Neutrinos and Nuclear Astrophysics at LUNA
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For the LUNA collaboration

• Nuclear Astrophysics
• The LUNA experiment
• Solar neutrinos:

\[ ^3\text{He}(^3\text{He},2p)^4\text{He} \rightarrow \text{pp chain } \nu's \]
\[ ^3\text{He}(\alpha,\gamma)^7\text{Be} \rightarrow \text{pp chain } \nu's \]
\[ ^{14}\text{N}(p,\gamma)^{15}\text{O} \rightarrow \text{CNO cycle } \nu's \]

• Big Bang Nucleosynthesis:

\[ ^3\text{He}(\alpha,\gamma)^7\text{Be} \rightarrow ^7\text{Li abundance} \]
\[ D(\alpha,\gamma)^6\text{Li} \rightarrow ^6\text{Li abundance} \]
\[ D(p,\gamma)^3\text{He} \rightarrow \text{Deuterium abundance (relic } \nu's) \]
Reaction rate for charged particles

\[ <\sigma v> = \sqrt{\frac{8}{\pi \mu}} \frac{1}{(KT)^{3/2}} \int_{0}^{\infty} \frac{S(E)}{E} \exp \left( -\frac{E}{KT} \right) \exp \left( -\sqrt{\frac{E_G}{E}} \right) dE \]

\( KT \ll \frac{Z_1 Z_2 e^2}{R_N} \Rightarrow \) tunneling probability

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

<table>
<thead>
<tr>
<th>Reaction</th>
<th>( E_0 )</th>
<th>( \sigma(E_0) ) (barn)</th>
</tr>
</thead>
<tbody>
<tr>
<td>( ^3\text{He}(^3\text{He},2p)^4\text{He} )</td>
<td>22</td>
<td>( 3 \times 10^{-12} )</td>
</tr>
<tr>
<td>( \text{D}(p,\gamma)^3\text{He} )</td>
<td>7</td>
<td>( 2 \times 10^{-9} )</td>
</tr>
</tbody>
</table>

\( \rightarrow 10^{-1}-10^2 \) events/day or even below at astrophysical energies…

\( \rightarrow \) Low background needed
Background at LNGS

Passive shielding is more effective underground since the $\mu$ flux, that create secondary $\gamma$s in the shield, is suppressed.
Underground measurements are well suited also for low Q-value reactions.
Voltage Range: 50-400 kV
Output Current: 1 mA (@ 400 kV)
Absolute Energy error: ±300 eV
Beam energy spread: <100 eV
Long term stability: 5 eV
Terminal Voltage ripple: 5 Vpp

A. Formicola et al., NIMA 527 (2004) 471.

Solar neutrinos:

$^{3}\text{He}(^{3}\text{He},2p)^{4}\text{He}$ pp chain
$^{3}\text{He}(\alpha,\gamma)^{7}\text{Be}$ pp chain
$^{14}\text{N}(p,\gamma)^{15}\text{O}$ CNO cycle

BBN:

$^{3}\text{He}(\alpha,\gamma)^{7}\text{Be} \rightarrow ^{7}\text{Li}/\text{H}$
$D(\alpha,\gamma)^{6}\text{Li} \rightarrow ^{6}\text{Li}/\text{H}$
$D(p,\gamma)^{3}\text{He} \rightarrow \text{D}/\text{H}$
Solar neutrinos

**PP chain**
- **pp I**: Low energy ν's. The rate is governed by the 
  \(^3\text{He}(^3\text{He},2p)^4\text{He}\) reaction.
- **pp II and pp III**: High energy ν's. The rate is governed by the 
  \(^3\text{He}(\alpha,\gamma)^7\text{Be}\) reaction.
- **hep**: negligible ν flux.

