Nuclear Astrophysics in underground laboratories: the LUNA experiment

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Abstract. One of the main ingredients of nuclear astrophysics is the knowledge of the thermonuclear reactions responsible for powering the stellar engine and for the synthesis of the chemical elements. At astrophysical energies the cross section of nuclear processes is extremely reduced by the effect of the Coulomb barrier. The low value of cross sections for charged particles prevents their measurement at stellar energies on Earth surface and often extrapolations are needed. The Laboratory for Underground Nuclear Astrophysics (LUNA) is placed under the Gran Sasso mountain and thanks to the cosmic-ray background reduction provided by its position can investigate cross sections at energies close to the Gamow peak in stellar scenarios. Many crucial reactions involved in hydrogen burning have been measured directly at astrophysical energies with both the LUNA-50kV and the LUNA-400kV accelerators, and this intense work will continue with the installation of a MV machine able to explore helium and carbon burnings. Based on this progress, currently there are efforts in several countries to construct new underground accelerators. In this talk, the typical techniques adopted in underground nuclear astrophysics will be described and the most relevant results achieved by LUNA will be reviewed. The exciting science that can be probed with the new facilities will be highlighted.

1. Introduction
Nuclear processes generate the energy that makes stars shine. Moreover they are responsible of the synthesis of the elements (and isotopes) in stars. As a matter of fact, hydrogen, helium and all isotopes until lithium and beryllium are synthesised mainly during the Big Bang Nucleosynthesis (BBN). All other nuclei are produced during the different characteristic phases of the star evolution [1].

The goal of nuclear astrophysics is to understand the nuclear processes, and in particular the cross sections, involved in the stellar nucleosynthesis, the production of solar neutrinos and that power the stars. As a mater of fact, nuclear astrophysics is an interdisciplinary field with deep connections with other fields of research starting from astronomy observations, atomic physics, neutrino physics etc.

Quiescent burning phases proceed through charged particles induced reactions in different stellar scenarios up to the formation of iron. Depending on the relevant temperature the relative velocity of ions is different. In particular, the astrophysical relevant energy region is given by the folding of two strongly energy dependent functions [1, 2]: the Maxwell-Boltzmann velocity distribution and the cross section of charged particle induced reactions. This forms a peak
structure called the Gamow peak. The maximum energy of this peak can be approximately calculated in units of MeV:

\[ E_G \approx 0.1220(Z_1^2 Z_2^2 \mu)^{1/3} T_9^{2/3} \]  

(1)

where \( Z_{1,2} \) are the atomic numbers of the two reaction partners, \( \mu = m_1 m_2 / (m_1 + m_2) \) the reduced mass, and \( T_9 = T / 10^9 \) K is the temperature of the astrophysical scenario under study. The Gamow energy of nuclear reactions taking place in the Sun, with its core temperature of \( T_9 \approx 0.016 \), is typically 20 keV depending on the precise reaction, leading to cross sections in the range of pbarn or even lower. The thermonuclear cross sections at the energies of the Gamow peak are very low and the reactions can occur only through tunnel effect. Therefore the cross section can be written taking into account the penetrability of the Coulomb barrier term and the astrophysical S-factor, which contains the nuclear component of the cross section:

\[ \sigma(E) = \frac{S(E)}{E} \exp(-2 \pi \eta), \]  

(2)

where \( \eta \) is the Sommerfeld parameter, given by:

\[ 2 \pi \eta = 31.29 Z_1 Z_2 (\mu/E)^{1/2}, \]  

(3)

\( \mu \) is the reduced mass (in units of amu), and \( E \) is the center of mass energy (in units of keV).

The cross section drops steeply with the energy due to the penetrability of the Coulomb barrier and the expected reaction rate in laboratory is too low and usually overwhelmed by the laboratory background [3]. In many cases, the minimum energy reachable with direct experiments is far from the energy of the Gamow peak, leading to substantial uncertainties. Being in an underground environment greatly helps in reducing the background due to the cosmic rays [4, 5]. As a matter of fact, the natural shielding provided by an underground site will guarantee a reduction of the cosmic flux of orders of magnitude. LUNA (Laboratory for Underground Nuclear Physics) [6] is placed under the Gran Sasso National Laboratories of INFN. Two accelerators were used during years. First a 50 kV accelerator [7] and then a 400kV accelerator [8].

