Nuclear astrophysics in underground laboratories

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Abstract.
Nuclear processes are responsible for energy generation that makes stars shine, for the synthesis of the elements in stars and also play a decisive role in explaining the chemical composition of the interstellar medium. The experimental determination of the reaction cross section at the astrophysical relevant energies is extremely difficult due to the Coulomb repulsion between the interacting nuclei which turns out in cross section values down to the fbar level. As a result, these cross sections are often too small to be measured in laboratories on the Earth’s surface, where the signal would be overwhelmed by the cosmic-ray induced background. An effective way to suppress the cosmic-ray induced background is to perform experiments in underground laboratories. 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
Nuclear astrophysics is an extremely rich field, strongly correlated with many other research fields like astronomy, stellar modelling, cosmology, neutrino physics and nuclear physics. Nuclear fusion reactions are the heart of nuclear astrophysics.

The whole life of stars can be described as a sequence of phases in which heavier and heavier elements are burnt inside the stellar core. Starting from primordial hydrogen and helium, a variety of elements is produced at each step and theoretical models try to match predicted elemental abundances with astronomical observations.

The interacting nuclei inside the stellar plasma are positively charged and repel each other with a force proportional to the nuclear charge. For this reason, even if fusion reactions have a positive Q-value, a temperature of about $10^7$ K in case of hydrogen burning is required so that the projectiles can penetrate the Coulomb barrier. In fact, the fusion can occur only if the Coulomb barrier is overcome. Classically the interaction energy must be higher than the effective height $E_C$ of the Coulomb barrier, while quantum mechanically one finds that there is a small probability for the particles with energy $E < E_C$ to penetrate the Coulomb barrier (Tunnel effect). Such energy represents the so called Gamow peak, which arises from the convolution
of the energy distribution of nuclei in the stellar plasma and the tunnelling probability through the Coulomb barrier between the interacting charged particles.

So far, to overcome these problems of the direct measurements, several indirect methods have been introduced and successfully adopted [1]. An alternative and unique solution to reduce the natural and cosmic background is to install an accelerator facility in a laboratory deep underground. The LUNA experiment is located under the Gran Sasso Mountain where an average thickness of 1400 m of rock, equivalent to 3800 m water, suppresses the muon and neutron fluxes by six and three orders of magnitude, respectively, compared with the Earth’s surface.

2. LUNA experiment

The 400 kV electrostatic accelerator provides a 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 [2], mainly due to the uncertainty on the $^{12}$C(p, $\gamma$)$^{13}$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. In the first case, the proton beam is guided and focused to the target station using an highly stable analysing magnet and a copper pipe extending to 2 mm from the target. The pipe is cooled to liquid nitrogen temperature and serves as a cold trap to prevent carbon buildup. A negative voltage is usually applied to the cold trap to suppress secondary electrons. The isolated target holder serves as a Faraday cup for beam integration. Furthermore the target is usually water cooled by deionized water.

The main advantage in using a gas target is the isotopical purity and the high stability of the target material over long periods of measurement. For nuclear astrophysics studies, the best solution is usually a windowless gas target; it avoids any energy straggling due to a solid containment along the beam path. In fact, at the low proton energies of interest for the astrophysics, a gas target separated from the accelerator by any solid wall would not be suitable because it is impossible to construct a window thin enough to reduce the energy straggling of the beam to less than 1 keV and, at the same time, thick enough to withstand the pressure gradient between target and accelerator (typical values are a few mbar). Therefore, to contain the gas inside the target chamber, a vacuum system with differential pumping stages has been adopted at LUNA. The setup includes, besides the analyzing magnet bending the beam to 45°, a vertical steering magnet, located right before the analyzing magnet, and vacuum pumps, necessary to maintain a pressure of $10^{-7}$ mbar inside the accelerating tube. Before reaching the gas target, the beam passes through several apertures AP3, AP2 and AP1, with decreasing diameter and hence increasing impedance which collimates the beam into the target chamber. The gas flows into the target chamber from the right in the Fig.1; it is inserted through valve VT, and then continues its path in the direction of the accelerator tank through the water-cooled aperture AP1. This aperture is sufficiently long and narrow to enable a typical pressure drop of a factor 30 between target chamber and first pumping stage. When isotopically enriched or rare gases are used, the exhaust from the Roots pumps cannot be discarded but must instead be recycled. The gas coming out from the first and the second stages can be compressed by a dry forepump, sent to a purifier which removes oxygen and nitrogen contamination and finally stocked in a buffer.

