Direct measurement of the ^{13}C(α,n)^{16}O reaction in the Gamow window of the s-process nucleosynthesis

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Abstract. One of the main neutron sources for the astrophysical s process is the ^{13}C(α,n)^{16}O reaction, which takes place in thermally pulsing asymptotic giant branch (TP-AGB) stars at environmental temperature around 90 MK. To model the nucleosynthesis process connected with the reaction, it is important to know with high accuracy the cross section reaction in the energy window 240-150 keV, the so called Gamow window. At these sub-Coulomb energies, direct cross section measurements are severely affected by the low event rate and low signal-to-noise ratio. In this work, a new study of the astrophysical S(E)-factor for the ^{13}C(α,n)^{16}O reaction is presented.
In the framework of the LUNA scientific programme, a direct measurement of the absolute cross section of the ^{13}C(α,n)^{16}O reaction in an energy window from 300 keV down to 230 keV, significantly closer to the Gamow peak, has been performed. Lower uncertainties with respect to literature values are obtained allowing to reduce overall uncertainties on reaction rates calculation. Selected stellar models have been computed to estimate the impact of our revised reaction rate. For stars of nearly solar composition, we find sizeable variations of some isotopes, whose production is influenced by the activation of close-by branching points that are sensitive to the neutron density, in particular ^{60}Fe, ^{205}Pb and and ^{152}Gd.

1. State of the art

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 ^{13}C pocket in a stellar environment of about $1-2\cdot10^8$ K, corresponding to a Gamow window between 150[1] and 240 keV, well below the Coulomb potential energy of the reaction. The reaction mechanism at low energies included contributions from two broad resonances: the $(1/2)^+$ near-threshold state and the $(3/2)^+$ at E_x =7239 keV (about E_{cm}= 800 keV).
The energy level of the near-threshold state is debated: Ajzenberg-Selove [2] attributed to this state as sub-threshold energy of E_x=-(3 $\pm$ 8) keV, while recently a study by Faestermann et al. [3] deduced a positive energy value at E_x =(4.7 $\pm$ 3.0) keV. A number of measurements of the $^{13}C(\alpha,n)^{16}O$ cross section have been carried out over the last 25 years, performed with direct [4–7], and indirect methods [8–13], in the following we breifly report some of them.
In 1993, Drotleff et al. measured the cross-section of the $^{13}C(\alpha,n)^{16}O$ reaction in an energy range E= 370-1000 keV with ^{3}He proportional counters embedded in a moderating polyethylene matrix. The minimum energy explored by [5] is about E=265 keV with an overall uncertainty of

