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Nuclear Astrophysics deep underground and the LUNA experiment

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Abstract. The cross sections of nuclear reactions relevant for astrophysics are crucial ingredients to understand the energy generation inside stars and the synthesis of the elements. In stars, nuclear reactions take place at energies well below the Coulomb barrier. As a result, their 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 a unique facility located at Gran Sasso National Laboratories (Italy) and devoted to Nuclear Astrophysics. The extremely low background achieved at LUNA allows to measure nuclear cross sections directly at the energies of astrophysical interest. Over the years, many crucial reactions involved in stellar hydrogen burning as well as Big Bang Nucleosynthesis have been measured at LUNA. This paper provides a short overview on underground Nuclear Astrophysics and discusses the latest results and future perspectives of the LUNA experiment.

1. Introduction

Nuclear fusion cross sections are relevant to many fields of astrophysics, including primordial nucleosynthesis, stellar evolution and nucleosynthesis, solar neutrino, gamma-ray astronomy etc. 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 the 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.

With the advent of precision astronomy, the abundances of the elements in the outer layers of stars are now measured with precisions at the percent level, calling for increasingly-accurate inputs to the stellar models. A much-needed input in order to predict stellar nucleosynthesis is the thermonuclear reaction rate (i.e. the number of reactions per unit time and volume occurring in a star at a given temperature) of all the nuclear reactions involved.

At typical astrophysical temperatures, the kinetic energy of the interacting particles is usually much lower than the Coulomb repulsive potential between the positively-charged nuclei. Therefore, nuclear reactions can only occur by quantum mechanical tunneling and the cross section decreases steeply with the energy [1]. Because of the interplay between the Maxwell-Boltzmann energy distribution of nuclei and the tunneling probability through the Coulomb barrier, thermonuclear reactions can only occur in a well-defined energy range, called the Gamow peak. At Gamow energies, nuclear cross sections can become extremely small (of the order of 10^{-9} - 10^{-12} barn), therefore, in typical experimental conditions, the expected counting rate can be much smaller than the environmental background in a detector.

2. Underground Nuclear Astrophysics

Environmental background is produced by cosmic rays and the decay of naturally-occurring radioactive isotopes (uranium and thorium chains and ^{40}K). The background from radioactive isotopes can be substantially reduced by shielding the detector with high-Z and high-density material (usually lead or copper). On the other hand, cosmic radiation at sea level is mainly made of muons, highly penetrating particles created in the upper atmosphere that leave a trace in most particle and gamma ray detectors and can generate spallation reactions in detector and surrounding materials, with consequent production of neutrons and radioactive nuclei.

An effective way to suppress environmental background is to perform experiments in deep-underground laboratories. Indeed, not only can the cosmic muon flux be substantially suppressed by a thick rock overburden, but detectors can also be shielded from low-energy gamma background using much thicker linings than overground because secondary emission of radiation from the interaction of cosmic rays within the shielding becomes negligible [2, 3, 4].

LUNA (Laboratory for Underground Nuclear Astrophysics), was the pioneering experiment in deep underground Nuclear Astrophysics, being operative since 1992. More recently, other deep-underground [5, 6] and shallow-underground [7] experiments devoted to Nuclear Astrophysics have been developed worldwide.

In the following section, latest results and future perspectives of the LUNA experiment will be outlined.

3. The LUNA experiment

LUNA is located at the Gran Sasso underground laboratories (LNGS), in central Italy. The laboratory is shielded by 1400 meters of mountain rocks, attenuating the cosmic-ray muon flux by about six orders of magnitude when compared with the surface of the Earth. Fig. 1 shows a comparison of HPGe background spectra taken overground and at LNGS with two different types of passive shielding.

The LUNA laboratory was started in 1992 with the installation of a 50-kV accelerator [9]. In 2001 the 50-kV machine was replaced by a 400-kV accelerator, which is still operational today. A third facility with a more energetic accelerator, named LUNA MV, will be installed in 2020. The LUNA 400-kV accelerator provides proton and alpha-particle beams with intensity as high as 500 μA on target. The beam energy stability is particularly important for nuclear astrophysics experiments, since the fusion cross section below the Coulomb barrier depends exponentially on the energy. The LUNA proton beam energy is calibrated with 0.3-keV accuracy and has a long term stability of 5 eV/h. The beam energy spread has been measured to be 100 eV [10]. Two beam lines are available at LUNA: one equipped with a solid-target setup and the other with a windowless gas target. Different gamma-ray or particle detectors can be used, tuning the detection system according to the specific needs of the nuclear reaction to be studied.

