The LUNA experiment
at the Gran Sasso Laboratory

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OUTLOOK

- **LUNA**: Why going underground to measure nuclear fusion reactions in a laboratory?

- **The Sun**: p-p chain, CNO cycle and solar neutrinos

- **Nucleosynthesis at work**: $^{26}\text{Al}$

- **Hot environment**: BBN and Novae

- **The LUNA-MV project**: A big step forward
Nucleosynthesis

- H burning $\rightarrow$ He
- He burning $\rightarrow$ C, O, Ne
- C/O ... Si burning $\rightarrow$ Fe
- Explosive burning

Solar Neutrinos and element abundances in stars and BBN

$T_{\text{SUN}} = 0.015$ GK $\sim 2$ keV
$T_{\text{RGB}} = 0.1$ GK $\sim 80$ keV
$T_{\text{NOVAE}} = 0.3$ GK $\sim 140$ keV
Reaction Rate for Charged Particles

The reaction rate for charged particles can be expressed as:

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

**Astrophysical factor**

**Gamow factor**

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

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

In the Sun: \( T = 1.5 \times 10^7 \) K

\( KT = 1 \) keV << \( E_{\text{coul}} \) (0.5-2 MeV)

\( \text{pbarn} < \sigma < \text{nbarn} \)
Extrapolation risks

Extrapolation down to astrophysical energies is needed but ...

Sometimes extrapolation fails!
How to improve signal to noise ratio

The cross section varies strongly with energy

- Precise beam energy resolution
- High purity and stable targets

and it’s very small at low energies

Experimental requirements

- Setup efficiency
- Natural background (cosmic radiation, radioactive isotopes)
- Beam induced background

Direct cross section measurements feasible with reduced cosmic-ray induced background

Underground measurements
Why Going Underground?

Surface

Gran Sasso

Neutrons: $4 \times 10^{-6} \text{ cm}^{-2}\text{s}^{-1}$ with fission and $(\alpha,n)$

Muons: $1 \text{/(m}^2\cdot\text{h})$, $E > 1 \text{ TeV}$

@ LNGS
1400 m rock overburden

Flux attenuation: $n 10^{-3}$

$\mu 10^{-6}$

Underground area 18000 m$^2$

Support facilities on the surface
Laboratori Nazionali del Gran Sasso

1400 m rock overburden

Flux attenuation: \( n \times 10^{-3} \, \mu \times 10^{-6} \)

underground area 18000 m\(^2\)
support facilities on the surface

3MeV \(<\ E_\gamma\ <\ 8\)MeV:

HpGe

0.5 Counts/s

3MeV \(<\ E_\gamma\ <\ 8\)MeV:

GOING UNDERGROUND

0.0002 Counts/s
LUNA I

BEAMS = P, α
Current max = 1 mA
Voltage range = 1 - 50 kV
Beam energy spread: 20 eV
Long term stability (8 h): $10^{-4}$ eV

LUNA II

Cockcroft-Walton accelerator

BEAMS = P, α
Current max = 500 µA (protons) 250 µA (alphas)
Voltage range = 50 - 400 kV
Absolute energy error: ±300 eV
Beam energy spread < 100 eV
Long term stability (1 h): 5 eV
\[ ^3\text{He} + ^3\text{He} \rightarrow ^4\text{He} \ + \ 2\text{p} \]

* possible solution of the Solar Neutrino Problem
* cross section measured directly at Gamow energies

count rate @ lowest energy: 2 cts/month
lowest cross section: 0.02 pbarn
background < 4 \times 10^{-2} \text{ cts/d in ROI}

\[ \text{P} + \text{D} \rightarrow ^3\text{He} + \gamma \]

\[ S(0) = 5.32(8) \text{ MeVb} \]

R. Bonetti et al., PRL 82 (1999) 26

C. Casella et al., NPA 706 (2002) 203

No extrapolation needed!
**Measurements at LUNA II**

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

* Key reaction in the p-p chain for $^7\text{Be}$ and $^8\text{B}$ neutrinos in the Sun
* Fundamental for $^7\text{Li}$ in BBN
* Gamma-prompt and activation method

A. Caciolli et al., EPJA 39 (2009) 179

**A. Caciolli et al.**, EPJA 39 (2009) 179

Measured background attenuation factor for the $^3\text{He}(\alpha,\gamma)^7\text{Be}$ setup is $\sim 10^{-5}$ !!!

