NUCLEAR COSMOLOGY DEEP UNDERGROUND*

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Thanks to the Big Bang Nucleosynthesis (BBN), it is possible to estimate the primordial abundance of all the elements produced in the first few minutes of the Universe. Inputs of the theory are: the cosmological model assumed and the nuclear cross section of the processes involved. The former consists in the ΛCDM (Lambda-Cold Dark Matter) model or its possible extensions. The latter usually implies low cross section measurements, often extremely difficult in standard nuclear experiments due to the high cosmic background present on the Earth surface. Therefore, the best solution is to go deep underground where this kind of background is much suppressed. As of today, the only facility in the world where it is possible to perform direct measurements of low cross section in a very low background context is LUNA — Laboratory for Underground Nuclear Astrophysics, located in the Laboratori Nazionali del Gran Sasso (LNGS), Italy. Thanks to the background suppression provided by about 1400 meters of rock and to the high current provided by the 400 kV accelerator, LUNA is able to investigate cross sections at energies of interest for the Big Bang Nucleosynthesis using as projectiles protons, ^{3}He and alpha particles. In this paper, I will report on the recent results obtained at LUNA for the ^{2}H(α,γ)^{6}Li reaction. This is the "key-reaction" in the primordial ^{6}Li production and the related cross section has never been directly measured before at relevant energies. Another important process in the BBN is the ^{2}H$(p,\gamma)^{3}$He reaction. The uncertainty on its cross section should explain the small discrepancy between observed and calculated primordial deuterium abundances. In order to reduce it, a new measurement of this cross section in the BBN energy range with an accuracy less than 3% is thus desirable. Such a measurement is planned at LUNA at the beginning of 2016. However, a feasibility test has already been performed. The results obtained are shown. Possible cosmological and theoretical nuclear physics outcomes from future LUNA data is also discussed.

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1. Big Bang Nucleosynthesis: an overview

About three minutes and half after the Big Bang, the Universe temperature was such that it was possible to synthesize isotopes heavier than hydrogen such as deuterium, tritium, helium, lithium and beryllium. These favourable conditions lasted for about twenty minutes. After that, the temperature was low and fusion reactions were no longer possible until first stars formation. The theory that predicts the primordial abundances of these light isotopes is the Big Bang Nucleosynthesis (BBN). Inputs of this theory are the cosmological model and the cross section of the nuclear reaction involved. The former is the ΛCDM model (or its extensions) whose parameters are constrained by cosmic microwave radiation measurements such as the ones recently done by the Planck Collaboration [1]. The latter are the reaction cross sections as measured in nuclear physics laboratories. Usually, due to the low-energy regimes in which these processes become important for BBN, relative cross sections assume very low values often requiring the use of deep underground laboratories. LUNA — Laboratory for Underground Nuclear Astrophysics [2, 3] is the only deep underground laboratory for Nuclear Astrophysics, located in the Laboratori Nazionali del Gran Sasso (LNGS, Italy).

Primordial abundances can also be estimated starting from spectroscopic measurements of ancient astrophysical objects such as quasars or metal-poor stars. These ones must be consistent with the BBN prediction. This is the case of ^{4}He where observations [4] and calculations [5] are in good agreement with each other. The situation is also good for deuterium even if a small discrepancy is present [6]. Different is the case of lithium where for ^{7}Li we have about a factor three disagreement, while for ^{6}Li three order of magnitude (the so-called first and second "lithium problem") [7]. In this paper, recent results obtained at LUNA on key-reactions for BBN, ^{2}H(α,γ)^{6}Li and ^{2}H(p,γ)^{3}He, will be presented.

2. The second lithium problem at LUNA

If non-standard physical solutions to the second lithium problem are excluded, the only possible explanations should come from astronomical observations or nuclear data. The astronomical detection of primordial ^{6}Li in halo metal-poor stars is still debated due to possible systematics introduced when the convective motion of stellar atmosphere is considered [8, 9]. As a consequence, future measurements with higher sensitivity resolution are desirable. At the same time, the reaction responsible for the primordial ^{6}Li destruction, *i.e.* the ^{2}H(α,γ)^{6}Li, was never measured directly in the energy range of BBN and only upper limits of the cross section were established. In order to solve this puzzle, this reaction has been studied at LUNA. The results obtained for two energy values 93 and 133 keV ruled out any possible nuclear solution to the second lithium problem [10]. The experimental setup used in that measurement campaign as well as the preliminary results obtained for other two energies (80 and 120 keV) will be discussed in details in the next sections.

