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Nuclear astrophysics experiments deep underground at LUNA: recent results and next steps at the new 3.5 MV facility

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At astrophysical energies the cross sections of nuclear processes are usually very small and cosmogenic background prevents their measurement on the Earth surface. Deep underground in the Gran Sasso Laboratory, crucial reactions involved in hydrogen burning has been measured by the LUNA (Laboratory for Underground Nuclear Astrophysics) Collaboration. Presently a new exciting experimental phase has started thanks to acquisition of the LUNA-3.5 MV accelerator, already installed and operating at Gran Sasso. The accelerator is able to provide hydrogen, helium and carbon high current beams and it will allow to study the key reactions shaping the evolution of massive stars. In particular, in 2023, a first data acquisition campaign will be focused on ^{22}Ne(α,n)^{25}Mg that for massive Asymptotic Giant Branch (AGB) stars represents the main source of neutrons, affecting the total abundances of the elements heavier than Fe. The present contribution is aimed to summarise the most recent results achieved at the 400 kV accelerator and to highlight the next steps of the experimental program connected to the new facility.

XVIII International Conference on Topics in Astroparticle and Underground Physics (TAUP2023)
28.08-01.09.2023
University of Vienna

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https://pos.sissa.it/

PoS(TAUP2023)313

1. Introduction

The low background environment of the Gran Sasso National Laboratory, about one million times lower than that on Earth's surface, together with the high intensity beams guarantees enhanced sensitivity to the low cross section of stellar fusion processes. Since thirty years the LUNA collaboration has been active in studying astrophysical reactions [1]. A new phase has recently started with the inauguration of the new Bellotti Ion Beam Facility in October 2023: the facility comprises the LUNA 3.5 MV accelerator and two beam lines for solid and gas targets, respectively. Details about LUNA-400 and LUNA-MV accelerators are reported in [2, 3]. The availability of high current H, He and C beams will open the possibility to study BBN and advanced burning processes over a broad energy range. In the next sections we report the recent results obtained at LUNA-400 accelerator on the $^{12}C(p,\gamma)^{13}N$ and $^{13}C(p,\gamma)^{14}N$ and $^{20}Ne(p,\gamma)^{21}Na$ reactions and we present the first experimental goals at LUNA-MV [4].

2. CNO cycle: the $^{12}C(p,\gamma)^{13}N$ and $^{13}C(p,\gamma)^{14}N$ reactions

The $^{12}C/^{13}C$ ratio can be directly measured from absorption lines in stellar spectra or by studying SiC grains in metheorites [5]. It represents therefore a precise benchmark for stellar models and a significant probe of nucleosynthesis and mixing processes during hydrogen burning in stars. There are several open questions asking for more precise nuclear data inputs. As an example, it is known that during Red Giant Branch (RGB) convective mixing, ^{13}C is pushed toward the surface: according to the models the ratio should drop to ~25, but some stars show 6-12 [6]. This disagreement could be an indication for extra-mixing processes. However, a fruitful exploitation of the carbon isotopic ratio as a probe of extra mixing requires a reliable evaluation of the stellar rates of both $^{12}C(p,\gamma)^{13}N$ (Q = 1.944 MeV) and $^{13}C(p,\gamma)^{14}N$ (Q = 7.551 MeV) reactions. Among other reasons of interest we remind that the $^{12}C(p,\gamma)^{13}N$ is one of the main sources of the solar CNO neutrino flux, recently observed by Borexino through the β^{+} decay of ^{13}N: its reaction rate controls the onset of the cycle, before equilibrium, and the radial profile of ^{13}N-ν emission citeBahcall 2006. The present uncertainty on the cross section is 30%, the desiderable 5%.

