# UNDERGROUND NUCLEAR ASTROPHYSICS AT LUNA*

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Since 1991, LUNA (Laboratory for Underground Nuclear Astrophysics) has played a leading role in the direct measurement of nuclear cross sections relevant to astrophysics, producing several pioneering results. Thanks to the shielding provided by the Gran Sasso mountain, LUNA enables measuring very small cross sections of the nuclear reactions involved in stellar and Big Bang nucleosynthesis at (or very close to) the energy range at which they occur in astrophysical scenarios. The present accelerator is provided with two beamlines, respectively dedicated to a solid target and to a differential-pumping extended gas target. The most recent measurements are briefly presented, together with the experimental techniques used, and the astrophysical implications. The imminent installation of a new 3.5 MV accelerator paves the way for the study of a number of key reactions regarding helium and carbon burning.

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## 1. The Laboratory for Underground Nuclear Astrophysics

The Laboratory for Underground Nuclear Astrophysics (LUNA) has recently completed the measurements on some reactions involved in different catalytic cycles of hydrogen burning. Among these reactions are $^{17}\mathrm{O}(p,\alpha)^{14}\mathrm{N}$ and $^{22}\mathrm{Ne}(p,\gamma)^{23}\mathrm{Na}$, investigated by means of a solid target and a gas target, respectively. A brief explanation of these measurements will highlight some remarkable features of the experimental setups recently

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used at LUNA. Subsequently, an overview of the LUNA-MV project will introduce the new facility that will be installed at LNGS and will allow the study of several reactions at higher energy.

LUNA is located in Italy, inside LNGS (Laboratori Nazionali del Gran Sasso), the underground laboratories of INFN (Istituto Nazionale di Fisica Nucleare). Since 1991, LUNA experiments have been yielding cross sections of several nuclear reactions relevant to astrophysics [1, 2]. A 1400 m thick rock overburden shields the laboratory from cosmic rays, reducing the muon and neutron fluxes by 6 and 4 orders of magnitude, respectively, in the energy region above 3 MeV [3]. The shielding provided to LUNA by the Gran Sasso mountain allows measuring very small cross sections of the nuclear reactions involved in stellar and Big Bang nucleosynthesis at (or very close to) the energy range at which they occur in astrophysical scenarios. At such low energy, the counting rate in the signal Region of Interest (ROI) can be as low as a few events per month.

The present machine is a 400 kV single-ended electrostatic accelerator [4], constructed and customized by High Voltage Engineering Europa to meet the requirements of the LUNA Collaboration. The accelerating potential is provided by an inline Cockroft–Walton high voltage (HV) generator, filtered and actively stabilized. The ion source is a radio-frequency source and provides a proton (alpha) current as high as 1 mA (0.5 mA) in the Faraday cup at 0°, before the analyzing magnet. The analyzing magnet (stability: $10^{-4}$/h) bends the beam in the 45° direction, selecting the desired component of the beam. A vertical steering magnet is also used to position the beam on the target. A pumping system keeps the vacuum inside the accelerating tube at about $10^{-7}$ mbar.

The machine is controlled by a computer in the control room, a few meters distant from the accelerator room. The controls of beamline gates and Faraday cups are located in the control room as well. A software tool allows the operators to monitor the status of the accelerator and to chose the ion source settings as well as the accelerator parameters and the analyzing magnet current. The software logs the parameters of the machine and an electronic logbook is filled by the operators each time a significant change in the configuration of the accelerator is made.

The beam energy spread at the exit of the accelerator was determined to be $< 100$ eV, while the energy drift is $< 5$ eV/h. The uncertainty on the beam energy is 0.3 keV, and is mainly due to the uncertainty on the $^{12}\mathrm{C}(p,\gamma)^{13}\mathrm{N}$ reaction $Q$-value used in the energy calibration. The calibration was rechecked in 2014 using the resonances in the $^{20,21}\mathrm{Ne}(p,\gamma)^{21,22}\mathrm{Na}$ reactions and was found to be consistent with the new measurements.

