Underground nuclear astrophysics at LUNA and the Bellotti Ion Beam facility of INFN-LNGS

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Abstract. Deep underground nuclear astrophysics with the LUNA experiment at the Gran Sasso National Laboratory by now has a 30-year history and a long track record of measuring crucial reactions for various nucleosynthesis scenarios, from the Big Bang to p-p and CNO reactions to the production of the heavy elements in the s process. With the recent installation of a 3.5 MV accelerator at the LNGS and the inauguration of the Bellotti Ion Beam Facility the stellar scenarios and astrophysically important nuclear reactions that can be investigated is expanding greatly. Recent LUNA results are presented together with the program and the experimental capabilities at the new user facility.

1 Introduction

The modeling of astrophysical and cosmological scenarios relies on an accurate knowledge of nuclear processes. Although there have been many advances in observational astrophysics in recent years [1–3], stellar models require a precise knowledge of nuclear interaction cross sections. They primarily influence the nucleosynthesis of elements in stars and in the early stage of our Universe, as well as the details of stellar evolution. As most of these reactions occur at energies quite below ones that can be investigated in the laboratory with present technologies, extrapolations are usually performed from higher-energy data down into the astrophysical range (often called the Gamow energy). Due to the exponential nature of this extrapolation, accurate and precise measurements at the lowest possible energy are required to support reliable stellar predictions.

Natural background in γ-ray measurements is one of the main limiting factors in performing cross section measurements. In surface laboratories it can jeopardize measurements already at hundreds of keV, whereas the Gamow peak (i.e. the energy window in which nuclear reaction occurs in stars) can lie at few tens of keV, completely outside of the experimental reach. To solve this background issue, the Laboratory for Underground Nuclear Astrophysics (LUNA) collaboration (and now others like CASPAR in the United Sates and JUNA in China [4, 5]) performs its measurements underground. LUNA is situated at the "Laboratori Nazionali del Gran Sasso" (LNGS) of the "Istituto Nazionale di Fisica Nucleare" (INFN) underneath the Gran Sasso mountain chain of central Italy. Here the 1.4 km of rock above (4.3 km water equivalent) grants a major shielding of natural background, as shown in Figure 1 (already published in [6]): especially at energies higher than 2.6 MeV, where the background due to cosmic rays is predominant, the effects of underground laboratory shielding are clearly visible. Also further layers of passive shielding around the detection system (usually lead) are much more effective: in surface laboratories cosmic rays can create secondary γ-rays through interaction with the shielding (and detectors) itself, reducing its effectiveness.

In general, the thicker the lead shielding is, the better the suppression, until other background sources dominate. To suppress this additional background, which is mainly caused by radioactive radon gas generated by the uranium and thorium contamination of surrounding rocks, a radon box is usually adopted. It is a (plastic) box surrounding the setup through which an inert gas, like nitrogen, is circulated, to keep radon from entering close to the detectors, further improving the background suppression. A reduction up to 5 orders of magnitude in the background spectra can be achieved in this way.

But not only γ-rays measurements are helped by going deep underground, also the sensitivity for measurements of neutron-releasing reactions (like the sources of the astrophysical s process, ^{13}C(α,n)^{16}O and ^{22}Ne(α,n)^{25}Mg [7, 8]) can greatly benefit from a reduction of the neutron background underground. On the Earth's surface, the neutron background is entirely dominated by secondary neutrons from cosmic-ray interactions in the atmosphere - deep underground these neutrons are shielded against and only a much smaller background (3 orders of magnitude lower than on the surface) due to fission and (α,n) reactions in the surrounding rock remains [9].

Even charged-particle measurements can benefit from the underground location, although it is a secondary effect from the suppression of interactions gamma-rays in certain particle detectors, reducing low-energy "noise" and increasing sensitivity [10].

