Latest results from LUNA experiment

Francesca Cavanna[1], *for the LUNA collaboration*
[1]INFN, Sezione di Genova, Via Dodecaneso 33, 16146 Genoa, Italy

DOI: http://dx.doi.org/10.3204/DESY-PROC-2016-05/10

Nuclear processes are responsible for energy generation that makes stars shine, and for the synthesis of the elements in stars and also play a decisive role in explaining the chemical composition of the interstellar medium. Thermonuclear fusion reactions convert protons into heavier elements from He to Fe. Deep underground in the Gran Sasso Laboratory the key reactions of the proton-proton chain, the carbon-nitrogen-oxygen cycle and the neon-sodium cycle have been studied down to the energies of astrophysical interest. The latest results are reviewed, together with future developments of underground nuclear astrophysics.

1 Nuclear astrophysics at Gran Sasso

At the Laboratory for Underground Nuclear Astrophysics (LUNA), in the Gran Sasso National Laboratory, several cross sections have been measured in the past down to the energies of astrophysical interest [1, 2].

At low energy, the cross section of a charged particle induced reaction steeply drops with decreasing energy due to the Coulomb barrier. Generally, it has a very low value at the Gamow Peak, the energy region where most reactions occur; this prevents a direct measurement in a laboratory on the Earths surface, where the signal to background ratio is too small because of cosmic ray interactions with detectors. The Gran Sasso underground facility is shielded against cosmic rays by a rock cover (1400 m thick) equivalent to 3800 m water, suppressing the muon and neutron flux by six and three orders of magnitude, respectively.

The measurement of the cross section for thermonuclear reactions require an experimental apparatus composed of an accelerator, a target, and a detection system.

The LUNA 400 kV accelerator delivers a proton beam of 500 μA or an alpha beam of 300 μA in the energy range of $E_{p-\alpha}$ = 50-400 keV. The ions can be sent into one of two different, beam lines, thereby allowing the parallel installation of solid and gas target setups.

For nuclear reactions in which charged particles are emitted, silicon detectors are usually adopted to make an in-beam measurement.

For nuclear reactions in which only γ-rays are emitted, the choice of the most suitable detector depends on the physical information desired. The 4π bismuth germanate (BGO) summing crystal used at LUNA can reach an efficiency as high as 70% for a 7-MeV γ ray, thus allowing the measurement of extremely low reaction yields. However, the BGO's energy resolution is very poor and does not allow measurements of cascades and branching ratios to different levels because most of the γ-ray transitions are summed in a single peak. With a germanium detector, the efficiency decreases to the level of a few per mil, but the energy resolution is much better, allowing complex γ-ray cascades to be disentangled. Moreover, angular distribution measurements can be made by placing the detector at different angles with respect to the ion beam.

2 Reactions studied at LUNA in the last years:

2.1 ^{17}O(p,α)^{14}N

This reaction plays an important role in the synthesis and abundance of key isotopes often used to test nucleosynthesis models of classical novae, Asymptotic Giant Branch (AGB) and post-AGB stars [3, 4, 5]. At energies of astrophysical interest its reaction rate is dominated [6] by a narrow and isolated resonance at E_p=70 keV. This resonance has been studied several times in the past, using both direct and indirect methods, as summarised in ref. [7]. However, the picture painted in the literature is still not completely satisfying. The uncertainty in the resonance strength is not negligible ($\approx$20%). Furthermore, published strength values obtained with direct measurements have all been retracted or reanalysed [7].

An experimental campaign aimed at measuring the E_p=70 keV resonance in $^{17}O(p,\alpha)^{14}N$ has been recently completed at the underground LUNA accelerator. The low background in the underground environment has been exploited in order to carry out a direct investigation of this weak ($\omega\gamma \approx$ neV) resonance employing the thick-target yield technique. Protons have been accelerated on a solid Ta_2O_5 target and alpha particles detected at backward angles using an array of silicon detectors (Fig.1). The setup has been commissioned using the well-known E_p=193 keV resonance in $^{17}O(p,\alpha)^{14}N$ [8].

A clear peak has been observed at E_p=71.5 keV. The alpha peak from the E_p=70 keV resonance appears where expected and has a signal significance higher than 5 sigma. Results of the analysis indicate a resonance strength that is significantly higher than reported in previous investigations. Because of the importance of this resonance [6], LUNA results is expected to have significant astrophysical consequences in a number of scenarios.

