

BBN, Neutrinos and Nuclear Astrophysics

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Big Bang Nucleosynthesis (BBN) theory describes the formation of light isotopes such as D , ${}^3\text{He}$, ${}^4\text{He}$, ${}^6\text{Li}$ and ${}^7\text{Li}$ in the first minutes of cosmic time. Their abundance only depends on the baryon density, on particle physics and on nuclear astrophysics, through the competition between the universal expansion rate and the yields of the relevant nuclear reactions. As the expansion rate increases with the number of neutrino families (and any other relativistic species), the comparison between computed and observed abundances of light isotopes allows to constrain the number of neutrinos species, provided that the knowledge of the relevant nuclear processes is accurate enough. Starting from the present uncertainty of the relevant parameters (i.e. baryon density, observed abundance of isotopes and BBN nuclear cross sections), it will be shown that a renewed study of several nuclear reactions, possibly with existing or proposed underground accelerator facilities, is essential to improve the accuracy of computed abundances of light isotopes, providing the BBN theory a powerful probe of particle physics beyond the standard model. In particular, it will be shown that the accurate measurement of the $D(p, \gamma){}^3\text{He}$ reaction at BBN energies (40-400 keV), is of primary importance to constrain the number of active neutrinos and/or the lepton degeneracy in the neutrino sector.

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1. Big Bang Nucleosynthesis

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

$$H^2 = \frac{8\pi}{3}G\rho \quad (1.1)$$

Where 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 (with $g_\gamma = 2$ degrees of freedom or helicities) and the three neutrino families (with $g_\nu = 2$, taking into account left-handed neutrinos and right-handed antineutrinos). Therefore, the abundance of primordial isotopes only depends on particle physics, on the baryon density Ω_b (or equivalently on the baryon-to-photon ratio η) and on the nuclear processes relevant in the BBN reaction chain, through the competition between the universal expansion rate and the yields of the relevant nuclear reactions.

As shown in figure 1, the nucleosynthesis begins with the formation of deuterium in the pro-

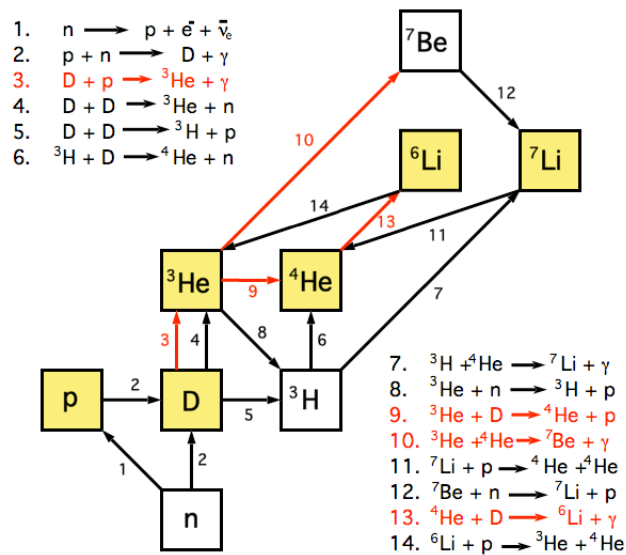


Figure 1: Leading processes of Big Bang Nucleosynthesis. Yellow boxes mark stable isotopes.

cess $p(n, \gamma)D$. Because of the large density of photons ($\eta \simeq 6 \cdot 10^{-10}$), the photo-dissociation delays the production of deuterium well after T drops below the binding energy of deuterium ($Q = 2.23 \text{ MeV}$). Nearly all the free neutrons end up bound in the most stable light element ${}^4\text{He}$. Therefore, the abundance of ${}^4\text{He}$ mostly depends on the fraction of free neutrons available, and its uncertainty is almost entirely due to the neutron lifetime error. Heavier nuclei do not form in any significant quantity both because of the absence of stable nuclei with mass number 5 or 8 (which impedes nucleosynthesis via ${}^4\text{He} + n$, ${}^4\text{He} + p$ or ${}^4\text{He} + {}^4\text{He}$ reactions) and of the large Coulomb barriers for reactions such as the ${}^3\text{H}({}^4\text{He}, \gamma){}^7\text{Li}$ and $D({}^4\text{He}, \gamma){}^6\text{Li}$. The primordial abundances of all the other stable isotopes, namely $(D/H)_{\text{BBN}}$, $({}^3\text{He}/H)_{\text{BBN}}$, $({}^7\text{Li}/H)_{\text{BBN}}$ and $({}^6\text{Li}/H)_{\text{BBN}}$ are

