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Direct measurement of the ^{17}O(p,α)^{14}N reaction at energies of astrophysical interest at LUNA

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The ^{17}O(p,α)^{14}N reaction plays a central role in several stellar sites, including giant branch stars and classical novae. A precise measurement of the reaction's cross-section at astrophysical energies could improve our understanding of these scenarios. A direct measurement was performed at the underground LUNA 400kV accelerator in Gran Sasso Laboratory, Italy. A purpose-built experimental setup was simulated and commissioned. Data taking has been completed, but analysis is still in progress.

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1. Introduction

Uncertainties in the reaction rate of the ^{17}O(p,α)^{14}N reaction influence the expected abundance of ^{17}O, which plays a key role in several stellar sites. In particular, in Asymptotic / Red Giant Branch (AGB/RGB) stars, experimentally observed isotopic abundances show a significant depletion in ^{17}O compared to model predictions. For some [1, 2], but not all [3] of these stars the difference could be explained by the onset of processes such as the Cool Bottom Process (CBP) or the Hot Bottom Burning (HBB). A better understanding of the expected ^{17}O destruction rate would help shed light on the physical nature of the processes occurring in giant branch stars, still not fully understood. Since our Sun will eventually enter the giant branch phase, an improved knowledge of ^{17}O(p,α)^{14}N could help understand its destiny as well.
The abundance of ^{17}O also plays a key role in classical novae [4]. During the temperature peak of the explosion stellar matter goes through the hot CNO cycle and - among other elements - ^{17}O is produced. Since classical novae are thought to be the primary source of ^{17}O in our galaxy, precise knowledge of its abundance in these sites is especially important.

The ^{17}O(p,α)^{14}N reaction was studied in detail at the underground 400kV LUNA accelerator in Gran Sasso Laboratory, Italy. At temperatures of astrophysical interest (0.03-0.4 GK), the reaction's S-factor is dominated by two narrow resonances at roughly E_p = 70 and 193 keV in the laboratory frame. The latter is reasonably well-known [5, 7], but direct information on the 70 keV resonance is incomplete because of its extreme weakness [8]. Indirect methods have also been used [9] because of the challenges of performing a direct measurement. A direct measurement of the resonance strength of the 70 keV resonance in ^{17}O(p,α)^{14}N was the final objective of a recently-completed experimental campaign at LUNA. The reduction in natural background afforded by the underground enviroment was expected to be critical for the success of this campaign.

2. Experimental setup

The main aim of the campaign was the direct measurement, in thick-target yield conditions, of the resonance strength ($\sim$ neV) of a narrow and isolated resonance at E_p = 70 keV in ^{17}O(p,α)^{14}N (Q=1.2 MeV). We used solid Ta_2O_5 targets, 95% enriched in ^{17}O and roughly 5 keV thick for 200 keV protons, produced as described in [11]. Since the width of the 70 keV resonance is roughly 130 eV [10], thick target yield conditions are fulfilled. Protons were accelerated by the LUNA 400kV machine at typical beam currents of 100 μA and alpha particles produced by the reaction at $E_\alpha \sim$ 1 MeV were detected with an array of eight silicon detectors mounted in an hemi-spherical configuration as shown in Figure 1. The silicon detectors were Canberra PIPS, with a surface area of 9 cm^2, 300 to 700 μm thick and a very thin dead layer under 50 nm thick. These detectors were arranged in an upper and a lower row at 135° and 102.5° at backward angles with respect to the beam axis. A list-mode capable acquisition software, MIDAS [12], was used to acquire the events.

To shield the detectors from the intense flux of elastically scattered protons, we mounted aluminised mylar foils, nominally 2.4 μm thick, in front of each detector. These scattered protons would have increased the dead time and damaged the detectors in a matter of hours. Foils had to

