Study of the $^{15}\text{N}(p,\gamma)^{16}\text{O}$ at LUNA

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Abstract. The $^{15}\text{N}(p,\gamma)^{16}\text{O}$ reaction links the first CNO cycle with the second one allowing the production of the oxygen and fluorine isotopes during the hydrogen burning in novae and AGB and RGB stars. In recent years, this reaction has been studied deeply by LUNA (Laboratory for Underground Nuclear Astrophysics). As a matter of fact three different experiments have been run to measure the $^{15}\text{N}(p,\gamma)^{16}\text{O}$ $S$ factor down to the energy of the novae and AGB hydrogen burning reaching for the first time the 72.8 keV in the center of mass. In this contribution the results of the first two experiments are summarized and the results of the recently performed experiment, which is dedicated to the study at very low energies, are presented.

1. Introduction

During hydrogen burning the p-p chain provides the energy supply in low mass stars whereas the CNO cycle is the principal nuclear process in the core of high Mass Sequence stars ($M \gtrsim 1.2 M_{\odot}$). The $^{15}\text{N}(p,\gamma)^{16}\text{O}$ ($Q$-value 12.127 MeV) links the first CNO cycle to the second one providing the path to produce the $^{16}\text{O}$ in stellar hydrogen burning [1]. This reaction was studied in pioneering experiments by Hebbard [2] in 1960 by using a NaI detector and by Rolfs and Rodney [3] in 1974 using a Ge(Li) detector. The NACRE [4] and CF88 [5] database used only the most recent dataset since there is a discrepancy between the results of the two experiments. New results on the $S$ factor have been recently published by Mukhamedzhanov et al. [6]. They measured the Asymptotic Normalization Coefficients (ANC) and performed an R-Matrix fit that includes previous data from direct cross section measurements. This work reports an $S$ factor lower by a factor of 2 than the one suggested by NACRE and in agreement with the Hebbards extrapolated $S$ factor [2]. Another recent R-Matrix analysis, using again the available direct data but limited to the capture reaction to the ground state [7], also indicates a much lower $S$ factor.

The LUNA collaboration decided to study the $^{15}\text{N}(p,\gamma)^{16}\text{O}$ reaction by performing three different experiments: one with a gas target setup and two others by using a solid target setup. The LUNA facility ([8] and reference therein), thanks to its underground position inside the Gran Sasso National Laboratory (LNGS), offers a favorable laboratory background for the $\gamma$-ray spectra with respect to analogue facilities on the Earth's surface, allowing studies at energies close to the Gamow peak [9, 10, 11]. In this work the two setups where an high efficiency BGO detector was used are described in details. The other experiment was performed in a collaboration between the LUNA collaboration and the Notre Dame University and it was dedicated to explore a large energy range from 120 keV up to 1800 keV in the center of mass in
order to perform an R-Matrix fit on a unique set of data. This experiment was described in a previous work and reference therein [12].

2. Gas Target Experiment
A reanalysis of $\gamma$-spectra acquired in a previous experiment was done to determine the cross section in a small energy range (from 230 keV down to 90 keV in the center of mass). The experiment was performed by using a windowless gas target setup with the target chamber filled with nitrogen gas (natural isotopic abundances) [13, 14].

A $4\pi$-BGO detector array which surrounds the target chamber was used to detect the $\gamma$-rays emitted by the $^{15}\text{N}(p,\gamma)^{16}\text{O}$ reaction (the region of interest was from 10 up to 14 MeV). The detector efficiency was determined with a GEANT4 code to be 70% for 12 MeV $\gamma$-rays.

The beam induced background due to the $^{11}\text{B}(p,\gamma)^{12}\text{C}$ reaction, which produces a $\gamma$-rays ($E_\gamma \approx 11.5$ MeV) in the same ROI of the $^{15}\text{N}(p,\gamma)^{16}\text{O}$ reaction, was the major source of systematic uncertainties since the signal was comparable with the one from the reaction studied (the $^{15}$N in natural nitrogen is 0.4% [15]). The beam induced background was taken into account by acquiring $\gamma$-spectra with helium gas in the target chamber. As a matter of fact, with helium only the contribution due to the boron contamination is present in the ROI of the $\gamma$-spectra. The obtained data show a reduction of the cross section of a factor 2 with respect the Rolfs and Rodney results [17].

3. Solid target setup
The statistics contribution was improved by a factor 200 choosing solid TiN target enriched in $^{15}$N. The targets were produced by the LNL of Padova and in HFZ of Karlsruhe using the reactive sputtering technique [16]. These targets were used in two different experiment: one performed with a HPGe detector in close geometry and dedicated to perform an R-Matrix fit with direct data acquired in a large energy range with the same setup [12] and another experiment performed with the same BGO detector already used with the gas target setup.

For the second experiment, since the target stability and the target properties are a fundamental parameter for the cross section analysis, the target irradiated at the LUNA accelerator were analyzed with SNMS (Secondary Neutral Mass Spectroscopy) [18] and high Z ERD (Elastic Recoil Detection) [19] in order to control the deterioration of the target and reduce the uncertainties on the isotopic abundances and the Ti/N stoichiometry ratio. Taking advantage of the high efficiency of the BGO detector for the first time, the cross section of the $^{15}\text{N}(p,\gamma)^{16}\text{O}$ reaction was measured down to 72.8 keV covering the total Gamow peak for nova explosion scenario. The $S$ factor has been determined by integrating the target profiles with an a priori $S$ factor and by comparing this integral with the measured yield. For the analysis, three different input $S$ factors have been used: the one given in [12], a constant $S$-factor, and a value obtained from iterating the procedure. Identical results were obtained. This procedure is explained in details in [21]. Finally, the reduction by a factor 2 with respect the previous NACRE extrapolation observed at these energies provides a 30% reduction of the $^{16}\text{O}$ production by the hydrogen burning in nova [1].

4. Summary and Conclusion
The $^{15}\text{N}(p,\gamma)^{16}\text{O}$ reaction has been deeply studied by the LUNA collaboration performing three different experiments. We have measured the cross section of this reaction in a huge range of data and an R-Matrix has been produced to extrapolate the $S$ factor at lower energies [12]. An other group has performed an R-Matrix fit on the same data obtaining an extrapolation in good agreement with the LUNA one [20]. Using a BGO detector the $^{15}\text{N}(p,\gamma)^{16}\text{O}$ $S$ factor has been also obtained in the center of mass energy range from 70 keV to 370 keV. The $S$ factor values are found to be lower by a factor of 2, compared to the previously accepted value [4]. The measured
energy range covers, for the first time, the whole Gamow peak for novae explosions and the upper half of the Gamow peak of RGB and AGB stars are covered with precise experimental data.

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