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New direct measurement of the ^{6}Li(p, γ)^{7}Be cross-section at LUNA

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Summary. — ^{6}Li+p fusion reactions take part in primordial nucleosynthesis and in the early stages of stellar evolution, prior to the main sequence. While the ^{6}Li(p,α)^{3}He cross-section is relatively well known, the ^{6}Li(p,γ)^{7}Be reaction is much debated, especially since a recent observation of a broad resonance at center-of-mass energy of 195 keV. Such resonance would correspond to an excited state of ^{7}Be which has neither been observed before, nor supported by theoretical models. In order to verify the existence of such resonance, a new study of the ^{6}Li(p,γ)^{7}Be and ^{6}Li(p,α)^{3}He reactions was performed by the LUNA Collaboration at Gran Sasso National Laboratories. The present work provides an overview of the LUNA experiment and a description of the setup and measurement strategy adopted for the ^{6}Li+p experimental campaign.

1. – Underground nuclear astrophysics and the LUNA experiment

Nuclear reactions provide most of the energy radiated by stars and are responsible for the synthesis of all chemical elements in the Universe, apart from primordial hydrogen and helium. The whole life of a star consists of a sequence of phases in which heavier and heavier elements are produced inside the stellar core starting from the primordial hydrogen and helium. Theoretical models try to match predicted elemental abundances with current high-precision astronomical observations. Therefore, modern stellar models require increasingly accurate inputs.

A much-needed input in order to predict stellar nucleosynthesis is the thermonuclear reaction rate, *i.e.*, the number of reactions per unit time and volume occurring in a star at a given temperature. At typical stellar temperatures, the kinetic energy of interacting nuclei is much lower than the Coulomb repulsive potential. As a consequence, nuclear reactions occur through quantum mechanical tunneling and the cross-section decreases steeply with the energy [1]. The interplay between the Maxwell-Boltzmann energy distribution and the tunneling probability through the Coulomb barrier defines the energy

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region, called the Gamow peak, in which nuclear reactions are more likely to occur. At Gamow energies, nuclear cross-sections may become extremely small (of the order of 10^{-9}–10^{-15} barn), therefore, under typical experimental conditions, the expected counting rate can be much smaller than the environmental background in the detection setup. The source of environmental background in a detector is twofold: cosmic muons and neutrons on one side and the decay of naturally occurring radioactive isotopes (uranium and thorium chains and ^{40}K) on the other. The background from radioactive isotopes can be suppressed by surrounding the detector with high-Z and high-density material (usually lead or copper). On the other hand, cosmic muons are highly penetrating particles that can generate spallation reactions in detectors and surrounding materials, with consequent production of neutrons and radioactive nuclei. An effective way to suppress cosmic-ray–induced background is to perform experiments in underground laboratories. Indeed, not only can the cosmic muon flux be substantially suppressed by a thick rock overburden, but detectors can also be shielded from low-energy gamma background using much thicker linings than overground because secondary emission of radiation from the interaction of cosmic rays within the shielding becomes negligible [2-5].

LUNA (Laboratory for Underground Nuclear Astrophysics), hosted at Gran Sasso underground laboratories (LNGS), Italy, was a pioneering experiment in deep underground nuclear astrophysics [6-8]. The laboratory is shielded by 1400 meters of rock (3800 meters of water equivalent), attenuating the cosmic-ray muon flux by about six orders of magnitude when compared with the surface of the Earth. Figure 1 shows a comparison of HPGe background spectra taken overground and at LNGS. In the region of interest for the ^{6}Li(p,γ)^{7}Be reaction ($E_\gamma = 5200$–6000 keV) the background is reduced by three-to-four orders of magnitude.

The LUNA laboratory was estabilished in 1991 with the installation of a 50 kV accelerator [9]. In 2001 the 50 kV machine was replaced by a 400 kV accelerator, which is still operational today [10].

