Latest results from LUNA

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Abstract. A precise knowledge of the cross section of nuclear fusion reactions is a crucial ingredient in understanding stellar evolution and nucleosynthesis. At stellar temperatures, fusion cross sections are extremely small and difficult to measure.
Measuring nuclear cross sections at astrophysical energies is a challenge that triggered a huge amount of experimental work. A breakthrough in this direction was the first operation of an underground accelerator at the Laboratory for Underground Nuclear Astrophysics (LUNA) in Gran Sasso, Italy. The 1400 meters of rocks above the laboratory act as a natural shield against cosmic radiation, suppressing the background by orders of magnitude.
The latest results achieved at LUNA are discussed, with special emphasis on the $^{22}\text{Ne}(p,\gamma)^{23}\text{Na}$ reaction. Future perspectives of the LUNA experiment are also illustrated.

1. Introduction

Nuclear fusion reactions provide most of the energy radiated by stars. Indeed, the whole life of a star consists of a sequence of phases in which heavier and heavier elements are burnt inside the stellar core. Moreover, nuclear reactions are responsible for the synthesis of the elements both in the early Universe and in stars.

Theoretical models have been developed to try to reproduce the elemental abundances observed in the stellar surface. An important input for these models is the thermonuclear reaction rate for all the nuclear reactions involved.

At astrophysical temperatures, the kinetic energy of the interacting particles follows a Maxwell-Boltzmann distribution and is usually much lower than the Coulomb repulsion between the nuclei. Therefore, nuclear reactions can only occur by quantum mechanical tunneling and the cross section decreases exponentially with the energy [1].

As a consequence of the interplay between the 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 become extremely small (of the order of 10^{-9} - 10^{-12} barns), therefore, in typical experimental conditions, the expected counting rate can be much smaller than the background in a detector.

In a gamma ray detector, the background origin is twofold: below 2.6 MeV it is maily due to the decay of environmental radioactive isotopes (uranium and thorium chains and ^{40}K). This background can be substancially reduced by shielding the detector with high Z and high density material (usually lead or copper). Above 2.6 MeV, the main source of environmental background is cosmic radiation. At sea level, most of the cosmic radiation is made of muons. The most efficient way to suppress the muon-induced background is to perform experiments in underground laboratories.

2. The LUNA experiment

The Laboratory for Underground Nuclear Astrophysics is located at Gran Sasso National Laboratories (LNGS), Italy [2]. The laboratory is shielded against cosmic radiation by 1400 meters of rock (3800 meters of water equivalent). This guarantees a six orders of magnitude reduction in the cosmic muon flux and a three orders of magnitude reduction in the neutron flux. As a consequence, the background in a gamma ray detector is also suppressed by three to five orders of magnitude.

The Laboratory for Underground Nuclear Astrophysics is equipped with a 400 kV accelerator providing high intensity proton or alpha beam. The beam can be delivered either to a solid target or to a windowless gas target. Different gamma-ray or particle detectors can be used, depending on the characteristics of the nuclear reaction to be studied.

3. Latest results

Since the installation of the LUNA 400 kV accelerator, several nuclear reactions have been studied relevant for stellar evolution and nucleosynthesis [3, 4, 5, 6, 7, 8, 9] as well as Big Bang nucleosynthesis [10]. The last two years were dedicated to the investigation of the ^{17,18}O(p,α)^{14,15}N reactions of the CNO cycle [11] and the ^{22}Ne(p,γ)^{23}Na reaction of the NeNa cycle.

In the following, the latest results on the ^{22}Ne(p,γ)^{23}Na reaction are discussed.

3.1. 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, Asymptotic Giant Branch (AGB) stars and classical novae explosions.

