Nuclear astrophysics deep underground: the case of the ^{15}N(p,γ)^{16}O reaction at LUNA

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Abstract
Measuring nuclear reactions of astrophysical interest at the relevant energies is not always possible on the Earth's surface because of the cosmic-ray background that dominates the spectra. The LUNA collaboration exploits the low-background enviroment of Gran Sasso National Laboratory to study these reactions at or close to the Gamow peak. The latest experimental efforts included the measurement of the ^{15}N(p,γ)^{16}O at beam energies between 77 and 350 keV. The status of these measurements is summarised in this contribution.

1 Introduction

Nuclear reactions that power a star generating energy and synthesising elements, take place inside the stars in a relatively narrow energy window: the Gamow peak. In this region, which is in most cases below 100 keV, far below the Coulomb energy, the reaction cross-section drops almost exponentially with decreasing energy. The extremely low value, from pico to femto-barn and even smaller, has always prevented its measurement in a laboratory at the Earth's surface, where the signal-to-background ratio would be too small because of the background generated by cosmic ray interactions. Therefore, the observed energy dependence of the cross section at high energies is usually extrapolated to the low-energy region, leading to substantial uncertainties. In particular, a possible resonance in the unmeasured region is not accounted for by the extrapolation, but it could completely dominate the reaction rate at the Gamow peak.

The ultra-low background environment of the underground facilities at Gran Sasso National Laboratories in Italy is therefore an ideal landscape for measuring nuclear reactions at or close to the Gamow peak. The cross section σ(E) for these reactions (where E is the centre of mass energy in keV) can be parametrised by the astrophyscal S-factor S(E), which is defined as

$$S(E) = \sigma(E) \cdot E \cdot e^{31.29 \cdot Z_1 \cdot Z_2 (\mu/E)^{1/2}}, \tag{1}$$

where Z_1 and Z_2 are the atomic numbers of the projectile and target, while μ is the reduced mass. The most important quantity to determine for each astrophysical nuclear reaction is the S-factor extrapolated to zero energy, S(0) [1].

2 The ^{15}N(p,γ)^{16}O reaction in nuclear astrophysics

In this work the ^{15}N(p,γ)^{16}O reaction was studied. This, together with the more significant ^{15}N(p,α)^{12}C, forms the branching point from the CN to the NO cycles, also known as first and second CNO sub-cycles, respectively [1] (see Figure 1). The ratio of the respective reaction rates has been determined to be about 1:1000 at stellar energies [2].

The ^{15}N(p,γ)^{16}O reaction at astrophysical energies ($\lesssim$1 MeV) is characterised by two wide resonances at proton-beam energies in the centre of mass of 335 and 1028 keV, respectively, which influence the excitation function. This reaction was studied for the first time in the early '60s by Hebbard [3], who performed a direct measurement for both the resonant and non-resonant cross-sections at proton-beam energies larger than 220 keV. This measurement yielded an S(0) value of (29.8$\pm$5.4) keV$\cdot$barn. A new measurement was performed a few years later [2], which managed to push the lower beam-energy limit

