Cross section measurements of fusion reactions at astrophysically relevant energies: the LUNA experiment
H burning $\rightarrow$ He
He burning $\rightarrow$ C, O, Ne
$C/O \ldots$ Si burning $\rightarrow$ Fe
explosive burning

the ambitious task of Nuclear Astrophysics is to explain the origin and relative abundance of the elements in the Universe

$M < 8 M_\odot$
star switches off
(white $\rightarrow$ black dwarf)

$M > 8 M_\odot$
star explodes
(supernova)

Solar system abundances
Globular cluster M 10

Red giant stars: 
H→He via CNO cycles in
H shell surrounding He core

Horizontal branch stars: 
He→C, O in core
H→He in shell

Main sequence stars: 
H→He via pp chains in core

Accurate nuclear physics information is crucial for understanding of stars

How do other stars produce energy?
How do they evolve?
Problem of extrapolation

\[ \sigma(E) \]

LOG SCALE

\[ E_G \]

many orders of magnitude

extrapolation needed!

\[ S(E) \]

LINEAR SCALE

extrapolation

direct measurement

low-energy tail of broad resonance

non resonant process

\[ -E_r \]

\[ 0 \]

\[ E_r \]

interaction energy E

Interaction energy E

CROSS SECTION

\[ R_{lab} = \sigma \cdot \varepsilon \cdot I_p \cdot \rho \cdot N_{av} / A \]

\[ \varepsilon \sim 10 \% \]

\[ pb < \sigma < nb \]

\[ I_p \sim mA \]

\[ \rho \sim \mu g/cm^2 \]

event/month < \( R_{lab} < \) event/day

\[ \sigma(E) = S(E) / E^{\exp(-2\eta\pi)} \]
orders of magnitude!

\[ 0.3 \text{ m}^3 \text{ Pb-Cu shield suppression}

three orders of magnitude below 2\text{MeV}

between \( E_g = 7 \) and 12\text{MeV} the bck suppression factor is 100 times

underground passive shielding is more effective since \( \mu \) flux, that create secondary \( \gamma \)'s in the shield, is suppressed

\[ \gamma \text{-ray natural background} \]
LUNA II 400kV accelerator

$U_{\text{terminal}} = 50 - 400\text{kV}$

$I_{\text{max}} = 500\mu\text{A (on target)}$

$\Delta E = 0.07\text{keV}$

Allowed beams: $\text{H}^+$, $^4\text{He}$, ($^3\text{He}$)
Key reactions measured at LUNA 50kV-400kV

**pp chain**

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

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

- 84.7 %

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

- 13.78 %

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

- 13.8 %

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

- 0.02 %

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

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

\[ ^8\text{B} \rightarrow 2\alpha + e^+ + \nu_e \]
Importance of experimental reaction rates for understanding of nucleosynthesis, energy production in stars, solar neutrino problem, theories of stellar evolution

The case of the $^{14}\text{N}(p,\gamma)^{15}\text{O}$ reaction

The rate of the energy production in the CNO cycle ($T>10^7\text{K}$ and $M>1.1M_\odot$) is governed by the $^{14}\text{N}(p,\gamma)^{15}\text{O}$ slowest reaction, a variation of its rate can influence:

- Neutrino fluxes of $\phi^{^{13}\text{N}}$ and $\phi^{^{15}\text{O}}$ depend almost linearly on $S_{14}(0)$
- Age of Globular Cluster

After LUNA measurements

- CNO neutrino flux decreases a factor $\approx 2$
- Globular Cluster age increases of $0.7-1\text{ Gyr}$

A close look on last LUNA works mainly: $^{25}\text{Mg}(p,\gamma)^{26}\text{Al}$, $D(\alpha,\gamma)^6\text{Li}$, $^{17}\text{O}(p,\gamma)^{18}\text{F}$
$^{25}\text{Mg}(p,\gamma)^{26}\text{Al} – \text{Astrophysical motivations}$

$Q = 6306 \text{ keV}$

$^{25}\text{Mg}\,+\,p \rightarrow ^{26}\text{Al}$

$\beta^+ \rightarrow \gamma$- ray 1.8 MeV

$T_{1/2} = 7.2 \times 10^5 \text{ y}$

$\ll$ galactic time scale

Evidence that $^{26}\text{Al}$ nucleosynthesis is still active (WR stars, SN and NOVAE)

Signature of $^{26}\text{Mg}$ production during the Hydrogen burning (RGB, AGB)
$^{25}\text{Mg}(p,\gamma)^{26}\text{Al}$ - HPGe spectra \[ E_R = 190 \text{ keV} \]

LUNA results fully cover the temperature range of core massive main sequence stars (Wolf-Rayet) as well as the H-burning shell of RGB and AGB stars.

**Astrophysical consequence** i.e. WR stars:

→ the expected production of $^{26}\text{Al}_{gs}$ in stellar H-burning zones is lower than previously estimated.

This implies a reduction of the estimated contribution of WR stars to the galactic production of $^{26}\text{Al}$. (O.Straniero et al. ApJ 763 (2013))
The claimed $^6$Li abundance in metal-poor stars is very large (Asplund et al. 2006) compared to BBN predictions (NACRE compilation). Possible reasons are:

- Systematics in the $^6$Li observation in the metal-poor stars
- Unknown $^6$Li sources older than the birth of the galaxy
- ...Lack of the knowledge of the $D(^4He,\gamma)^6$Li reaction.

IN FACT:

NO DIRECT MEASUREMENTS in the BBN energy region in literature (large uncertainty due to extrapolation)

INDIRECT coulomb dissociation measurements strongly depends on the theoretical assumptions, because the nuclear part is dominant.

FOR THE FIRST TIME, the $D(^4He,\gamma)^6$Li reaction has directly been studied...
Beam Induced Background and Natural Background

D+alpha ROI at $E_{\text{lab}}=400$ keV

Preliminary results ($E_{\text{lab}}=400/280$ keV)

400 keV: $T=18.2$ days; $<P>=0.306$ mbar; $Q=514$ C
280 keV: $T=20.5$ days; $<P>=0.308$ mbar; $Q=539$ C

Counting excess observed in the $E_{\text{lab}}=400$ keV RoI

Courtesy by C. Gustavino
\( \gamma \)-spectrum at resonance energy of the \(^{17}\text{O}(p,\gamma)^{18}\text{F}\) reaction
Total $^{17}\text{O}(p,\gamma)^{18}\text{F}$ reaction cross section measured between $E_{\text{cm}} \approx 200 - 370$ keV leading to a four-fold reduction in reaction rate uncertainty in novae region.

A. Di Leva et al. in preparation
The LNGS Underground Laboratory

- **LUNA MV**
  - (2012 --> ...)
  - 3.5MV

- **LUNA I**
  - (1992-2001)
  - 50 kV

- **LUNA II**
  - (2000-2014)
  - 400 kV
The LUNA MV project (Progetto Premiale, P.I. A. Guglielmetti) financial support for the first year 2.8ME

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:

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

(\(\alpha,\gamma\) 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.

Higher energy machine →
3.5 MV single ended positive ion accelerator
Summary

- Optimization of peak to background is crucial. High intensity beams, underground passive shielding
- Low energy measurements necessary to remove or reduce cross section extrapolation uncertainties
- $^{17}\text{O}(p,\alpha)^{14}\text{N}$ and $^{22}\text{Ne}(p,\gamma)^{23}\text{Na}$ cross section measurements are in progress
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- Based in L’Aquila, 20km from Gran Sasso National Laboratory
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