NUCLEAR ASTROPHYSICS DEEP UNDERGROUND: THE LUNA EXPERIMENT*

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LUNA (Laboratory for Underground Nuclear Astrophysics) is a nuclear astrophysics experiment running at the INFN Laboratori Nazionali del Gran Sasso (LNGS). Aim of the experiment is to measure the cross-section of fusion reactions that take place inside the stars and that, in the past, dominated the Big Bang nucleosynthesis (BBN). The low value of these cross-sections (varying from *pb* to fb and even smaller), in the astrophysical range of energies, prevent any kind of measurements at the Earth's surface. On the other hand, the low background of the LNGS underground laboratory allows LUNA to investigate these reactions at energies of astrophysical interest without the necessity of an extrapolation from the highest energies. Recently, the LUNA Collaboration has been engaged in the study of the $^2\mathrm{H}(\alpha,\gamma)^6\mathrm{Li}$ and $^{17}\mathrm{O}(p,\gamma)^{18}\mathrm{F}$ reactions. In this paper the experimental set-up will be described and the preliminary data will be discussed. The future possibilities of LUNA will also be outlined.

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1. Introduction

The "nuclei zoo" observed every day on the Earth is a consequence of the thermonuclear reactions that, in the past, dominated the first phases of the Universe (Big Bang Nucleosynthesis, BBN) and that now take place in stars and in "hot habitats" like novae or supernovae explosions. All these fusion reactions occur in a well defined energy range, the so-called Gamow peak [1], which depends on both the velocity distribution of the nuclei in

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the astro-physical environment (Maxwell–Boltzmann distribution) and the tunnelling probability of the Coulomb barrier. The resulting cross-section drops almost exponentially with decreasing energy. It can be written as

$$\sigma\left(E\right) \;=\; \frac{S\left(E\right)}{E}\exp\left(-2\pi\eta\right)\,, \tag{1.1a}$$

where $S\left(E\right)$ is the astrophysical S factor that includes the cross-section's pure nuclear behaviour and η is the Sommerfeld parameter

$$\eta \;=\; \frac{31.29}{2\pi}Z_1Z_2\sqrt{\frac{\mu}{E}}\,, \tag{1.1b}$$

where Z_1 and Z_2 are the atomic numbers of the projectile and target, μ is the reduced mass (in atomic mass units) and E is the energy (in keV) in the center-of-mass system. In the BBN and stellar environments, the Gamow peak has values smaller than a few hundreds of keV. At these energies, the reaction cross-section drops to values from picobarn to femtobarn and even smaller, preventing a direct measurement on the Earth's surface [2,3]. Thus extrapolation is needed. This could lead to substantial uncertainties, such as the possible presence of a resonance in the unmeasured energy region, not accounted for by the extrapolation.

The aim of the LUNA experiment [2,3] is measuring these cross-sections at the LNGS [4] low background environment. Two reactions are now under investigation at LUNA: $^{2}\mathrm{H}(\alpha,\gamma)^{6}\mathrm{Li}$ and $^{17}\mathrm{O}(p,\gamma)^{18}\mathrm{F}$.

The first is one of the most important reaction of the BBN. It determines the amount of primordial ^{6}Li in the Universe. Recently, ^{6}Li isotope has been detected in a number of metal poor stars and its quantity has been found to be higher than expected from BBN by 2–3 orders of magnitude [5]. Direct measurements of this reaction have been performed only down to 1 MeV and around the 711 keV resonance while the region of interest (ROI) for BBN is between 30 and 400 keV. This reaction has been measured at LUNA down to 130 keV (about 400 keV in the laboratory reference system) during 2010–2011.

The $^{17}\mathrm{O}(p,\gamma)^{18}\mathrm{F}$ that takes place in different stellar sites like red giants, AGB stars, massive stars and classical novae. It belongs to the CNO cycle and, together with the alternative $^{17}\mathrm{O}(p,\alpha)^{14}\mathrm{N}$ reaction, governs the ^{17}O and ^{18}F nucleosyntesis. Each stellar site is characterized by a different temperature range corresponding to a different energy window. As a whole, the reaction rate should be known from 18 to 390 keV proton beam energy. Measurement of the 193 keV resonance with both prompt gammas and activation methods has been performed during 2010–2011.