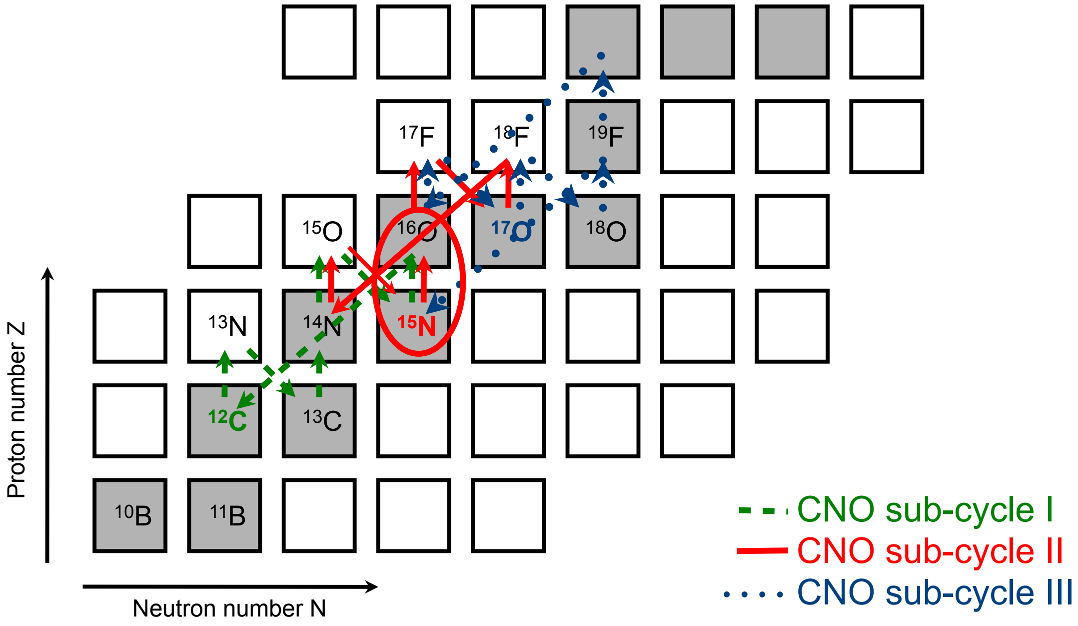

Fig. 1: Portion of the chart of nuclei with a schematic representation of the path followed by the CNO cycle. The subcycles I, II and III are highlighted by dashed green, solid-red and dotted blue arrows, respectively. The ^{15}N(p,γ)^{16}O reaction studied in this work is highlighted with a red contour.

down to only 155 keV. In this case the value obtained for S(0) resulted to be (64.0±6.0) keV·barn, approximately a factor of two higher than the previous value and not compatible with it within error bars. It is interesting to notice that the S(0) extrapolation in the widely adopted NACRE astrophysical compilation [4] was based mainly on the data between the two wide resonances at 335 and 1028 keV, with the direct capture component as a free parameter in the fit. Moreover, the data in Ref. [3] were ignored in this computation.

More recently, an asymptotic normalisation coefficient measurement for proton removal from the ground state and several excited states of ^{16}O was used to determine, with the R-matrix approach, the direct capture astrophysical S-factors to the corresponding states [5]. This yielded an S(0) value which is a factor of two lower than in the data of Ref. [2], (36.0±6.0) keV·barn. It corresponds to leak rates at 25 keV beam energy of one catalyst lost because of the ^{15}N(p,γ)^{16}O reaction for every 2200±300 cycles of the main CN cycle, against 2600±400 according to the S(0) value by [3] and 1200±300 according to the value by [2].

In order to obtain new information on this reaction, the data collected during a measurement of the ^{14}N(p,γ)^{15}O at LUNA with a natural gas target (99.6% ^{14}N, 0.4% ^{15}N) were reanalysed for the ^{15}N(p,γ)^{16}O reaction [6]. The data covered the energy range 90−230 keV in the centre of mass. The outcome of this measurement is that the S-factor is about a factor of two lower than in [2] and, within the small overlapping energy-region, in agreement with [3]. A new R-matrix fit, which takes the latter data set into account, together with the older literature data is therefore called for. In Figure 2 the data points available so-far are summarised. With the aim of improving the uncertainties on the lower energy points and covering a larger energy range with as much overlap with the existing data as possible, two new experiments were performed at LUNA. Small uncertainties for the low energy S-factor values are indeed critical for the extrapolation to zero energy and the clarification of the puzzle of the different available values.