The LUNA setup is ideally suited for the study of hydrostatic hydrogen burning taking place in stars at temperatures of 0.01 - 0.1 GK [11] and also explosive burning at temperatures up to 1 GK in sites such as the Big Bang [12], classical novae and supernovae [13].

Over the years, a large number of reactions involved in stellar hydrogen burning and Big Bang Nucleosynthesis have been investigated at LUNA. The cross section of those reactions was measured either within or very close to the Gamow window [14, 15].

4. Latest results and ongoing measurements

4.1. The ^{17}O(p,α)^{14}N reaction

Proton capture on ^{17}O is part of the CNO cycle of hydrogen burning and it proceeds through two alternative channels: ^{17}O(p,γ)^{18}F and ^{17}O(p,α)^{14}. The ratio of the (p,γ) to (p,α) cross sections determines the leak rate from the second to the third CNO cycle (see Fig. 2) and it affects the isotopic abundances of ^{17,18}O and ^{18,19}F and the flux of 511 keV gamma rays from

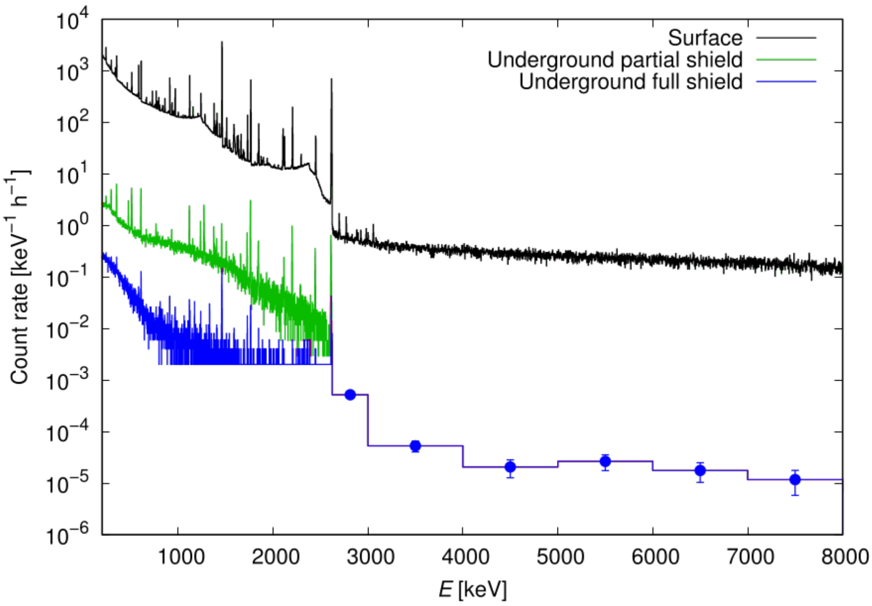

Figure 1. Environmental background spectra measured with an HPGe detector positioned at the Earth's surface, at LUNA with full passive shielding (4 cm thick copper, 25 cm thick lead and a radon box [8]) and at LUNA with a partial passive shield (4 cm thick copper and 25 cm thick lead) designed to host a second HPGe detector [32]. Above 2600 keV, the backgrounds in the two shielded cofigurations coincide.