The synthesis of sodium in RGB stars is still puzzling. Observations of galactic globular clusters show that the surface abundance of sodium in RGB stars anticorrelates with the oxygen abundance [12]. A possible explanation for this anticorrelation involves the pollution of the interstellar medium with material processed through hydrogen burning reactions at high temperatures in AGB stars. In the hydrogen burning shell of AGB stars, oxygen is efficiently destroyed by the CNO cycle and sodium is mainly produced by the ^{22}Ne(p,γ)^{23}Na reaction of the NeNa cycle [13].

Another scenario where the ^{22}Ne(p,γ)^{23}Na reaction is active are classical novae explosions. A sensitivity study showed that the ^{22}Ne(p,γ)^{23}Na reaction rate uncertainty strongly affects the final abundances of neon, sodium and magnesium isotopes, demonstrating the need for new experimental efforts on the ^{22}Ne(p,γ)^{23}Na cross section [14].

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. None of the resonances below 436 keV has ever been observed in either direct or indirect experiments (tab. 1). Moreover, the spin and parity assignment to the resonances is often uncertain and the mere existence of the three resonances at 71, 105 and 215 keV is still debated since it has been tentatively reported in [16] but has not been observed in subsequent experiments [17, 18].

As a consequence, the ^{22}Ne(p,γ)^{23}Na reaction rates reported in the widely adopted compilations by NACRE [19] and C. Iliadis et al. [20] are three orders of magnitude discrepant in the energy range of interest for hydrogen burning in AGB stars.

As a first step, a feasibility test was performed using the setup of the previous ^{2}H(α,γ)^{6}Li experiment [21]. For this test, neon gas with natural isotopic composition was used (90.48% ^{20}Ne, 0.27% ^{21}Ne and 9.25% ^{22}Ne).

Table 1. Summary of literature resonance strengths for ^{22}Ne(p,γ)^{23}Na resonances below 400 keV proton energy.

$E_{res,LAB}$ [keV]	J. Görres (direct) [15]	$\omega\gamma$ [eV] NACRE [19]	Iliadis et al. [20]
29	-	-	$\leq 2.6 \cdot 10^{-25}$
37	-	$(6.8 \pm 1.0) \cdot 10^{-15}$	$(3.1 \pm 1.2) \cdot 10^{-15}$
71	$\leq 3.2 \cdot 10^{-6}$	$\leq 4.2 \cdot 10^{-9}$	-
105	$\leq 6.0 \cdot 10^{-7}$	$\leq 6.0 \cdot 10^{-7}$	-
158	$\leq 1.0 \cdot 10^{-6}$	$(6.5 \pm 1.9) \cdot 10^{-7}$	$(9.2 \pm 3.7) \cdot 10^{-9}$
186	$\leq 2.6 \cdot 10^{-6}$	$\leq 2.6 \cdot 10^{-6}$	$\leq 2.6 \cdot 10^{-6}$
215	$\leq 1.4 \cdot 10^{-6}$	$\leq 1.4 \cdot 10^{-6}$	-
259	$\leq 2.6 \cdot 10^{-6}$	$\leq 2.6 \cdot 10^{-6}$	$\leq 1.3 \cdot 10^{-7}$
291	$\leq 2.2 \cdot 10^{-6}$	$\leq 2.2 \cdot 10^{-6}$	$\leq 2.2 \cdot 10^{-6}$
323	$\leq 2.2 \cdot 10^{-6}$	$\leq 2.2 \cdot 10^{-6}$	$\leq 2.2 \cdot 10^{-6}$
334	$\leq 3.0 \cdot 10^{-6}$	$\leq 3.0 \cdot 10^{-6}$	$\leq 3.0 \cdot 10^{-6}$
369	-	-	$\leq 6.0 \cdot 10^{-4}$
394	-	-	$\leq 6.0 \cdot 10^{-4}$

The aim of the test was to study the possible sources of beam induced background, and to have some hints on the sensitivity to the ^{22}Ne+p resonant cross section.

