Study of the $^{15}\text{N}(p,\gamma)^{16}\text{O}$ reaction at the LUNA accelerator with a BGO detector

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Abstract. The $^{15}\text{N}(p,\gamma)^{16}\text{O}$ reaction has been intensively studied by the LUNA collaboration. In this contribution the measurements performed using the same BGO detector and two different setups, with gas and solid target, are described in details. The measurement of the cross section for this reaction allows to determine the astrophysical S-factor. The results of the gas target experiment will be discussed while the analysis of the solid target data is still in progress.

1. Introduction

The $^{15}\text{N}(p,\gamma)^{16}\text{O}$ reaction ($Q$-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].

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 recently 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 of 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.

It is therefore clear that a new direct measurement is needed to understand this discrepancy. LUNA collaboration decided to perform an extended set of measurements on the $^{15}\text{N}(p,\gamma)^{16}\text{O}$ 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 spectra with respect to analogue facilities on the Earth’s surface, allowing to reach lower energies close to the Gamow peak.

Three different approaches were used to investigate this reaction: a gas target with a BGO detector, a solid target with the same BGO detector and a solid target with a High Purity Germanium detector. In this contribution only the experiments and the associated results involving the BGO detector will be discussed.
2. Experiments and Target analysis
The two experiments performed with the BGO detector at the LUNA accelerator exploited the high efficiency of the BGO to reach lower energies than feasible with a low efficiency HPGe detector, where statistic is limited.

The first measurement involved a windowless gas target cell filled with 1 mbar natural nitrogen (isotopic composition: 99.634\% $^{14}$N, 0.366\% $^{15}$N [7]). The main goal of this experiment was the study of the $^{14}$N(p,$\gamma$)$^{15}$O reaction at low energies [8, 9], but the presence of $^{15}$N in the target material allowed for a spin-off analysis of the $^{15}$N(p,$\gamma$)$^{16}$O reaction.

The cylindrical target chamber was surrounded by a 4$\pi$-BGO summing detector that, according to GEANT4 simulations and measurements with radioactive sources, has an efficiency of 70\% for 12 MeV $\gamma$-rays. The results from this experiment are already published [10] and all details are already presented in that paper and reference therein.

![Graph showing the S-factor for the $^{15}$N(p,$\gamma$)$^{16}$O reaction](image)

**Figure 1.** Astrophysical S-factor for the $^{15}$N(p,$\gamma$)$^{16}$O reaction as a function of the center of mass energy. The LUNA gas target are presented (blue circles) with data from Hebbard [2] (black diamonds) and from Rolfs and Rodney [3] (green triangles). The red curve represents the R-matrix fit from the ANC data [5].

In Figure 1 the S-factor obtained in the LUNA gas target measurements [10] is compared with the data from previous direct measurements [2, 3] and the results of the ANC analysis [5]. The LUNA results are lower than the adopted values in the NACRE database by a factor of 2 and lies below the ANC curve, which has 17\% uncertainty [5]. However, all these results are in agreement within error bars. The uncertainties for the LUNA data [10] are smaller than in previous direct measurements with a main contribution from the beam induced background, as produced by the $^{11}$B(p,$\gamma$)$^{12}$C reaction.

The second experiment involved the same BGO detector setup and a solid state target. The main purposes of this new set of measurements at the LUNA accelerator was to extend the cross section to energies as close as possible to the Gamow peak and to further reduce the previous uncertainty.

The use of enriched solid targets, with a nominal amount of $^{15}$N of 98\%, increased the statistic of two order of magnitude with respect to the natural nitrogen gas targets. The boron contamination was evaluated less then 1-2\% in all $\gamma$-spectra. Only at the lowest measured beam energies ($E_p = 80$ keV) the boron amount in the $\gamma$-spectra was about 3\%. In all of the cases its contribution to the systematic uncertainty was negligible with respect to other systematic uncertainties.

The targets were made of TiN on a tantalum backing and were produced in Karlsruhe and...

