

Experiences and Prospects of Nuclear Astrophysics in Underground Laboratories

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Abstract. Impressive progress has been made in the course the last decades in understanding astrophysical objects. Increasing precision of nuclear physics data has contributed significantly to this success, but now a better understanding of several important findings is frequently limited by uncertainties related to the available nuclear physics data. Consequently it is desirable to improve significantly the quality of these data. An important step towards higher precision is an excellent signal to background ratio of the data. Placing an accelerator facility inside an underground laboratory reducing the cosmic ray induced background by six orders of magnitude is a powerful method to reach this goal, even though careful reduction of environmental and beam induced background must still be considered. Experience in the field of underground nuclear astrophysics has been gained since 20 years due to the pioneering work of the LUNA Collaboration (Laboratory for Underground Nuclear Astrophysics) operating inside the underground laboratories of the Laboratori Nazionali del Gran Sasso (LNGS) in Italy. Based on the success of this work presently also several other projects for underground laboratories dedicated to nuclear astrophysics are being pursued worldwide. This contribution will give a survey of the past experience in underground nuclear astrophysics as well as an outlook on future developments.

1. Introduction

Accurate knowledge of thermonuclear reaction rates is important in understanding the energy generation, the neutrino luminosity and the element synthesis in stars. Due to the Coulomb barrier (height E_c) of the entrance channel, the reaction cross section $\sigma(E)$ drops nearly exponentially with decreasing energy E . Thus it becomes increasingly difficult to measure $\sigma(E)$ and to deduce the astrophysical $S(E)$ factor defined by the equation $\sigma(E) = S(E)/E \cdot \exp(-2\pi\eta)$ with the Sommerfeld parameter given by $2\pi\eta = 31.29 Z_1 Z_2 \sqrt{\mu/E}$. Z_1 and Z_2 are the nuclear charges of the interacting particles in the entrance channel, μ is the reduced mass in amu, and E is the center-of-mass energy in keV [1].

Experimental techniques have improved significantly to push the limit of measurements close to or even inside the thermal energy region in stars, which is determined by the Gamow peak $E_0 \pm \delta E_0$ and frequently lies far below the height of the Coulomb barrier, approximately at $E_0/E_c = 0.01$. But even in those cases in which direct measurements prove to be feasible, uncertainties in low energy stopping



power data or the insufficient understanding of the electron screening effect introduce significant systematic uncertainties [2].

As a result extrapolations of data from higher energies using e.g. R-matrix fits [3] are often required. In order to minimize the risks related to the extrapolation, the data sets used should cover a wide range of beam energies. It is important to aim for direct measurements at energies as close as possible to the Gamow Peak maintaining small statistical and systematic errors. Scattering experiments or transfer reactions can provide additional information. Indirect methods like the Trojan Horse technique can be exploited as an alternative tool for $\sigma(E)$ determination [2].

In the following we will focus on direct experiments at underground accelerators as a powerful tool to obtain nuclear cross sections inside the Gamow peak.

2. Background in detectors and its reduction

Due to their small reaction rate nuclear astrophysics experiments have to compete with background originating from cosmic rays (CR) and environmental radioactivity. At earth surface CR are mainly composed of muons [4]. Due to their high energy CR can penetrate even massive shielding. The energy deposition in a specific detector is related to its material and shape. Also secondary particles caused by CR interaction in surrounding materials interact with the detector.

While the direct interactions of CR can be efficiently rejected by active shielding (e.g. with plastic scintillators), events related to secondary particles (e.g. neutrons) are difficult to suppress and limit the efficiency of active shielding. Only the very massive shielding available in underground laboratories can provide a significant reduction of the CR flux of several orders of magnitude. This approach is commonly exploited by low event rate experiments in the field of Dark Matter research and Neutrino physics while presently only the LUNA¹ (Laboratory for Underground Nuclear Astrophysics) experiment performs accelerator-based nuclear astrophysics experiments in an environment deep underground.