The LUNA 400 kV accelerator provides proton and alpha-particle beams with intensities as high as 500 μA on target. Beam stability and beam energy resolution are

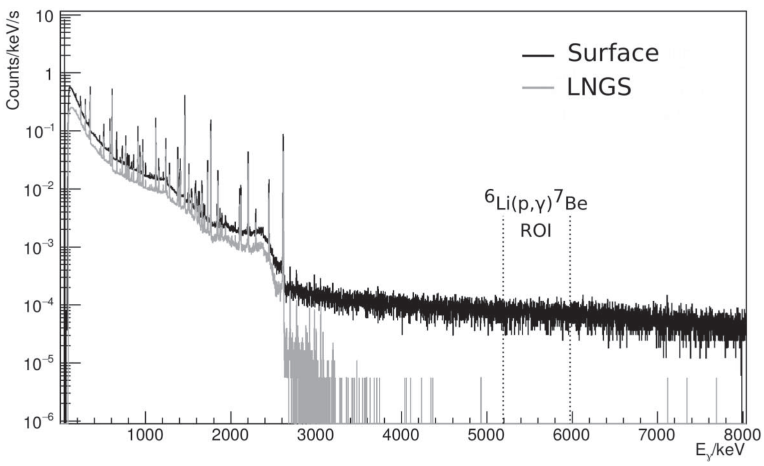

Fig. 1. – Environmental background spectra measured with an HPGe detector positioned at the Earth's surface and at Gran Sasso National Laboratories (LNGS). The dashed lines define the region of interest for primary gamma-rays from the ^{6}Li(p,γ)^{7}Be reaction.

particularly important for nuclear astrophysics experiments, since the fusion cross-section below the Coulomb barrier drops steeply with the energy and the data taking can potentially last for months or even years. Key features of the proton beam provided by the LUNA-400 kV accelerator are: long-term energy stability of 5 eV/h, beam energy spread of 100 eV and energy calibration with 0.3 keV accuracy [10]. Two beam lines are available at LUNA: one equipped with a solid-target setup and the other with a windowless gas target. Different gamma-ray or particle detectors can be used, tuning the detection system according to the specific needs of the nuclear reaction to be studied.

The LUNA setup is ideally suited for the study of hydrostatic hydrogen burning taking place in stars at temperatures of 0.01–0.1 GK [11] and also explosive burning at temperatures up to 1 GK in scenarios such as the Big Bang [12], classical novae and supernovae [13]. Over the years, a large number of reactions involved in stellar hydrogen burning and Big Bang Nucleosynthesis have been investigated at LUNA (see [14-24] for some recent results). The cross-section of those reactions was measured either within or very close to the Gamow window.

More recently, we have focused on the study of the ^{6}Li+p fusion reaction. ^{6}Li(p,γ)^{7}Be and ^{6}Li(p,α)^{3}He are responsible for lithium-6 depletion both during Big Bang Nucleosynthesis and in the early stages of stellar evolution. In stars, lithium isotopes are significantly depleted with time. As a matter of fact, ^{7}Li burning starts at temperatures of the order of 2.5 MK, while ^{6}Li is burned at even lower temperatures. Therefore, the surface abundance of lithium in a star drops as soon as mixing processes expose the surface layers to higher temperatures [25] and observations of the surface abundance of ^{6,7}Li can be used to constraint stellar mixing prior to the star entering the main sequence.

The following sections provide an overview of the state of the art on the ^{6}Li+p fusion reaction and a description of a new direct measurement of the ^{6}Li(p,γ)^{7}Be fusion cross-section recently preformed at LUNA.

2. – State of the art of the ^{6}Li+p fusion cross-section

Stellar ^{6}Li depletion proceedes mainly through the ^{6}Li(p,α)^{3}He reaction, whose cross-section is known to ∼5% accuracy at energies of astrophysical interest [26-28]. Nevertheless, the angular distribution of emitted alpha particles shows a prominent A1 coefficient that can only be reproduced admitting an interference of negative and positive parity excited states [29]. Although all known excited states in ^{7}Be have negative parity, a recent measurement of the ^{6}Li(p,γ)^{7}Be cross-section reported a resonance-like structure around $E_{cm} = 195$ keV [30]. In order to reproduce the observed astrophysical S-factor, an R-matrix calculation was performed assuming the existence of an excited state at $E \sim 5800$ keV, with $J^{\pi} = (1/2^{+}, 3/2^{+})$ and $\Gamma_p \sim 50$ keV. Such exited state, if confirmed, may appear as a resonance not only in the ^{6}Li+p reaction but also in the ^{3}He(^{4}He,γ)^{7}Be reaction from the proton-proton chain, at $E_{cm} = 4210$ keV. Therefore, it can potentially affect the extrapolation of the cross-section of the ^{3}He(^{4}He,γ)^{7}Be reaction to solar energies and, consequently, the estimated flux of ^{7}Be solar neutrino [31]. Figure 2 summarizes the state of the art of experimental determinations of the ^{6}Li(p,γ)^{7}Be astrophysical S-factor $S(E)$, defined as [1] $S(E) = E\sigma(E)\exp^{2\pi\eta}$, where the exponential term is the inverse of the Gamow factor, representing the probability of tunneling through the Coulomb repulsive barrier. Figure 2 shows how different experimental results give conflicting slopes of the S-factor.