Thanks to the experimental apparatus described above, several cross sections of crucial reactions of hydrogen burning and Big Bang Nucleosynthesis [3] have been measured in the past down to the energies of astrophysical interest [4, 5].
3. Latest results and ongoing measurements

The $^{22}\text{Ne}(p,\gamma)^{23}\text{Na}$ reaction

Recent studies of globular clusters (GC) with high-resolution, very large telescopes revealed a O-Na anti-correlations among evolved GC stars on the Red Giant Branch [6]. The stellar sources responsible for the GC chemical anomalies have not been indubitably identified yet. Competing nucleosynthesis sites today are massive AGB stars undergoing hot bottom burning [7] on the one hand, and fast rotating massive stars on the other hand. A possible approach consists in assuming that within each cluster there is a unique mechanism that produces some given amount of sodium and destroys almost all O (transforming it into N), and that the processed material is than mixed with a variable amount of pristine material [8]. Finally, any predictions of surface abundances strongly depend on the accuracy of the nuclear reaction rates of involved reactions. Since the reactions involved in the oxygen destruction have already been studied in the past, the major effort at LUNA in the last years has been devoted to the mechanism of sodium production, i.e. the $^{22}\text{Ne}(p,\gamma)^{23}\text{Na}$ reaction.

Another scenario where the $^{22}\text{Ne}(p,\gamma)^{23}\text{Na}$ reaction is active are classical novae explosions. The $^{22}\text{Ne}(p,\gamma)^{23}\text{Na}$ reaction rates reported in the compilations by NACRE [9] and STARLIB [10] are three orders of magnitude discrepant in the energy range of interest for hydrogen burning in AGB stars.

The $^{22}\text{Ne}(p,\gamma)^{23}\text{Na}$ Gamow window lies between 50 and 600 keV for AGB stars and classical novae. In this energy range, the proton capture on $^{22}\text{Ne}$ is dominated by a large number of resonances. While some of the resonances could be measured with good precision in overground experiments [11, 12], the resonances below 400 keV, including two tentative resonances at 70 and 100 keV, and the direct capture contribution were the subject of an extensive experimental campaign at LUNA.

The LUNA measurements were organized in two campaigns, both exploiting the windowless gas target system filled with neon gas enriched in $^{22}\text{Ne}$ isotope: in the first campaign, gamma rays were detected using two high-resolution HPGe detectors [13, 14, 15, 16] while the second campaign made use of a high-efficiency BGO detector [17, 18]. In the first campaign the resonances at 156.2, 189.5 and 259.7 keV were observed for the first time in a direct experiment. For these resonances, the complete excitation function was measured and then a long run at the energy of maximum yield was performed. The upper limits on the resonances at 70 and 100 keV were performed. For these resonances, the complete excitation function was measured and then a long run at the energy of maximum yield was performed.

Figure 1. Schematic lay-out of the LUNA windowless gas target setup.
keV were reduced significantly during the BGO phase and the non-resonant contribution to the cross section was measured for the first time in the center of mass energy range between 100 and 300 keV. Fig. 2 shows the updated reaction rate adopted in [18]. The two tentative resonances at 70 and 100 keV are included in the calculation of the median and high rates, while the low rate is calculated disregarding the two resonances. The remaining uncertainties on the $^{22}\text{Ne}(p,\gamma)^{23}\text{Na}$ reaction rate at low temperature have been greatly reduced. The new rate has been shown to enhance $^{23}\text{Na}$ production in the hot bottom burning [7] process.

The $^2\text{H}(p,\gamma)^3\text{He}$ reaction

The observed primordial abundance of deuterium, $(\text{D:H})_{\text{obs}}$, is presently known with very good accuracy, $(\text{D:H})_{\text{obs}} = (2.527 \pm 0.030) \times 10^{-5}$ [19] thanks to Damped Lyman-Alpha (DLA) systems at high redshift. On the contrary, the theoretical value of deuterium abundance $(\text{D:H})_{\text{BBN}}$ is presently much less accurate [20] due to the insufficient knowledge of $S_{12}$ in the relevant energy interval. Only a single data-set of $S_{12}$ is available in the relevant energy range [21] and, according to the Authors, it is affected by a systematic error of 9%. The situation is even worst when considering a 20% discrepancy of that data with the theoretical previsions [22]. For all these reasons an experimental effort to measure the cross section with 3% accuracy is needed.

The $^2\text{H}(p,\gamma)^3\text{He}$ experiment at LUNA has been performed with a windowless gas target filled with deuterium; 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 responsible for the broad energy distribution of the detected gamma rays coming from different directions inside the extended gas target. The $^2\text{H}(p,\gamma)^3\text{He}$ photons have an energy of about 5.5 MeV, far away from the energy of the commonly used radioactive sources. Thus, for determining the setup efficiency a different technique based on the well-known resonant reactions $^{14}\text{N}(p,\gamma)^{15}\text{O}$ and on $^{60}\text{Co}$ radioactive decay has been used. In order to reduce the systematic error due to the summing correction, the set-up efficiency has been measured exploiting the coincidence between two $\gamma$-rays emitted in cascade.
(from source as well as from reaction) and detected by two different germanium detectors, the main detector (Ge1) and a second one used as the acquisition trigger (Ge2). Whenever Ge2 detects an event 1, it enables Ge1 that can thus detect photon 2 emitted in cascade: the ratio of the observed photons with respect to the number of triggers provides the Ge1 efficiency. In case of $^{60}$Co, for each radioactive decay process, two photons, $1 = 1.17$ MeV and $2 = 1.33$ MeV, are produced. In the case of the resonant capture, several decay branches are able to provide two photons in cascade of energies up to 6.7 MeV, even higher than the $^2$H(p,γ)$^3$He reaction. This method allows fixing precisely the detector energy response.

