Nuclear astrophysics at Gran Sasso Laboratory: the LUNA experiment

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Abstract. LUNA is an experimental approach for the study of nuclear fusion reactions based on an underground accelerator laboratory. Aim of the experiment is the direct measurement of the cross section of nuclear reactions relevant for stellar and primordial nucleosynthesis. In the following the latest results and the future goals will be presented.

1 Introduction

The Laboratory for Underground Nuclear Astrophysics (LUNA) is located at Gran Sasso National Laboratories, Italy, where the 1400 meters of rocks dominating the laboratory guarantee a reduction of six orders of magnitude in the cosmic muon flux and a reduction of three orders of magnitude in the neutron flux. The 400 kV electrostatic accelerator provides an high intensity (~200 μA) proton or alpha beam. The beam energy spread at the exit of the accelerator was determined to be < 100 eV while the energy drift is < 5 eV/h. The uncertainty on the beam energy is 0.3 keV, mainly due to the uncertainty on the ^{12}C(p, γ)^{13}N reaction Q-value used in the energy calibration. The calibration has been rechecked several times and was found consistent with the new measurements. The beam can be delivered either to a solid or to a gas target. Different gamma-ray or particle detectors can be used, depending on the characteristics of the nuclear reaction to be studied.

Several experimental campaigns have been accomplished in the past; in particular reactions of hydrogen burning [16] e.g. ^{22}Ne(p,γ)^{23}Na [11–14], ^{17}O(p,α)^{14}N [9] and ^{23}Na(p,γ)^{24}Mg [17] were deeply studied and outstanding results were achieved. Also few reactions of Big Bang Nucleosynthesis were measured as the ^{2}H(α,γ)^{6}Li [15] and ^{2}H(p,γ)^{3}He reactions. This paper focuses on ^{17}O(p,α)^{14}N and ^{2}H(p,γ)^{3}He cross section measurements and, in the last part, on the future program.

2 ^{17}O(p,α)^{14}N

The ^{17}O$(p,\alpha)^{14}$N reaction (Q_{val}=1.2 MeV) plays a key role in several astrophysical scenarios, and in AGB stars in particular [1–3]. Models predict that massive AGB stars should produce significant amounts of cosmic dust, and yet no pre-solar grain appears to match the HBB signature expected from these stars [4]. The most obvious candidates, Group II grains, have ^{17}O/^{16}O ratios that are a factor of two lower than expected. For this reason is crucial the measurement of the ^{17}O$(p,\alpha)^{14}$N cross section.

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At energies of astrophysical interest its reaction rate is dominated [6] by a narrow and isolated resonance at E_p=70 keV. This resonance has been studied several times in the past, using both direct and indirect methods, as summarised in ref. [7]. However, the picture painted in the literature is still not completely satisfying. The uncertainty in the resonance strength is not negligible (≈20%). Furthermore, published strength values obtained with direct measurements have all been retracted or reanalysed [7].
An experimental campaign aimed at measuring the E_p=70 keV resonance in $^{17}O(p,\alpha)^{14}N$ was recently completed at the underground LUNA accelerator. We exploited the low background in the underground environment in order to carry out a direct investigation of this weak ($\omega\gamma \approx$ neV) resonance employing the thick-target yield technique. Protons were accelerated on a solid Ta_2O_5 target and alpha particles detected at backward angles using an array of silicon detectors. The setup was commissioned using the well-known E_p=193 keV resonance in $^{17}O(p,\alpha)^{14}N$ [8]. A clear peak was observed at E_p=71.5 keV at the expected energies. The alpha peak from the E_p=70 keV resonance appears where expected and has a signal significance higher than 5 sigma. Results of the analysis [9] indicate a factor of two increase in the rate of the ^{17}O(p,α)^{14}N reaction compared to [10]. This translates directly into a factor of two reduction in the expected ^{17}O isotopic content, which now closely matches the observed values [4, 5].

