Underground measurement at LUNA found no evidence for a low-energy resonance in the $^6\text{Li}(p, \gamma)^7\text{Be}$ reaction

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Abstract. The $^6\text{Li}(p, \gamma)^7\text{Be}$ reaction is involved in all three main nucleosynthesis scenarios: Big Bang Nucleosynthesis, the interaction of cosmic rays with interstellar matter, and stellar nucleosynthesis. Conflicting experimental results have been reported in literature for the $^6\text{Li}(p, \gamma)^7\text{Be}$ reaction cross section trend at astrophysical energies. A recent direct measurement found a resonance-like structure at $E_{\text{c.m.}} = 195$ keV, corresponding to an excited state at $E_x \approx 5800$ keV in $^7\text{Be}$ which, however, has not been confirmed by either theoretical calculations or other direct measurements. In order to clarify the existence of this resonance, a new experiment was performed at the Laboratory for Underground Nuclear Astrophysics, located deep underground at Laboratori Nazionali del Gran Sasso (Italy). The $^6\text{Li}(p, \gamma)^7\text{Be}$ cross section was measured in the energy range $E_{\text{c.m.}} = 60-350$ keV with unprecedented sensitivity and no evidence for the alleged resonance was found.

1 Introduction

According to simulations of the Galaxy chemical evolution most of the solar system lithium was provided by low-mass stars [1] while less than half of it was produced by Big Bang Nucleosynthesis (BBN) [2, 3] or Galactic cosmic rays interacting with interstellar matter.

The predicted BBN $^6\text{Li}/^7\text{Li}$ isotopic ratio is $\sim 10^{-5}$ [4], significantly lower than the solar system value of 0.08 [5]. Very low $^6\text{Li}/^7\text{Li}$ values are expected for neutrino nucleosynthesis [6] and for stellar sources as well. In contrast, in case of Galactic or structure formation cosmic rays the $^6\text{Li}/^7\text{Li}$ production ratio is close to unity [7].

The $^6\text{Li}/^7\text{Li}$ isotopic ratio has been indeed proposed as a tool to constrain non-standard lithium production mechanisms [8] and pollution of stellar atmospheres [9] in the context of the cosmological lithium problem.

The $^6\text{Li}(p, \gamma)^7\text{Be}$ reaction plays a key role in determining the stellar $^6\text{Li}/^7\text{Li}$. The $^6\text{Li}(p, \gamma)^7\text{Be}$ reaction may indeed not only deplete $^6\text{Li}$ but also convert some of it to $^7\text{Li}$, through $^7\text{Be}$ radioactive decay.

Measurements of the $^6\text{Li}(p, \gamma)^7\text{Be}$ reaction cross section at low energies have reported inconsistent results on the slope of the astrophysical $S$-factor [10, 11]. Moreover, the positive slope reported by [12] was interpreted as a new resonance at $E_{\text{c.m.}} = 195$ keV, corresponding to an excited level at $E_x \approx 5800$ keV with $J^\pi = (1/2^+, 3/2^+)$ and $\Gamma_p \approx 50$ keV. No evidence for such a resonance was found in the $^3\text{He}(^4\text{He}, \gamma)^7\text{Be}$ reaction at $E_{\text{c.m.}} = 4210$ keV as reported in recent comprehensive study [13].

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None of the theoretical calculations of the $^6$Li(p,γ)$^7$Be $S$-factor are able to reproduce the newly-reported resonance [14, 15, and references therein], unless this is added ad-hoc to reproduce the experimental data [16].

2 Experimental Setup

We performed a new experiment [17] at the Laboratory for Underground Nuclear Astrophysics (LUNA), located deep underground at Laboratori Nazionali del Gran Sasso (Italy) [18].

