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Deuterium burning measurement at LUNA and its astrophysical and nuclear implications

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Summary. — The D(p,γ)^{3}He reaction is responsible for the deuterium destruction during the Big Bang Nucleosynthesis (BBN) and affects the primordial deuterium abundance. This latter is sensitive to fundamental cosmological parameters such as the baryon density and the effective number of relativistic species. In this paper, we describe the most precise direct measurement of the D(p,γ)^{3}He reaction in the BBN energy range (E_{cm} = 30–280 keV) at the LUNA (Laboratory for Underground Nuclear Astrophysics) facility in Gran Sasso National Laboratories. Experimental results, cosmological consequences, and future prospects are reported here.

1. – Introduction

Our current understanding of the evolution of the Universe is based on the standard model of cosmology (the Λ Cold Dark Matter, ΛCDM model) which assumes a homogeneous and isotropic Universe governed by general relativity and by the Standard Model of particle physics with three active neutrino species ($N_\nu = 3$), corresponding to a contribution $N_{\text{eff}} = 3.045$ in the energy density of neutrinos [1, 2]. One of the pillars of the cosmological standard model is the Big Bang Nucleosynthesis (BBN), which occurs during the first minutes of cosmological time in a rapidly expanding hot and dense Universe, where a fraction of protons and nearly all free neutrons end up bound in ^{4}He, while D, ^{3}H, ^{3}He, ^{6}Li, ^{7}Li and ^{7}Be nuclei form in trace quantities. Assuming that the relevant nuclear reaction rates are known and the existence of three neutrino species, the primordial elemental abundances depend upon a single cosmological parameter, the baryon density $\Omega_b h^2$ [3]. The primordial abundances can be measured by observations of astronomical

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samples reflecting their primordial composition. Therefore, a comparison between the observed primordial abundances and those predicted by the BBN can be used to constrain the baryon density of the Universe. On the other hand, this parameter has recently been measured with an exquisite precision by the Planck experiment through the study of the anisotropies in the Cosmic Microwave Background (CMB) [4]. An independent determination of the baryon density is crucial to confirm our understanding of the cosmological model or point towards new physics. Among the light elements produced at the beginning of our Universe, deuterium is an excellent baryometer, because its primordial abundance is the most sensitive to $\Omega_b h^2$. In addition, the primordial abundance of deuterium has been recently measured with percent accuracy, $\mathrm{D/H} = (2.527 \pm 0.030) \times 10^{-5}$ at 68% of C.L. [5] from astrophysical sites not affected by stellar evolution. Deuterium is, indeed, destroyed in stars and no production mechanism is possible after BBN. The primordial deuterium abundance depends both on its production, via the well-known $\mathrm{p(n,\gamma)D}$, and destruction processes, via the $\mathrm{D(d,n)^3He}$, $\mathrm{D(d,p)^3H}$, and $\mathrm{D(p,\gamma)^3He}$ reactions. The evaluation of the nuclear reaction rates entering the BBN network is the most important issue to solve in order to get an accurate determination of light nuclide abundances and their corresponding uncertainties. Up to few years ago, the $\mathrm{D(p,\gamma)^3He}$ reaction was the most uncertain among the deuterium destruction channels. In the low-energy range ($E_{\mathrm{cm}} \simeq$ 2–20 keV), mostly relevant to hydrogen burning in the Sun and in protostars, cross sections were obtained with a systematic error of at most 5.3% with the 50 kV LUNA accelerator [6]. In the BBN energy range and beyond ($E_{\mathrm{cm}} \simeq$ 30–700 keV), several data sets were available, however not with the required accuracy. The available data sets were, indeed, affected by systematic errors of 9% or higher [7-10]. The situation was further compounded by the fact that a recent *ab initio* calculation [11] disagrees at the 8% level with the best fit of experimental data reported in Iliadis *et al.* [12]. These large uncertainties had a significant impact on the comparison between predicted and observed primordial abundance of deuterium. As a consequence of the poor experimental data for the $\mathrm{D(p,\gamma)^3He}$ reaction, firm conclusions on the cosmological model could not be drawn. For all these reasons, a new experimental campaign started at LUNA in 2016.

2. – Experimental setup and data analysis of the $\mathrm{D(p,\gamma)^3He}$ cross section measurement

The LUNA experiment takes advantage from a 400 kV accelerator that provides a proton beam in the energy range 50–400 keV, with an average current on-target of 200 μA, an energy resolution of 0.3 keV and a long-term stability of 5 eV per hour [13].

To access the $\mathrm{D(p,\gamma)^3He}$ cross section in the BBN energy range of interest, 30 keV $< \mathrm{E}_{cm} <$ 300 keV, we explored the full dynamic range of the accelerator in energy steps of 30–50 keV. The beam was focused on a windowless gas target filled with 0.3 mbar of molecular deuterium. The beam intensity was measured by a calorimeter which acts as beam stopper [14].

