Laboratory for Underground Nuclear Astrophysics

LUNA
MV

Round Table: “LUNA - MV at LNGS”

February 10-11, 2011

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Underground nuclear astrophysics beyond the hydrogen burning

LUNA started underground nuclear astrophysics twenty years ago in the core of Gran Sasso, below 1400 meters of dolomite rock. The extremely low laboratory background has allowed nuclear physics experiments with very small count rate, down to a few events per year. Thanks to this, the important reactions responsible for the hydrogen burning in the Sun have been studied down to the relevant stellar energies. As a consequence, it is now possible to use solar neutrinos to study the properties of the neutrino itself and to probe the deep interior of the Sun.

The solar phase of LUNA has reached the end and a rich program of nuclear astrophysics mainly devoted to the nucleosynthesis of the elements through the study of the CNO, Mg-Al and Ne-Na cycles is now developing at the 400 kV facility. However, we think that the time has come to face the next step beyond hydrogen burning: the helium burning. This include a few key reactions which are far rich of consequences, as $^{12}C(\alpha,\gamma)^{16}O$*, which shapes the nucleosynthesis in massive stars up to the iron peak and the properties of supernovae, together with* $^{13}C(\alpha,n)^{16}O$ *and* $^{22}Ne(\alpha,n)^{25}Mg$*, the stellar sources of the neutrons which synthesize most of the trans-iron elements through the S-process.*

This exciting and ambitious program requires a dedicated space of about 150 m^2 *where to install a 3.5 MV accelerator in an underground laboratory. To give birth to such a project a two day round table has been organize by LUNA in Gran Sasso in February 2011. At first the status of the similar projects in other underground laboratories has been presented, then the physics cases which can be addressed have been covered and finally the discussion has been focalized on the large amount of preparatory work already performed in Gran Sasso and on the way to harmonize the different projects in Europe.*

The summaries of the talks given at the round table are collected in this document. We are confident it will be the seed for the underground nuclear astrophysics of the next twenty years.

Carlo BROGGINI

Status of the Canfranc project

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The Canfranc Underground Laboratory (LSC) is a facility for Underground Science, under the Spanish Pyrenees close to Canfranc, Huesca. It is managed by a Consortium of the Spanish Ministry of Science and Innovation, the Aragon Regional Government and the University of Zaragoza. It provides about 2400 meters water equivalent of shielding from cosmic rays, leading to a muon flux of about $3\text{x}10^{-3}\text{m}^{-2}\text{s}^{-1}$ and neutron flux of approximately $2\text{x}10^{-2}\text{m}^{-2}\text{s}^{-1}$. It has two main experimental halls (40x15x12 m^3 and 15x10x7 m^3) and a smaller one, all equipped with the necessary underground services.
In 2009 an Expression of Interest (EoI) on *"CUNA - A Nuclear Astrophysics facility for LSC: The sources of neutrons in the stars and other reactions of astrophysical interest"* was submitted to the LSC Scientific Committee by Spanish groups and international partners, including the main players of the LUNA collaboration. The key reactions proposed were the neutron sources for the weak and main s-processes, namely the $^{22}\text{Ne}(\alpha,\text{n})^{25}\text{Mg}$ and the $^{13}\text{C}(\alpha,\text{n})^{16}\text{O}$. The possibilities for direct measurement of the reaction cross sections at the relevant astrophysical energies in surface laboratories are exhausted, and therefore underground measurements are indispensable. The LS Canfranc will be ideally suited for this kind of experiments. The EoI was put forward with an agreement for multisite complementarity within a EU-wide discussion, and collaboration with LUNA. Other measurements that could be addressed include (p,γ) reactions on Na and Al, and eventually Carbon burning reactions. Several other cases were skipped for the sake of complementarity with LUNA. A new hall was proposed in the EoI, with the support of the Laboratory. A 3.5 MeV HVee singletron fitted with a RF ion source was proposed as option for the accelerator. The LSC Scientific Committee recognized the quality of the Physics case and thought it was compatible with the LUNA3 LoI at LNGS. The collaboration was encouraged to present a full Letter of Intent in due time.
At present several work packages on "Science case", "Background and Shielding", "Accelerator and ion sources" and "Targets and experimental detection systems" have been setup for the CUNA project. At the end of 2010 the LS C Directorship started the feasibility study on the CUNA hall. A call for the pre-engineering feasibility study report has been launched and offers have already been received. The new hall should be separated from the existing ones, with three optional locations under study. The estimated area is of the order of 22x13 m^2, with height varying between 6 to 8 meters.
Neutron expertise and detection devices are already available within the CUNA collaboration. This includes a high efficiency array of ^3He proportional counters and liquid organic scintillator cells with neutron/gamma discrimination capabilities. Neutron background measurements at LSC have been scheduled. The plan is using ^3He counters with suitable polyethylene matrixes and Bonner spheres in collaboration with UA Barcelona and U Zaragoza. Simulation work has started too.
The aim of the collaboration is realising a dedicated CUNA hall and associated equipment at LSC. A letter of intent will be submitted to the LSC Scientific Committee by the end of 2011 detailing the experimental requirements, background assessment, accelerator and laboratory equipment design. There is fruitful collaboration with the Canfranc Underground Physics *Consolider* project and the LSC laboratory.
An excellent opportunity for an underground Nuclear Astrophysics laboratory, complementary to other projects, exists at Canfranc. It is our view that efforts to establish a EU network on underground Nuclear Astrophysics should be continued with the aim of developing a European programme with several MV complementary sites. In the Dresden meeting in April 2010 the agreement was that networking will strengthen the EU community, and that there is a need for open facilities and to enhance the links to astrophysical themes. The NuPECC Long Range Plan 2010 endorses this idea. The CUNA collaboration is ready to host next meeting at Canfranc.
Our proposal is to define common work packages for site-independent tasks and to try and involve the whole European Nuclear Astrophysics community for a wider collaboration in support of the next-generation underground laboratory.

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The Bulby mine: an opportunity for underground nuclear astrophysics

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Thermonuclear reactions in stars take place over a narrow energy region, the so-called Gamow peak, well below the repulsive Coulomb barrier of the interacting nuclei. Hence, reaction cross-sections drop exponentially with decreasing energy and become increasingly difficult to measure in terrestrial laboratories. In addition, low-energy cross section measurements on the Earth's surface are severely hampered by the high background produced in the interaction between cosmic rays (mainly their muon component) and any material within the experimental detection system. These studies are thus extremely time-consuming, taking up to several months for each reaction, and often rely on the extrapolation of high-energy data, with substantial associated uncertainties. When nuclear cross-section data are used as inputs to stellar evolutionary models, considerable uncertainties thus remain in many aspects of stellar evolution and nucleosynthesis.

Much progress in experimental techniques has been achieved over recent years and a combination of both active and passive shielding can be successfully exploited to reduce the cosmic-induced background. However, there is an intrinsic limitation to the improvement achievable by such means due to the fact that the addition of any more passive/active shields ultimately provides additional "target" material for interactions with muons and thus offers no further benefit to background reduction. In such cases, the only viable solution consists in carrying out measurements in sufficiently deep underground laboratories. Indeed, the potential of underground measurements has been dramatically demonstrated in the last decade by the pioneering work performed at the LUNA (Laboratory Underground for Nuclear Astrophysics) facility located in the Gran Sasso massif (Italy). At present, LUNA remains the only underground accelerator in the world specifically dedicated to Nuclear Astrophysics.

In the UK, the salt and potash mine at Boulby, run by Cleveland Potash, is Europe's second deepest mine at 1400m and is located on the north-east coast of England, just a few hours drive from major cities such as York, Manchester, Newcastle and Edinburgh. The depth of the salt layer in the mine (~1100m below surface) guarantees a six-order-of-magnitude reduction in the muon flux, thus rendering both passive and active shielding (if at all needed) much more effective than on the surface. Because of its extension and the composition of its salt layer, the mine would offer an extraordinary opportunity for hosting an accelerator facility, whose features would be unique worldwide. These include:

- a much lower background (typically by a factor of 10-30) than in other types of sedimentary rocks (particularly those high in U/Th content)
- no space constraints, thanks to the availability of large areas for the construction of the infrastructure (approximately 150-200 m^2 needed) and, hence, no problems of interference with other scientific programs (at present Dark Matter only)
- no constraints on the beam species, and/or reaction products, which can be generated
- safety and support infrastructure already in place and well established.

Indeed, all these features would make Boulby an *ideal* location for the installation of a world-leading accelerator facility, which would consolidate Europe's international lead in the field of experimental Nuclear Astrophysics.

Following encouraging discussions with the mine management a few years ago, a collaboration was set up to explore the possibility to host an accelerator-based laboratory for studies of nuclear astrophysics. This

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has led to the proposal of the ELENA (European Laboratory for Experimental Nuclear Astrophysics) Project, as outlined below.

Stage I: Feasibility Study and Design, with the following objectives and deliverables:
- Identification of best site for construction of infrastructure
- Laboratory design and specifications (including accelerator and ion source)
- Identification of scientific requirements and detection systems
- Identification of total costs and timescale related to construction of infrastructure

Stage II: Construction, Commissioning and Exploitation, with the following objectives and deliverables:
- Construction of underground infrastructure/laboratory
- Underground installation and commissioning of accelerator system
- Measurement of nuclear cross-sections of key astrophysical reactions.

The scientific programme envisioned at the ELENA facility would address key open questions, such as: *How do massive stars evolve? What are the reactions producing neutrons for the synthesis of most elements beyond iron? What is the detailed nucleosynthesis path during hydrogen and helium burning stages in stars?* and would lead to a deeper understanding of crucial energy generation processes and nucleosynthesis in stars.

Key reactions for initial investigations would be the following:

- $^{12}C+^{12}C$, referred to as *carbon burning*. This is the main parameter governing the evolution of massive stars and determines whether they will end up as white dwarfs or as core-collapse supernovae. It also affects the ignition conditions and time scales of type Ia supernovae which, unlike core-collapse supernovae, are believed to be the result of explosive thermonuclear runaway in binary stellar systems, where material is accreted on the surface of a compact, degenerate object (e.g. a massive white dwarf or a neutron star) from a less evolved companion.
- $^{13}C(\alpha,n)^{16}O$ and $^{22}Ne(\alpha,n)^{25}Mg$, both providing the neutron source for the s-process (a process responsible for the synthesis of about half of all heavy elements beyond Fe). The former, believed to provide the bulk of the neutron source for the s-process, takes place in thermally pulsing, low-mass, Asymptotic Giant Branch (TP-AGB) stars. The latter is believed to be essential for adjusting the final abundance patterns of the s-process branching, in particular, resulting in an increase of Sr, Y and Zr and a decrease of Ba elements.
- (p,γ) captures on Ne, Na, Mg and Al isotopes. Radiative capture reactions such as $^{22}Ne(p,\gamma)^{23}Na$, $^{23}Na(p,\gamma)^{24}Mg$ and $^{26}Al(p,\gamma)^{27}Si$ significantly influence the production of Ne, Na, Mg and Al in Asymptotic Giant Branch stars, while processes like $^{17,18}O(p,\gamma)^{18,19}F$, $^{33}S(p,\gamma)^{34}Al$ and many other proton-induced reactions on A=20-40 nuclei are crucial to the production of key isotopes often observed in novae ejecta and thus affecting the chemical evolution of the Galaxy.

