Nuclear astrophysics at Gran Sasso: the study of BBN and post-main sequence fusion reactions at LUNA

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Abstract. The first nuclei were formed a few minutes after the Big Bang, through the process called Big Bang nucleosynthesis, that left our universe containing about 75% hydrogen, 24% helium by mass, with small traces of other elements such as lithium and the hydrogen isotope deuterium. Heavier nuclei are produced during the different characteristic phases of the star evolution. At astrophysical energies the cross section of nuclear processes is usually extremely small and the cosmogenic background prevents their measurement at stellar energies on Earth surface. Deep underground in the Gran Sasso laboratory, several crucial reactions involved in hydrogen burning has been measured directly at astrophysical energies by the LUNA (Laboratory for Underground Nuclear Astrophysics) Collaboration with both the LUNA-50kV and the LUNA-400kV accelerators. This intense work will continue with the installation of a new LUNA-MV machine able to provide hydrogen, helium and carbon high current beams: the new facility will allow to explore the helium and carbon burning processes, by studying the key reactions shaping the evolution of massive stars towards their final fate. The present contribution is aimed to summarise the most recent results achieved by LUNA Collaboration and to highlight the rich experimental program connected to the new facility.

1. Introduction
Fusion reaction cross sections control the element formation in the earliest stages of the Universe and in all the stellar objects formed later on: for most stellar scenarios, the characteristic time for changes in the system is much larger than the time for collisions between the ions or atoms inside the stars. Thus the temperature profile is well-defined, giving rise to the concept of thermonuclear reactions [1]. The thermonuclear reaction rate depends on the Maxwell-Boltzmann velocity distribution and to the cross section $\sigma(E)$ energy dependence. Typical stellar temperatures correspond to peak energies of the Maxwell-Boltzmann distribution of $k_B T \sim 0.9-90$ keV. For charged particles reactions, these energies are well below the ~ MeV high Coulomb barrier due to the nuclei electrostatic repulsion and the nuclear reactions proceed only via tunnel effect. As a consequence, the extremely low values of the cross sections, ranging from pico to femto-barn and even below, has always prevented their measurements in a laboratory at the Earth’s surface where the signal to background ratio is too small mainly because of cosmic rays. The observed energy dependence of the cross-section at high energies is extrapolated...
leading to substantial uncertainties. In particular, the reaction mechanism might change, or there might be the contribution of unknown resonances which could completely dominate the reaction rate at the stellar energies. The LUNA collaboration has explored the possibility of housing a nuclear astrophysics experiment in an underground laboratory: it has started its activity in 1991 as a pilot project with a 50 kV electrostatic accelerator [2] installed inside the laboratory under Gran Sasso and, later on, with a 400 kV accelerator able to produce hydrogen and helium beams, LUNA 400 [3].

By fact, the extremely low laboratory background under Gran Sasso has allowed for the first time nuclear physics experiments with very small count rates, down to few events per month. This way, the important reactions responsible for the hydrogen burning in the Sun, such as the $^3\text{He}(^3\text{He},2\text{p})^4\text{He}$ [4], could have been studied down to the relevant stellar energies [5]. At the end of the solar phase, i.e. study of reactions relevant to the Sun, LUNA started a rich program devoted to the study of the Big Bang Nucleosynthesis (BBN) and of the synthesis of the elements through the CNO, Ne-Na and Mg-Al cycles. The goal is to explain the abundance of the light elements and to recognize the production site in stellar scenarios different from the Sun, like the hydrogen shells of Asymptotic Giant Branch (AGB) stars or the explosive phase of classical novae. In the following the latest results about the Mg-Al cycle and BBN nucleosynthesis reactions will be presented together with the future programs.

2. The Ne-Na and Mg-Al cycles: the study of the $^{23}\text{Na}(p,\gamma)^{24}\text{Mg}$ reaction

Asymptotic Giant Branch (AGB) stars provide a major contribution to the synthesis of the elements in the cosmos and specifically to the chemical evolution of stellar clusters and galaxies. At the base of the convective envelope of massive AGB stars temperatures as high as $T_9 \sim 0.1$ ($T_9$ is the stellar temperature in $10^9$ K) can be reached during the so-called hot bottom burning (HBB) process. As a result, in addition to the carbon-nitrogen-oxygen (CNO) cycle of hydrogen burning [5], also more advanced processes are operating such as the neon-sodium (NeNa) and magnesium-aluminum (MgAl) cycles [6, 7, 8, 9, 10, 11, 12].

The $^{23}\text{Na}(p,\gamma)^{24}\text{Mg}$ reaction, in particular, is the bridge between the NeNa and MgAl cycles. The reaction rate in the temperature range between 50-110 MK is dominated by two resonances at $E_p = 140$ and 251 keV, where $E_p$ is the proton beam energy in the laboratory system. Another narrow resonance at $E_p = 309$ keV is the principal component of the reaction rate at higher temperatures, up to $T = 1$ GK, while at lower energies, the non-resonant capture contribution dominates the reaction rate. In the LUNA measurement proton beams with energies of 130 to 400 keV, provided by the LUNA400 accelerator were used to bombard water-cooled solid targets. Typical beam intensities of 100-250 $\mu$A on target were obtained [13]. Two complementary setups were used to study the cross section: a segmented $4\pi$ BGO summing detector to search for the $140$ keV resonance with a large detection efficiency, and HPGe detector in close geometry at an angle of 55° to study the resonance strengths and gamma-ray branchings of the resonances at 251 keV and 309 keV.

