L’esperimento LUNA-MV ai Laboratori Nazionali del Gran Sasso

Francesca Cavanna
for the LUNA collaboration
Outlook

✓ Why measuring the cross section of nuclear fusion reactions powering stars

✓ Importance of going underground

✓ From LUNA to LUNA-MV: from Hydrogen burning to Helium and Carbon burning

✓ Scientific program of LUNA-MV

✓ Celebrating 25 years of LUNA: Silver Moon
Nuclear astrophysics

• Aim of nuclear astrophysics: understand nuclear reactions that shape much of the visible universe

• Nuclear fusion is the engine of stars: it produces the energy that stabilizes them against gravitational collapse and makes them shine

• Among the key parameters (chemical composition, opacity, etc.) to model stars, reactions cross sections play an important role

• The evolution of the stars is determined by fusion reactions

• They determine the origin of elements in the cosmos, stellar evolution and dynamic

• Many reactions ask for high precision data
The importance of going underground...

Sun:
\( \text{kT} = 1 \text{ keV} \)
\( \text{E}_C \approx 0.5-2 \text{ MeV} \)
\( \text{E}_0 \approx 5-30 \text{ keV} \)
for reactions of H burning

\( \text{kT \ but \ also \ E}_0 << \text{E}_C !! \)

\[
\sigma(E) = \frac{1}{E} \exp(-31.29 Z_1 Z_2 \sqrt{\mu/E}) S(E)
\]

Cross sections in the range of pb-fb at stellar energies

with typical laboratory conditions reaction rate \( R \) can be as low as few events per month
Rate and background

The rate $R$ has to be compared with background $B$

$B_{\text{beam induced}}$: reactions with impurities in the target, collimators,… secondary processes

$B_{\text{env}}$: natural radioactivity mainly from U and Th chains

$B_{\text{cosmic}}$: mainly muons

![Typical $\gamma$-ray spectrum at surface lab](image)
Background reduction – HpGe detectors - gamma

$3 \text{ MeV} < E_\gamma < 8 \text{ MeV}$

0.5 Counts/s

$E_\gamma < 3 \text{ MeV} \rightarrow$ passive shielding for environmental bck

Secondary gammas created by $\mu$ interactions are reduced

underground passive shielding is more effective!
Laboratory for Underground Nuclear Astrophysics

Radiation

- Muons: $10^{-6}$
- Neutrons: $10^{-3}$

LNGS/surface

LNGS (1400 m rock shielding $\equiv 4000$ m w.e.)
Hydrogen burning reactions

**pp chain**

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

- \(84.7\%\)
- \(13.8\%\)

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

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

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

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

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

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

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

**Ne-Na cycle**

**CNO cycle**

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

**Mg-Al cycle**

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

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

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

\[ ^{27}\text{Al} \rightarrow (\alpha,\gamma) ^{28}\text{Si} \]

\[ ^{28}\text{Si} \rightarrow (p,\alpha) ^{25}\text{Mg} \]

Francesca Cavanna

INFN2016
Big bang nucleosynthesis

1. $n \rightarrow p + e^- + \bar{\nu}$
2. $p + n \rightarrow D + \gamma$
3. $D + p \rightarrow ^3\text{He} + \gamma$
4. $D + D \rightarrow ^3\text{He} + n$
5. $D + D \rightarrow ^3\text{H} + p$
6. $^3\text{H} + D \rightarrow ^4\text{He} + n$

Viviana Mossa talk for details

7. $^3\text{H} + ^4\text{H} \rightarrow ^7\text{Li} + \gamma$
8. $^3\text{He} + n \rightarrow ^3\text{H} + p$
9. $^3\text{He} + D \rightarrow ^4\text{He} + p$
10. $^3\text{He} + ^4\text{He} \rightarrow ^7\text{Be} + \gamma$
11. $^7\text{Li} + p \rightarrow ^4\text{He} + ^4\text{He}$
12. $^7\text{Be} + n \rightarrow ^7\text{Li} + p$
13. $^4\text{He} + D \rightarrow ^6\text{Li} + \gamma$
Helium and carbon burning

In order to study reactions occurring at higher temperature than those belonging to hydrogen burning or BBN an higher energy machine is needed.
s-process nucleosynthesis