Despite the use of non enriched gas (only 9.25% ^{22}Ne) and a setup which was not optimized for this measurement, gamma-rays from the 186 keV resonance have been observed during the test in a 12 hours run. This resonance was never observed in previous experiments, and the literature upper limit for the resonance strength is $\omega\gamma < 2.6 \cdot 10^{-6}$ eV. Thanks to the LUNA observation it was possible to provide a lower limit $\omega\gamma \geq 0.12 \cdot 10^{-6}$ eV for the 186 keV resonance strength and thus to improve the literature information on this resonance [23].

Following the feasibility test, the characterization of the setup for the first experimental campaign on the ^{22}Ne(p,γ)^{23}Na resonances was started.

Using an extended gas target system requires to accurately know the gas density profile along the beam path. The gas density without beam was deduced from pressure and temperature values measured at different positions inside the target chamber. For this measurement, a dedicated setup was used with a target chamber of the same geometry as the one used for the cross section measurement, but equipped with several flanges along the beam axis allowing to connect pressure or temperature gauges. Then the beam heating effect in natural neon gas has been measured for the first time with the resonance scan technique, using the intense and well known ^{21}Ne(p,γ)^{22}Na resonance at 271.6 keV beam energy [22] and a collimated NaI detector [23].

Once the gas target characterization was completed, the study of the ^{22}Ne(p,γ)^{23}Na low-energy resonances started. For this experimental campaign, a proton beam was delivered to the windowless gas target filled with 99.9% enriched ^{22}Ne.

The gamma-rays emitted in the de-excitation of ^{23}Na were detected by two HPGe detectors collimated at 55° (where the second order legendre polynomimal is zero and possible angular distribution effects are minimal) and 90° with respect to the beam direction (fig. 1). The use of two detectors looking at different angles allows to estimate the effect of the gamma ray angular distribution on the resonance strength. In order to reduce the environmental background at gamma ray energies below 2.6 MeV, the two detectors were surrounded by a copper and lead shielding. This shielding ensured about four orders of magnitude background reduction for γ

ray energies below 3 MeV.
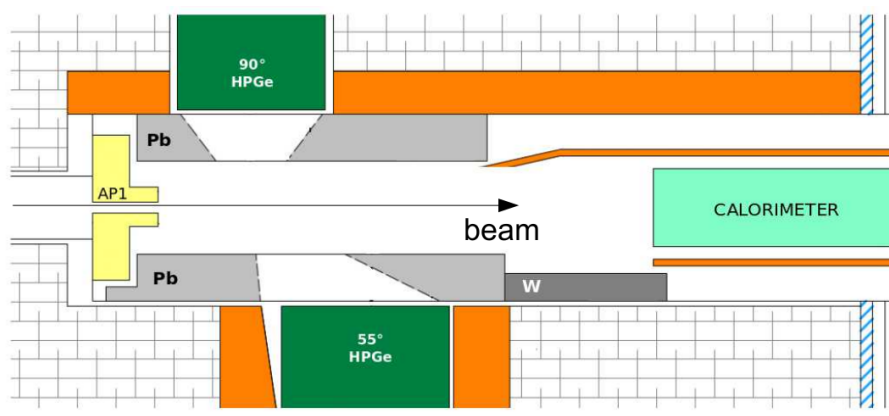
Figure 1. Sketch of the experimental setup used to study the ^{22}Ne(p,γ)^{23}Na low energy resonances at LUNA.

