Reaction rate measurements in underground laboratories

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Laboratory Underground Nuclear Astrophysics

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11th Symposium on Nuclei in the Cosmos, Heidelberg 19-23 July 2010
• Nuclear fusion reactions in Stars: H-burning
• Why going underground?
• The LUNA experiment:
  - Main nuclear reactions studied
  - Experimental techniques and challenges
• Perspectives in underground nuclear astrophysics
produces energy for most of the life of the stars

**pp chain**

\[
p + p \rightarrow d + e^+ + \nu_e \\
p + e^- + p \rightarrow d + \nu_e
\]

\[
p + p \rightarrow d + e^+ + \nu_e
\]

\[
p + e^- + p \rightarrow d + \nu_e
\]

\[
d + p \rightarrow ^3\text{He} + \gamma
\]

\[
^3\text{He} + ^3\text{He} \rightarrow a + 2p
\]

\[
^3\text{He} + ^4\text{He} \rightarrow ^7\text{Be} + \gamma
\]

\[
^3\text{He} + p \rightarrow ^4\text{He} + e^+ + \nu
\]

\[
^7\text{Be} + e^- \rightarrow ^7\text{Li} + \gamma + \nu_e
\]

\[
^7\text{Be} + p \rightarrow ^8\text{B} + \gamma
\]

\[
^8\text{B} \rightarrow 2a + e^+ + \nu_e
\]

\[
^7\text{Li} + p \rightarrow a + a
\]

**CNO cycle**

\[
13\text{C} \rightarrow (p,\gamma) 14\text{N} \rightarrow (p,\alpha) 17\text{O} \rightarrow (p,\gamma) 18\text{F}
\]

\[
13\text{N} \rightarrow (p,\alpha) 14\text{N} \rightarrow (p,\gamma) 15\text{O} \rightarrow (p,\gamma) 17\text{F}
\]

\[
12\text{C} \rightarrow (p,\alpha) 15\text{N} \rightarrow (p,\gamma) 16\text{O} \rightarrow (p,\alpha) 18\text{O}
\]

\[
4p \rightarrow ^4\text{He} + 2e^+ + 2\nu_e + 26.73 \text{ MeV}
\]

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New precise determination of Solar $\nu$ fluxes

Nuclear cross sections have to be known with comparable precision

$\Phi_B = \Phi_B (SSM) \cdot S_{33}^{-0.43} S_{34}^{0.84} S_{17}^{1} S_{e7}^{-1} S_{pp}^{-2.7} \text{com}^{1.4} \text{opa}^{2.6} \text{dif}^{0.34} \text{lum}^{7.2}$
Reaction rate for charged particles

**Gamow energy**

<table>
<thead>
<tr>
<th>Reaction</th>
<th>Energy</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^3\text{He}(^3\text{He},2p)^4\text{He}$</td>
<td>22 keV</td>
</tr>
<tr>
<td>d($p,\gamma$)$^3\text{He}$</td>
<td>7 keV</td>
</tr>
<tr>
<td>$^{14}\text{N}(p,\gamma)^{15}\text{O}$</td>
<td>27 keV</td>
</tr>
<tr>
<td>$^{12}\text{C}(\alpha,\gamma)^{16}\text{O}$</td>
<td>300 keV</td>
</tr>
</tbody>
</table>

$$
\sigma(E) = \frac{S(E)}{E} e^{-31.29Z_pZ_t \sqrt{\frac{\mu}{E}}}
$$

$\text{pb} < \sigma < \text{nb}$

event/month $< R_{\text{lab}} <$ event/day

Extrapolation is needed!!
Cosmic ray induced background

Underground laboratory

Advantage of underground measurements for reaction with high $Q$-values:

$d(p,\gamma)^3\text{He}$, $^{14}\text{N}(p,\gamma)^{15}\text{O}$, $^{15}\text{N}(p,\gamma)^{16}\text{O}$, $^{25}\text{Mg}(p,\gamma)^{26}\text{Al}$

$\gamma$-ray spectrum with $\gamma$-rays from $^{40}\text{K}$, $^{214}\text{Bi}$, and $^{232}\text{Th}$

$10^2$-$10^3$ reduction at $E_\gamma > 4$ MeV

<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>
</tr>
</tbody>
</table>

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Passive shielding is more effective underground since the $\mu$ flux, that create secondary $\gamma$s in the shield, is suppressed.

