The Underground Nuclear Astrophysics in the Precision Era of BBN: Present Results and Future Perspectives

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The Underground Nuclear Astrophysics in the Precision Era of BBN: Present Results and Future Perspectives

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Abstract. The abundance of light isotopes such as D, ^3He, ^4He, ^6Li and ^7Li produced during Big Bang Nucleosynthesis (BBN) only depends on particle physics, baryon density and relevant nuclear processes. At BBN energies ($0.01 \div 1$ MeV) the cross section of many BBN processes is very low because of the Coulomb repulsion between the interacting nuclei. As low-energy measurements on earth's surface are predominantly hampered by the effects of cosmic rays in the detectors, it is convenient to study the relevant reactions with facilities operating deep underground. Starting from the present uncertainty of the relevant parameters in BBN (i.e. baryon density, observed abundance of isotopes and nuclear cross-sections), it will be shown that the study of several reactions of the BBN chain, with existing or proposed underground accelerator facilities, can improve the accuracy of BBN calculations, providing a powerful tool to constrain astrophysics, cosmology and particle physics. In particular, a precise measurement of $D(p,\gamma)^3He$ reaction at BBN energies is of primary importance to calculate the baryon density of universe with an accuracy similar to the one obtained by Cosmic Microwave Background (CMB) experiments, and to constrain the number of active neutrino species. For what concern the so called "Lithium problems", i.e. the disagreement between computed and observed abundances of the ^7Li and ^6Li isotopes, it will be also shown the importance of a renewed study of the $D(\alpha,\gamma)^6Li$ reaction.

1. Introduction

In its standard picture, the Big Bang nucleosynthesis occurs during the first minutes of universe, with the formation of light isotopes such as D, ^3He, ^4He, ^6Li and ^7Li through the reaction network shown in figure 1. Their abundance essentially depends on the competition between the relevant nuclear processes and the expansion rate of the early universe. Therefore, their abundance depends on the standard model physics, on the baryon-to-photon ratio η and on the cross-sections of nuclear processes. Indeed, the BBN theory makes definite predictions for the abundances of the light elements as far as the knowledge of relevant parameters is accurate enough. Presently, we are in the exciting era of "high-precision" cosmology, with most of the cosmological parameters known to within a few percent. In particular, Cosmic Microwave Background (CMB) experiments provide a precise measurement of baryon density Ω_b and the derived η parameter [1, 2]. The universal expansion rate (i.e. Hubble parameter H) is determined through the Friedman equation by the total energy density, which is dominated by the number of relativistic species at these epochs. In the standard model, CMB photons, $e^{\pm}$ pairs and neutrinos. In addition, through their charged-current weak interactions, the electron-type neutrinos contribute to control the fraction of free neutrons available, which effectively determine the primordial abundance of ^4He. The nucleosynthesis chain begins with the formation of deuterium in the process $p(n,\gamma)D$. However, the density of photons is huge relative to the baryon

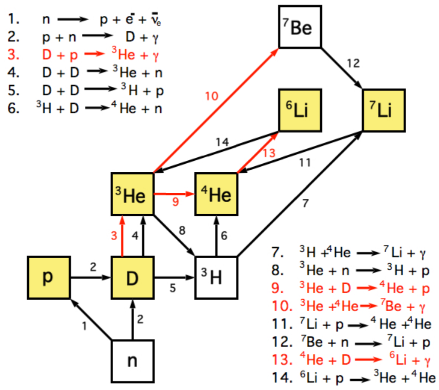

Figure 1. Leading processes of Big Bang Nucleosynthesis. Yellow boxes mark stable isotopes. The red arrows show the reactions that can be studied by exploiting existing or proposed underground accelerators.