2.2 ^{22}Ne(p,γ)^{23}Na

The ^{22}Ne(p,γ)^{23}Na reaction is involved in the hydrogen burning neon-sodium (NeNa) cycle which is active in Red Giant Branch stars (Gamow peak 30-100 keV), Asymptotic Giant Branch Stars (AGB), classical novae (Gamow peak 100-600 keV) [9] as well as in type Ia supernovae [10] and contributes to the nucleosynthesis of neon and sodium isotopes.

The ^{22}Ne(p,γ)^{23}Na is the NeNa cycle reaction with the most uncertain cross section. In the energy range relevant for astrophysics, the ^{22}Ne(p,γ)^{23}Na reaction rate was poorly known because of the contribution of a large number of resonances, many of which were never observed directly [11, 12], before the experiment performed at LUNA in 2015. The lowest-lying resonance with a directly measured strength was the one at $E_R^{lab} = 436\,\text{keV}$ [13]; for the resonances below that energy, only upper limits were reported in the literature [14, 15, 16]. The mere existence of several ^{23}Na energy levels, e.g. the ones corresponding to the E_p = 215, 104, and 70 keV resonances, is even doubted [17].

An experimental campaign structured in two phases has been started in 2013 to measure directly the resonance strength of several resonances below 400 keV. The data taking for the first phase, with High Purity Germanium Detectors (HPGe), has been concluded and the results have been published in 2015 [18]. The data taking for the second phase, with BGO detectors, has been recently accomplished, the data analysis is still on going.

Phase I: HPGe detectors

The setup consisted of two HPGe detectors, one at 90° with respect to the beam direction, and the other one at 55° effective angle. The use of two high resolution detectors with well defined solid angles allowed a measurement not only of the total resonance strength, but also of the different branching ratios of the resonance decay. The two detectors were surrounded by a 4 cm thick copper shielding and a 25 cm thick lead shielding in order to suppress the environmental background [19].

The gamma detection efficiency has been determined in the energy range of interest for the measurement (i.e. $440\,\mathrm{keV} < E_\gamma < 9.5\,\mathrm{MeV}$) with radioactive sources at the lower energies (^{7}Be, ^{137}Cs, ^{60}Co and ^{88}Y) and with the ^{14}N(p,γ)^{15}O nuclear reaction at the higher energies.

Enriched neon-22 gas has been used for the measurements; for each resonance the yield profile as a function of the proton beam energy has been studied in 1-2 keV steps.

The resonances at $E_R^{lab} = 156.2$, 189.5 and 259.7 keV have been detected for the first time. In Fig. 2 the spectrum of the $E_R^{lab} = 156.2\,\mathrm{keV}$ resonance is shown together with the identified ^{23}Na transitions. Also the background lines are shown. Detailed branching schemes have been developed for the new resonances, and in two cases, even a coincidence analysis of the two HPGe detectors has been possible. The thermonuclear reaction rate obtained with these new LUNA results [18] is shown in Fig. 3 compared with previous rates reported in literature.

Phase II BGO detector

In phase II of the experiment, a high-luminosity 4π bismuth germanate summing crystal (BGO) was used in order to address several low-energy resonances and the direct capture component, as well. The typical γ-ray detection efficiency of 70% of this detector [20] enable either a positive confirmation or a severe upper limit for the low-energy resonances that make up much of the discrepancy between the Sallaska and NACRE reaction rates (fig. 3).

The efficiency of the new setup was measured by means of four radioactive sources (^{7}Be, ^{137}Cs, ^{60}Co and ^{88}Y) and the well known E_p=278 keV resonance of the $^{14}\mathrm{N}(p,\gamma)^{15}\mathrm{O}$ reaction.

During the whole 2015 the data taking of this phase has been completed. The non resonant contribution to the S-factor has been measured in an energy range from 200 keV up to 360 keV and the two purported resonances at 70 and 105 keV, for which only upper limits exist from the HPGe phase, have been studied in detail.

2.3 Future project: LUNA-MV

In the last years LUNA obtained important achievements in experimental Nuclear Astrophysics, mainly studying hydrogen burning reactions. In order to make a step forward and be able to measure reactions belonging to the helium burning that are important at higher temperatures in stars that ultimately means larger interaction energies, a higher voltage accelerator is necessary. With this aim, a new project just started, the LUNA-MV, which foresees the installation of a 3.5 MV machine in hall B of Gran Sasso Laboratories. The LUNA MV accelerator will provide intense beams of H$^+$, ^{4}He$^+$, ^{12}C$^+$ e ^{12}C^{++} in the energy range: 200 keV - 3.5 MeV. The accelerator will be built and tested by November 2017. Delivery at LNGS is scheduled for

January 2018. Finally, by July 2018 the accelerator will be installed and tested in hall B. The first five years of experimental program foresee the measurement of ^{14}N(p,γ)^{15}O, ^{13}C(α,n)^{16}O, ^{22}Ne(α,n)^{25}Mg and ^{12}C+^{12}C. Important achievements are expected soon.