A proposal for “ELENA-Stage I” was submitted to the Science and Technology Facilities Council (STFC, UK) in December 2008 and presented to the STFC’s Projects Peer Review Panel in February 2009. The overall scientific merit of the proposal was unanimously recognised as *Fundable – High priority* by international referees and by PPRP. Unfortunately, however, following major cuts in STFC’s budget, no nuclear project within the UK (with the only exception of UK’s involvement in FAIR at GSI, Germany) was funded. Even though the ELENA project remains on the UK’s roadmap for nuclear physics, it is unlikely that the ELENA project will be funded in the foreseeable future. However, the opportunity offered by the Boulby mine to the wider international nuclear astrophysics community remains.

The Dresden Felsenkeller: A shallow underground option for accelerator-based nuclear astrophysics

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On 28-30 April 2010, there was a workshop in Dresden on "Underground nuclear-reaction experiments for astrophysics and applications" with 30 participants from a number of European countries [1]. Participants came from the astrophysics, observations, and theoretical and experimental nuclear physics communities. In addition, the various European underground accelerator projects in Gran Sasso / Italy, Canfranc / Spain, Boulby / UK, and Felsenkeller / Germany were all represented, as well as representatives from NuPECC and the European Physical Society.

As a result of the workshop, a white paper was drawn up [1] calling for *"a new MV scale underground accelerator be installed in Europe. Such a step is deemed essential to preserve European scientific leadership in this field, which is being challenged by competing projects in the US and China. (...) Due to the extensive science programme, the long running time per experiment, and the number of researchers involved (a head count revealed about 20 European groups already active in or interested in accelerator experiments underground), most participants see it necessary to call for at least two European underground facilities to be realized."* These recommendations flowed into the NuPECC 2010 Long Range Plan for nuclear physics [2]. A further outcome of the workshop was the recommendation to hold a follow-up workshop in early 2011 at Gran Sasso. Subsequent meetings will be hosted by Canfranc (early 2012) and Boulby (2013).

The Felsenkeller is a system of nine tunnels dug in the 1850's in the Plauenscher Grund former quarry in Dresden, just 5km from where is now Dresden main railroad station. It is also only 5km removed from TU Dresden with its over 30,000 students and from Helmholtz-Zentrum Dresden-Rossendorf (HZDR), a German national laboratory with over 800 employees and several different accelerators on site.

Since 1982, one of the Felsenkeller tunnels is used for a low-level γ-counting facility [2]. This facility is a founding member of the CELLAR collaboration of low-level underground laboratories. It is shielded from cosmic rays by 47m of rock, equivalent to about 110 m water. At this depth, the cosmic ray induced muon flux is attenuated by about a factor 30, much less than the attenuation observed deep underground, e.g. for 3400 meters water equivalent at Gran Sasso this suppression is a factor 10^6.

However, there are other factors contributing to the background at Gran Sasso, namely a depth-independent flux of high-energy neutrons caused by (α,n) reactions in the walls of the tunnel. As a result, the background is limited by the neutron flux, which is 10^3 times lower than at the Earth's surface, not 10^6 times as is the case for the muon flux. Even still, this does not pose a practical problem for the studies at LUNA, because the background has been shown to be negligible for all practical purposes [3-5].

A similar background study has now been conducted at Felsenkeller, using a „traveling" detector that had previously been used at Gran Sasso. It is seen that with an active muon veto suppressing the remaining muon flux, the background at Felsenkeller is only a factor 3 worse than at Gran Sasso, if one considers the crucial γ-energy region from 6-8 MeV where among others the γ-rays from the $^{14}N(p,\gamma)^{15}O$ and the $^{12}C(\alpha,\gamma)^{16}O$ reactions are emitted.

This opens the door for a staged approach: In a first stage, the easy access to a shallow-underground site in a major city such as the Dresden Felsenkeller is exploited to quickly gain momentum for higher-energy underground nuclear astrophysics. In a second stage, the experiences gained there would help the projected deep-underground accelerators such as LUNA-MV pursue the more challenging science cases,

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where even lower background is needed. Discussions are ongoing on obtaining a possible used accelerator for Felsenkeller.

It should be stressed that we see this idea not as a competition to the LUNA-MV project, but rather a service to the LUNA-MV community. Valuable hands-on experience might be gained in a first stage at Felsenkeller, helping a project like LUNA-MV to quickly overcome initial difficulties and fully exploit its even lower background.

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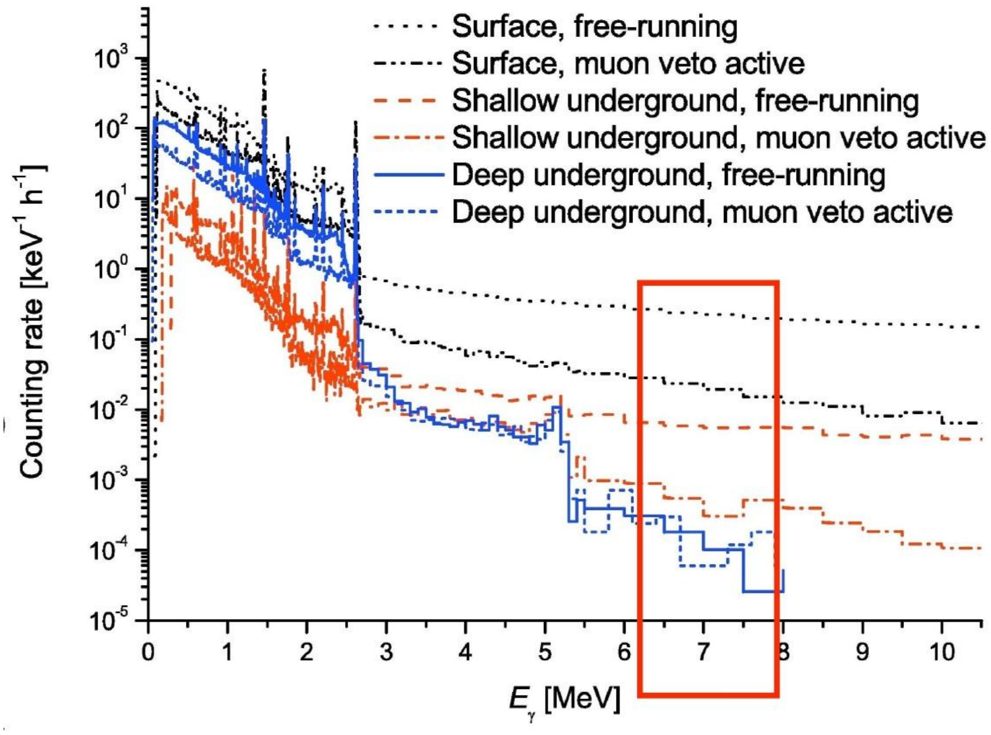

Figure: Background in one and the same escape-suppressed HPGe detector used at the Earth's surface, shallow underground (Felsenkeller), and deep underground (Gran Sasso).

Status of the DIANA project

Alberto LEMUT[*] (Lawrence Berkeley National Laboratory)

The DIANA project (Dakota Ion Accelerators for Nuclear Astrophysics) is a collaboration between the University of Notre Dame, Colorado School of Mines, Michigan State University, Regis University, University of North Carolina, Western Michigan University, and Lawrence Berkeley National Laboratory (LBNL), to build a next generation nuclear astrophysics accelerator facility deep underground.

In particular DIANA will address three fundamental scientific issues in stellar nucleosynthesis: 1) *solar neutrino sources and the metallicity of the Sun*; 2) *carbon-based nucleosynthesis;* and 3) *neutron sources for the production of trans-Fe elements in stars*. These are three long-standing, potentially transformational questions of relevance for the understanding of our Sun and the chemical evolution of our Universe.

DIANA will consist of two accelerators (Fig. 1), 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. Independent solid and jet target stations are under design for both accelerators for conducting two experimental campaigns simultaneously or preparing the next experimental campaign (Fig. 1). This feature will greatly enhance the ability to carry out the planned science program in a more efficient manner, since the experimental setups are difficult and time consuming. Moreover the high-energy accelerator will have the capability to provide beam to the low energy target stations (Fig. 1). This will allow a particular reaction to be measured with both accelerators in complementary energy ranges with identical target and detector setups, providing consistent high-precision data over a wide energy range. Very intense ion-beams (10 to 100 mA for the 400 kV, up to 1 mA for the 3 MV), are required continuously over long periods of time, in order to address the low count rates close to the Gamow window energies. In addition too the tight focus (< 1 cm) at the jet-gas target stream, and narrow beam energy resolution (about 2.5×10^{-4}). The ion source currently considered for the low energy machine is a microwave one based on the Chalk River development [1]. Recent developments demonstrated the extraction from an aperture of 9 mm diameter of 100 mA, 50 keV $^4He^+$ and $^1H^+$ beams [2]. Since these ion sources require no filament, they are very low maintenance and can run uninterruptedly for extended periods of time. The low energy accelerator consists of a 400 kV open-air platform (Fig. 1). It is being designed to extract all beams at 50 kV and post-accelerate them up to 400 kV. This approach allows for the maximum optimizations of the ion source independent of the required final beam energy, allowing for state of the art ion source design.

The high-energy accelerator possibilities under consideration are commercially available pelletrons or dynamitrons. The ion source currently proposed for the high energy machine is an Electron Cyclotron Resonance (ECR) ion source, capable of producing high intensity beams, up to 5 mA for single charged ions, and tenths of μ*A* of medium charge state heavier ions. In order to obtain relatively high ion currents at the lowest accelerating voltages, with a beam radius of a few millimeters, the accelerator tube of the high energy machine needs to be custom designed. In particular to reduce the beam expansion in the accelerator tube, the Shorting Rod (SR) technique will be adopted together with the installation of Einzel Lens (EL).

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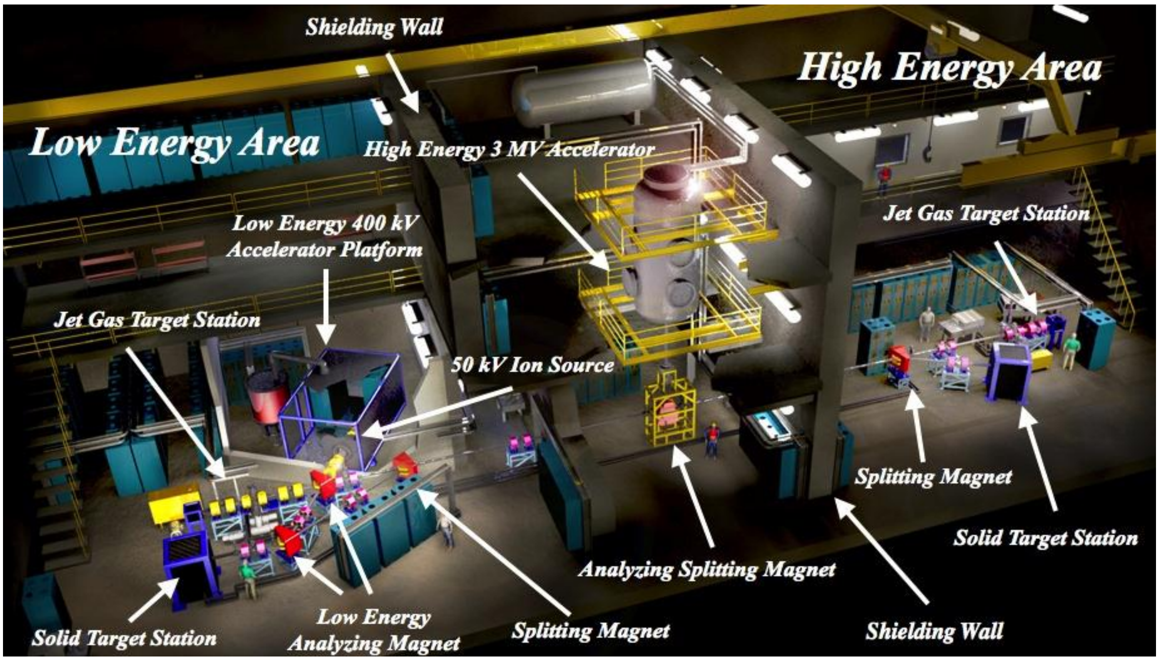

Figure 1: View of the DIANA accelerator facility.