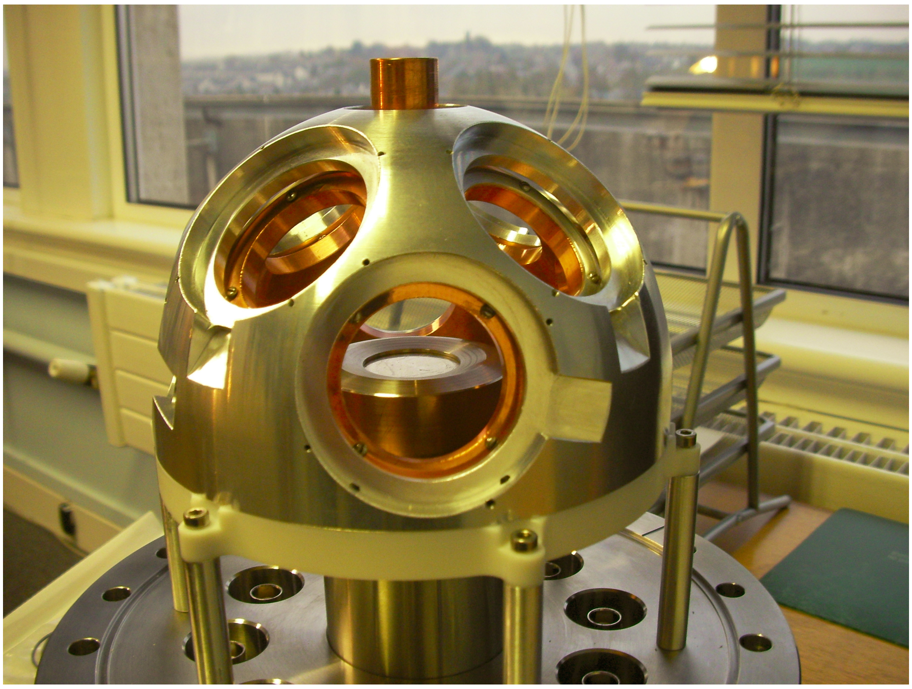

Figure 1: A picture of the scattering chamber before mounting the detectors. The proton beam enters from the copper tube on the top.

be thin enough to let the alpha particles through yet thick enough to stop the protons. An in-depth study was necessary to ensure a good compromise between the two requirements. To ensure that the effective thickness was in agreement with the nominal one and that inhomogeneities in the foil were under control we measured the thickness of foil samples. This measurement was performed by estimating the energy loss through the foils of collimated alpha particles emitted from a calibrated ^{241}Am source. Measured thicknesses agreed with the nominal value of 2.4 μm and the inhomogeneity was estimated to be around $\pm$ 0.1 μm. Simulations performed with SRIM [13] show that alpha particles, produced at 1 MeV by the reaction, would be detected at around 200 keV after the foils.

3. Commissioning

The setup was indipendently simulated using two GEANT4-based simulations, with the primary aim of obtaining the efficiency. Both simulations highlighted the presence of a geometric shadow effect that reduced the efficiency of the four detectors mounted at 102.5° by 20% roughly. The overall efficiency of the setup was estimated at around 15%.
We started commissiong the setup measuring a well-known resonance [14] at E_p = 151 keV in ^{18}O(p,α)^{15}N (Q=4 MeV), using targets enriched in ^{18}O rather than ^{17}O. The counting rate for this reaction was quite high (several hundred Hz per detector) and the energy of the α particle was easily detectable, even after the foils. This constituted an important first test of the stability of the setup and the reliability of the simulations for the efficiency. The presence of the shadow effect

was also confirmed.
The second test was performed on the E_p=193 keV resonance in ^{17}O(p,α)^{14}N (Q=1.2 MeV). It had an expected rate of a few counts/s/detector. Since the Q-value dominates the energy of the emitted alpha particles, the main aim of measuring the 193 keV resonance was to obtain an indication of the region of interest for the 70 keV resonance alpha peak.
Beam-induced background complicated the measurement at E_p = 193 keV and covered completely the signal at first. This beam-induced background was generated by the pile-up of backscattered charged particles leaking through the foils. Candidates are protons and high energy secondary electrons produced by the proton's passage through the foils. To reduce this beam-induced background, we placed 1 mm thick stainless steel collimators in front of each detector. With an 0.8 cm^2 aperture in their centre, compared to a detector area of 9 cm^2, the collimators signficantly reduced the chances of pile-up and thus effecively suppressed the beam-induced background.
Figure 2 (top) shows a typical spectrum acquired with the collimators mounted. Preliminary strength values obtained for this 193 keV resonance in ^{17}O(p,α)^{14}N are in agreement with literature values as shown in Figure 2 (bottom), paving the way for the start of the 70 keV resonance measurement.

4. Preliminary results

Data acquisition for the 70 keV resonance in ^{17}O(p,α)^{14}N took several months of beamtime and hundreds of coulombs of charge on target. We expected a very challenging experimental campaign since the overall rate had been estimated at a few alpha particles per hour and the detected energy (after the foils) at just 200 keV. Because of the difficulty in detecting a clear alpha peak, the constrains on the region of interest obtained from the measurement of the 193 keV resonance in the same reaction proved critical.
We acquired data on-resonance at 71.5 keV, off-resonance at 65 keV in order to study the beam-induced backgorund and without beam to study the natural background. Data taking is complete, but data analysis is still ongoing. Based on a preliminary analysis it would appear that most of the background in the region of interest identified for the alpha peak has a natural origin, coming from gamma rays Compton-scattering off the silicon detectors without releasing the full energy. That means we are in the conditions to take advantage of the underground environment of the LUNA facility. Most of the beam-induced background in the region of interest should come from the ^{10}B(p,α)^{7}Be reaction, boron being an inevitable contaminant in both the tantalum backings and the enriched oxygen solution. Study of this contamination and its effect is currently underway, but - while not negligible - the beam-induced background should be significantly smaller than the 70 keV signal.
The signal from the 70 keV resonance in ^{17}O(p,α)^{14}N has been observed with an high statistical significance, but the status of the analysis is too preliminary to give a final result.