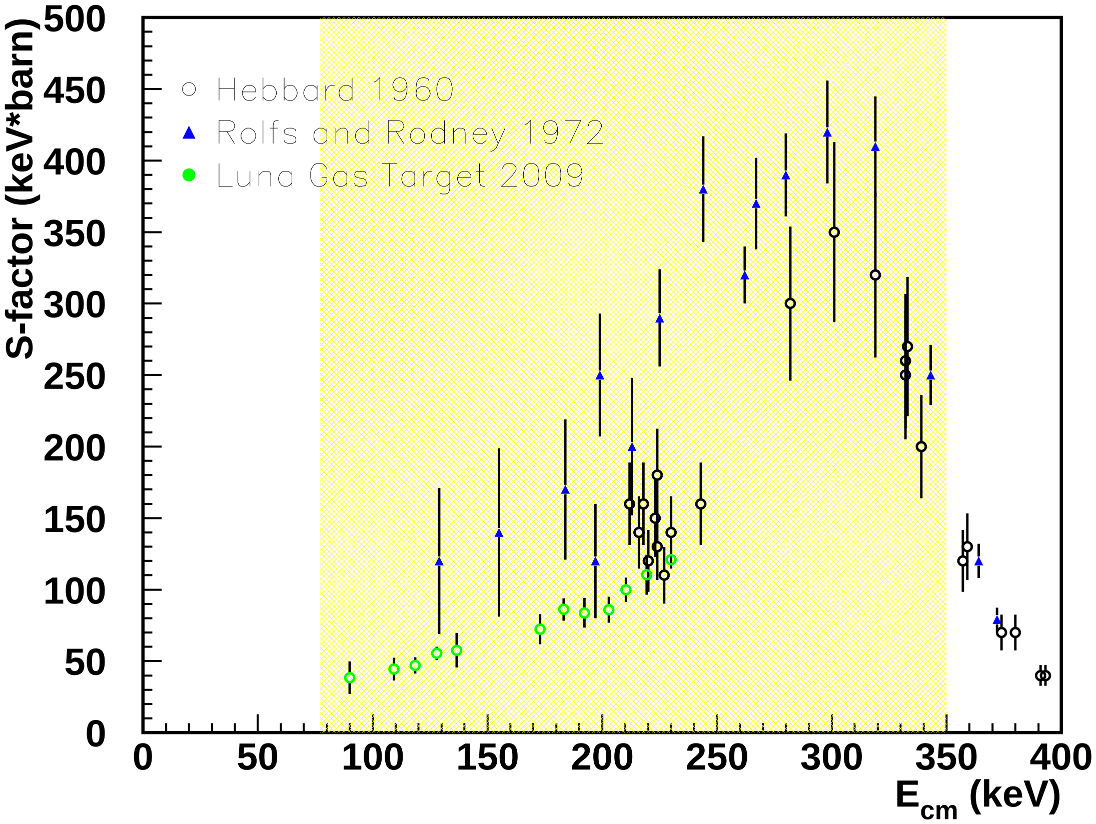

Fig. 2: Review of the experimental data available in literature for the $^{15}N(p,\gamma)^{16}O$ reaction at low energies. The data by Hebbard [3] are depicted with empty black circles, the data by Rolfs and Rodney [2] are represented through blue triangles, while the "LUNA-gas target" data [6] with green dots. The yellow-shaded area corresponds to the energy interval studied at LUNA in this work with the BGO detector and solid target, see Section 3.

3 Experiments

Two different approaches were used to measure the $^{15}N(p,\gamma)^{16}O$ reaction cross-section, with the common feature being the use of solid TiN targets enriched in ^{15}N. The first measurement, in collaboration with the University of Notre Dame, USA, used a High-Purity Germanium detector for better energy determination. The same set-up was used at three different accelerators (LUNA, covering the lower energy range, and two machines at the University of Notre Dame, covering the higher energies) to span over a wide energy interval (100−2000 keV) in the same experimental conditions. Data analysis is in progress. It will allow to perform R-matrix fits with a unique set of data and therefore study the energy dependence of the astrophysical S-factor.

In the second measurement, a low-resolution but high detection-efficiency approach was chosen. With respect to the LUNA-gas target measurement [6], several improvements were carried out in order to improve the data quality:

- solid targets enriched to 98% in ^{15}N were used. This allowed for an immediate improvement in statistics by more than 2 orders of magnitude, when the same charge is deposited on the target.
- A wider energy range (77−350 keV) was covered for better overlapping with the existing data and to push the lower-energy limit further down.

The target chamber was a cylinder which contained a coaxial copper tube ("cold finger") cooled to liquid nitrogen temperature, that served as a cold trap for impurities present in the vacuum, most of which consist of carbon. A negative voltage was applied to the cold finger to suppress secondary electron