2.4 Tables and figures

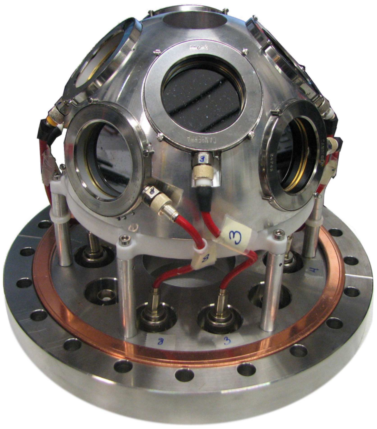

Figure 1: Picture of the target chamber used for the ^{17}O(p,α)^{14}N cross section measurement. All silicon detectors are mounted. Protective foils are mounted on the inner dome in front of each detector.

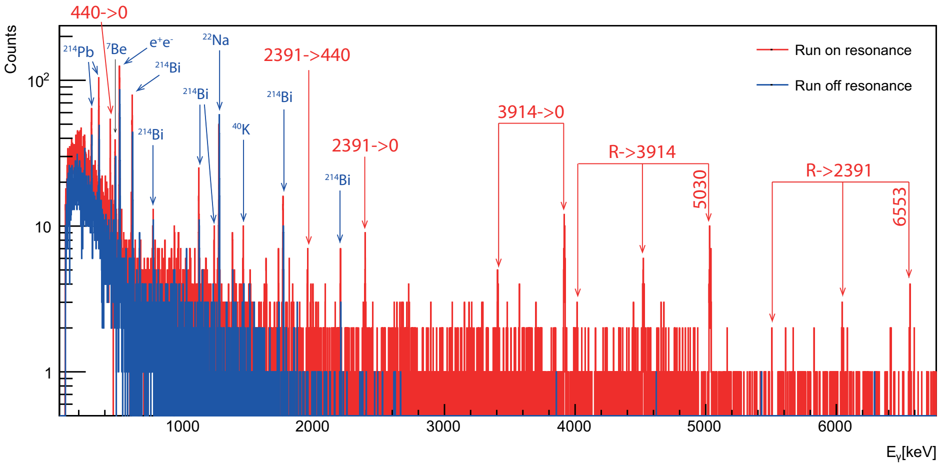

Figure 2: (Color online) In red spectrum measured at $E_p = 162$ keV, on top of the resonance at 156.2 keV. The off-resonance spectrum (in blue) is superimposed.

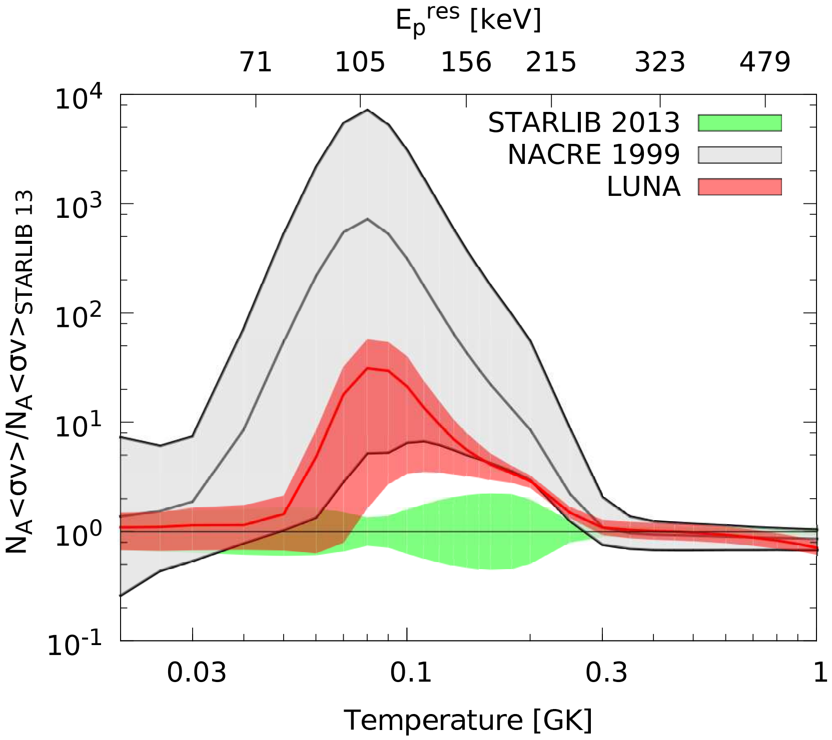

Figure 3: Thermonuclear reaction rate of LUNA [18], NACRE Collaboration [11] and STARLIB group [21], normalized to STARLIB group.