**CNO cycle**
- Cycle rate is governed by the slowest process, \(^{14}\text{N}(p,\gamma)^{15}\text{O}\).

The conservative way to explain the Solar neutrino deficit was the poorly known nuclear processes, instead of the more "exotic" ν oscillation solution.
Dear Professors Corvisiero and Rolfs:

I am writing to you about a historic opportunity of which I first became aware at the recent meeting on Solar Fusion Reactions at the Institute of Nuclear Theory, Washington University. At this meeting, I had the opportunity to see for the first time the results of the LUNA measurements of the important $3\overline{He} - 3\overline{He}$ reaction in a region that covers a significant part of the Gamow energy peak for solar fusion. This was a thrill that I had never believed possible. These measurements signal the most important advance in nuclear astrophysics in three decades.

- Nuclear solution excluded: “Green light” for Borexino, Kamland and SNO.
- Accurate knowledge of the solar neutrino flux: precise determination of $\sin \theta_{12}$.
- Study of the Sun interior using $\nu$’s as probe.

“The uncertainty on the predicted $^8$B neutrino flux due to $S_{34}$ is now reduced from 7.5% to 2.4% and the total uncertainty, including astrophysical parameters, goes from 12% to 10% [37]. Similarly, the uncertainty on $^7$Be predicted flux goes from 9.4% to 5.5%, being the contribution of $S_{34}$ error reduced from 8% to 2.5% [37].
BBN is the result of the competition between the relevant nuclear processes and the expansion rate of the early universe, governed by the Freidmann Equation:

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

\(H = \text{Hubble constant}\)
\(G = \text{Newton's gravitational constant}\)
\(\rho = \text{energy density (i.e. photons and neutrinos)}\)

The abundance of light isotopes ONLY depends on:
- Baryon density \(\Omega_b\) (from BBN and CMB experiments)
- Particle Physics (\(\tau_n, N_{\text{eff}}, \alpha..\))
- Nuclear Astrohetics, i.e. Cross sections of relevant processes at BBN energies

Direct observations are restricted to stable isotopes (D, \(^3\text{He}, ^4\text{He}, ^6\text{Li}, ^7\text{Li}\))

Uncertainties of direct observations:
- \(^4\text{He}: H\text{\text{II}} \text{regions, quite large systematics.}\)
- \(D: \text{QSO, Accurate measurements (% level).}\)
- \(^3\text{He}: \text{Solar System, very large systematics.}\)
- \(^7\text{Li}: \text{GC metal poor stars. (}^7\text{Li problem).}\)
- \(^6\text{Li}: \text{GC metal poor stars (controversial).}\)

BBN error budgets:
- \(^4\text{He}: \text{Almost entirely due to } \Delta \tau_n \ (1)\)
- \(D: \text{Mainly due to the } D(p,\gamma)^3\text{He reaction (3)}\)
- \(^3\text{He}: \text{Mainly due to the } ^3\text{He}(d,p)^4\text{He reaction (9)}\)
- \(^6\text{Li}: \text{Mainly due } D(\alpha,\gamma)^6\text{Li reaction (13)}\)
- \(^7\text{Li}: \text{Many reactions of the BBN network}\)
$D(\alpha,\gamma)^6\text{Li}$: The $^6\text{Li}/\text{H}$ abundance

First $D(\alpha,\gamma)^6\text{Li}$ cross section measurement at BBN energies

$S_{24}(134 \text{ keV }) = (4.0 \pm 0.8^{(\text{stat})} \pm 0.5^{(\text{syst})}) \times 10^{-6} \text{ keV b}$

$S_{24}(94 \text{ keV }) = (2.7 \pm 1.5^{(\text{stat})} \pm 0.3^{(\text{syst})}) \times 10^{-6} \text{ keV b}$

$^{6}\text{Li}/\text{H} = (0.74 \pm 16) \times 10^{-14}$

$^{6}\text{Li}/^{7}\text{Li} = (1.5 \pm 0.3) \times 10^{-5}$
$D(p,\gamma)^3\text{He}$ reaction: deuterium abundance

Primordial deuterium error budget (Di Valentino et al. 2014)

