# LUNA: The $^{15}$N(p,$\gamma$)$^{16}$O reaction study at low energies with a BGO detector



**Antonio Caciolli for the LUNA collaboration**[*]
*University of Siena, CGT San Giovanni Valdarno and INFN of Padua*
*E-mail:* `caciolli@pd.infn.it`

The $^{15}$N(p,$\gamma$)$^{16}$O reaction has been intensively studied by the LUNA collaboration. In this contribution the measurements performed using a 4$\pi$-BGO detector and a solid target setup are described. The data, which are being analyzed, cover for the first time the entire Gamow peak for nova scenarios and investigate the Gamow energies for AGB and RGB stars. A detailed report of the target analysis and the procedure to determine the S-factor is described while the final results are still under evaluation.

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[*]Speaker.

## 1. Introduction

The $^{15}$N(p,$\gamma$)$^{16}$O reaction ($Q$-value 12.127 MeV) links the first CNO cycle to the second one providing the path to produce $^{16}$O in stellar hydrogen burning [1].

The excitation curve was measured in pioneering experiments by Hebbard [2] and Rolfs and Rodney [3] using NaI and Ge(Li) detectors respectively. The reported low energy data differ by more than a factor of 2 and the same discrepancy also appears in the extrapolated S-factor. Of the two data sets, only the more recent one [3] was used in the NACRE compilation [4]. However, the reason of the discrepancy between these two sets remains unsolved.

New results on the S-factor have been published by Mukhamedzanov et al. [5]. They measured the Asymptotic Normalization Coefficients (ANC) and performed an R-Matrix fit including the previous direct data. This work provides an S-factor lower by a factor 2 than the one suggested by NACRE and in agreement with the Hebbard's 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 [6], also indicates a much lower S-factor.

LUNA (Laboratory for Underground Nuclear Astrophysics) collaboration decided to perform an extended set of measurements on the $^{15}$N(p,$\gamma$)$^{16}$O reaction using both gas and solid target setups. The LUNA facility, thanks to its underground position inside the Gran Sasso National Laboratory (LNGS), offers a favorable laboratory background for the $\gamma$-ray detection in experiments with low counting rate with respect to analogue facilities on the Earth's surface, allowing to reach lower energies close to the Gamow peak. In 2009 new data for the $^{15}$N(p,$\gamma$)$^{16}$O cross section have been published by the LUNA collaboration [7]. The experiment has been performed using a 4$\pi$-BGO detector and impinging a proton beam on a natural nitrogen windowless gas target [7]. These new data agree with the indication of the R-matrix fits [5, 6] and they provide a reduction of the cross section with respect to the previous direct data. A new experiment has been then performed with a HPGe detector and a solid target setup in collaboration with the Notre Dame University to collect, with both the LUNA accelerator and the JN and KN accelerators, a unique set of cross section data in a energy range from 130 keV up to 1800 keV in the laboratory system to perform a new R-matrix fit [8].

Instead, the Gamow peak for the nova explosions has been completely covered for the first time with the experiment described in this work. Thanks to the LUNA background characteristics the new set data cover quite the total energy range of the LUNA2 accelerator ($E_{CM}$ = 70 - 360 keV in 10 keV steps).

