IL NUOVO CIMENTO **42 C** (2019) 144
DOI 10.1393/ncc/i2019-19144-4

Colloquia: EuNPC 2018

Underground measurement of hydrogen-burning reactions on ^{17,18}O at energies of astrophysical interest

C. G. Bruno on behalf of the LUNA Collaboration(*)
School of Physics and Astronomy, The University of Edinburgh - Edinburgh, UK

received 5 February 2019

Summary. — Giant Branch stars are the site of several recirculating and mixing processes. Some of these processes can be traced using the rare, stable ^{17,18}O isotopes. At present, the abundance of ^{17,18}O in Giant Branch stars is affected by their destruction rate through the ^{17,18}O(p,α)^{14,15}N nuclear reactions. A direct measurement of these two nuclear reactions has been carried out at the underground LUNA accelerator in Laboratori Nazionali del Gran Sasso, Italy. Final results obtained for the ^{17}O(p,α)^{14}N reaction, and preliminary results on the ^{18}O(p,α)^{15}N reaction are reported.

1. – Introduction

The ^{17,18}O(p,α)^{14,15}N reactions play a key role in a number of stellar sites. In particular, these two reactions are responsible for the destruction of the rare, stable ^{17,18}O isotopes in Giant Branch stars. Giant Branch stars are the site of complex mixing and recirculating processes that affect both the production of energy and the synthesis of elements. The ^{17,18}O isotopes can be used to trace and constrain the mixing processes taking place inside of stars [1]. In particular, isotopic abundances in cosmic dust grains are one of the observables affected by mixing processes . An improved determination of the isotopic abundances in cosmic dust grains would offer significant new constraints to stellar models [2, 3], and was one of the motivations of the experimental campaign described in this paper.

At energies of astrophysical interest, the cross-section of the ^{17}O(p,α)^{14}N reaction is dominated by a narrow resonance at E_p=70 keV, corresponding to a resonance strength $\omega\gamma$ of the order of 1 neV. This resonance was studied several times using both direct [4] and indirect [5] methods. However, the picture painted in the literature was still not completely satisfying. The situation was more complex for the ^{18}O(p,α)^{15}N reaction for which a complex pattern of interferences between at least three states with the same spin-parity affects the reaction rate at energies of astrophysical interest [6].

(*) `https://luna.lngs.infn.it`

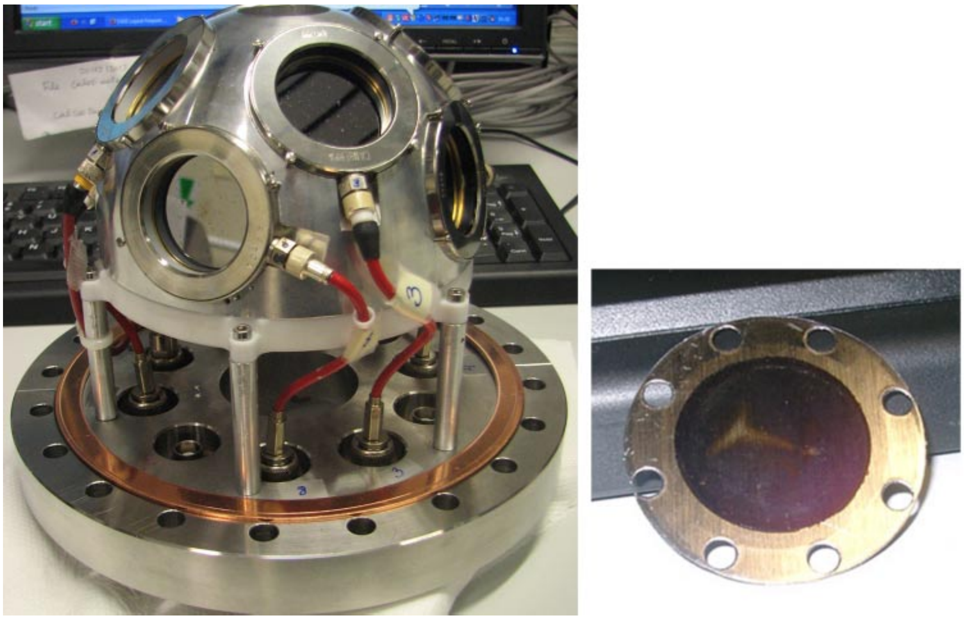

Fig. 1. – (Left) The reaction chamber used in the experiment. The proton beam enters from the hole in the top and reacts with a Ta_2O_5 solid target (right) placed in the centre of the hemispherical dome. Alpha particles produced are detected by an array of eight silicon detectors, protected by thin aluminised Mylar foils.