Advantage for underground measurements also for low Q-value reactions:

$^3\text{He}(\alpha,\gamma)^7\text{Be}$, $D(\alpha,\gamma)^6\text{Li}$
Natural radioactivity background

Underground salt mine

Courtesy of M. Aliotta

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Laboratory for Underground Nuclear Astrophysics

LUNA 1
50 kV
(1992-2001)

LUNA 2
400 kV
(2000 → 2013)

LABORATORI NAZIONALI
DEL GRAN SASSO
(shielding ≡ 3800 m w.e.)
$U_{\text{max}} = 50 - 400 \text{ kV}$

$I \sim 500 \mu\text{A} \text{ for protons}$

$I \sim 250 \mu\text{A} \text{ for alphas}$

- Energy spread: 72 eV
- Total uncertainty is $\pm 300$ eV between $E_p = 100 \div 400$ keV
H-burning measurements at LUNA

**pp chain**

\[ p + p \rightarrow d + e^+ + \nu_e \] 99.75 %

\[ p + e^- + p \rightarrow d + \nu_e \] 0.25 %

\[ d + p \rightarrow ^3\text{He} + \gamma \] 86 %

\[ ^3\text{He} + ^3\text{He} \rightarrow a + 2p \] 14 %

\[ ^3\text{He} + ^4\text{He} \rightarrow ^7\text{Be} + \gamma \] 2e^{-5} %

\[ ^7\text{Be} + e^- \rightarrow ^7\text{Li} + \gamma + \nu_e \] 99.89 %

\[ ^7\text{Be} + p \rightarrow ^8\text{B} + \gamma \] 0.11 %

\[ ^7\text{Li} + p \rightarrow a + a \] 99.99 %

\[ ^8\text{B} \rightarrow 2a + e^+ + \nu_e \] 0.01 %

50 kV

**Mg-Al cycle**

\[ ^{25}\text{Mg} \rightarrow (p,\gamma) ^{26}\text{Al} \]

\[ ^{26}\text{Al} \rightarrow (p,\gamma) ^{27}\text{Si} \]

\[ ^{27}\text{Si} \rightarrow (p,\alpha) ^{24}\text{Mg} \]

\[ ^{24}\text{Mg} \rightarrow (p,\gamma) ^{25}\text{Al} \]

\[ ^{25}\text{Al} \rightarrow (p,\alpha) ^{26}\text{Mg} \]

400 kV

**CNO cycle**

\[ ^{13}\text{C} \rightarrow (p,\gamma) ^{14}\text{N} \]

\[ ^{14}\text{N} \rightarrow (p,\alpha) ^{17}\text{O} \]

\[ ^{17}\text{O} \rightarrow (p,\gamma) ^{18}\text{F} \]

\[ ^{18}\text{F} \rightarrow (p,\gamma) ^{18}\text{O} \]

\[ ^{12}\text{C} \rightarrow (p,\alpha) ^{15}\text{N} \]

\[ ^{15}\text{N} \rightarrow (p,\gamma) ^{16}\text{O} \]

\[ ^{16}\text{O} \rightarrow (p,\alpha) ^{18}\text{O} \]

\[ ^{15}\text{N} \rightarrow (p,\gamma) ^{16}\text{O} \]

See Antonio Caciolli’s poster: NIC_XI_294

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The reaction $^{14}\text{N}(p,\gamma)^{15}\text{O}$ is discussed with its energy levels and angular momentum values.

