Underground Laboratories for Nuclear Astrophysics: Present Status and Future Opportunities

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Talk’s Layout

- why underground

- highlights from LUNA
  - LUNA phase I (1992-2001)
  - LUNA phase II (2000-present)
  - LUNA phase III (2015-2018)

- future projects
  - LUNA MV (Europe)
  - CASPAR (US)
  - Felsenkeller (Europe)

- announcement
Thermonuclear Reactions in Stars

low cross sections $\rightarrow$ low yields $\rightarrow$ poor signal-to-noise ratio

Yield = $N_p \times N_t \times \text{cross section} \times \text{detection efficiency}$

10$^{14}$ pps ($\sim$100 $\mu$A q=1+) typical stable beam intensities

10$^{19}$ atoms/cm$^2$ typical solid state targets

10$^{-15}$ barn (often even smaller)

Y = 0.3-30 counts/year

$\sim$1-10% for gamma rays (HPGe detectors)
The Needle in the Haystack

- improving signal (beam currents, target densities, efficiency)
- reducing noise (i.e. background)
- a combination of both
Experimental Challenges & Key Requirements

- long term stability & high energy-accuracy
- ultra pure targets & known stoichiometry
- high detection efficiency
- wide energy ranges for reliable extrapolations
- concurrent measurements with different techniques to minimize systematic dependencies

DEDICATED (UNDERGROUND) FACILITY
Sources of $\gamma$-ray Background

- natural radioactivity (from U and Th chains and from Rn)
- cosmic rays ($\mu$ons, $^1$H, $^3$H, $^7$Be, $^14$C, …)
- neutrons from $(\alpha,n)$ reactions and fission

![typical $\gamma$-ray spectrum at surface lab](image)

- ambient
- neutron induced
- cosmic rays
“Some people are so crazy that they actually venture into deep mines to observe the stars in the sky”

*Naturalis Historia* – Pliny, 44 A.D.

Nuclei in the Cosmos I, 1990, Baden/Vienna, Austria

Gianni Fiorentini & Claus Rolfs
LUNA: Laboratory for Underground Nuclear Astrophysics

Laboratori Nazionali del Gran Sasso

1.4km rock overburden million-fold reduction in cosmic background

first (and so far only) underground accelerator in the world
γ-ray Background at LUNA

<table>
<thead>
<tr>
<th>Radiation</th>
<th>LNGS/out</th>
</tr>
</thead>
<tbody>
<tr>
<td>muons</td>
<td>$10^{-6}$</td>
</tr>
<tr>
<td>neutrons</td>
<td>$10^{-3}$</td>
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</tbody>
</table>

Counts / h/keV

E$_{\gamma}$ [keV]

LUNA underground

surface

Which reactions can (should) be studied underground?

- high Q-value radiative capture reactions
- reactions producing neutrons
- some reactions producing charged particles (see Carlo Bruno’s talk)
- reactions not limited by beam-induced background
Gran Sasso National Laboratory

LUNA 1
(1992-2001)
50 kV

investigate reactions in solar pp chain

90° analysing magnet

duoplasmatron ion source on 50kV platform

entirely built by students!
The $^3\text{He}(^3\text{He},2p)^3\text{He}$ Reaction and the Solar Neutrino Puzzle

First measurement within solar Gamow energy! No extrapolation needed; no new resonance found.

At lowest energy measured: $\sigma \sim 20$ fb $\rightarrow$ 2 counts/month

LUNA Phase II (2002-present): 400 kV accelerator

$U_{terminal} = 50 - 400$ kV

$I_{max} = 500 \mu$A (on target)

$\Delta E = 0.07$ keV

beams: $H^+$, $^4$He, ($^3$He)
LUNA 400kV site

LUNA II
400kV
(2002-present)
The $^{14}\text{N}(p,\gamma)^{15}\text{O}$ reaction

slowest reaction in CNO cycle

lowest measured $\sigma = 2.4 \times 10^{-13}$ barn

- solar neutrino flux from CNO reduced by factor 2
- age of globular cluster increased by 1 Gy!!
The $^{17}\text{O}(p,\gamma)^{18}\text{F}$ reaction

first direct measurement within Gamow region for Classical Novae

$\omega_\gamma(183\text{keV}) = 1.67 \pm 0.12 \text{ meV}$ (most precise to date)
First Direct Measurement of the $^{17}\text{O}(p, \gamma)^{18}\text{F}$ Reaction Cross Section at Gamow Energies for Classical Novae


(LUNA Collaboration)
LUNA’s Achievements to Date

- electron screening & stopping power
  \[ d(\text{^3He},p)\text{^4He} \text{ and } \text{^3He}(d,p)\text{^4He} \]