Two components were identified and connected to stellar sites:

**Main s-process** \(90 \leq A < 210\)

- TP-AGB stars 1-3 \(M_\odot\)

  - Shell H-burning
    - \(T_9 \sim 0.1\) K
    - \(10^7-10^8\) cm\(^{-3}\)
  - \(^{13}\text{C}(\alpha,n)^{16}\text{O}\)
  - He-flash
    - \(0.25 \leq T_9 \lesssim 0.4\) K
    - \(10^{10}-10^{11}\) cm\(^{-3}\)
  - \(^{22}\text{Ne}(\alpha,n)^{25}\text{Mg}\)

**Weak s-process** \(A \leq 90\)

- Massive stars > 8 \(M_\odot\)

  - Core He-burning
    - \(3-3.5 \cdot 10^8\) K
    - \(10^6\) cm\(^{-3}\)
  - \(^{22}\text{Ne}(\alpha,n)^{25}\text{Mg}\)
  - C-burning
    - \(\sim 10^9\) K
    - \(10^{11}-10^{12}\) cm\(^{-3}\)
\(^{13}\text{C}(\alpha,n)^{16}\text{O}\): state of the art

- large statistical uncertainties at low energies
- large scatter in absolute values (normalization problem)
- systematic uncertainties (unknown, inconsistently treated)
- uncertainties in detection efficiencies (experimental vs simulated)
$^{13}\text{C}(\alpha,\text{n})^{16}\text{O}$: possible configurations

**Direct Kinematics**

- energy range $E_{\text{cm}} = 210 – 300$ keV ($E_{\text{beam}} \sim 275 – 400$ keV) at LUNA-400
- energy range $E_{\text{cm}} = 240 – 1060$ keV ($E_{\text{beam}} \sim 0.3 – 1.4$ MeV) at LUNA-MV
- $^4\text{He}$ beam
- $^{13}\text{CH}_4$ gas target:
  - ✓ $P = 1$ mbar
  - ✓ $L = 10$ cm
  - $2.5 \times 10^{17}$ atoms/cm$^2$
- $^{13}\text{C}$-enriched solid target:
  - ✓ density $2 \times 10^{17} - 10^{18}$ at/cm$^2$ (evaporation / implantation on Au, Ta, sapphire)

**Inverse Kinematics**

- $^{13}\text{C}$ beam (only possible at LUNA-MV)
- $^4\text{He}$ gas target:
  - ✓ $P = 1$ mbar
  - ✓ $L = 10$ cm
  - $2.5 \times 10^{17}$ atoms/cm$^2$
- neutron energy range: $E_n = 2 – 3.5$ MeV ($E_{\text{beam}} = 0.3 – 1.4$ MeV)
$^{13}\text{C}(\alpha,n)^{16}\text{O}$: expected rate

Enriched target $^{13}\text{C}$: 99% $I_\alpha = 200 \mu\text{A}$ (direct kinematics)

<table>
<thead>
<tr>
<th>$E_{\text{lab}}$ [keV]</th>
<th>$E_{\text{cm}}$ [keV]</th>
<th>Rate [neutr/h] $N_t = 10^{18}$ at/cm$^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1200</td>
<td>918</td>
<td>$2 \times 10^5$</td>
</tr>
<tr>
<td>1000</td>
<td>764</td>
<td>$4 \times 10^6$</td>
</tr>
<tr>
<td>800</td>
<td>612</td>
<td>$2 \times 10^7$</td>
</tr>
<tr>
<td>400</td>
<td>306</td>
<td>339</td>
</tr>
<tr>
<td>375</td>
<td>287</td>
<td>103</td>
</tr>
<tr>
<td>350</td>
<td>268</td>
<td>28</td>
</tr>
<tr>
<td>300</td>
<td>229</td>
<td>1.3</td>
</tr>
<tr>
<td>275</td>
<td>210</td>
<td>0.2</td>
</tr>
<tr>
<td>250</td>
<td>191</td>
<td>0.02</td>
</tr>
</tbody>
</table>

