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Deuterium burning measurement at LUNA and its astrophysical and nuclear implications

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Abstract.
The deuterium burning reaction D(p,γ)^{3}He at low energies is of primary importance in cosmology because it affects the primordial deuterium abundance, that in turn is very sensitive to fundamental cosmological parameters such as the baryon density and the amount of relativistic species permeating the early Universe. This reaction is also of a particular interest in theoretical nuclear physics because it offers a unique opportunity to test *ab – initio* calculations. In the following a recent study of the D(p,γ)^{3}He reaction in the $30 \lesssim E_{cm}[keV] \lesssim 280$ energy range will be presented. This measurement has been performed in the underground Gran Sasso Laboratory by the LUNA (Laboratory for Underground Nuclear Astrophysics) collaboration. In addition, the need of having new and precise measurement of the D(d,n)^{3}He and D(d,p)^{3}H reactions will also be discussed.

1 Introduction

Big Bang Nucleosynthesis (BBN) 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. The theoretical description of BBN is based on the standard cosmological model, which assumes a homogeneous and isotropic Universe, up to small perturbations, governed by the General Relativity theory and by the Standard Model of particle physics. Under these assumptions, BBN predicts the abundances of primordial nuclides, as a function of one parameter only, the density of ordinary matter, or baryon density, $\omega_b \equiv \Omega_b h^2$, where h is the reduced Hubble constant (see [1] for a recent review). On the other hand, the primordial abundance of the light elements can be measured by observations of astronomical 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, the only free cosmological parameter of the BBN model, under the assumption that there are three neutrino species.

Indeed, an independent estimate of ω_b can be obtained by observing the anisotropies in the Cosmic Microwave Background (CMB), the relic electromagnetic radiation left over from the Big Bang, which are measured with remarkable precision by the Planck experiment, leading to [2]: $\omega_b = 0.02242 \pm 0.00014$.

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Assuming that there are no changes in the value of ω_b from BBN down to CMB formation epoch, the precise CMB determination of ω_b implies that nowadays the theory of BBN, in its minimal scenario where only three neutrinos species are allowed, is a parameter free model and, as such, has become a high precision tool to investigate effects of physics beyond the Standard Model and/or exotic cosmological models (see for example [3]).

With the exception of lithium, whose predictions are at odds with observations [4, 5], a good agreement between predicted and observed primordial abundances of the light elements is reached, such an agreement is continuously updated in view of new experimental results and theoretical insights. The observed values of primordial abundances are usually provided by spectroscopic observations of ancient astrophysical objects. In the case of deuterium, its primordial abundance can be obtained from astrophysical sites not affected by stellar evolution since deuterium is destroyed during stellar evolution and no production mechanism after BBN is possible. The value of deuterium abundance relative to hydrogen has now reached a percent accuracy, D/H = $(2.527 \pm 0.030) \times 10^{-5}$ at 68% of C.L. [6].

Among the light elements produced during BBN, deuterium is an excellent indicator of cosmological parameters in the early Universe because its abundance is the most sensitive to ω_b and also depends on the radiation density, usually expressed in terms of the effective number $N_{\rm eff}$ of neutrino species [1]. The reactions involved in the synthesis of deuterium are: production via the well known p(n,γ)D process and destruction via the D(d,n)^{3}He , D(d,p)^{3}H and D(p,γ)^{3}He reactions. Once the deuterium bottleneck is overcome and deuterium is produced by the p(n,γ)D reaction, its amount crucially depends upon destruction rates. 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.

Among the deuterium destruction reactions, the most uncertain was the D(p,γ)^{3}He . Several data sets on its cross section, or equivalently the $S(E)$-factor were available in the literature before the LUNA measurement. In the low-energy range ($E_{\rm C.M.} \simeq 2 - 20$ 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% [7] using the 50 kV accelerator (now in disuse) of the Laboratory for Underground Nuclear Astrophysics (LUNA) at the Laboratori Nazionali del Gran Sasso (LNGS) in Italy [8]. At higher energies ($E_{\rm C.M.} \simeq 30 - 700$ keV), available data sets were affected by systematic errors of 9% or higher [9–12]. The situation was further compounded by the fact that a recent *ab initio* calculation [13] disagrees at the 20-30% level with both the S-factor of Ma *et al.* [9] and a best fit [14] to selected data [7, 9, 15, 16], widely used in BBN calculations. These large uncertainties had significant impact on the comparison between predicted and observed primordial abundance. As a consequence of the poor experimental data for the D(p,γ)^{3}He reaction, firm conclusions on the BBN stage and cosmological model couldn't be drawn with a satisfactory precision. For all these reasons, a new experimental campaign started at LUNA in 2016.