very sensitive to reaction yields of the relevant nuclear processes. The uncertainty of $(D/H)_{BBN}$ abundance is presently dominated by the $D(p, \gamma)^3\text{He}$ reaction, because the competing deuterium-burning channels $D(^2\text{H}, p)^3\text{H}$ and the $D(^2\text{H}, n)^3\text{He}$ have recently been studied with high accuracy [1, 2]. the $(^3\text{He}/H)_{BBN}$ error is mainly due to the $D(^3\text{He}, p)^4\text{He}$ process and, in a lower extent, to the $D(p, \gamma)^3\text{He}$ reaction [1]. For what concern the ^7Li isotope, there are several reactions contributing to its abundance uncertainty. For $\eta \simeq 6 \cdot 10^{-10}$, the $(^7\text{Li}/H)_{BBN}$ error budget mainly come from the uncertainties of the $^7\text{Be}(n, \alpha)^4\text{He}$, $^3\text{He}(^4\text{He}, \gamma)^7\text{Be}$ and $^7\text{Be}(^2\text{H}, p)2\alpha$ reactions. Finally, the theoretical error of $(^6\text{Li}/H)_p$ is almost entirely due to the the $D(\alpha, \gamma)^6\text{Li}$ process, that has been recently measured at BBN energies by the LUNA collaboration [3, 4, 5].

The results of BBN theory have to be compared with the direct observations of light isotopes in

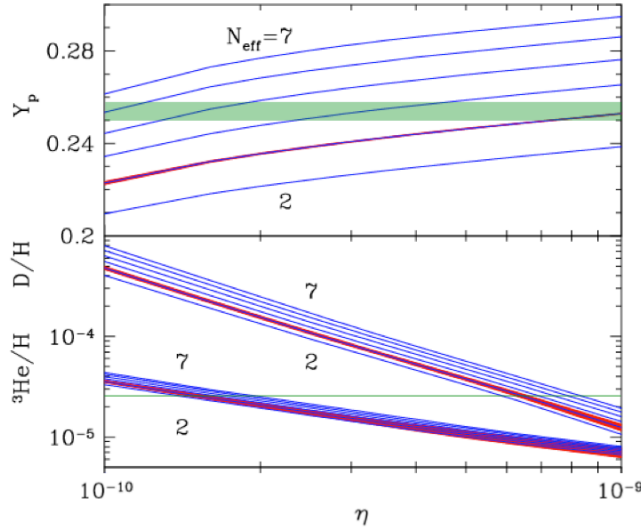


Figure 2: Yields of light nuclides as functions of the baryon-to-photon ratio, η . The blue lines indicate yields for a single value (integer plus 0.046) of N_{eff} . The red bands indicate the nuclear uncertainty on those yields for $N_{eff} = 3.046$. Also shown are horizontal green bands indicating observational constraints on ^4He and D abundances [6, 7].

the universe. As a general method, the primordial abundances are derived by extrapolating to zero metallicity the observations of light isotopes performed in metal-poor and/or faraway sites, where the abundances are thought to be less polluted by processes as stellar burning and cosmic-ray interactions. The primitive abundance of ^4He is deduced from observations in HII (ionized hydrogen) regions of compact blue galaxies. The uncertainty is mainly due to systematics such as plasma temperature or stellar absorption [6]. Observations in Damped Lyman-Alpha (DLA) systems at high redshifts provide the primordial abundance of deuterium with good accuracy [7]. The ^3He observations are limited to our galaxy, and are affected by large systematics uncertainties because this isotopes is both produced and destroyed in stars so that its primordial amount is quite uncertain [8]. The lithium abundance at BBN epoch is deduced from the observations of its characteristic absorption line at about 680 nm in low metallicity stars in the galactic halo. The observations show that the lithium abundance is almost independent of metallicity ("Spite plateau" [9]). This constant abundance is interpreted as corresponding to the BBN lithium yield. Finally, it is reported in liter-

