LUNA: present status and future prospects

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Reaction Rate for charged particles

\[ \sigma(E) = \frac{S(E)}{E} \exp \left( -31.29 \cdot Z_1 \cdot Z_2 \cdot \sqrt{\frac{\mu}{E}} \right) \]

Nuclear reactions that generate energy and synthesise elements take place inside the stars in a relatively narrow energy window: the Gamow peak

Gamow Energy for H-burning reactions:
few to several tens keV

\[ \text{pbarn} < \sigma < \text{nbarn} \]
Why going in underground

Below 3 MeV the background should be reduced by using a proper shielding but still the underground is fundamental for optimal results.
- 1400 m rock overburden (≈3800 m w.e.)
  - Flux attenuation: $n \cdot 10^{-3} \text{ (CaCO}_3\text{)}$
    $\mu \cdot 10^{-6} \text{ (1/m² h)}$

- underground area 18000 m²
- support facilities on the surface
Laboratory for Underground Nuclear Astrophysics

ACCELERATOR:
→ $50 < E_p < 400$ keV
→ $I \sim 250$ mA
→ $DE = 100$ eV

Windowless gas target:
- 3 differential pumping stages
- Gas recirculation and purification system

Solid Target
H-burning at LUNA

**pp chain**

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

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

- 84.7 %
- 13.8 %

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

- 13.78 %
- 0.02 %

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

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

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

\[ ^8\text{B} \rightarrow 2\alpha + e^+ + \nu_e \]
Recent Results: d(α,γ)$^6$Li

The amount of $^6$Li predicted by BBN is about 1000 lower than the observed one in metal poor stars.

BBN predicts $^6$Li/$^7$Li = 2 * 10^{-5} much below the detected levels of about $^6$Li/$^7$Li = 5 * 10^{-2}.
Recent Results: d(α,γ)^6Li

From the new data on the $^2$H(α,γ)^6Li reaction: $^6$Li/$^7$Li = (1.5 ± 0.3) * 10^{-5}

Standard BBN production as a possible explanation for the reported $^6$Li detections is ruled out. "Non standard" physics solutions?
Recent results: $^{17}\text{O}(p,\gamma)^{18}\text{O}$

$^{17}\text{O}+p$ is very important for hydrogen burning in different stellar environments:

- Red giants
- Massive stars
- AGB
- Novae

$\omega_{\gamma}(183\text{keV}) = 1.67 \pm 0.12 \text{meV}$

new transitions observed

The new reaction rate allows to calculate abundances of $^{18}\text{O}$, $^{18}\text{F}$, $^{19}\text{F}$ and $^{15}\text{N}$ using nova models with 10% precision

upcoming results

$^{17/18}O(p,\alpha)^{14/15}N$

proton beam from LUNA 400 kV
enriched $^{17}O$ or $^{18}O$ targets
8 silicon detectors
foils of Al Mylar to stop backscattered protons low alpha particle energy
(200-250 keV for $^{17}O(p,\alpha)^{14}N$ reaction)

In AGB stars ($T=0.03-0.1$ GK)
CNO cycle takes place in H burning shell

Measured $^{17}O/^{16}O$ and $^{18}O/^{16}O$ abundances in pre-solar grain give information on AGB surface composition

Information on mixing processes if cross sections are well known
upcoming results
background reduction at LNGS
Very preliminary analysis favours a larger strength value compared with literature. If confirmed, it would have an astrophysical impact. Analysis is still ongoing.
$^{18}O(p,\alpha)^{15}N$ preliminary results

In agreement with previous data, might improve precision on resonance energy and strength.

- 95 keV resonance strength: precision about 10% (20-30% literature)
- Energy determined with 0.5 keV precision (2.2 keV literature)
- 60 keV measured with about 20% statistical uncertainty
The Neon - Sodium cycle strongly influences the abundance of Ne, Na, Mg and Al isotopes in:

- Shell hydrogen burning in Red Giant Branch and Asymptotic Giant Branch stars (Na-O anticorrelation problem)
- Explosive H burning in classical novae and type Ia supernovae
upcoming results

$^{22}\text{Ne}(p,\gamma)^{23}\text{Na}$

Three resonances observed for the first time

<table>
<thead>
<tr>
<th>E [keV]</th>
<th>Jπ</th>
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<tbody>
<tr>
<td>9211.02</td>
<td>3/2+</td>
</tr>
<tr>
<td>9171</td>
<td></td>
</tr>
<tr>
<td>9147</td>
<td></td>
</tr>
<tr>
<td>9100</td>
<td>13/2+</td>
</tr>
<tr>
<td>9113</td>
<td></td>
</tr>
<tr>
<td>9072</td>
<td></td>
</tr>
<tr>
<td>9041</td>
<td>7/2+, 9/2+</td>
</tr>
<tr>
<td>9038.7</td>
<td></td>
</tr>
<tr>
<td>9002</td>
<td>15/2+</td>
</tr>
<tr>
<td>8972</td>
<td>5/2+</td>
</tr>
<tr>
<td>8945</td>
<td>7/2-</td>
</tr>
<tr>
<td>8944</td>
<td>3/2+</td>
</tr>
<tr>
<td>8894</td>
<td></td>
</tr>
<tr>
<td>8862</td>
<td></td>
</tr>
<tr>
<td>8818</td>
<td>1/2+</td>
</tr>
<tr>
<td>8826.7</td>
<td></td>
</tr>
<tr>
<td>8797</td>
<td>9/2-</td>
</tr>
<tr>
<td>8794</td>
<td></td>
</tr>
<tr>
<td>$^{22}\text{Ne} + p$</td>
<td>Q = 8794 keV</td>
</tr>
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</table>