2. The ^{2}H$(\alpha, \gamma)^6$ Li reaction

In order to investigate reaction cross-sections in the astrophysical energy range, LUNA installed two electrostatic accelerators (a 50 kV [6] and a 400 kV [7] one) deep underground. Outstanding features of both accelerators are a very small beam energy spread (70 eV), a very high beam current even at low energy (maximum value: 500 μA for protons, 250 μA for helium ions) and a long time stability (5 eV/h). The accelerated particles can be switched in two beam lines: one is used for solid targets and another one for gas targets. In the case of the ^{2}H$(\alpha, \gamma)^6$Li reaction, the alpha beam passes through the gas target chamber filled with deuterium gas at 0.3 mbar. The chamber is made of steel and is surrounded by a lead shield with a radon-suppression box. Another shield in High Density Polyethylene (doped with 5% of lithium) is present in order to absorb the neutrons that come from the $d(d,n)^3$He reaction due to the deuterons Rutherford scattered by the alpha beam. The neutron production is monitored by the detection of protons emitted in the $d(d,p)t$ reaction, with a silicon detector located near the interaction area.

The gamma rays produced by the ^{2}H$(\alpha, \gamma)^6$Li reaction are collected by a High Purity Germanium Detector (HPGe). The ROI for 400 keV alphas is [1585, 1625] keV. The preliminary results are shown in figure 1.

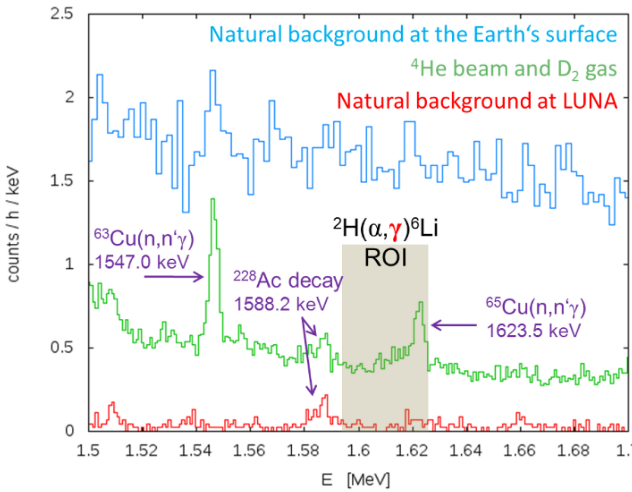

Fig. 1. The ^{2}H$(\alpha, \gamma)^6$Li ROI. The upper curve (blue) shows the natural background at the Earth surface, lower (red) — the natural background at LUNA, middle (green) — the ^{2}H$(\alpha, \gamma)^6$Li gamma spectrum.

This plot does not show any evident peak in the ROI. However, since the beam induced background (BIB) due to $(n, n'\gamma)$ reactions on different materials composing the experimental apparatus is expected to be higher than the signal, a new method was considered. This consists in acquiring spectra at two different beam energies (280 and 400 keV) and subtracting the 280 keV spectrum from the 400 keV one. Since the ROIs of the ^{2}H$(\alpha,\gamma)^6$Li signal are not overlapping at the two energies and the BIBs are expected to be similar, the result of the subtraction should be a positive signal in the 400 keV ROI. Measurements and data analysis are in progress.

3. The ^{17}O$(p,\gamma)^{18}$F reaction

Here a proton beam hits a ^{17}O solid target. Such (high purity and highly enriched in ^{17}O) targets are produced at LNGS by anodization processes on tantalum thin foils. The gammas produced by the ^{17}O$(p,\gamma)^{18}$F reaction are collected by a HPGe detector.

Two independent measurements of the 193 keV resonance strength have previously been performed by Fox *et al.* [8] and Chafa *et al.* [9, 10] using prompt gammas and activation methods, respectively. The values obtained are in disagreement by approximately a factor of 2. At LUNA the 193 keV resonance has been measured with both techniques. For the prompt gammas method, figure 2 shows an example of the primary and secondary gammas.