3 ^{2}H(p,γ)^{3}He

Big Bang Nucleosynthesis (BBN) describes the production of light nuclei in the first minutes of cosmic time. It started with deuterium formation through the p(n,γ)^{2}H reaction, when the Universe was cold enough to allow ^{2}H nuclei to survive to photo-disintegration. The main source of uncertainty on standard BBN prediction for the deuterium abundance is actually due to the radiative capture process ^{2}H(p,γ)^{3}He that destroys deuterium, because of the poor knowledge of its S-factor at BBN energies. Moreover, the paucity of ^{2}H(p,γ)^{3}He data represents the main obstacle to improve the accuracy on the determination of the baryon density and to constrain of the density of relativistic species existing at BBN epoch (only photons and 3 families of neutrinos are foreseen in the standard model). The low energy limit of this reaction cross section is well known thanks to the data coming from the LUNA measurement performed under the solar Gamow peak [18], as shown in figure 1, in the energy range of interest for the solar processes ($0\,\text{keV} < E_{cm} < 50\,\text{keV}$), the measurements of Griffiths et al. [19], Schmid et al. [20] and Bystritsky et al. [21] are also available, using a proton beam on a D_2O ice solid target. Some discrepancies exist for the lower energies data, but in [20] the authors stress on the presence of a systematic error in Griffiths's and Bailey's data due to the wrong stopping power used for the heavy-ice target, affecting the S-factor value by about 15%. In the $200\,\text{keV} < E_{cm} < 1\,\text{MeV}$ energy range, Griffiths et al. [22] and Bailey et al. [23] have measured the ^{2}H(p,γ)^{3}He cross section using once again a solid target. Warren et al. [24], instead, has measured the cross section of ^{3}He photodisintegration on a gas target and reaching a good agreement with direct measurement data. Finally in the BBN energy range only a single data set is currently available with a systematic error of 9% [25]. A measurement of this reaction cross section with a 3% accuracy in the BBN energy range ($30\,\text{keV} \lesssim E_{cm} \lesssim 300\,\text{keV}$) is thus desirable [26]. Adelberger et al. in [27] performed a fit of the reaction S-factor, using the experimental data [22], [18], [20] and [25]. The four data sets have been fitted by quadratic polynomial and plotted with the blue band in figure 1 that represents the 68% lower and upper bounds of the adopted best-fit. The fit performed by Angulo et al. in NACRE [28] is also shown. An updated version of NACRE fit has been developed by [29], adding the post-NACRE data set of LUNA [18], extending thus the energy range down to 2 keV. An evaluation of the $^2H(p,\gamma)^3He$ S-factor has been performed by Descouvemont et al. in [30]. Finally the result of ab-initio calculation are also reported [31].

The $^2H(p,\gamma)^3He$ experiment at LUNA consists of two main phases characterized by different setups. The former is a windowless gas target filled with deuterium surrounded by a 4π BGO detector. The high efficiency ($\sim 70\%$) of the BGO detector reduces the dependence of the reaction yield on the angular distribution of the emitted γ rays and thus allows to achieve a low systematic uncertainty. The detection efficiency has been determined by Monte Carlo simulations, as well as by measurements with radioactive sources (^{60}Co, ^{137}Cs, ^{88}Y) and $^{14}N(p,\gamma)^{15}O$ resonant reaction [12, 13]. The study of systematic uncertainties included also the determination of the beam heating effect obtained by varying the target pressure and beam intensity. The beam intensity value and uncertainty was determined by a proper calibration of the calorimeter. The $^2H(p,\gamma)^3He$ excitation function has been measured in the energy range $30\,\text{keV} \lesssim E_{cm} \lesssim 200\,\text{keV}$.