The $\mathrm{D(p,\gamma)^3He}$ reaction emits single γ-rays with an energy between 5.5 and 5.8 MeV, through direct capture mechanism. In this region of interest, the experiment fully exploits the 6 orders of magnitude suppression of cosmic background at Gran Sasso National Laboratories [15]. The γ-rays emitted by the $\mathrm{D(p,\gamma)^3He}$ reaction were detected by a large high-purity germanium detector (HPGe) at 90° with respect to the beam axis. In order to reach a total accuracy of 3% on the S-factor, it was crucial to minimize all the sources of systematic uncertainties entering in its determination. Here, we will briefly report the efforts done to achieve such a challenging goal.

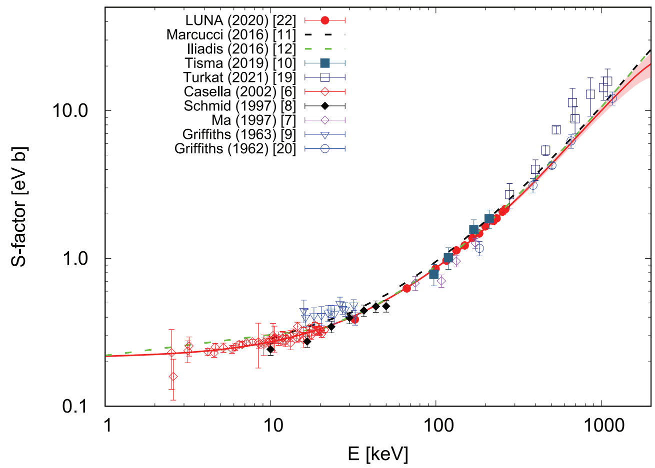

Fig. 1. – The S-factor of the D(p,γ)^{3}He reaction; LUNA results are represented with filled red circles. Other experimental data are also shown. The best fit (red solid line) includes all the reported experimental data up to LUNA measurement. The band represents the quoted 1σ uncertainty of the best fit values.

The cosmic ray induced background suppression at LUNA allowed keeping statistical uncertainty on the total number of counts, below 1%. For what concerns systematic uncertainties, the target density $\rho(z)$ was precisely determined from dedicated pressure and temperature measurements along the gas target, also considering the density reduction as a consequence of the beam heating effect [16]. The beam current was monitored during each run by measuring the power dissipated by the beam on the calorimeter, which was precisely calibrated during dedicated measurements [17]. The γ-ray detection efficiency ϵ(z,Eγ) was carefully evaluated as a function of both the γ-ray energy and the emission point in the target chamber [14].

The LUNA collaboration evaluated the D(p,γ)^{3}He S-factor in the BBN energy region with an unprecedented precision and accuracy compared with previous experimental works, as shown in fig. 1. A polynomial fit of literature and present data for the S(E) at $E \sim 0$–$2\,\mathrm{MeV}$ was performed and compared with previous attempts [12, 18], see fig. 1. Our high-precision S-factor data were followed by new experimental data above the BBN energy range [19] using implanted deuterium targets on tantalum backing (fig. 1). These last results do not agree with previous data sets [20] and show a different trend of the S-factor at high energies with respect to the LUNA S-factor fit. To constrain the tension between our LUNA data and the very recent high-energy data, a new measurement of the D(p,γ)^{3}He is planned to be made soon at the Felsenkeller laboratory, Germany [21].

3. – Conclusions and outlook

For several years, the D(p,γ)^{3}He reaction has been the main source of uncertainty for the predicted primordial deuterium abundance. The LUNA Collaboration measured the D(p,γ)^{3}He reaction in the BBN energy range within 3% uncertainty [22]. These new results provide constraints for the cosmological parameters compared to the precise primordial deuterium abundance from the BBN model with direct observation. Furthermore, the new D(p,γ)^{3}He cross-section data are important for theoretical nuclear physics because offer a unique opportunity to test *ab initio* calculations. To study the impact of the new high-precision D(p,γ)^{3}He S-factor on the primordial deuterium and cosmological parameters, we used the numerical BBN code PArthENoPE [23]. The LUNA results [22] opened the path to new cosmological implication studies calling for new high-precision measurement of the D(d,n)^{3}He and D(d,p)^{3}H reactions in the BBN energy range which have become the most prominent sources of uncertainty for the primordial deuterium abundance. A deeper discussion on the LUNA results and their cosmological implication can be also found in [24-27]. Presently, a study of the D(p,γ)^{3}He angular distribution is ongoing using the *Peak Shape Analysis* method [28]. By studying the shape of the peak produced in the γ-spectra by the reaction, it is possible to obtain the angular distribution; a dedicated paper containing the relevant results will be published soon.

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