2 Experimental setup and data analysis of the D(p,γ)^{3}He cross section measurement

The LUNA400 accelerator provided a high intensity proton beam (beam current 100-300 μA) in the 50-400 keV energy range. The beam entered in a cylindrical reaction chamber filled with high purity molecular deuterium at a 0.3 mbar pressure. The beam was stopped by a copper calorimeter that measured its intensity. Two large high-purity germanium detectors (HPGe) faced to the reaction chamber at 90° to the beam axis were used to detect the photons emitted by the D(p,γ)^{3}He reaction. The latter proceeds through direct capture to the ^{3}He ground state with the emission of a single gamma with an energy in the range 5.5 - 5.8 MeV. Since these energies are above the natural radioactivity endpoint, it is possible to fully exploit the suppression of cosmic ray induced background due to the Gran Sasso mountain [8, 17]. The incoming proton can be captured both in a *s*-wave or *p*-wave orbital angular momentum state and the emitted gamma-ray shows a not isotropic angular distribution dominated by the M1 and E1 components. To measure the cross section in the energy range of interest (30 keV < E_{cm} < 300 keV) for BBN we explored the full dynamic range of the LUNA-400 accelerator in 30-50 keV energy steps. The main source of beam induced background was due to the $^{19}F(p,\alpha\gamma)^{16}O$ reaction from the interaction of protons with fluorine contaminant usually present on collimators along the gas target and on the calorimeter. This beam-induced background was quantified in dedicated control runs in which inert ^{4}He gas was used instead of deuterium.

For an extended gas target setup, the cross section depends on: N_γ, the number of counts after background subtraction, $\rho(z)$ the gas density profile, $\epsilon(z)$ is the gamma detection efficiency as a function of position along the beam axis, $W(z)$ which accounts for the photon angular distribution and N_p the number of projectiles impinging the target.

A major effort was devoted to prevent or minimize any source of systematic uncertainty in the previous mentioned quantities to reach an accuracy of three percent on the S-factor. N_γ is essentially affected by the statistical error, that in our measurements was always lower than 1% for $E_{\mathrm{p}>100}$ keV ($E_{\mathrm{C.M.}} >$ 70 keV), as a consequence of the suppression in the cosmic ray induced background with respect to surface experiments. The target density $\rho(z)$ was determined by measuring the pressure and temperature profiles along the target as well as the beam heating effect due to the power released by the incident beam in the gas target [18]. The integrated beam current N_p was measured with a consolidated technique in which the beam power was monitored during each run by measuring the power dissipated by the beam on the copper calorimeter where the beam was stopped [19]. In an extended gas target the interaction with proton beam can take place at different positions along the beam axis, resulting in different energies of the emitted photons and in different geonetrical angles subtended by the HPGe detector. Therefore, the γ-ray detection efficiency ϵ(z) must be carefully determined as a function of both position and energy. The γ-rays emitted by the $D(p,\gamma)^3He$ reaction ($Q = 5.5$ MeV) have typical energies $E_\gamma = 5.5$-5.8 MeV, i.e. far away from the energy of the commonly used radioactive sources. The efficiency $\epsilon(z)$ of the HPGe detector was measured along the beam line, by filling the reaction chamber with N_2 and exploiting the resonance of the $^{14}N(p,\gamma)^{15}O$ reaction at E_r = 259 keV. This reaction produces cascade γ-rays in a large energy range (0.7-7 MeV), in such a way the efficiency were precisely determined [20]. Finally, the $W(z)$ function has been unfolded from the shape of full energy peak of photons produced by the $D(p,\gamma)^3He$ that depends on the angular distribution of emitted photons. The detailed description of the measurements performed to determine the above mentioned quantities and uncertainties can be found in [20].

Finally, the LUNA collaboration obtained the S-factor shown in Figure 1 where the LUNA data [21] are reported together with literature data. The new data show a significantly reduced uncertainty with respect to previous experimental datasets. The polynomial best fit of S(E) for $E \sim 0-2$ MeV to previous datasets are also shown [14, 22] and the fit in which this new data set is considered (red line). The bands represent the quoted 1σ uncertainty of the best fit values.