density ($\eta \simeq 6 \cdot 10^{-10}$). Because of the large number of photons per baryon, photo-dissociation delays the production of deuterium well after T drops below the binding energy of deuterium ($Q = 2.23\ MeV$, the "deuterium bottleneck"). Nearly all the free neutrons end up bound in the most stable light element ^4He, while 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 ^4He+n, ^4He+p or $^4He+^4He$ reactions) and of the large Coulomb barriers for reactions such as the $^3H(^4He,\gamma)^7Li$ and $^3He(^4He,\gamma)^7Be$. The uncertainty of ^4He abundance weakly depends on details of the reaction network, and it is almost entirely due to neutron lifetime error. The error of computed D abundance is presently dominated by the $D(p,\gamma)^3He$ reaction. In fact, the $D(^2H,p)^3H$ and the $D(^2H,n)^3He$ reactions have recently been measured with high accuracy [4]. the ^3He error is mainly due to the $D(^3He,p)^4He$ process and, in a lower extent, to the $D(p,\gamma)^3He$ reaction [3]. For what concern the ^7Li isotope, there are several reactions contributing to the total uncertainty for this nuclide. For $\eta \simeq 6 \cdot 10^{-10}$, leading contributions to the theoretical estimate come from $^7Be(n,\alpha)^4He$,$^3He(^4He,\gamma)^7Be$ and $^7Be(^2H,p)2\alpha$ reactions. Finally, the theoretical error of ^6Li is very large, and it is almost entirely due to the poor knowledge of the $D(\alpha,\gamma)^6Li$ cross-section.
The computed abundances of D and ^4He are in agreement with observations within errors, confirming the overall validity of BBN theory. The ^3He observations are presently affected by large systematics errors, making this isotope not a powerful probe for the BBN theory. For what concern the "heavy" isotopes of Lithium, the observed abundance of ^7Li is a factor 2-4 lower than the predicted one ("The lithium problem") [5]. Recently, some observation indicates that the amount of ^6Li observed in metal poor stars is unexpectedly large compared to BBN predictions (see figure 2). 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") [5].
As stated above, the knowledge of several nuclear processes is affected by large uncertainties because of their low cross-section at BBN energies. Therefore, to reduce the background induced by cosmic rays, their study must be performed with facilities operating underground. Presently, the only underground accelerator in the world is the LUNA 400 kV accelerator, located inside the Gran Sasso laboratory, Italy [6], while many new facilities operating in the MV range have recently been proposed [7, 8, 9]. In the following, it will be discussed the feasibility of accurate measurements of the $D(\alpha,\gamma)^6Li$ and $D(p,\gamma)^3He$ reactions, and their impact in cosmology and particle physics.

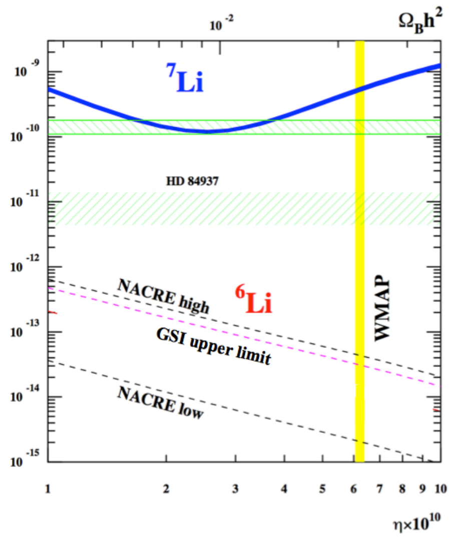

Figure 2. Predicted and observed BBN production ratios for ^6Li and ^7Li as a function of η. The blue band denotes the range of predicted ^7Li yields, The dashed black lines indicate the calculated ^6Li uncertainty and the dashed violet line is the upper limit obtained with the recent measurement by Hammache et al. [19]. Observational data are indicated by horizontal green-hatched areas. The yellow vertical band shows the WMAP η value [1]. The large uncertainty in the predicted ^6Li abundance is due to the lack of direct measurements of the $D(\alpha,\gamma)^6Li$ reaction in the BBN energy region.