- solar fusion reactions
  \[ \text{^3He}(\text{^3He},2p)\text{^4He}, \text{^2H}(p,\gamma)\text{^3He}, \text{^3He}(\alpha,\gamma)\text{^7Be} \]

- CNO and Mg-Al cycles
  \[ ^{14}\text{N}(p,\gamma)^{15}\text{O}, \; ^{15}\text{N}(p,\gamma)^{16}\text{O}, \; ^{25}\text{Mg}(p,\gamma)^{26}\text{Al} \]

- explosive hydrogen burning in novae and AGB stars
  \[ ^{17}\text{O}(p,\gamma)^{18}\text{F}, \; ^{17}\text{O}(p,\alpha)^{14}\text{N} \]

- BBN and the lithium problem
  \[ ^{2}\text{H}(\alpha,\gamma)^{6}\text{Li} \]

over 50 publications (including 10 Letters, 2 Reviews)
20 Master Theses and 15 PhD Theses
Training Opportunities

hands-on experience on:

• ion source and accelerator systems
• beam transport and optimization
• vacuum systems
• target preparation and characterization
• detection systems and electronics
• data acquisition techniques and data analysis
• small-sized international collaboration
THE LUNA COLLABORATION (as of June 2014)

- Laboratori Nazionali del Gran Sasso, Italy
  A. Best, A. Boeltzig, A. Formicola, S. Gazzana, M. Junker, L. Leonzi
- Helmholtz-Zentrum Dresden-Rossendorf, Germany
  D. Bemmerer, M. Takacs, T. Szucs
- Università di Padova and INFN, Padova, Italy
  C. Brogolini, A. Caciolli, R. Depalo, R. Menegazzo
- INFN, Roma I, Italy
  C. Gustavino
- Institute of Nuclear Research (MTA-ATOMKI), Debrecen, Hungary
  Z. Elekes, Zs. Fülöp, Gy. Gyürky, E. Somorjai
- Osservatorio Astronomico di Collurania, Teramo, and INFN, Napoli, Italy
  O. Straniero
- Ruhr-Universität Bochum, Bochum, Germany
  F. Strieder
- Università di Genova and INFN, Genova, Italy
  F. Cavanna, P. Corvisiero, F. Ferraro, P. Prati
- Università di Milano and INFN, Milano, Italy
  A. Guglielmetti (Spokesperson), D. Trezzi
- Università di Napoli "Federico II", and INFN, Napoli, Italy
  A. Di Leva, G. Imbriani, C. Savarese
- Università di Torino and INFN, Torino, Italy
  G. Gervino
- University of Edinburgh, UK
  M. Aliotta, C. Bruno, T. Davinson, D. Scott
Current Limitations

- strong limitation on neutron production
- limited beam species (protons, alphas, $^3$He)
- limited energy range
open questions
&
future projects
\[ ^{13}\text{C}(\alpha,n)^{16}\text{O} \]

importance: s-process in AGB stars
Gamow region: 130 - 250 keV
min. measured E: 270 keV

Open Questions

Cat's Eye
$^{22}\text{Ne}(\alpha,\text{n})^{25}\text{Mg}$

Importance: weak s-process component

Gamow region: 360-690 keV

Min. measured E: 700 keV

Upper limits

$\omega \gamma < 60$ neV

Underground sensitivity assuming 50x reduction in n background

$^{12}\text{C}(\alpha,\gamma)^{16}\text{O}$

Importance: evolution of all stars

Gamow region: 300 keV

Min. measured $E$: 0.9 MeV

Open Questions
$^{12}\text{C} + ^{12}\text{C}$ fusion

importance: evolution of massive stars

Gamow region: 1 – 3 MeV

min. measured $E$: 2.1 MeV (by $\gamma$-ray spectroscopy)

extrapolations differ by 3 orders of magnitude!
LUNA MV site
LUNA MV

3.5MV single-ended machine
max 500µA on target; mostly H, $^4$He, $^{12}$C beams
Scientific Program at LUNA MV

- **Neutrino Physics**
  \[ ^3\text{He}(\alpha,\gamma)^7\text{Be} \]

- **Neutron Sources**
  \[ ^{13}\text{C}(\alpha,n)^{16}\text{O} \text{ and } ^{22}\text{Ne}(\alpha,n)^{25}\text{Mg} \]

- **Stellar Helium Burning**
  \[ ^{12}\text{C}(\alpha,\gamma)^{16}\text{O} \]

