IL NUOVO CIMENTO **42 C** (2019) 116
DOI 10.1393/ncc/i2019-19116-8

Colloquia: EuNPC 2018

Underground measurement of proton-induced reactions on ^{6}Li at LUNA

T. Chillery on behalf of the LUNA Collaboration(*)
SUPA, School of Physics and Astronomy, University of Edinburgh - Edinburgh, UK

received 5 February 2019

Summary. — A discrepancy exists between the ^{6}Li abundances predicted from big bang nucleosynthesis models and those measured in pre-main sequence stars. To further constrain the predicted abundances of ^{6}Li in these stars, high accuracy measurements are required of reactions destroying ^{6}Li, namely ^{6}Li(p,γ)^{7}Be and ^{6}Li(p,α)^{3}He. Their reaction cross-sections were recently measured at astrophysically relevant energies at the Laboratory for Underground Nuclear Astrophysics (LUNA). I present both the experimental setup and current status of the data 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 WMAP observations of the cosmic baryon density [1]. Comparing these primordial predictions to modern day observations, the abundances of hydrogen and helium are in good agreement [2]. However the predicted abundance of ^{7}Li is 2-4 times higher than observed, and inversely the predicted ^{6}Li abundance is 5000 times lower than measured. This large discrepancy in ^{6}Li abundance is currently attributed to proton-induced spallation reactions occuring predominantly in the convective zones of pre-main sequence (PMS) stars [3], however this is expected to destroy more ^{7}Li than ^{6}Li. The destruction processes of ^{6}Li therefore need to be studied more thoroughly, providing an improved knowledge of lithium abundances to assist astrophysics theorists developing convective models of PMS stars.

In this study two destructive processes of ^{6}Li were measured, ^{6}Li(p,γ)^{7}Be and ^{6}Li(p,α)^{3}He, using the LUNA-400kV accelerator located at Gran Sasso, Italy. Gran Sasso provides excellent natural shielding from cosmic rays, thus reducing background radiation and improving measurements at astrophysically relevant energies compared to similar experiments on the Earth's surface. The LUNA-400kV has previously been used

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(*) `https://luna.lngs.infn.it`

to study other reactions of astrophysical interest [4-7]. Data collection for the aforementioned ^{6}Li reactions has been completed, and analysis is currently ongoing.

In current literature the ^{6}Li(p,α)^{3}He S-factor is reported to display a non-resonant behaviour at low energies. In a recent paper [8], the ^{6}Li(p,γ)^{7}Be reaction rate has also been studied to low energies. However the S-factors reported show a sudden drop at decreasing energies, which was not previously accounted for by works in [9-12]. To explain this trend a resonance was proposed at E_r = 195 keV with a proton width Γ_p = 50 keV. Determining the ^{6}Li(p,γ)^{7}Be S-factor at E_{cm} = 64 - 338 keV, thus confirming or denying the proposed resonance, is the final objective of this ongoing experimental campaign at LUNA.

2. – LUNA Experimental Setup

A schematic diagram of the LUNA solid target chamber used for this experimental campaign is shown in figure 1. The accelerator was operated at proton energies E_{lab} = 75 - 394 keV (E_{cm} = 64 - 338 keV), the beam was focused using two circular apertures (of diameter 6 mm and 3 mm) onto ^{6}Li-enriched (^{6}Li/$^{\mathrm{nat}}$Li $\sim$ 95 %) targets. The targets were mounted at 55^{o} to the beam axis. A copper tube was mounted in close proximity to the target and cooled with liquid nitrogen (LN_2) to suppress carbon build-up on the target. A -300 V voltage bias was applied to this same Cu tube for secondary electron suppression. The beam current on target was monitored and recorded during each run. Gamma-rays were detected using a high purity germanium (HPGe) Ortec detector mounted in close geometry on the target axis (source to detector crystal distance <2 cm). Charged particles were measured at a backward angle of 135^{o} using a single silicon detector. Both a 1 mm collimator and 5 μm thick Mylar were mounted in front of the silicon to drastically reduce flux from the backscattered proton beam entering the Si detector.

The silicon detector was calibrated using both a fixed ^{241}Am source and the well-known 151 keV resonance in the ^{18}O(p,α)^{15}N reaction [13]. The HPGe detector was calibrated using both fixed ^{137}Cs, ^{60}Co, and ^{88}Y sources and the well-known 259 keV resonance in the ^{14}N(p,γ)^{15}O reaction [14]. Various ^{6}Li-enriched targets were used during the two months of experiment: $^{6}Li_2O$ with nominal thicknesses 20-40 μg/cm^2, $^{6}LiWO_4$ with nominal thicknesses 100-130 μg/cm^2, and an 'infinitely thick' (>450 μg/cm^2) LiCl target. The oxide and tungstate targets were evaporated on tantalum backings, while the LiCl was evaporated on a Cu backing. The targets were water cooled during beam bombardment.

3. – LUNA Preliminary Results

The HPGe efficiency was determined using gamma rays from both the fixed sources and the ^{14}N(p,γ)^{15}O reaction. As a result of the geometry the detection of gamma rays from a cascade source (for example ^{60}Co) was strongly affected by summing effects(^{1}). The measured HPGe efficiency was corrected using an analytical summing correction similar to one presented in [14]. In addition, Geant4 Monte Carlo simulations are cur-

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(^{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 (<charge collection time of the crystal) resulting in an enhancement of the sum-peak area while simultaneously reducing the individual gamma photopeak areas.

