Underground Nuclear Astrophysics: Present and future of the LUNA experiment

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Why Nuclear astrophysics?

Nuclear reactions are responsible for the synthesis of the elements in the celestial bodies and BBN:

- Understanding the Sun
- Stellar population
- Evolution and fate of stars
- Big Bang Nucleosynthesis
- Isotopic abundances in the cosmos
- Cosmology
- Particle Physics
- Theoretical nuclear physics

For a 15 $M_{\text{Sun}}$ star:

<table>
<thead>
<tr>
<th>Reaction</th>
<th>Timescale</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hydrogen burning</td>
<td>10 million years</td>
</tr>
<tr>
<td>Helium burning</td>
<td>1 million years</td>
</tr>
<tr>
<td>Carbon burning</td>
<td>300 years</td>
</tr>
<tr>
<td>Oxygen burning</td>
<td>200 days</td>
</tr>
<tr>
<td>Silicon burning</td>
<td>2 days</td>
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</table>
Why Underground Measurements?

Very low cross sections because of the Coulomb barrier

Underground accelerator to reduce the background induced by Cosmic Rays

\[
\sigma(E) = \frac{S(E)}{E} e^{-\sqrt{\frac{E_G}{E}}}
\]
Gran Sasso National Laboratories

Background reduction with respect to Earth’s surface:

\[ \mu \sim 10^{-6} \]
\[ \gamma \sim 10^{-2}-10^{-5} \]

neutrons \( \sim 10^{-3} \)
Passive shielding is more effective underground since the $\mu$ flux, that create secondary $\gamma$s, is suppressed.
Many reactions regulating the Hydrogen burning in stars have been studied by LUNA:
- pp-chain,
- CNO cycles
- Ne-Na cycle
- Mg-Al cycle

With outstanding results related to:
- Mixing parameters of solar neutrinos
- Stellar evolution
- Age of Universe
- Isotopic abundances
- Temperature and metallicity of Sun
LUNA 50 kV

1991: Birth of **underground** Nuclear Astrophysics. Thanks to E. Bellotti, C. Rolfs and G. Fiorentini

\[ ^3\text{He}(^3\text{He},2p)^4\text{He} \quad \text{(solar } \nu) \]
\[ ^2\text{H}(p,\gamma)^3\text{He} \quad \text{(BBN)} \]

- \( E_{\text{beam}} \approx 1 - 50 \text{ keV} \)
- \( I_{\text{max}} \approx 500 \mu\text{A} \) protons, \(^3\text{He}\)
- Energy spread \( \approx 20 \text{ eV} \)
Solar Neutrinos

In the Sun, 98% of neutrinos are produced by the p-p chain.

Following the Fowler idea, a natural way to explain the observed neutrino deficit was the existence of a narrow resonance inside the $^3$He+$^3$He solar gamow peak.
\(^3\text{He}(^3\text{He},2p)^4\text{He}\) reaction

- First measurement below the Gamow peak
- 2 events/month @ \(E_{\text{cm}}=16.5\) keV \(\rightarrow s(16.5\) keV\)=20\(\pm10\) fb
- No evidence for a narrow resonance \(\rightarrow\) SSM validation
- LUNA measurement “triggered” the second generation of solar neutrino experiment (Borexino, Kamland, SNO), focused on the measurement of ν’s mixing parameters
LUNA 400 kV
Still the word’s only underground accelerator