Because of the hindering effect of the Coulomb barrier, carrying out a direct measurement of the ^{17,18}O(p,α)^{14,15}N reactions at energies of astrophysical interest is very challenging. Rates as low as a few counts per hours are predicted - this weak signal could easily be lost in the natural radioactive background. In order to reduce the background, the experimental campaign described in this paper was carried out at the underground LUNA (Laboratory for Underground Nuclear Astrophysics) [7] at INFN LNGS (Istituto Nazionale di Fisica Nucleare – Laboratori Nazionali del Gran Sasso), Italy. The background reduction afforded by the underground environment (see later) was instrumental in carrying out the measurement. This experimental campaign was part of a larger effort aimed at directly measuring CNO cycle reactions [8-11] at energies of astrophysical interest, in order to reduce the present uncertainties and reduce the reliance on potentially dangerous extrapolation to the low centre-of-mass energies at which nuclear reactions take place in stars. See ref. [12] for a review of recent and future experimental measurements at LUNA.

2. – Methodology

The experiment was carried out at the underground 400-kV LUNA linear accelerator located at LNGS, Italy. A purpose-built setup [13], manufactured by the mechanical workshop of the School of Physics and Astronomy, Edinburgh University (UK), was used to carry out the measurement of both ^{17,18}O(p,α)^{14,15}N reactions. Fig. **1** shows a picture of this reaction chamber. A proton beam, with typical intensities of $100-150\mu$A, entered the chamber from the hole in the top and interacted with a solid Ta_2O_5 target.

The target was produced by anodising water, enriched in either ^{17}O or ^{18}O, on a tantalum backing. Extensive studies of the composition of the target and its behaviour under beam bombardment were carried out [14]. Even at the relatively high proton beam intensities at LUNA, targets showed modest degradation (less than 20%) up to 20 Coulomb of charge deposited. See ref. [13] for more details on the systematic studies of target degradation.

Alpha particles produced by the interaction of the beam on the target were detected by an array of eight silicon detector positioned at backward angles with respect to the beam axis. Four of these detectors were placed at 135^o, and four more at 102.5^o in the laboratory frame. In order to shield the detectors from the intense flux of elastically scattered protons on the solid target, thin aluminised Mylar foils were mounted in front of each detector. The thickness of these foils was chosen so as to stop the recoiling protons while letting the alpha particles generated by the ^{17,18}O(p,α)^{14,15}N reactions through with detectable energies. For the ^{17}O(p,α)^{14}N reaction, 2.4 μm aluminised Mylar foils were chosen, while for the ^{18}O(p,α)^{15}N reaction 5.5 μm aluminised Mylar foils were selected. Foils were mounted on a copper dome inside that on which the detectors were housed. A copper cold finger, cooled to liquid nitrogen temperatures, was placed in thermal contact with the dome to prevent carbon deposition on the target. Furthermore, the dome was biased at -300V with respect to ground in order to repel secondary electrons produced by the beam interacting with the target. The backing of the solid target stopped the beam and acted as a Faraday cup.

3. – Underground background reduction in silicon detectors

While the advantage of performing underground gamma spectroscopy measurements underground is well-established [7], the background reduction in charge-particle experiments afforded by an underground environment is less known. A systematic study of the background observed underground in LNGS and overground in Edinburgh by the silicon detectors utilised in this experimental campaign was carried out. Fig. **2** shows a comparison of the natural backgrounds acquired with and without a 5 cm lead shield surrounding the reaction chamber, underground in LNGS (Italy) and overground in Edinburgh (UK).