Environmental radioactivity is another source of background which reaches gamma energies of up to 3.5 MeV. It is caused by radionuclides belonging to natural radioactive series (²¹⁴Bi, ²²⁶Ra, ²¹⁴Pb, ²⁰⁸Tl...), long-lived natural radionuclides (⁴⁰K, ⁸⁷Rb ..), radionuclides of cosmogenic origin (³H, ¹⁴C, ²²Na, ⁷Be..) and radionuclides of artificial origin (⁹⁵Nd, ¹³⁷Cs, ⁹⁰Sr, ¹⁴⁴Ce..). These nuclides can be found outside but also inside the detectors themselves. The related background can be reduced by careful material selection and cleaning and by massive passive shielding with high purity lead and copper. As CR induce secondary particles when interacting with passive shielding, the reduction of the CR flux inside an underground laboratory makes massive Pb and Cu shielding more efficient underground than above ground. Furthermore, the higher the rock coverage of a site the higher the reduction of the underground CR flux and the higher the suppression of background achieved by lead and copper shieldings in the gamma energy range up to 3.5 MeV [5].

The interaction of the ion beam with traces of material on the target can give rise to beam induced background which is specific for each reaction. In particular materials with atomic numbers lower than or similar to the target material are candidates for beam induced backgrounds. Consequently each reaction must be considered separately taking into account beam energy and particle spectrum involved as well as Q-value and resonance structure of the background reactions. The type of the target (gaseous or solid) and the target production process are of fundamental importance. In some particular cases background can be induced also by target nuclei scattered by the impinging projectiles [6].

¹<http://luna.lngs.infn.it>

The excellent signal to background ratio in the high resolution spectra of HPGe detectors favors the identification of the background, but they provide a limited efficiency with respect to high density materials like BGO or suffer consistent intrinsic background (e.g. LaBr₃). On the other hand detectors with low resolution disfavor a reliable background recognition. In any case, the spectra obtained when operating underground improve significantly the identification and subsequent suppression of beam induced background.

3. The LUNA experiment at LNGS

Presently the LUNA Collaboration operates the worldwide only underground accelerator inside the Laboratori Nazionali del Gran Sasso (Italy) run by the Italian Istituto Nazionale di Fisica Nucleare (INFN)². The underground laboratories consist in three halls (100m long, 20m wide, 18m high). They are covered by 1400 m of rock corresponding to 3800 meter of water equivalent (m.w.e.) which reduce the cosmic muon flux by six orders of magnitude³. Located long side the motorway Teramo – Rome the underground site is accessible even for trucks of extra width and length. Inside the laboratories lifting equipment up to 40t, ventilation and 3 MW electrical power provided by redundant sources are available. Safety relevant plants like ventilation and fire detection are monitored by a laboratory wide supervision system together with selected experiment specific information. Firefighters and guards are available permanently in the underground control room.

LNGS hosts clean rooms usable for material cleaning, assembling and decontamination, a chemistry laboratory equipped, among others, with an ICPMS facility, electronic and mechanical workshops and an experienced engineering division. The LNGS facility STELLA (SubTERRanean Low Level Assay) is available for measurements of low radioactivity samples. LNGS is a reference point for a vivid international scientific community involving more than 900 scientist.

The LUNA collaboration started its activities at LNGS in 1992 installing a home made 50kV accelerator [7]. A concept of an MV scale underground accelerator facility was published in 1993 [8]. Since year 2000 LUNA is operating a 400kV Singletron machine [9]. Reviews of the scientific activities of LUNA can be found in [10] [11].

4. Experience after 20 Years of LUNA

As in all fields of science it is important to identify the scientific goal of an experiment beforehand. As an example the ³He(³He,2p)⁴He experiment was set up to exclude a resonance proposed by W. Fowler as a solution to the so called “Solar Neutrino Problem” [12]. To rule out the “desperate explanation of the solar neutrino puzzle” great efforts were taken to push the limit of the measurements to the lowest possible energy accepting data points with large errors (up to 100%). Finally, LUNA showed that there is not any evidence for a narrow resonance at low energies and that the cross section $\sigma(E)$ increases at solar energies as expected from the electron screening effect. This finding ruled out the astrophysical solution of the solar neutrino problem [13] [14].

Also the LUNA measurements on ²⁵Mg(p, γ)²⁶Al have been performed to directly determine the resonance strength $\omega\gamma$ of the important low energy resonances at 198 keV, 130 keV and 92 keV of this reaction which is the galactic source of ²⁶Al. As this isotope is frequently observed in astronomy via the well known 1.809 MeV gamma line associated to its radioactive decay, an understanding of these nucleosynthesis processes is important [15]. The levels in the compound nuclei ²⁶Al corresponding to the

²<http://www.lngs.infn.it>

³https://www.lngs.infn.it/lngs_infn/contents/lngs_en/research/europe/web_ILIAS_A1/JRA1/ilias-last/workpack1.htm

resonances of interest were already well known and the $\omega\gamma$ s of the resonances at 198 keV and 92 keV had been measured by direct and indirect experiments.