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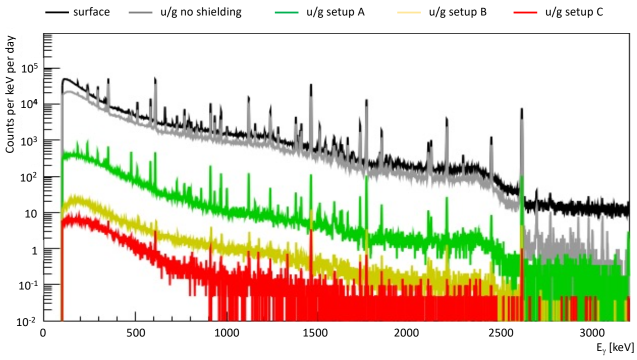

Figure 1. Background measurement in LNGS: on surface (black), underground (gray), underground with 15 cm of lead shielding (green), same but with 25 cm of lead shielding (yellow) and with the addition of a radon box (red). Already published in [6].

This major background suppression allowed the LUNA collaboration to measure cross sections in previously inaccessible energy regions, some of which are described in the following sections.

2 LUNA and LUNA400

The first accelerator [11] at LNGS was built to study the ^{3}He(^{3}He, 2p)^{4}He reaction [12] inside the Sun Gamow window (15-27) keV for ^{3}He(^{3}He, 2p)^{4}He. It was able to deliver 10-50 keV proton and helium beams at high intensity (few 100 μA) and stability (ΔE/E $\sim 10^{-4}$) with small energy spread (< 25 eV). The beam emitted from a duoplasmatron source was accelerated through the accelerator resistor chain column powered by a 50 kV power supply. A double focusing 90^o bending magnet was used as analysing and focusing elements. The target was a recirculated windowless gas type, for which several apertures (from 25 mm to 7 mm in diameter) were installed before the reaction chamber. A calorimeter at the end of the beam line allowed for the measurement of the ion beam current. Two detection setups were employed: for 20 keV < E$_{cm}$ < 25 keV four ΔE-E silicon detector telescopes were placed inside the gas target around the beam line and with several dead layers (1 μm Mylar foil and 1 μm Aluminum one) to stop ^{3}He elastically scattered, ^{4}He produced in the reaction and light photons due to beam-target interaction; for energies down to 16.5 keV an higher efficiency setup composed by eight Si detectors forming a double square box was realized, aiming at measure proton in coincidence. Also the parasitic reactions ^{3}He(d, p)^{4}He and d(^{3}He, d)^{4}He, due to deuterium contamination in both the gas target ($\sim$ 0.1 ppm and the ion beam through HD+ molecules in the beam), where studied in detail, since their cross section is orders of magnitudes larger than the one of ^{3}He(^{3}He, 2p)^{4}He.

The LUNA results contributed to an increase our understanding of Solar neutrino energy losses (at that time the "solar neutrino problem") and the link between solar luminosity and energy generation. The interested reader can find a more extended review on the topic in literature [13]. It worth noting that the energies investigated by LUNA where so low that atomic effects, usually neglected in nuclear reaction experiments, became effective. It is a still poorly known phenomenon [14] which in the future will be hopefully better studied with the use of supersonic jet targets [15, 16] ionized as plasma jet [17].

As a major upgrade, a 400 keV Inline-Cockcroft-Walton accelerator (LUNAII or LUNA400) was installed at the LNGS [18] to perform measurements of nuclear reaction of interest for the CNO cycle, Big Bang nucleosynthesis (BBN) and the s-process. Using a radio-frequency plasma source it is able to deliver up to 1 mA of proton beam and 500 μA He$^+$ beam with high energy stability ($\Delta E/E < 10^{-4}$). A 45^o analysing magnet, together with electrostatic steerers, quadrupole magnets and a switching magnet allow the operation of two different beam lines. One is equipped with a windowless gas target while the other is devoted to solid target measurements. The gas target beam line, more extensively described elsewhere [19], is sectioned by several apertures (down to 7 mm at the reaction chamber entrance) that are pumped independently by high flow root pumps and turbo molecular pumps. A calorimeter at the end of the beam line allows for an ion beam current measurement. The line was designed to study proton and alpha capture on Neon isotopes (e.g. [20–22]), and the p+d reaction (e.g. [23]). Both 4 π BGO and HPGe detectors were used in the many measurement campaigns performed. One of the more recent and high-impact results of measurements using this setup is the cross section of the p+d reaction [23], which improved the nuclear physics input to BBN calculations and their reliability of using primordial abundances to probe the physics of the early Universe.