The four background spectra can be broadly divided in three energy regions. Below 2 MeV approximately, both the underground environment and the presence of a lead shield significantly reduce the natural background observed by the silicon detector array. This behaviour is consistent with the reduction in Compton-generated electrons produced by gamma rays interacting with the silicon detectors without depositing the full energy. These electrons could generate a signal on their own, or by pile-up effects. In the region between 2 MeV and 5 MeV, the background is reduced by the underground environment but not by the presence of a lead shield. The physical origin of this background is not immediately obvious, but the tails from higher energies clearly play a role. Finally, the region around 5 MeV and above is dominated by a background peak that is neither reduced by moving underground or by the presence of a lead shield. This peak could be produced by intrinsic activity of the silicon detectors themselves. These results show that moving underground and using a lead shield to carry out charge-particle spectroscopy measurement can result in more than a factor of 10 reduction in natural background.

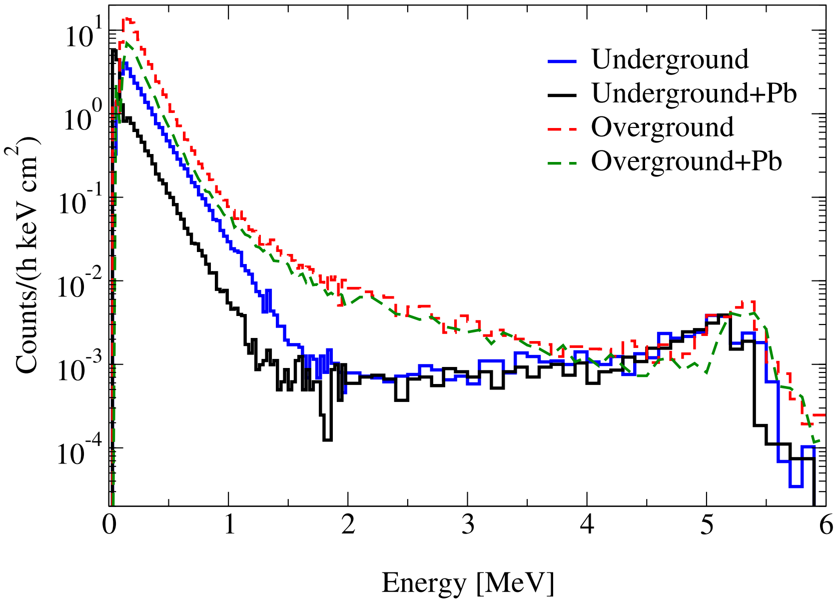

Fig. 2. – Comparison between natural background observed overground in Edinburgh (UK) and underground in LNGS (Italy) with an without a 5 cm lead shielding surrounding the reaction chamber. See text for details.

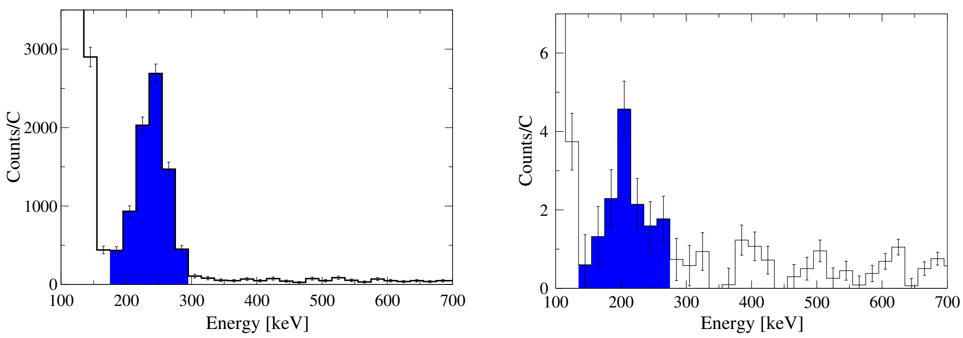

Fig. 3. – Alpha particle spectra acquired at E_p=193 keV (left) and E_p=70 keV (right), for the $^{17}O(p,\alpha)^{14}N$ reaction. The regions of interest for the resonance signal are highlighted in blue. The apparent peak at very low energies is caused by a mix of electronic noise and delta electrons travelling through the foils.