<table>
<thead>
<tr>
<th>Reaction</th>
<th>Rate Symbol</th>
<th>Symbol</th>
<th>$\sigma_{2H/H} \cdot 10^5$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$p(n, \gamma)^2\text{H}$</td>
<td>$R_1$</td>
<td>$\pm 0.002$</td>
<td></td>
</tr>
<tr>
<td>$d(p, \gamma)^3\text{He}$</td>
<td>$R_2$</td>
<td>$\pm 0.062$</td>
<td></td>
</tr>
<tr>
<td>$d(d, n)^3\text{He}$</td>
<td>$R_3$</td>
<td>$\pm 0.020$</td>
<td></td>
</tr>
<tr>
<td>$d(d, p)^3\text{H}$</td>
<td>$R_4$</td>
<td>$\pm 0.013$</td>
<td></td>
</tr>
</tbody>
</table>

Physics:
1) **Cosmology**: measurement of $\Omega_b$.
2) **Particle physics**: measurement of $N_{\text{eff}}$.
3) **Nuclear physics**: comparison of data with “ab initio” predictions.
**D(\(p,\gamma\))^{3}\text{He}** reaction: Physics

1) **Cosmology**: The deuterium abundance is very sensitive to the cosmic baryon density \(\Omega_b\). Assuming **Standard Model** \((N_{\text{eff}}=3)\):

\[
100\Omega_b h^2 (\text{CMB}) = 2.20 \pm 0.03 \text{ (PLANCK2013)}
\]

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

2) **Particle physics**: The deuterium abundance is also sensitive to the number of neutrino families. With the present \(^{2}\text{H}(p,\gamma)^{3}\text{He}\) data at BBN energies we have:

\[
N_{\text{eff}} (\text{CMB}) = 3.36 \pm 0.34 \text{ (PLANCK 2013)}
\]

\[
N_{\text{eff}} (\text{BBN}) = 3.57 \pm 0.18 \text{ (COOKE\&PETTINI 2013)}
\]

\[
N_{\text{eff}} (\text{SM}) = 3.046
\]

3) **Nuclear Physics**: Present \(S_{12}\) data differ from “ab initio” predictions of about 30%.
\[ D(p,\gamma)^3\text{He} \]  

*Good agreement between CMB and BBN results, suggesting the presence of “dark radiation”.*

*The poorly known cross-section of the \(^2\text{H}(p,\gamma)^3\text{He}\) reaction at BBN energies represents the most important obstacle to improve the constraints on the existence of “dark radiation”.*
**D(p,γ)^3He reaction: Possible Setup**

**Experimental goals:**
- Measurement of the Total cross section in wide energy range: 40<E_{lab}(keV)<400
- Good accuracy, with systematics at the 3% level.
- Measurement of the differential cross section at several energies.
**D(p,γ)³He reaction: Possible Setup**

Doppler effect and high resolution Germanium detector to extract the angular distribution.

**Validation test: october 2014.**
2014: Preliminary measurements (systematics understanding and calibration definition).
2015-2016: Differential and total cross section measurement in a wide energy range.
Conclusions

-As in the past (solar neutrinos), Nuclear astrophysics is important to constrain neutrino physics.

-We presently are in the “Precision Era” of Cosmology. BBN parameters, such as $\Omega_b$, $(D/H)_p$ are known with high (and increasing) precision. The precision of abundance calculations is presently limited by the measurement accuracy at BBN energies.

-The study at low energy must be done with Underground accelerators, with present (LUNA) or future facilities (e.g. the approved LUNA-MV accelerator).

-The $^3\text{He}(\alpha,\gamma)^7\text{Be}$ LUNA measurement at BBN energies makes very unlikely a nuclear solution for the “Lithium problem”.

-Likewise, the recent measurement of the $D(\alpha,\gamma)^6\text{Li}$ rules out the possibility of a standard explication for the purported $^6\text{Li}$ problem: In fact, for the first time, the calculated abundance of $^6\text{Li}$ is based on a solid experimental footing.

-The future measurement of the $D(p,\gamma)^3\text{He}$ cross section is of crucial importance to precisely calculate the $D$ abundance and therefore to increase the BBN and CMB sensitivity to $N_{\text{eff}}$ and lepton degeneracy.