- **Slowest reaction of CNO cycle**
- **Determines rate of CNO neutrinos from the Sun**
- **Determines the age of the Globular Clusters**

**2 experimental approaches**

- **HpGe + solid target ($E_{\text{min}}=120$ keV)**
- **BGO crystal + gas target ($E_{\text{min}}=70$ keV)**

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**14N(p,γ)15O**

**BGO phase**

Spectrum at $E_b=80$ keV

Reaction Rate = $10.95 \pm 0.83$ counts/day

Background rate = $21.14 \pm 0.75$ counts/day

**HPGe phase**

Spectrum at $E_b=200$ keV

$^{14}\text{N}(p,\gamma)^{15}\text{O}$

$^{11}\text{B}(p,\gamma)^{12}\text{C}$
For a precise S-factor extrapolation, new high energy data are needed.

Both results confirm the low reaction rate:

- GC age increases of 0.7-1 Gyr
- CNO neutrino flux decreases a factor $\approx 2$
- more efficient dredge up in AGB stars

M.Marta: NIC_XI_279  
P.Bertone: NIC_XI_206

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Major nuclear source of uncertainty for $^8$B neutrino flux determination

<table>
<thead>
<tr>
<th>Reaction</th>
<th>$\Delta \Phi_B/\Delta \sigma$</th>
<th>$\Delta \Phi_B/\Phi_B$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^3$He($^3$He,2p)$^4$He</td>
<td>-0.43</td>
<td>2.1%</td>
</tr>
<tr>
<td>$^4$He(α,γ)$^7$Be</td>
<td>0.84</td>
<td>7.5%</td>
</tr>
<tr>
<td>$^7$Be(p,γ)$^8$B</td>
<td>1.00</td>
<td>3.8%</td>
</tr>
</tbody>
</table>

Large uncertainty derived from discrepancy between results obtained with prompt gamma detection and activation techniques

Main goal: high precision measurement
$^3$He($\alpha,\gamma$)$^7$Be: prompt $\gamma$ and activation

- $^3$He recirculating gas target
- HpGe detector in close geometry for online $\gamma$ detection
- Removable calorimeter cap for offline $^7$Be counting (with separated HPGe Detector)
- Si-monitor for target density measurements (beam heating effect)
- $0.3 \text{ m}^3$ Pb-Cu shield around detector
- Chamber in OFC to reduce background on the detector

Uncertainties

<table>
<thead>
<tr>
<th>Prompt- $\gamma$</th>
<th>Activation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam current</td>
<td>$^7$Be detection efficiency</td>
</tr>
<tr>
<td>Target density</td>
<td>Beam current</td>
</tr>
<tr>
<td>Detection efficiency</td>
<td>Target density</td>
</tr>
<tr>
<td>Angular distribution</td>
<td>$^7$Be backscattering</td>
</tr>
<tr>
<td>$^3$He purity</td>
<td>$^7$Be collection efficiency</td>
</tr>
<tr>
<td></td>
<td>$^7$Be distribution effects</td>
</tr>
<tr>
<td></td>
<td>478 keV branching</td>
</tr>
<tr>
<td></td>
<td>$^7$Be life time</td>
</tr>
<tr>
<td></td>
<td>$^3$He purity</td>
</tr>
</tbody>
</table>
$^3\text{He}(\alpha,\gamma)^7\text{Be}$: prompt $\gamma$ and activation

**Prompt gamma measurements**

**Activation measurements**

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no discrepancy between prompt and activation methods

decrease of uncertainty on $^8$B neutrino flux. From LUNA results:

There is a new measurement in energy region $0.65 < E < 2.5$ MeV with recoil separator (ERNA)

S-factor extrapolation would benefit from full-energy range experiment (0.1-2 MeV) to determine S-factor energy dependence at low energies

\[
\frac{\Delta \Phi_B}{\Phi_B} = 8\% \rightarrow 3\%
\]
\( ^{25}\text{Mg}(p,\gamma)^{26}\text{Al} \)

- Radioactive \(^{26}\text{Al}\) in the galaxy \(\rightarrow\) evidence that \(^{26}\text{Al}\) nucleosynthesis is still active (SN and NOVAE)

- \(^{26}\text{Mg}\) excess in meteorites \(\rightarrow\) Signature of \(^{26}\text{Mg}\) production during Hydrogen burning (AGB)