The measured strength of the 309 keV resonance, $\omega_{\gamma,309} = 108(19)$ meV [13], was found in good agreement with literature [14] and was constrained with a comparable uncertainty. Thanks to the reduced cosmic ray background, the uncertainty on the 251 keV resonance strength was decreased from 33% to 17% : $\omega_{\gamma,251} = 482(82)$ $\mu$eV. New previously unobserved decay branches were found for the decay of the corresponding state in $^{24}\text{Mg}$ at $E_x = 11931$ keV. With the highly efficient BGO detector, a signal for the 140 keV resonance with a large detection efficiency, and HPGe detector in close geometry at an angle of 55° to study the resonance strengths and gamma-ray branchings of the resonances at 251 keV and 309 keV.

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to at most +50% -35% at 0.07GK and +17% -14% at 0.1GK. Accordingly, LUNA results imply a significant reduction of the uncertainties in the nucleosynthesis calculations [13].

Figure 1. Fractional contributions of the narrow resonances and the non-resonant cross section to the reaction rate at different stellar temperatures before (left) and after (right) the LUNA measurement.

3. BBN nucleosynthesis: the D(p,γ)³He reaction

The primordial deuterium abundance represents a powerful tool to test standard cosmology. Direct observations of deuterium abundance [15] can be used to tightly constrain the universal baryon density and the amount of relativistic particles existing in the early Universe as long as accurate Big Bang Nucleosynthesis (BBN) predictions are provided [16, 17]. However, BBN calculations are affected by some uncertainty because the cross section of the deuterium-burning reaction D(p,γ)³He is poorly known at BBN energies (E_{cm}=30-300 keV). The low energy limit of this reaction cross section is well known thanks to the LUNA measurement performed in 2002 under the solar Gamow peak [18] but in the BBN energy region only few data are available in the literature with many affected by 9% systematic errors. The Q-value of the ²H(p,γ)³He reaction is quite large (Q=5.493 MeV) so that the gamma-ray energy is above the natural radioactivity endpoint, a feature that fully exploits the cosmic ray suppression at the Gran Sasso National laboratory. A dedicated effort was devoted by the LUNA collaboration towards a renewed measurement of the D(p,γ)³He cross section with unprecedented precision. A large HpGe detector was placed at a distance of ~4 cm from the beam axis and coupled to a windowless deuterium gas target, 33 cm long. Thanks to high energy resolution of the HpGe (~10 keV at 6 MeV) this configuration is less sensible to beam induced backgrounds at the higher energies (E_{cm} > 140 keV). Several checks have been performed to reduce possible systematical effects. The beam induced background has been precisely evaluated by repeating each measurement with the target filled by inert gas (He). The efficiency have been determined with a precision of ~2% thanks to the experimental data taken with radioactive sources (¹³⁷Cs, ⁶⁰Co and ⁸⁸Y) at low energies and with the well-known resonant reaction ¹⁴N(p,γ)¹⁵O at E_r = 259 keV, emitting γ rays in the D(p,γ)³He energy range. The beam power was measured through a constant temperature gradient calorimeter precisely calibrated by comparison with a Faraday cup measurement taken in vacuum conditions. A series of detailed commissioning measurements of the experimental setup have demonstrated that the total systematic error is below 3% in the whole energy range E_p = 50 - 400 keV covered for the D(p,γ)³He reaction study at LUNA. This represents a significant step forward compared to the literature data and will allow for a determination of the predicted deuterium abundance to the same level of accuracy as the observed one [15](~ 1.5%). The cross section results and implications in cosmology and particle physics will be published in a forthcoming paper.
4. Future programs: the LUNA-MV facility
A beam of higher energy is required to extend these studies to reactions between heavier isotopes, as those operating during more advanced phases of stellar evolution, namely the He and the C burnings: a new accelerator (LUNA-MV) will be installed at LNGS able to provide intense beams of $^1H^+$, $^4He^+$, $^{12}C^+$ and $^{12}C^{++}$ in the energy range: 350keV - 3.5MeV.

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. The flagship of the program is the $^{12}C^+ + ^{12}C$ fusion that constrains the temperature at which C burning takes place: the lower the C-burning temperature, the lower is the stellar mass limit for C ignition. This limit separates the progenitors of white dwarfs, nova and type Ia supernovae, from those of core-collapse supernovae, neutron stars, and stellar mass black holes. Both the two decay channels (proton and $\alpha$) have never been studied below 2 MeV. At the LUNA MV it will be possible to measure the cross section down to 1.7 MeV.

An important open issue of nuclear astrophysics are the neutron sources: the $^{13}C(\alpha,n)^{16}O$ and the $^{22}Ne(\alpha,n)^{25}Mg$ reactions are thought to be responsible for the production of neutrons involved in the slow neutron capture process, called the astrophysical s-process. So far these reactions have not yet been measured in the relevant energy range and they should be addressed by an underground accelerator.

But even if more extensively studied, several important processes of H-burning are presently known only at energies well above the Gamow peak. Theoretical extrapolations to low energies are therefore unavoidable: among these processes, the $^{14}N(p,\gamma)^{15}O$ reaction. A renewed effort will be pursued at LUNA and it will involve both LUNA accelerators: the existing LUNA 400 kV machine as well as the new LUNA-MV facility. The combination of the two systems will allow to cover the necessary energy range with a sufficient overlap and without any hole between 200 keV and 1.5 MeV, allowing to reduce the systematics down to the goal of 5%. The $^{14}N(p,\gamma)^{15}O$ reaction will allow also to perform the commissioning and the tuning of the LUNA MV accelerator.

In conclusion LUNA has demonstrated that an underground laboratory is the perfect blend to push toward the energies of interest the study of the reactions involved in the stellar burnings, its achievements have triggered similar facilities already in operation in the United States[19] or under construction in the Republic of China[20]. This worldwide effort will allow in the next decades to take important steps forward in the field of nuclear astrophysics.

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