Next-generation underground laboratory for Nuclear Astrophysics

Document prepared by:
M. Aliotta, L.M. Fraile, Z. Fülop, A. Guglielmetti
June, 2011

Executive summary

This document originates from discussions held at the LUNA-MV Roundtable Meeting that took place at Gran Sasso on 10-11 February 2011, as the second of a series of meetings initiated in Dresden in 2010 (Workshop on "Underground nuclear reaction experiments for astrophysics and applications" [1]).

This document serves as a call to the European Nuclear Astrophysics community for a wider collaboration in support of the next-generation underground laboratory and identifies the tasks needed to successfully accomplish the preparatory work for the installation of a multi-MV underground Nuclear Astrophysics laboratory.

In order to state your interest to contribute to any of the Work Packages (WP) presented below, please add your name, contact details, subject of expertise, and WP number under the *International Collaborators* sheet at the end of this document. A WP co-ordinator will be selected among the interested scientists in order to set the relevant milestones and deadlines. In addition, an overall coordinator/spokesperson will be identified to monitor the progress of each WP. The coordinator will also serve as liaison for scientifically related questions among different WPs and will explore funding opportunities within international programmes to support the WPs network.

The ultimate goal of this initiative will be the preparation and submission of a full proposal in support of the next-generation facility at one of the available sites.

Background

At present, LUNA is the only accelerator-based underground facility in the world specifically dedicated to Nuclear Astrophysics. Yet, its capabilities are limited and several key reactions remain beyond present means. New, upgraded facilities are thus highly needed. Based on the remarkable success of the LUNA 400 kV accelerator, and in view of the wide science programme and required long running-time per experiment, there is an opportunity for a co-ordinated effort of more than one facility. This is recognised and fully endorsed by the international community, as summarised in the recent NuPECC Long Range Plan 2010[1]: *The effort to put into operation a machine of several MV in a European deep underground laboratory should be considered with the highest priority. This could be achieved in the next three to five years with the opportunity to measure one or two key reactions within the next decade. Considering the high scientific interest in measuring several more nuclear reactions, the case could be made to complete the programme with a second facility designed for a complementary set of measurements.*

1 http://www.nupecc.org/lrp2010/Documents/lrp2010_final_hires.pdf

Current proposals for future upgrades include: LUNA-MV (Italy) [2], CUNA Canfranc (Spain) [3], and Boulby (UK) [4]. With the exclusion of the latter, for which funding in the immediate future seems highly unlikely, the other two proposals have received encouraging support from the local scientific committees and stand a good chance to come to existence in the near future. However, a wider participation that involves contributions at various levels (funding, personnel, expertise, equipment) is required from the wider community to turn the proposed projects into concrete realisation. As part of a staged approach, using a shallow-underground site at Felsenkeller Dresden/Germany is under discussion. This would encompass bringing a used accelerator to this already-existing facility, greatly speeding up progress and reducing cost. However, the background at Felsenkeller is a factor of 3-10 higher than at Gran Sasso, meaning that the most challenging measurements would still have to be done deep underground.

As for LUNA-MV (Italy), the development of a full project for the preparation of the site inside LNGS [5] (floor sealing, ventilation, power supply, …) is almost complete. The shielding of the experimental hall from the rest of the laboratory is under study. Simulations on the expected neutron fluxes have been carried out and technical solutions are being proposed. It is expected that this work will be completed by summer 2011, together with permission requests to local authorities for safety-related issues.

At Laboratorio Subterráneo de Canfranc (LSC – CUNA, Canfranc) [6] tender has been launched for pre-engineering design of the Nuclear Astrophysics cave, which should be completed by the end of 2011. Permit for excavation is expected within the next year, after which excavation work may start. Neutron measurements and simulations are under way. Funds for the accelerator are being sought in parallel. A full Letter of Intent will be presented to the LSC Scientific Committee in October 2011. Canfranc will organize and host the next edition of the "Underground nuclear reaction-experiments for astrophysics and applications" Round Table at the end of 2011 or early 2012.

Irrespective of the specific site that will be chosen, the main goal will be the installation of a single-ended MV machine coupled with a suitable ion source to accelerate light species, mostly hydrogen and alpha particles. The science cases that will be addressed are amongst the most important in Nuclear Astrophysics and will require the development of state-of-the-art techniques in every aspect of the investigation. This includes optimal ion source and accelerator performance, target production, and ad-hoc detection devices. In addition, detailed simulations as well as advanced astrophysical modelling capabilities are required. In Europe, a strong knowledge and skill base in each of these areas is available, but a coordinated action to exploit this expertise in support of a future underground facility is presently lacking. This document provides the basis to start that coordination.

The following sections present: a brief overview of the science; a list of the required work packages; and a speculative timeline for the realisation of a next-generation underground laboratory at either site.

Science cases

Key reactions to be studied:

- **^{12}C(a,g)^{16}O** is the "Holy Grail" of nuclear astrophysics.
  It plays a fundamental role in the evolution of any star during the helium-burning phase and determines the ratio between two fundamental elements: carbon and oxygen. At the typical Gamow peak energy for helium-burning, ~300 keV, the expected cross section is of the order of 10^{-17} barn and is dominated by both ground-state transitions (through E1 and E2 contributions and their interference with 1- and 2+ states) and cascade transitions. In order to obtain a reliable extrapolation at low energies, the E1 and E2 amplitudes need to be fitted separately. Existing data sets extend to a minimum energy of about 1 MeV and show systematic differences.
  At present, extrapolated S_{300} values differ by up to 100% and the calculated carbon abundance left by helium burning changes accordingly.