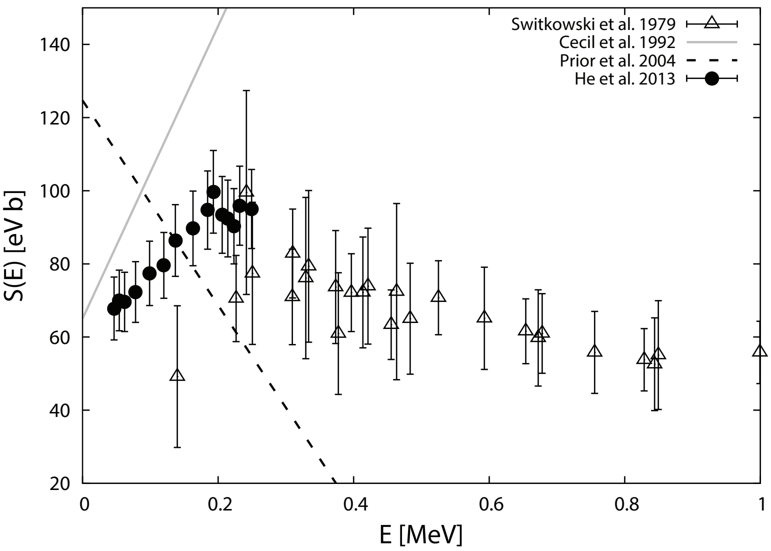

Fig. 2. – Summary of the literature data on the ^{6}Li(p,γ)^{7}Be cross-section [30, 32-34]. Data from [33] and [34] are reported as lines, since those experiments only provided information on the slope of the S-factor.

In order to verify the existence of the 195 keV resonance, a new direct measurement was performed at LUNA exploiting the low-background conditions of the experiment (see fig. 1).

3. – Experimental setup

A new ^{6}Li(p,γ)^{7}Be cross-section measurement was performed delivering a proton beam to a solid lithium target. Before reaching the target, the beam was collimated by a circular aperture of 0.3 cm diameter and passed through a copper tube cooled with liquid nitrogen. The tube served as a cold trap to prevent buildup of contaminants on target, moreover it was biased to -300 V for secondary electron suppression. This setup allowed to use the scattering chamber as a Faraday cup to integrate the beam current on target. The target holder was oriented at 55° with respect to the beam axis and designed to allow direct water-cooling of the target backing in order to dissipate the power deposited by the beam. An HPGe gamma-ray detector with 104% relative efficiency was mounted in close geometry at 55° from the beam direction, while a silicon detector was installed at 125° (see fig. 3) to detect charged particles from the competing reaction ^{6}Li(p,α)^{3}He. Given the high cross-section of the (p,α) reaction and in order to limit the particle flux reaching the detector, the silicon detector was mounted on a linear actuator to adjust its distance from the target and it was collimated with a 1 mm diameter and 1 mm thick copper collimator. A mylar foil placed in front of the detector absorbed the protons scattered on target. With this setup, the (p,γ) and (p,α) channels were measured concurrently in each irradiation.

4. – Target preparation and analysis

^{6}Li solid targets were produced at the Institute for Nuclear Research (Atomki, Hungary) using two different compounds: lithium oxide and lithium tungstate. Lithium

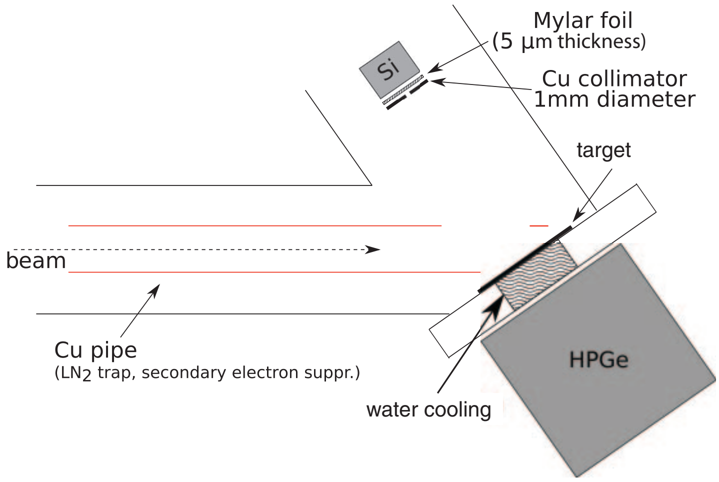

Fig. 3. – Sketch of the experimental setup. The most relevant components are labeled.

