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BBN, NEUTRINOS AND NUCLEAR ASTROPHYSICS

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Abstract

The big bang nucleosynthesis (BBN) theory describes the formation of light isotopes in the first minutes of cosmic time, as a result of the competition between the universal expansion rate and the yields of relevant nuclear reactions. Since the expansion rate is proportional to the density of relativistic particles, the abundances of light isotopes allows to constrain the number of neutrinos species. In particular the primordial abundance of deuterium $(D/H)_{obs}$ is presently measured with high accuracy, providing a constraint on the number of neutrino families consistent only broadly with the three neutrino species foreseen by the standard model. The most important obstacle to improve the constraints on the existence of dark radiation is the uncertainty of the $^2H(p,\gamma)^3He$ cross section at BBN energies. This reaction will be studied at the underground Gran Sasso Laboratory (LNGS) with by the LUNA accelerator. The goal is to measure the cross section of the $^2H(p,\gamma)^3He$ reaction at BBN energies with high accuracy. The forthcoming LUNA measurement and its impact in cosmology, as well as in particle and nuclear physics is discussed.

Table 1: *List of the leading reactions and corresponding rate symbols controlling the deuterium abundance after BBN. The last column shows the error on the ratio D/H coming from experimental (or theoretical) uncertainties in the cross section of each reaction, for a fixed baryon density $\Omega_b h^2 = 0.02207$.*

Reaction	Rate Symbol	$\sigma_{D/H} \cdot 10^5$
$p(n,\gamma)^2H$	R_1	± 0.002
$d(p,\gamma)^3He$	R_2	± 0.062
$d(d,n)^3He$	R_3	± 0.020
$d(d,p)^3H$	R_4	± 0.0013

1 Introduction

In the standard cosmology the expansion rate of the universe is governed by the Freidmann equation:

$$H^2 = \frac{8\pi}{3} G\rho \tag{1}$$

Were H is the Hubble parameter, G is the Newton's gravitational constant and ρ is the energy density which, in the early Universe, is dominated by the "radiation", i.e. the contributions from massless or extremely relativistic particles. The only known relativistic particle at the Big Bang Nucleosynthesis (BBN) epoch are the photons and the three neutrino families. Indeed, the primordial abundance of isotopes depends on the radiation density, on the baryon density Ω_b and on the nuclear cross sections of BBN chain. The measured abundance of deuterium D/H_{obs} in Damped Lyman-Alpha (DLA) systems at high redshifts has been recently measured with high precision [1], providing $(D/H)_{obs} = (2.53 \pm 0.04) \times 10^{-5}$. The theoretical value obtained assuming standard ΛCDM model, the baryon density measured by the PLANCK experiment [2] and using the public BBN code PArthENoPE [3] is $(D/H)_{BBN} = (2.65 \pm 0.07) \times 10^{-5}$. Interestingly, the theoretical value of D/H is less accurate with respect to the measured one, mainly because of the uncertainties of the BBN nuclear processes responsible for the initial deuterium production and its subsequent processing into $A = 3$ nuclei. The four leading reactions responsible of the deuterium abundance are listed in Table 1 [4]. This table shows that the main source of uncertainty is presently due to the radiative capture process $D(p,\gamma)^3He$ converting deuterium into ^3He.

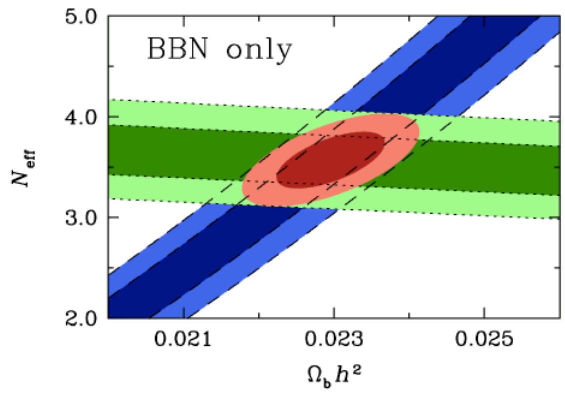

Figure 1: *The 1 σ and 2 σ confidence contours (dark and light shades respectively) for N_{eff} and $\Omega_{b,0}$ derived from the primordial deuterium abundance (blue), the primordial He mass fraction (green), and the combined confidence contours (red)* [1].