At low energies (critical for nuclear astrophysics studies) the beam expands rapidly due to the space charge, causing the beam to scrape the tube, and therefore reducing the current transported by the tube. Furthermore the final beam diameter will be too high to be efficiently transported in the beam lines by the focusing elements. To reduce the expansion effect, an alternative approach is to use the Variable Voltage Gradient (VVG) technique, where the voltage is graded smoothly along the column. In addition the column will be equipped with an embedded Electrostatic Quadrupole Triplet (EQT), installed in the middle of the column, providing additional focusing.

Ultra low background High Purity Ge detectors embedded in low radioactivity passive copper and lead shield are currently considered [3]. To reduce the systematic errors due to poor knowledge of angular distributions at astrophysical energies, the detectors will be segmented. Furthermore to minimize the Rn induced background the detectors and passive shielding will be installed inside a Rn suppression box, fluxed continuously with high purity nitrogen.

Currently the DIANA project efforts are funded by the National Science Foundation (NSF, NSF-09-500 grant, Selection Phase 4, Proposal ID 091728). The DIANA Preliminary Design Report is due to NSF by end of September 2012 (end FY 2012).

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The LUNA-MV project: from 2007 to now

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Nuclear reactions that generate energy and synthesize elements take place inside the stars in a relatively narrow energy window: the Gamow peak. The extremely low value of the cross-section inside the Gamow peak has always prevented its measurement in a laboratory at the Earth's surface, where the signal to background ratio is too small because of cosmic ray interactions. In order to explore this new domain of nuclear astrophysics, LUNA (Laboratory for Underground Nuclear Astrophysics) started in 1991 its activity by installing a 50 kV electrostatic accelerator underground at the National Gran Sasso Laboratory (LNGS), followed in the year 2000 by a second 400 kV one. The first fifteen years were dedicated to the measurement of cross sections of nuclear reactions essential for our Sun and related physics. Outstanding results have been obtained on three important reactions of the p-p chain, namely the ^{3}He(^{3}He,2p)^{4}He, ^{2}H(p,γ)^{3}He and ^{3}He(^{4}He,γ)^{7}Be and on the bottleneck reaction of the CNO cycle, ^{14}N(p,γ)^{15}O (for a recent review see for instance [1]). Later on the "non solar" phase of the experiment started, mainly devoted to the study of (p,γ) reactions on Nitrogen, Oxygen, Neon, Sodium and Magnesium isotopes, belonging to CNO, NeNa and MgAl cycles of hydrogen burning. These cycles become important for second generation stars whose central temperatures and masses are higher than our Sun and whose evolution stage is such that the necessary seeds for those reactions are already present. Results have been already obtained for the ^{15}N(p,γ)^{16}O [2,3] and ^{25}Mg(p,γ)^{26}Al [4] reactions while other measurements are on-going or planned for the next 2-3 years.

Complementary to this project, in 2007, as a result of a feasibility study, a number of nuclear reactions was selected as candidates for future measurements at LNGS, on the basis of their importance in nuclear astrophysics and on the profit they could achieve in being measured underground. These extremely relevant reactions need a higher energy machine, in the MV range, to be measured. These cases were collected in a Letter of Intent (LoI) [5] which was presented to the LNGS Scientific Committee (SC). Aim of the LoI was to describe the physics case, discuss the possible technical solutions envisaged by the LUNA collaboration and finally propose a space request to LNGS to allocate a single stage electrostatic accelerator with a maximum terminal voltage of 3.5 MV. This would allow to study reactions such as the ^{12}C(α,γ)^{16}O, the ^{13}C(α,n)^{16}O, the ^{22}Ne(α,n)^{25}Mg, and few (α,γ) reactions having deep consequences in several topics of nuclear astrophysics such as nucleosynthesis, stellar evolution, supernova mechanism and so on. The choice of allocating the machine at LNGS was again due to the extremely reduced background offered by the rock coverage while the presence of a running experiment in situ was considered an "extra bonus" since people, knowledge and materials were already present. The first outcome of the SC was: *"A possible construction of a new LUNA accelerator was also discussed. The SC noted that this project needs a better specification in terms of its physics goals and also stressed that the issue of any neutron pollution was critical in considering deployment in a low background Laboratory like LNGS"* As a consequence, an addendum to the LoI [6] was submitted to the SC. This document, beside better specifying the astrophysical importance of the foreseen reactions (especially the ^{12}C(α,γ)^{16}O) , was focussed on a possible shielding solution and relative calculations of the neutron flux outside the shielding itself. The second outcome of the SC was based on both documents (LoI and addendum) *"The SC recognizes the important physics programme of the proposal, a natural development of the current experiment which gave outstanding results. Nevertheless, the SC noted that the LUNA-MV project has a non-negligible impact on the whole Laboratory's activity, mainly under two respects: (i) the underground space needed and (ii) the possible radio-activity pollution. The space needed by LUNA-MV can be evaluated to be approximately 1/5 of a main experimental hall. This space, if allocated, will definitively saturate the total available space underground for a substantial time. This scenario has important consequences for the Laboratory, preventing any further development of the approved experiments as well as any new experiment proposal. The second issue*

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concerns the neutron and gamma activity connected with a 3 MV accelerator. This activity, even if properly shielded as discussed in the LOI/addendum, could still seriously increase the Laboratory background, the low level of which is a major advantage of the Gran Sasso Laboratory. Based on these two important points the SC was not able to recommend approval of LUNA-MV to proceed to a full proposal for deployment at Gran Sasso. Nevertheless, the SC reiterates its view that the science of the LUNA-MV project is very important and hopes the collaboration will be successful in finding an alternative location". Alternative locations were searched for, among them the Mount Soratte bunker was considered. This is a tunnel which was excavated during the Second World War, located close to Roma (Italy) at 420 m above the sea level with rock coverage of only 100-200 m and no infrastructure. The background was measured with a large volume NaI detector and found to be only a factor 50-80 reduced with respect to the surface, for gamma energies from about 4 to 12 MeV. This has to be compared with the LNGS reduction of a factor 2000 from about 3 to 8 MeV and even more at higher energies. The solution had therefore to be abandoned. In July 2008 a meeting among the INFN President and Executive Board and the spokesperson of the collaboration was held. The President and the Board strongly supported the idea to continue the LUNA activity with the MV machine in Gran Sasso. A suitable place was found to host the new accelerator, far from all the other experiments, in the region occupied by the interferometer (node B). The third SC committee recommendation (October 2008) was *".... Regarding theLUNA MV project the SC recommends that, in order to prepare a full proposal, the collaboration should discuss the details of the project with the Laboratory management, with a particular attention to the experimental set-up location and the possible neutron pollution."* One year later the SC gave a similar but more precise suggestion, namely: *"....the committee recommends that the Director set-up a small committee to address the issue of possible neutron generation and the operation of the experiment, in order to ensure that the neutron backgrounds are at a suitable level"*. The committee was formed. Different expertises in the field of nuclear astrophysics, neutron shielding, accelerators, safety and radioprotection were covered by this committee formed by five scientists. The collaboration and the committee interacted over two months on different issues. Upon request, the collaboration provided a document [7] with updated calculations of the neutron production rates obtained with the most recent results for the respective cross sections, showing that the maximum neutron production rate is 1800 n/s. Realistic values for the beam intensity and target stoichiometry, isotopic ratio and areal density were considered, while the maximum beam energy was chosen in order to reach a good overlap with existing literature data. The maximum alpha beam intensity is due to the technical characteristics of the foreseen accelerator, which was better specified with respect to the LUNA LoI [5]. This would be a closed, single-ended positive-ion accelerator with a maximum terminal voltage of 3.5 MV. Following the submission of the update to the LoI [7], several questions were raised by the committee and addressed by the collaboration. The possible location of the facility turned out to be one the major issues which influences all the other technical decisions (shielding, pollution, safety, …). The interferometric node was identified as the best possible solution due to its size and distance from the other LNGS experiments. After the Committee submitted his review on the LUNA-MV project to the SC, the LUNA spokesperson got the following recommendation: "*Concerning the proposed operation of a high voltage LUNA-MV accelerator, the SC was pleased to hear the conclusions of the review committee which addressed the issue of neutron pollution underground. This careful analysis, performed taking into account also possible activation effects on the ground water, showed a very low increase in the neutron background. The SC recognizes the important efforts made by the collaboration to reduce and characterize this background. The SC recommends close interaction with the Laboratory management to address the specific issue of the underground location of the experimental set-up, particularly in view of possible interference with the ground water. The SC repeats its view that the scientific importance merits the establishment of the new experiment..."* Last September a real feasibility study started with the great involvement of the technical divisions of LNGS and LNF. Finally, the last meeting of the SC (October 2010) gave the following outcome : *"The SC was pleased to see that the collaboration had initiated a technical study of the LUNA Mega Volt (LUNA-MV) project. The SC supports the idea of organizing a roundtable on this topic, foreseen for February 2011 in LNGS, with the aim of involving other European groups in the LUNA-MV activity and the objective of producing a Letter of Intent"*. The Round Table has been organized and a short review of the topics presented and discussed is reported in the contributions to these Proceedings.

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[3] P. J. Le Blanc et al.,Phys. Rev C 82 (2010), 055804
[4] The LUNA Collaboration, LUNA-MV Letter of Intent- LoI 42/07
[5] The LUNA Collaboration, Addendum to the LUNA-MV Letter of Intent- LoI 42/07
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A Megavolt Accelerator for Underground Nuclear Astrophysics

Matthias JUNKER[*] (Laboratori Nazionali del Gran Sasso)

The experimental program put forward by the community interested in Underground Nuclear Astrophysics demands for the construction of an underground accelerator, able to produce ion beams with energies of several MeV for signally charged particles. The experience gained at LUNA in successfully running accelerators in the underground laboratory of the Laboratori Nazionali del Gran Sasso (LNGS) can be used as a starting point for the implementation of such a machine.

Not only the specific conditions in an underground laboratory but the scientific program envisaged poses some important conditions in choosing the accelerator. The physics cases with the highest priority involve reactions with alpha beams with an energy between 3.5 MeV and 350 keV. The new machine must allow easy modification of the beam energy needed for the study of non resonant processes, resonance profiles and broad resonances. Due to the low cross sections involved the beams must be intense and stable in energy and in time, operating contentiously over several weeks without the permanent presence of an operator on site. These conditions strongly disfavor tandem accelerators which deliver only poor alpha beams.

Underground locations normally pose strict limitations concerning available surface and volume as well as on the accessibility of the experimental site itself. Moreover particular infrastructural and environmental conditions must be taken under consideration. This applies to availability of electricity, ventilation and safety in particular when accelerators involving pressure vessels or explosive gases are considered. At the same time a well protected and reliable remote control of specific parameters of the machine and of the experimental equipment must be provided by any hosting laboratory.

Running and maintaining such an accelerator and the related scientific program requires a lot of technical and scientific skills. In particular the availability of mechanical and electronic workshops as well as dedicated technical and scientific staff personnel in the hosting laboratory is mandatory for efficient operation. The presence and accessibility of a low level counting laboratory, a chemistry lab and a vivid scientific community are desirable.