$I_\alpha = 1 \mu\text{A}$

Lower beam current at high energy to reduce the neutron production

$\approx 1$-$2$ months
Beam time with bck $= 0$

A neutron detector with high efficiency and low intrinsic background is required!
$^{13}$C($\alpha$,n)$^{16}$O: neutron detector

- RH radius of the target chamber
- $^3$He tubes positioned in two concentric ring: $r_1$ inner radius, $r_2$ outer radius
- Polyethylene matrix
- Simulation optimized for $E_n = 2$ MeV
- 16 stainless tubes (1 inch diameter, 40 cm long, P = 10 atm)
- Efficiency @ 2 MeV about 25%
- Low intrinsic background about 0.5 counts/h/counter in the region of interest
\(22 \text{Ne}(\alpha,n)25 \text{Mg}\)

- The lowest well studied resonance at 832 keV dominates the rate (Drotleff et al. 1993)
- The influence of a possible resonance at 635 keV was ruled out based on parity (Longland et al. 2009)
- Theoretical extrapolations may be affected by other unknown low-energy resonances
- Same neutron detector as for \(^{13}\text{C}(\alpha,n)^{16}\text{O}\)
- Gas target with enriched \(^{22}\text{Ne}\) gas
- The \(22 \text{Ne}(\alpha,\gamma)26 \text{Mg}\) has been measured at LUNA 400, currently under analysis
The $^{12}\text{C} + ^{12}\text{C}$: reaction channels and state of the art

- $^{12}\text{C} + ^{12}\text{C} \rightarrow ^{24}\text{Mg} + \gamma$  \(Q = 13.93\) MeV negligible
- $^{12}\text{C} + ^{12}\text{C} \rightarrow ^{23}\text{Mg} + \text{n}$  \(Q = -2.62\) MeV endothermic for low energies (relevant \(E_{\text{CM}} > 3\) MeV)

- $^{12}\text{C} + ^{12}\text{C} \rightarrow ^{20}\text{Ne} + \alpha$  \(Q = 4.62\) MeV
- $^{12}\text{C} + ^{12}\text{C} \rightarrow ^{23}\text{Na} + \text{p}$  \(Q = 2.24\) MeV

- $^{12}\text{C} + ^{12}\text{C} \rightarrow ^{16}\text{O} + 2\alpha$  \(Q = -0.12\) MeV three particles \(\rightarrow\) reduced probability
- $^{12}\text{C} + ^{12}\text{C} \rightarrow ^{16}\text{O} + ^{8}\text{Be}$  \(Q = -0.21\) MeV higher Coulomb barrier

Coulomb barrier: \(E_C = 6.7\) MeV

Quiescent carbon burning: \(0.9\) MeV < \(E_{\text{CM}}\) < 3.4 MeV

Gamow energy 1.7-2.1 MeV for quiescent carbon burning

For explosive carbon burning ignition may occur for \(E_{\text{CM}}\) as low as 0.7 MeV
\( ^{12}\text{C} + ^{12}\text{C} \): astrophysical motivations

- \( M_{\text{up}} \): minimum stellar mass for the occurrence of hydrostatic carbon burning
  - \( M_{\text{up}} \) depends on \(^{12}\text{C} + ^{12}\text{C}\) cross section

- Influence on the ignition of type Ia supernovae
  - The existence of the resonance at 1.5 MeV would have profound consequences for the physical conditions in the SN Ia explosion (central density, degree of neutronization ...)

- Impact on nucleosynthesis in massive stars:
  - The amount of neutrons available for the s-process decreases with increasing p channel strength compared to \( \alpha \) channel
    \[ ^{22}\text{Ne}(\alpha,n)^{25}\text{Mg} \text{ suppressed compared to } ^{22}\text{Ne}(p,\gamma)^{23}\text{Na} \]

\[ ^{12}\text{C} + ^{12}\text{C} \rightarrow ^{23}\text{Na} + p \]
\[ ^{12}\text{C} + ^{12}\text{C} \rightarrow ^{20}\text{Ne} + \alpha \]
\( ^{12}\text{C} + ^{12}\text{C} : \text{measurement strategy} \)