2 Baryon density.

The most recent CMB-derived baryon density is provided by the PLANCK collaboration [2]. Assuming standard ΛCDM model:

$$\Omega_{b,0}(CMB) = (2.205 \pm 0.028)/h^2 \tag{2}$$

In this equation, $\Omega_{b,0}$ is the present day baryon density of the universe and h is the Hubble constant in units of 100 $km\ s^{-1}$Mpc^{-1}.
The baryon density can be independently inferred by means of standard BBN theory, by comparing the observed deuterium abundance with the abundance obtained with BBN prediction [1]:

$$\Omega_{b,0}(BBN) = (2.202 \pm 0.019 \pm 0.041)/h^2 \tag{3}$$

The error terms in eq. 3 reflect the uncertainties in observed deuterium abundance and BBN calculation [1]. The latter is due to the 3% uncertainty of computed $(D/H)_{BBN}$, that is mainly due to the experimental error of $^2H(p,\gamma)^3He$ cross section at BBN energies [5, 1]. Therefore, to improve the $\Omega_{b,0}(BBN)$ accuracy, is necessary a renewed measurement of the $^2H(p,\gamma)^3He$ cross section

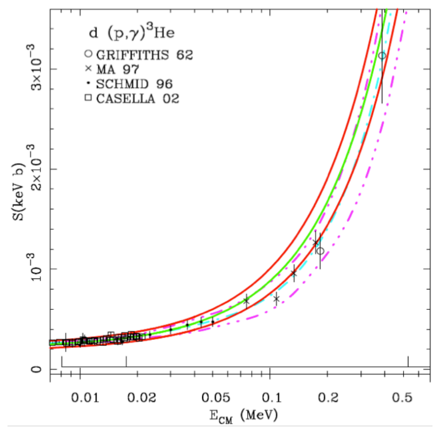

Figure 2: *S-factor data for the reaction $^2H(p,\gamma)^3He$. The best-fit curve (dash-dot curves) and theoretical calculation (solid) are shown. All errors are shown as 2 σs.*

in the BBN energy range.

3 Neutrinos

In cosmology, the definition of "neutrino" is any relativistic particle contributing to the radiation density with respect to photons. For standard cosmology the number of effective neutrino families is $N_{eff} = 3.046$ [1]. The CMB-only bound obtained by the PLANCK experiment is [2]:

$$N_{eff}(CMB) = 3.36 \pm 0.34 \tag{4}$$

It is possible to bound the density of relativistic species by comparing the predicted and the observed abundances of ^4He and D/H [1, 5]. the BBN-only bound reported in [1] is:

$$N_{eff}(BBN) = 3.57 \pm 0.18 \tag{5}$$

It is worth to point out that CMB and BBN constraints are in good agreement and provide a suggestive, but still inconclusive, hint of the presence of dark radiation. The BBN bound on N_{eff} is graphically shown in Figure 1. The

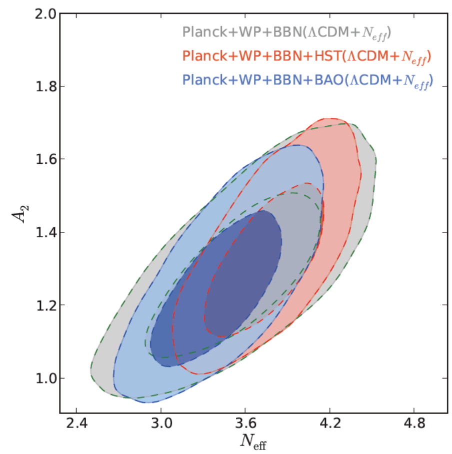

Figure 3: *2-D contour plots in the N_{eff} vs A_2 plane, showing preferred parameter regions at the 68% and 95% confidence levels in the case of the extended ΛCDM model with extra relativistic degrees of freedom.* [4]*.*

confidence contours related to the ^4He abundance (green bands) are due to systematics errors of observations. Instead, the uncertainty due to the deuterium abundance (blue bands) is mainly due to the paucity of $^2H(p,\gamma)^3He$ data at BBN energies, making the study of the $D(p,\gamma)^3He$ reaction at low energy also important for the neutrino physics.

4 The deuterium abundance and $D(p,\gamma)^3He$ reaction.

In nuclear astrophysics the nuclear cross section $\sigma(E)$ is often factorized as follows:

$$\sigma(E) = \frac{S(E)e^{-2\pi\eta^*}}{E} \qquad (6)$$

In this formula, the exponential term takes into account the Coulomb barrier, while the astrophysical factor $S(E)$ contains all the nuclear effects. The Sommerfeld parameter η^* is given by $2\pi\eta^* = 31.29 Z_1 Z_2 (\mu/E)^{1/2}$. Z_1 and Z_2 are the nuclear charges of the interacting nuclei. μ is their reduced mass (in units of a.m.u.), and E is the center of mass energy (in units of keV).
Figure 2 shows the data of the $D(p,\gamma)^3He$ reaction in literature. The precise

