Towards a direct measurement of the $^{17}O(p, \gamma)^{18}F$ 65 keV resonance strength at LUNA

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Abstract. The $^{17}O(p, \gamma)^{18}F$ reaction plays a crucial role in the hydrogen burning phases of different stellar scenarios. At temperature of interest for AGB nucleosynthesis (20 MK < T < 80 MK) the main contribution to the astrophysical reaction rate comes from the poorly constrained 65 keV resonance. The strength of this resonance is presently determined only through indirect measurements, with a reported value of $\omega\gamma = (1.6 \pm 0.3) \times 10^{-11}$ eV. With typical experimental quantities for beam current, isotopic enrichment and detection efficiency, this strength yields to an expected count rate of less than one count per Coulomb, making the direct measurement of this resonance extremely challenging.
A new high sensitivity setup has been installed at LUNA (Laboratory for Underground Nuclear Astrophysics) of Laboratori Nazionali del Gran Sasso. The high performance LUNA 400kV accelerator underground location guarantees, indeed, a reduction of cosmic ray background by several orders of magnitude. The residual background was further reduced by a devoted shielding of lead and borated (5%) polyethylene. On the other hand, the 4π BGO detector efficiency was optimized installing aluminum target chamber and holder. With about 400 C accumulated on Ta_2O_5 targets, with nominal ^{17}O enrichment of 90%, the LUNA collaboration has performed the first direct measurement of the 65 keV resonance strength.

1 Introduction

The isotopic ratios observed in presolar grains are the fingerprint of their progenitor composition. Attributing their origin to specific type of stars, however, often proves challenging. Asymptotic Giant Branch (AGB) stars are expected to have contributed a large fraction of meteoritic stardust. Yet, models struggle to match observations. This is a long-standing puzzle, which points to serious gaps in our understanding of the lifecycle of stars and dust in our Galaxy. The oxygen isotopic ratios are strongly affected by the $^{17}O + p$ reactions, taking part to the CNO cycle active in the giant star H-burning shell [1]. A recent direct measurement of the 65 keV resonance in the $^{17}O(p, \alpha)^{14}N$ reaction ($Q = 1192$ keV) at LUNA had a paramount impact in determining the origin of some of the presolar grains [1]. On the other hand the 65 keV resonance in the (p,γ) channel is still poorly constrained. The $^{17}O(p, \gamma)^{18}F$ reaction (Q

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= 5607 keV) affects, indeed, both the ^{17}O depletion and ^{18}O production (^{18}F decays to ^{18}O with a $T_{\frac{1}{2}}$ = 109.77 m). An accurate measurement of the resonance strength can improve the reaction rate determination and will help to constrain the present AGB models.

The strength of the E_R = 65 keV resonance is presently determined only through indirect measurements. The Γ_γ and Γ_α are provided by the measurement of the ^{14}N(α,γ)^{18}F and ^{14}N(α,α)^{14}N reaction cross section respectively [2, 3]. The Γ_p is derived from the $\omega\gamma$ of the ^{17}O$(p, \alpha)^{14}$N channel and it contributes the most to the final uncertainty because of the discrepant results reported in literature [4, 5]. The presently adopted resonance strength is $\omega\gamma_{(p,\gamma)}$ = (16 ± 3) peV [6]. Such a low resonance strength translates into an expected rate as low as one reaction per Coulomb, thus a direct measurement requires both a high sensitivity setup and a devoted technique to monitor and subtract potential beam-induced background (BIB). In following sections the setup, the analysis and the preliminary results are presented.