\[ {^{14}\text{N}(p,\gamma)^{15}\text{O}} \] (CNO-I cycle)
\[ {^{3}\text{He}(^{4}\text{He,\gamma})^{7}\text{Be}} \] (Sun, BBN)
\[ {^{25}\text{Mg}(p,\gamma)^{26}\text{Al}} \] (Mg-Al Cycle)
\[ {^{15}\text{N}(p,\gamma)^{16}\text{O}} \] (CNO-II Cycle)
\[ {^{17}\text{O}(p,\gamma)^{18}\text{F}} \] (CNO-III Cycle)
\[ {^{2}\text{H}(^{4}\text{He,\gamma})^{6}\text{Li}} \] (BBN)
\[ {^{22}\text{Ne}(p,\gamma)^{23}\text{Na}} \] (Ne-Na Cycle)
\[ {^{2}\text{H}(p,\gamma)^{3}\text{He}} \] (BBN)
\[ {^{13}\text{C}(\alpha,n)^{16}\text{O}} \] (s-process)
\[ {^{12,^{13}}\text{C}(p,\gamma)^{13,^{14}}\text{N}} \] \(\left(\text{^{12}C/^{13}C ratio}\right)\)
\[ {^{22}\text{Ne}(\alpha,\gamma)^{23}\text{Na}} \] (s-process)

\[ E_{\text{beam}} \approx 50 – 400 \text{ keV} \]
\[ I_{\text{max}} \approx 300 \mu\text{A} \] protons, \(^{4}\text{He}\)

Energy spread \(\approx 70\text{ eV}\)
Hydrogen burning cycles

Sun: ~15 MK
Massive Stars: ~ 100 MK
AGB:~30-100 MK
Novae~100-400 MK

Mg-Al cycle
Ne-Na cycle
CNO-I
CNO-II
CNO-III

(p,γ)
β+

(p,α)
$^{17}\text{O}(p,\gamma)^{18}\text{F}$ and $^{17}\text{O}(p,\alpha)^{14}\text{N}$ reactions

high-intensity proton beam onto $\text{Ta}_2\text{O}_5$ targets
HPGe detector in close geometry for prompt $\gamma$-ray measurement
 targets prepared by anodization of Ta backing in $^{17}\text{O}$-enriched water

Caciolli et al. EPJA 48 (2012) 144
$^{17}\text{O}(p,\gamma)^{18}\text{F}$ and $^{17}\text{O}(p,\alpha)^{14}\text{N}$ reactions

- protective aluminized Mylar foils (2.4 µm) before each detector
- expected alpha particle energy $E \sim 200$ keV (from 70 keV resonance)
LUNA 400-Hydrogen burning

$^{17}\text{O}(p,\gamma)^{18}\text{F}$ and $^{17}\text{O}(p,\alpha)^{14}\text{N}$ reactions

First measurement within Novae Gamow window

Di Leva et al., PRC 89 (1) (2014) 015803
Scott et al., PRL 109 (20) (2012) 202501

LUNA rate is a factor of 2 higher than the rate previously adopted, compatible with the hypothesis of oxygen enriched pre-solar grains in group II produced by massive AGB stars

Bruno et al., PRL 117, 142502 (2016)
Lugaro et al., Nature Astronomy 1, 0027 (2017)
BBN is the result of the competition between the relevant nuclear processes and the expansion rate of the early universe:

\[ H^2 = \frac{8\pi}{3} G \rho \]

\[ \rho = \rho_\gamma \left(1 + \frac{7}{8} \left(\frac{4}{11}\right)^{4/3} N_{\text{eff}}\right) \]

Calculation of primordial abundances only depends on:
- Baryon density \( \Omega_b \)
- Particle Physics (\( N_{\text{eff}}, \alpha \ldots \))
- Nuclear Astrophysics, i.e. Cross sections of relevant processes at BBN energies
$^{3}\text{He}(\alpha,\gamma)^{7}\text{Be}$ reaction

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<td>$^{6}\text{Li}/^{7}\text{Li}$</td>
<td>$(1.5\pm0.3)\times10^{-5}$</td>
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-LUNA data well inside the BBN energy region
-Low uncertainty (4%)
-Simultaneous measurement of prompt and delayed $\gamma$s
-Consolidation of “Lithium Problem”
First measurement in the BBN energy region → LUNA data exclude a nuclear solution for the $^6\text{Li}$ problem...

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$D(\alpha,\gamma)^6\text{Li}$ reaction

NEW!