Both reactions have been studied at LUNA-400 down to the lowest energies to date ($E_{c.m.}$ = 60 keV) reaching for the first time the high energy tail of hydrogen burning in the shell of giant stars [8]. Three different types of targets were used: 4mm thick ^{nat}C disks, and ^{nat}C and 99% enriched ^{13}C powders evaporated onto chemically cleaned Ta backings, which were produced and characterised at ATOMKI Laboratory (HG). The entire target chamber was isolated and acted as a Faraday cup. Two complementary detection systems were used: the first involved the use of a 120% HPGe detector at an angle of 0° to the beam axis and at a distance of ~ 1.4 cm from the target; the second detection system was based on a 4π BGO detector segmented into six crystals of equal shape and size [8]. Given the much higher efficiency of the BGO compared with the HPGe, the second setup allowed to push measurements to the lowest accessible energies ($E_{c.m.}$ = 60 keV), i.e., within the Gamow energy region of interest for AGB and, for the first time, RGB stars. Two different approaches were followed in the analysis: the study of prompt γ-ray emission and activation measurements in the case of the $^{12}C(p,\gamma)^{13}N$ reaction, looking at the two 511 keV γ-coincidence from the ^{13}N-β^{+}decay ($T_{1/2}$=10 min., η=22%). The cross sections, obtained with both prompt γ-rays and activation methods, came out in excellent agreement with each other (Fig. 1) and they are the most precise to date with overall systematic uncertainties of 7–8%. Compared with most of the literature, LUNA results are systematically lower, by 25 % for the $^{12}C(p,\gamma)^{13}N$ [9, 10] reaction and by 30% for $^{13}C(p,\gamma)^{14}N$ [11]. The extrapolation of S-factor to the lowest energies of astrophysical interest was performed using the R-matrix formalism implemented in AZURE2 code [8] (Fig. 1). The LUNA S-factors dominate R-matrix extrapolations at the lowest energies: the revised reaction rates resulted in a reduced C isotopic ratio at relevant temperature for mixing effects in giant stars [8].

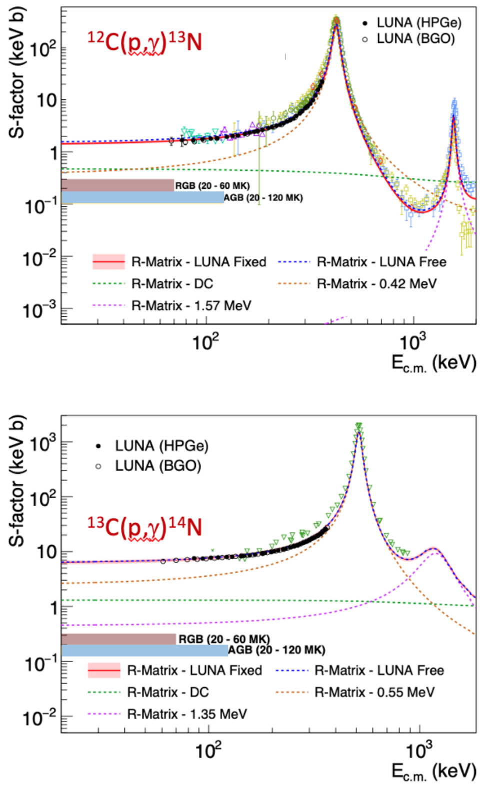

Figure 1: R-matrix fit to literature S-factor data [8]: LUNA data for HpGe (BGO) phases are shown as filled (open) black circles. See [8] for details.

3. NeNa cycle

Much experimental activity was devoted in the last years to the study of NeNa and MgAl cycles reactions because of their relevance to the synthesis of Ne, Na, and Mg isotopes. The typical astrophysical sites are RGB stars, AGB stars and O-Ne Novae in the temperature range between 0.1 and 1 GK [12]. The $^{20}Ne(p,\gamma)^{21}Na$ is the first reaction and the bottleneck of the NeNa cycle: having the slowest reaction rate, it controls the speed of the entire cycle. In order to better constrain the overall astrophysical reaction rate of this reaction the LUNA collaboration has started a new experimental effort [13] to precisely measure the 368 keV resonance strength and to improve the knowledge of the cross section at proton energies below 400 keV. Natural composition neon gas