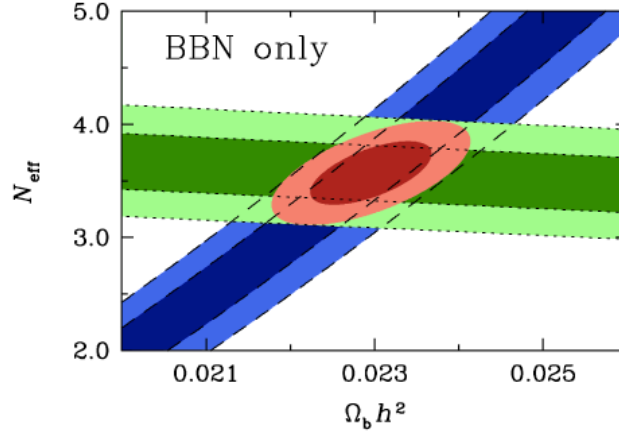


Figure 3: The 1σ and 2σ confidence contours (dark and light shades respectively) for N_{eff} and $\Omega_{b,0}$ derived from the primordial deuterium abundance (blue), the primordial He mass fraction (green), and the combined confidence contours (red) [7].

Table 1: Calculated and observed abundances of light isotopes derived from standard BBN and from direct astrophysical observations.

Isotope	SBBN Theory	Observations
Y_p	0.24771 ± 0.00014 [17]	0.254 ± 0.003 [6]
D/H	$(2.66 \pm 0.07) \times 10^{-5}$ [17]	$(2.53 \pm 0.04) \times 10^{-5}$ [7]
${}^3\text{He}/H$	$(1.00 \pm 0.07) \times 10^{-5}$ [33]	$(0.9 \div 1.3) \times 10^{-5}$ [8]
${}^7\text{Li}/H$	$(5.24^{+0.71}_{-0.67}) \times 10^{-10}$ [33]	$1.23^{+0.68}_{-0.32} \times 10^{-10}$ [34]
${}^6\text{Li}/{}^7\text{Li}$	$(1.5 \pm 0.3) \times 10^{-5}$ [5]	${}^6\text{Li}/{}^7\text{Li} \simeq 10^{-2}$ [24, 11]

ature a controversial measurement in which the asymmetry of the absorption line of Li is thought to be due to the isotope shift in atomic lines of 6Li with respect 7Li [10, 11].

Table 1 shows both the results of BBN calculations (assuming standard Model physics and the η parameter derived from cosmic microwave background (CMB) experiments and the results of direct observations of light isotopes. The computed abundances of D and 4He are in marginal agreement with observations, confirming the overall validity of the standard BBN theory. However, the tension between observations and theory may indicate the existence of dark radiation, as it will be discussed in the following. The 3He is considered not a powerful probe for the BBN theory, because of the large systematic errors of the value derived from observations. For what concern the "heavy" isotopes of lithium, the abundance of 7Li derived from observations ($({}^7Li/H)_{obs}$) is a factor ≈ 4 lower than the predicted $({}^7Li/H)_p$ ("The lithium problem") [12, 11]. Moreover, the amount of 6Li observed in metal poor stars is unexpectedly large compared to BBN predictions (${}^6Li_{obs}/{}^6Li_{BBN} \approx 10^3$) [10]. Even though many of the claimed 6Li detections are controversial, for a very few metal-poor stars there still seems to be a significant amount of 6Li ("The second Lithium problem") [12, 11]. The difference between predictions and observations of both the lithium isotopes may be due to new physics, such as the existence of supersymmetric particles in the early

Universe ([12, 11] and references therein).

In summary, the BBN theory provides a powerful tool to constrain particle physics and cosmology. A consistent theory (cosmology and particle physics) should provide the matching of BBN primordial abundances and the ones derived from observations. Therefore, it is presently very important a renewed study of the relevant nuclear processes, to reduce the error budget due to nuclear astrophysics. In the following I will focus the attention on the deuterium abundance, whose abundance depends to the baryon density and to the dark radiation. The study of the $D(p, \gamma)^3\text{He}$ process at BBN energies is of crucial importance, as it is the main source of uncertainty of $(D/H)_{BBN}$, and $(D/H)_{obs}$ is presently available with an error at the percent level. This study can be performed in existing [13] or in future underground accelerator facility

2. Baryon density and neutrinos.

The most recent CMB-derived baryon density is provided by the PLANCK collaboration [17]. Assuming standard model:

$$\Omega_{b,0}(CMB) = (2.205 \pm 0.028)/h^2 \quad (2.1)$$

In this equation, $\Omega_{b,0}$ is the present day baryon density of the universe and h is the Hubble constant in units of $100 \text{ km s}^{-1} \text{ Mpc}^{-1}$.