2.1. Experimental setup

In the ^{2}H(α,γ)^{6}Li measurement, an alpha beam provided by the LUNA 400 kV accelerator [11], pass through three different pumping stages and finally goes in a windowless gas target chamber filled with deuterium at a pressure of 0.3 mbar. The beam is characterised by: high current of the order of hundreds μA also at low energies, very small beam energy spread (70 eV) and long time stability (5 eV/h). Inside the gas chamber, a steel collimator system is also present in order to reduce the beam spot dimensions. A lead castle and an anti-radon box flushed with nitrogen is provided for decreasing the gamma background coming from environmental radioactivity. For what concerns the cosmic ray radiation, it is completely negligible thanks to the about 1400 meter Gran Sasso rocks that provide a reduction of a factor six in the muon flux and three in the neutron one. The gamma rays produced by the ^{2}H(α,γ)^{6}Li reaction are collected by a High Purity Germanium (HPGe) detector. A huge beam induced background due to the Rutherford scattering of the alpha ions on the deuterons present in the gas target is also present. As a matter of fact, these energetic scattered deuterons collide with the other deuterons present in the gas chamber, producing the parasitic ^{2}H(^{2}H,n)^{3}He reaction with consequent $(n, n'\gamma)$ reactions on the surrounding materials. In

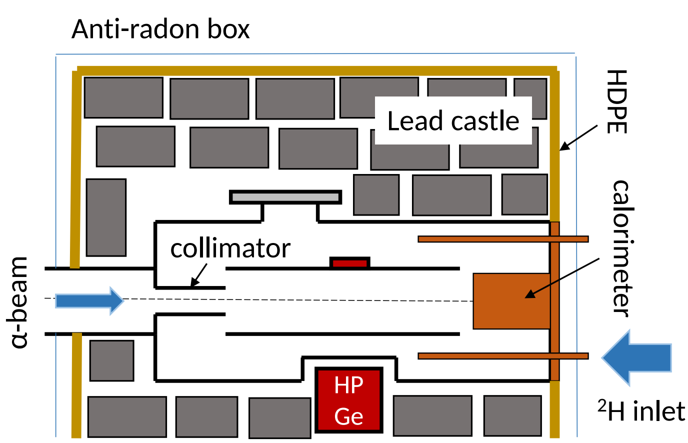

Fig. 1. Setup used at LUNA for the ^{2}H(α,γ)^{6}Li cross section measurement campaign. More details are reported in [12].

order to not increase the natural neutron background of the LNGS, a borated High Density Polyethylene (HDPE) castle is mounted between the lead castle and the anti-radon box. The alpha particles stop on the calorimeter where the beam current is measured. The setup used at LUNA for the $^{2}\mathrm{H}(\alpha,\gamma)^{6}\mathrm{Li}$ reaction is summarized in Fig. 1. More details are reported in [12].

2.2. Preliminary results

In nuclear astrophysics, the nuclear cross section is parametrized by the astrophysical S-factor, defined as

$$S(E) = \sigma(E) E \exp\left(31.29 Z_1 Z_2 \sqrt{\frac{\mu}{E}}\right) , \tag{2.1}$$

where $\sigma(E)$ is the nuclear cross section, E the energy in the center-of-mass system (expressed in keV), Z_1 and Z_2 the electrical charges of the colliding nuclei and μ is the reduced mass in atomic mass units. At LUNA, four