Presently a study of the $D(p,\gamma)^3He$ angular distribution is ongoing using a novel approach the "Peak Shape Analysis" method. The experimental differential cross section is in nice agreement with theoretical predictions.

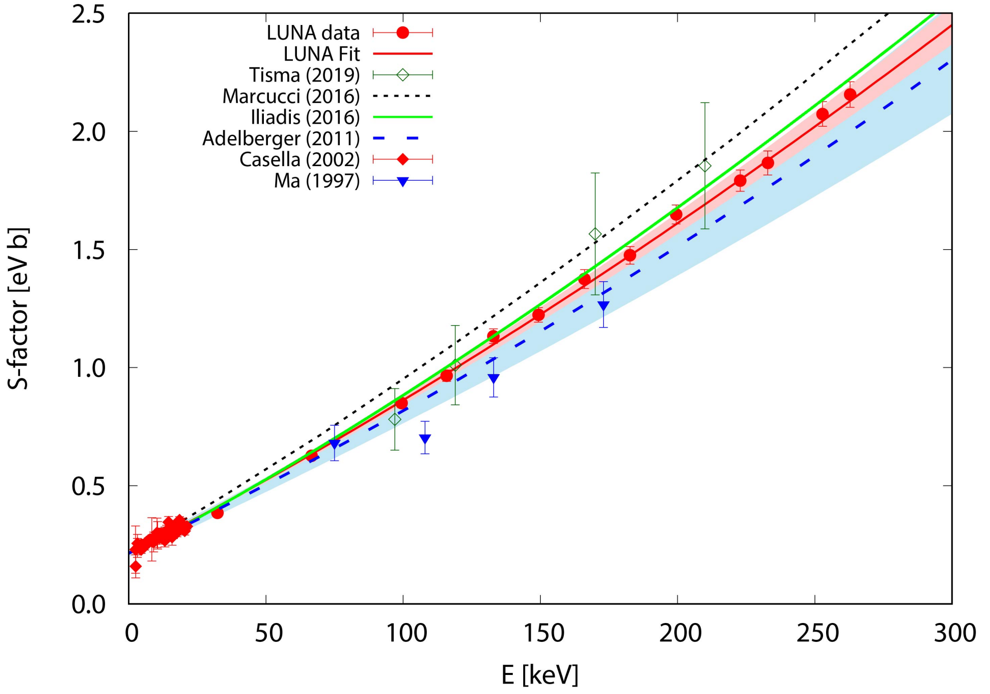

Figure 1. S-factor of the D(p,γ)^{3}He reaction; LUNA results are represented with filled red circles. Other experimental data are also shown. The best fit (red solid line) include all the reported experimental data. Band represents the 68% confidence level.

3 Conclusions and outlook

To explore the impact of our D(p,γ)^{3}He S-factor on the predicted primordial deuterium abundance, we used the second release [23] of the numerical BBN code PArthENoPE. Under the assumption of the ΛCDM model, with $N_{\rm eff}$ = 3.045, we performed a Bayesian likelihood analysis to derive $\Omega_b h^2$ using the observed deuterium abundance, (D/H)$_{\rm obs}$, and the theoretical behaviour of (D/H)$_{\rm BBN}$ (now including the new LUNA data). We obtained $\Omega_b h^2$(BBN) = 0.02233 ± 0.00036, a value which is a factor of 2 more precise than that deduced using a previous S factor [14] and now in much better agreement with the $\Omega_b h^2$ based on CMB data.

After the release of the LUNA results [21], several papers were published discussing the cosmological implications with the inclusion of the new D(p,γ)^{3}He rate. A deeper discussion on the LUNA results and their cosmological implication can be also found in [24–27]. The new challenge is now the measurement of the D(d,n)^{3}He and D(d,p)^{3}H reactions which have became the most prominent source of uncertainty in the determination of the primordial deuterium abundance.