The baryon density can be independently inferred by means of standard BBN theory, by comparing primordial deuterium abundance (by far, the most sensitive isotopes to $\Omega_{b,0}$), with the value obtained with BBN calculations. The baryon density is independently obtained with comparison of $(D/H)_{BBN}$ and $(D/H)_{obs}$. Observations in Damped Lyman-Alpha (DLA) systems at high redshifts provide the primordial abundance of deuterium $(D/H)_p = (2.53 \pm 0.04) \times 10^{-5}$, corresponding to the following Universal baryon density [7]:

$$\Omega_{b,0}(BBN) = (2.202 \pm 0.019 \pm 0.041)/h^2 \quad (2.2)$$

The error terms in eq. 2.2 reflect the uncertainties in observed deuterium abundance and BBN calculation [7]. The latter is due to the 3% uncertainty of computed $(D/H)_{BBN}$. In turn, this uncertainty is dominated by the experimental error of $^2\text{H}(p, \gamma)^3\text{He}$ cross section at BBN energies ($30 \lesssim E_{cm}(keV) \lesssim 400$) [18, 7]. Therefore, a renewed accurate measurement of $^2\text{H}(p, \gamma)^3\text{He}$ can remarkably reduce the error of the BBN-derived baryon density. It is worth to point out that the η parameter obtained by CMB experiments and BBN theory gives respectively the Universal situation at $z \simeq 1000$ and $z \approx 10^{10}$. The matching of this independent measurements could represent a constrain to possible γ annihilation of super symmetric particles generated in the early universe, after the first minutes of cosmic time and before the recombination epoch ($\simeq 380.000$ years).

In cosmology, the definition of "neutrino" is any relativistic particle contributing to the radiation density with respect to photons. For standard cosmology $N_{eff} = 3.046$ and $\xi = 0$, where N_{eff} is the number of neutrino families and ξ is the lepton asymmetry [7, 19]. Both D and ^4He abundances depend on the expansion rate of universe, therefore they allow to bound N_{eff} by using the BBN theory alone or in combination with CMB results [7, 18, 19]. Figure 2 shows the BBN abundance

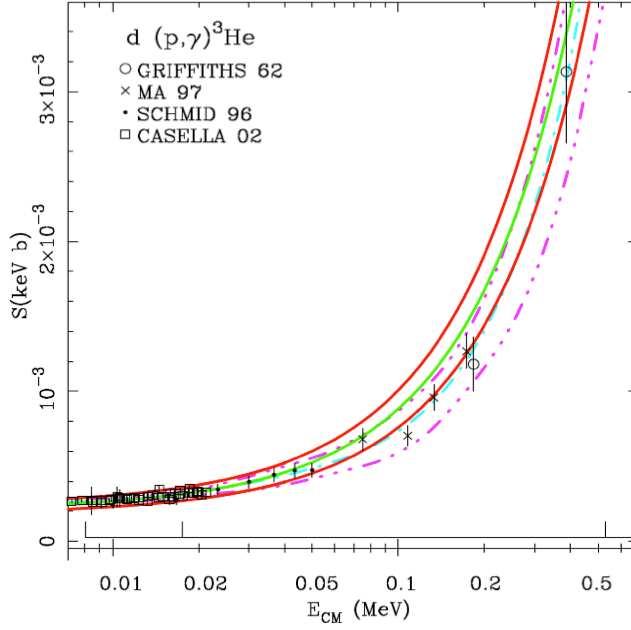


Figure 4: S-factor data for the reaction ${}^2\text{H}(p, \gamma){}^3\text{He}$. The best-fit curve (dash-dot curves) and theoretical calculation (solid) are shown. All errors are shown as 2σ s.

predictions as a function of the baryon-to-photon ratio, for $N_{eff} = 2$ to 4. Also shown are the observational constraints on ${}^4\text{He}$ and D abundances.