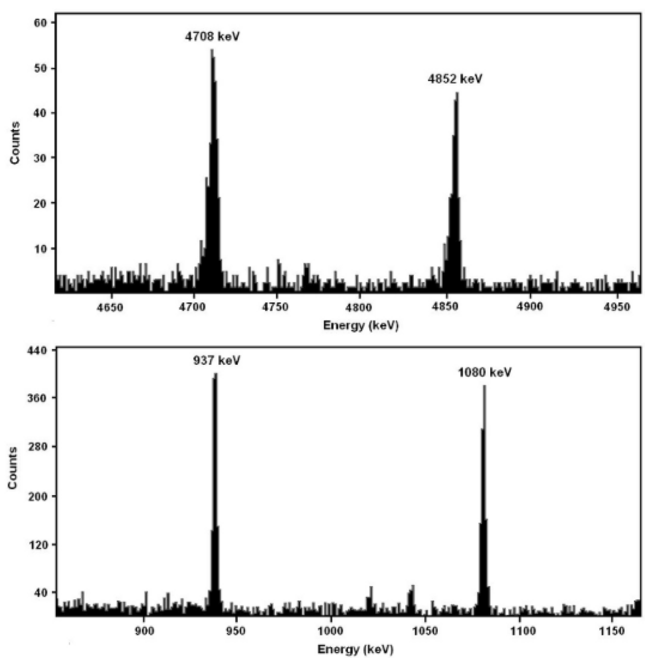

Fig. 2. Gamma-ray spectra showing the two primary (top panel) and two secondary (bottom panel) gamma-ray peaks from the ^{17}O$(p,\gamma)^{18}$F reaction, after background subtraction. The beam energy is 197.9 keV.

For the activation method, which consists in detecting the ^{18}F β^+ activity followed by positron annihilation and 511 keV gamma emission, figure 3 shows the decay plot. A first fit gives a value of the half-life in good agreement with the reference value of about 110 minutes.

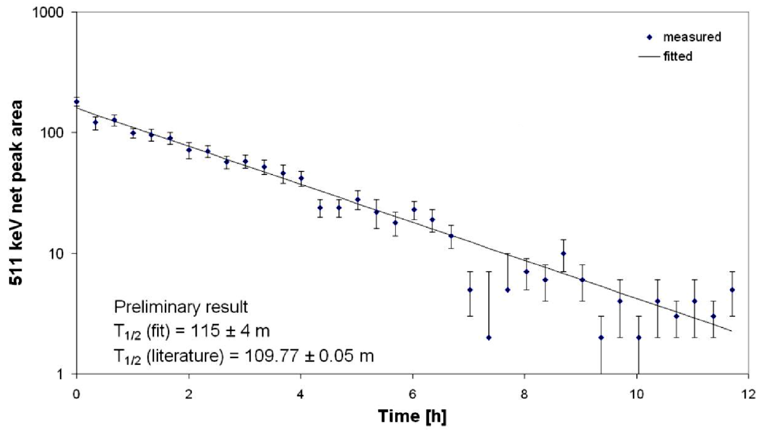

Fig. 3. Activation decay plot. The linear fit gives a half-life of 115 ± 4 min in good agreement with the reference value of 109.77 ± 0.05 min.

4. Conclusions

In this paper we report on the last measurements still in progress at LUNA. Results will be published soon.

In the future, the LUNA Collaboration will be involved in the measurement of the $^{22}\mathrm{Ne}(p,\gamma)^{23}\mathrm{Na}$ and $^{23}\mathrm{Na}(p,\gamma)^{24}\mathrm{Mg}$ cross-sections.

The natural next step is an upgrade of the LUNA apparatus in order to be able to study reactions of the helium burning such as $^{12}\mathrm{C}(\alpha,\gamma)^{16}\mathrm{O}$ witch shapes the nucleosyntesis in massive stars up to the iron peak and the proprieties of supernovae, and the $^{13}\mathrm{C}(\alpha,n)^{16}\mathrm{O}$ and $^{22}\mathrm{Ne}(\alpha,n)^{25}\mathrm{Mg}$ which provide the stellar sources of neutrons responsible for the production of most of the trans-iron elements through the *s*-process. For this purpose a 3.5 MV electrostatic accelerator is needed. A letter of intent for installing such machine underground has been submitted to the LNGS scientific committee in 2007 and the full proposal is under development.

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