classical novae, due to β^+ decay of ^{18}F.
At astrophysical energies, the ^{17}O(p,γ)^{18}F cross section depends on the narrow resonances at 64.5 keV and 183 keV, lying on the tail of two broad resonances at 557 keV and 677 keV, and on the direct capture component. The 183-keV resonance and the direct-capture cross section have both been studied at LUNA combining prompt gamma-ray spectroscopy and the activation technique [16].
The ^{17}O(p,α)^{14}N reaction has also been investigated at LUNA. Its cross section is also dominated by the resonances at 183 keV and 64.5 keV, but while the 183-keV resonance has a well known strength, the 64.5-keV resonance was debated: the first direct measurement performed gave an upper limit on the strength $\omega\gamma < 0.8$ neV [17], later revised to $\omega\gamma < 22$ neV [18]. A second direct experiment provided a strength of $\omega\gamma = 5.5^{+1.8}_{-1.5}$ neV [19] (adopted by the NACRE compilation [20]), later re-analyzed multiple times to give $\omega\gamma = 4.8 \pm 0.5$ neV (adopted in the reaction rate compilation by C. Iliadis et al. [21]). Finally, indirect measurements performed with the Trojan-horse technique provided $\omega\gamma = 3.4 \pm 0.6$ neV [22].
At LUNA, the ^{17}O(p,α)^{14}N reaction has been studied delivering the proton beam to solid Ta_2O_5 targets enriched in ^{17}O. Alpha particles from the reaction were detected with an array of eight Si detectors surrounded by a 5 cm thick lead shielding [23]. The natural background observed in the detectors was a factor of 15 lower compared to overground [23]. Thanks to this, both the 183-keV resonance and the weak resonance at 64.5 keV could be properly measured by LUNA in ^{17}O(p,α)^{14}N [24].
For the 183-keV resonance an $\omega\gamma = (1.68 \pm 0.03_{stat} \pm 0.12_{syst})$ meV was found, in good agreement with the literature.
For the 64.5-keV resonance, a strength $\omega\gamma = (10.0 \pm 1.4_{stat} \pm 0.7_{syst})$ neV was measured [24]. Such a value is about a factor of 2 higher than the previously estimated, thus leading to a factor

of 2 increase in the reaction rate of shell hydrogen burning in red giant and AGB stars (see Fig. 2).

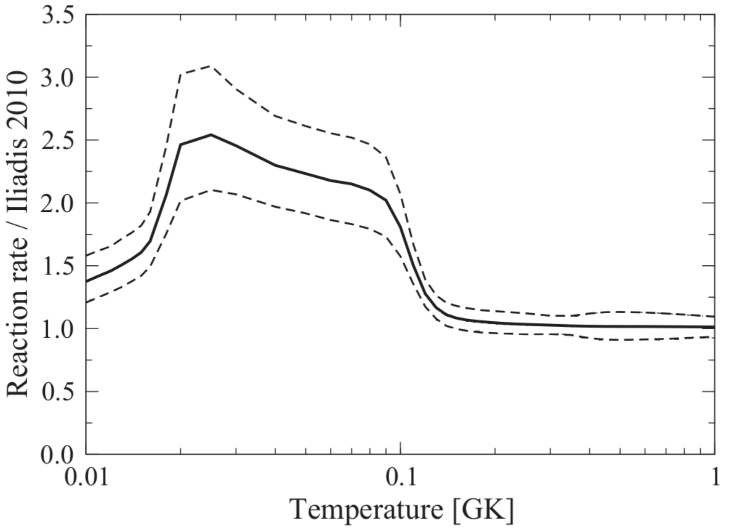

Figure 2. ^{17}O(p,α)^{14}N reaction rate obtained adopting the LUNA strength for the 64.5 keV resonance

The new resonance strength has increased by 20% the predicted ^{16}O/^{17}O ratio after the first dredge up in red giant stars [25] and it has allowed for the firm identification of the production site of a oxygen-rich star grain population [26].

4.2. The ^{22}Ne(p,γ)^{23}Na reaction

The neon-sodium cycle of hydrogen burning contributes to the synthesis of the isotopes between ^{20}Ne and ^{23}Na in Red Giant Branch (RGB) stars [27], Asymptotic Giant Branch (AGB) stars [28] and classical novae explosions [29]. The ^{22}Ne(p,γ)^{23}Na reaction rates reported in the widely adopted compilations by NACRE [20] and C. Iliadis et al. [21] are three orders of magnitude discrepant in the energy range of interest for hydrogen burning in AGB stars.

The ^{22}Ne(p,γ)^{23}Na Gamow window for AGB stars and classical novae extends from 50 to 600 keV. In this energy range, the proton capture on ^{22}Ne is dominated by a large number of resonances. While some of the resonances could be measured with good precision in overground experiments [30, 31], 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 two tentative resonances are actually the reason why the rates from the two compilations are so different. Indeed, while NACRE decided to keep the two resonances with their upper limits, Iliadis et al. decided to disregard them.