\( ^{12}\text{C} \) target: thick (1 mm) or thin (40 \( \mu \text{g}/\text{cm}^2 \) which corresponds to 0.18 \( \mu \text{m} \)):
- Thick targets enhance counting rates and are more resistant
- Thin targets: Carbon build-up issues. Less auto-absorption for particles

\[ ^{12}\text{C} + ^{12}\text{C} \rightarrow ^{20}\text{Ne} + \alpha_i + \gamma_i \]
In particular \( E_\gamma = 1634 \text{ keV} \) first excited state

\[ ^{12}\text{C} + ^{12}\text{C} \rightarrow ^{23}\text{Na} + p_i + \gamma_i \]
In particular \( E_\gamma = 440 \text{ keV} \) first excited state

Particle yield  \rightarrow  Gamma yield

- High efficiency HPGe detector at 0° for gammas
- 4 Si detectors (100 mm\(^2\), 500 \( \mu \text{m} \) thick) for \( \alpha \) and \( p \) at \( E_{\text{CM}} > 2.5 \text{ MeV} \)
- 2\Delta E-E telescopes for \( p \) at \( E_{\text{CM}} < 2.5 \text{ MeV} \)
- Data taking: 2 years to reach 30\% uncertainty on the cross section
Current status of LUNA-MV

- Contract for the accelerator signed in March 2016 between INFN and HVEE
- Total cost: 3.5 Meuro
- July 2016: updated scientific program submitted to 3rd commission
- February-March 2017 preparation of the infrastructure in hall B

Installed in the north side of Hall B
The accelerator and neutron shielding

- \(^1\text{H}^+\) (TV: 0.3 – 0.5 MV): 500 \(\mu\text{A}\)
- \(^1\text{H}^+\) (TV: 0.5 – 3.5 MV): 1000 \(\mu\text{A}\)
- \(^4\text{He}^+\) (TV: 0.3 – 0.5 MV): 300 \(\mu\text{A}\)
- \(^4\text{He}^+\) (TV: 0.5 – 3.5 MV): 500 \(\mu\text{A}\)
- \(^{12}\text{C}^+\) (TV: 0.3 – 0.5 MV): 100 \(\mu\text{A}\)
- \(^{12}\text{C}^+\) (TV: 0.5 – 3.5 MV): 150 \(\mu\text{A}\)
- \(^{12}\text{C}^{++}\) (TV: 0.5 – 3.5 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 / h
- Beam current stability: < 5% / h

- 80 cm thick concrete shielding
- Monte Carlo simulations have been performed to predict the neutron flux outside the shielding
- Two different codes: GEANT4 & MCNP
- \(E_n = 5.6\) MeV, \(2 \times 10^3\) n/s, isotropic

\[
\Phi_n (\text{MCNP}) = 1.38 \times 10^{-7} \text{n/(cm}^2\text{s)}
\]
\[
\Phi_n (\text{GEANT4}) = 3.40 \times 10^{-7} \text{n/(cm}^2\text{s)}
\]
\[
\Phi_n (\text{LNGS}) = 3 \times 10^{-6} \text{n/(cm}^2\text{s)}
\]
# LUNA-MV Schedule

<table>
<thead>
<tr>
<th>Action</th>
<th>Date</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beginning of the clearing works in Hall B</td>
<td>February 2017</td>
</tr>
<tr>
<td>Beginning of the construction works in Hall B</td>
<td>September 2017</td>
</tr>
<tr>
<td>Beginning of the construction of the plants in the LUNA-MV building</td>
<td>December 2017</td>
</tr>
<tr>
<td>Completion of the new LUNA-MV building and plants</td>
<td>April 2018</td>
</tr>
<tr>
<td>LUNA-MV accelerator delivering at LNGS</td>
<td>May 2018</td>
</tr>
<tr>
<td>Conclusion of the commissioning phase</td>
<td>December 2018</td>
</tr>
<tr>
<td>Beginning First Experiment</td>
<td>January 2019</td>
</tr>
</tbody>
</table>
$^{14}\text{N}(p,\gamma)^{15}\text{O}$: starting measurement