The CMB-only bound is $N_{eff}(CMB) = 3.36 \pm 0.34$ [17], while the BBN-only bound reported in [7] is $N_{eff}(BBN) = 3.57 \pm 0.18$. It is worthwhile to point out that both CMB and BBN constraints are in good agreement and provide a suggestive, but still inconclusive, hint of the presence of dark radiation. The BBN-only bound is graphically shown in Figure 3, in which the green band represents the confidence contour related to the helium abundance. As stated above (see 1), this uncertainty mainly depends on observational systematics. Instead, the blue band is the confidence contour for deuterium. According to eq. 2.2, this uncertainty mainly depends on the accuracy of the ${}^2\text{H}(p, \gamma){}^3\text{He}$ at BBN energy, that is the single most important obstacle to improve the BBN constraints on the existence of dark radiation.

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

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

$$\sigma(E) = \frac{S(E)e^{-2\pi\eta^*}}{E} \quad (3.1)$$

$S(E)$ contains all the nuclear effects. For non-resonant reactions, it is a smoothly varying function of energy. In this formula, the exponential term takes into account the Coulomb barrier, while the astrophysical factor $S(E)$ contains all the nuclear effects. For non-resonant reactions, it is a smoothly varying function of energy. The Sommerfeld parameter η^* is given by

$2\pi\eta^* = 31.29Z_1Z_2(\mu/E)^{1/2}$. 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 4 shows the available S_{12} data for this reaction. The precise low-energy data come from the LUNA measurement performed with the 50 keV accelerator [20]. Only a single dataset of S_{12} is currently available in the relevant energy range [21], in which the authors state systematic uncertainty of 9%. Figure 4 also shows the energy dependence of S_{12} as obtained by "ab initio" calculations [18, 22, 23, 24].

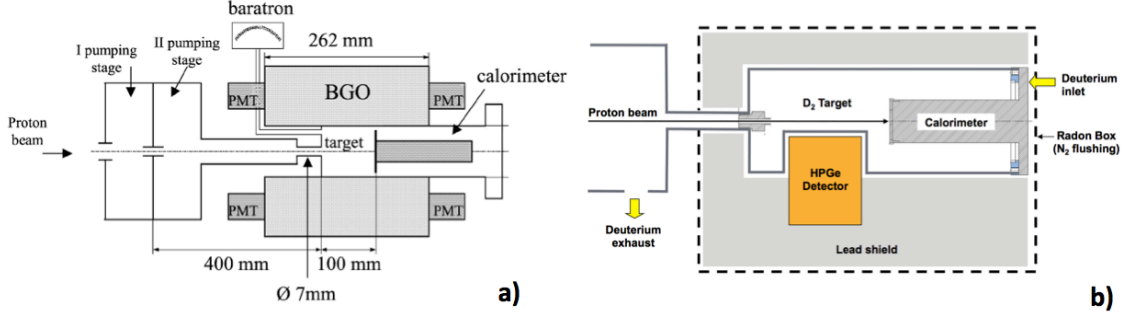


Figure 5: a): Scheme of gas target setup and BGO detector. b): Scheme of gas target setup and HPGe detector.

The feasibility of studying the ${}^2\text{H}(p,\gamma){}^3\text{He}$ reaction ($Q = 5.5 \text{ MeV}$) with good accuracy has been demonstrated at $2.5 < E_{cm}(\text{keV}) < 22$ with the previous LUNA 50 keV accelerator (see figure 4) [20]. Figure 5 a) shows the scheme of the setup used in [20], where a barrel BGO detector is implemented. Figure 5 b) shows the scheme of the setup used for the study of the ${}^2\text{H}(\alpha, \gamma){}^6\text{Li}$ reaction, where a large Germanium (HPGe) detector detects the photons produced in the reaction [25]. The high efficiency ($\sim 70\%$, see [20]) of the LUNA BGO 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 at a γ ray energy of 6.13 MeV exploiting the 340 keV resonance in the ${}^{19}\text{F}(p, \alpha\gamma){}^{16}\text{O}$ reaction. With the proposed setup the expected counting rate (full detection γ -peak) is of the order of $10^4 - 10^5 \text{ events/hour}$ in the considered energy range (see figure 6), making the measurements with BGO detector relatively fast for what concern statistics and allowing to determine the beam heating effect and the target density in asymptotical conditions, by performing dedicated measurements in which target pressure and beam intensity are varied. Finally, the beam intensity error can be minimized by a proper calibration of the calorimeter (1.5% uncertainty in ref. [26]). 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 ${}^2\text{H}(p, \gamma){}^3\text{He}$ 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 5b). 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 ${}^2\text{H}(p,\gamma){}^3\text{He}$ reaction. This study provides a useful tool for nuclear theoretical models. In fact, as stated above, the tension between existing data at BBN energies and “ab initio” calculations is presently debated.