2 Experimental setup

The measurement was performed at LUNA laboratory, located in the deep underground facility of Laboratori Nazionali del Gran Sasso (LNGS) [7]. Thanks to the 1400 m overburden of rock, the muon cosmic ray background is reduced by six orders of magnitude with respect to the overground laboratories [8]. The residual background at $E_\gamma \leq$ 3 MeV is due to natural radioactivity from the laboratory and the rock while at higher energy it is mainly neutron-induced background [9]. In order to increase our sensitivity, the residual background was further reduced by a three layer shielding which was installed all around the detector and the target chamber. The shielding was made of 1 cm thick layer of borated(5%) polyethylene, 15 cm thick lead shielding and 5 cm thick borated (5%) polyethylene envelope, see Fig.1. The detected background was reduced by a factor 4.3(1) in the region 5.2 $< E_\gamma <$ 6.2 MeV with respect to using an only lead shielding [10]. The LUNA 400kV accelerator [11] provided high stability and high intensity proton beam, E_p = 80 keV and $\mathrm{I_p}$ = 200 μA, which was delivered through a Cu pipe to the target. The copper tube was used as cold finger, to prevent carbon build-up, and as secondary electron suppressor with applied - 300 V. The Ta_2O_5 solid targets were produced by anodization of tantalum backings in 90% ^{17}O enriched water doped in ^{18}O at the level of 5% [12]. The target was water cooled to prevent target degradation, which was monitored via periodical scan of the E_R = 143 keV resonance in the ^{18}O$(p, \gamma)^{19}$F reaction [13].
In order to minimize the γ-ray absorption, both the scattering chamber and the target holder were made in aluminum, providing an increase in efficiency of more than 20% with respect to the previous stainless-steel and brass setup. The high efficiency (74% at 661 keV) Bismuth-Germanium-Oxide (BGO) detector surrounded the reaction chamber, covering a 4π solid angle. The detector is made of six optically independent crystals, coupled with a listmode DAQ which allows both a single crystal reading and the offline construction of the add-back spectrum, namely by adding coincident events in the individual crystals [14]. A 3D model of the detection setup is shown in Fig.1.

3 Analysis and preliminary results

An accurate Montecarlo simulation of the setup was crucial for the analysis of the acquired data. The simulation was developed using the Geant4 toolkit [15] and it was validated using the devoted spectra acquired with ^{60}Co and ^{137}Cs sources mounted in the same configuration as the Ta_2O_5 target. In addition a spectrum on top of the ^{14}N$(p, \gamma)^{15}$O E_R = 270 keV resonance was used to fine tune the simulation, see Fig.2 for a comparison between simulated and

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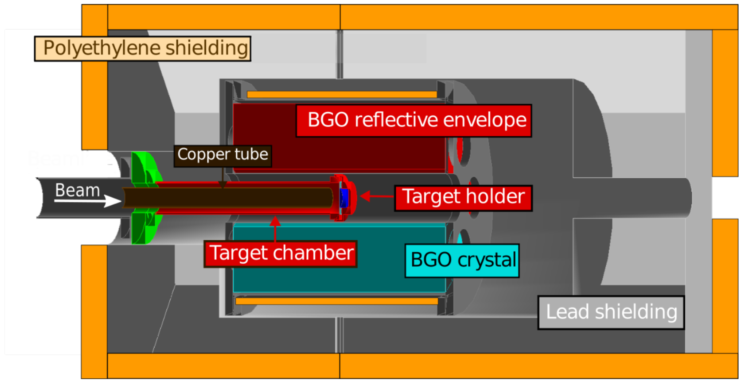

Figure 1. Section of the 3D model of the present experimental setup, which was used in the Geant4 simulation.

experimental spectrum. After proper normalisation, the average residuals between simulated and measured spectra was ≤ 3% in all three cases. This value also represents the uncertainty of detection efficiency from the simulations.

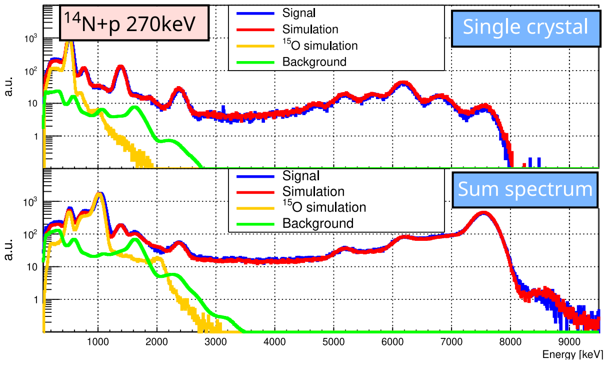

Figure 2. Comparison of simulated (red) and measured (blue) spectra of ^{14}N$(p,\gamma)^{15}$O 270 keV resonance. In green and yellow are represented environmental background and ^{15}O decay spectra respectively, included in the simulation.