The solid target line (see e.g. [24–33] for the different updates in time) was designed to perform close geometry experiments and was updated during the years including both lead and polyethylene shielding. Also moveable detector stations were added to perform both reaction cross section (e.g. with a 4π BGO detector [34]) and target degradation measurements (e.g. with a fixed angle HPGe detector). A -300 V biased N$_2$ cooled pipe (cold finger) in front of the water cooled target was installed to reduce carbon build up and suppress secondary electron emission from the target to allow for a reliable charge measurement. Some of the more recent results are the ^{12}C(p, γ)^{13}N and ^{13}C(p, γ)^{14}N [33] reaction cross section measurements which, together with a Monte Carlo R-Matrix analysis, improved both the accuracy and the precision of our understanding of these two reactions in the framework of the CNO cycle.

3 LUNAMV

More recently, a 3.5 MV Singletron$^®$ accelerator was installed at the new "Bellotti Ion Beam Facility" of the INFN-LNGS [35]. It was designed to deliver a high intensity proton beam up to 1 mA, as well as helium and

Table 1. The maximum current deliverable by LUNA MV accelerator [36].

	I_{max} [μA]
$^{1}H^{+}$	1000
$^{4}He^{+}$	500
$^{12}C^{+}$	150
$^{12}C^{++}$	100

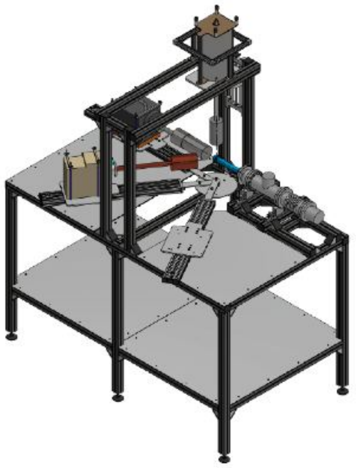

Figure 2. ^{14}N(p, γ)^{15}O measurement setup at LUNAMV

carbon beams (see Table 1), with high stability [36] in both current and energy ($\Delta E/E < 10^{-5}$). To exclude any interference with close-by rare event searches, the accelerator hall was surrounded by 80 cm thick concrete walls to shield any neutrons that might be emitted during its operation. In addition, neutron sensors located inside and outside the accelerator hall provide interlocks to stop operations whenever the neutron flux inside the hall reaches 1/3 of the natural underground neutron flux. Two beam lines are presently installed, with first campaigns to measure ^{14}N(p, γ)^{15}O, ^{12}C +^{12} C, ^{22}Ne(α, n)^{25}Mg and ^{22}Ne(α, γ)^{26}Mg

- ^{14}N(p, γ)^{15}O: already measured with the LUNA400 accelerator [24], this reaction was recently measured at the Notre Dame University [37], at the Helmholtz-Zentrum Dresden-Rossendorf [38] and at the Institute for Nuclear Research (Atomki) [39] finding discrepancies ($\sim$ 50%) in the estimate of the ground state transition component of the S-factor. In Figure 2 the measurement setup is presented. It allows for two experimental phases: one in close geometry with a high efficiency HPGe detector and a second phase with 3 HPGe detecrtors at larger distance for angular distribution measurements. Targets are ^{14}N implanted in tantalum, whose characterization was performed at the LUNA400 accelerator and will be presented with first measurement results in a forthcoming paper [40].
- ^{12}C +^{12} C: recent measurements of the reaction [41, 42] sparked high interest in the community, and despite recent efforts to perform direct cross section measurements [43–45], new low energy data appear necessary

