Towards the study of $^2\text{H}(p, \gamma)^3\text{He}$ reaction in the Big Bang Nucleosynthesis energy range in LUNA

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Abstract. The Big Bang Nucleosynthesis began a few minutes after the Big Bang, when the Universe was sufficiently cold to allow deuterium nuclei to survive photo-disintegration. The total amount of deuterium produced in the Universe during the first minutes depends on the cosmological parameters (like the energy density in baryons, $\Omega_b h^2$, and the effective neutrino number, $N_{\text{eff}}$) and on the nuclear cross sections of the relevant reactions. The main source of uncertainty in the deuterium estimation comes from the $^2\text{H}(p, \gamma)^3\text{He}$ cross section.

Measurements of Cosmic Microwave Background (CMB) anisotropies obtained by the Planck satellite are in very good agreement with the theoretical predictions of the minimal $\Lambda$CDM cosmological model, significantly reducing the uncertainty on its parameters. The Planck data allows to indirectly deduce with very high precision the abundances of primordial nuclides, such as the primordial deuterium fraction $^2\text{H}/\text{H} = (2.65 \pm 0.07) \cdot 10^{-5}$ (68% C.L.).

The astrophysical observations in damped Lyman-α systems at high redshifts provide a second high accuracy measurement of the primordial abundance of deuterium $^2\text{H}/\text{H} = (2.53 \pm 0.04) \cdot 10^{-5}$ (68% C.L.).

The present experimental status on the astrophysical S-factor of the $^2\text{H}(p, \gamma)^3\text{He}$ reaction in the BBN energy range, gives a systematic uncertainties of 9%. Also the difference between ab-initio calculations and experimental values of $S_{12}$ is at the level of 10%.

In order to clarify the actual scenario, a measurement of $^2\text{H}(p, \gamma)^3\text{He}$ cross section with a precision of a few percent in the 70-400 keV energy range is planned at LUNA in 2016. A feasibility test of the measurement has been performed in October 2014, giving the preliminary results on the cross section. The experimental setup for the test and final measurement campaign will be presented.

1. Introduction

The Big Bang Model is supported by three observational evidences: the cosmic expansion, the Cosmic Microwave Background (CMB) radiation and Big Bang Nucleosynthesis (BBN). BBN predicts the primordial abundances of the light cosmological elements, like $^4\text{He}$, $^2\text{H}$, $^3\text{He}$ and $^7\text{Li}$ that are produced through twelve key nuclear reactions.

The abundance of light isotopes depends on the energy density in baryons $\Omega_b h^2$ and on the number of neutrino families, $N_{\text{eff}}$. $\Omega_b h^2$ is measured from the angular power spectrum of the CMB temperature anisotropies. A precise value of this parameter was updated by the recent measurements of Planck satellite to $\Omega_b h^2 = 0.02207 \pm 0.00033$ [1]. Assuming $\Lambda$CDM, the Planck constraints on the baryonic density can be translated into a prediction for the primordial deuterium fraction $^2\text{H}/\text{H} = (2.65 \pm 0.07) \cdot 10^{-5}$ (68% C.L.) [2].
The abundance of $^2$H is directly measured on known deuterium absorption-line systems, including some new data from very metal-poor Lyman-α systems at high redshifts. The $^2$H/H ratio in these clouds is thought to reflect the primordial abundance and the adopted average value is $^2H/H = (2.53 \pm 0.04) \cdot 10^{-5}$ (68% C.L.) [3].

An independent estimation on the cross section of the radiative capture reaction $^2H(p, \gamma)^3$He can be extracted from a combined analysis of Planck data and of the deuterium abundance in Lyman-α systems, assuming the standard cosmological model. The cross section for proton-deuterium capture is an important parameter not only in models of BBN, but also in stellar hydrogen burning and deuterium depletion in low-mass protostars, which is believed to be essential for their genesis and evolution.

