The LUNA-MV facility at Gran Sasso

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Abstract. About 25 year ago LUNA (laboratory for Underground Nuclear Astrophysics) opened the era of underground nuclear astrophysics installing a home-made 50 kV ion accelerator under the Gran Sasso mountain. A second machine, with a terminal voltage of 400 kV, was then installed and it is still in operation. Most of the processes so far investigated were connected to the physics of solar neutrinos and hence to the hydrogen burning phase in stars. The interest in next and warmer stages of star evolution (i.e. helium and carbon burning) pushed a new project based on an ion accelerator in the MV range called LUNA-MV. Thanks to a special grant of the Italian Ministry of Research (MIUR), INFN is now building, inside one of the major halls at Gran Sasso, a new facility which will host a 3.5 MV single-ended accelerator able to deliver proton, helium and carbon beams with intensity in the mA range.

1. Nuclear astrophysics and LUNA

Stellar evolution and related nucleosynthesis play a fundamental role in the understanding the origin of the chemical elements and in many related astrophysical problems such as the determination of the cosmic distance scale through primary and secondary distance indicators (like Cepheids, and thermonuclear type Ia supernovae), the formation and evolution of galaxies and stellar clusters, the supernova engine mechanisms, and the Big Bang. In addition, stellar evolution is a powerful tool to investigate fundamental physics, such as the existence of particles beyond those included in the standard model, axions or some particles belonging to hidden sectors (e.g. hidden photons). The main goal of nuclear astrophysics is to provide an experimental base for all these studies. Thousands of nuclear interactions, either strong or weak processes, are of astrophysical interest. For most of them, the knowledge of their cross sections (or reaction rates) at relatively low energy is required to understand the synthesis of the elements. In a few cases, these interactions even have a direct influence on the physical parameters characterizing stellar interiors, such as temperature and density, and, in turn, determine the stellar lifetimes.

Underground nuclear astrophysics was born twenty five years ago in the core of Gran Sasso, with the aims of measuring cross sections in the low energy range and of deriving reaction rates directly at stellar temperatures. LUNA (Laboratory for Underground Nuclear Astrophysics) started its activity as a pilot project with a 50 kV accelerator [1] and still remains the only laboratory in the world running an accelerator deep underground, currently a 400 kV accelerator with hydrogen and helium beams [2]. The extremely low laboratory background has allowed for the first time nuclear physics experiments with very low count rates, down to a couple of events per month. Only in this way, the important reactions responsible for the hydrogen burning in the Sun could be studied down to the relevant stellar energies [3],[4]. Such decisive achievements have motivated the proposals for two similar facilities currently...
under construction in the Republic of China and in the United States. Notable highlights at LUNA include the following: the exclusion of the ‘ghost’ resonance in the cross section of $^3$He($^3$He,$^2p$)$^4$He within the solar Gamow peak and the precise measurement of $^3$He($^3$He,$^4$Be)Be which has firmly established the correctness of the nuclear ingredients of the proton-proton chain in the standard solar model. Equally important, the direct measurement of the bottle-neck reaction of the CNO cycle, $^{14}$N(p,$\gamma$)$^{15}$O, at very low energy provided a cross section lower by about a factor of two than existing extrapolations, decreasing by the same amount the flux of CNO neutrinos from the Sun and increasing by about one billion years the limit on the age of the Universe. Furthermore, the LUNA results have paved the way to the study of the metallicity of the core of the Sun through the forthcoming measurement of the CNO solar neutrinos. Several years ago, at the end of the solar phase, a rich program started devoted to the study of Big Bang Nucleosynthesis and of the nucleosynthesis of the elements through the CNO, Ne-Na and Mg-Al cycles. The motivation here is to reproduce the abundance of the light elements and to identify the production site in stellar scenarios different from the Sun: hydrogen burning at the higher energies corresponding to the hydrogen shell of Asymptotic Giant Branch (AGB) stars or to the explosive phase of classical Novae. The 400 kV current LUNA accelerator and the unique low-background conditions of the underground LNGS laboratory have been and still are the perfect blend for the study of most of the proton-capture reactions involved in the stellar H burning. On the other hand, 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.

The LUNA MV project has been developed to overcome such a limit with the new 3.5 MV single-ended accelerator to be installed in Gran Sasso. The accelerator will be devoted to the study of those key reactions of helium and carbon burning that determine and shape both the evolution of massive stars towards their final fate and the nucleosynthesis of most of the elements in the Universe. In particular, the $^{12}$C($\alpha$,$\gamma$)$^{16}$O and $^{12}$C+$^{12}$C reactions are the most ambitious goals of this project. The first of these two reactions competes with the triple-alpha during the He burning. Both release a comparable amount of energy (about 7 MeV), but the He consumption of the $^{12}$C+alpha is only 1/3 of that of the 3-alpha. Therefore, a change of the $^{12}$C+alpha reaction directly affects the He burning lifetime. Furthermore, it determines the C/O ratio left at the end of the He burning. This is a fundamental quantity affecting, for instance, white dwarf cooling timescale and the outcomes of both type Ia and core-collapse supernovae $^{12}$C+$^{12}$C is the trigger of C burning. The temperature at which C burning takes place depends on its rate: the larger the rate, the lower the C-burning temperature. Since the temperature controls the nucleosynthesis processes, reliable estimations of all the yields produced by C burning, for example the weak component of the s process which produces the elements between Fe and Sr, require precise knowledge of the $^{12}$C+$^{12}$C rate. The $^{12}$C+$^{12}$C rate also determines the lower 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. This mass limit also controls the estimations of the expected numbers of these objects in a given stellar population, which are required to answer crucial questions such as: how many neutrons stars are there in the Milky Way? How many double neutron stars are there in close binaries? And what is the expected merging rate?