(i.e. 1.9 and 0.8 counts/day with $\Delta E = 20$ keV)

**Uncertainties on the Neutrino Fluxes**

$^8\text{B} \rightarrow$ from 12% to 10%

$^7\text{Be} \rightarrow$ from 9.4% to 5.5%

**S_{3,4}(0) = 0.560(17) \text{ keVb}**

F. Confortola et al., PRC 75 (2007) 065803
**CNO cycle**

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

**Bottleneck of the CN cycle studied both with solid and gas target**
- CNO neutrino fluxes reduced by a factor of 2
- Globular Cluster Age increased by 0.7 - 1.0 Gy
- Reduced uncertainties below 8%

**Link the first and second CNO cycles**
- Totally covered the Nova Gamow peak
- Reduced the S-factor by a factor of 2
- Reduction \(^{16}\text{O}\) produced by novae explosions

M. Marta et al., PRC 83(2011)045804

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

Radioactive $^{26}$Al in the Galaxy
- first results from SPI/INTEGRAL -

Map of Galactic $^{26}$Al as obtained from COMPTEL

synthesis of new elements by super-massive stars in the Cygnus constellation

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

Reactions per day (200\text{uA})
\[ \begin{array}{c|c|c}
\text{E}_{\text{CM}} (\text{keV}) & \text{E}_x (\text{keV}) & \text{J}^\Pi \\
\hline
0.5 \times 10^7 & 304 & 6610 \quad 3^- \\
1 \times 10^5 & 190 & 6496 \quad 5^+(4^+), 6280 \quad 3^+ \\
25 & 130 & 6436 \quad 4^- \\
25 & 93 & 6414 \quad 0^+, 6399 \quad 2^-, 6364 \quad 3^+ \\
58 & 37 & 6343 \quad 4^+ \\
6306 & Q & \text{Name evadeive AGB or WR stars (T_F-0.95)} \\
\end{array} \]

\( ^{25}\text{Mg} + p \quad ^{26}\text{Al} \)

isomeric state

190 keV resonance
Charge = 25 C

B. Limata et al., PRC 82 (2010) 015801
Recent activity: $^{17}\text{O}(p, \gamma)^{18}\text{F}$

$^{17}\text{O}+p$ is of paramount importance for understanding hydrogen-burning in different stellar environments:

- AGB and RGB stars
- Massive stars
- Classical novae

It is important for galactic synthesis of $^{17}\text{O}$, $^{18}\text{F}$, and predicted O isotopic ratios in presolar grains.

It affects directly the production of $^{17}\text{O}$, $^{18}\text{O}$, $^{18}\text{F}$, and $^{19}\text{F}$ in classical novae.
TARGET PREPARATION

**Ta₂O₅ targets**

17O enrichment up to 69% (with 5% ¹⁸O)

Backing treated with citric acid and cooled to 25 °C during the anodization process

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**Stoichiometry and isotopic ratio** from 151 keV ¹⁸O(p,γ)¹⁹F resonance scans, RBS and SIMS measurements

 Targets stable up to ~ 20 °C

Caciolli et al. EPJA48(2012)144
$^{17}$O($p,\gamma$)$^{18}$F: Prompt Gamma Spectroscopy

- Efficiency measured at three different distances to correct for summing effect
- Lead shielding to reduce the natural background at low $\gamma$ energies by a factor of 2
- New branchings observed

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Also measured with activation technique

$E_p = 193$ keV

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18F
S-Factor

- **S-factor measured for the First time down to 200 keV**
- **Uncertainty reduced by a factor of 4 with respect to previous works**
- **Novae Gamow Peak covered totally for the first time with experimental data**

D. Scott et al. PRL 109 (2012) 208001 Editors' Suggestion
6Li and 7Li nucleosynthesis

Unfolding primordial abundances
Observation of a set of primitive objects, born when the Universe was young, and extrapolate to zero metallicity: Fe/H, O/H, Si/H → 0

7Li abundance: observation of the absorption line at the surface of metal-poor stars in the halo of our Galaxy
6Li abundance: no direct observation. From the asymmetry of the 7Li absorption line

The Li problems

Observational Results:

\(^7\text{Li}\) abundance is 3-4 times lower than foreseen (Spite Plateau): well established \(^7\text{Li}\) problem

\(^6\text{Li}\) abundance is orders of magnitude higher than expected (Asplund 2006)

However the Second Lithium problem is debated, because convective motions on the stellar surface can give an asymmetry of the absorption line, mimicking the presence of \(^6\text{Li}\)

Uncertainty from \(^2\text{H}(\alpha,\gamma)^6\text{Li}\)
D(\(\alpha, \gamma\))\(^6\)Li REACTION

Why is it important? How much do we know about it?