A nuclear reaction emitting gamma rays can be studied by detecting all gammas of a cascade using a BGO summing detector in 4π geometry. This yields a single peak (called summing peak) in the spectrum located at $Q+E_{\text{beam}}$ where Q is the reaction's Q-value and E_{beam} is the beam energy [16]. In this case the summing peak is far above the energy region effected by room background as the Q-value of the reaction is 6.3 MeV. The efficiency of a summing detector depends on the branching ratio of the reaction [16]. Thus the resonances at 304 and 198 keV were studied at LUNA beforehand with a standard HPGe detector. The resulting level information and $\omega\gamma$ s have been used in a Monte Carlo simulation to determine the detector's efficiency. It should be pointed out that in the measurements of the 98 keV resonance the intrinsic detector background as well as the beam induced background posed severe problems due to the low resolution of BGO detector. A Monte Carlo code had to be used to disentangle the spectra exploiting the segmentation of the detector. Finally LUNA was able to redetermine the $\omega\gamma$ of the resonance at 198 keV reducing the related uncertainty by a factor of two. The $\omega\gamma$ of the resonance at 92 keV has been measured for the first time by a direct experiment [17].

The goal for investigating the reaction of ${}^3\text{He}({}^4\text{He},\gamma){}^7\text{Be}$ by LUNA was different from the cases discussed previously. This reaction had been studied already by direct gamma spectroscopy and by detection of the ${}^7\text{Be}$ ejectiles. As the data available obtained with the two different techniques appeared to show a systematic discrepancy [18] LUNA aimed to measure $\sigma(E)$ with both techniques with low statistical and systematic uncertainties.

The cross section in the solar Gamow Peak of ${}^3\text{He}({}^4\text{He},\gamma){}^7\text{Be}$ is about 6 orders of magnitude smaller than $\sigma(E)$ of ${}^3\text{He}({}^3\text{He},2p){}^4\text{He}$. At the same time the prompt gammas emitted by ${}^3\text{He}({}^4\text{He},\gamma){}^7\text{Be}$ have energies of about 1.6 MeV, within the energy range dominated by environmental background. Thus energy resolution as well as environmental and intrinsic radioactivity were important issues. LUNA studied the prompt gammas and the beta-delayed gammas emitted in the decay of ${}^7\text{Be}$ with HPGe detectors [19]. Thus, the efficiency reached is significantly lower than in the experiments described previously. Massive lead and copper shielding including a radon box were installed to suppress environmental radioactivity. Detailed studies of the detector geometry were performed to avoid uncertainties as effect of the angle distribution. In several runs prompt gammas and ${}^7\text{Be}$ were detected simultaneously in collaboration with the LNGS facility STELLA excluding several systematic uncertainties.

Due to the extremely low background and the expertise of low event counting gained at LNGS it was possible to measure few data points with small systematic and statistical errors. However, even though LUNA has published the lowest energy data points available in literature they have been taken at beam energies above the solar Gamow Peak [19]. Consequently the LUNA data must be extrapolated together with data available at higher energies. The small uncertainties of the LUNA results put strong constraints on the extrapolation.

Overall, the precision of the new data stimulated renewed efforts to develop improved nuclear models ([20][21][22] and references therein). To further reduce the uncertainty of the extrapolation a measurement should be performed which covers a wide energy range from the lowest energies investigated by LUNA to the highest energy data by ERNA [23] overcoming the need to match several data sets with different systematic uncertainties.

Another example for the impact of the underground data at LUNA are the measurements of the reaction ${}^{14}\text{N}(p,\gamma){}^{15}\text{O}$. This reaction is of great importance for stellar evolution, solar neutrinos and for the age determination of Globular Clusters [24]. It had been measured by Schröder et al. [25] via gamma

spectroscopy using different accelerators covering a beam energy range from 3.3 to 0.24 MeV. As the data did not enter inside the solar Gamow Peak ($E_g = 26$ keV) an extrapolation had been performed based on a Breit Wigner formalism indicating $S(0) = 3.20 \pm 0.5$ keVb. In particular the authors assumed an effect of a sub-threshold state at -507 keV for the direct transition to the ground state. Later Angulo et al. [26] re-analyzed the data set of [25] and published a result of 1.77 ± 0.20 keV almost a factor of two lower than the previously accepted result. This difference is due to the fact that Angulo et al. could not reproduce the effect of the sub-threshold state indicated by Schröder et al.