## 2. Experiments and Target analysis

The experiment has been performed at the 400 kV underground accelerator of LUNA. The detection setup is the same used to study the $^{24}$Mg(p,$\gamma$)$^{25}$Al and the $^{25}$Mg(p,$\gamma$)$^{26}$Al reactions [9]. Briefly, the beam passed through three apertures (10.0 mm, 3.0 mm, and 5.0 mm, respectively) which allowed to focus the beam each time on the same area on the target surface. The third collimator was placed at 1 m distance from the target. The target was water-cooled to reduce the deterioration due to the impinging beam. A typical beam intensity from 30 up to 150 $\mu$A was delivered on target by the accelerator during the measurements. A cold trap, filled with liquid nitrogen, minimized the carbon build-up on target: a 1 m long copper tube (28 mm diameter) was placed in between the last collimator and the target and it was connected thermally to the cold trap, which was cooled to $LN_2$ temperatures. It extended to within 2 mm from the target. A negative voltage (300 V) was applied between this tube and the target to suppress the secondary electrons escape both from the last aperture and from the target. The beam current deposited on the target was integrated to obtain the charge deposited; the uncertainty on the charge collected was estimated to be about 2%. A turbo pump system under the cold trap led to a pressure in the target chamber of better than $5{\cdot}10^{-7}$ bar. As a matter of fact no carbon deposition was observed on the targets. The target chamber was surrounded by a $4\pi$-BGO summing crystal [10] to detect the $\gamma$ radiation with a large efficiency. The detector has a cylindrical shape with a coaxial hole. The detector is made of 6 crystals, each covering a $60^\circ$ azimuthal angle. Each crystal was coupled to a photomultiplier tube (PMT). The signal of each PMT was acquired separately on event-by-event base and the sum spectrum was reconstructed offline.

The trigger was given by the hardware sum of the gain-matched signals from the dynodes of the PMTs.

Enriched solid targets, with a nominal amount of $^{15}$N of 98%, were used. The beam induced background was checked in all spectra. The main contribution from the induced beam background has been due to the $^{11}$B(p,$\gamma$)$^{12}$C reaction which emits a $\gamma$-ray ($E_\gamma$ = 11.7 MeV) in the same region of interest of the $^{15}$N(p,$\gamma$)$^{16}$O. Runs with a boron contribution higher than 3% of the total statistic in the ROI were rejected from the analysis.

The targets were made of TiN on a tantalum backing and were produced in Karlsruhe and Laboratori Nazionali di Legnaro (LNL) using the reactive sputtering technique [12]. The target thickness was estimated to be about 100 nm (14 keV at $E_p$ = 278 keV resonance of the $^{14}$N(p,$\gamma$)$^{15}$O reaction). The understanding of the target properties and the nitrogen behavior during the time of measurements is crucial for the data analysis. Different techniques were used not only at the LUNA facility but also at other overground laboratories, in order to characterize the target parameters like the element abundances and the deterioration effect due to the impinging beam:

- Resonance scan profiles performed at the Forschungszentrum Dresden-Rossendorf (FZD);
- Elastic Recoil Detection (ERD) with high-Z beam performed in Munich.

Thanks to the ERD technique, which has been performed at the tandem accelerator in Munich with a 170 MeV $^{127}$I beam, the initial stoichiometry TiN has been deduced. The isotopic ratio of the nitrogen in the targets has been determined both with the ERD technique and by performing resonance scans on the narrow resonance at $E_p$ = 278 keV of the $^{14}$N(p,$\gamma$)$^{15}$O reaction. As a matter of fact, the measured yield on the plateau ($Y$), corrected for the efficiency of the setup, is related to the effective stopping power, which depends both on the stoichiometry Ti/N and on the isotopic ratio:

$$Y = \frac{\lambda^2}{2\pi} \frac{\omega\gamma}{\frac{\mathrm{N}}{^{14}\mathrm{N}}\varepsilon_N + \left(\frac{\mathrm{Ti}}{\mathrm{N}}\right)_{ERD} \frac{\mathrm{N}}{^{14}\mathrm{N}}\varepsilon_{Ti}} \tag{2.1}$$

where $\lambda$ is the De Broglie wavelength, $\varepsilon_i$ is the stopping power reported in the SRIM database [11] for the element $i$, and the stoichiometry is the one measured by ERD. Since $^{14}$N and $^{15}$N are the only nitrogen isotopes in the targets, the amount of $^{15}$N can be easily deduced from equation (2.1).

| Target | Ti/N | $^{15}$N/N$_{tot}$ | $^{15}$N/N$_{tot}^{ERD}$ |
|---|---|---|---|
| 1 | 0.973±0.015 | 0.984±0.020 | |
| 2 | 0.993±0.015 | 0.984±0.020 | 0.995 |
| 3 | 0.98±0.02 | 0.984±0.020 | |
| 4 | 0.971±0.016 | 0.985±0.020 | |
| 5 | 1.18±0.02 | 0.946±0.019 | 0.96 |
| 6 | 1.16±0.02 | 0.942±0.019 | 0.96 |

**Table 1:** The stoichiometry ratio and the $^{15}$N isotopic abundances obtained for each target with the ERD technique. The $^{15}$N abundances measured with the resonance scans are also reported with their uncertainties.