A schematic view of the experimental setup is shown in Fig.1. The LUNA-400 accelerator [19] high-intensity proton beam was collimated by a 3 mm diameter aperture and delivered through a copper pipe to the target, mounted at 55° with respect to the beam direction. The Cu tube was used both as a cold trap and for secondary electron suppression. Three evaporated targets (thicknesses 100 – 200 µg/cm$^2$) were made from $^6$Li$_2$WO$_4$ powder and one (thickness 20 µg/cm$^2$) was made using $^6$Li$_2$O powder. The $^6$Li isotopic enrichment level was 95% for all targets, which were water cooled during irradiation in order to limit target degradation [17].

A High-Purity Germanium (HPGe) detector positioned in close geometry to the target and at 55° with respect to the beam direction was used to detect $^6$Li(p,γ)$^7$Be reaction γ-rays. To detect the α and $^3$He particles from the $^6$Li(p,α)$^3$He reaction concurrently with the gamma rays from the $^6$Li(p,γ)$^7$Be reaction, a silicon detector was installed at 125° from the beam direction. Efficiencies for both detectors were obtained using GEANT simulations, fine tuned through the comparison with experimental results [17].

3 Analysis and Results

To make consistency checks and verify results are unaffected by systematic effects, a measurement of the $^6$Li(p,γ)$^7$Be and $^6$Li(p,α)$^3$He excitation functions was performed for each target in the whole dynamic range of the LUNA-400 accelerator [17].

The $^6$Li(p,γ)$^7$Be experimental yield was calculated from the sum of the contributions from the direct capture to the ground state ($\gamma_0$) and to the 429 keV excited state of $^7$Be ($\gamma_1$).

For the calculation of the $^6$Li(p,γ)$^7$Be reaction $S$-factor, we adopted a relative approach [17]: the (p,γ) yield was normalized at each energy to the (p,α) yield. This ratio can be expressed in terms of the (p,γ) and (p,α) $S$-factors. We adopted for the $^6$Li(p,α)$^3$He reaction
the \( S \)-factor parametrization from [20]. For the \((p,\alpha)\) channel, the angular distribution coefficients \( A_k \) and related uncertainties were taken from [21, and references therein]. For the \((p,\gamma)\) channel we adopted the theoretical angular distribution described in [14]. Finally the measured \( S \)-factor was corrected for electron screening using the adiabatic approximation [22] with screening potential \( U_e = 273 \text{ eV} \) [20].

Our \( S \)-factor data have a monotonic dependence on the energy and show no evidence of the resonance reported by [12], see Fig.2. The \(^6\text{Li}(p,\gamma)^7\text{Be}\) reaction cross section was measured in the energy range \(60 - 350 \text{ keV}\) with \( \leq 2\% \) statistical and 12\% systematic uncertainty. An R-matrix fit of our data and the data from [23] was performed and used to calculate a new \(^6\text{Li}(p,\gamma)^7\text{Be}\) reaction rate. The proposed reaction rate is 9\% lower than NACRE [24] and 33\% higher than reported in NACREII [16] at 2 MK, relevant for \(^6\text{Li}\) depletion in pre-main sequence stars, and the reaction rate uncertainty has been significantly reduced [17], see Fig.3.

The result of a recent indirect study supports LUNA extrapolation for the \(^6\text{Li}(p,\gamma)^7\text{Be}\) \( S \)-factor [25].

![Figure 2: Astrophysical S-factor for the \(^6\text{Li}(p,\gamma)^7\text{Be}\) reaction as obtained by LUNA in red [17]. Previous experimental data and theoretical evaluations are also shown for comparison. The solid black line represents an R-matrix fit of LUNA data and data from [23].](image)
Figure 3: Reaction rate for the $^6\text{Li}(p,\gamma)^7\text{Be}$ reaction, normalized to the NACRE rate [24]. The NACRE II rate [16] is also shown for comparison. Dashed lines represent the uncertainty on the NACRE rate, while shaded areas represent the uncertainties from LUNA experiment (red) and from NACRE II (grey).

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