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

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Abstract. The ^{6}Li(p,γ)^{7}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}Li(p,γ)^{7}Be reaction cross section trend at astrophysical energies. A recent direct measurement found a resonance-like structure at $E_{\mathrm{c.m.}} = 195$ keV, corresponding to an excited state at $E_{\mathrm{x}} \sim 5800$ keV in ^{7}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}Li(p,γ)^{7}Be cross section was measured in the energy range $E_{\mathrm{c.m.}} = 60$-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}Li/^{7}Li isotopic ratio is $\sim 10^{-5}$ [4], significantly lower than the solar system value of 0.08 [5]. Very low ^{6}Li/^{7}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}Li/^{7}Li production ratio is close to unity [7].

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

Measurements of the ^{6}Li(p,γ)^{7}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 $E_{\mathrm{c.m.}} = 195$ 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}He(^{4}He,γ)^{7}Be reaction at $E_{\mathrm{c.m.}} = 4210$ 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

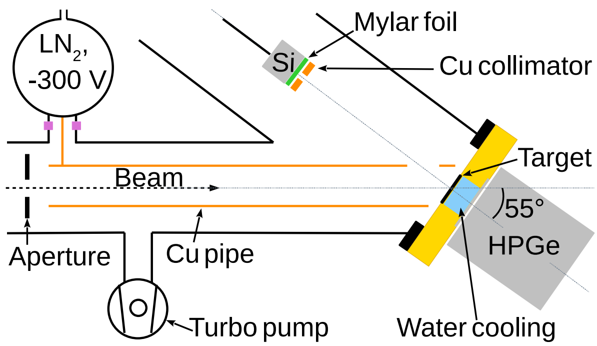

Figure 1: Sketch of the experimental setup used for the measurement of the ^{6}Li(p,γ)^{7}Be cross section at LUNA [17].

[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 (γ_0) and to the 429 keV excited state of ^{7}Be (γ_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,α) channel, the angular distribution coefficients A_k and related uncertainties were taken from [21, and references therein]. For the (p,γ) 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 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}Li(p,γ)^{7}Be reaction cross section was measured in the energy range 60 – 350 keV with ≤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}Li(p,γ)^{7}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}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}Li(p,γ)^{7}Be S-factor [25].

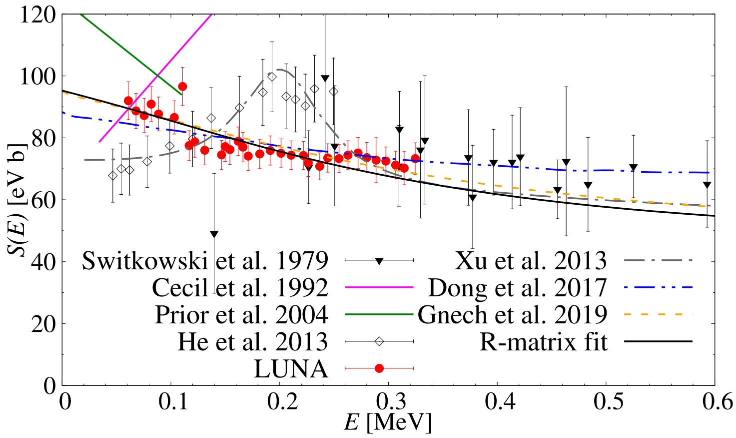

Figure 2: Astrophysical S-factor for the ^{6}Li(p,γ)^{7}Be reaction as obtained by LUNA in red [17]. Previous experimental data and theoretical evaluations are also shown for comparison. The solid black line represents an R-matrix fit of LUNA data and data from [23].

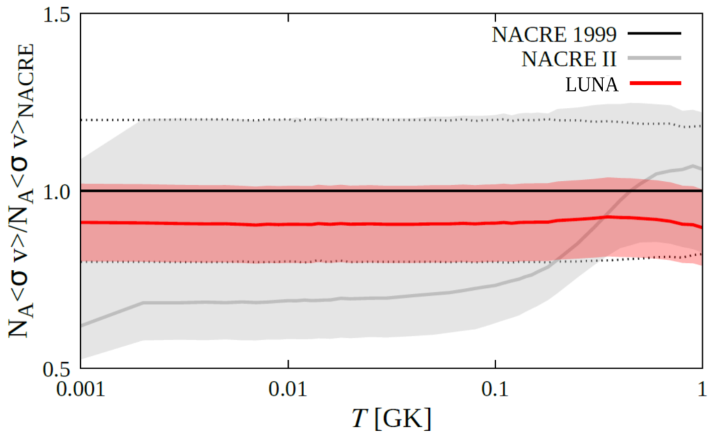

Figure 3: Reaction rate for the ^{6}Li(p,γ)^{7}Be reaction, normalized to the NACRE rate [24]. The NACRE II rate [16] is also shown for comparison. Dashed lines represent the uncertainty on the NACRE rate, while shaded areas represent the uncertainties from LUNA experiment (red) and from NACRE II (grey).

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