experimental campaigns were performed for a validation: at low neutron energies, below 1 MeV, the activation measurement of the $^{51}V(p,n)^{51}Cr$ reaction was performed at the Van De Graaff accelerator installed at the Institute for Nuclear Research ATOMKI (Debrecen, Hungary); at high energy a certificated AmBe radioactive source was used, whose average energy is at about 4 MeV. The interpolation of experimental data constrained the efficiency in the region of interest (E_n=2.5 MeV) to (34±3)% and (38±3)% for the vertical and horizontal detector arrangements,respectively [8].

Figure 1b shows the absolute neutron detection efficiency of the horizontal setup.



(a) Drawing of the horizontal neutron detector array used for the LUNA measurement[8].



(b) Experimental (filled symbols) and simulated (dashed line) efficiency curves[8] of the horizontal setup. Efficiencies related to the inner (squares and dotted lines) and outer (triangles and dash-dotted lines) ring of the setups are also shown, respectively. The linear fit of the experimental data (solid lines) allows to interpolate the proposed efficiency value in the experimental region of interest (E_n=2.4 MeV) (empty diamond).

^{13}C targets used during the measurement at LUNA have been produced evaporating 99% ^{13}C isotopically enriched powder on tantalum backings.
To check target stochiometry, depth profile and uniformity immediately after the evaporation, an extensive target characterization was performed by means of Nuclear Resonant Reaction Analysis (NRRA) of the ^{13}C(p,γ)^{14}N reaction at 1.75 MeV at the Tandetron accelerator installed at ATOMKI [10].
The monitoring of the above mentioned quantities 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 dynamic range of the accelerator.
For this reason, a new method of analysis was developed [11]. Data taking at LUNA consisted of long α-beam runs with accumulated charges of $\approx$ 1 C per run, interspersed by short proton-beam runs with open moderator and HPGe detector in close geometry, with typical accumulated charges of 0.2 C at most. During the last mentioned proton runs, the target degradation can be checked fitting the direct capture de-excitation to the ground state peak shape of ^{13}C(p,γ)^{14}N reaction with the HPGe detector. Proton beam runs were all performed at the same reference energy, E_p = 310 keV.

3 Results and future prospectives

Thanks to the impressive background suppression and the novel approach of target degradation monitoring, the LUNA collaboration measured the ^{13}C(α,n)^{16}O reaction cross section in an energy range 230 keV<$E_{c.m.}$<305 keV, apporaching the high energy edge of the Gamow window with an unprecedented uncertainty lower than 20% in the entire dataset[12]. Results are shown in Figure 2.

The new LUNA data were used together with data by Heil, Drotleff and Harissopulos for an R-matrix extrapolation using the Azure2 code. The latter dataset shows a clear discrepancy with respect to the other two. For this reason, in our analysis the Harissopulos dataset was scaled up by a factor of 1.37. Nevertheless, there are no strong motivations for doing so and in order to investigate the effect of the two different normalizations, we performed R-matrix calculation using data by Harissopulos et al. as a reference for the

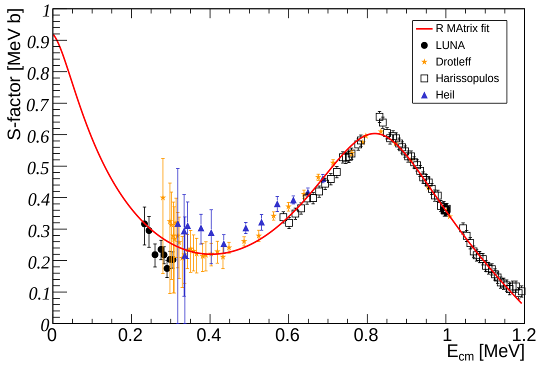


Figure 2: (Colour online) R-matrix extrapolation (red curve) of the astrophysical S(E) factor of ^{13}C(α,n)^{16}O calculated using the new LUNA dataset together with the Heil, Drotleff and Harissopulos data. The figure is adapted from [12].

normalization of Heil and Drotleff. In the Gamow window we found comparable results in both scenarios.

Finally, the astrophysical reaction rate R=N$_A$ $<\sigma v>$ as a function of stellar temperature was calculated by integration of the R-matrix cross section. Thanks to excellent quality of the data, the reaction rate At T= 0.1 GK is evaluated with an overall uncertainty of about 15%. In particular we took into consideration the reaction rate at -2σ uncertainty, where more ^{13}C survives and it is it burned at a higher temperature ($\sim$ 200 MK) into a convective shell powered by a subsequent thermal pulse. This generates a second neutron burst characterized by higher neutron density and lower exposure.

For stars of nearly solar composition (metallicity Z = 0.02, and Y = 0.27), this causes considerable variations of some isotopic abundances. In particular, the two radioactive nuclei ^{60}Fe and ^{205}Pb, as well as ^{152}Gd are influenced. This is due to the fact that the mentioned isotopes are close-by branching points that are sensitive to the neutron density. Even though the excellent results achieved, there are still open points due to different energy scales among datasets at higher energies (500 keV<E$_{c.m.}$<800 keV).
With the installation of the new LUNA MV facility, which will provide a maximum terminal voltage of 3.5 MV, the LUNA collaboration is planning to extend the measurement of the ^{13}C(α,n)^{16}O at higher energies covering the energy range up to 1 MeV. This will give the unique possibility to provide a complete dataset over a wide energy range with well known uncertainties and avoiding normalizations [13].

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