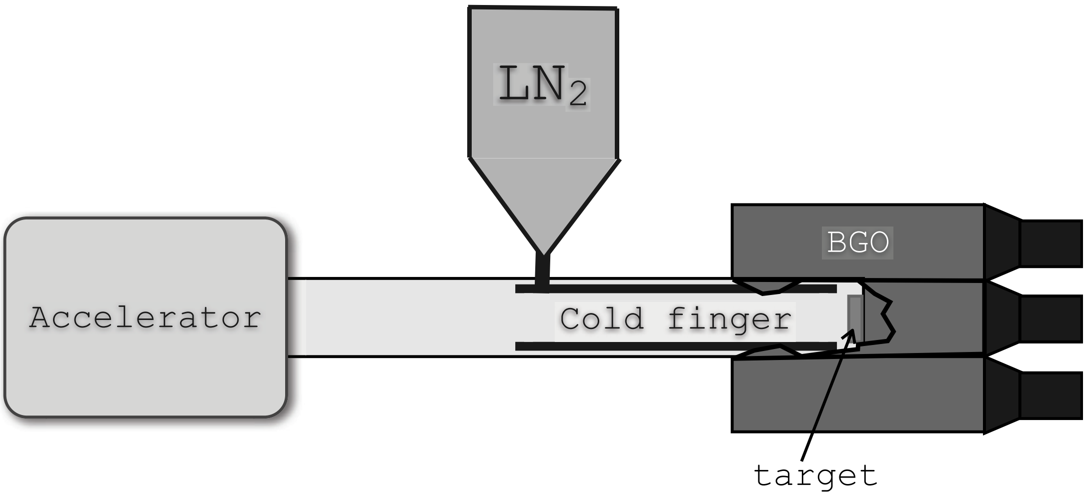

Fig. 3: Schematic representation of the experimental set-up. The drawing is not to scale.

emission from the target that would introduce a rather large systematic uncertainty on the measurement of the charge deposited on the target itself. The TiN target-material (15-20 keV-thick, i.e. $\sim$100 nm) was deposited on a tantalum backing that was positioned on the target-chamber cap. In order to dissipate as much of the heat generated by the beam impinging on the target as possible, the target holder was water cooled. For this measurement the same high-efficiency BGO detector of Ref. [6] was used. It is a total γ absorption spectrometer, shaped as a cylinder composed of six cloves, with a coaxial hole that allows to host in its centre the target chamber, see Figure 3, that reaches detection efficiencies of about 65% for 12 MeV γ-rays. The information on the γ-rays detected by the BGO spectrometer was transferred to a data acquisition system and written to disk for off-line analysis. The total charge deposited on each target ranged between 26 and 45 C.

The impinging of such amounts of beam on the target material causes the deterioration of the target qualities. Namely, the main effect is a change in shape of the target profile. This deterioration needs to be monitored and be well understood in order to correct for it while determining the cross section and subsequently the S-factor. Usually narrow resonaces are used to scan through the target and deduce its thickness. Since no narrow resonance is available for ^{15}N+p at proton energies below 400 keV, the narrow resonance in the ^{15}N(p,$\alpha\gamma$)^{12}C reaction at 429 keV was chosen. In order to perform this necessary complementary measurement the targets were shipped at the end of the experiment to the Forschungzentrum Rossendorf (FZD), Germany, where such a measurement could be done. For each target two spots were chosen for such an investigation, one far from the area hit by the beam at LUNA (*off-spot*) and one inside it (*in-spot*). The region of the target irradiated at LUNA could be clearly identified by the eye as a much darker than the non-irradiated area. In Figure 4 an example of the so-obtained profile for *in-spot* and *off-spot* measuring conditions is shown. From these profiles the target thickness can be determined by fitting an appropriate function to the data points (see Figure 4).

In order to understand the composition of the target and its variation along the depth of the target layer, the targets were afterwards sent to ATOMKI, Debrecen, Hungary for an analysis with the Secondary Neutral Mass Spectrometry (SNMS) technique. This allows to determine the relative concentration of the various isotopes in the material analysed. In Figure 5 an example of such an analysis is shown: as happened for the 429 keV resonance scan, two regions of the target were investigated, one *off-spot* and one *in-spot*. It is clear from the plots in Figure 5 that the variation of the target depth and composition is dramatic.

The information collected with these complementary measurement shall be implemented into the data analysis procedure to determine the cross section and the S-factor at the several energies investigated. This will allow to account for the target consumption during the irradiation with the proton beam.

