The Study of the $^{6}\text{Li}(p,\gamma)^{7}\text{Be}$ Reaction at LUNA

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Abstract. The $^{6}\text{Li}(p,\gamma)^{7}\text{Be}$ reaction is mainly involved in two astrophysical scenarios: the primordial nucleosynthesis and $^{6}\text{Li}$ consumption in pre-main and main sequence stars. A recent measurement of $^{6}\text{Li}(p,\gamma)^{7}\text{Be}$ reaction S-factor reported a resonance-like structure at $E_{\text{cm}}=195$ keV, which has not been confirmed neither by other direct measurements nor by theoretical calculations.

A new experiment was performed at the Laboratory for Underground Nuclear Astrophysics (LUNA). The extremely low background environment allowed to measure the $^{6}\text{Li}(p,\gamma)^{7}\text{Be}$ cross section down to low energies with unprecedented sensitivity leading to clarify the existence of the claimed resonance. Details on the experimental setup and the preliminary results of the ongoing analysis are reported in this work.

1. Introduction

The consumption of $^{6}\text{Li}$ plays an important role in two astrophysical scenarios: Big Bang Nucleosynthesis (BBN) [1], and the early stages of stellar evolution [2]. In both scenarios $^{6}\text{Li}$ depletion proceeds through both $^{6}\text{Li}(p,^{3}\text{He})^{4}\text{He}$ and $^{6}\text{Li}(p,\gamma)^{7}\text{Be}$ reactions. During BBN these two reactions take place at $T \leq 0.8$ GK, corresponding to Gamow peaks energies of 40-320 keV, while in pre-main and main sequence stars they are activated for $T \geq 3$ MK, corresponding to Gamow peaks energies of 3-15 keV.

Both the $^{6}\text{Li}(p,^{3}\text{He})^{4}\text{He}$ and $^{6}\text{Li}(p,\gamma)^{7}\text{Be}$ reactions have been extensively studied, a summary of literature data for both reactions is presented in fig. 1. While the former cross section is well constrained by the experimental works, see [3] and references therein, the $^{6}\text{Li}(p,\gamma)^{7}\text{Be}$ state of art is still puzzling. Indeed the two main datasets, reported in [4,5], overlap only in a small energy region. Then $^{6}\text{Li}(p,\gamma)^{7}\text{Be}$ reaction S-factor is poorly constrained at low energies. The measurement reported in [6] resulted in a decreasing S-factor with decreasing energy, see the solid magenta line in the right panel of fig. 1. This trend was not confirmed by following theoretical studies [7–9] or the experimental study reported in [10] and plotted in fig. 1, right panel, with the solid green line. More recently the work published in reference [5] reports a previously unseen resonance at $E_{\text{cm}}=195$ keV, see black diamonds in the right panel of fig. 1. Based on an R-matrix fit of the experimental data a positive spin-parity, $J^{\pi} = 1/2^{+}$
Finally the most recent theoretical work, based on cluster model, predicted a resonance. The new resonance might also affect the extrapolation of the contribution by both negative and positive parity excited states to be reproduced by the R-matrix fit [13]. The new level may solve the puzzle of why the reported resonance could definitely describe the S-factor slope at low energies. Furthermore the new proposed level may solve the puzzle of why the $^6\text{Li}(p,^3\text{He})^4\text{He}$ angular distribution is dominated by the $A_1$ coefficient [12], which requires the contribution by both negative and positive parity excited states to be reproduced by the R-matrix fit [13]. The new resonance might also affect the extrapolation of $^3\text{He}(\alpha,\gamma)^7\text{Be}$ cross section at low energies. Recently a study aimed to investigate the existence of the resonance measuring the $^3\text{He}(\alpha,\gamma)^7\text{Be}$ reaction cross section reported only an upper limit [14]. Finally the most recent theoretical work, based on cluster model, predicted a resonance. 

or $3/2^+$ was assigned to the corresponding new excited state in $^7\text{Be}$, $E_x \sim 5.8$ MeV, see fig. 2. The reported resonance could definitely describe the S-factor slope at low energies. Furthermore the new proposed level may solve the puzzle of why the $^6\text{Li}(p,^3\text{He})^4\text{He}$ angular distribution is dominated by the $A_1$ coefficient [12], which requires the contribution by both negative and positive parity excited states to be reproduced by the R-matrix fit [13]. The new resonance might also affect the extrapolation of $^3\text{He}(\alpha,\gamma)^7\text{Be}$ cross section at low energies. Recently a study aimed to investigate the existence of the resonance measuring the $^3\text{He}(\alpha,\gamma)^7\text{Be}$ reaction cross section reported only an upper limit [14]. Finally the most recent theoretical work, based on cluster model, predicted a resonance. 

