The LUNA experiment

Men in pits or wells sometimes see the stars....

Aristotle

- Stellar Energy+Nucleosynthesis
- H Burning (past and present) + He and C Burning
- $\sigma(E_{\text{star}})$ with $E_{\text{star}} \ll E_{\text{Coulomb}}$

$$\sigma(E) = S(E) e^{-2\pi\eta} E^{-1}$$

$$2\pi\eta = 31.29 Z_1 Z_2 \sqrt{\mu/E} \quad \mu = m_1 m_2 / (m_1+m_2), \ E \text{ in keV}$$

Reaction Rate(star) $\div \int \Phi(E) \sigma(E) \, dE$

Gamow Peak

Extrap. $\leftarrow$ Meas $\rightarrow$

Maxwell Boltzmann

Carlo Broginni
INFN-Padova

The LUNA experiment experiment
1979 proposed by A. Zichichi, 1989 MACRO experiment ON

1400 m of dolomite rock, CaMg(CO$_3$)$_2$, (~3800 m w.e.)
Surf.: 17 800 m$^2$, Vol.: 180 000 m$^3$, Ventilation: 1 vol / 3.5 hours
(Rn in air 20-80 Bq m$^{-3}$)

**Muon flux**: $1.1 \text{ m}^{-2}\text{h}^{-1}$, 6 orders of magnitude reduction

**Neutron flux, mainly from ($\alpha$,n)**: $2.92 \times 10^{-6} \text{ cm}^{-2}\text{s}^{-1}$ (0-1 keV), $0.86 \times 10^{-6} \text{ cm}^{-2}\text{s}^{-1}$ (> 1 keV), 3 orders of magnitude reduction

**Gamma rays**: only 1 order of magnitude reduction, but with thick shield about 5 orders of magnitude in the region of natural radioactivity and 4-5 orders above 3.2 MeV without any shield

**Alpha particles**: factor ~15 below 3 MeV (shielded Si detector)
Laboratory for Underground Nuclear Astrophysics: LUNA

Beam: H, He
Voltage Range: 50-400 kV
Output Current: ~1 mA
Absolute Energy error: ±300 eV
Beam energy spread: <100 eV
Long term stability (1 h): 5 eV
Terminal Voltage ripple: 5 Vpp Ge detector
Hydrogen burning in the Sun @15*10^6 degrees:

6*10^{11} kg/s H → He
+0.7% M_H → E

4H → He +2e^+ + 2\nu_e + 26.7 MeV

3^He burning in the p-p chain

No ghost resonance @ solar Gamow peak

Activation=prompt gamma
no monopole contribution to \sigma
\sigma at low energy with 4% error
The CNO Cycle

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

(p,γ)

1) "High" energy: solid target + HpGe
2) Low energy: gas target + BGO

beam energy 90 keV

\[ S_1(0)=1.57\pm0.13 \text{ keV b as reported by indirect measurements (Mukhamedzhanov et al. 2003)} \]

\[ \frac{1}{2} \nu_{\text{cno}} \text{ from the Sun} \]

\[ * \text{ Globular Cluster age +1Gy} \]

\[ * \text{ more C at the surface of AGB stars} \]

\[ \nu_{\text{cno}} = F(S_{1,14}, Z_{\text{core}}) \]

probe of the metallicity \( Z \) of the Sun core
LUNA beyond the Sun: isotope production in the hydrogen burning shell of AGB stars (~30-100 $T_6$), Nova nucleosynthesis (~100-400 $T_6$) and BBN

AGB R Sculptoris - ALMA

Nova Cigni - Hubble
\[ ^{15}\text{N}(p,g)^{16}\text{O} \quad Q=12.13 \text{ MeV} \]

\[ ^{25}\text{Mg}(p,g)^{26}\text{Al} \quad Q=6.3 \text{ MeV} \]

\[ ^{17}\text{O}(p,g)^{18}\text{F} \quad Q=5.6 \text{ MeV} \]

\[ ^{2}\text{H}(\alpha,g)^{6}\text{Li} \quad Q=1.47 \text{ MeV} \]

\[ ^{17}\text{O}(p,\alpha)^{14}\text{N} \quad Q=1.2 \text{ MeV} \]

\[ ^{22}\text{Ne}(p,g)^{23}\text{Na} \quad Q=8.8 \text{ MeV} \]

\[ ^{23}\text{Na}(p,g)^{24}\text{Mg} \quad Q=11.7 \text{ MeV} \]

\[ ^{18}\text{O}(p,g)^{19}\text{F} \quad Q=8.0 \text{ MeV} \]

\[ ^{18}\text{O}(p,\alpha)^{15}\text{N} \quad Q=4.0 \text{ MeV} \]

- First measurement of the 92 keV resonance in \[^{25}\text{Mg}(p, g)^{26}\text{Al}, \omega_{\gamma}=(2.9\pm0.6)\times10^{-10}\text{eV}\]
  Sky Map @ 1.8 MeV

- Uncertainty on \[^{16}\text{O}, ^{17}\text{O}, ^{18}\text{O}\] and \[^{19}\text{F}\] at Nova temperature less than 10% (from 40-50%)