The LUNA measurements were organized in two campaigns, both exploiting the windowless gas target system filled with 99.9% enriched ^{22}Ne: in the first campaign, gamma rays were detected using two high-resolution HPGe detectors [32, 33, 34] while the second campaign made use of a high-efficiency BGO detector [35]. 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. New gamma-decay modes have also been observed for the three resonances detected. For the non-detected resonances new upper limits have been measured. The new upper limits are two to three orders of magnitude lower than the previous direct measurement, proving the improvement in sensitivity that can be achieved in underground experiments [33, 34].

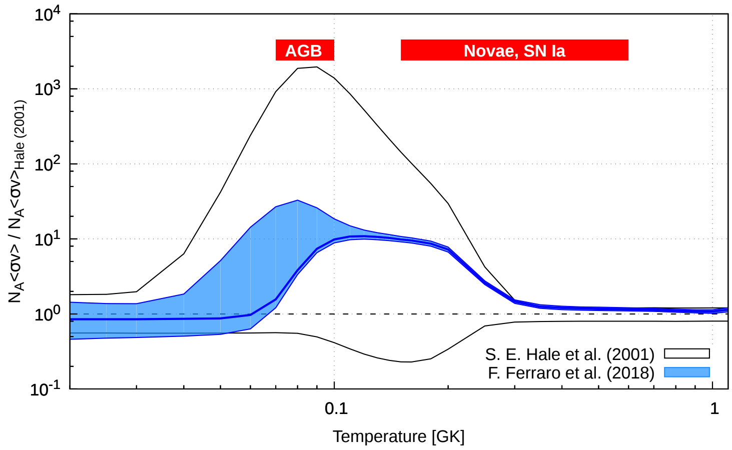

Figure 3. Reaction rate calculated adopting the LUNA results on the ^{22}Ne(p,γ)^{23}Na reaction

The upper limits on the resonances at 70 and 100 keV were further reduced during the BGO phase and the non-resonant contribution to the cross section was measured for the first time in the energy range between 100 and 300 keV in the center of mass. Fig. 3 shows the updated reaction rate for the ^{22}Ne(p,γ)^{23}Na reaction, calculated including the new LUNA results. The reaction rate adopted in [36] is also shown for comparison. 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.

4.3. Ongoing experiments

A rich scientific program is underway at LUNA. Experiments for which the data analysis was just finalized include the study of the ^{23}Na(p,γ)^{24}Mg reaction with both a germanium and a BGO detector, and of the ^{18}O(p,γ)^{19}F and ^{18}O(p,α)^{15}N [37] reactions.
Two reactions for which the data taking was just concluded are ^{2}H(p,γ)^{3}He and ^{6}Li(p,γ)^{7}Be, briefly described below.

The ^{2}H(p,γ)^{3}He reaction is involved in the Big Bang Nucleosynthesis (BBN) network and it determines the abundance of primordial deuterium. Observational information on the primordial deuterium abundance is obtained with percent precision from the spectroscopic measurement of metal-poor damped Lyman-alpha (DLA) systems. These systems are the oldest astrophysical environments where deuterium is detected. The most recent observed deuterium abundance is [D/H] $= (2.527 \pm 0.030) \cdot 10^{-5}$ [38], while predictions oscillate from $(2.439 \pm 0.052) \cdot 10^{-5}$ to $(2.587 \pm 0.055) \cdot 10^{-5}$ depending on the cross section adopted for the ^{2}H(p,γ)^{3}He reaction [39]. As a matter of fact, only a few experimental points exist for the ^{2}H(p,γ)^{3}He cross section in the energy region of interest, with an overall systematic uncertainty at the 6-10% level [40].
The cross section of the ^{2}H(p,γ)^{3}He reaction was already measured at LUNA with the 50-kV accelerator to explore the energy region where the reaction takes place in pre-main sequence stars and in the Sun. A new experiment has now been performed at the 400-kV accelerator to cover the energy range of BBN. The experiment was performed using the windowless gas target filled with deuterium at a pressure of 0.3 mbar, surrounded by two different types of gamma detectors, each in a different phase of the data taking: a 4π BGO and one HPGe detector (see

fig. 4). The geometry of the BGO reduces the dependence of the detector response on the angular distribution of the emitted gamma rays [41]. On the other hand, the second phase of the experiment allows to infer the angular distribution exploiting the high energy resolution of the germanium detector and the Doppler shift of gamma ray energies.

