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Target characterizations for direct measurement of the $^{13}C(\alpha, n)^{16}O$ reaction at LUNA 400

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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 due to the low cross section. Moreover a dominant component of systematic uncertainty comes from target behaviour under beam irradiation.
This work presents a detailed characterization of enriched ^{13}C targets in order to test reproducibility and uniformity of the evaporation method, stability and purity of targets under a high intensity proton beam (100-200 uA) for the study of this reaction at the Laboratory for Underground Nuclear Astrophysics (LUNA) facility installed at Laboratori Nazionali del Gran Sasso (LNGS, INFN). A procedure to evaluate the target thickness and to monitor its degradation is discussed and preliminary results are presented.

1 Status of the art and next LUNA measurement

The $^{13}C(\alpha, n)^{16}O$ reaction is the major neutron source for the main component of the *s*-process in low mass ($1 - 3M_{\odot}$) Asymptotic Giant Branch (AGB) stars, whose temperature of interest is around $1 - 2 \cdot 10^8$ K. This corresponds to a Gamow window between 120 and 250 keV. As shown in Figure 1, altough several direct measurements have been performed [1–4], no dataset covering this energy range is available yet. This causes differences of one order of magnitude in the extrapolations towards low energies. In addition, the low energy cross section is affected by the presence of the 6.356 MeV near threshold resonance in ^{17}O.

The LUNA collaboration plans the measurement of the cross section of this reaction going down in energy approaching the Gamow window with an overall accuracy of 10%. This will be performed at LNGS, combining a neutron background reduction of 3 orders of magnitude compared with the surface [5] with an intense alpha beam delivered by the LUNA 400 accelerator [6].

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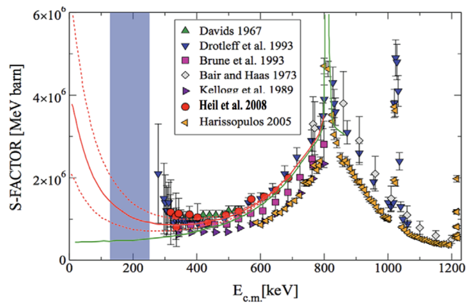

Figure 1. State of the art of the direct measurement for the $^{13}C(\alpha, n)^{16}O$ reaction adapted from Heil et al. [1]. The violet band represents the Gamow window, the red solid line is the extrapolation of the astrophysical *S*-factor down to this region and its error bands are indicated by red dashed lines. The green line is an extrapolation in which the near threshold resonance is omitted.

2 Characterization of ^{13}C enriched targets

Targets under investigation have been produced in MTA Atomki (Debrecen, HU) evaporating 99% enriched ^{13}C powder on tantalum backing using the electron gun technique. A total number of 10 targets were produced.
An accurate determination of the target thickness can usually be obtained by means of the Nuclear Resonant Reaction Analysis (NRRA), scanning a well known narrow resonance [7].
Due to the fact that in the LUNA 400 energy range (50-400 keV) neither $^{13}C(\alpha, n)^{16}O$ nor the $^{13}C(p, \gamma)^{14}N$ reactions can excite any resonance state, an alternative approach needs to be tested. The idea is to use the gamma signature in a HPGe detector using the off resonance cross section of $^{13}C(p, \gamma)^{14}N$ reaction (Q = 7550.56 keV) of the broad resonance at E_p = 550 keV (Γ = 23 keV), so its low energy tail could reach energies in the LUNA 400 accelerator range. This technique has already been successfully used at LUNA[8]. The feasibility study was divided in two phases, described in the next sections.

2.1 Measurements at Atomki

After the evaporation, all the enriched targets have been exposed to a proton beam at the 2MV Tandetron built at MTA Atomki, in order to scan the narrow resonance at E_p = 1748 keV (Γ = 122 eV) through the well known NRRA method and estimate their thickness to use as reference value at LUNA.
The current during this measurement was limited to 500 nA to prevent damage to the targets. γ-rays were detected using a HPGe detector at 0° with respect to the beam direction.
A dedicated set up permitted to rotate an off axis target holder and thus irradiate targets in different points, evaluating the uniformity of the evaporation process (Figure 2(a)). Figure 2(b) shows that there are variations in the width of the profile at a level of $< 5\%$: the difference of height in the plateau is due to a different relative position between target and detector that changes slightly the efficiency; the displacement of the leading edge (∼100 eV) was not fully understood. This means that in the error budget a 2% of systematic uncertainty will be added. Further investigation on this will be done in the future.

