“Direct measurement of the $^2\text{H}(\alpha,\gamma)^6\text{Li}$ cross section at energies of astrophysical interest”

Alessandro Bellini
INFN Genova, Italy
LUNA Collaboration
The $^2\text{H}(\alpha,\gamma)^6\text{Li}$ Nuclear Reaction

**Introduction**

- $^6\text{Li}$ has the next-highest predicted primordial abundance after D, $^3\text{He}$, $^4\text{He}$ and $^7\text{Li}$

**Challenge:** what is the origin of observed $^6\text{Li}$ in old halo star?

- Primordial?
- Pre-galactic?
- Exotic origin?

- Primordial $^6\text{Li}$ production $\rightarrow$ $^2\text{H}(\alpha,\gamma)^6\text{Li}$

$^6\text{Li}$ has been found in non negligible quantities in very old low metallicity halo stars $\rightarrow$ unexpectedly high amount (2-3 orders of magnitude compared to available BBN network predictions - NACRE)
The $^2\text{H}(\alpha,\gamma)^6\text{Li}$ Nuclear Reaction

Status of Art

- Direct measurements: does not exist at BBN energies; only above 1 MeV (Robertson et al., 1981) and around the resonance at 711 keV (Mohr et al., 1996).

- At energy of astrophysical interest only indirect measurements using Coulomb dissociation exist (Kiener et al., 1991; Mukhamedzhanov et al., 1995; Hammache et al., 2010).

- All the estimates are still differing by more than one order of magnitude.

- Expected cross section of few pico-barns

At LUNA a direct measurement at energies of astrophysical interest is possible!

---

**S-factor of the D+α reaction as a function of the interaction energy**


---
**LUNA Underground Facility**

**@ Laboratori Nazionali del Gran Sasso**

- \( R_{\text{lab}} = \sigma I_p \varepsilon \rho N_{AV} / A \)
  - \( I_p \sim mA; \varepsilon \sim 10\%; \rho \sim \mu g/cm^2 \)
  - \( pb < \sigma < nb \)
- \( \text{events/month} < R_{\text{lab}} < \text{events/day} \)
- Low cross section condition → poor signal-to-noise ratio → improve yields or reduce background.
- **Advantages of going underground @ LNGS:**
  - Natural shielding of about 1400 m of rocks (4000 m w.e.)
  - Muon flux reduced by a factor \( 10^6 \); neutron flux reduced by a factor \( 10^3 \) (referring to the surface)
Detectors can be shielded passively with proper Pb-Cu shield as on surface, but underground passive shielding is more effective since $\mu$ and neutron fluxes, that create secondary $\gamma$'s in the shield, are suppressed. The decaying $^{222}$Rn and its daughters produce secondary $\gamma$ radiation. A popular solution of this problem is to house the detector in a box with a small overpressure of flushing nitrogen.
LUNA Underground Facility
Experimental Apparatus

- **LUNA II ACCELERATOR**
  - Installed in 2000
  - $V_{\text{MAX}} = 400$ kV
  - High beam intensity:
    - 350 $\mu$A protons
    - 300 $\mu$A $\alpha$ particles
  - High stability
  - High energy resolution
  - $\Delta E_{\text{beam}} \leq 100$ eV
LUNA Underground Facility
Experimental Apparatus

- Windowless differentially pumped gas target
- Adjustable target thickness (D₂ target, 18 cm long, pressure range 0.1 ÷ 1.2 mbar)
- Good isotopical purity
- High stability over long run periods

HpGe detector
(135% relative efficiency)
Located in close geometry (distance from target: 5mm)
Simulated total gamma efficiency in the ROI is 2.5%

Calorimeter (made of copper) for beam intensity measurement (termic power measurement)
LUNA Underground Facility
Experimental Apparatus

- Lead passive shielding
- Radon-box
- PE shielding

\[ T_{\text{meas}} = 4.8 \text{ d} \]
Beam Induced Background

- **Reactions induced by a beam**
  
  \[ \text{D}(d,n)^3\text{He} \quad \text{&} \quad \text{D}(d,p)^3\text{H} \]

- Neutron interaction with set-up (inelastic scattering) produce a γ background

- Neutron production control needed
  
  - LNGS Scientific Committee
  
  neutron production limit

  - \( \frac{10 \text{neutrons}}{\text{sec}} \)

  \( \text{e.g. 130} \mu\text{A a beam at 0.5 mbar D}_2 \text{ gas target pressure} \)