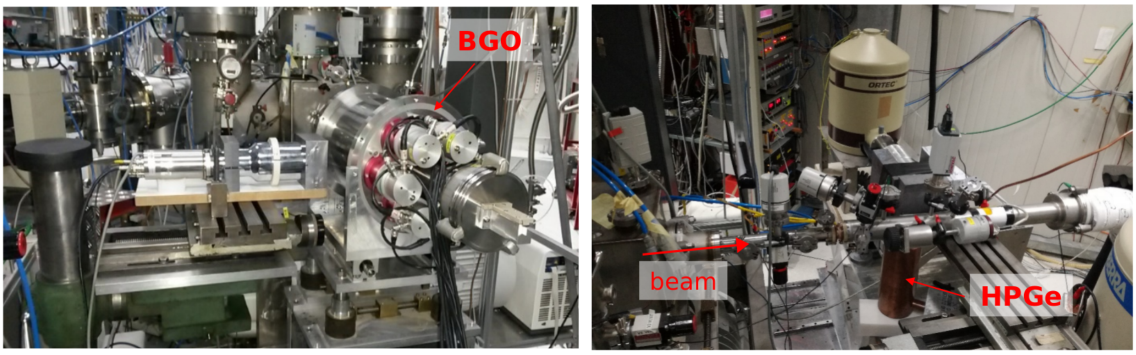

Figure 4. Photos of the two experimental setups adopted for the study of the ^{2}H(p,γ)^{3}He reaction

The goal of the experiment is to reach an overall systematic uncertainty on the 3% level combining the results from the two phases.

The ^{6}Li(p,γ)^{7}Be and ^{6}Li(p,α)^{3}He reactions are responsible for lithium-6 depletion in the early stages of stellar evolution and contribute to Bang Nucleosynthesis. The ^{6}Li(p,α)^{3}He reaction has been studied by many groups, and in order to explain the angular distribution of the emitted alpha particles, an R-matrix fit of the experimental data requires the contribution of both negative- and positive-parity excited states [42]. The existence of positive-parity excited states in ^{7}Be has never been verified experimentally. A recent measurement of the ^{6}Li(p,γ)^{7}Be cross section discovered a resonance-like structure around 195 keV [43]. The observed S-factor is roughly reproduced by an R-matrix fit assuming the existence of an excited state with E $\sim$ 5800 keV, J$^{\pi}$ = (1/2^{+}, 3/2^{+}) and $\Gamma_p \sim$ 50 keV.
In order to verify the existence of such state, a simultaneous measurement of the ^{6}Li(p,γ)^{7}Be and ^{6}Li(p,α)^{3}He reactions has been performed at the LUNA solid target beam line. Gamma rays were detected using a HPGe detector in close geometry at 55°, while α and ^{3}He particles were detected by a Si detector at 125°. Targets of three different compositions were used (lithium oxide, lithium tungstate and lithium chloride) in order to evaluate possible systematic effects due to target composition and thickness. The data taking was completed in September 2017 and the analysis is presently ongoing.

A rich program is still scheduled for the LUNA 400 kV accelerator. The reactions ^{13}C(α,n)^{16}O, ^{22}Ne(α,γ)^{26}Mg, relevant for s-process nucleosynthesis, are presently under investigation while (p,γ) reactions on ^{12}C and ^{13}C are scheduled for the future.

5. The LUNA-MV project

The future of LUNA involves the installation of a new 3.5-MV accelerator. This machine will be devoted to the study of nuclear reactions that take place at higher temperatures than those occurring during the hydrogen-burning processes studied so far at the 50-kV and 400-kV facilities.
The new accelerator will provide high-intensity hydrogen, helium and carbon beams [44]. Two different beam lines will be built, one devoted to solid target and the other to gas

target experiments. This will allow the study of key reactions of helium burning (namely the ^{12}C(α,γ)^{16}O reaction and (α,n) reactions on ^{12}C and ^{22}Ne) and to further investigate the ^{14}N(p,γ)^{15}O and the ^{3}He(^{4}He,γ)^{7}Be reactions, already measured at the LUNA 400-kV facility, over a wide energy range in order to reduce their experimental uncertainties.
The LUNA-MV building will be surrounded by a 80 cm thick concrete neutron shielding to preserve the low neutron background conditions of LNGS.
The construction of the infrastructure is in progress and the installation of the accelerator is scheduled for the next year.

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