In the INFN Gran Sasso Laboratory, the rate of muon and neutron fluxes are reduced by 6 and 3 orders of magnitude, respectively. In the gamma-ray spectrum below 3 MeV still remains the contribution due to the radioactive isotopes in the experimental room. This can be suppressed by adding an additional shielding made of copper and lead as described in Ref. [3, 9].

A review of the results achieved by the LUNA collaboration will be presented in this paper, combined with a discussion on the future projects for nuclear astrophysics in underground with MV accelerators.

2. Solar Hydrogen burning

The first reaction studied by the LUNA collaboration was the \( ^3\text{He}(^3\text{He,2p})^4\text{He} \) reaction. This is a key reaction of the proton proton chain and, at the beginning of the seventies, a possible resonance in the \( ^3\text{He}(^3\text{He,2p})^4\text{He} \) Gamow peak was suggested to explain the results of the Homestake experiment [10]. The cross section of this reaction was measured covering the Gamow peak for the Sun for the first time [11, 12]. The debated resonance [13, 14] was not observed, removing a possible nuclear explanation for the solar neutrino problem.

Another important reaction performed with the actual LUNA400 accelerator was the \( ^3\text{He}(\alpha, \gamma)^7\text{Be} \) reaction, which controls the \(^7\text{Be} \) and \(^8\text{B} \) neutrinos and it is also fundamental for the production of \(^7\text{Li} \) during the Big Bang Nucleosynthesis (BBN). This reaction was studied by using both the gamma prompt detection [15, 16] and the activation techniques [17, 18] finding a perfect agreement. This way the overall systematics were reduced, but also the discrepancy observed in the previous data in literature was solved.
3. The CNO cycles

The $^{14}\text{N}(p,\gamma)^{15}\text{O}$ reaction is the bottleneck of the CN cycle and therefore the $^{13}\text{N}$ and $^{15}\text{O}$ neutrinos are controlled by this reaction. The LUNA collaboration has studied this reaction by means of different experiments and different experimental setups. The first one was characterised by a solid target coupled with a HPGe detector \cite{19, 20}, while a subsequent experiment was done by using of a windowless gas target and a 4$\pi$-BGO detector to measure the total cross section in a wide range of energies (down to 70 keV in the center of mass) \cite{21, 22}, totally covering the nova explosion scenario with experimental data.

In order to reduce this nuclear uncertainties in the solar model, a new measurement was performed at LUNA by measuring three energy points above the 259 keV resonance and leading to and extrapolated value $S_{1,14}(0)=1.57\pm0.13$ keV barn \cite{23, 24}. More complete discussion can be found in recent reviews on this reaction \cite{25, 26}. It has to be noted that, the last two experiments performed in an high energy range, above the LUNA energies, \cite{27, 28} reports a discrepancy in the extrapolated S-factor for the ground state transition which has to be solved in future measurements. A recent activation experiment has also been performed on this reaction for the study of the main resonances affecting the S-factor at astrophysical energies \cite{29}.

While the $^{14}\text{N}(p,\gamma)^{15}\text{O}$ reaction is the bottleneck, the $^{15}\text{N}(p,\gamma)^{16}\text{O}$ links the first and the second CNO cycles and before LUNA, the data in literature shown a discrepancy between the direct measurements. By performing three different experiments \cite{30, 31, 32} the LUNA collaboration reduced the extrapolated cross section in the Sun by a factor of two and covered totally with direct data the Gamow peak in the region of nova explosion where this reaction impacts most, leading to a reduction of 30% of the $^{16}\text{O}$ produced in that scenario.

For the study of proton induced reaction on oxygen isotopes, a novel technique for producing tantalum oxide targets was directly developed by the LUNA group \cite{33}. This was an important results, since the target characterisation is one of the most important source of uncertainty in direct experiments. This way a long campaign of measurements was started leading to several important results for the $^{17}\text{O}(p,\gamma)^{18}\text{F}$ reaction \cite{34, 35}, and the $^{17}\text{O}(p,\alpha)^{14}\text{N}$ reaction \cite{36, 37, 38}. This latter reaction has been also studied with indirect methods \cite{39}. The LUNA results on the 65 keV resonance are in disagreement with their results leading to the need of a further investigation on this discrepancy. In the case of the $^{17}\text{O}(p,\gamma)^{18}\text{F}$ reaction, a measurement from the group of TUNL has been published in 2015 \cite{40} reporting a perfect agreement with the LUNA results.

