Study of the $^2\text{H}(p,\gamma)^3\text{He}$ reaction in the BBN energy range at LUNA

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Abstract. Using Big Bang Nucleosynthesis with the recent cosmological parameters obtained by the Planck collaboration, a primordial deuterium abundance value $D/H = (2.65 \pm 0.07) \times 10^{-5}$ is obtained. This one is a little bit in tension with astronomical observations on metal-poor damped Lyman alpha systems where $D/H = (2.53 \pm 0.04) \times 10^{-5}$. In order to reduce the BBN calculation uncertainty, a measurement of the $^2\text{H}(p,\gamma)^3\text{He}$ cross section in the energy range 10-300 keV with a 3% accuracy is thus desirable. Thanks to the low background of the underground Gran Sasso Laboratories, and to the experience accumulated in more than twenty years of scientific activity, LUNA (Laboratory for Underground Nuclear Astrophysics) planned to measure the $^2\text{H}(p,\gamma)^3\text{He}$ fusion cross section at the BBN energy range in 2015-2016. A feasibility test of the measurement has been recently performed at LUNA. In this paper, the results obtained will be shown. Possible cosmological outcomes from the future LUNA data will be also discussed.

1. Introduction
About three minutes and half after the Big Bang during the so called “Big Bang Nucleosynthesis” (BBN) era, thanks to the cosmic expansion, the Universe pass through a phase in which nuclear forces were able to synthesize light elements like Hydrogen, Helium, Lithium and Beryllium. From the theoretical point of view, the Universe expansion is described by the ΛCDM (Lambda Cold Dark Matter) model whose parameters are constrained by cosmological measurements. Using the experimental cross section of the reaction involved, it’s thus possible to calculate the abundances of the primordial isotopes produced during the BBN. This values can be compared with the astronomical observations obtained in ancient astrophysical objects. Using the recent cosmological parameter values obtained by the PLANCK [1], a good agreement between BBN calculations and astronomical observations has been obtained except for Lithium (the so called “Lithium problem”). In the case of primordial deuterium, an accurate abundance determination has been obtained both from the astronomical and nuclear-astrophysical point of view. $D/H = (2.53 \pm 0.04) \times 10^{-5}$ value has been recently obtained by Cooke et al. [2] in metal-poor damped Lyman alpha systems. This one is a little bit in tension with BBN calculations $D/H = (2.65 \pm 0.07) \times 10^{-5}$ [3]. In order to clarify the actual situation, a reduction of the uncertainty is thus mandatory. From the BBN side, the main contribution to the error budget comes from the nuclear sector, i.e. the measurement of the cross sections involved in the deuterium production and destruction. It can be produced by neutron capture on proton and destructed with the $^2\text{H}(p,\gamma)^3\text{He}$, $^2\text{H}^2(p, p)^3\text{H}$, $^2\text{H}(^2\text{H}, n)^3\text{He}$ nuclear reactions. Up to now, the main contribution to the $D/H$ error budget is due to the uncertainty on the $^2\text{H}(p,\gamma)^3\text{He}$ cross section [3]. This cross
section has been measured in the past by many authors but the energy range relevant for the BBN (10 keV < E < 300 keV) is up to now covered only by a limited subset [4, 5] of them providing an overall 6-10% error on the S-factor [3]. As suggested by many authors [1, 3, 6], a new precise measurement of the $^2$H(p,γ)$^3$He cross section in the BBN energy of interest is thus desirable. Thanks to the experience accumulated in about two decades of scientific activity and to the low natural background provided by the Laboratori Nazionali del Gran Sasso (LNGS), a new direct measurement of the $^2$H(p,γ)$^3$He cross section has been planned at LUNA (Laboratory for Underground Nuclear Astrophysics) at the BBN energy range between the end of the 2015 and the beginning of 2016. A feasibility test has been performed at LUNA in October 2014. In the next sections a description of the apparatus used and the results obtained will be shown.

![Figure 1.](image1)

**Figure 1.** Experimental setup: The proton beam enters in the gas target filled of deuterium through the collimator (1), passes through the steel pipe (2) and reaches the calorimeter (3). The deuterium gas inlet is below the calorimeter (4). The pressure is kept constant by means of a feedback system controlled by pressure gauge (5). The γ-rays produced by the $^2$H(p,γ)$^3$He reaction are detected by a HPGe detector (6).

**Figure 2.** The $^2$H(p,γ)$^3$He counting rate taken at LUNA during the 2014 feasibility test. The $^2$H(p,γ)$^3$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 6.1 MeV for the 340 keV run is due to the $^{19}$F(p,αγ)$^{16}$O reaction on fluorine contaminant.