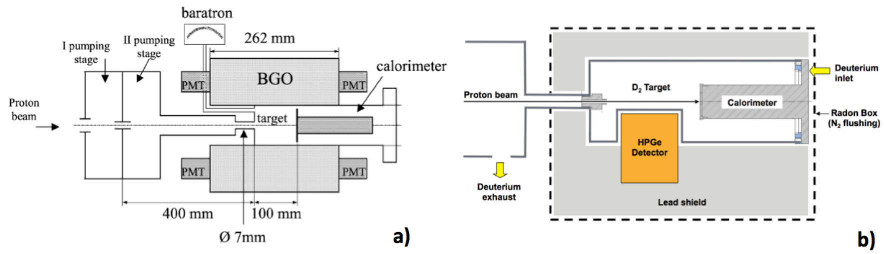

Figure 4: *a): Scheme of gas target setup and BGO detector. b): Scheme of gas target setup and HPGe detector.*

low-energy data come from the LUNA measurement performed with the 50 kV accelerator [6]. Only a single dataset of S_{12} is currently available in the relevant BBN energy range, in which the authors state systematic uncertainty of 9% [7]. Figure 2 also shows the behavior of S_{12} obtained by the theoretical "ab initio" calculation [5, 8]. It is worthwhile to note that the theoretical result is systematically larger than the best fit value derived from the experimental data in the BBN energy range. The existing difference between theory and data let some author to adopt the theoretical curve [5] or the S_{12} value obtained from measurements [2]. Figure 3 shows the 2-D contour plots in the N_{eff} vs A_2 plane, where A_2 is the $D(p,\gamma)^3He$ reaction rate normalized to the value obtained with data fit [4]. Interestingly, the figure 3 favor a $S_{12}(E)$ trend close to the one obtained with *ab initio* calculation, and a N_{eff} value higher than 3 [4]. Therefore, the measurement of $S_{12}(E)$ at BBN energies is of primary importance in theoretical nuclear physics and to understand the origin of the $\sim$ 20% difference between data and *ab initio* calculation for the ^3He isotope [5, 8].

5 The $D(p,\gamma)^3$He reaction at LUNA

The feasibility of studying the ^2H(p,γ)^{3}He reaction ($Q = 5.5\ MeV$) at low energy and with good accuracy has been demonstrated with the previous LUNA 50 kV accelerator (see figure 2), in the $2.5 < E_{cm}(keV) < 22$ energy range [6]. The present LUNA 400 kV facility [9] make possible to extend the measurements up to $E_{cm} = 266\ keV$, i.e. well inside the BBN energy range. Figure

4 a) shows the scheme of the setup used in [6], where a barrel BGO detector is implemented. The high efficiency ($\sim 70\%$) of the BGO detector reduces the dependence of the detector response on the angular distribution of the emitted γ rays and thus is a prerequisite to achieve a low systematic uncertainty. The detection efficiency can be determined by precise Monte Carlo simulations, as well as performing dedicated measurements and calibrations, e.g. by measuring the absolute efficiency exploiting the 340 keV resonance in the $^{19}F(p,\alpha\gamma)^{16}O$ reaction ($E_\gamma = 6.13\ MeV$). With the proposed setup the expected counting rate (full detection γ-peak) is of the order of $10^4 - 10^5$ $events/hour$ in the $40 < E_{cm}(keV) < 266$ energy range, making the measurements with BGO detector relatively fast for what concern statistics and allowing to precisely determine the beam heating effect by varying target pressure and beam intensity, in order to unfold the target density in asymptotical conditions. Finally, the beam intensity error can be minimized by a proper calibration of the calorimeter (1.5% uncertainty in ref. [11]). Although the large angular coverage of BGO detector makes the counting yield nearly independent of the angular distribution of emitted photons, an exhaustive study of the $^2H(p,\gamma)^3He$ reaction includes the study of angular distribution of emitted γ-rays, in order to precisely evaluate the response of BGO detector. This study can be accomplished by using the HPGe detector facing the gas target in a close geometry, as it is shown in figure 4b). The angular distribution can be inferred by exploiting the high energy resolution of the detector and the doppler effect affecting the energy of γ's produced along the beam line by the $^2H(p,\gamma)^3He$ reaction. This study is also important for theoretical nuclear physics, because in *ab initio* calculation the interaction details are considered. Therefore, it predict the angular distribution of photons produced in the $^2H(p,\gamma)^3He$ reaction.

6 Conclusions

The improvements of direct observations of deuterium abundance [1] and the accuracy of CMB data [2] make the lack of ^{2}H(p,γ)^{3}He reaction data at BBN energies the main obstacle to improve the constraints on $\Omega_{b,0}(BBN)$, N_{eff} and lepton degeneracy ξ [1, 5]. The study of the $^2H(p,\gamma)^3He$ reaction in the BBN energy range will be performed with the LUNA facility at the underground Gran Sasso laboratory, where the very low environmental background allows accurate measurements at energies below the coulomb barrier [12]. With the present 400 kV LUNA accelerator it is possible to measure the $^2H(p,\gamma)^3He$ cross section in the $40 < E_{cm}(keV) < 266$ energy range with an accuracy better than 3%, i.e. considerably better than the 9% systematic uncertainty estimated in [7]. This goal can be achieved by using the BGO detector already used in [6]. The accurate measurement of the $^2H(p,\gamma)^3He$ absolute cross section will be accomplished with the study of the angular distribution of emitted γ-rays by means of a large Ge(Li) detector, in order to compare the data with *ab initio* predictions.

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