**Experimental set-up adjustments:** reduction of diffused deuterons mean free path
LUNA Underground Facility
Experimental Apparatus

\[ n_{\text{produced}} = p_{\text{produced}} \frac{\sigma_{D(d,n)^3He}}{\sigma_{D(d,p)^3H}} ; \quad p_{\text{produced}} = \frac{p_{\text{measured}}}{\eta_{Si}} \]

D(d,n)^3He & D(d,p)^3H
(cross section known with high precision)

\[ E_{\text{beam}} = 360 \text{ keV}, I_{\text{beam}} = 289 \mu A, \]
\[ P_{D2} = 0.2 \text{ mbar}, T_{\text{meas}} = 2.48 \text{ d} \]

- Si detector
- 1500 \mu m
- Al window
- Peltier cooling
$^{2}\text{H}(\alpha,\gamma)^{6}\text{Li} \rightarrow \text{ROI} \rightarrow 1580 \div 1630 \text{ keV}$

(@ 400 keV)

$^{2}\text{H}(\alpha,\gamma)^{6}\text{Li} \rightarrow Q = 1.46 \text{ Mev}$

$$E_{\gamma} = E_{cm} + Q + \Delta E_{\text{Doppler}} - \Delta E_{\text{Recoil}}$$
Data Taking

Best Experimental Conditions

- Maximum beam energy: $E_{\text{beam}} = 400$ keV ($E_{\text{cm}} = 133$ keV)
  - Signal $\propto P$
  - Beam Induced Background $\propto P^2$
  - Current limits vs $D_2$ pressure (neutron production)

- $D_2$ pressure: $P = 0.2$ mbar

- Maximum beam current ($I_{\text{beam}} = 260$ $\mu$A)

- Measurements from October 21$^{st}$ 2010 to November 1$^{st}$ 2010, 75% duty cycle $\rightarrow \sim 200$ h
Data Taking

Measured Spectra

$E_a = 400 \text{ keV}, \ I_{\text{beam}} = 260 \mu A, P_{\text{d2}} = 0.2 \text{ mbar}$

Laboratory Background
Data Taking

Measured Spectra

$^{63}\text{Cu}$ (1547 keV) $^{2}\text{H}(\alpha,\gamma)^{6}\text{Li}$ ROI

$^{65}\text{Cu}$ (1623 keV)

$E_\alpha = 400$ keV, $I_{\text{beam}} = 260 \mu$A, $P_{\text{D2}} = 0.2$ mbar

Laboratory Background

$(471 \pm 8) \frac{\text{counts}}{\text{day}}$
Spectra Analysis

- $^2\text{H}(\alpha,\gamma)^6\text{Li ROI}$
  - Laboratory background: $(76 \pm 4) \frac{\text{counts}}{\text{day}}$
- Measured Spectra: $(471 \pm 8) \frac{\text{counts}}{\text{day}}$
- Expected Signal: $(44 \pm 2) \frac{\text{counts}}{\text{day}}$

(Calculated using existing indirect data of Hammache et al.)

Signal-to-Noise ratio $\approx \frac{1}{10}$
Spectra Analysis
Copper Peaks

$^{65}\text{Cu} \at \ 1623 \text{ keV}$

Cu? HpGe detector and calorimeter
Spectra Analysis

Copper Peaks

$E_{\text{beam}} = 400 \text{ keV}$  
$E_{\text{beam}} = 360 \text{ keV}$

Signal counting rate reduction by 25%
Spectra Analysis
Copper Peaks

\[ E_{\text{beam}} = 360 \text{ keV} \]

\[ E_{\text{beam}} = 400 \text{ keV} \]

\[ ^{65}\text{Cu} @ 1623 \text{ keV} \]
Beam Induced Background Measurements

$E_{\text{4He beam}} = 400$ keV

Beam Induced Background: dominant part of the spectra → to be measured with high precision

- $^2\text{H}(^3\text{He},p)^4\text{He}$

Allow to measure only beam induced background without the signal

Simulations show a very similar diffused deuterium distributions

Using $^3\text{He}$ beam same beam induced background is expected

$E_{\text{3He beam}} = 370$ keV

TO BE DONE!!!
Challenging direct measurement due to the beam induced background produced by neutrons to measure with the highest precision.

The $^2\text{H}(^3\text{He},p)^4\text{He}$ could be used to subtract the beam induced background.

High statistic measurements with $^3\text{He}$ and $^4\text{He}$ are in progress.
The LUNA collaboration: