LUNA-MV and LUNA
status and next steps

Davide Trezzi
INFN & University of Milan
LUNA-MV

Nuclear Astrophysics at the LNGS

• Feb 2016: neutron shielding validated by INFN-FISME
• Mar 2016: contract between INFN and HVEE signed (LUNA-MV accelerator).
  • Jul 2016: LUNA-MV proposal
  • Dec 2016: Silver Moon (silvermoon.lngs.infn.it)
• June 2018: NIC @ LNGS

Installed in the north side of Hall B

Building construction: Sep 2017
Accelerator delivering: Jul 2018
First experiment: Jan 2019
The LUNA-MV accelerator

\[ ^1\text{H}^+ \text{ (TV: } 0.3 - 0.5 \text{ MV)}: 500 \mu\text{A} \]
\[ ^1\text{H}^+ \text{ (TV: } 0.5 - 3.5 \text{ MV)}: 1000 \mu\text{A} \]
\[ ^4\text{He}^+ \text{ (TV: } 0.3 - 0.5 \text{ MV)}: 300 \mu\text{A} \]
\[ ^4\text{He}^+ \text{ (TV: } 0.5 - 3.5 \text{ MV)}: 500 \mu\text{A} \]
\[ ^{12}\text{C}^+ \text{ (TV: } 0.3 - 0.5 \text{ MV)}: 100 \mu\text{A} \]
\[ ^{12}\text{C}^+ \text{ (TV: } 0.5 - 3.5 \text{ MV)}: 150 \mu\text{A} \]
\[ ^{12}\text{C}^{++} \text{ (TV: } 0.5 - 3.5 \text{ MV)}: 100 \mu\text{A} \]

inline Cockcroft Walton accelerator

TERMINAL VOLTAGE: 0.2 – 3.5 MV

Precision of terminal voltage reading: 350 V
Beam energy reproducibility: 0.01% TV
Beam energy stability: 0.001% TV / hrs
Beam current stability: < 5% / hrs
The LUNA-MV scientific program

- $^{13}\text{C}(\alpha,n)^{16}\text{O}$: AGB STARS AND SUPERNOVAE EXPLOSION investigate the energy range of interest were no data / a few data are presents.
- $^{14}\text{N}(p,\gamma)^{15}\text{O}$: SUN provide valuable data to reduce the error in the low energy extrapolation of the cross section.
- $^{12}\text{C}+^{12}\text{C}$: MASSIVE STARS AND UNIVERSE investigate the energy range of interest and solve disagreement in existing data.
- $^{22}\text{Ne}(\alpha,n)^{25}\text{Mg}$: AGB STARS AND SUPERNOVAE EXPLOSION investigate the 0.47 – 1.20 MeV energy range
- $^{12}\text{C}(\alpha,\gamma)^{16}\text{O}$ : MASSIVE STARS the holy grail of Nuclear Astrophysics. Investigate the low energy range where no data / a few data are presents. (not before 2023)
The $^{13}\text{C}(\alpha,n)^{16}\text{O}$ reaction

heavy elements nucleosynthesis

The $^{13}\text{C}(\alpha,n)^{16}\text{O}$ reaction takes place in thermally pulsing, low-mass, asymptotic giant branch (ABG) stars. This reaction is the “neutron source” for the s-process and the nucleosynthesis of heavy elements.

M. Heil et al., PRC 78 (2008) 025803

Measured at LUNA 400 kV in November 2017 (early?)

Analyzed in direct ($E_\alpha = 0.3 - 1.4 \text{ MeV}$) and inverse kinematics at LUNA-MV ($E_{^{13}\text{C}} = 0.9 - 4.5 \text{ MeV}$)

NO DATA AVAILABLE BELOW 300 keV

EXTRAPOLATION ERROR (factor 4)
The $^{14}\text{N}(p,\gamma)^{15}\text{O}$ reaction

Control the CNO cycle during the hydrogen burning $\rightarrow$ CNO neutrino flux.

A good reaction to be used for testing the new LUNA-MV machine

DAY ZERO EXPERIMENT
The $^{12}\text{C}+^{12}\text{C}$ reaction

Carbon burning

The fusion reaction $^{12}\text{C}+^{12}\text{C}$ is critically important in nuclear astrophysics: it regulates the energy production and nucleosynthesis of the carbon burning phase and ultimately influences the global chemical evolution of the Universe.

\[
\begin{align*}
^{12}\text{C} + ^{12}\text{C} & \rightarrow ^{16}\text{O} + 2^{4}\text{He} \\
^{12}\text{C} + ^{12}\text{C} & \rightarrow ^{20}\text{Ne} + ^{4}\text{He} \\
^{12}\text{C} + ^{12}\text{C} & \rightarrow ^{23}\text{Na} + ^{1}\text{H} \\
^{12}\text{C} + ^{12}\text{C} & \rightarrow ^{24}\text{Mg} + \gamma
\end{align*}
\]

$^{12}\text{C}^{++}$ beam must be used in order to reach the MeV energy range.

Figure 6: Modified astrophysical $S$ factor relative to the 1634 keV transition (i.e., the de-excitation of the first excited state of $^{20}\text{Ne}$ populated by the $^{12}\text{C}(^{12}\text{C},\alpha)^{20}\text{Ne}$ reaction).
LUNA 400 kV activities
past, present and future

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<th>REACTION</th>
<th>TARGET</th>
<th>DETECTOR</th>
<th>DATA TAKING</th>
<th>DATA ANALYSIS</th>
<th>PI</th>
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<tbody>
<tr>
<td>$^{18}$O(p,γ)$^{19}$F</td>
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Details presents on the new LUNA website presented during the Silver Moon event
LUNA-MV and LUNA: status and next steps

$^2\text{H}(p,\gamma)^3\text{He}$ reaction at LUNA

Big Bang Nucleosynthesis

Total amount of deuterium produced in the early Universe depends on the cosmological parameters and on the nuclear cross sections of the reactions involved (main source of uncertainty $^2\text{H}(p,\gamma)^3\text{He}$).