References

[1] H. Costantini, A. Formicola, G. Imbriani, M. Junker, C. Rolfs, and F. Strieder. LUNA: a laboratory for underground nuclear astrophysics. *Rep. Prog. Phys.*, 72(8):086301–+, August 2009.

[2] Carlo Broggini, Daniel Bemmerer, Alessandra Guglielmetti, and Roberto Menegazzo. LUNA: Nuclear Astrophysics Deep Underground. *Annu. Rev. Nucl. Part. Sci.*, 60:53–73, 2010.

[3] M. Lugaro, A. I. Karakas, L. R. Nittler, C. M. O. Alexander, P. Hoppe, C. Iliadis, and J. C. Lattanzio. On the asymptotic giant branch star origin of peculiar spinel grain OC2. *Astron. Astrophys.* , 461:657–664, January 2007.

[4] S. Palmerini, M. L. Sergi, M. La Cognata, L. Lamia, R. G. Pizzone, and C. Spitaleri. The RGB and AGB Star Nucleosynthesis in Light of the Recent ^{17}O(p, α)^{14}N and ^{18}O(p, α)^{15}N Reaction-rate Determinations. *Astrophys. J.* , 764:128, February 2013.

[5] K. M. Nollett, M. Busso, and G. J. Wasserburg. Cool Bottom Processes on the Thermally Pulsing Asymptotic Giant Branch and the Isotopic Composition of Circumstellar Dust Grains. *Astrophys. J.* , 582:1036–1058, January 2003.

[6] M. Q. Buckner, C. Iliadis, K. J. Kelly, L. N. Downen, A. E. Champagne, J. M. Cesaratto, C. Howard, and R. Longland. High-intensity-beam study of ^{17}O(p ,γ)^{18}F and thermonuclear reaction rates for ^{17}O+p. *Phys. Rev. C* , 91(1):015812, January 2015.

[7] M. L. Sergi, C. Spitaleri, M. La Cognata, L. Lamia, R. G. Pizzone, G. G. Rapisarda, X. D. Tang, B. Bucher, M. Couder, P. Davies, R. deBoer, X. Fang, L. Lamm, C. Ma, M. Notani, S. O'Brien, D. Roberson, W. Tan,

M. Wiescher, B. Irgaziev, A. Mukhamedzhanov, J. Mrazek, and V. Kroha. Improvement of the high-accuracy ^{17}O(p ,α)^{14}N reaction-rate measurement via the Trojan Horse method for application to ^{17}O nucleosynthesis. *Phys. Rev. C* , 91(6):065803, June 2015.

[8] C. G. Bruno, D. A. Scott, A. Formicola, M. Aliotta, T. Davinson, M. Anders, A. Best, D. Bemmerer, C. Broggini, A. Caciolli, F. Cavanna, P. Corvisiero, R. Depalo, A. Di Leva, Z. Elekes, Z. Fülöp, G. Gervino, C. J. Griffin, A. Guglielmetti, C. Gustavino, G. Gyürky, G. Imbriani, M. Junker, R. Menegazzo, E. Napolitani, P. Prati, E. Somorjai, O. Straniero, F. Strieder, T. Szücs, and D. Trezzi. Resonance strengths in the ^{17,18}O(p, α)^{14,15}N reactions and background suppression underground. Commissioning of a new setup for charged-particle detection at LUNA. *European Physical Journal A*, 51:94, August 2015.

[9] Christian Iliadis, Art Champagne, Jordi José, Sumner Starrfield, and Paul Tupper. The effects of thermonuclear reaction-rate variations on nova nucleosynthesis: A sensitivity study. *Astrophys. J. Suppl. Ser.*, 142:105–137, 2002.

[10] D. A. Chamulak, E. F. Brown, F. X. Timmes, and K. Dupczak. The Reduction of the Electron Abundance during the Pre-explosion Simmering in White Dwarf Supernovae. *Astrophys. J.* , 677:160–168, April 2008.