### 2. Experimental Setup

The $^2$H(p,γ)$^3$He reaction has been studied impinging a proton beam provided by the LUNA 400 kV accelerator on a windowless gas target filled with 0.3 mbar deuterium. The beam exhibits a current of about 150 µA and an energy varying between 50 and 400 keV with low spread and long term stability. The current has been measured at the 5% level using a calibrated constant temperature gradient calorimeter. A scratch of the setup is shown in figure 1. The gamma rays produced during the reaction have been collected by a High Purity Germanium Detector (HPGe) with a 137% relative efficiency. No shielding has been provided during the test. As a matter of fact, the natural background, due to cosmic rays and environmental radioactivity, is reduced by the LNGS rock shield. The reduction is strongest for the high energy gammas produced by cosmic rays. Gammas that came from the environmental radioactivity have a cut off at 2.6 MeV, well below the Region of Interest (RoI) for the $^2$H(p,γ)$^3$He reaction and thus negligible for our purposes. The RoI can be calculated from kinematic and it is within 5.5 MeV and 5.8 MeV. During the test we could provide only an upper limit < 2 counts/day for the natural background rate in the $^2$H(p,γ)$^3$He. This energy region is really close to the 6.1 MeV gamma peak coming from the $^{19}$F(p,αγ)$^{16}$O reaction on fluorine contaminant present on the beam stop i.e. the calorimeter endcap. This reaction has a strong resonance at 340 keV beam energy.
An on-resonance run has been taken during the test in order to estimate the maximum beam-induced background. This has been found to be $2.9 \times 10^3$ counts/C. Direct capture on Carbon has been also found, but the gamma rays produced are at energy lower than the $^2\text{H}(p,\gamma)^3\text{He}$ RoI. Another possible source of background is the $^2\text{H}(^2\text{H},n)^3\text{He}$ between deuterons elastically scattered by the proton beam and deuteron at rest in the gas target. These fast neutrons produce high energy gammas through $(n,n')\gamma$ reaction with the surrounding materials. In order to reduce the proton-deuteron scattering a 3 cm in diameter steal pipe has been mounted along the beam line. However the gamma spectrum acquired during the $^2\text{H}(p,\gamma)^3\text{He}$ test don’t show any neutron induced background neither produced in the gas target nor with implanted deuterium on the beam collimator and calorimeter endcap.

3. Data Analysis and Results
The $^2\text{H}(^2\text{H},n)^3\text{He}$ gamma ray spectra has been acquired for proton energies: 379.8, 339.8, 261.5, 202.4 and 114.8 keV. The noise to signal ratio approaches to zero and the background sources are practically negligible also when the energy is close or at the $^{18}\text{F}(p,\alpha\gamma)^{16}\text{O}$ resonance. Unfortunately, due to troubles with the LUNA 400 kV accelerator, the measure of the HPGe efficiency at high energy has not been done. Montecarlo simulations in order to estimate this value are under investigation. In this paper no S-factor values are thus provided. The shape of the $^2\text{H}(^2\text{H},n)^3\text{He}$ is determined by the kinematic of the process and the angular distribution of the gamma emitted. Starting from the measured peak is thus possible to extract not only the total cross section but also the differential one. During the test done at LUNA, it was validated the procedure in order to do this. However, due to the low statistics acquired no differential cross section has been provided in this paper.

4. Conclusions
The $^2\text{H}(p,\gamma)^3\text{He}$ reaction has been studied at LUNA during a feasibility test. Possible beam induced backgrounds as well as unknown systematics have been investigated. In 2015 and 2016 this reaction will be measured at LUNA with high accuracy. New experimental techniques in order to reduce systematics to the 3% level are under investigation. This reduction will be achieved also using two different experimental setups and detectors. In a first phase, an extended windowless gas target with a HPGe detector will be used in order to obtain the differential cross section of the $^2\text{H}(p,\gamma)^3\text{He}$ reaction in the BBN energy range. In a second phase, a $4\pi$ BGO detector will be used in order to investigate the lowest energies achieved by the LUNA 400 kV accelerator.

Future cosmological scenarios will depend on the degree of precision in the primordial deuterium abundance estimation. A 20% increase in the $^2\text{H}(p,\gamma)^3\text{He}$ cross section is requested in order to have an agreement between observed and calculated primordial deuterium abundance when the $^4\text{He}$ abundance is well reproduced by the BBN theory. In contrary, it’s necessary to modify the Universe expansion rate by means of an increase of cosmological model degree of freedoms like, for example, the number of neutrino families $N_{\text{eff}}$.

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