**BBN predictions (PLANCK+SFII)**

$^2\text{H}/\text{H} = (2.65 \pm 0.07) \times 10^{-5}$

**ASTRONOMICAL observations**

$^2\text{H}/\text{H} = (2.53 \pm 0.04) \times 10^{-5}$

**THEORETICAL calculations (MARCUCCI et al.)**

$^2\text{H}/\text{H} = (2.49 \pm 0.04) \times 10^{-5}$

L. E. Marcucci et al., PRL 116 (2016) 102501
$^2\text{H}(p,\gamma)^3\text{He}$ reaction at LUNA

PHASE I – BGO Detector

**BGO Detector**
- Weakly dependence from angular distribution
- High detector efficiency (Montecarlo tuned with $^{60}\text{Co}$, $^{88}\text{Y}$, $^{137}\text{Cs}$ and 269 keV $^{14}\text{N}(p,\gamma)^{15}\text{O}$ resonance)
- High statistics
- Accurate calorimeter calibration
- Accurate density profile
- Beam heating effect estimation
- Expected systematic uncertainty $\leq 3.0 – 3.8\%$
\( ^2 \text{H}(p,\gamma)^3 \text{He} \) reaction at LUNA

preliminary data analysis

**BGO + NaI Detector**

- Weakly dependence from angular distribution (not known \( \rightarrow \) HPGe phase)
- High detector efficiency (Montecarlo tuned with \(^{60}\text{Co}, ^{88}\text{Y}, ^{137}\text{Cs}\) and 269 keV \(^{14}\text{N}(p,\gamma)^{15}\text{O}\) resonance). New measurement accomplished but not analysed.
- High statistics
- Accurate calorimeter calibration
- Accurate density profile (preliminary analysis used approximated values)
- Beam heating effect estimation (not analysed)
- Expected systematic uncertainty \( \leq 3.0 - 3.8\% \) (5% in the plot)

CROSS SECTION HIGHER THAN LITERATURE
preliminary agreement with Marcucci et al.
$^2\text{H}(p,\gamma)^3\text{He}$ reaction at LUNA

PHASE II – HPGe Detector

HPGe + NaI Detector

- Possibility to measure the angular distribution using the peak shape analysis (Energy → $\theta$ angle)
- Accurate detector efficiency determination with different experimental methods
- High energy range (> 100/150 keV)
- Accurate calorimeter calibration
- Accurate density profile, controlled also online
- Expected systematic uncertainty ≤ 4.3%
Improved Direct Measurement of the 64.5 keV Resonance Strength in the $^{17}\text{O}(p,\alpha)^{14}\text{N}$ Reaction at LUNA

C. G. Bruno et al. (LUNA Collaboration)

**FIG. 3.** Overlay of time-normalized on-resonance $(E_p = 71.5 \text{ keV})$, off-resonance $(E_p = 65 \text{ keV})$, and natural background spectra in counts/h (lines are to guides to the eye). Also shown is the histogram (in counts/C) obtained after a bin-by-bin subtraction of the time-normalized natural background spectrum from the on-resonance one. The shaded peak corresponds to the region of interest of the alpha particles from the 64.5 keV resonance. Note the different $y$ axes.

**FIG. 4.** Ratio of the $^{17}\text{O}(p,\alpha)^{14}\text{N}$ reaction rate of the present work (solid line) and of Buckner et al. [21] (dotted line) to the $^{17}\text{O}(p,\alpha)^{14}\text{N}$ reaction rate of Iliadis [22]. Dashed and dash-dotted lines correspond to the upper and lower limits as given here and by Buckner et al., respectively.

$$\omega \gamma_{\text{LUNA}} = 8.7 \pm 1.2^{\text{stat}} \pm 0.6^{\text{syst}} \text{ neV}$$
The LUNA collaboration

- A. Boeltzig*, G.F. Ciani*, L. Di Paolo, A. Formicola, I. Kochanek, M. Junker, | INFN LNGS /*GSSI, Italy
- D. Bemmerer, M. Takacs, T. Szucs | HZDR Dresden, Germany
- C. Brogguni, A. Caciolli, R. Depalo, P. Marigo, R. Menegazzo, D. Piatti | Università di Padova and INFN Padova, Italy
- C. Gustavino | INFN Roma1, Italy
- Z. Elekes, Zs. Fülöp, Gy. Gyurky | MTA-ATOMKI Debrecen, Hungary
- M. Lugaro | Monarch University Budapest, Hungary
- O. Straniero | INAF Osservatorio Astronomico di Collurania, Teramo, Italy
- F. Cavanna, P. Corvisiero, F. Ferraro, P. Prati, S. Zavatarelli | Università di Genova and INFN Genova, Italy
- A. Guglielmetti, D. Trezzi | Università di Milano and INFN Milano, Italy
- A. Best, A. Di Leva, G. Imbriani, | Università di Napoli and INFN Napoli, Italy
- G. Gervino | Università di Torino and INFN Torino, Italy
- M. Aliotta, C. Bruno, T. Davinson | University of Edinburgh, United Kingdom