Underground Measurement of $^{6}\text{Li}(p,\gamma)^{7}\text{Be}$ and $^{6}\text{Li}(p,^3\text{He})^4\text{He}$ Performed at LUNA

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Abstract. Proton-induced reactions on $^{6}\text{Li}$ play an important role in nuclear astrophysics studies in relation to primordial lithium abundances. Whilst big bang nucleosynthesis theory excludes the existence of primordial $^{6}\text{Li}$, the $^{6}\text{Li}/^{7}\text{Li}$ abundance ratio observed in pre-main sequence stars is $\approx 0.5$. The $^{6}\text{Li}(p,^3\text{He})^4\text{He}$ and $^{6}\text{Li}(p,\gamma)^{7}\text{Be}$ reactions are the main processes that contribute to $^{6}\text{Li}$ destruction in stars. Both reactions were recently studied at LUNA via proton bombardment of $^{6}\text{Li}$-enriched targets, with complementary target composition studies performed at HZDR. Improvements on the precision of the low-energy S-factor values are expected from this study. Notably, the low-background measurement at LUNA will assist the search for a recently claimed $^{6}\text{Li}(p,\gamma)^{7}\text{Be}$ low energy resonance at $E_r \approx 195$ keV. I present the LUNA experimental setup and preliminary results of the ongoing analysis.

1. Introduction

The primordial abundances of isotopes formed during the early stages of the Universe have been predicted from big bang nucleosynthesis (BBN) theory coupled with recent cosmic microwave background (CMB) observations of the cosmic baryon density [1]. The predicted abundances are then compared with measured abundances in the atmospheres of metal-poor stars found in the stellar halo (Population II) of our Galaxy. In the case of hydrogen and helium the theoretical and observed abundances are in good agreement [2]. For lithium isotopes the current BBN framework predicts the abundances of $^{7}\text{Li}$ are a factor 2–4 higher than measured, and inversely the predicted abundances of $^{6}\text{Li}$ are a factor $10^3$ lower than measured. Whilst this large discrepancy is currently attributed to $^{6}\text{Li}$ production due to proton spallation and fusion reactions, the environments encountered in low mass pre-main sequence (PMS) stars is expected to destroy more $^{6}\text{Li}$ than $^{7}\text{Li}$. Recent findings [3–5] report an explanation whereby the $^{6}\text{Li}$ abundances derived from stars are significantly reduced by including non local thermodynamic equilibrium (NLTE) and 3D modelling in the lithium line models. These pioneering efforts in observational astronomy require parallel advances in nuclear physics measurements of the destructive reactions on $^{6}\text{Li}$.

In this study two destructive reactions of $^{6}\text{Li}$ were measured concurrently, $^{6}\text{Li}(p,^3\text{He})^4\text{He}$ and $^{6}\text{Li}(p,\gamma)^{7}\text{Be}$, using the LUNA-400kV accelerator located at Gran Sasso, Italy. Gran Sasso provides excellent natural shielding from cosmic rays, thus reducing the background radiation [6] and allowing for improved measurements at astrophysically relevant energies compared to experiments performed on Earth's surface. The LUNA-400kV accelerator has been successfully...
used to measure other reactions at energies of astrophysical interest [7–16]. The measurements of the two aforementioned reactions have been completed and the ongoing analysis will be summarised here.

In current literature the $^6\text{Li}(p,^3\text{He})^4\text{He}$ reaction S-factor has been studied extensively and does not exhibit any resonant structure at low energies ($E_{\text{cm}} < 1 \text{ MeV}$). The $^6\text{Li}(p,\gamma)^7\text{Be}$ state of art is more puzzling since a recent measurement [17] discovered a decreasing trend in the S-factor at low energies ($E_{\text{cm}} < 400 \text{ keV}$) of relevance in BBN. This structure was attributed to the presence of a previously unobserved positive parity resonance state in $^7\text{Be}$ at $E_r = 195 \text{ keV}$ in the c.m frame with a proton width $\Gamma_p = 50 \text{ keV}$ and spin-parity $J^\pi = \frac{1}{2}^+$ or $\frac{3}{2}^+$. The presence of this resonance would describe the observed $^6\text{Li}(p,\gamma)^7\text{Be}$ S-factor trend. Determining the $^6\text{Li}(p,\gamma)^7\text{Be}$ S-factor at low energies, thus confirming or denying the existence of this low energy resonance, is the final objective of this ongoing campaign at LUNA.

2. LUNA Experimental Setup

A schematic diagram of the solid target chamber used in the $^6\text{Li}$ measurement campaign is provided in figure 1. The LUNA-400kV accelerator was operated between energies $E_p = 75 - 395 \text{ keV}$ ($E_{\text{cm}} = 64 - 338 \text{ keV}$). The beam was focused into the target chamber using two circular apertures (of diameter 6 mm and 3 mm) onto $^6\text{Li}$-enriched ($^{6}\text{Li}/^{nat}\text{Li} \sim 95\%$) solid targets (of diameter 23 mm). The targets were mounted at 55° to the beam axis. The beam passed through a copper pipe which was cooled using liquid nitrogen (LN$_2$) to function as a cold trap for removal of heavy contaminants in the beamline and to reduce carbon build-up on target. This same copper tube was biased to -300 V for secondary electron suppression. The beam current was measured on a run by run basis. During beam bombardment the solid target chamber was kept at a low pressure of order $10^{-6}$ mbar. The targets consisted of Li$_2$O of nominal thicknesses 20 - 40 µg/cm$^2$, Li$_2$WO$_4$ of nominal thicknesses 100 - 130 µg/cm$^2$, or an “Infinitely thick” (> 450 µg/cm$^2$) LiCl. The Li$_2$O and Li$_2$WO$_4$ compounds were evaporated onto 0.25 mm tantalum backings at the ATOMKI laboratories in Debrecen, the LiCl compound was heated directly onto a copper backing at the University of Naples. During beam irradiation the targets were water cooled to dissipate the beam power deposited on target.