4. The Ne-Na and Mg-Al cycles at LUNA

The nucleosynthesis in the neon sodium cycle occurs via many reactions. In particular, the uncertainty on the $^{22}\text{Ne}(p,\gamma)^{23}\text{Na}$ dominates the uncertainty of the entire cycle. As a matter of fact, this reaction has several resonances below 400 keV and many of them were only given as upper limits based on indirect measurements. In particular, the databases \cite{41, 42} reported a discrepancy of a factor one thousand. A fully shielded setup has been implemented \cite{9} to observe for the first time three resonances and to improve the upper limits for other three resonances \cite{43, 44}. Finally, an updated reaction rate has been obtained, which is significantly higher than the one given in the most recent compilation of reaction rates \cite{42}. As a consequence, new values for the ejected mass of $^{22}\text{Ne}$ and $^{23}\text{Na}$ in thermally pulsing AGB stars have been obtained with much reduced uncertainties \cite{45}. A second campaign was performed implementing a high efficiency BGO detector \cite{46} that allows to also measure for the first time the direct capture component of the cross section \cite{47}. This reaction has been also studied in inverse kinematics at the DRAGON facility \cite{48} reporting a reaction rate in good agreement with the one in \cite{47}.

The study of the CNO cycles is the natural precursor for the hydrogen burning in Mg-Al cycles. The problem of the $^{26}\text{Al}$ production is one of the most interesting cases \cite{49}. LUNA measured precisely several resonances for $^{24,25}\text{Mg}(p,\gamma)^{26,27}\text{Al}$ in order to reduce the uncertainties.
on those reactions as requested in the astrophysical models [50, 51]. The impact of the LUNA results is discussed in details in a recent work [52].

5. Science case for a future higher-energy accelerator underground

Many other reaction of helium and carbon burning must be studied in order to solve important puzzles of nuclear astrophysics. Those studies are not accessible with the actual LUNA400 accelerator as discussed in Ref. [53].

A new accelerator is under construction and will be installed in the next future in the Gran Sasso Laboratory in order to expand the accessible energy range by using a 3.5 MV single ended machine. This accelerator will be able to produce proton, helium and carbon beams with high current and high precision and stability in energy.

The first reaction to be studied will be the $^{14}$N(p,γ)$^{15}$O. The solar composition problem has been already addressed above and recently a new measurement has been performed at high energy founding discrepancies with the LUNA data [27]. The new MV machine will allow to cover with a unique set of data a wide energy range from 2 MeV down to the LUNA400 energies, allowing to reduce the systematics down to the goal of 5%.

Another important open issue of nuclear astrophysics is the neutron source reactions: the $^{13}$C(α,n)$^{16}$O and the $^{22}$Ne(α,n)$^{25}$Mg reactions. The first one is under study, in a different energy range at the LUNA400 accelerator with a huge effort on keeping the target stability under control [54]. The latter, instead, has a threshold of about 500 keV in the laboratory system and will be accessible only with the new accelerator. More information on those two reactions and the available data in literature can be found in [25, 55].

The $^{12}$C+$^{12}$C is the trigger of the carbon burning and is a key reaction to predict the final stage of a star. It determines which is the mass required to a star to ignite this burning stage. In addition, this reaction also affects the outcome of type Ia supernovae. Among the open channels at astrophysical energies (from around 0.7 to 3.5 MeV in the center of mass), the two most important channels are the one emitting charged particles (alphas and protons). These two channels (proton and α) have never been studied down below 2 MeV in direct experiments [25]. Recently, the combined efforts of γ-ray and particles detection in coincidence have pushed the experimental sensitivity [56, 57] still keeping the limit at 2 MeV for this kind of experiments. By using indirect methods, such as the trojan horse one, the astrophysical S-factor for those two channels has been determined down to 0.8 MeV covering the whole Gamow peak [58]. Due to the intrinsic need of normalisation to direct data of the trojan horse method, a claim for new direct results down to 1.5 MeV have been reported recently [59]. A detailed comparison between the indirect data and the already published direct data is also reported in [59]. By using the future LUNA MV accelerator, it will be possible to measure the cross section down to 1.7 MeV. This way a better overlap between the indirect and direct methods will be possible leading to stronger result on the reaction rate for this important thermonuclear reaction.