[1] Energies are in the centre of mass system, if not stated differently

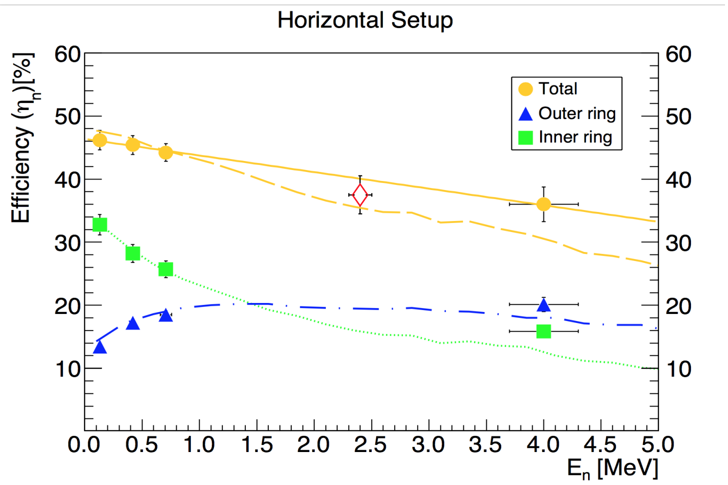
about 60%. The high quoted uncertainty was due to the low signal to noise ratio at low energy and by the difficulty encountered to keep under control the target degradation.
Harissopoulos et al. [6] measured the $^{13}C(\alpha,n)^{16}O$ reaction absolute cross-section in an energy range E =0.8-8 MeV in steps of 10 keV with a setup similar to Drotleff et al.. In Harissopoulos' work an overall uncertainty of 4% was achieved.
In 2008, Heil et al. [4] performed a new direct $^{13}C(\alpha,n)^{16}O$ cross-section in the energy range E=420-900 keV. Heil used a n-γ converter based on a Cd-doped paraffin sphere surrounded with 42 BaF_2 γ-detectors. In this work, the authors recognized the main source of systematic error as the change of target stoichiometry caused by the buildup during the beam irradiation. At higher energies, overall uncertainties could be reduced to the level of 5%. Heil performed a multichannel R-matrix analysis leading to a S(E) factor extrapolation uncertainty, in the Gamow peak, of about 20%. The main difference between the two analysis, Heil and Harissopoulos, concerns the discrepancy at E_r=800 keV resonance. A recent work by deBoer et al. [14] states that one of the main source of uncertainty for R-Matrix analysis is due to normalisation factors of the $^{13}C(\alpha,n)^{16}O$ data, directly connected to systematic uncertainties (not always clearly reported) on different dataset.
Additional indirect studies aimed to determine the spectroscopic factor and/or the asymptotic normalization coefficient (ANC) of the $1/2^+$ level of ^{17}O near threshold, which represents a large source of uncertainty at low energies. Kubono et al. [8] evaluated a spectroscopic factor S_α=0.01, but data were reanalyzed by Keeley et al. [9], that evaluated a 40 times larger value. The ANC method was used for the first time in the work by Johnson et al. by the ^{6} Li(^{13}C, d)^{17}O sub-Coulomb transfer reaction [10]. These results were recently revisited in the article by Avila et al. [11]. Other indirect measurements were obtained with the Trojan Horse Method (THM) [12, 13], the reaction rate was calculated again and compared with the Heil's one: the two rates are compatible almost everywhere, but the greater discrepancy is just located in the most interesting region for astrophysics, where Trippella calculated a lower reaction rate with a discrepancy at T=0.9 10^8 K of around 12% [13].
Therefore, it is crucial to achieve an experimental determination of the cross sections of $^{13}C(\alpha,n)^{16}O$ with an overall uncertainty of 20%, whereas recent combined analysis of existing data show that systematic uncertainties and model ambiguities presently limit our knowledge of the astrophysical rate of $^{13}C(\alpha,n)^{16}O$.

2. Experimental setup at LUNA 400

The LUNA 400kV high current accelerator [15] installed at deep underground laboratory, Laboratori Nazionali del Gran Sasso, can benefit of the rock shield against cosmic rays, reducing the neutron environmental background by three orders of magnitude lower than above ground [16].
For the first time, the LUNA collaboration designed and installed a neutron detector, consisting in 18 low intrinsic background ^3He counters arranged in two concentric rings (6 in the inner ring, 12 in the outer ring) with respect to the target chamber. 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 counters are embedded in a polyethylene moderator. The whole setup is surrounded by a 2 inches absorbed made of borated polyethylene to further reduce the environmental background [17]. Counters have been arranged in two different configurations (either a vertical or a horizontal orientation) to optimize neutron detection efficiency, target handling and target cooling. Moreover a wave functions pulse shape discrimination (PSD) from the raw preamplifier from detectors allowed the rejection of remaining alpha signals [18] obtaining a final background in the whole setup of about 1 count/hours, more that two orders of magnitude lower than the previous experiments in surface laboratories.

The moderator was designed with the aim to open it and the insert a High-Purity Germanium (HPGe) detector in close geometry for the target monitoring.
The efficiency maximization for both experimental configurations 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 Dee 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 arrangement, respectively [17]. Figure 1 shows the absolute neutron detection efficiency of the horizontal setup.