Figure 1. Schematic diagram of the experimental setup at LUNA.
Charged particles were measured using an ultra low background Ortec silicon (Si) detector mounted at 125° with respect to the beam axis on a movable actuator arm inside the target chamber (target-to-detector distance = 9.3 or 10.3 cm). The Si detector has an active area 25 cm$^2$ with depletion depth 100 µm. Both a 1 mm collimator and a 5 µm mylar foil were mounted in front of the Si to drastically reduce the flux from backscattered proton beam. The Si detector was calibrated using both a fixed $^{241}$Am alpha source and alphas from the known 151 keV resonance of the $^{18}$O($p,\alpha$)$^{15}$N reaction [18]. Gamma rays were detected using a high purity germanium (HPGe) Ortec detector mounted in close geometry to the targets axis (target-to-crystal distance < 2.5 cm). The HPGe detector was calibrated using fixed $^{137}$Cs, $^{60}$Co, and $^{88}$Y gamma sources and gammas from the well-known $E_r = 259$ keV resonance of the $^{14}$N($p,\gamma$)$^{15}$O reaction [19].

3. LUNA Preliminary Analysis and Results

![Figure 2. HPGe Photopeak Efficiency. The measured efficiencies corrected for true summing effects is shown by the black line; simulated efficiencies are shown by the black squares with statistical errors.](image)

The HPGe efficiency was determined using gammas from both the fixed sources and the $^{14}$N($p,\gamma$)$^{15}$O reaction. Because of the close geometry, gamma rays that follow a cascade decay (e.g from a $^{60}$Co source) will result in the measured efficiencies being affected by true coincidence summing (TCS) effects\(^1\). The measured efficiencies were thereby corrected by applying an analytical summing correction, as shown by the black line in figure 2. To cross-check this correction, the solid target setup with HPGe detector was modelled using Geant4 Monte Carlo simulations to determine the efficiencies (and summing corrections) at given gamma energies, see the black squares in figure 2.

During the measurement the $^6$Li($p,\gamma$)$^7$Be direct capture (DC) and 429 keV decay gamma rays were detected by the HPGe. See figure 4a for a sample spectrum focused on the DC energy range.

\(^1\) True summing effects occur when there is a non-negligible probability for multiple gamma rays to enter the detector in a short time window (shorter than the charge collection time of the crystal) resulting in an enhancement of the sum-peak area while simultaneously reducing the individual gamma photopeak areas.
Figure 3. A sample gamma-ray spectrum acquired on a Li$_2$WO$_4$ target irradiated by a proton beam of 294 keV.

Figure 4. Zoom into the DC→0 peak with empirical fit.

of interest. The DC→0 and DC→429 peaks were fitted using an empirical formula, allowing the peaks to be integrated and the target thickness to be fitted as a free parameter. The target thicknesses were thereby determined for all runs during irradiation, and the target degradation was then calculated by normalising to the first measurement run, see figure 5 for a sample target degradation plot. Using knowledge of the peak integrals, HPGe efficiency, and beam current deposited, the yields have been calculated for three Li$_2$WO$_4$ targets, two Li$_2$O targets, and the one LiCl target, and S-factors are currently being calculated.

4. HZDR Analysis and Results
After bombardment at LUNA, the $^6$Li-enriched targets were characterised at the Helmholtz-Zentrum Dresden-Rossendorf (HZDR) laboratory in Germany using nuclear reaction analysis.
Figure 5. Target degradation of a Li$_2$WO$_4$ target. The target thicknesses normalised to the first measurement run are shown for LUNA runs (black) and the HZDR NRA measurement (blue). The red line is a fit of the LUNA data with 68% confidence levels included. Errors shown are statistical.

Figure 6. Target profile obtained using NRA at HZDR for a Li$_2$WO$_4$ target. Error bars are total.

(NRA) of the $^6$Li($\alpha,\gamma$)$^{10}$B resonance at $E_{\text{lab}} = 1175$ keV [20]. “Fresh” targets of a similar composition were also studied using the same experimental setup at HZDR to act as a control for comparison with the targets irradiated at LUNA. The target profile collected for one of
the irradiated Li$_2$WO$_4$ targets is shown in figure 6. Alongside the NRA study, the target compositions were determined at HZDR using elastic recoil detection analysis (ERDA) [21].

5. Future Outlook
Two destructive reactions, $^6$Li(p,$^3$He)$^4$He and $^6$Li(p,$\gamma$)$^7$Be, have been recently studied during an experimental campaign at LUNA. These measurements have been complemented by target characterisation studies at HZDR. The Si and HPGe efficiencies have been determined from radioactive sources and beam induced reactions. The $^6$Li nuclear reactions were studied across $E_{\text{cm}} = 64 - 338$ keV. The target degradation has been derived for each target from the DC component of the $^7$Be decay. Yields for both destructive reactions have been determined, and both S-factor and reaction rate calculations are being finalised.

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