The excited state corresponding to the resonance reported in [5] is shown too. The theoretical prediction by [9] is shown for comparison.
trend of the $^6$Li(p,$\gamma$)$^7$Be reaction S-factor which excludes the presence of a low energy resonance [9], see dashed blue line in fig. 1 right panel.

The aim of the $^6$Li+p campaign at LUNA is to verify the existence of the low energy resonance proposed in [5] by measuring the $^6$Li(p,$\gamma$)$^7$Be reaction at bombarding energies between 80 and 390 keV.

2. Experimental Setup

The $^6$Li(p,$\gamma$)$^7$Be reaction was investigated at the Laboratory for Underground Nuclear Astrophysics (LUNA) [15], located under 1400 m of Gran Sasso rock (Italy), which guarantee an unprecedented reduction of the cosmic rays background [16]. The high intensity and high stability H$^+$ beam was delivered from LUNA 400kV accelerator [17] to a devoted solid target scattering chamber, see fig. 3. A static circular collimator of 3 mm diameter reduced the size of the beamspot to fit inside the target area ($\sim$ 23 mm diameter). Then the protons were sent through a copper tube, see top left inset in fig. 3, which was both cooled to serve as a cold trap for removal of contaminants in the beam line and biased for secondary electron suppression. Finally the beam struck the water cooled target mounted on a brass flange at 55° to the beam axis, see fig. 3 and top right inset. The scattering chamber and target were insulated from the rest of the beamline, thus they work as a Faraday cup to allow the determination of the total charge accumulated during a measurement.
Solid targets of nominal composition, $^6\text{Li}_2\text{O}$, $^6\text{Li}_2\text{WO}_4$, and $^6\text{LiCl}$, and thickness ranging from $20 \ \mu\text{g/cm}^2$ up to infinite were irradiated. The nominal enrichment in $^6\text{Li}$ was 95% for all the compounds. The $^6\text{Li}_2\text{O}$ and $^6\text{Li}_2\text{WO}_4$ compounds were evaporated on a previously cleaned disk shaped tantalum backing, 0.25 mm thick, at the ATOMKI laboratories in Debrecen (Hungary). Separately, the $^6\text{LiCl}$ target was produced at the chemistry laboratories of the University of Naples, it was heated directly on the copper backing, then it expanded onto the backing and solidified into a thick film.

In order to detect the charged particles from the $^6\text{Li}(p,^3\text{He})^4\text{He}$ reaction an ultra low background Si detector by ORTEC, 25 mm$^2$ active area and 100 $\mu$m depletion depth, was installed on a movable holder at 125° with respect to the beam direction. Both a 5 $\mu$m thick mylar foil and a 1 mm diameter copper collimator were positioned in front of the detector to limit the intensity of the scattered protons impinging on the Si surface. During the measurements at LUNA the Si was at 10.3 or 9.3 cm from the target centre, see fig. 3 and top left inset.

An ORTEC coaxial HPGe detector was used for the gamma-ray spectroscopy of the $^6\text{Li}(p,\gamma)^7\text{Be}$ reaction. The HPGe was positioned parallel to the target axis at a target-to-detector end cap distance $d \sim 1.69$ cm, see fig. 3.

3. Analysis and Results

Sample of gamma and charged-particle spectra acquired during the $^6\text{Li}(p,\gamma)^7\text{Be}$ campaign at LUNA are shown in fig. 4. In the left spectrum the gammas from the direct capture to the ground ($\gamma_0$) and first excited state ($\gamma_1$, $\gamma_2$) of $^7\text{Be}$ are well visible, as well as the $^4\text{He}$ and $^3\text{He}$ peaks in the right spectrum.