During five experimental campaigns, about 400 C were accumulated on $Ta_2^{17}O_5$ targets. In order to monitor the BIB, 300 C were collected on target made as $Ta_2^{17}O_5$ targets but using Ultra Pure Water (UPW), with natural (0.04%) ^{17}O abundance. Tantalum is, indeed, a natural absorber of H and D [16] and the p+D (Q = 5493 keV) reaction produces a single γ-ray very close in energy to the ^{17}O$(p,\gamma)^{18}$F 65 keV resonance γ-ray, see Fig.3. Due to the poor BGO resolution the p+D and ^{17}O+p sum peaks overlap. Moreover the p+D cross section is much higher than the case of interest as reported by recent high precision measurement at LUNA [17, 18]. In order to subtract the p+D BIB, two approaches were applied. The first approach is based on the comparison between on resonance add-back spectra acquired with ^{17}O target and UPW targets. For the analysis a ROI $E_\gamma \in [5.35; 5.95]$ MeV was adopted and the corresponding yield was obtained for both types of spectra, namely acquired with ^{17}O

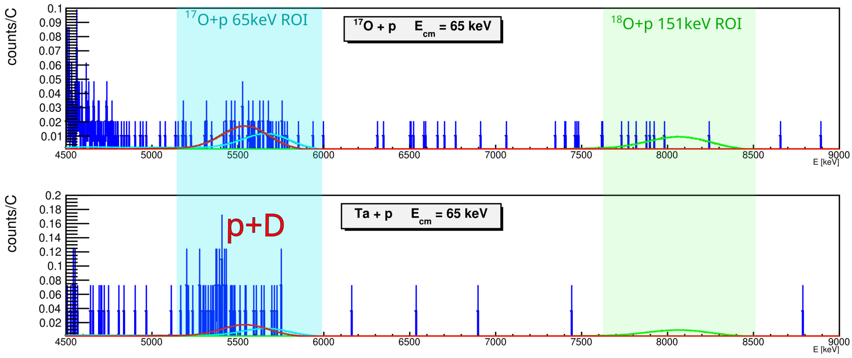

Figure 3. Spectra acquired shooting a E_{lab} = 80 keV proton beam on ^{18}O (top), ^{17}O (top) targets and naked Ta backings (bottom). The $p + d$ peak in the bottom spectra indicates a contamination in the Ta backings estimated at 3 p.p.m. level. The coloured peaks are shown to guide the eye.

targets and UPW targets. A clear excess of counts was observed in the former, Fig.4 and the net counts, calculated subtracting from the ^{17}O counts the background counts observed in the UPW spectra, were far above the critical limit. The resonance strength was derived in a monte carlo based approach [19–21]. The background and the signal, observed in the same ROI but in UPW and $^{17}\mathrm{O} + \mathrm{p}$ spectra respectively, were assumed to follow a Poisson distribution, and 10^6 samples were taken for each. The net counts were calculated at each iteration and the resultant probability density function actually shows a maximum at which the resonance strength was determined.

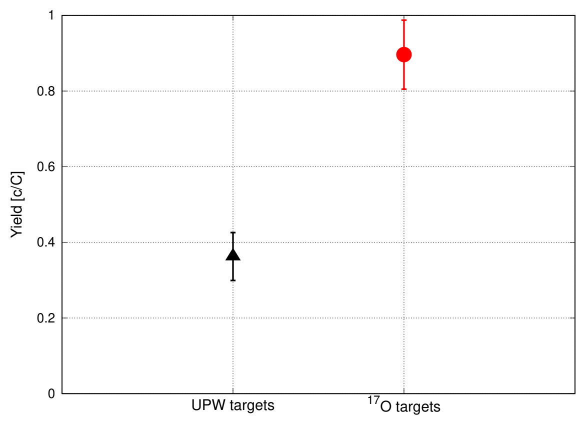

Figure 4. Yields of on resonance spectra acquired with UPW target, black, (negligible ^{17}O) and ^{17}O enriched target, red.

In addition a second technique was developed which combines our knowledge of the E = 5672 keV de-excitation branching ratios, signature of the reaction of interest only, and of the BGO detector segmentation. The technique consists of selecting multiplicity 2 and 3 transition γ-rays, contributing to the sum peak, ROI = 5350-5950 keV in the addback spectrum, and with energies matching the 5672 keV de-excitation chain. Multiplicity 1 events were rejected as due to BIB. This approach allows an almost complete background subtraction while losing only a small amount of γ-rays from the resonance, which correspond to the 5672 keV de-excitation towards the ground state (multiplicity 1 and I_γ = 6%). Residual spurious coincidences due to BIB were subtracted applying the same analysis on UPW target spectra. Both analysis found consistent preliminary $\omega\gamma$, which point to higher value than the indirect estimates.

At the time of writing this proceeding, the last acquired data is being analysed and an in-depth evaluation of the uncertainties is being performed. A technical paper on the detector, setup and analysis technique is ongoing, while the final results will be published in a devoted paper.

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