The gamma detection efficiency for the two detectors has been measured at several positions along the target chamber with ^{7}Be, ^{137}Cs, ^{60}Co and ^{88}Y point-like sources. The efficiency curve was then extended up to 6.79 MeV using the intense ^{14}N(p,γ)^{15}O resonance at 278 keV [3]. During about five months of data taking, all the resonances between 70 and 334 keV have been investigated. The resonances at 158, 186 and 259 keV have been 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 observed. Moreover, for the 186 and 259 keV resonances the statistics is high enough to allow the study of gamma-gamma coincidences between the two detectors. Fig. 2 shows the long run spectrum over the 259 keV resonance. The observed transitions are also indicated.
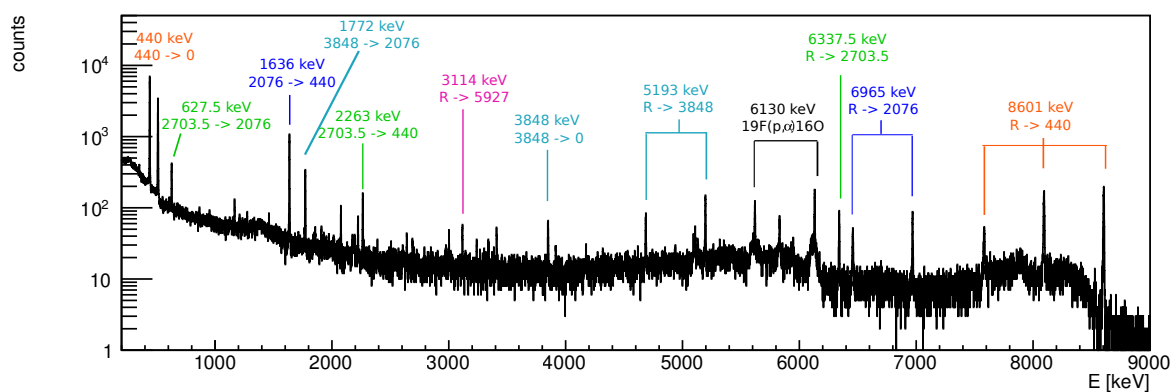
Figure 2. Long run spectrum taken with the 55° at 264 keV beam energy, over the 259 keV resonance.

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, demonstrating the improvement in sensitivity that can be achieved in underground experiments.

3.2. Ongoing measurements

A new experimental campaign on the ^{22}Ne(p,γ)^{23}Na reaction is currently ongoing at LUNA. The aim of this phase is to measure the direct capture contribution to the ^{22}Ne + p cross section and to increase the sensitivity to the tentative resonances at 71, 105 and 215 keV. In this phase, the windowless gas target chamber is surrounded by a high-efficiency BGO detector covering most of the solid angle around the target.

In parallel, the reactions ^{23}Na(p,γ)^{24}Mg of the NeNa cycle and ^{18}O(p,γ)^{19}F of the hot CNO cycle are under investigation on the solid target beam line.

4. Future perspectives

A new scientific program for the LUNA 400 kV accelerator has been approved. The program will last until 2018 and includes six reactions relevant for Big Bang nucleosynthesis and stellar hydrogen and helium burning.

The first of those reactions to be investigated is the ^{2}H(p,γ)^{3}He, which represents the main uncertainty on ^{2}H abundance from standard Big Bang nucleosynthesis calculations.

The future of LUNA also involves the installation of a new higher voltage machine, in the MV range. 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 with the 400 KV accelerator.

This project, named "LUNA-MV", involves the realization of a unique facility inside the underground Gran Sasso Laboratory centred on a 3.5 MV single-ended accelerator providing high intensity hydrogen, helium and carbon beams. Two different beam lines are foreseen devoted to solid and gas target experiments, respectively. This will allow us to study the 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 re-investigate the ^{14}N(p,γ)^{15}O and the ^{3}He(^{4}He,γ)^{7}Be reactions over a wide energy range in order to further diminish its experimental uncertainties.

The LUNA-MV project was approved by the LNGS Scientific Committee in 2010 and it obtained financial support from the Italian Research Ministry in 2012. The tender for the accelerator has been published in 2015.

A key issue for LUNA-MV is the realization of a neutron shielding to the rest of the laboratory and to the internal rock surfaces to preserve the low background characteristic of LNGS. In order to evaluate the neutron flux produced by the reactions above mentioned, a series of GEANT4 simulations of the LUNA-MV building are currently being finalized.

The construction of the building and the infrastructure is planned to start in 2017, while the commissioning is expected to start in 2018.

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