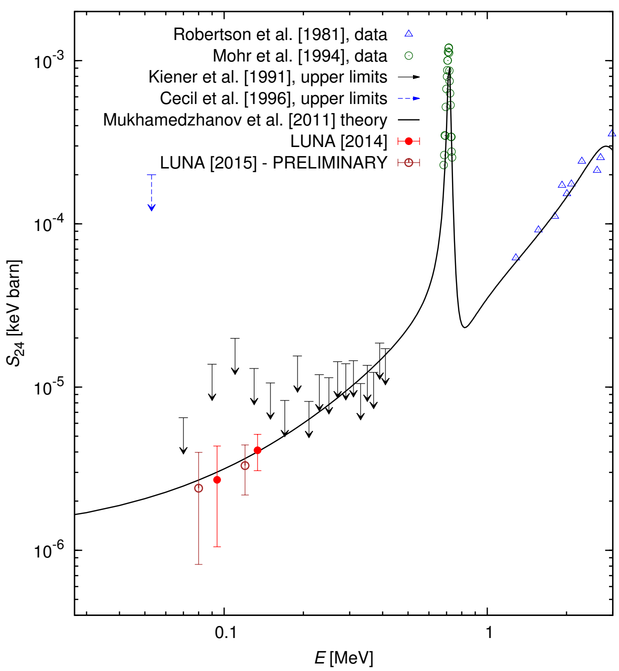

Fig. 2. Astrophysical S-factor of the $^{2}\mathrm{H}(\alpha,\gamma)^{6}\mathrm{Li}$ reaction. Full circles (red) — the LUNA data published in 2014 [10]. Open circles (brown) — the preliminary analysis of the new 80 and 120 keV data points. Previously measurements and the Mukhamedzhanov theoretical curve are also reported [10].

different energies have been investigated: 80, 93, 120 and 133 keV. In order to extract the ^{2}H(α,γ)^{6}Li cross section, two different analysis method have been developed, both providing consistent results. However, only the 133 keV dataset have enough statistics in order to apply a peak shape analysis. The LUNA S-factor values for the two data points at 93 and 133 keV have been recently published [10]. The analysis of the other two energies is till in progress. Our preliminary results are shown in Fig. 2 and the numerical values reported here:

$$S(80\ \mathrm{keV}) = \left(2.4 \pm 1.5^{\mathrm{stat}} \pm 0.5^{\mathrm{syst}}\right) \times 10^{-6}\ \mathrm{keVb}\,, \tag{2.2}$$

$$S(93\ \mathrm{keV}) = \left(2.7 \pm 1.6^{\mathrm{stat}} \pm 0.4^{\mathrm{syst}}\right) \times 10^{-6}\ \mathrm{keVb}\,, \tag{2.3}$$

$$S(120\ \mathrm{keV}) = \left(3.3 \pm 1.0^{\mathrm{stat}} \pm 0.5^{\mathrm{syst}}\right) \times 10^{-6}\ \mathrm{keVb}\,, \tag{2.4}$$

$$S(133\ \mathrm{keV}) = \left(4.0 \pm 0.9^{\mathrm{stat}} \pm 0.5^{\mathrm{syst}}\right) \times 10^{-6}\ \mathrm{keVb}\,. \tag{2.5}$$

Using the new ^{2}H(α,γ)^{6}Li cross section, a BBN lithium abundance ratio of $^6\mathrm{Li}/^7\mathrm{Li} = (1.5 \pm 0.3) \times 10^{-5}$ is obtained, excluding a standard BBN production as a possible explanation for the reported ^{6}Li observations.

3. Studying the primordial deuterium at LUNA

Deuterium is the first nucleus produced by neutron capture on protons at the beginning of the so-called "Big Bang Nucleosynthesis era". However, the main uncertainty on the primordial deuterium abundance calculation $^2\mathrm{H/H} = (2.65 \pm 0.07) \times 10^{-5}$ comes from the ^{2}H(p,γ)^{3}He cross section, known at the 6%–10% level in the BBN energy range [6]. This uncertainty is higher than the one obtained in astronomical observations where the abundance $^2\mathrm{H/H} = (2.53 \pm 0.04) \times 10^{-5}$ is obtained [13]. Moreover, a small discrepancy between the two values is present. Due to these motivations, a new measurement campaign of the ^{2}H(p,γ)^{3}He cross section is planned at LUNA in 2016. The main goal is to span, with high precision measures, the overall BBN energy range. This one is fully covered by the LUNA 400 kV accelerator machine [11]. In order to obtain a high precision cross section measurement (at the percent level), a reduction of all possible systematics is desirable. This can be achieved using different set-ups and detectors. Thus, the LUNA measurement campaign will be organized in two different experimental phases, both using a windowless gas target.

In the former phase, a 4π BGO detector will be used. This one is practically insensible to the angular distribution of the γ rays emitted by the ^{2}H(p,γ)^{3}He reaction. Moreover, thanks to the high efficiency (about 70%), the detector is able to collect data also at low energies.

In the latter phase, the HPGe detector used in the ^{2}H(α,γ)^{6}Li measurement campaign will be adopted. With this detector, a high energy resolution γ-ray spectrum can be obtained. Thus, from the ^{2}H$(p,\gamma)^3$He peak shape analysis, it will be possible to extract the angular distribution of the γ rays emitted *i.e.* the differential cross section. In order to investigate possible unknown systematics, a feasibility test has been done at LUNA in October 2014.