## 2. Study of the $^{22}$Ne$(p,\gamma)^{23}$Na reaction with a gas target

### *2.1. Motivation*

The $^{22}$Ne$(p,\gamma)^{23}$Na reaction belongs to the neon–sodium (NeNa) cycle of hydrogen burning [5], which may be activated in different astrophysical scenarios [6], provided that the temperature is high enough and the seed nuclei are present. These conditions are commonly met in the Hot Bottom Burning (HBB) region of Asymptotic Giant Branch (AGB) stars [7]. The NeNa cycle influences the nucleosynthesis of the isotopes between $^{20}$Ne and $^{27}$Al, and contributes to the abundances on the stellar surface [8].

The $^{22}$Ne$(p,\gamma)^{23}$Na reaction has been recently studied at LUNA [9–11], TUNL [12] and HZDR [13]. Upper limits on three tentative resonances at 71, 105 and 215 keV were determined [10], but the uncertainty due to the tentative resonances at 71 and 105 keV still affects the reaction rate.

A new high-efficiency setup was developed at LUNA to investigate the low-energy tentative resonances in the $^{22}$Ne$(p,\gamma)^{23}$Na reaction and the non-resonant component of the cross section [14–16]. This setup, together with a large solid angle, segmented bismuth germanate (BGO) detector, was used to study a number of different reactions, including the $^{22}$Ne$(\alpha,\gamma)^{23}$Na and $^{2}$H$(p,\gamma)^{3}$He reactions.

### *2.2. Setup*

The windowless, extended gas target consists of three differential pumping stages, the target chamber, the gas pipeline and a recycling system, as shown in Fig. 1.

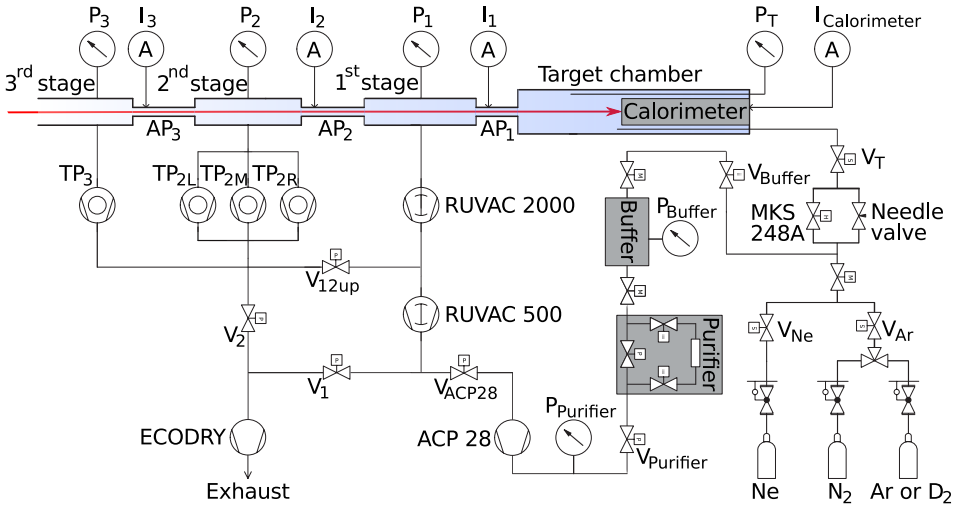



Fig. 1. Scheme of the differential pumping system. A gray/red arrow shows the direction of the beam.

The pumping stages produce a strong pressure gradient between the interaction chamber and the beamline. Three water cooled apertures do not only collimate the beam, but also provide the correct gas flow and determine the pressure drop.

The gas target system can either recycle the gas or let it flow away. The gas is injected in the system through a needle valve and a feedback-controlled valve, providing a constant flux and a variable flux respectively, depending on the pressure set-point. A purifier can be used to remove hydrocarbons, oxygen and nitrogen from the recycled noble gases. The gas is then re-injected in the interaction chamber through the inlet valves.

The gas inlet tube ends close to the beam stop, which is realized by means of a power compensation calorimeter. Another tube arrives in the middle of the chamber and is connected to an MKS Baratron type 626 pressure gauge. This gauge, together with its controller and the MKS 248A valve, provides the feedback which keeps the pressure inside the interaction chamber stable.