Beam induced background is a problem of major importance in experiments which involve low reaction cross sections. Part of this problem are particles (e.g. 13C) carried with the beam while passing through the accelerator beam lines. These particles are deposited on the target or the beam stop and can build up to self targets jeopardizing the target purity needed by the experiment. This effect can be mitigated by using oil-free pumping systems and beam lines with metal sealing.

The presence of other experiments exploiting the low background environment of an underground laboratory requires that the experimental activities involving a MeV-machine do not alter the background conditions outside its dedicated experimental area in all its operational conditions. While the production of X-rays is not a problem any more with modern MeV-machines, the production of neutrons cannot be excluded. This is a basic difference to the LUNA 400kV accelerator where the available beam energies are well below the thresholds of most of the relevant (p,n) and (p,a) reactions. The few remaining cases like 13C(p,n) have been treated individually in the operating license of the accelerator.

On the contrary in the case of the MeV-machine the neutron production must be evaluated in detail and dedicated shielding are needed. This shielding can have a strong impact on the available place and the accessibility of the experimental site. They also interfere e.g. with the ventilation. Finally the cost of such an installation must be considered. An optimization of the shielding by Monte Carlo Simulation is needed. A good knowledge of the underground neutron flux as a function of energy is another important ingredient for optimizing the neutron shield to the effective needs.

The natural neutron background of an underground laboratory is so low that a real time measurement of the reference flux is not possible. To overcome the problem a detailed simulation of the shielding can also be used to identify the upper limits for neutron flux inside the shiedling which in turn can be checked experimentally with standard equipment.

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In the course of the experiments performed at LUNA it has turned out that the location in an underground laboratory and the need for high availability and reliability of the accelerator poses operative constrains to activities involving accelerator development. The machine is supposed to be reliable and easy to maintain the way that the experimental actives can be focused as much as possible on the those aspects which are related to the underground location itself. It is advisable to bring machine innovation and accelerator related R&D in laboratories above ground until the new technology has proven to be sufficiently reliable.

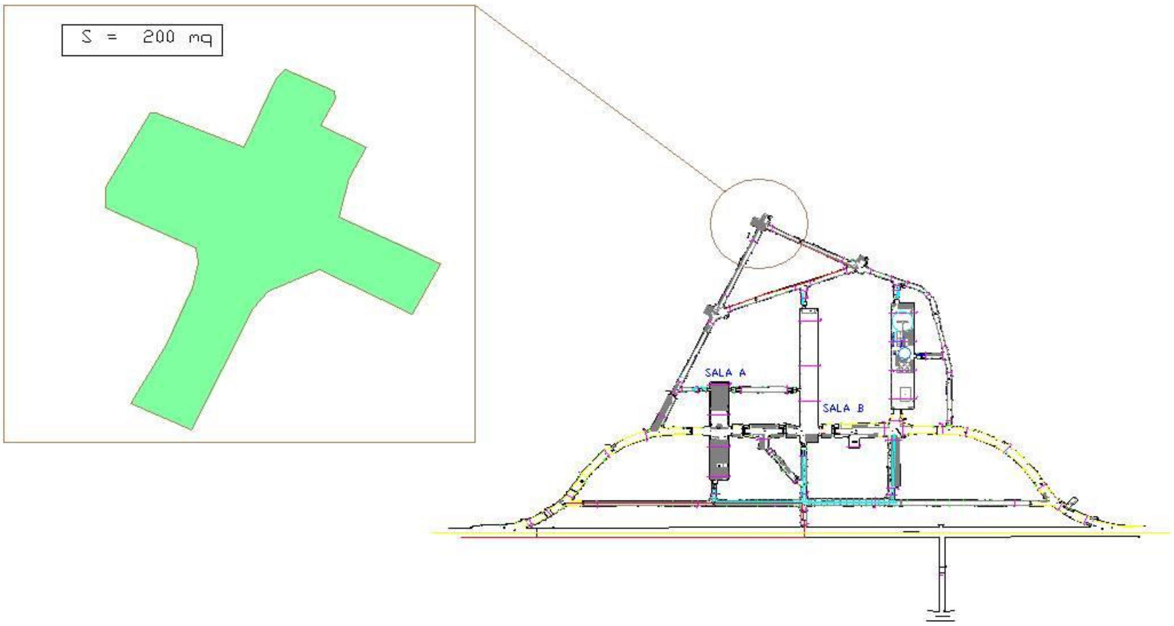
The setups for experiments in Underground Nuclear Astrophysics often involve detector setups with heavy lead shielding and complex pumping systems which are difficult to modify. On the other hand experience at LUNA has shown that it is advantageous to have one experiment in the construction or evaluation phase while another initiative is taking data. This approach helps to optimize the use the accelerator itself and the related scientific output. An accelerator system with at least 2 beam lines is highly desirable.

***Picture 1**: Example of the layout of 3.5MV accelerator at LNGS*

As an example of a possible design for a MV-machine in an underground laboratory the basic outline of the proposed LUNA-MV machine at the Laboratori Nazionali del Gran Sasso (LNGS) is presented in Picture 1. It is based on a commercial single ended 3.5 MV Singletron equipped with an RF source. The accessible energy range links this accelerator to the already operating LUNA 400 kV machine which can be used to extend the energy range below 350 keV. The proposed ion source has proven to deliver alpha beams of at least 200mA with a duty cycle of four weeks. Possibly more performing source concepts are not put forward as they still do not reach the needed reliability or are even incompatible with the available place. All other components are commercially available, too. The machine is equipped with two beam lines. Heavy neutron shielding designed on the basis on a detailed Monte Carlo simulation is located at the exits of the experimental area. Control and service rooms are placed outside the shielded area. On site 100 kW of electrical power, telephone lines, LAN, ventilation, compressed air and water cooling are available. Safety plants include oxygen and hydrogen monitors, a fire detection and extinguishing system and accelerator access control. The site is connected to the control room of the underground labs of LNGS supervision. Automatic alarming of the responsible researcher in case of unexpected problems will be performed by e-mail and SMS.

The Site for LUNA-MV at LNGS

Paolo MARTELLA[*] (Laboratori Nazionali del Gran Sasso)



SITUATION TODAY IS:

- Installations present, which must be partially removed;
- Consider presence of Ermes Experiment;
- Consider presence of drinkable water collection plants;
- Consider water dropping from the tunnel wall.

STEP 1: ORGANIZATION OF WORK

- Removal of equipment and facilities;
- Cleaning the area;
- Topographic measurements of the gallery and installations inside;
- Detailed design of the tunnel cover and waterproofing;
- Implementation of floor coating for waterproofing (see next slides)
- Construction of steel frames and panels (next slides)
- Implement new Plants
  - Electrical Plants;
  - Ventilation;
  - Cranes;
  - Safety, Telecommunication, IT;
  - Pneumatics.

STEP 2 : COLLECTING WATER FLOWING FROM TUNNEL WALLS

- Concrete kerbstone around perimeter of the new building;
- Installation of new water channel around perimeter (outside building).

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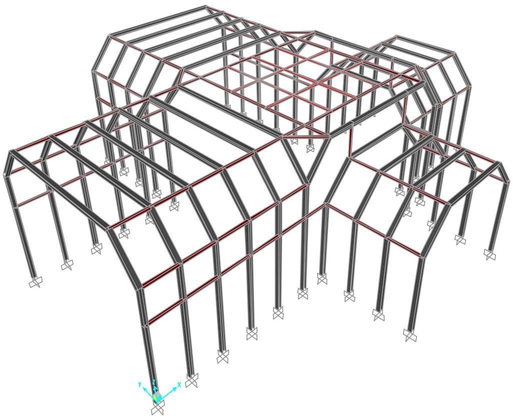
STEP 3 : WATERPROOFING FLOOR

- Installation of floor sealing;
    - Impermeabilization of floors
    - protection of the sheath through and reinforcement of floor by new concrete layer h = 0.20 meters;
    - Polyurethane layer h = 9 mm;
    - Construction of n. 2 ramps at entrance node.

STEP 4 : WORKS WALL COVERINGS

- Steel frame construction;
- Galleries with cover panels in rock wool;
- Creation of " Ermes" independent access;
- Crane 1000 kg.



STEP 5 : PROVIDE GENERAL INFRASTRUCTURE TO SITE

- **Electric Power Line:**

Task: Placing of general power line (for 100kW electrical power (3P+N+T)
Status: Defined, executive project tbd;

- **Ventilation:**

Task: Construction of air duct (Diam. 260mm);
Status: Planning completed, ordered;

- **Compressed Air Line:**

Task: Line to connect to LNGS compressed air system;
Status: Defined, executive project tbd;

- **Safety Plant Line:**

Task: Placing cabling for connections to LNGS safety plants and site Supervision;
Status: Defined, executive project tbd;

- **Telephone & Networking**

Task: Placing cabling for connection to telephone network & LAN;
Status: Defined, executive project tbd;

STEP 6: PROVIDE GENERAL INFRASTRUCTURE INSIDE SITE

- **Electric Power Line:**

Task: Internal power distribution;
Status: tbd.

- **Ventilation:**

Task: Ventilation of experimental areas;
Status: tbd.

- **Compressed Air Line:**

Task: Compressed air system;
Status: tbd.

- **Safety Plant Line:**

Task: Placing of sensors for Oxigen, Hydogen, Fire, Access Control, ...
Status: tbd;

- **Telephone & Networking**

Task: Placing IT infrastructure in experimental area;
Status:tbd.

The Shielding of the LUNA-MV site

Davide TREZZI* (Istituto Nazionale di Fisica Nucleare, Sezione di Milano)
Bruno DULACH† (Laboratori Nazionali di Frascati)

The LUNA-MV program [1] involves reactions which directly or through possible contaminants in the target produce neutrons. In a very low background environment such as the Laboratori Nazionali del Gran Sasso (LNGS), it's mandatory not to increase the neutron flux above its average value.

In this document we report the preliminary study of the LUNA-MV neutron shielding by Monte Carlo simulations.

The main sources of neutrons will be the reactions $^{13}C(\alpha,n)^{16}O$ and $^{22}Ne(\alpha,n)^{25}Mg$. The first one is also a parasitic reaction in the study of the $^{12}C(\alpha,\gamma)^{16}O$, due to the ^{13}C residual contamination in the target layer.

The neutron production rate for each reaction in the energy range under investigation in the LUNA-MV project versus the alpha beam energy is shown in figure 1. The maximum value of about *2000 neutrons per second* is obtained for the $^{13}C(\alpha,n)^{16}O$ reaction. Also the maximum neutron kinetic energy of 5.6 MeV is reached by the $^{13}C(\alpha,n)^{16}O$ reaction.

In this preliminary study the worst case was considered i.e. highest neutron production rate and energy.

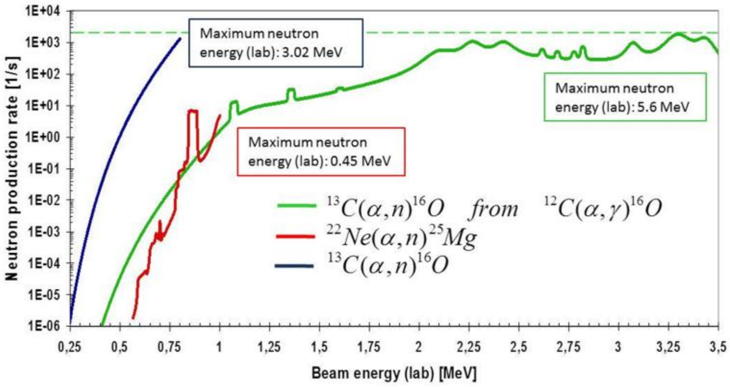


figure 1: neutron production rate vs the α beam energy in the laboratory frame. The green dash line is the maximum neutron rate produced in the LUNA-MV project. In the boxes the maximum neutron energy for each reaction is reported.