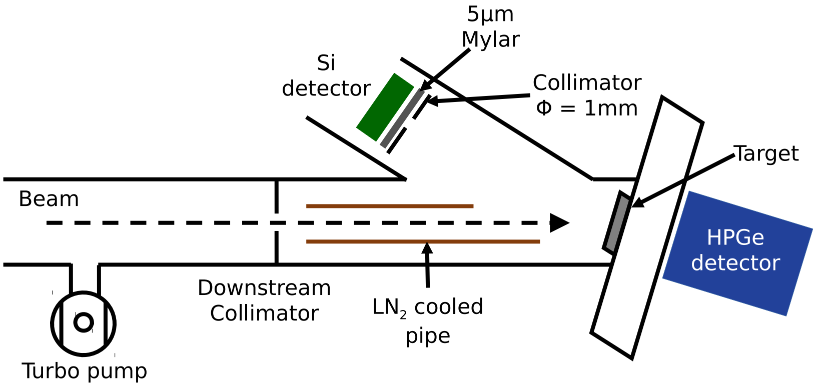


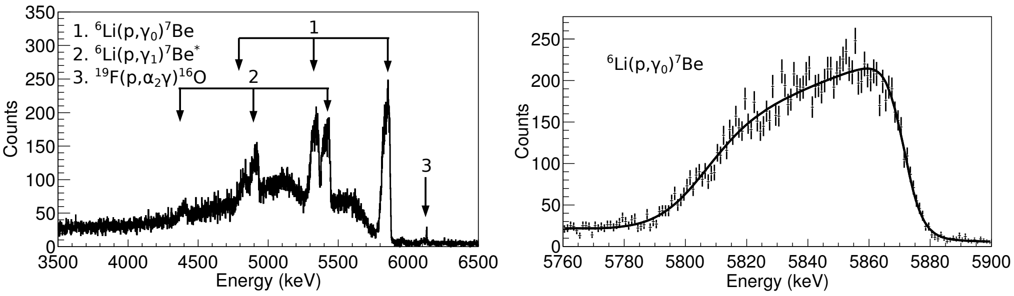
Fig. 1: Schematic diagram of the experimental setup at LUNA.

rently underway to cross check the efficiencies and summing correction of the HPGe detector.

During the measurement, the ^{6}Li(p,γ)^{7}Be direct-capture (DC) gamma-rays were detected by the HPGe. See figure 2(a) for a sample spectrum focused on the relevant energy range of the DC peaks. An empirical fit incorporating physical parameters associated with the target was performed on the DC→0 and DC→429 peaks (see figure 2(b)), thus allowing both the peaks to be integrated and the target degradation to be quantified from the fitted target thickness. Using knowledge of the peak integrals, beam current, and HPGe efficiency, preliminary yields have been extracted for one of the ^{6}LiWO$_4$ targets, and S-factors are currently being extracted.

4. – HZDR Preliminary Results

After bombardment at LUNA, the ^{6}Li-enriched targets were characterised at the Helmholtz-Zentrum Desdren-Rossendorf (HZDR) laboratory in Germany using nuclear resonance analysis (NRA) of the ^{6}Li(α,γ)^{10}B resonance at E$_{\mathrm{lab}}$ = 1173 keV [15]. The target profile collected for one of the ^{6}Li$_2$WO$_4$ targets is shown in figure 3. 'Fresh' targets



(a) Gamma ray spectrum at E$_p$=294keV. Direct capture transitions can be easily distinguished for the three reactions labelled.

(b) Fit applied to DC→0 peak

Fig. 2: Sample ^{6}Li(p,γ)^{7}Be gamma ray spectrum. Error bars are statistical.

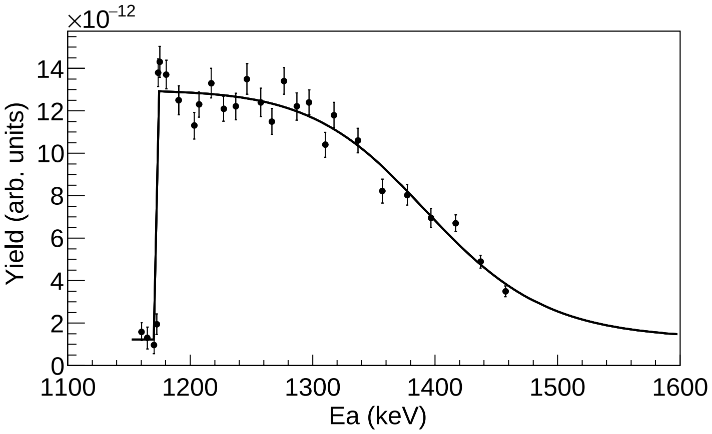


Fig. 3: Target profile obtained using NRA at HZDR for a $^{6}Li_2WO_4$ target. Error bars are total.

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. Alongside the NRA study, the targets composition was determined at HZDR using elastic recoil detection analysis (ERDA).

5. – Future Outlook

Two destructive reactions, ^{6}Li(p,γ)^{7}Be and ^{6}Li(p,α)^{3}He, have recently been studied during an experimental campaign at LUNA, with complementary target characterisation performed at HZDR. The Si and HPGe detector efficiencies have been determined using fixed sources and proton-induced beam reactions. The ^{6}Li nuclear reactions were measured across E_{cm} = 64 - 338 keV. Analysis is currently ongoing to cross-check the HPGe summing correction using Geant4 simulations, and extract S-factors for both destructive reactions.

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