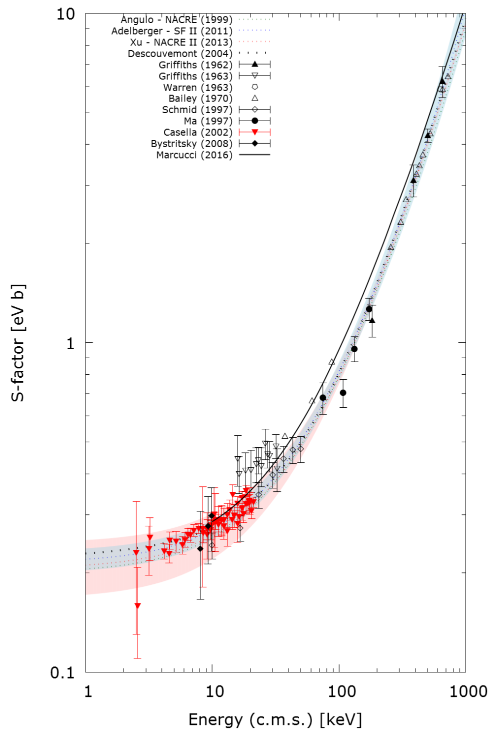

Figure 1. $^2H(p,\gamma)^3He$ S-factor as a function of center of mass energy

The latter phase, instead, focuses on the $70\,\text{keV} \lesssim E_{cm} \lesssim 260\,\text{keV}$ energy range. The set up consists of a 137% HPGe detector in close geometry with the interaction chamber. With this setup the angular distribution can be inferred by exploiting the high energy resolution of the detector and the Doppler effect that changes along the beam line the energy of the detected γ rays. This study provides an important experimental ground for theoretical nuclear physics. This measurement requires the detection efficiency to be known with high accuracy along all the target chamber. The procedure adopted couples the main HPGe detector (Ge1) to an auxiliary one (Ge2) and exploits the coincidence between two γ-rays emitted in cascade. The main decay channel of the E_r = 259 keV resonance (BR=57,8%) is particularly useful to determine the germanium efficiency, because it produces two gammas in cascade, with energy E_1= 1384 keV (close to the energy of ^{60}Co γ-rays) and E_1= 6172 keV (close to the energy of photons produced by the ^{2}H(p,γ)^{3}He reaction). Whenever the auxiliary counter detects an event 1, it enables the other counter that can thus detect the corresponding cascade emitted photon 2. The detection efficiency of Ge1 can be evaluated by the ratio between the number of events that has triggered the acquisition and the number of events actually acquired by the detector itself. The effect of the coincidence acquisition is shown in figure 2, where the spectrum of the ^{14}N(p,γ)^{15}O resonance acquired by Ge1 in inclusive configuration is shown on the left. Selecting the resonance emitted photon at 1.3 MeV with Ge2, the resulting coincidence spectrum of Ge1 (on the right in figure 2) shows the only peak of the corresponding cascade photon at 6.1 MeV.

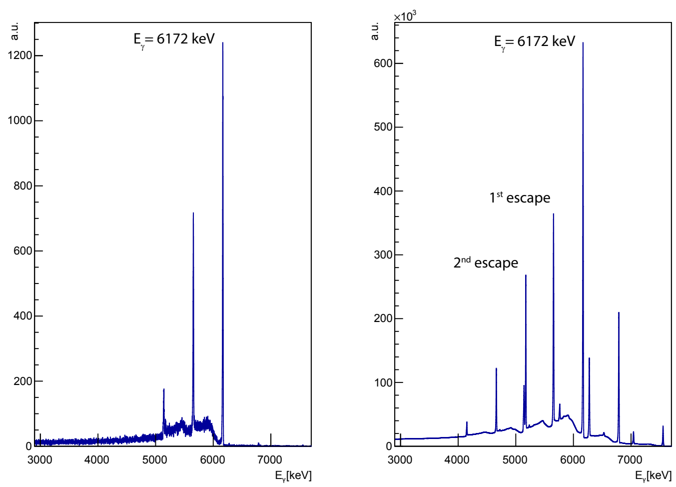

Figure 2. ^{14}N(p,γ)^{15}O resonance spectra: left the one acquired in coincidence configuration, right the one acquired in inclusive configuration

4 LUNA-MV

A new accelerator will be installed soon at LNGS to allow the study of nuclear reactions involved in helium and carbon burning. The LUNA MV accelerator will provide intense beams of H^+, $^4H^+$, $^{12}C^+$ e $^{12}C^{++}$ in the energy range: 350 keV - 3.5 MeV, and is presently under construction at High Voltage Engineering Europe (HVEE) in The Netherlands. It will be equipped with two beam lines, one for measurement at the solid target and the other one for gas or solid target, accordingly to the experimental need.

Delivery at LNGS is presently scheduled for December 2018. A six months commissioning phase is scheduled thereafter so that the first physics experiments are envisaged at middle 2019.

Since spring 2016, the design and construction of the new LUNA-MV laboratory inside Hall B has been started. The clearance of the LUNA-MV area in Hall B has been accomplished, the beginning of the construction works is forseen for the next months and the delivering of the full equipped LUNA-MV laboratory (accelerator room and technical building) by march 2018.

A full proposal (available on the LUNA web site https://luna.lngs.infn.it/) for the first five years of activity at LUNA-MV has been approved by the LUNA Collaboration in July 2016 and submitted both to LNGS and to INFN-CSN3. In particular, the first cross section to be measured will be the ^{14}N(p,γ)^{15}O in a much wider energy range compared to what was done at LUNA400. This way the tuning of LUNA MV will be done and we will more precisely extrapolate the reaction cross section within the Gamow peak of the Sun, i.e. the burning energy region. Then, the focus of the activity will be the study of ^{12}C+^{12}C: the understanding of its cross section at low energy will be the main goal of the first 5 years of LUNA MV. Alternating in time with ^{12}C+^{12}C, the study of ^{13}C(α,n)^{16}O will be performed on the other beam line (the accelerator can feed only one line at a time). Finally, ^{22}Ne(α,n)^{25}Mg will be the last reaction covered by this scientific plan. On the other hand, ^{12}C(α,γ)^{16}O will be the main goal of the second scientific plan at LUNA MV, starting in the year 2023.

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