(90.48% ^{20}Ne) was used inside a windowless gas target system [16], with a typical working pressure of 2 mbar. The beam intensity was measured by a calorimetric approach in order to avoid possible uncertainties due to the beam charge state fluctuations [16]. Because of the relatively low Q-value (2431.68 keV), most of the expected gamma-ray lines are below 3 MeV, i.e. in a region of the spectrum dominated by ambient radioactivity. At the proton energies in the range 50 - 400 keV, we expected to mainly observe the transitions to the 2424.9 keV and the 331.9 keV excited states in ^{21}Na, while transitions to the ground state should be much weaker. A fully shielded setup was essential: the detection system consisted of two HPGe with 90% and 130% relative efficiency, respectively. The detectors were shielded by a few centimetres of high-conductivity oxygen-free copper and by about 25 cm of low radioactivity lead placed in an anti-radon box : the environmental background was thus reduced by about three orders of magnitude in the region of interest [15]. A complete scan of the $E_{c.m.}$= 368 keV was performed by changing the beam energy and therefore populating the resonance in different positions along the target. The uncertainty on the resonance energy ($E_{c.m.}$=368.0±0.5 keV) was reduced by a factor 10 respect to the literature and the branching ratios for the transitions to the 2424.9 keV and the 331.9 keV excited states in ^{21}Na, as well to the ground state have been determined. Once corrected for the detection efficiency, each position of the resonance scan returned a very well consistent value for the strength for both detectors: the average value of 0.112±0.002(stat)±0.005(sys) confirms the result obtained by Rolfs and co-workers [12], with a factor 3.5 smaller uncertainty. Later on it was started the campaign to measure the direct capture process for energies E_p = 260 - 380 keV taking long runs at p = 2 mbar. At E_p = 400 keV the pressure was decreased to 0.5 mbar in order to not excite the 368 keV resonance. We observed the primary gammas for all the transitions. The LUNA astrophysical factors have been fitted in a R-matrix formalism together with literature data by Rolfs et al. [12] and Lyons et al. [14]. The new stellar rate is show in Fig. 2 where the temperature regions for the different astronomical sites are also indicated. The uncertainty was more that halved at 0.2 GK, very relevant for novae. The impact of the new results for specific astrophysical scenarios was evaluated. In particular for a 5 $M_{\odot}$, low metallicity TP-AGB star the ^{21}Ne abundance was reduced by 26% respect to the reference NACRE compilation [18]. In O-Ne novae of 1.25 M accreting material at a rate of $+2{\cdot}10^{-10}$ $M_{\odot}$/year the production of Ne, Na, and Al isotopes is decreased by 5-40%, in particular 20% reduction in the produced ^{22}Na. A detailed description of the astrophysical consequences is reported in [13].

4. Next steps at the Bellotti Ion Beam Facility

The Bellotti Ion Beam Facility facility is placed in the north side of Hall B in the Gran Sasso Laboratory and it consists of an accelerator room with concrete walls and a multistory building housing the control room and technical facilities. The 3.5 MV linear DC accelerator (LUNA-MV) was developed by High Voltage Engineering to fulfill the stringent requirements on beam intensity and stability. The need for high-intensity protons as well as carbon ions in the charge state 2^+ were the reasons for choosing an electron cyclotron resonance (ECR) ion source. The accelerator operates at a terminal voltage range of 300 kV - 3.5 MV, while the ion source can operates at maximal voltage equal to 40 kV. In the present system, mA intensity could be maintained over a large dynamic range: compared to previous Singletron accelerators, the LUNA-MV has improved

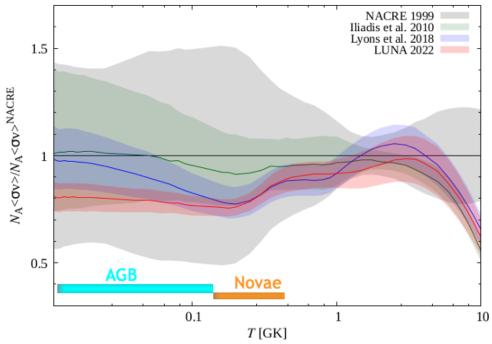

Figure 2: LUNA thermonuclear reaction rate (red) compared with NACRE [18] compilation (grey), Iliadis et al. (green) [17], and Lyons et al. [14] (blue) rates. The shaded area shows the 1σ-uncertainty. The rates are normalized to NACRE.

terminal voltage stability and ripple ($\sim 10^{-5}$). The beam energy reproducibility is of the order of 10^{-4}.

The first experimental phase at LUNA-MV will be focused on selected key processes of post main sequence stellar phases [4]: in detail, the $^{22}Ne(\alpha, n)^{25}Mg$, that is a source of neutrons for the s-process in asymptotic giant branch and thermally pulsing stars, and the ^{12}C + ^{12}C reactions, key process of carbon burning and real "Holy Grail" of nuclear astrophysics. Even if more extensively studied, also other important processes of H-burning will be better constrained thanks to the new facility: as example the $^{14}N(p, \gamma)^{15}O$ reaction, presently known only at energies well above the Gamow peak. The success of the LUNA approach has driven similar underground facilities already in operation in the US and in the Republic of China. This worldwide effort will allow in the next decades to achieve important advancements in the field of nuclear astrophysics.

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