3.1. ^{2}H(p,γ)^{3}He feasibility test at LUNA

The set-up used for the ^{2}H$(p,\gamma)^3$He feasibility test is similar to the one described in Section 2.1. The only difference is that the lead castle, the anti-radon box and the HDPE shielding have been removed. This modification reduces a possible attenuation of the γ rays between the interaction point and the HPGe detector. The natural background level was obviously higher than in past LUNA experiments. However, the high ^{2}H$(p,\gamma)^3$He γ rays energy (of the order of 5–6 MeV) as well as the LNGS cosmic rays reduction make the natural background contribution negligible, less than 0.07 events/hour. The main source of background is the Beam Induced Background (BIB). Two are the main BIB contributions expected for this experiment: (p,γ) reactions on contaminants and $(n,n'\gamma)$ reaction on surrounding materials. The former depends on the purity of the material adopted in the mechanical parts production. The latter is due to the neutrons produced by the ^{2}H(^{2}H,n)^{3}He reaction, as described in Section 2.1 but with a lower cross section due to the use of protons instead of alphas. During the feasibility test, all the calibration procedures have been tested except the HPGe detector efficiency. Monte Carlo simulations in order to estimate this value are under investigation.

3.2. Results

The ^{2}H$(p,\gamma)^3$He γ-ray spectra have been acquired for proton energies 379.8, 339.8, 261.5, 202.4 and 114.8 keV (see Fig. 3). As expected, the noise-to-signal ratio approaches zero and the background sources are practically negligible. The contaminants found during the feasibility test are ^{12}C and ^{19}F. Proton direct capture on ^{12}C is thus present, producing low-energy γ rays (about 2.25 MeV), well outside the ^{2}H$(p,\gamma)^3$He region of interest. The main BIB contribution comes from the ^{19}F$(p,\alpha\gamma)^{16}$O reaction. It shows a huge resonance at 340 keV with 6.1 MeV γ-ray emission peak. The associated Compton γ rays sum up to the ^{2}H$(p,\gamma)^3$He signal and must be subsequently subtracted. Fortunately, this events are negligible also when the energy is close or at the resonance energy value. During the test done at LUNA, the procedure adopted by the collaboration in order to extract the angular distribution of the ^{2}H$(p,\gamma)^3$He γ rays was also validated. However, due to the low statistics acquired, no differential cross section could be extracted.

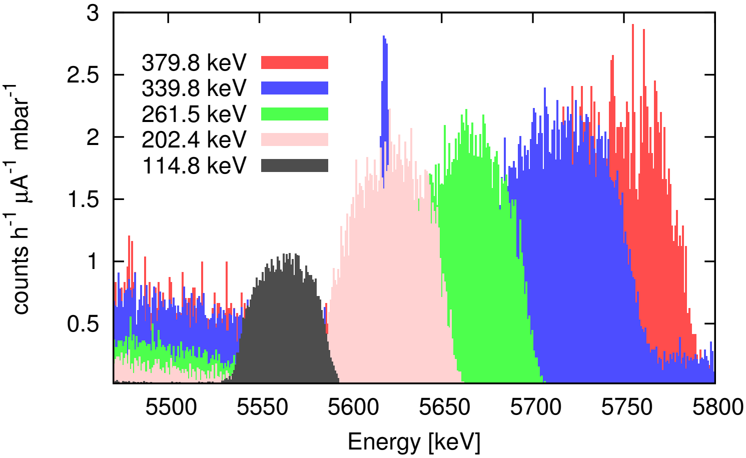

Fig. 3. The ^{2}H$(p,\gamma)^3$He counting rate taken at LUNA during the 2014 feasibility test. The ^{2}H$(p,\gamma)^3$He peak is broad due to the Doppler effect of the emitted gammas and the recoil of the ^{3}He nuclei. Its width depends on the setup geometry. The narrow peak at 5.6 MeV for the 340 keV run is the first escape associated to the ^{19}F$(p,\alpha\gamma)^{16}$O reaction on fluorine contaminant.

4. Conclusion

In this paper, the recent results obtained at LUNA on reactions involved in the BBN network have been presented. The study of the ^{2}H$(\alpha,\gamma)^6$Li reaction shows how the nuclear astrophysics can give indications on the solution of important astrophysical puzzles like the second lithium problem. At the same time, the ^{2}H$(p,\gamma)^3$He measurement campaign planned at LUNA in 2016 could provide strong constraints on the cosmological parameters. In conclusion, thanks to nuclear astrophysical measurements, it is now possible to investigate the early ages of the Universe.

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