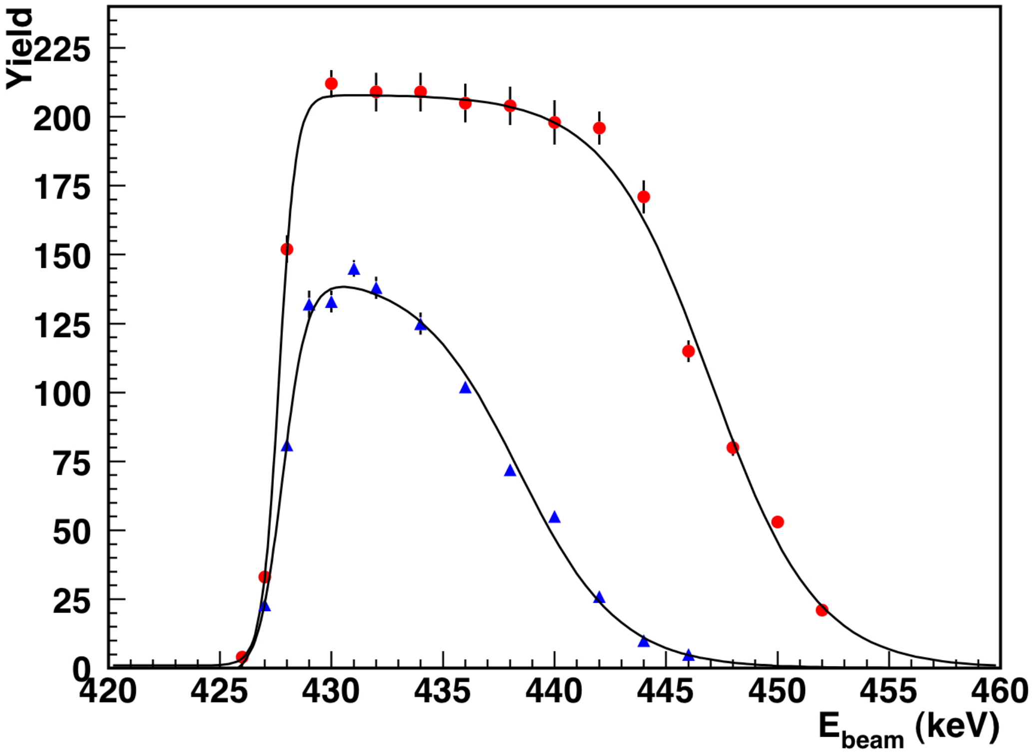

Fig. 4: Target scan for the 4^{th} target used at LUNA for the ^{15}N(p,γ)^{16}O measurement. The scan was performed at FZD with the narrow ^{15}N(p,$\alpha\gamma$)^{12}C resonance at 429 keV. The experimental data points (with error bars) are represented by red circles (*off-spot*) and blue triangles (*in-spot*). The solid lines display the respective fits. See text for details.

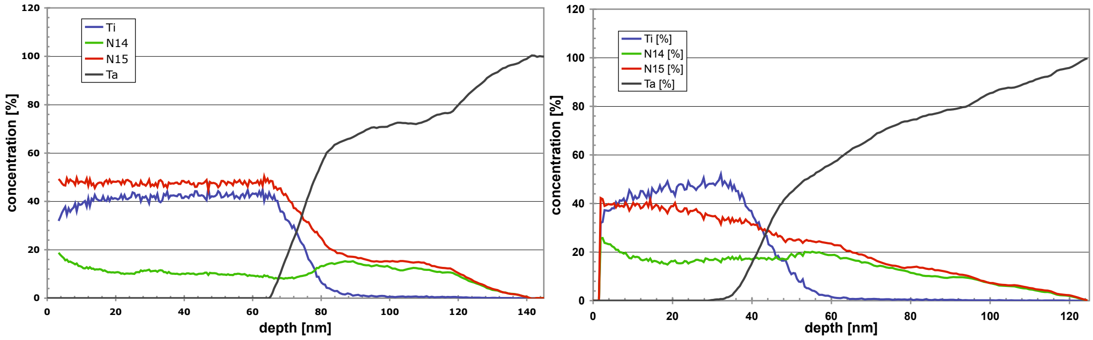

Fig. 5: Left panel: Concentration of Ti, ^{14}N, ^{15}N and Ta in a region of the target (4^{th} target used at LUNA) not irradiated by the beam (*off-spot*) obtained by the SNMS analysis. Right panel: concentration of the same isotopes in a region of the same target that was hit by the beam (*in-spot*).

4 Summary and outlook

In two measurements performed at the LUNA facility at Gran Sasso National Laboratories, data were collected to determine the S-factor of the CNO-cycle reaction ^{15}N(p,γ)^{16}O down to energies lower than previously achieved and with smaller uncertainties. This is important in order to perform better fits to zero-energy and determine S(0), clarifying the puzzle of the discordant values available in literature.

For the experiment with the BGO detector, complementary measurements on the target material were necessary for understanding the evolution of the target thickness and composition with the charge deposited on it. The data analysis of these experiments is in progress and has to be implemented into the main data analysis routine.

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