Anders2014 Trezzi2016
D\( (p,\gamma)^3\text{He} \) reaction

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Reduction of \( (D/H)_{\text{BBN}} \) error of a factor 3 with LUNA 50 kV

C.Gustavino  Bormio2018
The error budget of computed abundance of deuterium is mainly due to the $D(p,\gamma)^3\text{He}$ reaction measurements (9% error) NOT in agreement with recent "Ab-Initio" calculations.

(Di Valentino, C.G. et al. 2014)

Measurement goal:
- Cross section measurement at $30<E_{cm}<260$ with $\sim 3\%$ accuracy
- Differential cross section measurement at $100<E_{cm}<260$

Physics:
- Cosmology: measurement of $\Omega_b$.
- Neutrino physics: measurement of $N_{\text{eff}}$.
- Nuclear physics: comparison of data with "ab initio" predictions.
D(p,γ)³He reaction: Ω_b and N_{eff}

- BBN provides a precise estimate of Baryon density Ω_b, through the comparison of (D/H)_{BBN} and (D/H)_{obs}:

\[ \Omega_b h^2 (BBN) = 2.20 \pm 0.04 \pm 0.02 \quad \text{(Cooke2013)} \]
\[ \Omega_b h^2 (BBN) = 2.16 \pm 0.01 \pm 0.02 \]

-Dpγ data fit

-Dpγ ”ab-initio”

D/H observations

From CMB data:
\[ \Omega_b h^2 (CMB) = 2.22 \pm 0.02 \quad \text{(PLANCK2015)} \]

-Deuterium abundance also depends on the density of relativistic particles, (photons and 3 neutrinos in SM). Therefore it is a tool to constrain “dark radiation”.

Assuming literature data for the D(p,g)³He reaction:

N_{eff} (BBN) = 3.57 \pm 0.18 \quad \text{(Cooke&Pettini 2013)}
N_{eff} (CMB) = 3.36 \pm 0.34 \quad \text{(PLANCK 2013)}
N_{eff} (SM) = 3.046
D(p,γ)^3He reaction: setup

**BGO detector**

\[ E_γ = \frac{m_p^2 + m_d^2 - m_{He}^2 + 2E_γ m_d}{2(E_p + m_d^2) - p^2 \cos(θ_{cm})} \]

Proton beam → BGO detector → γ → Ge(Li) detector
Next: LUNA MV

Funded by the Italian Research Ministry as a “premium project”. First run scheduled in June 2019.

Terminal Voltage $\approx 0.2 – 3.5$ MeV
$I_{\text{max}} \approx 100-1000$ $\mu$A protons, $^4\text{He}, ^{12}\text{C}^+, ^{12}\text{C}^{++}$

Starting program:

- $^{14}\text{N}(p,\gamma)^{15}\text{O}$ (CNO I Cycle)
- $^{12}\text{C}^{+}^{12}\text{C}$ (Carbon burning)
- $^{13}\text{C}(\alpha,n)^{16}\text{O}$ (s-process)
- $^{22}\text{Ne}(\alpha,n)^{25}\text{Mg}$ (s-process)
Carbon Burning & type Ia supernovae

- Critical mass for the fate of a star
- Population of WD, novae, SN1a, SN, NS and BH.
- Duration of quiescent carbon burning
- Complex chains involving C→Si nuclei
- Affects s-process
- Strongly affects the abundance of elements
- Type 1a supernovae outcomes

\[ ^{12}C + ^{12}C \rightarrow ^{16}O + 2 \, ^{4}He \]
\[ \rightarrow ^{20}Ne + ^{4}He \]
\[ \rightarrow ^{23}Na + p^+ \]
\[ \rightarrow ^{23}Mg + n \]
\[ \rightarrow ^{24}Mg + \gamma \]
s-process

$^{13}\text{C}(\alpha,n)^{16}\text{O}$ → LUNA 400 and LUNA-MV

$^{22}\text{Ne}(\alpha,n)^{25}\text{Mg}$ → LUNA-MV
The LUNA collaboration

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