A LabVIEW software runs on a NI cRIO system, controlling the beam calorimeter and logging its data. Another LabVIEW software and an NI FieldPoint system are used for the slow control of the gas target. The pressure inside the pumping stages and the interaction chamber is monitored and logged. The software allows to open and close the remotely controlled valves inside the accelerator room and monitor the status of the pumps.

### *2.3. Results*

The high efficiency of the BGO detector also allowed a deeper investigation of the low-energy resonances at 156.2, 189.5 and 259.7 keV. New upper limits were put on the tentative resonances at 71 and 105 keV. The non-resonant component of the cross section was measured as well, and a new evaluation of the thermonuclear reaction rate was obtained. Following this work, the $^{22}\mathrm{Ne}(p,\gamma)^{23}\mathrm{Na}$ reaction rate is now the best known rate in the NeNa cycle. Detailed results will be presented in forthcoming papers.

## 3. Study of the $^{17}\mathrm{O}(p,\alpha)^{14}\mathrm{N}$ reaction with a solid target

### *3.1. Motivation*

The $^{17}\mathrm{O}(p,\alpha)^{14}\mathrm{N}$ reaction takes part in the CNO cycle and affects the synthesis of rare isotopes such as $^{17}\mathrm{O}$ and $^{18}\mathrm{F}$, found in stardust grains and meteorites [17]. Since oxygen isotopes are brought to surface by deep mixing phenomena, their abundance in dust grains can be used to test astrophysical models involving mixing processes [18] such as HBB or cool bottom processing plus additional extra mixing, provided that the Thermonuclear Reaction Rates (TNRR) of the reactions in the CNO cycle are known. In particu-

lar, the origin of Group II grains [19] was poorly known mainly because of the uncertain evaluations of the $^{17}O(p,\alpha)^{14}N$ TNRR over the relevant temperature range ($T = 0.03$–$0.1$ GK).

Two resonances at $E_R^{cm} = 183$ and 64.5 keV determine the rate of the $^{17}O(p,\alpha)^{14}N$ reaction between 0.01 and 0.1 GK. Different measurements of the resonance at $E_R^{cm} = 183$ keV are mutually consistent and led to a precise determination of its strength [20]. On the other hand, disagreement remained concerning the precise energy of the $E_R^{cm} = 64.5$ keV resonance, see *e.g.* Refs. [20–22].

Thanks to the background reduction provided by the LNGS and the optimized detection setup, LUNA improved the determination of the $E_R^{cm} = 64.5$ keV resonance strength and shed light on the origin of Group II grains.

### *3.2. Setup*

The solid target beamline is provided with two slits and a quadrupole. A number of turbo-molecular pumps keep a pressure of about $10^{-7}$ mbar inside the beamline.

During the $^{17}O(p,\alpha)^{14}N$ measurements, the beam impinged on a solid $Ta_2O_5$ target, enriched in $^{17}O$ and supported by a water-cooled tantalum backing. The target was placed inside an instrumented interaction chamber, which consisted of two concentric domes (as shown in Fig. 2). The outer aluminum dome supported eight Canberra PIPS silicon detectors. The detectors had a sensitive area of 900 mm$^2$, a $< 50$ nm thick dead layer and a resolution of about 40 keV FWHM at the 5.486 MeV peak from $^{241}$Am. Four

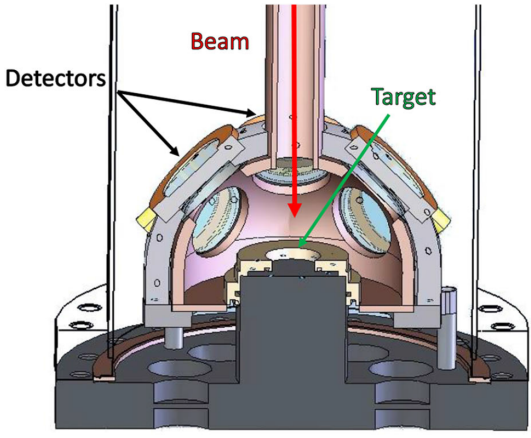



Fig. 2. Sketch of the target chamber used during the measurements on the $^{17}O(p,\alpha)^{14}N$ reaction.

detectors were placed at 135° and four at 102.5°. The inner copper dome was used both to suppress the secondary electrons and support the protective foils in front of the silicon detectors. Aluminised Mylar foils significantly reduced the number of back-scattered protons impinging on the detectors, letting the alpha particles go through. Steel collimators were used in front of the detectors to reduce the pile-up from the surviving protons. Moreover, to avoid carbon deposition on the target, the inner dome was cooled by means of a cold finger at liquid nitrogen temperature. A detailed description of the experimental setup is given in Ref. [23].