The LUNA-MV apparatus will be located in the B-NODE of the LNGS underground laboratory (for more details see P. Martella report). The natural average total neutron flux in the lab is $\Phi_N = 3.3 \cdot 10^{-6}\ cm^{-2}s^{-1}$ [2].

In order to maintain this value just outside the LUNA-MV experimental hall, we investigate the possibility to build up two possible shielding configurations, named respectively the *wall configuration* and the *labyrinth configuration*.

In the wall configuration the experimental hall is closed by a bored concrete door (1 meter thick) while in the other one the door is substituted by a system of three blocks in bored concrete shifted each other in order to make a sort of labyrinth. In both configurations a bored concrete frame is present as shown in figure 2. This is a concrete wall, 1 meter thick, with an aperture of 3 x 3 m in the wall configuration and 3 x 3.2 m in the labyrinth configuration. The frame will provide the access to the LUNA-MV experimental hall.

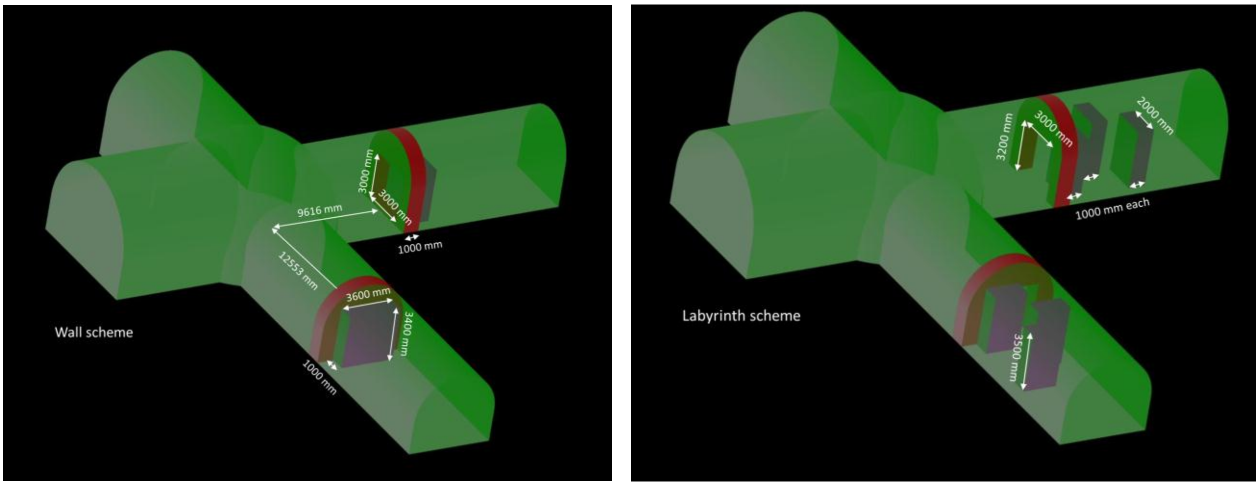


figure 2: the wall and labyrinth scheme as visualized by using the GEANT4 RayTracker graphical driver. In green the LUNA-MV site (B-NODE, air filled), in violet the door and blocks, in red the frame.

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Thus a GEANT4 Monte Carlo simulation has been developed by using the LSC tool [3]. The neutron source, located at the tunnels cross point (at one meter from the ground), is point like and isotropic and produce $5.6\,MeV$ monoenergetic neutrons with a rate of 2000 neutrons per second. One million events for each configuration has been simulated. The neutron flux Φ , computed in 68 positions (near the tunnel’s walls and the door / blocks), is given by:

$$\Phi = R\frac{N}{S}$$

where R is the neutron rate and N is the number of neutrons that cross the fluxmeter plane (a square with surface $S = 16\,m^2$) divided by the total number of events. In the previously conditions the minimum flux detectable by the simulations is $\Phi_{low} = 1.25 \cdot 10^{-8}\,cm^{-2}s^{-1}$. The bored concrete’s chemical composition is (percentage in weight): 8% Portland cement, 29% sand, 56% Colemanite and 7% water.

Figure 3 shows the neutron flux versus the distance from the frame, at the right tunnel, with both configurations (wall and labyrinth). *These simulations show that the wall configuration is more efficient in terms of neutron shielding than the labyrinth one*.

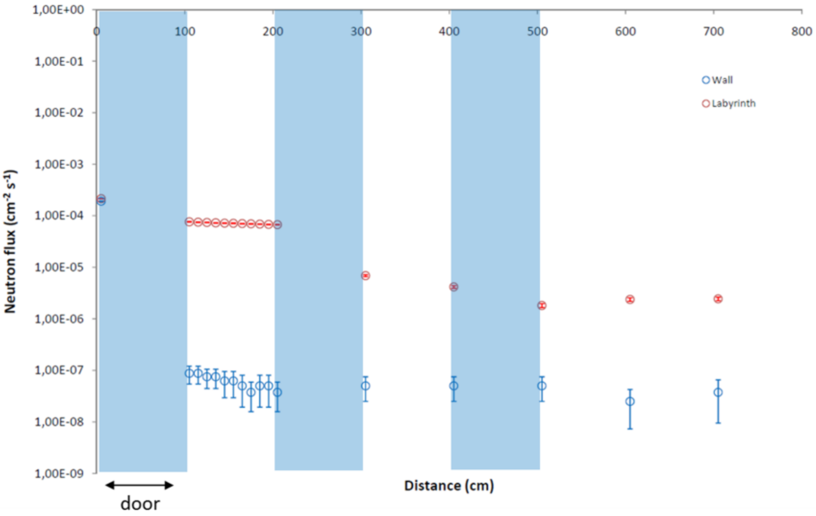

figure 3: the neutron flux versus the distance from the frame in the case of the wall (blue circles) and labyrinth (red circles) configurations. The blue boxes represent the positions of the door for the wall configuration or the position of each block for the labyrinth configuration.

A second set of simulations have been developed in order to reduce the neutron flux outside the experimental hall when the source is not located in the cross point but in the “real” position of the solid and gas target as reported in M. Jünker report. Thus we implement two hypothetical raw solid and gas chambers. The first one is a cylinder 80 mm in diameter, 300 mm length and the second one is a box of 120 x 120 x 500 mm. The thickness of the steel is 40 mm.

As reported in P. Martella report, we also implement the concrete pavement (200 mm thick). Last, the experimental hall is covered by HDPE (Li) panels as shown in figure 4. The number of fluxmeters has been increased from 68 to 160 as well as the statistics from 1 million to 4 million events.

The HDPE (Li) chemical composition is: 13.6% hydrogen, 81.4% carbon, 5.0 % lithium. In this conditions the minimum flux detectable by the simulation is $3.125 \cdot 10^{-9}\,cm^{-2}s^{-1}$.

In figure 5 and 6 the neutron fluxes in the right and bottom tunnels versus the distance from the tunnel when the gas or solid target is turn on are shown.

The simulation give a neutron flux just outside the LUNA-MV experimental hall well below the natural neutron background for both gas and solid target experiments. The average neutron flux, one meter inside the Gran Sasso rocks, is $3.75 \cdot 10^{-9}\,cm^{-2}s^{-1}$ at the top, $5.94 \cdot 10^{-9}\,cm^{-2}s^{-1}$ at the ground and $2.75 \cdot 10^{-6}\,cm^{-2}s^{-1}$ at the walls.

Monte Carlo simulations of the LUNA-MV site are an important tool in order to choose the best neutron shielding configuration. In future it will be possible to increase the statistics by parallel computing and implements more details such as the gas and solid detector and a more complex shielding. It will be possible to do a neutron flux map of the overall LNGS underground laboratory.

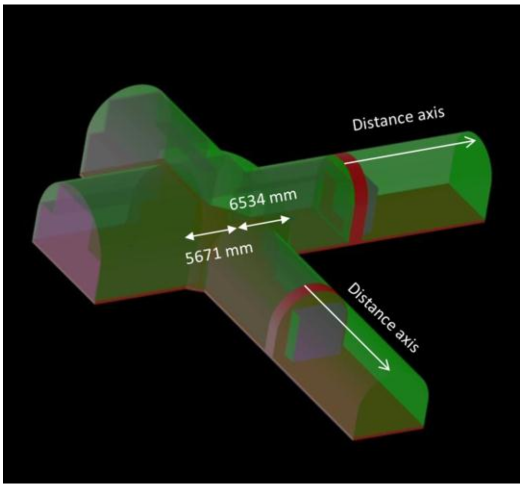

figure 4: the simulation scheme as visualized by using the GEANT4 RayTracker graphical driver. In green the LUNA-MV site, in violet the doors, in red the frame and the concrete pavement, in pink the HDPE (Li) panels. The solid and gas target chambers are not visible in figure.

I thank B. Dulach, A. Cecchetti and P. Martella for the technical support.

References

[1] LUNA – MV Letter of Intent 42/07, submitted to LNGS scientific board (2007)

[2] Belli et al., Il Nuovo Cimento 101A (1989) 959-966

[3] LSC, Lemmo's nuclear astrophysics Simulation Code ALemut@lbl.gov .

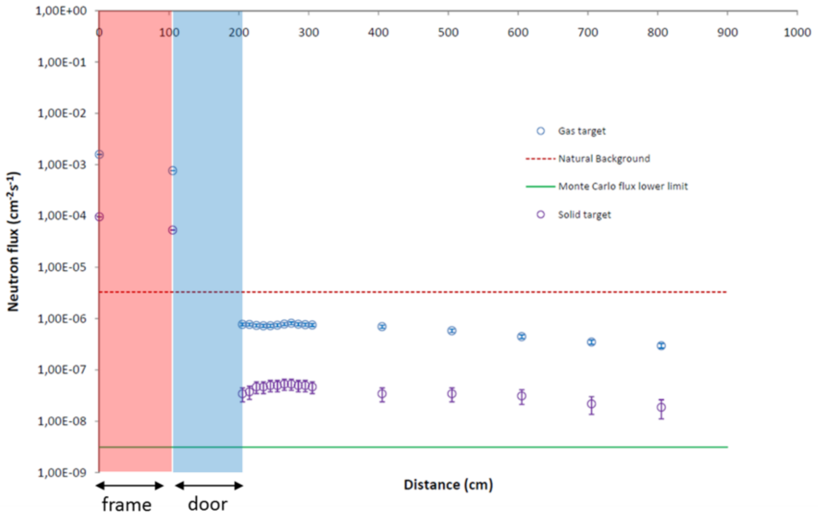

figure 5: the neutron flux versus the distance from the tunnel in the case of gas or solid target turned on (right tunnel). The red box represents the frame while the blue one represents the door. The red dotted line is the natural neutron flux at the LNGS underground laboratory and the green line is the simulation minimum detectable flux.