Figure 1. (Colour online) Experimental efficiency points (filled symbols) and the simulated efficiency curve (dashed line) for the horizontal setup. Total efficiency, inner ring and outer ring are indicated in yellow green, blue, respectively. The linear fit of the experimental data (solid lines) and the proposed efficiency value at E_n = 2.4 MeV (red empty diamonds) are also presented [17]



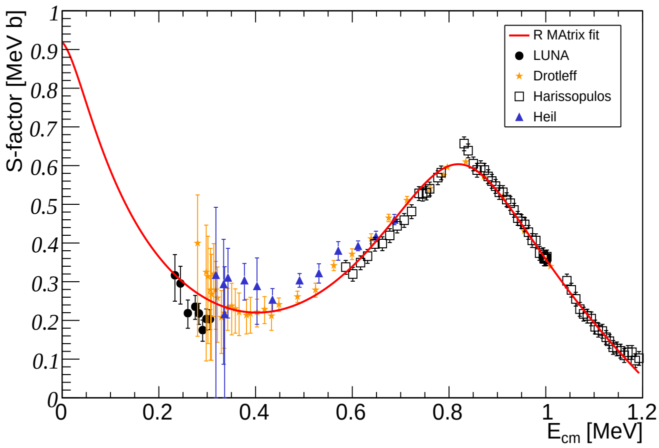
^{13}C targets used during the measurement at LUNA have been produced evaporating 99% ^{13}C isotopically enriched powder on tantalum backings.
To check target stochiometry, depth profile and uniformity immediately after the evaporation, an extensive target characterization was performed by means of 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 [19].
A precise knowledge of all above quantities is an essential ingredient for an absolute cross section measurement, unfortunately at LUNA the NRRA technique is not applicable, due to the lack of resonances in the energetic dynamic range of the accelerator.
For this reason, a new analysis method for easily monitor target degradation or build-up of contamination during the whole period of bombardment was developed [20]. Data taking at LUNA consisted in long α-beam runs with accumulated charges of $\approx$ 1 C per run, interspersed by short proton-beam runs at the same reference energy, E_p = 310 keV (typical accumulated charges of 0.2 C at most) with the HPGe detector in close geometry. During the proton-beam runs, the target degradation was checked fitting the peak shape of the γ-ray direct capture de-excitation to the ground state of the ^{13}C(p,γ)^{14}N reaction.

3. Extrapolation to the relevant astrophysical energy

Due to to the impressive background suppression and the novel approach of target degradation monitoring, the LUNA collaboration was able to measure the ^{13}C(α,n)^{16}O reaction cross section in an energy range from 305 keV down to 230 keV, approaching the high energy edge of the Gamow window with an uncertainty lower than 20% [21].

Results are shown in Figure 2. The new LUNA data were fitted together with data by Heil,

Figure 2. (Colour online) R-matrix analysis (red curve) of the astrophysical S(E) factor of ^{13}C(α,n)^{16}O calculated using the new LUNA data together with the Heil, Drotleff and Harissopulos ones. Figure adapted from [21].



Drotleff and Harissopoulos for a complete R-Matrix analysis developed by the Azure2 code. Since Harissopoulos' dataset shows a clear discrepancy with respect the other ones, they were scaled up by a factor 1.37. More details on the data reduction and the subsequent analysis are reported in [21].

In summary, 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. Due to the improved experimental information the present revised reaction rate of the ^{13}C(α,n)^{16} at T= 0.1 GK is known with an overall accuracy of about 15%. In particular, we took into consideration the reaction rate at -95% uncertainty, where more ^{13}C survives and it is 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 Y = 0.27 and Z = 0.02), this cause 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 therefore sensitive to the neutron density.

4. Outlook

It is worth noting, however, that even if a great achievement and unprecedented sensitivity have been obtained with the measurement at low energy, there is still a significant discrepancy at higher energies (500<E$_{cm}$<800) might be due to different energy scales among literature dataset. The LUNA collaboration is planning to extend the measurement of the ^{13}C(α,n)^{16}O at higher energies using the new MV facility installed at the LNGS laboratory. The accelerator will be able to operate at terminal voltage (TV) between 300 kV and 3.5 MV. This new facility will be able to accelerate ion beams of H^+, $^4He^+$, and carbon ions (^{12}C and ^{13}C) both singly and double charged, with the intensity reported in table 1 [22].

Table 1. Beam intensity on target [22]

Ion Species	Current ($e\mu$A) TV range: 3.5-0.5 MV (0.5- 0.3 MV)
$^1H^+$	1000 (500)
$^4He^+$	500 (300)
$^{12/13}C+$	150 (100)
$^{12/13}C++$	100 (60)

This will give the unique possibility to measure the direct cross section (and may be in inverse kinematics in a long term plan,too) over a wide energy range avoiding renormalization to other dataset hampered with unknown systematic uncertainties.

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