oxide powder was produced at Legnaro National Laboratories starting from isotopically-enriched metallic lithium. Both compound powders were evaporated on 0.2 mm thick tantalum backings. All targets were enriched in ^{6}Li at the 95% level. The targets used for the LUNA measurements were characterized at the Helmholtz-Zentrum Dresden-Rossendorf (HZDR) using two independent techniques: Nuclear Reaction Analysis (NRA) and Elastic Recoil Detection Analysis (ERDA). Combining the results from the two techniques it was possible to obtain a complete characterization of the targets: while ERDA provides the abundances of different light elements in the target, NRA provides a more detailed distribution of the ^{6}Li as a function of the depth. Nuclear reaction analysis exploited the well-known and narrow ^{6}Li(α,γ)^{10}B resonance at 1175 keV, $\omega\gamma = (366 \pm 17)$ meV and $\Gamma_r = 1.7$ eV. Figure 4 shows the resonance scans obtained for the four targets used at LUNA. Resonance scans were also measured on fresh targets that had not been irradiated at LUNA, in order to investigate the effect of irradiation with intense proton beam.

5. – Data taking and data analysis

Complete ^{6}Li+p excitation functions were measured on four targets: three targets made of lithium tungstate and one made of lithium oxide. The center of mass energy range between 60 and 350 keV was explored, spanning completely the energy range of the new alleged resonance.

Target deterioration due to irradiation with intense ion beam was periodically checked by acquiring spectra at a reference energy. Target thickness was derived both from the reaction yield and from a line shape analysis of the primary gamma-ray peaks [10] and it was found to be always lower than 20%.

Lithium oxide is known to change its composition when exposed to air moisture, therefore assessing its composition at the time of the measurement is non-trivial. On the other hand, lithium tungstate is more stable but more difficult to characterize with ERDA because tungsten atoms are similar in mass to the tantalum in the backing. A detailed comparison of results obtained with different targets will help evaluate possible systematic effects due to target properties.

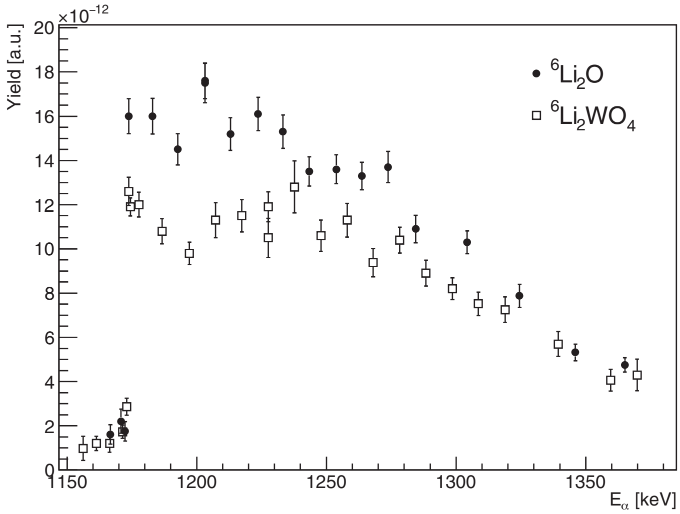

Fig. 4. – Scans of the ^{6}Li(α,γ)^{10}B resonance at 1175 keV performed on two different targets used for the measurement of the ^{6}Li+p cross-section at LUNA.

Since charged particles and gamma-ray spectra were acquired simultaneously in each run, it will also be possible to use the (p,α) cross-section (which is relatively well known from the literature) as a normalization standard in case target characterization is not sufficiently accurate. The data analysis is presently being finalized.

6. – Conclusions

The energy trend of the S-factor of the ^{6}Li(p,γ)^{7}Be reaction is presently under debate because of the detection of an inversion in the slope of the S-factor attributed to a previously unknown resonance a center-of-mass energy of 195 keV. In order to confirm or disprove the existence of such resonance, a new direct measurement of the ^{6}Li+p cross-section was performed deep underground at LUNA, taking advantage of the unique low background conditions. The setup used for the experiment and the data taking strategy were illustrated in the present paper, preliminary results were shown during the presentation and will soon be published.

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