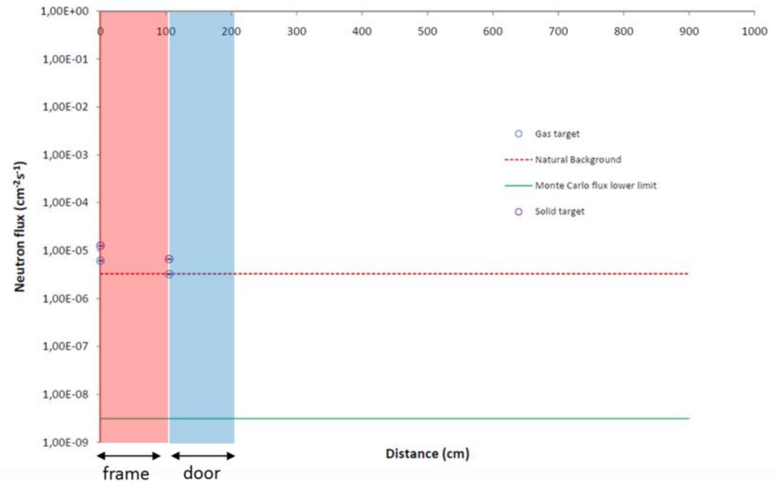

figure 6: the neutron flux versus the distance from the tunnel in the case of gas or solid target turned on (bottom tunnel). The red box represents the frame while the blue one represents the door. The red dotted line is the natural neutron flux at the LNGS underground laboratory and the green line is the simulation minimum detectable flux.

The $^{12}C(\alpha,\gamma)^{16}O$ reaction from the astrophysical point of view

Oscar STRANIERO* (Istituto Nazionali di AstroFisica, Sezione di Teramo)

The available laboratory experiments devoted to the measurement of the cross section of the $^{12}C(\alpha,\gamma)^{16}O$ reaction have been extended down to about 1 MeV, well above the Gamow's peak energy (about 0.2-0.3 MeV) corresponding to the stellar temperatures experienced within the core of a He-burning stars (namely, 1 to 2 x 10^8 K). As a matter of fact, low energy measurements are hampered by the extremely small value of the cross section (<10 pb). In these conditions, either cosmic and natural background make difficult direct γ-ray detection. Then, extrapolation procedures have been used to extract the astrophysical S-factor. Such an extrapolation is based on the fitting of differential cross sections in the investigated region and requires the inclusion of the phase correlation between the two incoming partial waves that contribute to the two multipoles. For these reason, even the evaluation of the uncertainty affecting the $^{12}C(\alpha,\gamma)^{16}O$ reaction rate is a hard task. According to Buchman (1997), at E=300 keV the possible value of the reaction rate should range between $Na<\sigma,v>$ =0.5 and 2.2 (in 10^{-15} cm^3 mol^{-1} s^{-1}). The NACRE collaboration (Angulo et al. 1999) adopts a slightly smaller range of accepted values, namely between 0.9 and 2.1. Finally, Kunz et al. (2002) suggest $Na<\sigma,v>$= 1.25 with a 30% uncertainty range.

The most striking effect of a change of the $^{12}C(\alpha,\gamma)^{16}O$ reaction rate is the significant variation of the amount of C (and O) left in the stellar core after the He-burning. More quantitatively, the quoted uncertainty leads to a central C mass fraction ranging between 0.15 and 0.5, the two extreme values being obtained by adopting the highest and the lowest reaction rate, respectively. Such a change in the carbon abundance have many important astrophysical consequences.

First of all, the late evolution of a massive stars (from the C burning up to the core collapse) is strongly dependent on the amount of C left in the core after the He-burning In particular a smaller C abundance implies a shorter duration of the C-burning phase. Such an occurrence leads to a steeper M-R relation in the core, because the nuclear energy release is insufficient to supply the energy loss (mainly due to thermal neutrino emission), so that the star should contract. Therefore, the core collapse and the following explosion are influenced by a variation of the C left by the He burning. The imprint of such an influence can be searched in the chemical composition of the explosive debris. The intermediate-light elements, Ne, Na, Mg, and Al, which are produced in the C-burning shell, scale directly with the C abundance left by the previous He burning, simply because they depend on the amount of available fuel. On the contrary, all the elements whose yields are produced by any of the four explosive burnings (complete explosive Si burning, incomplete explosive Si burning, explosive O burning, and explosive Ne burning) scale inversely with the C abundance left by the He burning, because the mass-radius relation in the deep interior of a star steepens as the C abundance reduces.

As a result we found that a low C abundance (about 0.2 dex by mass fraction) is required to obtain yields reproducing a scaled solar distribution. One may claim that such an occurrence could be used to constrain the $^{12}C(\alpha,\gamma)^{16}O$ reaction rate. Unfortunately this is not the case. In fact, the C abundance after the core-He burning also depends on the efficiency of the convective mixing. There exists a longstanding debate among the astrophysical community concerning the actual extension of the convective core during the He burning. As a matter of fact, the uncertainty of this hydro-dynamical process cannot be distinguished by the uncertainty due to the nuclear reaction rates. It implies that only a better knowledge of the $^{12}C(\alpha,\gamma)^{16}O$ reaction rate at stellar energy would allow us to constrain the convection theory (or vice versa).

The poor knowledge of the C amount left by the core He burning also affect the late evolutionary phase of low and intermediate mass stars. Normally, these stars terminate their life as C-O white dwarfs. The properties of these object, in particular their cooling timescale, depends on the chemical composition. Due to the larger atomic number, the O crystallization occurs at lower density than that of C. Then, a large C abundance implies a delayed liquid-solid phase transition and, due to the resulting release of latent heat , a longer cooling phase. As a result, by combining the uncertainties (convection plus nuclear reaction rate) affecting the He-burning phase, we find a 14% uncertainty in the estimated WD cooling timescale. Note

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that the cooling timescale is a potential stellar clock, a useful tool to date old stellar systems like Globular Clusters.

Low and intermediate mass stars belonging to interactive binary systems are also progenitors of thermonuclear (type Ia) supernovae. The light curve of these supernovae around the maximum, which is the most important observed outcome, is powered by the decay of ^{56}Ni into ^{56}Co. Since the amount of ^{56}N produced by the explosion depends on the nuclear fuel (C/O), also in this case the uncertainty on the $^{12}C(\alpha,\gamma)^{16}O$ reaction rate (as well as those affecting the evaluation of the size of the convective core during the He-burning evolutionary phase) hampers our understanding of these astronomical phenomena. We recall that type Ia SNe are used as standard candles to determine the distances of the host galaxies up to redshift z=1. It makes these objects a fundamental tool for modern cosmology. Thanks to type Ia SNe, in fact, we know that the expansion of the Universe has been accelerated during the last 5-6 Gyr. Such a conclusion derives from the assumption that distant SNe behaves like the local ones, for which an independent calibration of the distance is available. Only a full comprehension of the physics of these stellar explosions could allow us to safely extend the local calibration to the distance Universe.

The rates of neutron – realeasing reactions in He-burning phases and their astrophysical consequences

Maurizio BUSSO[*], Enrico Maiorca[†], Sara Palmerini[‡]
(Università di Perugia – Istituto di Fisica Nucleare, Sezione di Perugia)

Abstract. We briefly recall the general features of s-process nucleosynthesis in stars, as induced by the activation of the neutron-releasing reactions $^{13}C(\alpha,n)^{16}O$ and $^{22}Ne(\alpha,n)^{25}Mg$ and illustrate some recent results on s-element abundances in the Galactic disc. On this basis we discuss the astrophysical relevance of new, precise measurements of the rates for the neutron-producing processes and their possible effects on our general views on heavy-element nucleosynthesis in the Galaxy.

1. The general picture of the s-process. Fifty six years ago, Cameron [1] and Greenstein [2] advanced the first hypotheses on the neutron sources that might have promoted neutron-capture nucleosynthesis in the hydrostatic phases of stellar evolution. Then the compilation of meteoritic abundances [3] and the fundamental clarification of nucleosynthesis processes operated by Burbidge, Burbidge, Fowler and Hoyle [4] opened the road for the modern theories of heavy element production in stars, including the slow neutron captures that provide the formation of 50% of the elements beyond iron, the so-called s-process. Here "s" means "slow" and indicates that most of the neutron captures encountered in the mechanism are slower than most competing β-decays, so that the flow runs along the valley of β-stability. The modern views on such processes can be summarized with reference to a classical plot (Figure 1) illustrating the values of the products σN_s between the neutron capture cross sections and the s-process component of the meteoritic abundances of stable isotopes beyond Fe in the solar system.

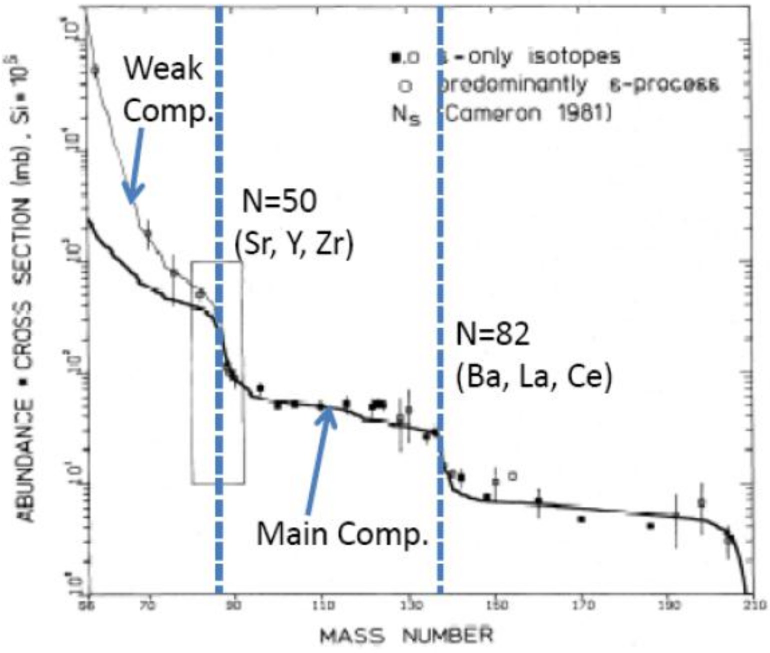

Figure 1: The trend of the σN_s products in the solar system and their attribution to the two components of the s-process.