### *3.3. Results*

Thanks to the very low background obtained at LUNA [23], the $E_{\mathrm{R}}^{\mathrm{cm}} = 64.5$ keV resonance was directly measured with unprecedented precision, leading to a stellar reaction rate being approximately a factor of 2 higher than what was previously measured at the relevant temperatures [24]. This led to a significant enhancement in the $^{16}\mathrm{O}/^{17}\mathrm{O}$ ratio expected from AGB stars. The measurements carried out at LUNA have a major impact on the origin of stardust grains [18] and $^{17}\mathrm{O}$ stellar yields [25].

## 4. LUNA-MV

A new accelerator will be soon installed at LNGS to allow the study of nuclear reactions involved in helium and carbon burning. The LUNA-MV accelerator will provide intense beams of $\mathrm{H}^+$, $^4\mathrm{He}^+$, $^{12}\mathrm{C}^+$ and $^{12}\mathrm{C}^{++}$ in the energy range of 350 keV–3.5 MeV and is presently under construction at High Voltage Engineering Europe (HVEE) in the Netherlands. The machine will be optimized for high long- and short-term energy stability, long duty cycle and long-term operation without personnel on site.

A preliminary test will be carried out at the production site. Delivery at LNGS, planned for late 2018, will be followed by a six-month-long commissioning phase. Physics experiments are scheduled starting from early 2019.

A simplified sketch of the buildings and infrastructure of the future LUNA-MV installation is shown in Fig. 3. A 80 cm thick concrete wall will completely surround the accelerator, its beamlines and the target stations. Two sliding doors of the same thickness and material will cover the entrances on opposite sides of the building. Two simulations, performed independently using Geant4 and MCNP codes, proved a negligible contribution of the experiment to the neutron flux outside the concrete building (contribution up to 20% of the natural neutron background inside LNGS).

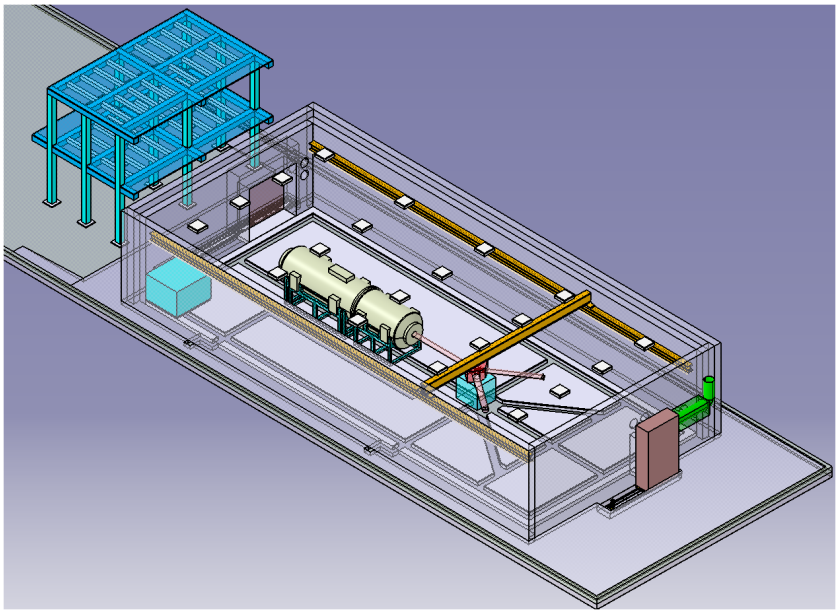


Fig. 3. Sketch of the LUNA-MV accelerator and buildings.

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