4. – The ^{17}O(p,α)^{14}N reaction

At energies of astrophysical interest, the ^{17}O(p,α)^{14}N reaction (Q-value=1.2 MeV) is dominated by two narrow and isolated resonances at E_p=193 keV and 70 keV. The E_p=193 keV resonance is quite well-known, and has been shown to play a key role in classical novae nucleosynthesis [15]. On the other hand, the picture painted in the literature for the E_p=70 keV by direct [4] and indirect [5] investigations is more complicated. This second resonance is extremely challenging to measure because of its small strength $\omega\gamma \sim$ 1 neV. Counting rates of the order of as few counts / day were expected. To further compound the situation, alpha particles for this reaction were emitted with energies around E_α=1 MeV, but were detected only at around E_α=200-250 keV after the aluminised Mylar foils. In order to carry out the challenging measurement of the E_p=70 keV resonance, the well-known E_p=193 keV resonance was measured using the same setup and the same foils. The signal for this E_p=193 keV intense resonance was quite clear above the background (Fig. **3** (left)). At these low proton beam energies, the kinematics the ^{17}O(p,α)^{14}N reaction are dominated by the reaction Q-value, and therefore the energy of the alpha particles detected after being emitted through the E_p=193 keV and the E_p=70 keV resonances are extremely close ($\sim$ 50 keV). Thus an energy region of interest (ROI) for the alpha particles generated through the E_p=70 keV resonance was established from the observed alpha particle energy at the E_p=193 keV resonance. This ROI was used to extract the signal at E_p=70 keV, as shown in Fig. **3** (right). In-depth analysis were performed in order to remove the natural background, exclude the presence of beam-induced background on contaminants and further confirm the width and energy of the ROI [16]. Finally, the number of counts was extracted using a Maximum Likelihood analysis technique. The final (bare) resonance strength value was $\omega\gamma = 10.0 \pm 1.4_{\rm stat} \pm 0.7_{\rm syst}$, significantly higher than the strength reported in previous direct measurements [4].

Because of the astrophysical importance of this E_p=70 keV resonance, and of the ^{17}O(p,α)^{14}N reaction more in general, this measurement had several important consequences in a number of astrophysical scenarios, ranging from galactic chemical evolution to the effects of extra-mixing episodes in asymptotic giant branch (AGB) stars [17]. One of the most important consequence of the revised reaction rate [16] was in the first direct evidence of production of cosmic dust in intermediate-mass AGB stars [18]. These starts are expected to produce significant amounts of stardust, yet until now no grains matching the expected isotopic compositions had been found. The increase in the reaction rate allowed to match Oxygen-rich Group II to the expected isotopic abundances in intermediate-mass AGB stars, solving a long-standing puzzle in stellar evolution [3, 18].

5. – The ^{18}O(p,α)^{15}N reaction

At energies of astrophysical interest, the reaction rate of the ^{18}O(p,α)^{15}N reaction (Q-value=3.98 MeV) is dominated by a complex interference pattern involving three resonances at approximately E_p=151, 600 and 800 keV, having the same spin-parity J^π=1/2$^+$. Tensions between datasets have been reported at astrophysically relevant energies below 1 MeV. A direct measurement or close to energies of astrophysical interest is especially challenging because of the low cross-sections involved (less than 1 nbarn). An experimental campaign aimed at measuring the cross-section of the ^{18}O(p,α)^{15}N reaction in the energy range E_p=60-360 keV has been completed at the LUNA-400 accelerator using the reaction chamber previously described. Cross-section lower than 1 pbarn/sr were measured at the lowest beam energies. A sample spectrum acquired at E_p=90 keV

