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

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Abstract. The $^6\text{Li}(p, \gamma)^7\text{Be}$ reaction is mainly at work in three nucleosynthesis scenarios: Big Bang Nucleosynthesis, $^6\text{Li}$ depletion in pre-main and in main sequence stars and cosmic ray interaction with interstellar matter. The $^6\text{Li}(p, \gamma)^7\text{Be}$ S-factor trend was poorly constrained at astrophysical energies because of conflicting experimental results reported in literature. A recent direct measurement, indeed, found a resonance-like structure at $E_{cm} = 195$ keV, corresponding to an excited state at $E_x \sim 5800$ keV in $^7\text{Be}$ which, however, has not been confirmed by either other direct measurements or predicted by theoretical calculations.

In order to clarify the existence of this resonance, a new experiment was performed at the Laboratory for Underground Nuclear Astrophysics (LUNA), located deep underground in Gran Sasso Laboratory. Thanks to the extremely low background environment, the $^6\text{Li}(p, \gamma)^7\text{Be}$ cross section was measured in the center-of-mass energy range $E = 60-350$ keV with unprecedented sensitivity.

No evidence for the alleged resonance was found. LUNA results was confirmed by latest published indirect determination of $^6\text{Li}(p, \gamma)^7\text{Be}$ S-factor and it is supported by a recent theoretical study.

1 Introduction

Lithium abundance involves mainly three nucleosynthesis scenarios. The Galactic chemical evolution models predict, indeed, that most of the solar lithium was provided by low-mass stars [1] while the rest was produced by Big Bang Nucleosynthesis (BBN) [2, 3] or by Galactic cosmic rays interacting with interstellar matter.

The $^6\text{Li}/^7\text{Li}$ isotopic ratio has been proposed as a tool to constrain non-standard lithium production mechanisms [4] and pollution of stellar atmospheres [5] in the context of the cosmological lithium problem. Recent (re-)observations of metal poor stars either severely reduced or provided only upper limits for the lithium isotopic ratio [6–8], suggesting that $^6\text{Li}$ depletion must occur in halo stars, which in turn call into question the $^7\text{Li}$ abundance observed in these stars corresponds to the primordial value [9].

The $^6\text{Li}(p, \gamma)^7\text{Be}$ reaction ($Q$ value = 5606.85(7) keV) has a crucial role in determining the stellar $^6\text{Li}/^7\text{Li}$ ratio. The $^6\text{Li}(p, \gamma)^7\text{Be}$ reaction not only deplete $^6\text{Li}$ but it also convert some of it to $^7\text{Li}$, through $^7\text{Be}$ radioactive decay.

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The slope of the astrophysical $S$-factor is poorly constrained at low energies given the inconsistent results reported in literature [10, 11]. Moreover, a new resonance at $E_{\text{c.m.}} = 195$ keV, corresponding to an excited level at $E_x \approx 5800$ keV with $J^e = (1/2^+, 3/2^+)$ and $\Gamma_p \approx 50$ keV, was claimed by [12]. In a recent comprehensive study of the $^3\text{He}(^4\text{He}, \gamma)^7\text{Be}$ reaction ($Q$ value = 1587.14(7)) no evidence for such a resonance was found at $E_{\text{c.m.}} = 4210$ keV [13].

None of the theoretical calculations of the $^6\text{Li}(p, \gamma)^7\text{Be}$ $S$-factor can 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

A new experiment [17] was performed at the Laboratory for Underground Nuclear Astrophysics (LUNA), at Laboratori Nazionali del Gran Sasso (Italy) [18]. The LUNA deep-underground location guarantees the reduction of environmental background by several orders of magnitude with respect to overground laboratories, enabling high-sensitivity measurements to be performed.

A schematic view of the experimental setup is shown in Fig.1. The high-intensity proton beam was provided by LUNA-400 accelerator [19] and it was collimated 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, to improve the scattering chamber vacuum and prevent carbon build-up on target, and for secondary electron suppression. The evaporated targets were made from $^6\text{Li}_2\text{WO}_4$ or $^6\text{Li}_2\text{O}$ powder, with thicknesses $100 – 200 \mu\text{g/cm}^2$ and $20 \mu\text{g/cm}^2$ respectively. The $^6\text{Li}$ isotopic enrichment level was 95% for all targets, which were water cooled to limit target degradation during irradiation [17].