- Day 0 reaction at LUNA-MV
- Already very well study at LUNA-400
  - Formicola et al. (PLB 591, 61, 2004), Imbriani et al. (EPJA 25, 455, 2005), Bemmerer et al. (NPA 779, 297, 2006), Lemut et al. (PLB 634, 483, 2006), Marta et al. (PRC 78, 022802(R), 2008)
- Solid target + HPGe detector
- At high energies (above $E_p = 270$ keV): high counting rate = short and easy measurement

**SCIENTIFIC INTEREST**

- Recently re-measured by Li et al. (PRC 93, 055806, 2016) and by Daigle et al. (PRC 94, 025803, 2016)
- Two ingredients needed to address the ‘solar abundance problem’ [Serenelli09-16]
  1. CNO neutrino flux
  2. $^{14}\text{N}(p,\gamma)^{15}\text{O}$ cross section
- Globular Clusters age estimation
Silver Moon: The first and the next 25 years of LUNA at Gran Sasso

- Underground nuclear astrophysics was born twenty five years ago in Gran Sasso, when LUNA started its activity with a 50kV accelerator, implementing the visionary idea of Enrico Bellotti, Gianni Fiorentini and Claus Rolfs
- The extremely low laboratory background has allowed for the first time the realization of nuclear physics experiments with very small count rates, down to a couple of events per month
- Today, after the first 25 years of LUNA, a new phase has started with the ambitious LUNA-MV project
- Program available at: silvermoon.lngs.infn.it

December 1st – 2nd 2016: SAVE THE DATE
LUNA collaboration

- A. Best, A. Boeltzig*, A. Formicola, G.F. Ciani*, M. Junker, I. Kochanek | INFN LNGS /*GSSI, Italy
- D. Bemmerer, M. Takacs | HZDR Dresden, Germany
- C. Broggi, A. Caciolli, R. Depalo, R. Menegazzo, D. Piatti | Università di Padova and INFN Padova, Italy
- C. Gustavino | INFN Roma1, Italy
- 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. 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

Project coordinator
Prati

LUNA Collaboration Board

RAE
Di Paolo

GLIMOS
Di Paolo

Building & Infrastructure
Di Paolo

Equipment coordinator
Junker

Civil engineering
Martella

Plants
Franciotti

DAQ & computing
Menegazzo / Caciolli

LUNA-MV Accel. Imbriani

Beam lines
Di Leva

Targets
Zavatarelli

Detectors
Junker
<table>
<thead>
<tr>
<th>Competitor</th>
<th>Bck.</th>
<th>Acceler.</th>
<th>Beam intensity</th>
<th>Program</th>
<th>Expected start</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>LUNA</td>
<td>LNGS</td>
<td>LUNA 400</td>
<td>~300 $\mu$A</td>
<td>$^{13}$C($\alpha$,$n$) et al.</td>
<td>2017</td>
<td>Solid target</td>
</tr>
<tr>
<td>JUNA</td>
<td>~ 2 OoM better</td>
<td>400 kV – ECR</td>
<td>10 mA !</td>
<td>$^{25}$Mg($p,\gamma$) $^{13}$C($\alpha$,$n$) $^{12}$C($\alpha,\gamma$)</td>
<td>Mid 2016 2019</td>
<td>Gas target + $^3$He tubes in liq. Scint.</td>
</tr>
<tr>
<td>CASPAR</td>
<td>~ LNGS</td>
<td>Old 1 MV</td>
<td>150 $\mu$A</td>
<td>$^{14}$N($p,\gamma$) ? $^{13}$C($\alpha,n$) $^{22}$Ne($\alpha,n$)</td>
<td>Mid 2016 ?</td>
<td>Gas target + $^3$He tubes</td>
</tr>
<tr>
<td>LUNA MV</td>
<td>LNGS</td>
<td>3.5 MV + ECR</td>
<td>1 mA</td>
<td>$^{14}$N($p,\gamma$) ? $^{13}$C($\alpha,n$) $^{22}$Ne($\alpha,n$) $^{12}$C + $^{12}$C</td>
<td>2019 ?</td>
<td></td>
</tr>
</tbody>
</table>
Background

![Graph showing background counts vs energy](image)

- **Counts/(h keV cm²)**
- **Energy [keV]**

Legend:
- **Underground**
- **Underground+Pb**
- **Overground**
- **Overground+Pb**