LUNA investigated this reaction between 120 keV and 370 keV with a HPGe detector and solid targets [27][28] and between 70 keV and 370 keV with a summing BGO detector and a gas target system [29]. The good signal to background ratio in the HPGe data of LUNA allowed to identify the branching ratios of the different gamma cascades also at the lowest energies. In this context it became obvious that the ground state transition data published in [25] had not been corrected for the “Summing in” effect. This effect describes the coincident detection of two gamma rays belonging to the same cascade which simulates a single gamma ray related to a direct ground state transition. If this correction is omitted the extrapolation of the direct ground state transition and, to a minor extend, of the other transitions are falsified. Based on the LUNA data it was possible to correct the Schröder data a posteriori (see [28] for details) and a reliable extrapolation has been performed using the corrected Schröder and the LUNA data.

The measurements performed by LUNA with the BGO detector extended to even lower energies. Still the solar Gamow Peak has not been reached. Due to the summing of all different gammas of one cascade the BGO data do not contain nuclear physics information usable to support an extrapolation of high energy data. Still these data are of great value to verify independently the extrapolations made on the basis of the available data [19][29].

Also in the measurements of $^{15}\text{N}(p,\gamma)^{16}\text{O}$ high energy data taken above ground and low energy data obtained underground have been used to support an R-matrix fit down to the stellar Gamow peak. In a joint effort of the University of Notre Dame (USA) and the LUNA collaboration high energy data between 1.8 MeV and 285 keV were taken at the University of Notre Dame and data between 400 and 130 keV were taken at LUNA. In this context the limited energy range of the present LUNA 400kV accelerator posed some problems as the resonance at $E = 440$ keV in $^{15}\text{N}(p,\gamma)^{16}\text{O}$, commonly used for normalization and target checks, is not accessible at LUNA [30].

Similar issues had to be faced in the present work at LUNA for $^{17}\text{O}(p,\gamma)^{18}\text{F}$. This reaction has been studied in a wide energy region ($E_{\text{cm}} = 160$ to 370 keV) appropriate to explosive hydrogen burning in classical novae. The reaction cross section was measured using both prompt γ -ray detection and activation approaches taking advantage of the knowledge gained in during the measurements of $^3\text{He}(^4\text{He},\gamma)^7\text{Be}$. Results from the non-resonant reaction contributions have been analyzed in a global fit and lead to a total astrophysical S-factor $S(0) = 4.81$ keV barn. The strength of the $E_{\text{cm}} = 183$ keV resonance, $\omega\gamma = 1.67 \pm 0.12$ μeV , has been determined with the highest precision to date and was found to dominate the astrophysical reaction rate at temperatures $0.1 < T < 0.4$ GK relevant to novae explosions. A global fit to the experimental data and other data from the literature has led to an improved recommended reaction rate. The abundances of key isotopes such as ^{18}F , ^{18}O , ^{19}F and ^{15}N have been evaluated through nova models calculations and have been obtained with a precision of 10%, i.e. sufficient to put firmer constraints on observational features of novae nucleosynthesis. The results presented in this study are now sufficiently precise for nova model calculations [31].

5. Upcoming possibilities in underground nuclear astrophysics

The examples above show that underground nuclear astrophysics is a powerful tool not only in pushing measurements to lower energies but also, and even more, in providing high quality data which can be used to reduce the uncertainties of unavoidable extrapolations.

Stimulated by the success of the LUNA experiment several next generation facilities for underground nuclear astrophysics have been proposed in the last years. A series of workshops has been organized in Europe (Barcelona 2009, Dresden 2010, Gran Sasso 2011, Canfranc 2012) [32]⁴. In its Long Range Plan 2010 [33] NUPECC recommends to “fully exploit the currently existing large-scale research infrastructures (...) and (to) perform limited-size upgrades to ensure the best use of the large investments made in the past: (...)” and in particular “the nuclear astrophysics underground accelerator LUNA at INFN Gran Sasso, and the exploration of advanced new facilities.”