![Figure 4: Left: HPGe spectrum acquired at $E_p = 265$ keV, $I = 100 \ \mu$A for a $^6\text{Li}_2\text{O}$ target, logarithmic scale. A linear scale zoom of the region between $\sim 4$ MeV and $\sim 6$ MeV is also shown. Right: the corresponding charged-particle spectrum.](image-url)
for seven target-to-detector distances, black dots in fig. 5 left panel. The measured efficiency was reproduced simulating a circular beamspot with radius $R = 5$ mm, which becomes an ellipse when projected on the target at $55^\circ$ to the beam direction, and 3 mm off from the target center along the horizontal axis, see red line in fig. 5. The simulated beamspot was in good agreement with the experimental beamspot, a sample is reported in fig. 5 right panel. In addition the Geant3 simulation code was used to investigate the effect of different beamspot sizes and positions on the Si efficiency due to the refocusing of the beam.

The HPGe efficiency was measured at different source-to-detector distances up to

$E_{\gamma} \sim 7.5$ MeV using standard radioactive pointlike sources ($^{137}$Cs, $^{60}$Co, and $^{88}$Y) and exploiting the well known $E_{\text{lab}} = 278$ keV $^{14}$N(p,$\gamma$)$^{15}$O resonance [20]. The experimental data were used to tune the Geant4 simulation code, see fig. 6. Once the simulated efficiencies agreed with measurements the simulation code was exploited to correct the efficiencies for the True Coincidence Summing (TCS)‡. Indeed $^6$Li(p,$\gamma$)$^7$Be proceeds through a cascade, see fig. 2, and thus the experimental yield must be corrected for the TCS. In addition the simulations were used to investigate the effect of different beam spot dimensions and positions effect on the HPGe efficiency.

After the irradiation at LUNA the targets were delivered to the Helmholtz-Zentrum

‡ True coincidence summing occurs when two gamma rays emitted from a source are detected within a timescale shorter than the temporal resolution of the detector. If both gammas are detected with their full energy, this results in a peak in the spectrum at an energy equal to the sum of the two gamma-ray energies, known as “summing-in”. Consequently there will be fewer events recorded at the individual energies of the two gamma rays, or if only one gamma is detected with its full energy whilst the other releases any amount of energy, then events are lost from the full-energy peak of the first gamma, known as "summing-out". This has an effect on the determined efficiencies of the detector, which becomes more pronounced at larger solid angles.
Dresden-Rossendorf (HZDR) laboratories in Dresden (Germany). Two different Ion Beam Analysis techniques were used to characterize the targets: Nuclear Reaction Analysis (NRA) and Elastic Recoil Detection Analysis (ERDA). The former was performed exploiting the well known resonance at $E_{\text{lab}} = 1175$ keV of the $^6\text{Li}(\alpha,\gamma)^{10}\text{B}$ reaction ($\omega\gamma = 366 \pm 17$ meV, $\Gamma = 1.7$ eV) [21]. The resonance scans performed on targets are reported in fig. 7. The profile scans were fitted with a proper function in order to get the target thickness. Alongside the NRA study, the target compositions were determined using ERDA.

Since the analysis of the target was performed after irradiation at LUNA it was decided to investigate any possible target degradation caused during LUNA campaign. The online target thickness, $D_X$, was obtained, run by run, by the $\gamma_0$ peak shape analysis, see fig. 8 left panel. The results, normalised to the first runs thickness $D_{X_0}$, are shown as black dots in fig. 8, right panel, for the target $^6\text{Li}_2\text{WO}_4$-3. The target thickness obtained by NRA is plotted as a blue triangle, in agreement with last runs performed at LUNA and showing a target thickness reduction of $\sim 20\%$.

4. Conclusion and Future Outlook

The $^6\text{Li}(p,\gamma)^7\text{Be}$ reaction has been recently studied at LUNA across 80 - 390 keV. The Si and HPGe efficiencies have been determined from measurements of radioactive sources and beam induced reactions combined with simulations. These measurements have been complemented by target characterisation studies at HZDR. Target degradation has been investigated and observed for each target by peak shape analysis. Yields for both $^6\text{Li}(p,\gamma)^7\text{Be}$ and $^6\text{Li}(p,^3\text{He})^4\text{He}$ reactions have been determined and a relative approach calculation of the S-factor is ongoing with results to be published soon.
Figure 7: The $^6\text{Li}(\alpha,\gamma)^{10}\text{B}$ 1175 keV resonance scans obtained for the targets irradiated at LUNA. Red and blue lines are the fit of the experimental data.

Figure 8: Left: an example of the peak shape analysis performed to obtain the target thickness run by run. Right: target thickness obtained from peak shape analysis during measurements at LUNA, black dots. NRA result for target thickness is the blue triangle. Red line is the linear trend of the thicknesses measured at LUNA with 68% confidence level.

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