References

[1] P.A. Zyla, R.M. Barnett, J. Beringer, O. Dahl, D.A. Dwyer, D.E. Groom, C.J. Lin, K.S. Lugovsky, E. Pianori, D.J. Robinson et al., Prog. Theor. Exp. Phys. **2020** (2020)

[2] N. Aghanim et al. (Planck), Astron. Astrophys. **641**, A6 (2020)

[3] F. Iocco, G. Mangano, G. Miele, O. Pisanti, P.D. Serpico, Phys. Rept. **472**, 1 (2009)
[4] M. Spite, F. Spite, Nature **297**, 483 (1982)
[5] B.D. Fields, Annu. Rev. Nucl. Part. Sci. **61**, 47 (2011)
[6] R.J. Cooke, M. Pettini, C.C. Steidel, Astrophys. J. **855**, 102 (2018)
[7] C. Casella, H. Costantini, A. Lemut, B. Limata, R. Bonetti, C. Broggini, L. Campajola, P. Corvisiero, J. Cruz, A. D'Onofrio et al., Nucl. Phys. A **706**, 203 (2002)
[8] F. Cavanna, P. Prati, Int. J. Mod. Phys. A **33**, 1843010 (2018)
[9] L. Ma, H. Karwowski, C. Brune, Z. Ayer, T. Black, J. Blackmon, E. Ludwig, M. Viviani, A. Kievsky, R. Schiavilla, Phys. Rev. C **55**, 588 (1997)
[10] G. Schmid, B. Rice, R. Chasteler, M. Godwin, G. Kiang, L. Kiang, C. Laymon, R. Prior, D. Tilley, H. Weller, Phys. Rev. C **56**, 2565 (1997)
[11] G. Griffiths, M. Lal, C. Scarfe, Can. J. Phys. **41**, 724 (1963)
[12] I. Tišma, M. Lipoglavšek, M. Mihovilovič, S. Markelj, M. Vencelj, J. Vesić, Eur. Phys. J. A **55**, 137 (2019)
[13] L. Marcucci, G. Mangano, A. Kievsky, M. Viviani, Phys. Rev. Lett. **116**, 102501 (2016)
[14] E. Adelberger, A. García, R. Robertson, K. Snover, A. Balantekin, K. Heeger, M. Ramsey-Musolf, D. Bemmerer, A. Junghans, C. Bertulani et al., Rev. Mod. Phys. **83**, 195 (2011)
[15] G. Griffiths, E. Larson, L. Robertson, Can. J. Phys. **40**, 402 (1962)
[16] G. Schmid, M. Viviani, B. Rice, R. Chasteler, M. Godwin, K. G.C., L. Kiang, A. Kievsky, C. Laymon, R. Prior et al., Phys. Rev. Lett. **76**, 3088 (1996)
[17] F. Ferraro, G.F. Ciani, A. Boeltzig, F. Cavanna, S. Zavatarelli, Frontiers in Astronomy and Space Sciences **7**, 119 (2021)
[18] F. Cavanna, R. Depalo, M.L. Menzel, M. Aliotta, M. Anders, D. Bemmerer, C. Broggini, C.G. Bruno, A. Caciolli, P. Corvisiero et al., Eur. Phys. J. A **50**, 179 (2014), `1411.2888`
[19] F. Ferraro, M. Takács, D. Piatti, V. Mossa, M. Aliotta, D. Bemmerer, A. Best, A. Boeltzig, C. Broggini, C. Bruno et al., Eur. Phys. J. A **54**, 44 (2018)
[20] V. Mossa, K. Stöckel, F. Cavanna, F. Ferraro, M. Aliotta, F. Barile, D. Bemmerer, A. Best, A. Boeltzig, C. Broggini et al., Eur. Phys. J. A **56**, 144 (2020), `2005.00002`
[21] V. Mossa, K. Stöckel, F. Cavanna, F. Ferraro, M. Aliotta, F. Barile, D. Bemmerer, A. Best, A. Boeltzig, C. Broggini et al., Nature **587**, 210 (2020)
[22] C. Iliadis, K.S. Anderson, A. Coc, F.X. Timmes, S. Starrfield, Astrophys. J. **831**, 107 (2016)
[23] R. Consiglio, P. de Salas, G. Mangano, G. Miele, S. Pastor, O. Pisanti, Comp. Phys. Comm. **233**, 237 (2018)
[24] O. Pisanti, G. Mangano, G. Miele, P. Mazzella, J. Cosmol. Astropart. Phys. **04**, 020 (2021)
[25] T.H. Yeh, K.A. Olive, B.D. Fields, J. Cosmol. Astropart. Phys. **03**, 046 (2021)
[26] C. Pitrou, A. Coc, J.P. Uzan, E. Vangioni, Mon. Not. Roy. Astron. Soc. **502**, 2474 (2021)
[27] J. Moscoso, R.S. de Souza, A. Coc, C. Iliadis, Astrophys. J. **923**, 49 (2021)