Any astrophysical scenario for \(^{26}\text{Al}\) nucleosynthesis must be concordant with both observations

\( \text{T}_{1/2}=7.2 \times 10^5 \text{ y} \quad \ll \text{galactic time scale} \)

\begin{align*}
E_R &= 304, 190 \text{ keV} \\
E_R &= 304 \text{ keV} \\
E_R &= 304, 190, 130, 93 \text{ keV}
\end{align*}

CIRCE lab. Caserta, Italy

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$^{25}\text{Mg}(p, \gamma)^{26}\text{Al}$

**HpGe phase**

**BGO phase**

<table>
<thead>
<tr>
<th>$E_R$ [keV]</th>
<th>$\omega_\gamma$ [meV]</th>
<th>$\omega_\gamma$ [meV]</th>
<th>$\omega_\gamma$ [meV]</th>
<th>$\omega_\gamma$ [meV]</th>
<th>$\omega_\gamma$ [meV]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>LUNA</td>
<td>LUNA</td>
<td>AMS</td>
<td>LUNA</td>
<td>AMS</td>
</tr>
<tr>
<td>304</td>
<td>31.2 ± 0.9</td>
<td>30.6 ± 0.8</td>
<td>1.01 ± 0.06</td>
<td>29 ± 2</td>
<td>24 ± 2</td>
</tr>
<tr>
<td>190</td>
<td>(8.6 ± 0.8)$\times 10^{-4}$</td>
<td>(9.2 ± 0.7)$\times 10^{-4}$</td>
<td>-</td>
<td>(7.1 ± 1.0)$\times 10^{-4}$</td>
<td>(1.5 ± 0.3)$\times 10^{-4}$</td>
</tr>
</tbody>
</table>

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Present and future measurements at LUNA

• $^{15}$N(p,γ)$^{16}$O: solid target with HpGe (0.12 < E < 2.5 MeV) in collaboration with ND
  solid target with BGO $E_{\text{min}}$=70 keV

• D(α,γ)$^{6}$Li: gas target with HpGe IN PROGRESS

• $^{17}$O(p,γ)$^{18}$F: IN PREPARATION

• $^{22}$Ne(p,γ)$^{23}$Na

• $^{18}$O(p,γ)$^{19}$F

• $^{23}$Na(p,γ)$^{24}$Mg

...
Perspectives

Relevant questions remain about:
energy production, time scale and nucleosynthesis

Which other reactions could benefit from an underground measurement?

He-burning reactions:
$^{12}\text{C}(\alpha,\gamma)^{16}\text{O}$  $^{14}\text{N}(\alpha,\gamma)^{18}\text{F}$  $^{15}\text{N}(\alpha,\gamma)^{19}\text{F}$  $^{18}\text{O}(\alpha,\gamma)^{22}\text{Ne}$ ...

Neutron sources:
$^{13}\text{C}(\alpha,n)^{16}\text{O}$  $^{22}\text{Ne}(\alpha,n)^{25}\text{Mg}$

Heavy Ion burning:
$^{12}\text{C} + ^{12}\text{C}$,  $^{16}\text{O} + ^{12}\text{C}$

→ Need higher energies than the one delivered by LUNA 400 kV

→ New future facilities are proposed for underground nuclear astrophysics
Proposed projects

• LUNA-Upgrade, Laboratori Nazionali del Gran Sasso, Italy

• DIANA, Homestake Mine, SD USA

• ELENA, Boulby Mine, UK

• CUNA, Canfranc Laboratorio Subterranéo de Canfranc, Spain

• Felsenkeller shallow underground laboratory, Dresden, Germany

See M. Wiescher’s talk on Friday!!
LUNA has proved that for many nuclear reactions of astrophysical importance, there is a great advantage of an underground study.

Extremely low reaction rate measurements need special effort to achieve background reduction, target stability, beam stability and intensity.

New underground facilities are foreseen in the future around the world → new challenges to improve accelerator, target and detector technologies should be faced.
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