Since the $^{14}$N is in a very small quantity in the targets, the final error on the $^{15}$N concentration in the targets is small affected by the uncertainty on the $^{14}$N abundances calculated by eq. (2.1). The $^{15}$N has been found to be 96% or 99% (depending on the different set of targets) with a 2% uncertainty.

The results deduced from the ERD technique for the isotopic abundance are in very good agreement with those established at LUNA, confirming that the target properties are under control in the analysis (see table 1).

To understand the target deterioration during the experiment two different regions of the target surface were analyzed with resonance profile scans in order to extrapolate the relevant information for the target area irradiated by the LUNA beam and for a region not irradiated that correspond to the conditions after and before the $^{15}$N(p,$\gamma$)$^{16}$O measurements. The beam (1$\mu$A) was provided by the Tandetron Accelerator of the Forschungszentrum Dresden-Rossendorf to investigate the target by using the resonance at 430 keV (in the laboratory system) of the $^{15}$N(p,$\alpha\gamma$)$^{12}$C reaction. The target profiles, reconstructed from the resonance profile scans, can be integrated with the cross section in order to calculate the expected yield as:

$$Y_{sim} = \int_{x_0}^{x_{max}} S(E_p) \cdot E_p e^{\frac{212.85}{\sqrt{E_p}}} \cdot \eta_{BGO} \cdot n_{target}(x) \frac{^{15}N}{N} \mathrm{d}x \tag{2.2}$$

where $E_p$ is the beam energy. In the eq. (2.2) a theoretical S-factor was assumed. Three different types of theoretical S-factor have been used in eq. (2.2): the one reported in [5], a constant S-factor, and a recursive value obtained from the analysis process. In each case the same results were obtained within 1%. By comparing the experimental yield $Y_{exp}$ with the calculated one, it is possible to determine the S-factor as follows:

$$S(E_{eff})_{exp} = \frac{Y_{exp}}{Y_{sim}} \cdot S(E_{eff})_{th} \tag{2.3}$$

where the effective energy in the center of mass has been calculated through the definition [13]:

$$E_{eff} = \frac{\int_{x_0}^{x_{max}} S(E) \cdot E e^{\frac{212.85}{\sqrt{E}}} \cdot n_{target}(x) \cdot \frac{^{15}N}{N} \cdot E \cdot \mathrm{d}x}{\int_{x_0}^{x_{max}} S(E) \cdot E e^{\frac{212.85}{\sqrt{E}}} \cdot n_{target}(x) \cdot \frac{^{15}N}{N} \mathrm{d}x}. \tag{2.4}$$

In eq. (2.4) the theoretical S-factor was used.

An independent analysis of the same data was conducted using a different algorithm. In this approach the absolute reaction cross-section was determined at each beam-energy point collected. These cross-sections were associated to an effective interaction energy following the iterative method described in [13]. The S-factor data obtained with this independent analysis are in perfect agreement with the results described in this paper.

## 3. Summary and outlook

For the first time the Gamow peak in nova scenarios is completely covered by a unique set of data and the upper part of the AGB gamow peak is also investigated with this experiment. A factor 2 lower with respect the Rolfs data (adopted by the NACRE database) has been found similarly with [7, 8]. The present results seem in agreement with the Hebbard results in the overlapping region with a strong reduction of the uncertainties. The systematic uncertainties due to the setup properties are still in phase of evaluation but they will be lower than the contribution due to the one on the target analysis.

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