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Laboratory for Underground Nuclear Astrophysics

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Abstract. Nuclear reactions shape the life and death of stars and they produce most of the chemical elements in the Universe. The cross section, at the energy of the Gamow peak, is a crucial ingredient to improve our knowledge on stellar and Universe chemical evolution. Its low value at stellar energies prevent direct measurements in earth-based laboratories. In recent years low energy data significantly improved thanks to underground facilities, pioneered by the Laboratory for Underground Nuclear Astrophysycs (LUNA). LUNA started its activity in 1991 with a 50 kV electrostatic accelerator installed under Gran Sasso, which is a natural shield against cosmic rays ensuring a ultra low background environment. LUNA early activity was dedicated to reactions relevant to the Sun, and then, thanks to the installation of a new accelerator (LUNA400), it focused on the study of the Big Bang Nucleosynthesis (BBN) and of the CNO, NeNa and MgAl cycles. LUNA is now facing the next steps, helium and carbon burning, thanks to the new 3.5MV accelerator, which has just started its activity at the Bellotti Facility of LNGS. The accelerator provides hydrogen, helium and carbon beams, allowing to study the reactions that shape both the evolution of massive stars to their final fate and the synthesis of most of the elements in the Universe.

1 Introduction

Stars, like cauldrons in the cosmos, cook most of the elements out of primordial ingredients, H and He, via thermonuclear reactions. During different phases of their evolution, stars possibly eject back into the interstellar medium most of the new products created in their interiors. New generations of stars, in turn, formed out of this enriched cosmic soup and will further contribute to the chemical evolution of the Universe.

To access the chemical evolution of stars, galaxies, and, ultimately, of the Universe, the cross section — i.e., the probability for a reaction to occur— is a key input for stellar models. Nuclear astrophysics aims to replicate in the laboratory these reactions to measure their cross section to better understand the network of processes that describes the observed abundances distribution. Inside the small energy range, the so called Gamow window, at which nuclear reactions take place in stars cross sections are in the pico- to femtobarn range corresponding to extremely low counting rates, ranging from a few counts per hour to a few counts per year in the most extreme cases. Therefore, cross section evaluations at stellar temperatures often must rely on extrapolations from data taken at higher energies. Extrapolating cross

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Table 1. List of the reactions investigated at LUNA with the indication of the related scenario with a reference for details.

Reaction(s)	Scenario	References
^{2}H(α, γ)^{6}Li, ^{2}H(p, γ)^{3}He, ^{3}He(α, γ)^{7}Be	BBN	[10–14]
^{2}H(p, γ)^{3}He, ^{3}He+^{3}He	pp-chain and $\nu_\odot$ problem	[15, 16]
^{6}Li(p,γ)^{7}Be	Protostar, cosmic-ray and BBN	[17]
^{12,13}C(p,γ)^{13,14}Ne	CNO kick-off reactions	[18]
^{14,15}Ne(p,γ)^{15,16}O	CNO bottleneck reaction	[19–22]
^{17,18}O(p,γ)^{18,19}F	CNO cycle	[23–26]
^{17,18}O(p,α)^{14,15}N	CNO cycle	[27, 28]
^{20,22}Ne(p,γ)^{21,23}Na	NeNa cycle	[29–33]
^{23}Na(p,γ)^{24}Mg, ^{25}Mg(p,γ)^{26}Al	MgAl cycle	[34, 35]
^{22}Ne(α,γ)^{26}Mg, ^{13}C(α,n)^{16}O	*s*-process	[36, 37]

section down to low energies is extremely risky procedure, since, for example, the possible contributions from unknown resonances (either above or below threshold) or the electron screening effect [1] cannot be taken into account properly.

To constrain extrapolations, experimental efforts must be dedicated to pushing direct measurements to lower and lower energies. Deep underground laboratories are unique locations for key experiments in nuclear astrophysics, thanks to their reduction of the background from cosmic-rays, by several orders of magnitude [2]. The combination of such a low background location and a high intensity accelerator has been the foundation of long successful campaigns at LUNA [2], and motivated the construction of several new deep-underground accelerator facilities – CASPAR [3], JUNA [4], LUNA-MV [5] – as well as a shallow-underground accelerator laboratory, the Felsenkeller [6].