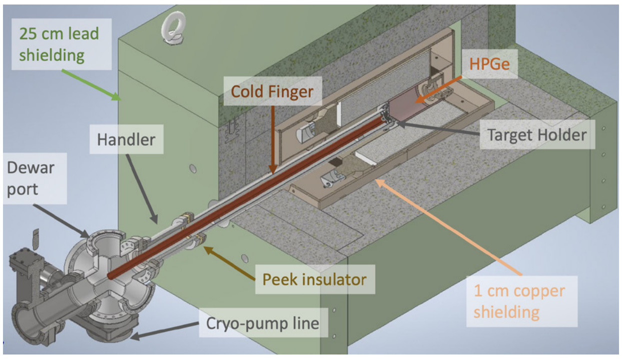

Figure 3. ^{12}C +^{12} C measurement setup at LUNAMV

to solve the present order of magnitude discrepancy between stellar cross section estimates. The LUNA collaboration will perform a measurement of the reaction γ-rays associated with the α - ^{12}C(^{12}C, α_1)^{20}Ne: Q = 4.62 MeV MeV, 1.63 MeV γ-ray - and proton - ^{12}C(^{12}C, p$_1$)^{23}Na: Q = 2.24 MeV, 0.44 MeV γ-ray - particle emission. As shown in Figure 3, 25 cm thick lead shielding and 1 cm of copper lining will be employed to allow for measurements of rates as low as 100 reaction/day. The detection system will be composed of 18 NaI detectors serving as Compton shield for a close geometry high efficiency HPGe detector. Few mm of water cooled standard graphite as well as pyrolytic carbon targets will be employed.

- ^{22}Ne(α, n)^{25}Mg together with ^{13}C(α, n)^{16}O are the most important reactions for the production of s-process neutrons [46, 47], responsible for the production of about half the heavy elements in the Universe. Aside from a resonance located around $E_{cm} \approx$ 700 keV, only upper limits are known for this reaction cross section in the astrophysically relevant energy range. The LUNA MV measurements, funded through the the ERC project SHADES ("Scintillator-He3 Array for Deep-underground Experiments on the S-process")[48], focus on the ^{22}Ne(α, n)^{25}Mg cross section down to the neutron threshold (565 keV) with a ^{3}He proportional counters - EJ-309 liquid scintillator array [49], a high purity recirculated ^{22}Ne windowless gas target and relying on both the high intensity ion beam and low background environment of the Bellotti Facility at LNGS to further improve sensitivity.

- ^{22}Ne(α, γ)^{26}Mg plays a relevant role as competing channel to ^{22}Ne(α, n)^{25}Mg one. Our knowledge of its cross section is similarly limited as the one of ^{22}Ne(α, n)^{25}Mg, making new high sensitive measurements desirable. A new detection array (Figure 4) of NaI is under development at the University of Naples "Federico II" within the Italian Ministry of University and Research funded project "EASγ" (Experimental and Astrophysical Study of ne22(α, γ)), which aims to perform cross section measurements as down as possible in energy.

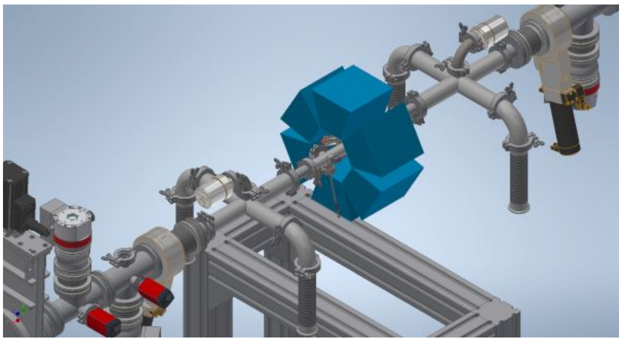

Figure 4. The setup envised for the ^{22}Ne(α,γ)^{26}Mg measurements in shown.

4 Conclusions

The Laboratory for Underground Nuclear Astrophysics (LUNA) has so far provided the nuclear astrophysuics community with high precision low energy reaction cross sections for 30 years. Thanks to the low background of the INFN-LNGS laboratory, reactions of major interest for Big Bang Nucleosynthesis - D(p, γ)^{3}He - pp chain - ^{3}He(^{3}He, 2p)^{4}He - the CNO cycle - ^{14}N(p, γ)^{15}O, ^{12}C(p, γ)^{13}N, ^{13}C(p, γ)^{14}N and many others - have been studied in the first two phases of the collaboration program. With the installation of a new 3.5 MV accelerator at the Bellotti facility in LNGS, a new measurement program starting with ^{14}N(p, γ)^{15}O, ^{12}C+^{12}C, ^{22}Ne(α, n)^{25}Mg and ^{22}Ne(α,γ)^{26}Mg will soon produce relevant scientific results.

Acknowledgements

This work was funded by the INFN, the European Union (ERC-StG 2019 SHADES, grant agreement #852016) and the Italian Ministry for Universities and Research (grant no. R20SLAA8CJ). We are grateful to the mechanical workshop of INFN Bari for the design of figure 2.

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