2. Existing experimental data

The main uncertainty for standard BBN calculations of deuterium comes from the rate of radiative capture reaction $^2H(p, \gamma)^3$He. This is the first reaction in a chain that rapidly burn $^2$H into $^3$He and eventually $^4$He. The experimental data of proton-deuterium radiative capture reaction are measured in a wide energy range from 2.5 keV to 1.75 MeV.

The low energy limit of the $^2H(p, \gamma)^3$He cross section is well known thanks to the recent results of the underground experiment LUNA [4]. During BBN, the relevant energy range is around $E_{cm} = 30 - 300$ keV and for such energies, the uncertainty on $\sigma(E)$ is at the level of 6 - 10 %. There are several data sets for this reaction in the BBN window: however, some of these measurements need detailed consideration. It has been suggested that the Griffiths’63 [5] and Bailey’70 [6] experiments used incorrect stopping powers and, consequently, their low energy behaviour is 15% too high. The Schmid’97 [7] data set suffer from poor energy resolution, with typical uncertainties greater than 10%. Ma’97 [8] data has the systematic uncertainties estimated to be ±9% at $40 \leq E_{cm} \leq 110$ keV. Moreover, the discrepancy between $ab\ initio$ calculations [9], [10] and experimental fit of S(E) from the Solar Fusion II is at the level of 10%.

In order to clarify the scenario, a very precise measurement of $^2H(p, \gamma)^3$He in the energy range $E_{cm} = 70 - 400$ keV is planned at LUNA.
3. Experimental setup and results from the test run
In October 2014, a campaign to test the feasibility of the setup for the precise measurement was held with an High Purity Germanium (HPGe) detector. The experimental setup was based on a windowless gas target chamber filled with deuterium at 0.3 mbar (without recirculation) and a HPGe (at 90° with respect to the beam direction). No lead castle and anti-radon box were present, since the natural background is negligible in the RoI of γ’s produced by the $^2$H(p, γ)$^3$He reaction.

The S(E) was measured at different energies: 112.5 keV, 163.9 keV, 199.5 keV, 259.5 keV, 340 keV and 380 keV with an average current of 150 $\mu$A. The results can be seen on Figure 1, together with existing data points.

During the test run, no neutron production or neutron/deuterium implantation was noticeable. The fluorine contamination occurs as a narrow peak at high energy for 380 keV run due to $^{19}$F(p, αγ)$^{16}$O strong resonance.

In order to obtain the S(E) reported here, a Monte Carlo detection efficiency estimation was used. In the future, a procedure for the experimental determination of the detection efficiency will be adopted.

4. Final measurement campaign
The possibility to study the $^2$H(p, γ)$^3$He in the solar energy range (2.5 - 22 keV) with good accuracy has been already demonstrated at LUNA [4]. The final measurement of $^2$H(p, γ)$^3$He reaction in the BBN energy range is planned at the beginning of 2016. This measurement will be divided into two phases: Phase I (BGO) and Phase II (HPGe).

In Phase I, a 4π BGO detector will reduce the (systematic) uncertainty of the detector response for the angular distribution of the emitted γ-rays. The detection efficiency can be determined by performing a dedicated calibrations and by precise Monte Carlo simulations. With the proposed setup, the expected counting rate will be of the order of $10^4 - 10^5$ events/hour in the considered energy range under the normal conditions (I=100 $\mu$A, p=0.1 mbar, l=17.7 cm).

Phase II will be devoted to the study of the angular distribution of emitted γ-rays. This will be accomplished by using a HPGe detector facing the gas target in close geometry within a new target chamber. The expected counting rate will be of the order of $10^3 - 10^4$ events/day under the same running conditions of Phase I.

5. Conclusions
The feasibility test showed that a precise measurement of the $^2$H(p, γ)$^3$He cross section is possible at LUNA. In order to minimise the systematic uncertainties, the campaign will be done with two detectors. The improved accuracy in the $^2$H(p, γ)$^3$He cross section measurement will be fundamental for the BBN. Moreover, the study of γ angular distribution will provide a useful tool for nuclear theoretical models.

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