To measure the cross section a scan in the energy range of interest ($30$ keV < $E_{cm}$ < $300$ keV) with 30-50 keV steps has been performed; two runs were done for each energy: one with deuterium gas inside the scattering chamber, the other with $^4$He in order to evaluate the beam induced background contribution and the eventual deuterium implantation. A sample spectrum acquired at 175 keV beam energy is reported in figure 4. The data taking has been completed, the analysis is ongoing.

![HPGe spectrum with deuterium at $E_{lab} = 175$ keV](image)

**Figure 3.** $^2$H(p,γ)$^3$He spectrum measured at 175 keV beam energy with deuterium gas. The full energy peak is clearly visible together with the second and the third escape peaks.
Figure 4. Beam induced background spectrum measured at 175 keV beam energy with helium gas. Highlighted the region of interest for the $^2\text{H}(p,\gamma)^3\text{He}$ where there are no relevant contaminants.

The $^{13}\text{C}(\alpha,n)^{16}\text{O}$ reaction
The $^{13}\text{C}(\alpha,n)^{16}\text{O}$ reaction is the major neutron source for the main component of the s-process in low mass (1-3M$_\odot$) Asymptotic Giant Branch (AGB) stars in the temperature range 1-2 10$^8$ K. These temperatures translate in a Gamow window of 140-230 keV.

Several experimental efforts were devoted to this reaction in the past; the lowest energy point has been measured by Drotleff [23] with an uncertainty of 50%.

LUNA has devoted a big experimental effort to the measurement of the $^{13}\text{C}(\alpha,n)^{16}\text{O}$ reaction to approach the Gamow window.

The setup adopted for the measurement is composed by an array of 18 $^3\text{He}$ counters with low internal background, arranged in two rings concentric with respect to the target chamber. Since the neutrons have an energy of $\sim$2 MeV, to increase the capture probability through the reaction $^3\text{He}(n,p)^3\text{H}$, they are moderated by a polyethylene matrix surrounding the counters. A study of intrinsic background of the counters has been performed by comparing their alpha activity with other detectors from Notre Dame [24]). The complete analysis of the runs gave an activity of $1.6 \times 10^{-6}$ alpha cm$^{-2}$ s$^{-1}$, and $6 \times 10^{-5}$ alpha cm$^{-2}$ s$^{-1}$, for the LUNA and the Notre Dame counters, respectively. This means that the intrinsic activity of the new LUNA counters is a factor of 37 lower, which is a key feature for a successful measurement of the low energy $^{13}\text{C}(\alpha,n)^{16}\text{O}$ cross section. An extensive production of evaporated targets enriched in $^{13}\text{C}$ at 99% on tantalum backing has been done in MTA-ATOMKI, Debrecen. A picture of the experimental setup is shown in figure 5. The data taking is over, the analysis is ongoing and the new results will be published soon.

4. The future: LUNA-MV project
The LUNA MV project has been developed to study the phases of stellar evolution successive to the quiescent Hydrogen burning, in particular the helium and carbon burning phases. To face the challenge, a new 3.5 MV single-ended accelerator will be installed in Gran Sasso in the forthcoming months. The new accelerator will deliver hydrogen, helium and carbon high-intensity beams. The direct measurement of the cross section of the $^{12}\text{C}+^{12}\text{C}$ reaction at the relevant astrophysical energies is the main goal of the first part of the project. The neutron sources relevant for stellar nucleosynthesis beyond iron i.e. $^{13}\text{C}(\alpha,n)^{16}\text{O}$ and $^{22}\text{Ne}(\alpha,n)^{25}\text{Mg}$ will be studied as well at the new LUNA-MV facility.
Figure 5. Experimental setup adopted for the measurement of the $^{13}$C($\alpha$,n)$^{16}$O reaction.

The new accelerator will be installed inside the Hall B of the Gran Sasso underground laboratory. The accelerator will be deployed inside a new room with concrete walls. The concrete walls and the room roof (thickness of 80 cm) serve as neutron shielding to prevent any possible background to the other experiments installed in the same site. The shielding guarantees that, in the worst operating conditions (i.e.: maximum energy and beam intensity), the neutron flux just outside the accelerator room will be about one tenth of the laboratory natural background.

The LUNA-MV accelerator is a custom Inline Cockcroft Walton accelerator, manufactured at High Voltage Engineering Europe (HVEE) [25]. The Terminal Voltage will range from 0.2 to 3.5 MV. As with the present LUNA400 accelerator, ion beams of H+, $^4$He+, $^{12}$C+ and $^{12}$C++ in the energy range from 0.350 to 7 MeV could be sent to two different beam lines.

Thanks to the success of the LUNA collaboration showing the potential of underground nuclear astrophysics, now other laboratories around the world are presently under construction or just in operation, in particular one in the Republic of China (JUNA) and another one in the United States (CASPAR). In the close future it will possible to compare experimental results of the different laboratories.

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