- First measurement of \[^{2}\text{H}(\alpha,g)^{6}\text{Li}\] at the BBN energies: \[^{6}\text{Li}/^{7}\text{Li}=(1.5\pm0.3)\times10^{-5}\], no nuclear solution to the primordial \[^{6}\text{Li}\] problem
The Ne-Na Cycle

\[ ^{22}\text{Ne}(p, g)^{23}\text{Na} \quad Q=8.8 \text{ MeV} \]

Only upper limits (~μeV) on the strength of the resonances below 400 keV (factor 1000 on the reaction rate) →

Ne, Na, Mg and Al yield in AGB and Novae (up to a factor 100)
Windowless gas target with recirculation $^{22}$Ne enriched at 99.9%, effective target length: 8 cm
2 HPGe detectors at 55° (130%) and 90° (88%)
Cu+Pb (~ 30 cm) + anti-Radon shielding

- Resonances studied with a few neV strength sensitivity and 700 eV uncertainty on the energy
- 156.2, 189.5 and 259.7 keV resonances measured for the first time. Increase by a factor 10-30 of the reaction rate for T in the range 0.08-0.3 GK
- New upper limits on 71, 105 and 215 keV
- Yield measured at 291, 320 and 334 keV compatible with Direct Capture
High efficiency phase: Windowless gas target + BGO detector to study the low resonances @ 71 and 105 keV (~0.05 neV strength sensitivity) + Direct Capture

**A bridge towards LUNA-MV:**

\[ ^{13}C(\alpha,n)^{16}O \] - neutron source (LUNA-MV)

\[ ^{12}C(p,g)^{13}N \text{ and } ^{13}C(p,g)^{14}N \] - \(^{12}C/^{13}C\) in the deepest layers of H-rich envelopes of any star

\[ ^2H(p,g)^3He \] - \(^2H\) production in BBN

\[ ^{22}Ne(\alpha,g)^{26}Mg \] - competes with \(^{22}Ne(\alpha,n)^{25}Mg\) neutron source (LUNA-MV)

\[ ^6Li(p,g)^7Be \] - low energy resonance?
A new accelerator, LUNA-MV, will be installed at the north side of Hall B at LNGS (ICARUS space) during the first months of 2018.

New shielded accelerator room (80 cm concrete walls and ceiling) to suppress the produced neutrons.

In the worst case scenario $\Phi_n^{\text{mean}}$ is a factor 20 lower than laboratory $\Phi_n$ with a similar spectrum.
Inline Cockcroft Walton accelerator, terminal voltage: 0.3-3.5 MV
High current \( H^+ \) (1 mA), \(^4\text{He}^+\), \(^{12}\text{C}^+\) and \(^{12}\text{C}^{++}\) (100 e\(\mu\)A) beams in the energy range: 0.3 MeV-3.5 (7) MeV, Energy stability \(10^{-5} \times \text{TV}\) or 20 V over 1 h

Scientific program > 10 years mainly devoted to:

**Helium-Burning** (in stars: \(\sim100\ T_6, \sim10^5\ \text{gr/cm}^3\))

\(^{12}\text{C}(\alpha,\text{g})^{16}\text{O}\) one of the most important reactions of nuclear astrophysics: production of the elements heavier than \(A=16\), star evolution from He burning to the explosive phase (core collapse and thermonuclear SN) and ratio \(C/O\)

**Sources of the neutrons** responsible for the S-process: 50% of the elements beyond Iron

\(^{13}\text{C}(\alpha,\text{n})^{16}\text{O}\): isotopes with \(A\geq90\) during AGB phase of low mass stars

\(^{22}\text{Ne}(\alpha,\text{n})^{25}\text{Mg}\): isotopes with \(A<90\) during He and C burning in massive stars

**Carbon-Burning** (\(\sim500\ T_6, \sim3\cdot10^6\ \text{gr/cm}^3\))

\(^{12}\text{C}(^{12}\text{C},\alpha)^{20}\text{Ne}\), \(^{12}\text{C}(^{12}\text{C},\text{p})^{23}\text{Na}\) determine the lower stellar mass bound for the Carbon ignition

\(+ (\alpha,\text{g})\) on \(^3\text{He}\), \(^{14}\text{N}\), \(^{15}\text{N}\), \(^{18}\text{O}\)……
\( ^3\text{He} (^3\text{He,2p})^4\text{He}: \sigma \) down to 16 keV
no resonance within the solar Gamow Peak

\( ^3\text{He}(\alpha,g)^7\text{Be}: \ ^7\text{Be} \approx \text{prompt g} \) cross section measured with 4\% error

\( ^{14}\text{N}(p,g)^{15}\text{O}: \sigma \) down to 70 keV
\( \nu_{\text{cno}} \) reduced by \( \sim 2 \) with 8\% error \( \rightarrow \) Sun core metallicity
Globular cluster age increased by 0.7-1 Gy
More carbon at the surface of AGB stars

\( ^{25}\text{Mg}(p,g)^{26}\text{Al}: \) measurement of the 92 keV resonance, \( \omega \gamma = (2.9 \pm 0.6) \times 10^{-10} \) eV
Uncertainty on \( ^{16}\text{O}, ^{17}\text{O}, ^{18}\text{O} \) and \( ^{19}\text{F} \) from Novae less than 10\%

\( ^2\text{H}(\alpha,g)^6\text{Li}: \) no nuclear solution to the \( ^6\text{Li} \) problem

Future: Helium and Carbon burning with the new 3.5 MV accelerator

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