Initial phase: (5-8 years)
LUNA-MV – timescale

- **2014**: €3.5M assigned for accelerator
- **2014**: start tender process
- **2016**: OPERA dismounted and area cleared
- **2017**: site refurbishment
- **2018**: installation of accelerator
The Future of LUNA 400KV (2015-18)

- neutron sources and neutron poisons
  $^{13}\text{C}(\alpha,n)^{16}\text{O}$ (also LUNA MV), $^{22}\text{Ne}(\alpha,\gamma)^{26}\text{Mg}$

- $^{12}\text{C}/^{13}\text{C}$ abundance in H-rich envelopes of stars
  $^{12}\text{C}(p,\gamma)^{13}\text{N}$ and $^{13}\text{C}(p,\gamma)^{14}\text{N}$

- deuterium production in BBN
  $^{2}\text{H}(p,\gamma)^{3}\text{He}$

- further constraints on $^{3}\text{He}(\alpha,\gamma)^{7}\text{Be}$
  $^{6}\text{Li}(p,\gamma)^{7}\text{Be}$
Compact Accelerator Systems for Performing Astrophysical Research

Collaboration between:
University of Notre Dame
Colorado School of Mines
South Dakota School of Mines and Technology

SURF: Sanford Underground Laboratory at Homestake (4300 m.w.e.)
Proposed CASPAR configuration

- Relocation of Notre Dame 1 MV accelerator
- Effective energy range ~ 150 keV – 1 MeV
- Beam production in range of 100 – 150 µA protons and alphas
- Current plan for refurbishment and upgrade
- Re-circulating windowless gas target

Aggressive time line:
Installation complete by mid-2015
Scientific Program at CASPAR

- Neutrino Physics
  $^3\text{He}(\alpha,\gamma)^7\text{Be}$

- Neutron Sources and Neutron Poisons
  $^{22}\text{Ne}(\alpha,n)^{25}\text{Mg},\;^{22}\text{Ne}(\alpha,\gamma)^{26}\text{Mg},\;^{17}\text{O}(\alpha,n)^{20}\text{Ne},\;^{17}\text{O}(\alpha,\gamma)^{21}\text{Ne}$

- CNO neutrinos and Solar Metallicity
  $^{12}\text{C}(p,\gamma)^{13}\text{N},\;^{14}\text{N}(p,\gamma)^{15}\text{O},\;^{16}\text{O}(p,\gamma)^{17}\text{F},\;^{17}\text{O}(p,\gamma)^{18}\text{F}$

- Stellar helium burning and alpha clustering
  $^{12}\text{C}(\alpha,\gamma)^{16}\text{O},\;^{16}\text{O}(\alpha,\gamma)^{20}\text{Ne},\;^{20}\text{Ne}(\alpha,\gamma)^{24}\text{Mg}$

- From Late Stellar Evolution to Supernova
  $^{12}\text{C}(^{12}\text{C},p)^{23}\text{Na},\;^{12}\text{C}(^{12}\text{C},\alpha)^{20}\text{Ne},\;^{12}\text{C}(^{16}\text{O},\alpha)^{24}\text{Mg},\;^{12}\text{C}(^{16}\text{O},p)^{27}\text{Al},\;^{12}\text{C}(^{16}\text{O},n)^{27}\text{Si}$

- Nuclear Plasma Physics
  $^{2}\text{H}(^2\text{H},n),\;^{2}\text{H}(p,\gamma),\;^{3}\text{He}(^{3}\text{He},2p),\;^{10}\text{B}(p,\alpha),\;^{11}\text{B}(p,3\alpha),\;^{14}\text{N}(\alpha,\gamma)$
Felsenkeller

- 4 km from TU Dresden, 25 km from HZDR campus
- 47 m of rock (130 m.w.e.)
- Deepest underground $\gamma$-counting lab in Germany
- 5MV accelerator recently acquired

See Daniel Bemmerer’s talk for update on current status
Summary and Outlook

Underground measurements have led to new precision era and have revolutionized experimental nuclear astrophysics and our understanding of stellar energy generation, nucleosynthesis, and neutrino physics.

New underground facilities will open up exiting new opportunities for further major breakthrough in the field.
VIII International Conference
Nuclear Physics in Astrophysics

The University of York
The University of Edinburgh

18 – 22 May 2015,
The Royal York, York, UK
http://npa2015.iopconf.org

Organised by the Institute of Physics in conjunction with the Universities of York and Edinburgh

IOP Institute of Physics
This talk is dedicated in memoriam to Alberto Lemut, a former member of the LUNA Collaboration and dear friend of ours.

with special thanks to:
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