Direct cross-section measurement of $^{13}$C($\alpha$,n)$^{16}$O in the s-process Gamow peak

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Abstract.

The main neutron source for the slow neutron capture process in low mass Asymptotic Giant Branch stars is the $^{13}$C($\alpha$,n)$^{16}$O reaction. This reaction is responsible for the production of half of the natural heavy elements in the Universe. Up to now, no direct measurements have reached the energy region of interest for astrophysics, the so called Gamow window, which lies between 140 and 230 keV in the center of mass. In this paper we describe the experiment carried out at the LUNA experiment at the Laboratori Nazionali del Gran Sasso and present first preliminary results.

1. Introduction

The slow neutron capture process, the s-process, is responsible for the abundance about half of the heavy elements in the universe. The main source of the neutron flux for this process is the $^{13}$C($\alpha$,n)$^{16}$O reaction produced during thermal pulses of low mass Asymptotic Giant Branch (AGB) stars at temperatures about 90 MK [1, 2]. Such range of temperatures is translated to kinetic energies in the center of mass between 140 and 230 keV, far below the Coulomb barrier.

The huge suppression of the cross section because of the Coulomb barrier, and hence the very low reaction rate, makes from this experiment an enormous challenge. Various measurements have been performed in the past with remarkable results [3, 4, 5, 6]. However, the environmental background on the surface of the earth limited how far down in energy those experiments were able to measure.

The S-factors of the experiments performed up to date [3, 4, 5, 6] are displayed in figure 1. The shadowed region in the plot displays the Gamow window for the s process. As it can be observed, the lowest datapoint given by Heil et al. is 40 keV above this ROI with uncertainty larger than 50%.
Figure 1. State of art \(^{13}\text{C(}\alpha,\text{n})^{16}\text{O}\) S-Factor at low kinetic energies from the up-to-date measurements \([3, 4, 5, 6]\). The astrophysical ROI for this reaction is displayed by the shadowed region.

In addition to the experimental uncertainties of the direct cross section data the strength of a near threshold resonance, which can have a large impact on the reaction rate, can not be fixed by direct measurements, increasing the difficulty of constraining astrophysical scenarios.

2. Experimental setup
The measurement was performed at the LUNA-400 experiment at the LNGS. The low neutron background environment provided by the underground shielding, reduced by three orders of magnitude this component compared to the earth surface and therefore increases dramatically the sensitivity for low count rate experiments \([7, 8]\).

During the experiment, eighteen 1 inch diameter \(^3\text{He}\) counters were used. Twelve of them 40 cm long and other six of 25 cm long\(^1\). The detectors were embedded inside a borated polyethylene matrix and surrounded by a 2.54 cm thick 5 % borated polyethylene shielding to further reduce the environmental neutron background.

The detectors were arranged in two different experimental configurations as is displayed in 2 and read out through charge sensitive preamplifiers. Their raw waveforms were directly digitized for posterior pulse shape discrimination \([9]\). While the vertical experimental setup was used during the high energy part of the experimental campaign because of its sensitivity to angular distributions, the horizontal arrangement was preferred for the lowest energy measurements due to the higher detection efficiency. The use of two configurations provide a way to validate the background subtractions and the efficiency calibration.

Targets used for the measurement were produced at MTA ATOMKI (Hungary) by evaporating 99 % enriched \(^{13}\text{C}\) powder on tantalum backings. An extensive and intensive target characterization were performed, paying special attention to stoichiometry, density and profile through Nuclear Resonance Analysis (NRRA) of the \(^{13}\text{C}(p,\gamma)^{14}\text{N}\) reaction at 1.1 MeV.

\(^1\) Manufactured by GE Reuter Stokes, model numbers RS-P4-0816-217 and RS-P4-0810-249. Filling pressure was 10 bar.
3. Experimental procedure and analysis

The stoichiometry and profile of the $^{13}$C targets change with the accumulated $\alpha$ charge. This effect, labelled here as target degradation, is one of the main effects to account for during the experiment. As it was mentioned in the previous section, if in the energy region available there is a resonance, periodic NRRA can be performed to monitor the changes in the target.

Unfortunately, NRRA is not possible for the $^{13}$C in the energy range available by the accelerator. For this reason, a new methodology has been used to control the degradation that is based on a fitting procedure for the ground transition of the $^{13}$C($p,\gamma$)$^{14}$N reaction. A full paper of the methodology is in preparation. The targets were monitored through this methodology between short $\alpha$ irradiations.

Nevertheless, the accurate and good results of the methodology can be observed in the left
panel of figure 3 where is shown the yield for individual irradiations with different amount of charges. While without the correction (red) the individual yields have large differences because of the different degradation, the corrected yields converges removing the systematic because of this effect.

Another key point for the successful measurement of this complicated low-counting rate experiment is the background suppression. Following the procedure described in [9] and by the modification of the pulse shape discrimination regions, the total background registered by the entire array was 1.05 counts/hour with a relative efficiency of 88%. This, not only improve the signal to background ratio but in addition increase the sensitivity of the setup allowing to push even further down the energy to measure. The effect can be observed in the right panel of Fig 3, where if we compare the results using and not using the pulse shape routine the difference signal to background ratios are factor2 different.

4. Preliminary results
By the use of the two methodologies we were be able to measure down to 305 keV in the laboratory system as it displayed in figure 4, 40 keV lower than the previous state-of-art measurements. The two lowest data points are the Gamow window for this reaction, fullfilling the goal of this experiment.

Figure 4. Preliminary experimental $^{13}$C($\alpha$,n)$^{16}$O yield measured at LUNA-400 as a function of the laboratory energy.

It is worth to mention that the reaction yield change two order of magnitude from 400 keV down to lowest data point and the statistical uncertainties for the individual energies measured are always lower than 15%.

5. Conclusion and outlook
The $^{13}$C($\alpha$,n)$^{16}$O is main source of neutrons for the s-process. Its cross-section were measured at LUNA-400 down to unprecedented energies, directly into the astrophysical region of interest, 40 keV lower than the previous state-of-art direct measurements.
A new methodology has been developed to control the degradation of the targets based on the \( ^{13}\text{C}(p,\gamma)^{14}\text{N} \) ground transition. A full paper of the methodology is in preparation.

The still in progress analysis of the cross-section and S-factor of the final experimental results will be reported in a full paper, evaluating the astrophysical impact of this measurement.

Acknowledgments

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