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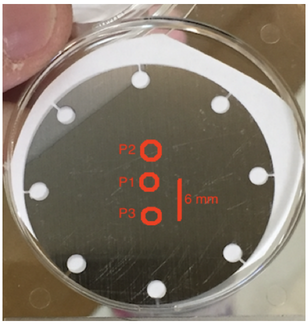
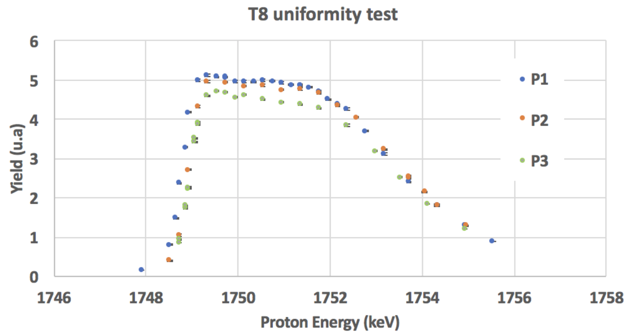


(a)



(b)

Figure 2. (a) An evaporated target; the red circles indicate the points where the target was irradiated to evaluate the uniformity of evaporation. (b) Resonance scans at positions P1, P2 and P3. For each point enough counts were accumulated to reach the 1% of statistical uncertainty in the plateau and 3% far from the resonance energy. A 3% of systematic uncertainty should be added from the charge measurement.

2.2 Measurements at LUNA 400

After the test in Atomki, targets were transported to LNGS and two of them were irradiated at the LUNA-400 facility. Here the stability of the targets under proton beam with higher current (120 uA) was tested. After an exposition of 33 C, the yield in the peak of direct capture at E_p = 310 keV is reduced by ~ 17% (Figure 3(a)). Spectra have been acquired with a HPGe at 55° with a relative efficiency of 120%.
The tail of the broad resonance at 550 keV increases the cross section of the $^{13}C(p,\gamma)^{14}N$ reaction. The shape of the primary peak comes from the behaviour of the cross section that changes with the decreasing of the beam energy in the targets. Moreover the shape is also influenced by the energy loss of the projectiles in carbon, since the stopping power is energy dependent.
The thickness of the target was evaluated by the fit of the primary full energy peak from a transition directly to the ground state (Figure 3(b)).

3 Results and conclusions

The thickness of the evaporated targets measured in two independent ways at Atomki and LUNA cannot be compared directly; it is necessary to normalise the two with the stopping power, different for the two beam energies, taken from the software package SRIM [9] and a term that takes into account the different angle between the beam line and the target (90° at Atomki, 55° at LUNA). Thickness comparison is shown in Table 1. The surface densities evaluated using the above normalisations agree within the uncertainties even if the discrepancy between the two values is at level of 10%. The systematic uncertainties (in percentage) of the method is expected to be reduced at 5% thanks to an improvement in the peak fitting procedure of the Gamma Shape Method.
As a conclusion the targets characterization confirmed the reproducibility and homogeneity of the ^{13}C enriched evaporated targets prepared with electron gun evaporation method. Moreover, under a proton beam, targets show a high stability with a deterioration of 17% after an accumulated charge of 33 C. Further investigation is needed to understand targets' behaviour after the alpha beam irradiation,

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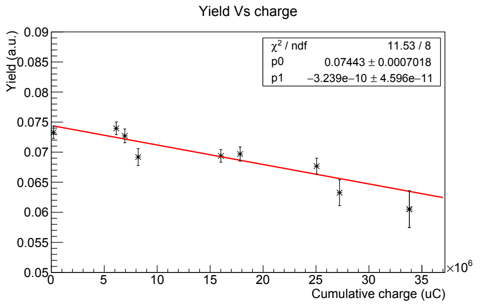
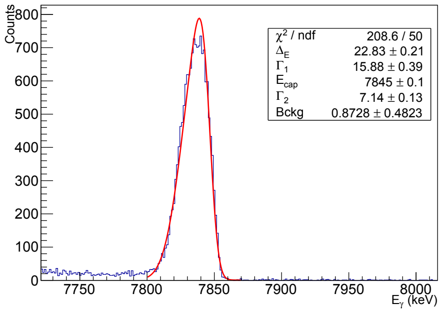


(a)



(b)

Figure 3. (a)Yield as a function of the cumulative charge on the target at the reference energy $E_p = 310$ keV. The solid line is a linear best fit to the data. (b) The direct capture peak of the transition of the $^{13}C(p,\gamma)^{14}N$ at $E_p = 310$ keV to the ground state. The red curve represents the peak fit and the values of the parameters are inside the textbox.

Table 1. Thickness comparison with the two methods

	Atomki	LUNA
Thickness from fit (keV)	4.61±0.02	22.83±0.2
Stopping power (keV/10^{18}atoms/cm^2)	3.1±0.2	9.7 ± 0.6
Surface density (10^{18}atoms/cm^2)	1.49±0.09	1.35± 0.08

because higher mass of projectiles could cause a faster degradation.
The gamma-shape analysis showed good agreement with the target thickness determination using the resonance scan method and confirm its applicability for direct measurement of $^{13}C(\alpha,n)^{16}O$ reaction.

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