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

Riccardo Maria Gesuè$^1$* for the LUNA collaboration

$^1$Università degli Studi di Napoli and INFN Division of Napoli, Via Cintia, 80126 Napoli (Italy)

Abstract. The $^{17}\text{O}(p,\gamma)^{18}\text{F}$ reaction plays a crucial role in AGB nucleosynthesis as well as in explosive hydrogen burning occurring in type Ia novae. At the temperatures of interest for the former scenario (20 MK $< T < 80$ MK) the main contribution to the astrophysical reaction rate comes from the poorly constrained $E_R = 65$ keV resonance. The strength of this resonance is presently determined only through indirect measurements, with an adopted value $\omega\gamma = (16 \pm 3)$ peV.

A new high sensitivity setup was installed at LUNA, located at LNGS. The underground location of the LUNA 400kV accelerator guarantees a reduction of the cosmic ray background by several orders of magnitude. The residual background was further reduced installing a devoted shielding. On the other hand, to increase the efficiency, the 4π BGO detector was coupled with Al target chamber and holder. With more than 400 C accumulated on Ta$_2$O$_5$ targets, nominal $^{17}\text{O}$ enrichment of 90%, the LUNA collaboration has performed the first direct measurement of the 65 keV resonance strength.

1 Introduction

The $^{17}\text{O}(p,\gamma)^{18}\text{F}$ reaction takes part in the CNO cycle, active in the giant stars H-burning shell or in explosive burning scenarios (i.e. type Ia novae). The precise knowledge of the $^{17}\text{O}(p,\gamma)^{18}\text{F}$ nuclear reaction rate at typical temperatures of H-shell burning in AGB stars (20 MK $\leq T \leq 80$ MK) is needed to address several astrophysical problems regarding the Oxygen isotopic ratio [1]. The post first dredge-up (FDU) Oxygen ratios predicted by theoretical models [2], often differ form observed surface abundances of low-mass giant stars ($M < 2M_\odot$) at the tip of the RGB on the Hertzsprung-Russell diagram. Moreover, in a group of pre-solar grains, are observed a moderate $^{18}\text{O}$ depletion and a high $^{17}\text{O}$ enrichment that cannot be retrieved by models. In this context the $^{17}\text{O}(p,\gamma)^{18}\text{F}$ reaction rate plays a key role, directly affecting the $^{17}\text{O}$ depletion and $^{18}\text{O}$ production ($^{18}\text{F}$ decays with a $T_{1/2} = 109.77'$ in $^{18}\text{O}$).

The past $^{17}\text{O}(p,\gamma)^{18}\text{F}$ reaction study performed at Laboratory for Underground Nuclear Astrophysics (LUNA) was mainly focused at Gamow energies for classical novae (160 keV $\leq E_{cm} \leq 370$ keV), using both the prompt $\gamma$-ray detection and the activation method, leading to a precise determination of the $E_R = 183$ keV resonance strength [3] (resonance energies are expressed in the center of mass). However, the main contribution to the astrophysical reaction rate at temperatures of interest for the AGB star H-burning shell comes from the $E_R = 65$ keV

*e-mail: riccardo.gesue@na.infn.it
resonance. An accurate measurement of the resonance strength can improve the reaction rate determination and will help to constrain the RGB and AGB models. The strength of the $E_R = 65\text{ keV}$ resonance is presently determined only through indirect measurements [4–6] providing the $\Gamma_\gamma$ and $\Gamma_\alpha$, while the $\Gamma_p$ is derived from the $\omega\gamma(\alpha,\gamma)$ [7]. The adopted value is $\omega\gamma = (16 \pm 3)\text{ peV}$.

Since the expected rate is as low as one reaction per Coulomb [8], a direct measurement of the $E_R = 65\text{ keV}$ resonance strength required both a high sensitivity setup and a devoted technique for beam-induced background (BIB) suppression. In following sections the setup, the analysis and the preliminary results found will be described.

2 Experimental setup

The measurement was performed at LUNA, located in the deep underground facility of Laboratori Nazionali del Gran Sasso (LNGS). Thanks to the 1400 m overburden of rock, here the muon cosmic ray background is reduced by six orders of magnitude with respect to the surface [9]. Such a low cosmic-ray background in turn allows the deployment of thick passive shielding to absorb the natural radioactivity signals. In particular, a 15 cm thick lead shielding used for $\gamma$ absorption was surrounded with a 5 cm borated (5%) polyethylene for $n$ absorption: the polyethylene reduced the detected background of a factor 4 in the region of interest (ROI) of our measurement (5.2 - 6.2 MeV), with respect to using only lead. The LUNA 400kV accelerator [10] was able to provide a high stability 200$\mu$A current on target at projectile energy $E_p = 80\text{ keV}$. The high efficiency (74% at 661 keV) Bismuth-Germanium-Oxide (BGO) detector was installed around the reaction chamber, covering a $4\pi$ angle around the target. The detector is made of six optically independent crystals, which coupled with a DAQ that records the time stamp of each reading allows both single crystal spectra and the construction of the add-back spectrum, namely by adding coincident events in the individual crystals. In order to minimize the $\gamma$-ray absorption, Aluminium was used as construction material for the scattering chamber and the target holder. A 3D model of the detection setup is shown in Fig.1.