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The isotopes with the lowest Mass Number (A≤88-90) are attributed to a first component of the process (called *weak* s-process component) produced in massive stars during core-He and shell-C burning [5,6]. The main neutron source for their production is the ^{22}Ne(α,n)^{25}Mg reaction. The heavier isotopes (all those with A≥88-90) are ascribed to a *main* s-process component, occurring primarily during the Asymptotic Giant Branch (AGB) phases of low mass stars ($M \leq 3\ M_{\odot}$, see [7,8,9]). For them, the synthesis is mainly due to the activation of the ^{13}C(α,n)^{16}O neutron source in the radiatively-stratified He-rich layers, during the relatively long quiescent phases separating two thermal instabilities of the He-burning shell (see [10] for the evolutionary details). Here the ^{13}C needed is produced thanks to a proton injection into the ^{4}He- and ^{12}C-rich layers at the envelope penetration after a thermal instability (this penetration is called Third Dredge-Up or TDU). The proton injection has been attributed either due a smooth profile of the velocities of convective bubbles at the border of the convective envelope [10] or to some non-convective diffusive process [11]. In both cases a rather typical reservoir of ^{13}C (called the ^{13}C-pocket) is formed, where subsequently neutron production and neutron captures occur, in conditions of small neutron density and temperature ($\leq 10^{7}$ n/cm^{3} and 8keV, respectively). For the main component. the ^{22}Ne(α,n)^{25}Mg reaction is activated only marginally in the intermediate convective regions that develop at the thermal instabilities (usually called *Thermal Pulses*); it works at about 23 keV on average, producing small neutron exposures but relatively high n-densities (10^{10} n/cm3) and takes care of fixing the final isotopic abundances around reaction branchings that depend on the temperature or on the neutron density itself (see an example in Figure 2)

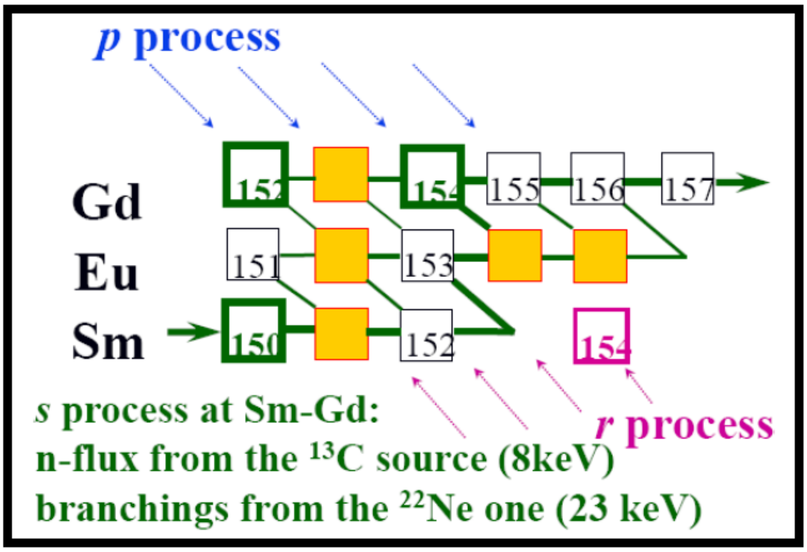

Figure 2: The s-process isotopic abundances of Sm, Eu and Gd are affected by reaction branchings that depend on temperature and neutron density.

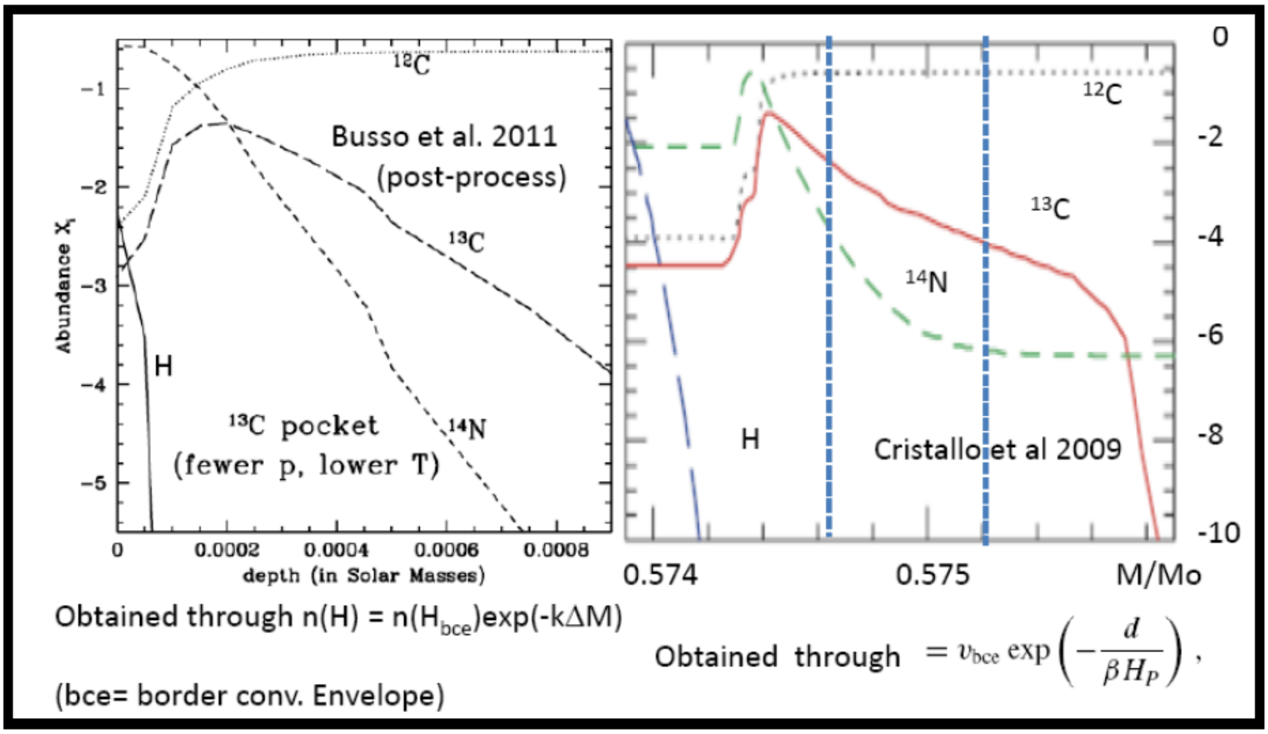

Figure 3: Two recently-published forms of the 13C-procket in AGB stars

2. On the possible effects of changes in the reaction rates for neutron production.

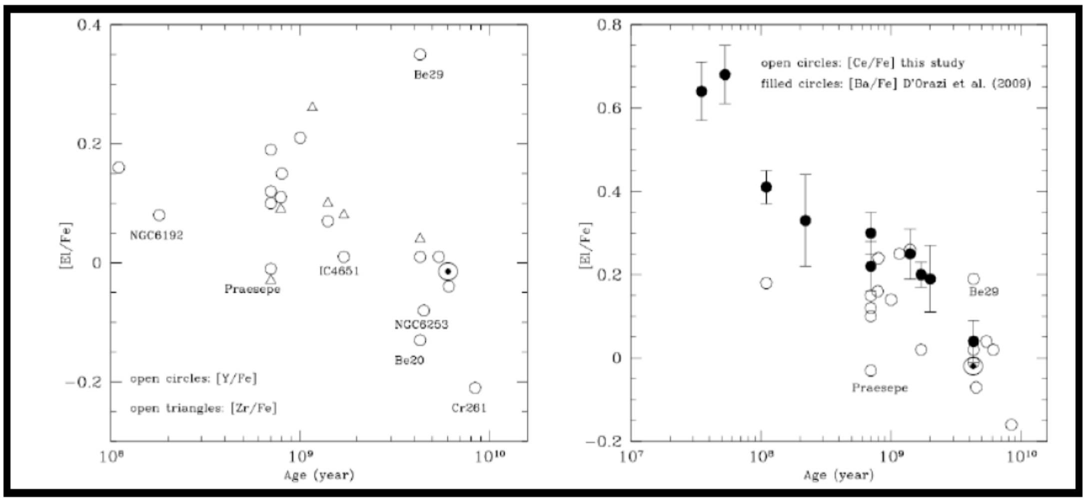

Figure 4: The increase of s-element abundances in recent stellar systems

2.1 The rate of the reaction $^{13}C(\alpha,n)^{16}O$.

On the basis of the scenario described above, it was shown [12] that the chemical evolution of s-elements up to the solar formation age could be well reproduced. Very recently however observations of open clusters by [13,14] revealed that the above picture is insufficient to account for the s-element enrichment in the more recent galactic disk, where a large s-process enhancement exists. This indicates that AGB stars of very small mass ($M \leq 1.5 M_\odot$), contributing in the Galaxy only after the solar formation, must have more extended 13C pockets and therefore produce s-elements more abundantly.

These enlarged ^{13}C reservoirs would cover regions of the star where a higher temperature (10 keV) is present and would induce higher n-densities. With the above problems in mind we can speculate that a new measurement of the rate for the $^{13}C(\alpha,n)^{16}O$ reaction might have the following effects:

i) for stellar masses above 1.5 $M_{\odot}$,. The neutron density at 8keV is so low that a possible increase of the rate (as suggested by [15]) would have minimal effects, unless it is larger than a factor of 3-5. More relevant would be a reduction of the rate with respect to the values indicated by [16]. This is a real possibility, if the rate is less affected than so far assumed by the contribution of a sub-threshold resonance [17]. In such a case ^{13}C might have insufficient time to burn in the interpulse phase, and would end up burning, at least partially, in the convective thermal pulse. Here the extra energy generated would be crucial and might induce phenomena like a shell-splitting [18], strong changes in the neutron density and large modifications in our present picture of the s-process.

ii) for masses below 1.5 $M_{\odot}$, both an increase and a decrease of the rate might be critical, as the slightly higher temperature would emphasize the effects on the otherwise low n-density. Again. some ^{13}C in the cooler layers might remain unburned, with the same destabilizing effects described at point i).

2.2 The rate of the reaction $^{22}Ne(\alpha,n)^{25}Mg$.

For this reaction it is common to use the rate suggested in [19], where any contribution from the possible resonance of ^{22}Ne + α at 633keV (affecting both ^{25}Mg and ^{26}Mg) was discarded. This assumption was found to be essential to avoid the main component to be characterized by a too high n-density than allowed by the analysis of the reaction branchings. This hypothesis is also important for maintaining the delicate equilibrium between He-burning and C-burning effects in Massive stars. It is therefore clear that a modification of this scenario by a hypothetical new measurement stating that the effects of that resonance must instead be considered and are important would have a dramatic effect on the present picture of s-problems. But also measurements confirming the present assumptions would of course be important: they would guarantee an experimental basis to speculations so far adopted without a solid ground.

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The seeds of the S-process: experimental issues in the study of $^{13}C(\alpha,n)^{16}O$ and $^{22}Ne(\alpha,n)^{25}Mg$

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Current stellar models supports the $^{13}C(\alpha,n)^{16}O$ and $^{22}Ne(\alpha,n)^{25}Mg$ reactions as the dominant neutron sources for the main component of the s process in thermally pulsing, low-mass, asymptotic giant branch (TP-AGB) stars and in massive stars with $M > 8M_{SUN}$, respectively. Both the reactions have been objects of intensive experimental studies in the past: the most up-dated results are described in the articles published after the last experiments performed in Karlsrüe, [1], and Stüttgart, [2]. In both the cases, the astrophysical energy window was not reached since the reaction rate was much lower than the background.

The temperature during the s process in the ^{13}C pocket of 90×10^6 K corresponds to a Gamow peak around 190 keV for the $^{13}C(\alpha,n)$: direct measurements with small uncertainties stopped at about 350 keV [1] and the reaction rate is presently obtained through extrapolations to lower energies. Unfortunately the extrapolation is complicated by the unknown influence of sub-threshold resonances [1] and, as a matter of fact, large uncertainties (up to 100%) still affects the nuclear inputs to stellar models.

The situation is even worst for the $^{22}Ne(\alpha,n)^{25}Mg$ reaction which has a negative Q-value ($Q = -0.473$ MeV): data with reasonable uncertainties are available down to about 800 kev [2] and at lower energies, two different data sets show discrepancies up to two orders of magnitude [2]. In this reaction too, the existence of resonances at low energy has been suggested but never confirmed and reaction rates at astrophysical energies suffer of very large uncertainties [2].

From the experimental point of view, both the cross sections can me measured detecting the emitted neutrons. The ^{13}C neutrons have energies of a few MeVs (Q-value = 2.216 MeV) and, in the Karlsrüe experiment, they have been detected with a sophisticated Stüttgart 4π ball composed of 41 BaF_2 surrounding a n/γ converter (paraffin loaded with Cd at 3%), the solid target being positioned in the centre of the converter [1]. The ^{22}Ne neutrons have lower energies and they have been detected in the Stüttgart experiments by a 4π detector based on 3He proportional counters placed inside a neutron moderator (polyethylene + paraffin) and surrounding a windowless gas target [2]. Therefore, in both the experiments, thermalized neutrons were detected and the cosmic background rate was reduced by passive and active shielding. It is interesting to note that the Authors of the most recent article [1] claim that: “ *Any further improvement of the stellar rate require an extension of the experimental data toward lo energies. Since the present technical possibilities appear to be exhausted, a reduction of the remaining uncertainty can probably only be achieved in a underground laboratory*”. As a matter of fact, the neutron background inside the Laboratori Nazionali del Gran Sasso, LNGS, is reduced of about three orders of magnitudes with respect to the surface [3] and this gives the possibility to extend the study of both the reactions, provided that a MV-accelerator is installed underground.