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Nuclear Physics in Astrophysics IV
Journal of Physics: Conference Series 202 (2010) 012036
doi:10.1088/1742-6596/202/1/012036
Legnaro laboratories using the reactive sputtering technique [11]. The target thickness was estimated to be about 100 nm (14 keV at $E_p = 278$ keV) All targets suffered deterioration due to the intense beam current (typically 100 $\mu$A) that impinged on the target material for extended time, depositing several tens of Coulomb of charge on each target. Moreover, the target stoichiometry between titanium and nitrogen and the isotopic ratio of $^{14}$N and $^{15}$N are two important parameters in the data analysis. These target characteristics should be studied in depth when using enriched targets and their changes during the measurements should not be neglected in the data analysis.

The target characteristics were investigated with three different techniques in order to obtain the complete information on stoichiometry, isotopic ratio and the target deterioration:

- Resonance scan profiles performed at the Forschungszentrum Dresden-Rossendorf (FZD);
- Secondary Neutral Mass Spectrometry (SNMS) performed at ATOMKI in Debrecen;
- Elastic Recoil Detection (ERD) with high-Z beam performed in Munich.

All the target analysis were performed after the LUNA beam irradiation, since some of these technique are destructive. Two different regions of the target surface were analyzed with each technique in order to extrapolate the relevant information for the target area irradiated by the LUNA beam (“beamspot”) and for a region not irradiated (“outside”) that correspond to the conditions after and before the $^{15}$N($p,\gamma$)$^{16}$O measurements. One technique, often used in this type of experiments with solid targets, is the scan of the target with a narrow resonance. The beam (1$\mu$A) was provided by the Tandetron Accelerator of the Forschungszentrum Dresden-Rossendorf to investigate the target using the resonance at 430 keV (in the laboratory system) of the $^{15}$N($p,\alpha\gamma$)$^{12}$C reaction.

![Figure 2](image_url)

**Figure 2.** Resonance profile scan of the target used in the solid target measurements. The black points are related to the “outside” area and the red ones to the “beamspot” area. The points are fitted with a Fermi like function.

In Figure 2 the data for one of the target are displayed. By interpolating between the two profiles it is possible to extract information about the amount of $^{15}$N in the target during the measurements, as a function of the accumulated charge. From the leading edge in the two profiles situated at the same energy we can exclude any contamination of the target surfaces during the measurements at LUNA. The results obtained by the resonance scans have been used to monitor relative changes and not to obtain absolute values since the $\omega\gamma$ of the resonance and the angular distribution of the emitted $\gamma$-rays are affected by large uncertainties.

In order to know the exact stoichiometry, the targets were analyzed using SNMS and high-Z ERD techniques. While the high-Z ERD analysis is still in progress the SNMS results are shown
in Figure 3 for one of the targets. Also in this case two regions of the target were analyzed: one related to the “beamspot” area and the other to the “outside” area.

SNMS uses rare gas ions at low energy (0.5 - 5 keV) to sputter the atoms from the target surface and obtain a depth profile detecting the sputtered atoms. As shown in Figure 3, the SNMS method provides not only results about the $^{15}$N concentration, but also about the stoichiometry and the isotopic concentration. The tantalum concentration was evaluated to determine the target thickness. All information collected on the target characteristics is necessary to evaluate the effective energy ($E_{\text{eff}}$) and effective stopping power ($\epsilon_{\text{eff}}$), since $E_{\text{eff}}$ and $\epsilon_{\text{eff}}$ are strictly dependent on the atomic composition and the atomic concentration in the targets. The results of SNMS and resonance scan analysis were compared and compatible values for the target deterioration and the profile shape were obtained.

![Figure 3](image)

**Figure 3.** Target profile as obtained with the SNMS technique. The left and right panels correspond to the “outside” and “beamspot” areas, respectively.

3. Summary and outlook

The LUNA collaboration has performed a detailed study of the $^{15}$N(p,$\gamma$)$^{16}$O reaction with natural $N_2$ gas target and enriched solid target. The data analysis of the solid target measurements is still in progress. To improve the uncertainty on the deduced S-factor, a precise knowledge of the target characteristics and their evolution after intense beam irradiation is required. The targets analysis seems to give promising results and a complete overview of the targets characteristic.

4. Acknowledgment

Financial support by INFN and in part by the European Union (TARI RII3-CT-2004-506222, AIM 025646 and SPIRIT 227012) and the Hungarian Scientific Research Fund (T49245 and K68801) is gratefully acknowledged.

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