The measurement was performed using $\text{Ta}_2\text{O}_5$ solid targets produced by anodization of tantalum backings in 90% $^{17}\text{O}$ enriched water. Targets were doped with 5% $^{18}\text{O}$, thus allowing the periodical scan of the $E_R = 143\text{ keV} ^{18}\text{O}(p,\gamma)^{19}\text{F}$ resonance to monitor target degradation and thickness.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{detector_setup.png}
\caption{Section of the 3D model of the detector setup used in the Geant4 simulation.}
\end{figure}
3 Analysis and preliminary results

During five measurement campaigns, about 400 C were cumulated on $^{17}$O targets. An accurate Montecarlo simulation of the setup was crucial for the analysis of the acquired data. The simulation was developed using the Geant4 toolkit [11] and it was optimized on the well-known spectra of $^{60}$Co and $^{137}$Cs sources, and $^{14}$N($p, \gamma$)$^{15}$O $E_R = 270$ keV resonance. See Fig. 2 for a comparison between simulation and measurement of $^{14}$N($p, \gamma$)$^{15}$O. The average residuals between simulated and measured spectra after normalisation was below 3% in all three cases. This value also represents the precision at which the detection efficiency can be determined from the simulations.

![Figure 2](image-url)

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.

A low (3 p.p.m.) deuterium contamination on the Ta backing produced a single $\gamma$ peak at the same energy of the $^{17}$O($p, \gamma$)$^{18}$F 65 keV resonance peak. In Fig. 3 the BIB peak is clearly visible and due to a contamination in the Ta backing. In order to subtract this BIB an innovative technique was developed which made use of our knowledge of the $E = 5672$ keV de-excitation branching ratios and of the BGO detector segmentation. The technique iso-

![Figure 3](image-url)

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

lates multiplicity 2 and 3 transition $\gamma$-rays with the expected energies for the 5672 keV de-
excitation chain from the multiplicity 1 BIB. This allows an almost complete background subtraction while losing only a small amount of resonance $\gamma$, since the probability of ground state transition (multiplicity 1) is 6%. The analysis lead to a preliminary $\omega\gamma$ determination of about double the value of 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 separate paper.

References

[1] A. Boeltzig, C.G. Bruno, F. Cavanna, S. Cristallo, T. Davinson, R. Depalo, R.J. deBoer, A. Di Leva, F. Ferraro, G. Imbriani et al., Eur. Phys. J. A 52, 75 (2016)
[2] C. Abia, S. Palmerini, M. Busso, S. Cristallo, A&A 548, A55 (2012)
[3] A. Di Leva, D.A. Scott, A. Caciolli, A. Formicola, F. Strieder, M. Aliotta, M. Anders, D. Bemmerer, C. Broggini, P. Corvisiero et al., Phys. Rev. C 89, 015803 (2014)
[4] H.B. Mak, G. Ewan, H. Evans, J. MacArthur, W. McLatchie, R. Azuma, Nuclear Physics A 343, 79 (1980)
[5] V. Landre, P. Aguer, G. Bogaert, A. Lefebvre, J.P. Thibaud, S. Fortier, J.M. Maison, J. Vernotte, Phys. Rev. C 40, 1972 (1989)
[6] J.C. Blackmon, A.E. Champagne, M.A. Hofstee, M.S. Smith, R.G. Downing, G.P. Lamaze, Phys. Rev. Lett. 74, 2642 (1995)
[7] M.Q. Buckner, C. Iliadis, K.J. Kelly, L.N. Downen, A.E. Champagne, J.M. Cesaratto, C. Howard, R. Longland, Phys. Rev. C 91, 015812 (2015)
[8] G.F. Ciani, D. Piatti, R.M. Gesuè, for the LUNA collaboration, EPJ Web Conf. 260, 11003 (2022)
[9] A. Best, A. Caciolli, Z. Fülöp, G. Gyürky, M. Laubenstein, E. Napolitani, V. Rigato, V. Roca, T. Szücs, Eur. Phys. J. A 52, 72 (2016)
[10] A. Formicola, G. Imbriani, M. Junker, D. Bemmerer, R. Bonetti, C. Broggini, C. Casella, P. Corvisiero, H. Costantini, G. Gervino et al., Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment 507, 609 (2003)
[11] S. Agostinelli, J. Allison, K. Amako, J. Apostolakis, H. Arai, P. Arce, M. Asai, D. Axen, S. Banerjee, G. Barrand et al., Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment 506, 250 (2003)