A third topic is to complement some of the proton- and α-capture reactions studied at the LUNA2 accelerator at higher energy. Such a continuation is particularly important for the Big Bang reactions $^4$He(α,γ)$^7$Be and $^2$H(α,γ)$^6$Li, where the present LUNA2 400 kV machine can only cover the lower part of the relevant energy region.

6. Future underground accelerator facilities

Based on the successes of the LUNA collaboration, around the world several efforts are underway to install high-current, stable-beam accelerators in underground sites. The MV machine that will be installed at the INFN National Laboratories of Gran Sasso has been already described above and the synergy with the actual LUNA400 machine has been discussed. Other facilities have been proposed worldwide for installing an accelerator in deep underground laboratory: for example in US [60] and in China [61]. As part of a staged approach, even an accelerator
laboratory in a shallow-underground facility such as Felsenkeller (Dresden, Germany) is now operative.

At present, the existing LUNA400 machine continues its scientific program. The next few years will show where this highly successful approach will eventually be complemented by one or more higher-energy accelerators underground. The technique is sufficiently mature to address not only the data needs of the astrophysics community, but it has the potential to benefit also the astroparticle and other communities.

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References

[1] Iliadis C 2007 Nuclear Physics of Stars (Weinheim: Wiley-VCH)
[2] Rolfs C and Rodney W 1988 Cauldrons in the Cosmos (Chicago: University of Chicago Press)
[3] Cacioli A et al., 2009 Eur. Phys. J. A 39 179–186
[4] Bemmerer D et al., 2005 Eur. Phys. J. A 24 313–319
[5] Best, A et al., 2016 Eur. Phys. J. A 52 72
[6] Brogginii C, Bemmerer D, Guglielmetti A and Menegazzo R 2010 Annu. Rev. Nucl. Part. Sci. 60 53–73
[7] Greife U et al. 1994 Nucl. Inst. Meth. A 350 327
[8] Formicola A, et al., 2003 Nucl. Inst. Meth. A 507 609–616
[9] Caciolli A et al., 2009 Eur. Phys. J. A 39 179–186
[10] Bemmerer D et al., 2006 Eur. Phys. J. A 24 313–319
[11] Best, A et al., 2016 Eur. Phys. J. A 52 72
[12] Brogginii C, Bemmerer D, Guglielmetti A and Menegazzo R 2010 Annu. Rev. Nucl. Part. Sci. 60 53–73
[13] Greife U et al. 1994 Nucl. Inst. Meth. A 350 327
[14] Formicola A, et al., 2003 Nucl. Inst. Meth. A 507 609–616
[45] Slemer A, et al., 2017 Monthly Notices of the Royal Astronomical Society 465 4817
[46] Ferraro F, et al., 2018 The European Physical Journal A 54 44
[47] Ferraro F, et al., 2018 Phys. Rev. Lett. 121(17) 172701
[48] 2019 First inverse kinematics study of the $^{22}\text{ne}(p, ?)^{23}\text{na}$ reaction and its role in aGB star and classical nova nucleosynthesis (Preprint 1910.01698)
[49] Iliadis C, Champagne A, Chieffi A and Limongi M 2011 The Astrophysical Journal Supplement Series 193 16
[50] Limata B et al. 2010 Phys. Rev. C 82 015801
[51] Strieder F, et al., 2012 Phys. Lett. B 707 60-65
[52] Straniero O, et al., 2013 Astrophys. J. 763 100
[53] LUNA MV Scientific Proposal https://luna.lngs.infn.it/images/LUNA-MV-5y-proposal.pdf
[54] Ciani, G F, et al., 2020 Eur. Phys. J. A 56 75
[55] Trippella O and Cognata M L 2017 The Astrophysical Journal 837 41
[56] Fruet G, et al., 2020 Phys. Rev. Lett. 124(19) 192701
[57] Tan W P, et al., 2020 Phys. Rev. Lett. 124(19) 192702
[58] Tumino A, et al., 2018 Nature 557 687–690
[59] Beck C, Mukhamedzhanov A M and Tang X 2020 The European Physical Journal A 56 87
[60] Robertson D, Couder M, Greife U, Strieder F and Wiescher M 2016 Underground nuclear astrophysics studies with CASPAR European Physical Journal Web of Conferences (European Physical Journal Web of Conferences vol 109) p 09002
[61] Liu W, et al., 2016 Progress of Jinping Underground laboratory for Nuclear Astrophysics (JUNA) European Physical Journal Web of Conferences (European Physical Journal Web of Conferences vol 109) p 09001