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

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Abstract. The ^{6}Li(p, γ)^{7}Be reaction is mainly at work in three nucleosynthesis scenarios: Big Bang Nucleosynthesis, ^{6}Li depletion in pre-main and in main sequence stars and cosmic ray interaction with interstellar matter. The ^{6}Li(p, γ)^{7}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 $E_{c.m.} = 195$ keV, corresponding to an excited state at $E_x \sim 5800$ keV in ^{7}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}Li(p, γ)^{7}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}Li(p, γ)^{7}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}Li/^{7}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}Li depletion must occur in halo stars, which in turn call into question the ^{7}Li abundance observed in these stars corresponds to the primordial value [9].

The ^{6}Li(p,γ)^{7}Be reaction (Q value = 5606.85(7) keV) has a crucial role in determining the stellar ^{6}Li/^{7}Li ratio. The ^{6}Li(p,γ)^{7}Be reaction not only deplete ^{6}Li but it also convert some of it to ^{7}Li, through ^{7}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 $E_{\mathrm{c.m.}} =$ 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, was claimed by [12]. In a recent comprehensive study of the ^{3}He(^{4}He,γ)^{7}Be reaction (Q value = 1587.14(7)) no evidence for such a resonance was found at $E_{\mathrm{c.m.}} = 4210$ keV [13].

None of the theoretical calculations of the ^{6}Li(p,γ)^{7}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}Li$_2$WO$_4$ or ^{6}Li$_2$O powder, with thicknesses 100 – 200 μg/cm^2 and 20 μg/cm^2 respectively. The ^{6}Li isotopic enrichment level was 95% for all targets, which were water cooled to limit target degradation during irradiation [17].

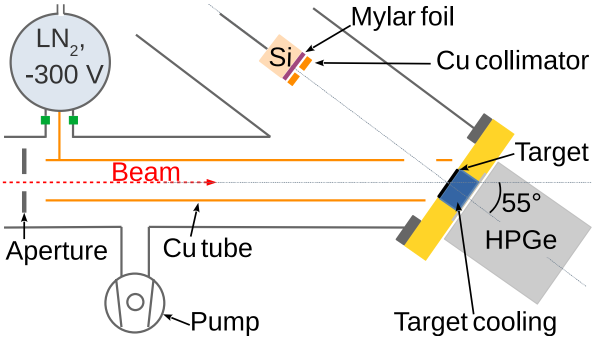

Figure 1. Sketch of the experimental setup used for the measurement of the ^{6}Li(p,γ)^{7}Be cross section at LUNA [17].

To detect ^{6}Li(p,γ)^{7}Be reaction γ-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 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. Efficiencies for both detectors were obtained using GEANT simulations, fine tuned through the comparison with experimental results for γ and α standards as well as for known resonances of ^{14}N(p,γ)^{15}O and ^{18}O(p,α)^{15}N reactions [17]. The total uncertainty is 4% and 8% for the HPGe and Si detector efficiency respectively.

3 Results and Discussion

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 in order to make consistency checks and verify results are unaffected by systematic effects [17].

The ^{6}Li(p,γ)^{7}Be experimental yield was calculated as 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).

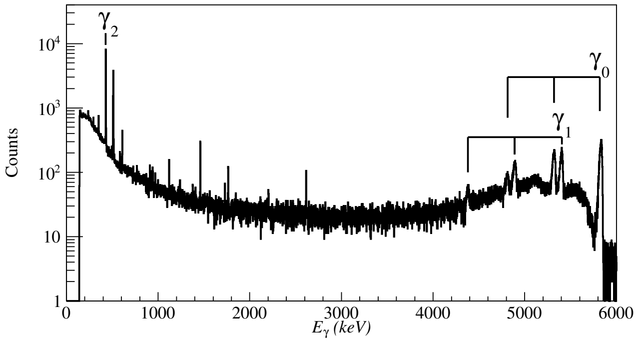

Figure 2. Experimental γ spectrum acquired at E_p = 265 keV. The ^{6}Li(p,γ)^{7}Be proceeds through direct capture (DC) to either the ground state of ^{7}Be, γ_0, or its first excited state, γ_1, with subsequent emission of a 429 keV secondary gamma ray, γ_2.

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 ratio between (p,γ) and (p,α) S-factors. We adopted for the ^{6}Li(p,α)^{3}He reaction the S-factor parametrization reported in [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]. 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 ± 5 eV b. The R-matrix fit was used to calculate a new ^{6}Li(p,γ)^{7}Be reaction rate, which is 9% lower than NACRE [24] and 33% higher than reported in NACREII [16] at temperatures relevant for ^{6}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}Li(p,γ)^{7}Be S-factor, reporting an $S(0)$ = 92 ± 12 eV b [25]. A recent theoretical study found a consistent trend for the ^{6}Li(p,γ)^{7}Be S-factor predicting a S-factor to zero energy of 98.3 eV b [26]

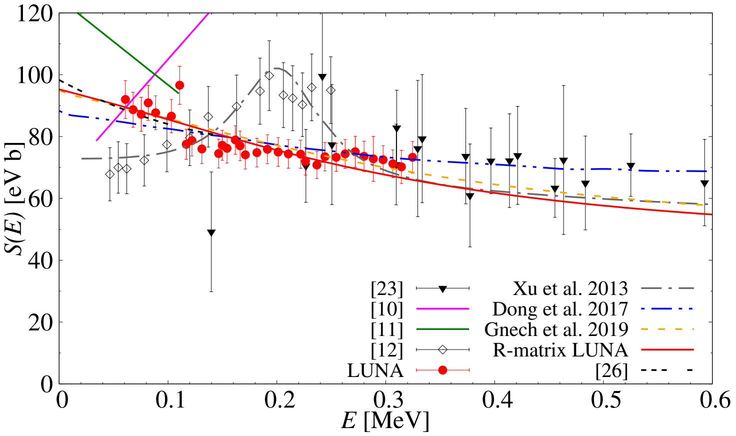

Figure 3. Astrophysical S-factor for the ^{6}Li(p,γ)^{7}Be reaction as obtained by LUNA in red [17]. Previous experimental data and theoretical evaluations are also shown for comparison. The solid red line represents an R-matrix fit of LUNA data and data from [23].

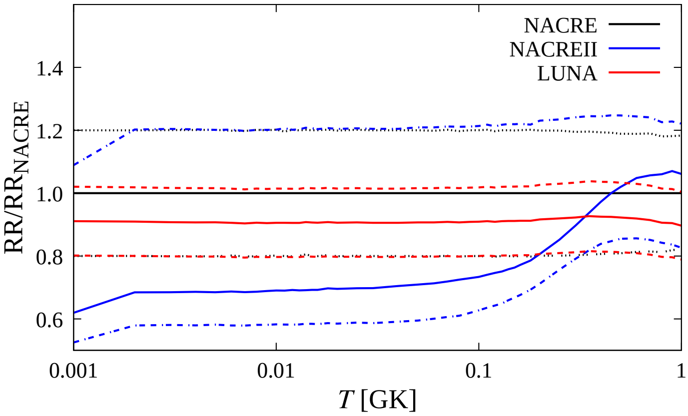

Figure 4. Reaction rate for the ^{6}Li(p,γ)^{7}Be reaction, normalized to the NACRE rate [24]. The NACRE II rate [16] is also shown for comparison. Dashed lines represent the uncertainty on the NACRE rate (black), on NACREII rate (blue) and on LUNA rate (red).

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