LUNA started its activity in 1991 with the installation of a 50 kV accelerator at the Laboratori Nazionali del Gran Sasso (LNGS) of the Italian Istituto Nazionale di Fisica Nucleare (INFN). The accelerator was designed to investigate nuclear reactions from the p–p chain at energies close to the solar Gamow window [7]. Thanks to the success of those early measurements and due to the constant need of maintenance of the ion source the 50 kV accelerator was replaced in 2001 with a 400 kV electrostatic machine, still in operation today [8]. Its energy range has allowed for the investigation of many key reactions at the relevant energies of hydrogen burning, in different phases of stellar evolution, and of big bang nucleosynthesis (BBN), see Table 1 for a list of reactions studied by LUNA. The high intensity beam from LUNA 400-kV accelerator, up to 1 mA for H^+ and 0.5 mA for He^+, is directed either toward the gas- or the solid-target station. Since last year a new accelerator is working at LNGS with a dynamic range between 300 keV and 3.5 MeV and providing intense beams of H^+, He^+, C^+ and C^{2+} [9]. Given these features the accelerator will allow to investigate reactions of the helium and carbon burning. The new accelerator is part of the Bellotti Ion Beam facility (IBF) at LNGS and recently LUNA proposed and get approved measurements of the key processes ^{14}N(p,γ)^{15}O, ^{22}Ne(α,n)^{25}Mg and the ^{12}C+^{12}C reaction.

In the following sections I will describe one of the investigation ongoing at LUNA400 and I will introduce some of the future measurements planned by LUNA.

2 The Study of the ^{17}O(p,γ)^{18}F reaction

The oxygen isotopic ratios, observed in observed in giant stars [38] and in dust grains [39], are strongly affected by the ^{17}O + p reaction rates. These reactions take part to the CNO cycle active in the H-burning shell at $T = 20$ - 80 MK [40]. At these temperatures the $^{17}O(p,\gamma)^{18}F$ reaction (Q = 5607 keV) rate is dominated by the poorly constrained 65 keV resonance.

The strength of this resonance is presently determined only through indirect measurements, the Γ_γ and Γ_α were provided by measurement of the $^{14}N(\alpha,\gamma)^{18}F$ and $^{14}N(\alpha,\alpha)^{14}N$ reaction respectively [41, 42]. The Γ_p, is derived from the $\omega\gamma$ of the $^{17}O(p,\alpha)^{14}N$ channel and it contributes the most to the final uncertainty because of the discrepant results reported in literature [27, 43]. The most recent resonance strength evaluation is $\omega\gamma_{(p,\gamma)} = (16 \pm 3)$ peV [44]. Such a low resonance strength translates in an expected rate as low as 0.08 reactions per hour (assuming a fully enriched target and a beam current of 100 μA), thus a direct measurement of the E_r = 65 keV resonance strength required both a high sensitivity setup and a dedicated technique to monitor and subtract potential beam-induced background (BIB), both described in detail in [45].

The proton beam provided by LUNA400kV accelerator, 200 μA at E_p = 80 keV was delivered through a Cu pipe, acting as cold trap and secondary electron suppressor, to the target. The Ta_2O_5 solid targets were produced by anodization of tantalum backings in 90% ^{17}O enriched water doped with 5% ^{18}O [46]. Target degradation was prevented by water cooling the target and it was monitored via periodical scan of the E_r = 143 keV resonance in the $^{18}O(p,\gamma)^{19}F$ reaction [26].
Both the scattering chamber and the target holder were made in aluminum, providing an increase in efficiency of more than 20% with respect to the previous stainless-steel and brass setup. The high efficiency (74% at 661 keV) Bismuth-Germanium-Oxide (BGO) detector surrounded the reaction chamber, covering a 4π angle. The detector is made of six optically independent crystals, which coupled with a listmode DAQ allows both a single crystal reading and the construction of the add-back spectrum, namely by adding coincident events in the individual crystals. To increase our sensitivity, the residual background was further reduced by a three layer shielding which was installed all around the detector and the target chamber. The shielding is made of 1 cm thick layer of borated(5%) polyethylene, 15 cm thick lead shielding and 5 cm thick borated (5%) polyethylene envelope. The detected background, of $2.6(3) \times 10^{-8}$ counts/(s $\cdot$ 20 keV), was reduced by a factor 4.3 $\pm$ 0.1 in the region of interest (ROI) for our measurement (5.2 - 6.2 MeV), with respect to using only lead [45].

An accurate (the uncertainty was estimated at 3% level) Montecarlo Geant4 based simulation of the setup was crucial for the analysis of the acquired data and efficiency determination [45].

About 400 C were accumulated on top of the resonance with $Ta_2^{17}O_5$ targets and 300 C with targets made with ultra pure water (UPW), with negligible amount of ^{17}O to monitor the BIB. Tantalum is, indeed, a natural absorber of H and D [47] and the p+D (Q = 5493 keV) reaction produces a single γ peak at the same energy of the $^{17}O(p,\gamma)^{18}F$ 65 keV resonance sum-peak. Moreover the p+D cross section is much higher than the case of interest.