Already in 2007 LUNA submitted a Letter of Intent (LOI) to the LNGS scientific committee proposing to measure $^{12}\text{C}(\alpha,\gamma)^{16}\text{O}$, and (α,γ) reactions on $^{14,15}\text{N}$ and ^{18}O , which are key reactions of the He burning. In addition the LOI suggested investigations on $^{13}\text{C}(\alpha,n)^{16}\text{O}$, $^{22}\text{Ne}(\alpha,n)^{25}\text{Mg}$, the neutron sources for the s-process. A renewed study of the reaction $^3\text{He}(\alpha,\gamma)^7\text{Be}$ over a wide energy range has been included later into the scientific program.

As these reactions are relevant at higher temperatures (larger energies) than reactions belonging to the hydrogen-burning studied so far at LUNA, the collaboration proposed to install a single ended machine with a terminal voltage of approximately 3.5 MV in the underground laboratories of LNGS. The physics program of the LOI has been approved by the LNGS Scientific Committee, but as the impact of the neutrons produced by the proposed measurements was of concern, this issue has been evaluated by an external committee of experts. Implementing a proper shielding of the neutron background of the proposed experiments can be reduced to a level which is a factor 100 lower than the natural neutron flux inside LNGS. The installation of the MV scale accelerator at LNGS has been approved by the Scientific Committee in 2010. In summer 2012 the Italian Ministry of Research has granted financial support to INFN which allows for site preparation and accelerator installation.

In 2009 CUNA (Canfranc Underground Nuclear Astrophysics) has been proposed at the Laboratorio Subterráneo de Canfranc (LSC) located under the Pyrenees (2500 m.w.e)⁵. The accelerator-based nuclear astrophysics project foresees the installation of a multi MV accelerator coupled with a RF source delivering proton and alpha beams. An engineering design has recently been completed for an independent experimental hall, distant from the rest of the caves at the LSC. A viable alternative presently under consideration is the refurbishing and extension of one of the existing caves. Neutron background measurements and simulations have recently been completed [34]. Funds for the accelerator are being sought at present. A Letter of Intent, extending the case presented in the Expression of Interest from 2009, will be presented to the LSC Scientific Committee by the collaboration in the next few months [35].

The Felsenkeller Underground Accelerator⁶ has been proposed by a group of scientists from the Helmholtz Zentrum Dresden Rossendorf (HZDR) and the University of Dresden several of them involved also in LUNA and in other research activities of LNGS. They foresee the installation of a used MV scale accelerator in a site shielded by 112 m.w.e., called Felsenkeller, an old brewery cellar close to Dresden

⁴Web pages of the workshops on next generation underground nuclear astrophysics installations:

http://www.fnuc.es/workshop/LSC_Program.htm <http://www.hzdr.de/db/Cms?pNid=2088>

<http://luna.lngs.infn.it/luna-mv>, <http://nuclear.fis.ucm.es/nucaastro/>

⁵<http://www.lsc-canfranc.es/>

⁶<http://www.hzdr.de/db/Cms?pNid=2088>

(Germany). Given the shallow shielding the background is significantly higher than at LNGS. The facility will be shared with other research groups and will thus be available for nuclear astrophysics only for limited times. Recently, a used 5 MV NEC Pelletron tandem accelerator system has been delivered to HZDR and is now undergoing a refurbishing at HZDR [36].

In the USA the DIANA project (Dakota Ion Accelerators for Nuclear Astrophysics)⁷, a collaboration of University of Notre Dame, University of North Carolina, Western Michigan University, Colorado School of Mines and Lawrence Berkeley National Laboratory aims to build a nuclear astrophysics underground accelerator facility. DIANA is designed to achieve large laboratory reaction rates by delivering ion beam currents up to 100 mA to a high density super-sonic jet-gas target as well as to a solid target. It will consist of two accelerators, 50-400 kV and 0.4-3 MV that will cover a wide range of ion beam intensities, with sufficient energy overlap to consistently connect the results to measurements above-ground. DIANA will address scientific issues in the field of solar neutrino sources and the metallicity of the sun, carbon-based nucleosynthesis and neutron sources for the production of trans-Fe elements in stars .

6. References

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⁷<http://www.jinaweb.org/underground/DIANA/index.html>

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