Among the key processes for stellar nucleosynthesis, the sources of neutrons represent a longstanding and debated open problem [5],[6]. Neutron-captures (slow or rapid, i.e., the s or r process, respectively) were early recognized as the most important mechanism to produce the elements heavier than iron. The identification of the astrophysical sites where these processes may operate requires accurate knowledge of the efficiency of the possible neutron sources. Various reactions have been identified as promising neutron sources. Among them $^{13}$C($\alpha$,$n$)$^{16}$O and $^{22}$Ne($\alpha$,$n$)$^{25}$Mg represent the most favored candidates. This is because they operate from relatively low temperatures typical of He burning (100 - 300MK) and because $^{13}$C and $^{22}$Ne are relatively abundant nuclei in stellar interiors. The $^{13}$C($\alpha$,$n$)$^{16}$O reaction operates in the He-burning shell of low-mass (less than 4 solar masses) AGB stars and it is the neutron source reaction that allows the creation of the bulk of the s-process elements such as Sr, Zr and the light rare earth elements in the Universe. The $^{22}$Ne($\alpha$,$n$)$^{25}$Mg reaction operates in the He-burning shell of high-mass (more than 4 solar masses) AGB stars and during the core-He burning
and the shell-C burning of massive stars (more than 10 solar masses). Underground experiments with LUNA MV will allow us to gain a full understanding of these two reactions through the direct measurement of their cross sections in the energy range of astrophysical interest.

2. The new LUNA-MV facility

The LUNA-MV facility will be installed at the north side of Hall B (Figure 1) and will consist of an accelerator room with concrete walls and a further building hosting the control room and technical facilities including the cooling system, the electric power center, the monitors to guarantee the radiation levels. (Figure 2). The concrete walls and ceiling (thickness of 80 cm) of the accelerator room serve as neutron shielding. The dimensions have been identified by GEANT4 simulations and subsequently validated with independent calculations at the INFN central radioprotection service (LNF-ISME) using an MCNP code. Considering the worst case scenario for the operation of the LUNA-MV facility of maximum neutron production rate of \( R_n = 2 \times 10^3 \text{s}^{-1} \) with an energy \( E_n = 5.6 \text{MeV} \), the MCNP simulations determined a mean value for the neutron flux outside the accelerator room, \( \Phi_n \), of about \( \Phi_n \approx 1.4 \times 10^7 \text{cm}^{-2} \text{s}^{-1} \). According to the same simulations \( \Phi_{n,\text{max}} \approx 5.7 \times 10^7 \text{cm}^{-2} \text{s}^{-1} \), is reached outside the shielding at the point closest to the target stations. This point is located at the north side of the accelerator room, far away (i.e. about 50-60 m) from other experimental installations present in Hall B. The \( \Phi_{n,\text{max}} \) values is about a factor 5 lower than \( \Phi_{\text{LNGS}} \approx 3.10^6 \text{cm}^{-2} \text{s}^{-1} \), the reference neutron background at LNGS (sum of the thermal, epi-thermal and fast components). In addition, the energy distribution of the neutrons produced by LUNA MV just outside the shielding is very similar to that of the natural background at LNGS: about 20% have energy higher than 1 keV and the fraction with a residual energy greater that 1 MeV is less than 1%.

The LUNA-MV accelerator [7] is an Inline Cockcroft Walton accelerator currently under construction at High Voltage Engineering Europe (HVEE). The machine will cover a Terminal Voltage (TV) range from 0.2 to 3.5MV and will deliver ion beams of \(^1\text{H}^+\), \(^4\text{He}^+\), \(^{12}\text{C}^+\) and \(^{12}\text{C}^{2+}\) in the energy range from 0.350 to 7 MeV into two different beam lines (see Figure 1). A key feature to perform experiments on reactions important in astrophysics scenarios is the intensity of the beam delivered to the target. Such intensity will be particularly high with LUNA-M, as summarized in Table 1. Once LUNA-MV will be deployed at LNGS, a six months installation and commissioning phase at LNGS will start and first data taking for physics experiments is presently envisaged to start during the year 2019.

Table 1: Nominal beam intensity of the future LUNA-MV accelerator [7].

| Accelerated ion | Terminal Voltage range (MV) | Maximum I (\(\mu\text{A})\) on target |
|----------------|-----------------------------|--------------------------------------|
| \(^1\text{H}^+\) | 0.3 – 0.5 | 500 |
| \(^4\text{He}^+\) | 0.5 – 3.5 | 1000 |
| \(^{12}\text{C}^+\) | 0.3 – 0.5 | 100 |
| \(^{12}\text{C}^{2+}\) | 0.5 – 3.5 | 150 |
| \(^{12}\text{C}^{2+}\) | 0.5 – 3.5 | 100 |
Figure 1: Location of the future LUNA-MV in Hall B of LNGS. Also shown are the first LUNA1 site (now dismissed) and the presently running LUNA2 laboratory equipped with a 400 kV single-ended electrostatic accelerator.

Figure 2: Location of the LUNA-MV installation with the 3.5 MV accelerator with two beam lines.
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