- **^{13}C(α,n)^{16}O** and **^{22}Ne(α,n)^{25}Mg** provide the neutron source for the s-process, responsible for the synthesis of about half of all heavy elements beyond Fe. Only few experiments have been performed to investigate these reactions and none of them was able to reach the relevant astrophysical energies. For the ^{13}C(α,n)^{16}O reaction, only energies down to 270 keV were directly studied [7], whereas the energies of astrophysical relevance are around 170-200 keV. In order to distinguish between different S-factor extrapolations, a direct measurement of the ^{13}C(α,n)^{16}O at $E_{\alpha}<270$ keV is highly desirable.
  The ^{22}Ne(α,n)^{25}Mg cross section at stellar temperatures is mainly affected by ~~a~~ resonance at Eα=828 keV. However, a contribution by another α-unbound natural-parity state at Eα=633 keV may be theoretically possible [8]. Recently, measurements below the 828 keV resonance were performed but only upper limits were obtained for the astrophysical S-factor and a new upper limit ($\omega\gamma$<60 neV) for the 633 keV resonance strength was reported [9].

- **(α,γ)** reactions on **^{14,15}N** and **^{18}O**. These reactions belong to the CNO, NeNa and MgAl cycles and are important both for main-sequence and for more evolved stars. The knowledge of the cross sections for these reactions is essential to model the nucleosynthesis of light nuclei and the subsequent evolution up to ^{56}Fe. For those nuclei for which more than one reaction channel is opened, the measurement of the branching ratios for the various reactions is extremely important.

Work packages

<u>WP1: Accelerator + ion source</u>

Requirements/Specifications: 3.5MV single-ended machine (HVEE); long-term stability; high currents; appropriate ion source.

<u>WP2: Gamma detectors</u>

Requirements: high detection efficiency; good energy resolution; large solid angle.

<u>WP3: Neutron detectors</u>

Requirements:

For the $^{13}C(\alpha,n)^{16}O$ reaction, the minimum and maximum energy of the neutrons to be detected are 2.1 and 3.0 MeV, respectively.

For the $^{22}Ne(\alpha,n)^{25}Mg$ reaction, the minimum and maximum energy of the neutrons to be detected are 40 and 450 keV, respectively.

<u>WP4: Solid targets</u>

Requirements: high purity; stability under beam bombardment; large number of atoms

<u>WP5: Gas target</u>

Requirements: high purity; good control of beam-induced heating effects; good knowledge of effective interaction energy

<u>WP6: Simulations</u>

Requirements: reaction rates; beam-induced background; detectors' response.

<u>WP7: Stellar model calculations</u>

Requirements: energy range of astrophysical relevance; knowledge of key resonances of interest; dependencies on nuclear input parameters

Timeline

Key milestones of the project include:
- Preparation/construction of experimental hall
- Installation and commissioning of accelerator and ion source

Likely order of reactions to be measured: $^{13}C(\alpha,n)^{16}O$; $^{22}Ne(\alpha,n)^{25}Mg$; $^{12}C(\alpha,\gamma)$; other (α,γ)
Future possibilities for acceleration of heavy ions will be explored.

For the **LUNA-MV project** the following timeline is envisaged:
6 months for the site preparation;
6 months for implementation of power supply, ventilation, safety systems
12 months for accelerator installation and first beam line commissioning.
For the accelerator a bid will be necessary. Estimate of the necessary time for the bid is uncertain, being very much dependent on the regulations at the time when the bid will be realized (approximately 1 year).

For the **LSC project**, the pre-engineering design of the Nuclear Astrophysics cave is currently going through tendering process. The pre-engineering should be completed by the end of 2011. Permit for excavation is expected within the following year, after which excavation work may start.
A Letter of Intent will be presented to the LSC Scientific Committee in October 2011.

The decision about the final choice of site for the next-generation facility is at present contingent to ongoing developments at each site. However, the tasks outlined in the Work

Packages are largely independent of the final choice of the site and will have to be carried out in preparation for either facility to become operational.

Please state your interest in being involved in any of the work packages listed, by providing details in the separate sheet International Collaborators and send to Alessandra Guglielmetti (alessandra.guglielmetti@mi.infn.it) by 31 July 2011.

References

[1] http://www.hzdr.de/db/Cms?pOid=31027

[2] LUNA MV – Letter of Intent (2007) LNGS-LOI 42/07 and Addendum

[3] CUNA, *A Nuclear Astrophysics facility for LSC: The sources of neutrons in the stars and other reactions of astrophysical interest*
Expression of Interest to the Canfranc Underground Laboratory, EoI-12-2009

[4] The ELENA underground project at Boulby; *Proposal for a Feasibility Study* (2009) submitted to STFC, UK

[5] http://www.lngs.infn.it/

[6] http://www.lsc.canfranc.es/

[7] M. Heil et al., Phys. Rev. C **78** (2008) 025803

[8] M. Pignatari *et al*.: Nucl. Phys. A**758** (2005) 541.

[9] M. Jaeger *et al*.: Phys. Rev. Lett. **87** (2001) 202501.

International Collaborators

If you are interested in being involved in the next-generation European underground facility for Nuclear Astrophysics, please add your name, institution, work package number(s) of interest, and relevant expertise. Then, please cut and paste this table into a separate file and send by 31 July 2011 to: **Alessandra Guglielmetti (alessandra.guglielmetti@mi.infn.it)**.

Feel free to forward the entire document to other colleagues as you think appropriate.

Name	Institution	Work Package(s)	Relevant expertise