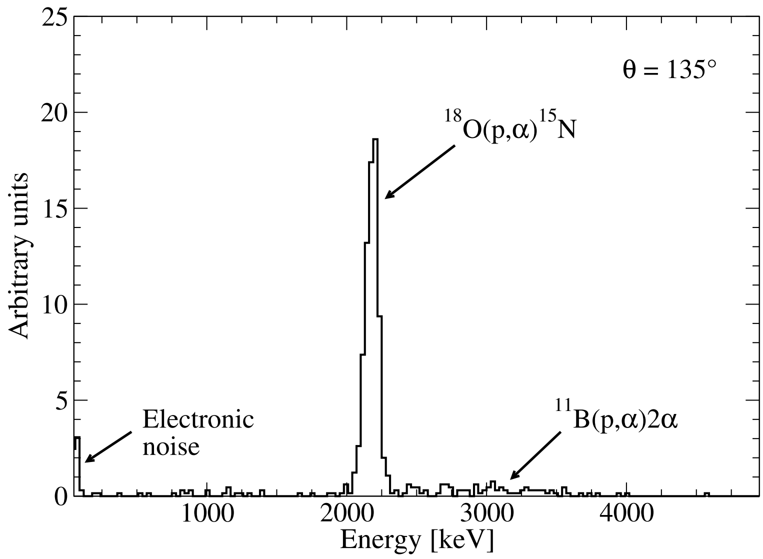

Fig. 4. – The energy spectrum acquired by a single detector positioned at 135^o at E_p=90 keV for $^{18}O(p,\alpha)^{15}N$ reaction. Natural background is negligible and has not been subtracted. See text for details.

is shown in Fig. **4**. Natural background is almost absent at the energies of the alpha peak signal. The only source of beam-induced background is from the $^{11}B(p,\alpha)^8Be(2\alpha)$ reaction. Boron contaminants are likely present in the Ta_2O_5 target, and/or in the oil of the vacuum pumps connected to the beamline. The broad peak from this contaminant reaction can be barely seen, and is negligible with respect to that of the $^{18}O(p,\alpha)^{15}N$ reaction. Results from the analysis will soon be published [19].

6. – Conclusions

Hydrogen-burning reactions on rare, stable $^{17,18}O$ isotopes play a key role in a number of scenarios, including in particular AGB stars. An experimental campaign aimed at measuring the $^{17,18}O(p,\alpha)^{14,15}N$ reactions at the underground LUNA-400 accelerator in Laboratori Nazionali del Gran Sasso, Italy, has been completed. Results on the commissioning of the setup and the quantitative estimate of the background reduction afforded by the underground environment [13], as well as result on the E_p=70 keV resonance in the $^{17}O(p,\alpha)^{14}N$ reaction [16] have been published. These results had a significant impact in a number of stellar scenarios [17], and solved a long-standing puzzle in stellar evolution [18]. Data from the direct measurement of the $^{18}O(p,\alpha)^{15}N$ reaction down to the lowest energy to date have been analysed, and will soon be published [19].

* * *

This work was supported by the UK Science and Technology Facilities Council (STFC). The author would like to gratefully acknowledge all members of the LUNA collaboration.

REFERENCES

[1] Lebzelter T. *et al.*, *Astron. Astrophys.*, **578** (2015) A33
[2] Nittler L.R. *et al.*, *Astrophys J.*, **483** (1997) 475
[3] Lugaro M. *et al.*, *Astron. Astrophys.*, **461** (2007) 657
[4] Blackmon J.C. *et al.*, *Phys. Rev. Lett.*, **14** (1995) 74
[5] Sergi M.L. *et al.*, *Phys. Rev. C*, **91** (2015) 065803
[6] Lorenz-Wirzba H. *et al.*, *Nucl. Phys. A*, **313** (1979) 346-362
[7] Costantini H. *et al.*, *Rep. Prog. Phys.*, **72** (2009) 086301
[8] Cavanna F. *et al.*, *Phys. Rev. Lett.*, **155** (2015) 25
[9] Depalo R. *et al.*, *Phys. Rev. C*, **94** (2016) 5
[10] Slemer A. *et al.*, *MNRAS*, **465** (2017) 4
[11] Trezzi D. *et al.*, *Astropart. Phys.*, **89** (2017) 57-65
[12] Boeltzig A. *et al.*, *Eur. Phys. J. A*, **52** (2016) 4
[13] Bruno C.G. *et al.*, *Eur. Phys. J. A*, **51** (2015) 94
[14] Caciolli A. *et al.*, *Eur. Phys. J. A*, **48** (2012) 144
[15] Newton J.R. *et al.*, *Phys. Rev. C*, **75** (2007) 055808
[16] Bruno C.G. *et al.*, *Phys. Rev. Lett.*, **117** (2016) 142502
[17] Straniero O. *et al.*, *Astron. Astrophys.*, **598** (2017) A128
[18] Lugaro M. *et al.*, *Nature Astronomy*, **1** (2017) 27
[19] Bruno C.G. *et al.*, *in preparation*, (2018)