To detect $^6\text{Li}(p, \gamma)^7\text{Be}$ reaction $\gamma$-rays a High-Purity Germanium (HPGe) detector was positioned in close geometry to the target and at 55° with respect to the beam direction. In addition a Silicon (Si) detector was installed at 125° from the beam direction to detect the $\alpha$ and $^3\text{He}$ particles from the $^6\text{Li}(p, \alpha)^3\text{He}$ reaction concurrently with the gamma rays from the $^6\text{Li}(p, \gamma)^7\text{Be}$ reaction. Efficiencies for both detectors were obtained using GEANT simulations, fine tuned through the comparison with experimental results for $\gamma$ and $\alpha$ standards as well as for known resonances of $^{14}\text{N}(p, \gamma)^{15}\text{O}$ and $^{18}\text{O}(p, \alpha)^{15}\text{N}$ reactions [17]. The total uncertainty is 4% and 8% for the HPGe and Si detector efficiency respectively.

![Figure 1. Sketch of the experimental setup used for the measurement of the $^6\text{Li}(p, \gamma)^7\text{Be}$ cross section at LUNA [17].](image-url)
3 Results and Discussion

A measurement of the $^6\text{Li}(p,\gamma)^7\text{Be}$ and $^6\text{Li}(p,\alpha)^3\text{He}$ excitation functions was performed for each target in the whole dynamic range of the LUNA-400 accelerator in order to make consistency checks and verify results are unaffected by systematic effects [17].

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

![Figure 2. Experimental $\gamma$ spectrum acquired at $E_p = 265$ keV. The $^6\text{Li}(p,\gamma)^7\text{Be}$ proceeds through direct capture (DC) to either the ground state of $^7\text{Be}$, $\gamma_0$, or its first excited state, $\gamma_1$, with subsequent emission of a 429 keV secondary gamma ray, $\gamma_2$.](image)

For the calculation of the $^6\text{Li}(p,\gamma)^7\text{Be}$ reaction $S$-factor, we adopted a relative approach [17]: the $(p,\gamma)$ yield was normalized at each energy to the $(p,\alpha)$ yield. This ratio can be expressed in terms of the ratio between $(p,\gamma)$ and $(p,\alpha)$ $S$-factors. We adopted for the $^6\text{Li}(p,\alpha)^3\text{He}$ reaction the $S$-factor parametrization reported in [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]. The measured $S$-factor was corrected for electron screening using the approximation in [22] and assuming a screening potential $U_e = 273$ eV [20].

The present $S$-factor has a monotonic dependence on the energy and show no evidence of the resonance reported in [12], see Fig.3. The measurement covered the center-of-mass energy range $60 - 350$ keV and the reported statistical and systematic uncertainty were $\leq 2\%$ and $12\%$ respectively. Combining current data and the high energy results reported in [23] an R-matrix fit was performed providing an extrapolated $S$-factor to zero energy $S(0) = 95 \pm 5$ eV b. The R-matrix fit was used to calculate a new $^6\text{Li}(p,\gamma)^7\text{Be}$ reaction rate, which is $9\%$ lower than NACRE [24] and $33\%$ higher than reported in NACREII [16] at temperatures relevant for $^6\text{Li}$ depletion in pre-main sequence stars. Moreover the reaction rate uncertainty has been significantly reduced [17], see Fig.4.

The result of a subsequent indirect study confirms LUNA extrapolation down to low energies for the $^6\text{Li}(p,\gamma)^7\text{Be}$ S-factor, reporting an $S(0) = 92 \pm 12$ eV b [25]. A recent theoretical study found a consistent trend for the $^6\text{Li}(p,\gamma)^7\text{Be}$ $S$-factor predicting a $S$-factor to zero energy of 98.3 eV b [26].
Figure 3. 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 red line represents an R-matrix fit of LUNA data and data from [23].

Figure 4. 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 (black), on NACREII rate (blue) and on LUNA rate (red).

References

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