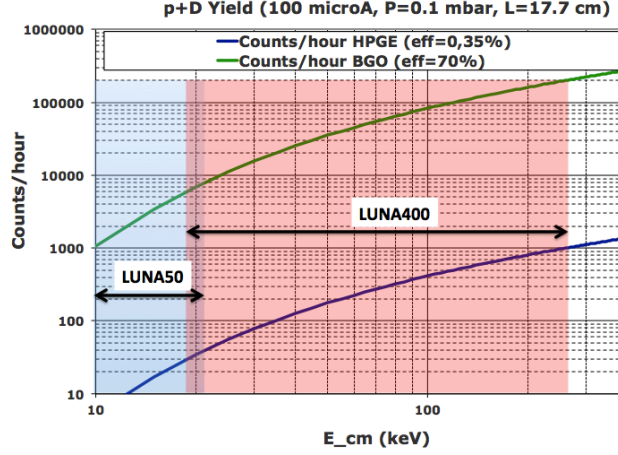


Figure 6: Reaction Yields at LUNA400, using the BGO detector (green line, see figure 5a) and the HPGe detector (blue line, see figure 5b). In the figure the working conditions, the energy range of the proposed experiment and the one of the previous LUNA measurement are also indicated [20].

4. Conclusions

The progress on direct observations of deuterium abundance [7] and the accuracy of CMB data [17] make the lack of ${}^2\text{H}(p,\gamma){}^3\text{He}$ reaction data at BBN energies the main obstacle to improve the constraints on $\Omega_{b,0}(\text{BBN})$, N_{eff} and lepton degeneracy ξ [7, 18, 27, 28]. A precision study of the ${}^2\text{H}(p,\gamma){}^3\text{He}$ reaction inside the BBN energy region of interest, with the goal of improving the present 9% systematic uncertainty of the S_{12} factor, is extremely important in this concern. As light nuclei are involved in this process, the ${}^2\text{H}(p,\gamma){}^3\text{He}$ reaction is of high interest also in theoretical nuclear physics, in particular for what concern “ab-initio” modelling. To reduce the background induced by cosmic rays, this study must be performed with facilities operating underground. Presently, the only underground accelerator in the world is the LUNA 400 kV accelerator at the Gran Sasso laboratory, Italy [13]. The “Gran Sasso” mountain provides a natural shielding which reduces the muon and neutron fluxes by a factor 10^6 and 10^3 , respectively. The suppression of the cosmic ray induced background also allows an effective suppression of the γ -ray activity by a factor 10^2 - 10^5 , depending on the photon energy [29]. The ultra-low background at LNGS made possible the study of other leading processes of the BBN network, such as ${}^2\text{H}(p,\gamma){}^3\text{He}$ and ${}^2\text{H}({}^3\text{He},p){}^4\text{He}$ at very low energy [20, 30, 31], by using the 50 kV accelerator [32], and the ${}^3\text{H}({}^4\text{He},\gamma){}^7\text{Be}$, already studied with the present facility [13]. The low environmental background achievable underground made possible the recent first direct measurement of the ${}^2\text{H}(\alpha,\gamma){}^6\text{Li}$ astrophysical factor at Big Bang energies [5, 3, 4], providing a solid experimental footing to calculate

the $({}^6\text{Li}/H)_{\text{BBN}}$ primordial abundance. More in general, the present "Era of precision cosmology" requires the accurate measurements of several reaction at BBN energies, in the whole BBN energy range. This program can be accomplished with present (LUNA) and proposed facilities [14, 15, 16].

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