$^{23}\text{Na}$
upcoming results

$^{22}\text{Ne}(p,\gamma)^{23}\text{Na}$

<table>
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</thead>
<tbody>
<tr>
<td>71 ?</td>
<td>$\leq 3.2 \cdot 10^{-6}$</td>
<td>$\leq 4.2 \cdot 10^{-9}$</td>
<td>-</td>
<td>$\leq 3.4 \cdot 10^{-9}$</td>
</tr>
<tr>
<td>105 ?</td>
<td>$\leq 6.0 \cdot 10^{-7}$</td>
<td>$\leq 6.0 \cdot 10^{-7}$</td>
<td>-</td>
<td>$\leq 7.0 \cdot 10^{-9}$</td>
</tr>
<tr>
<td>156.2</td>
<td>$\leq 1.0 \cdot 10^{-6}$</td>
<td>$(6.5 \pm 1.9) \cdot 10^{-7}$</td>
<td>$(9.2 \pm 3.7) \cdot 10^{-9}$</td>
<td>$(1.5 \pm 0.1) \cdot 10^{-7}$</td>
</tr>
<tr>
<td>189.5</td>
<td>$\leq 2.6 \cdot 10^{-6}$</td>
<td>$\leq 2.6 \cdot 10^{-6}$</td>
<td>$\leq 2.6 \cdot 10^{-6}$</td>
<td>$(1.87 \pm 0.05) \cdot 10^{-6}$</td>
</tr>
<tr>
<td>215 ?</td>
<td>$\leq 1.4 \cdot 10^{-6}$</td>
<td>$\leq 1.4 \cdot 10^{-6}$</td>
<td>-</td>
<td>$\leq 2.4 \cdot 10^{-8}$</td>
</tr>
<tr>
<td>259.7</td>
<td>$\leq 2.6 \cdot 10^{-6}$</td>
<td>$\leq 2.6 \cdot 10^{-6}$</td>
<td>$\leq 1.3 \cdot 10^{-6}$</td>
<td>$(6.9 \pm 0.2) \cdot 10^{-6}$</td>
</tr>
</tbody>
</table>
ongoing:

\( ^{22}\text{Ne}(p,\gamma)^{23}\text{Na} \) - BGO phase

Goal of the BGO phase: reduce further the upper limits on resonances at 71 and 105 keV, direct capture

setup already mounted and calibrated
data taken until autumn 2015
ongoing:

$^{18}\text{O}(p,\gamma)^{19}\text{F}$ and $^{23}\text{Na}(p,\gamma)^{24}\text{Mg}$

Goal of $^{18}\text{O}(p,\gamma)^{19}\text{F}$ measurement: 95 keV resonance and DC component. BGO detector first, HPGe if feasible

Goal of $^{23}\text{Na}(p,\gamma)^{24}\text{Mg}$ measurement: 144 keV resonance and DC component.

BGO detector first. HPGe if feasible

A fully shielded setup with 15 cm lead is used
future reaction

$^{13}\text{C}(\alpha,n)^{16}\text{O}$ – neutron source (LUNA MV)

$^{12}\text{C}(p,\gamma)^{13}\text{N}$ and $^{13}\text{C}(p,\gamma)^{14}\text{N}$ – relative abundance of $^{12}\text{C}-^{13}\text{C}$ in the deepest layers of H-rich envelopes of any star

$^{2}\text{H}(p,\gamma)^{3}\text{He}$ – $^{2}\text{H}$ production in BBN (feasibility test already performed)

$^{22}\text{Ne}(\alpha,\gamma)^{26}\text{Mg}$ – competes with $^{22}\text{Ne}(\alpha,n)^{25}\text{Mg}$ neutron source (LUNA MV)

$^{6}\text{Li}(p,\gamma)^{7}\text{Be}$ – improves the knowledge of $^{3}\text{He}(\alpha,\gamma)^{7}\text{Be}$ key reaction of p-p chain (LUNA MV)
**LUNA-MV**

LUNA MV accelerator will be installed in the south part of Hall C of LNGS laboratory (OPERA location)

Provisionary dimensions of the hall: 27x11x5 m³

OPERA decommissioning started in Jan 2015. Should be finished by October 2016
LUNA-MV

Accelerator:
Intense H+, 4He+, 12C+ e 12C++ beams in the energy range: 350 keV-3.5 MeV.
One beam line with all necessary elements (magnets, pumps, valves, ...).

Total budget about 3.9 Meuro: from LUNA MV «Premium projects» (total 5.3 Meuro) of the Italian Research Ministry

Tender published last April on European official gazette. Two factories are qualified and have been officially invited to produce an offer before September 2015.

Tender assignment: 50% technical performances (beam intensity, beam quality, maintenance, additional components, ...) , 50% price

Timeline:
Contract signed by 12/2015.
Accelerator built and tested by the producing company by 11/2017.
Accelerator delivered to LNGS by 01/2018
Accelerator installed and tested at LNGS by 07/2018. Then first experiments
LUNA-MV

$^{13}\text{C}(\alpha,n)^{16}\text{O}$ and $^{22}\text{Ne}(\alpha,n)^{25}\text{Mg}$: neutron sources for the s-process (formation of heavy elements)

$^{12}\text{C}(\alpha,\gamma)^{16}\text{O}$: key reaction of Helium burning: determine C/O ratio and stellar evolution

$^{12}\text{C}(\alpha,\gamma)^{16}\text{O}$: key reaction of Helium burning: determine C/O ratio and stellar evolution

$^{12}\text{C}+^{12}\text{C}$: energy production and nucleosynthesis in Carbon burning. Global chemical evolution of the Universe

Reactions occurring at higher temperature than those belonging to Hydrogen burning or BBN
The LUNA collaboration

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Thank you!