5. Summary and outlook

The 70 keV resonance in ^{17}O(p,α)^{14}N is important in a variety of stellar sites and in giant branch stars in particular. Its resonance strength is extremely weak ($\sim$ neV) and thus challenging

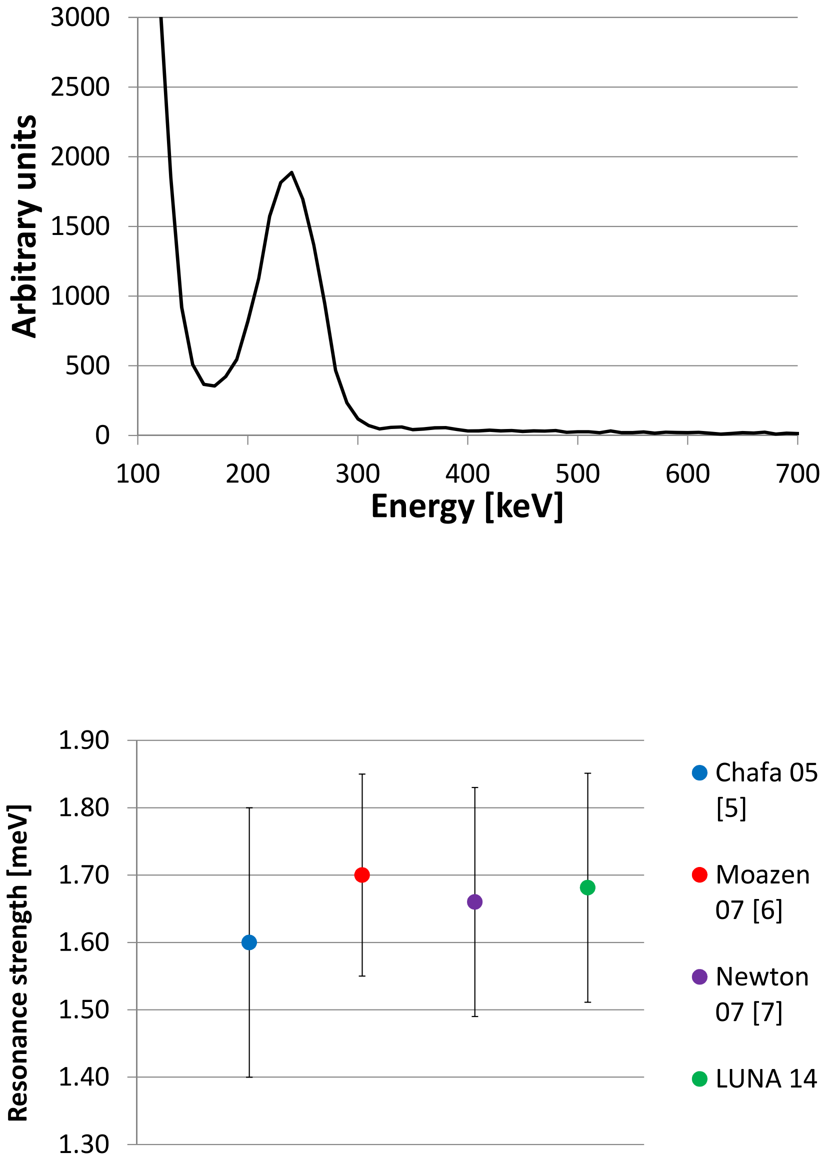

Figure 2: (Top) A typical spectrum of the $^{17}O(p,\alpha)^{14}N$ reaction acquired at E_p = 193 keV. The alpha peak is at around 250 keV as expected. (Bottom) Comparison of resonance strength value obtained with literature [5, 6, 7]. Statistical and systematical errors have been plotted.

to measure at a surface laboratory, but a precise value would help constraining astrophysical models. An experimental campaign aimed at measuring the strenght of this resonance in direct kinematics has recently been completed at LUNA, in the underground Gran Sasso Laboratory, Italy. A purpose-built setup consisting of a solid Ta_2O_5 target, eight silicon detectors and aluminised Mylar foils to shield them has been mounted and commissioned using the 151 keV resonance in $^{18}O(p,\alpha)^{15}N$ and the 193 keV resonance in $^{17}O(p,\alpha)^{14}N$. Data taking for the 70 keV resonance has been completed, but the data analysis is still ongoing. First results appear encouraging and a precise, new value for the strength of the 70 keV resonance in $^{17}O(p,\alpha)^{14}N$ should be obtained shortly.

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