In order to subtract this BIB a technique was developed which combines our knowledge of the E = 5672 keV de-excitation branching ratios, signature of the resonant state of interest only, and of the BGO detector segmentation. Thanks to the list mode acquisition, multiplicity 2 and 3 transition γ-rays, contributing to the sum peak (ROI = 5200-6200 keV in the addback spectrum) and with energies matching the 5672 keV de-excitation chain, were selected. Multiplicity 1 events were rejected as due to p+D reaction. This allows an almost complete background subtraction while losing only a small amount of resonance γ, since the probability of ground state transition (multiplicity 1) is 6%. Residual spurious coincidences by BIB were subtracted applying the same analysis on UPW target spectra.

To accurately obtain the resonance strength another contribution must be taken into account, the direct capture component, which was estimated down to the energy of interest from the R-matrix fit of the data in literature [48–54].

The final result of the resonance strength must be corrected for the screening effect as suggested in [1]. It must be underlined that a recent paper suggested a different treatment [55]. The error budget on the resonance strength accounts for uncertainty of the efficiency (3%), branchings (6%), stopping power uncertainty (4%), charge integration (2%) and target composition. It must be stressed out the for the stopping powers for proton in Ta a recent work reported a higher value, by 12% with respect to the SRIM database [56], with an impact on the resonance stregth within the total uncertainty.

At the time of writing this proceeding, the last acquired data is being analysed and an in-depth evaluation of the uncertainties is being performed. The final results of the first direct measurement of the 65 keV resonance in the $^{17}O(p,\gamma)^{18}F$ reaction will be published soon in a dedicated paper.

3 Outlooks

Two accelerators are now working at the LNGS. One of the main goal of the next LUNA400kV activity is the measurement of the ^{23}Na(p,α)^{20}Ne reaction, crucial to improve our current understanding of the globular cluster Na/O anticorrelation [57]. At temperatures of interest ($T \sim 0.05 - 0.1$GK), four narrow resonances at centre of mass resonant energies $E_r = 37$, 138, 167 and 170 keV are known to exist in the ^{23}Na(p,α)^{20}Ne reaction [58]. In particular, nuclear uncertainties in the rate of the ^{23}Na(p,α)^{20}Ne reaction are dominated by the strength of the tentative $E_r = 138$ keV resonance [58].

LUNA is planning to investigate this resonance exploiting the benefit of the underground location, which guarantees a reduction in the background of about one order of magnitude, and the high performance of the LUNA 400 kV accelerator. A dedicated particle detectors array and new sodium targets have been designed and are now under installation and characterization, respectively.

In parallel LUNA collaboration will be at work at the Bellotti IBF on both beam lines with the investigation of the ^{22}Ne(α,n)^{25}Mg and the ^{12}C+^{12}C reaction.

The former reaction is of crucial importance for nucleosynthesis via *s*-process. The ^{22}Ne(α,n)^{25}Mg reaction is, indeed, the main neutron source in massive stars. At energies of interest the rate is dominated by many tentative resonances and the strong $E_\alpha = 832$ keV resonance [59–62]. LUNA collaboration will investigate the ^{22}Ne(α,n)^{25}Mg reaction cross section down to the threshold energy of $E_\alpha = 564$ keV using a dedicated extended gas target, presently installed and under characterization at the Bellotti IBF. A neutron detector array, which combines 18 ^{3}He counters and 12 scintillators, placed in a borated polyethylene passive shielding will be used. The measurement will start soon.

The ^{12}C+^{12}C reaction is of crucial importance to determine the evolution of stars having a significant impact on the M_{up} parameter [63]. The available direct data, for the main fusion channels the ^{12}C(^{12}C,α)^{20}Ne and the ^{12}C(^{12}C,p)^{23}Na reactions, extend down to 2.2 MeV [64–70] while the energies of astrophysical interest is between 1 and 2 MeV. However, a recent debated indirect measurement reported data down to low energies showing several resonances [71, 72]. LUNA is going to directly access the ^{12}C+^{12}C reaction cross section inside the Gamow window for the first time. The first measurement phase, indeed, aims to explore the 3.5 - 2.0 energy range while a second phase will extend down to 1 MeV, exploiting the deep underground location and the intense carbon beam available at the Bellotti IBF. For the forthcoming phases, the LUNA measurement will focus on γ-rays emitted due to the de-excitation of the first excited states in ^{20}Ne and ^{23}Na respectively. The detection system consists of a High Purity Germanium detector, with a relative efficiency of 150%, located at 0° with respect to the beam direction. The HPGe detector will be in close geometry to maximize the solid angle mitigating also the possible angular distribution effect. In addition an anti-Compton array of NaI scintillators will be installed all around the target and the HPGe detector. The detectors and the scattering chamber will be embedded in a dedicated shielding. Different types of target are now under test. Preliminary characterization of the setup and measurement at high energies will start soon. LUNA is also working on future phases dedicated to the study of $^{12}C(^{12}C,\alpha)^{20}Ne$ and the $^{12}C(^{12}C,p)^{23}Na$ channels via particle detection.

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