[11] Carmen Angulo, M. Arnould, M. Rayet, P. Descouvemont, D. Baye, C. Leclercq-Willain, A. Coc, S. Barhoumi, P. Aguer, C. Rolfs, R. Kunz, J. W. Hammer, A. Mayer, T. Paradellis, S. Kossionides, C. Chronidou, K. Spyrou, S. degl'Innocenti, G. Fiorentini, B. Ricci, S. Zavatarelli, C. Providencia, H. Wolters, J. Soares, C. Grama, J. Rahighi, A. Shotter, and M. Lamehi Rachti. A compilation of charged-particle induced thermonuclear reaction rates. *Nucl. Phys. A*, 656:3–187, 1999.

[12] C. Iliadis, R. Longland, A. E. Champagne, and A. Coc. Charged-particle thermonuclear reaction rates: III. Nuclear physics input. *Nucl. Phys. A*, 841:251–322, 2010.

[13] R. Depalo, F. Cavanna, F. Ferraro, A. Slemer, T. Al-Abdullah, S. Akhmadaliev, M. Anders, D. Bemmerer, Z. Elekes, G. Mattei, S. Reinicke, K. Schmidt, C. Scian, and L. Wagner. Strengths of the resonances at 436, 479, 639, 661, and 1279 keV in the ^{22}Ne(p ,γ) ^{23}Na reaction. *Phys. Rev. C* , 92(4):045807, October 2015.

[14] J. Görres, C. Rolfs, P. Schmalbrock, H. P. Trautvetter, and J. Keinonen. Search for low-energy resonances in ^{21}Ne(p,γ)^{22}Na and ^{22}Ne(p,γ)^{23}Na. *Nucl. Phys. A*, 385:57–75, 1982.

[15] J. Görres, H. W. Becker, L. Buchmann, C. Rolfs, P. Schmalbrock, H. P. Trautvetter, A. Vlieks, J. W. Hammer, and T. R. Donoghue. Proton-induced direct capture on ^{21}Ne and ^{22}Ne. *Nucl. Phys. A*, 408:372–396, October 1983.

[16] S. E. Hale, A. E. Champagne, C. Iliadis, V. Y. Hansper, D. C. Powell, and J. C. Blackmon. Investigation of the ^{22}Ne(p,γ)^{23}Na reaction via (^{3}He,d) spectroscopy. *Phys. Rev. C*, 65:015801, 2001.

[17] R. B. Firestone. Nuclear Data Sheets for A = 23. *Nucl. Data Sheets*, 108:1–78, 2007.

[18] F. Cavanna, R. Depalo, M. Aliotta, M. Anders, D. Bemmerer, A. Best, A. Boeltzig, C. Broggini, C. G. Bruno, A. Caciolli, P. Corvisiero, T. Davinson, A. di Leva, Z. Elekes, F. Ferraro, A. Formicola, Z. Fülöp, G. Gervino, A. Guglielmetti, C. Gustavino, G. Gyürky, G. Imbriani, M. Junker, R. Menegazzo, V. Mossa, F. R. Pantaleo, P. Prati, D. A. Scott, E. Somorjai, O. Straniero, F. Strieder, T. Szücs, M. P. Takács, D. Trezzi, and LUNA Collaboration. Three New Low-Energy Resonances in the ^{22}Ne (p ,γ)^{23}Na Reaction. *Physical Review Letters*, 115(25):252501, December 2015.

[19] F. Cavanna et al. A new study of the ^{22}Ne(p,γ)^{23}Na reaction deep underground: Feasibility, setup, and first observation of the 186 keV resonance. *Eur. Phys. J. A* , 50:179, 2014.

[20] C. Casella, H. Costantini, A. Lemut, B. Limata, D. Bemmerer, R. Bonetti, C. Broggini, L. Campajola, P. Cocconi, P. Corvisiero, J. Cruz, A. D'Onofrio, A. Formicola, Z. Fülöp, G. Gervino, L. Gialanella, A. Guglielmetti, C. Gustavino, G. Gyurky, A. Loiano, G. Imbriani, A. P. Jesus, M. Junker, P. Musico, A. Ordine, F. Parodi, M. Parolin, J. V. Pinto, P. Prati, J. P. Ribeiro, V. Roca, D. Rogalla, C. Rolfs, M. Romano, C. Rossi-Alvarez, A. Rottura, F. Schuemann, E. Somorjai, F. Strieder, F. Terrasi, H. P. Trautvetter, A. Vomiero, and S. Zavatarelli. A new setup for the underground study of capture reactions. *Nucl. Inst. Meth. A*, 489:160–169, August 2002.

[21] A. L. Sallaska, C. Iliadis, A. E. Champagne, S. Goriely, S. Starrfield, and F. X. Timmes. STARLIB: A Next-generation Reaction-rate Library for Nuclear Astrophysics. *Astrophys. J. Suppl. Ser.* , 207:18, July 2013.