- \(D(\alpha, \gamma)^6\)Li is the main reaction for \(^6\)Li production
- In BBN, this reaction occurs at energies in the range \(50 < E_{cm} < 400\) keV
- No direct measurement exists at \(E_{cm} < 650\) keV (\(E_{lab} < 1950\) keV)
- Theoretical calculations for the astrophysical S-factor differ by more than one order of magnitude

LUNA direct measurement at \(E_{cm} \leq 133\) keV
Beam Induced Background

\[(n,n'\gamma)\] REACTIONS on the surrounding materials (Pb, Ge, Cu)

\[\gamma\text{-ray background}\] in the ROI for the D\((\alpha,\gamma)\)\(^6\)Li DC transition (\(\sim 1.6\) MeV)

LNGS constraints on available **beam time and neutron production**
Spectrum from $D(\alpha,\gamma)^{6}\text{Li}$

$E_\alpha = 400\text{ keV}$, $P(D) = 0.3\text{ mbar}$, $Q = 263\text{ C}$

WELL UNDERSTOOD BEAM INDUCED BACKGROUND

M. Anders et al., EPJA 49 (2013) 28
Experimental setup

- Germanium detector close to the beam line to increase the **detection efficiency**
- Pipe to reduce the path of scattered deuterium, to **minimize** the d(d,n)³He reaction yield
- Target length optimized
- Copper removal
- **Silicon detector** to monitor the neutron production through the d(d,p)³H reaction
- Lead, Radon Box to reduce and stabilize Natural Background
- **Borated polyethylene** envelope to reduce neutron contamination
Some results

What should we observe? A single γ-ray with

$$E_\gamma = 1473.48 + E_{CM} \pm E_{DOPPLER}$$

P(D$_2$) = 0.3 mbar, Q(400) = 263 C, Q(280) = 278 C
Next measurements

- $^{17}\text{O}(p,\alpha)^{14}\text{N}$ data taking for 65 keV and 183 keV resonances (end 2013)

- $^{22}\text{Ne}(p,\gamma)^{23}\text{Na}$ setup under construction and calibration (2014)

- $^{18}\text{O}(p,\alpha)^{15}\text{N}$, $^{18}\text{O}(p,\gamma)^{19}\text{F}$, and $^{23}\text{Na}(p,\gamma)^{24}\text{Mg}$ under study
A new accelerator underground

Limits of a 400 kV accelerator

- Solar fusion reactions
- Stellar Helium and Carbon burning
- Neutron sources for astrophysical s-processes

A new, higher energy underground accelerator is needed!

Proposed solutions:

- LUNA-MV at Gran Sasso National Laboratory (Italy)
- CANFRANC (Spain)
- Felsenkeller (Germany) <-- shallow underground
- DIANA (formerly part of DUSEL) (United States)
- China
- South America
April 2007: a Letter of Intent (LoI) was presented to the LNGS Scientific Committee (SC) containing key reactions of the He burning and neutron sources for the s-process:

\[ ^{12}\text{C}(\alpha,\gamma)^{16}\text{O} \]
\[ ^{13}\text{C}(\alpha,n)^{16}\text{O} \]
\[ ^{22}\text{Ne}(\alpha,n)^{25}\text{Mg} \]

(\(\alpha,\gamma\)) REACTIONS ON \(^{14,15}\text{N}\) AND \(^{18}\text{O}\)

These reactions are relevant at higher temperatures (larger energies) than reactions belonging to the hydrogen-burning studied so far at LUNA

**Single ended 3.5 MV positive ion accelerator**
In a very low background environment such as LNGS, it is mandatory not to increase the neutron flux above its average value.

- \(^{13}\)C(\(\alpha, n\))\(^{16}\)O
  - beam intensity: 200 \(\mu\)A
  - Target: \(^{13}\)C, \(2 \times 10^{14}\) at/cm\(^2\) (99\% \(^{13}\)C enriched)
  - Beam energy (lab) \(\leq 0.8\) MeV

- \(^{22}\)Ne(\(\alpha, n\))\(^{25}\)Mg
  - beam intensity: 200 \(\mu\)A
  - Target: \(^{22}\)Ne, \(1 \times 10^{14}\) at/cm\(^2\)
  - Beam energy (lab) \(\leq 1.0\) MeV

- \(^{13}\)C(\(\alpha, n\))\(^{16}\)O from \(^{12}\)C(\(\alpha, \gamma\))\(^{16}\)O
  - beam intensity: 200 \(\mu\)A
  - Target: \(^{13}\)C, \(1 \times 10^{14}\) at/cm\(^2\) (\(^{13}\)C/\(^{12}\)C = 10\(^{-5}\))
  - Beam energy (lab) \(\leq 3.5\) MeV

- Maximum neutron production rate: 2000 n/s
- Maximum neutron energy (lab): 5.6 MeV

The estimated n-flux (Fluka & Geant 4 simulations) will increase less than 1\% of the LNGS natural flux!
Italian Research Ministry financed the LUNA-MV special project with 2.8 MEuro in 2012

**Time schedule:**

**2012 - 2013** Hall preparation, Tender for the accelerator and shielding

**2014** Beam lines R&D, Infrastructures

**2015** Accelerator installation, Beam lines construction, Detectors installation

**2016** Calibration of the apparatus and first tests of beam on target

**Location** at LNGS underground laboratory still **uncertain**!

**New funding** from 2**nd** “Progetto Premiale” **under discussion**!
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New collaborators are welcome!