The Luna collaboration performed several feasibility studies taking as reference the performance of the detector used in Stüttgart (basically: detection efficiency = 50%): the counting rate expected with both the reactions is shown in *Figure 1*.

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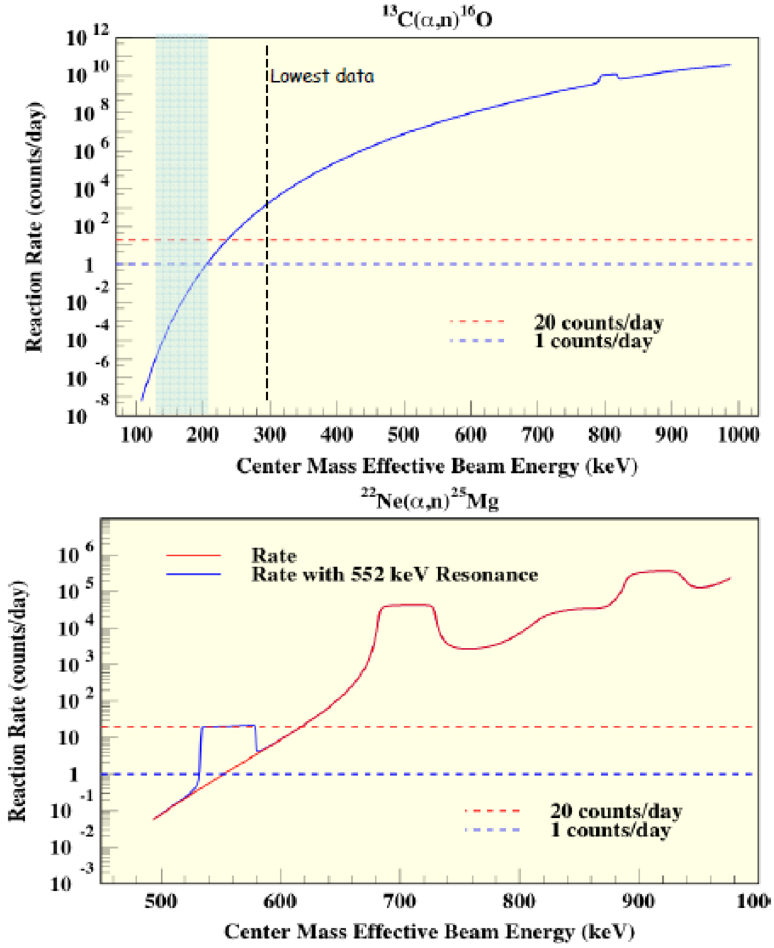

Figure 1: *expected counting rate at the MV-LUNA facility in LNGS. Experimental parameters:* $^{13}C - I_{\alpha} = 200$ *μA, target thickness: 2* 10^{17} *at/cm*^{2} *;* $^{22}Ne - I_{\alpha} = 200$ *μA, target thickness: 1* 10^{18} *at/cm*^{2}

In both the cases a new underground experiment can provide a step-forward in the understanding of the stellar processes: with $^{13}C(\alpha,n)$ the Gamow peak region could be reached avoiding the need of any further extrapolation. However, to exploit the peculiar advantages offered by the underground environment, an effort to design and build new neutron detectors with improvement performance is also required. In particular, the possibility to get information on neutron energy, for instance with the use of liquid scintillators and pulse shape discrimination techniques (e.g. [4]) should be deeply investigated.

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Stellar helium burning studied at LUNA-MV
The ^{14}N(α,γ)^{18}F, ^{15}N(α,γ)^{19}F, ^{16}O(α,γ)^{20}Ne, and ^{18}O(α,γ)^{22}Ne

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In addition to the so-called „holy grail“ of nuclear astrophysics, the ^{12}C(α,γ)^{16}O reaction discussed in the contribution by R. Menegazzo, there are a number of (α,γ) reactions contributing to stellar helium burning and to setting the stage for the weak s-process.

The reaction chain ^{14}N(α,γ)^{18}F(+)^{18}O(α,γ)^{22}Ne produces some ^{22}Ne that is necessary for the ^{22}Ne(α,n)^{25}Mg neutron source reaction. The reaction ^{15}N(α,γ)^{19}F is important because it may directly produce fluorine, an element that is found in surprising amounts in some stars. Finally, the ^{16}O(α,γ)^{20}Ne reaction essentially terminates main helium burning due to its low cross section. In massive stars, , this reaction plays an important role during the following carbon burning. This is so because the α-particles released by e.g. ^{12}C(^{12}C,α)^{20}Ne are easily captured by ^{16}O, the most abundant among the light isotopes, so that this reaction may be considered as one of the bottlenecks of the carbon-burning nuclear network.

All these reactions are taking place in stellar scenarios that are somewhat hotter than our Sun. As an illustration, the Gamow peaks for some of these reactions are plotted, as a function not of the center-of-mass energy as usual, but of the α-beam energy important for planning an accelerator. It is clear that while the existing 0.4MV LUNA accelerator is perfectly suited for the study of the ^{3}He(α,γ)^{7}Be reaction taking place in solar hydrogen burning, this is not the case for the reactions of helium burning. They necessitate a higher energy accelerator as the proposed LUNA-MV machine.

These helium-burning reactions have been studied before at the surface of the Earth, but the data did not reach the astrophysically relevant energies.

The ^{16}O(α,γ)^{20}Ne reaction has been studied in experiments at energies above 1 MeV α-beam energy [1], but the extrapolation to the relevant energy range depends on an R-matrix fits with many sharp poles. Using an intensive α-beam, an ultra-low background environment such as LUNA-MV, and an oxygen gas target (possibly depleted in ^{18}O to reduce the background) it would be possible to obtain data even below the lowest resonance at E_α = 1.1 MeV, and in addition study the cross section at higher energies to better constrain the R-matrix fit.

The ^{18}O(α,γ)^{22}Ne reaction is dominated by sharp resonances. The lowest one at E_α = 0.47 MeV has been studied before [2], but the uncertainty is large, because only one branch could be observed due to the

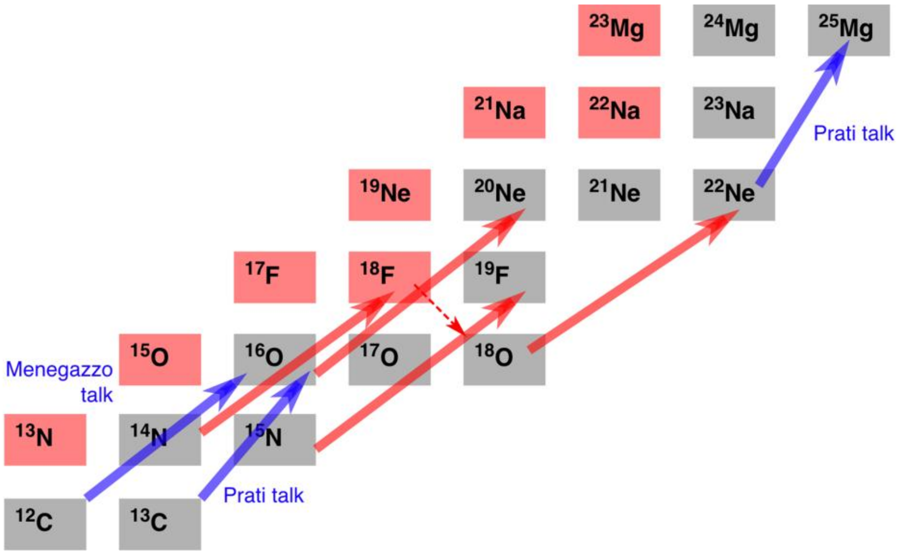

Figure: *Nuclear reactions of helium burning discussed in the present contribution (red) and in the contributions by R. Menegazzo and P. Prati (blue).*

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extremely high background. This would be a clear case for a startup measurement at LUNA-MV. Already in 24 hours of beamtime, abundant statistics and also experimental information on the hitherto unknown branching could be gained. In addition, any possible direct-capture component below the lowest resonance could be constrained.

The $^{15}N(\alpha,\gamma)^{19}F$ reaction is a very similar case, again dominated by sharp resonances. The resonance at E_α = 0.46 MeV could not be studied at the surface of the Earth [3] due to its very low predicted strength. At LUNA-MV, in principle a direct measurement with a summing detector would be possible, however this would require a lead shielding of the large summing crystal, improved pile-up rejection, and an essentially hydrogen-free beam to avoid ion beam induced background.

Summarizing, the „other“ helium-burning reactions besides the $^{12}C(\alpha,\gamma)^{16}O$ present several cases where with some research and development work very rewarding measurements can be done at the LUNA-MV facility.

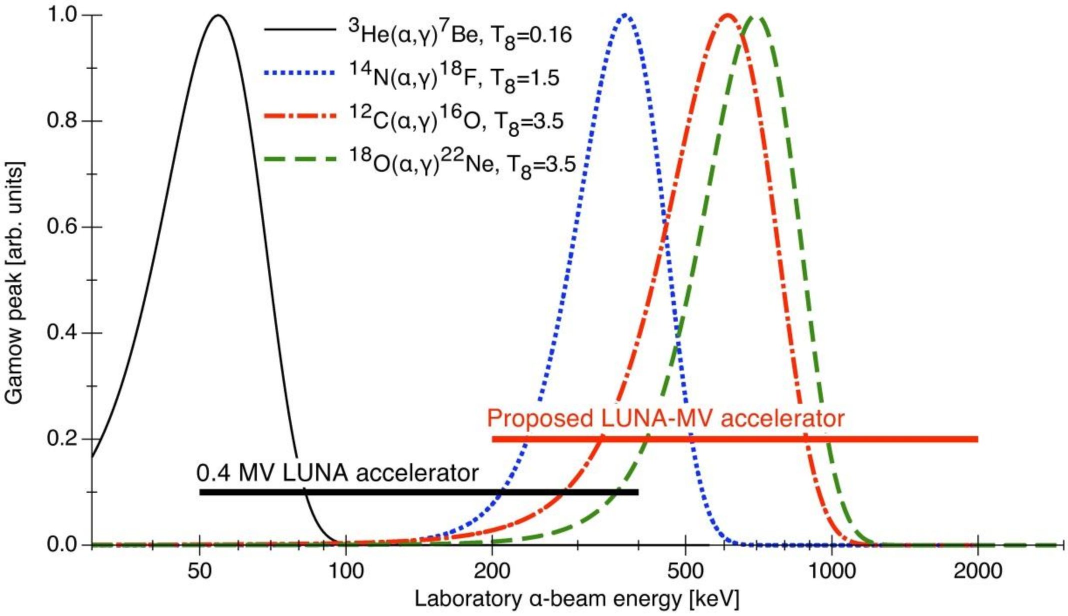

Figure: *Gamow peaks for $^3He(\alpha,\gamma)^7Be$ (T_8=0.16, Sun) and several helium burning reactions at relevant stellar temperatures. T_8 = stellar temperature in 10^8 K.*

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