2. The Lithium problem(s)

As shown in figure 2, the abundance of ^7Li observed in metal poor stars is several σs lower with respect to BBN predictions, while the amount ^6Li is order of magnitudes higher with respect to calculations [5]. The difference between observed and calculated abundances of ^7Li and ^6Li may reflect systematics in the observed values, post-primordial processes or physics beyond the Standard Model (see for example [15] and references therein). However, as shown in figure 2, the theoretical error of ^6Li abundance is very large because the cross-section of the leading process to synthesize ^6Li is poorly known. As a matter of fact, the $^2H(\alpha,\gamma)^6Li$ cross-section is very small at BBN energies ($30 \div 400\ keV$), because of the Coulomb barrier and because electric dipole transition is suppressed for the iso-scalar particles ^2H and ^4He. Therefore, the $^2H(\alpha,\gamma)^6Li$ cross-section has been measured only for energies greater than 1 MeV and around the 711 keV resonance [16, 17]. As shown in figure 3, there are two indirect attempts to determine the $^2H(\alpha,\gamma)^6Li$ cross-section at BBN energies, using the Coulomb dissociation technique [18, 19]. A direct attempt to directly measure the $^2H(\alpha,\gamma)^6Li$ cross-section in the BBN energy range by in-beam γ spectroscopy resulted only in an upper limit [11]. Very recently this cross-section have been measured at BBN energies by the LUNA collaboration [12, 13, 14]. The measurement has been done with the underground 400 kV accelerator, by using an α beam impinging a deuterium gas target and detecting the prompt γs with a lithium-drifted germanium detector. In this measurement the advantage of operating underground is reduced by the existence of a weak but inevitable beam induced background. In fact, the $^2H(\alpha,\alpha)^2H$ Rutherford scattering induces a small amount of $^2H(^2H,n)^3He$ reactions, with the production of few neutrons/second. The neutrons produced by the $^2H(^2H,n)^3He$ reaction induce $(n,n'\gamma)$ reactions in the germanium detector and in the surrounding materials, generating a neutron-induced background in the spectrum. Therefore, the LUNA measurement is limited to a narrow energy range around $E_{cm} = 130\ kV$. In fact, the maximal energy of the α particle beam in LUNA is only 400 keV and the Coulomb barrier makes unfavorable the signal-to-noise ratio at much lower beam energies. In any case, this first positive measurement of the $^2H(\alpha,\gamma)^6Li$ cross-section establishes that the study of this reaction at BBN energy is feasible, if it is carried out underground. Therefore, the proposed underground accelerators operating in the MeV region [7, 8, 9] allow a detailed study of this reaction in a wide energy range. In fact, it will be possible to cover the full BBN energy range and also overlap the Mohr's direct measurement around the 711 keV resonance ($E_{lab} = 2.1\ MeV$), making possible the calculation of ^6Li abundance with unprecedented precision and without any theoretical assumptions.

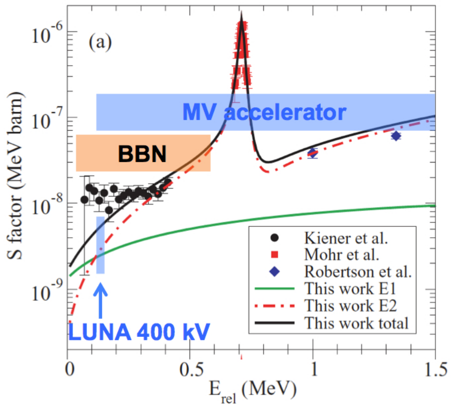

Figure 3. S-factor data for the reaction $D(\alpha,\gamma)^6Li$. Direct measurements [16, 17] are reported together with the indirect Coulomb Dissociation (CD) measurement by [18]. The Theoretical E1, E2, and total S factors curves are inferred from the CD data of Hammache et al. [19]. The energy range of the direct measurement performed with the LUNA 400 kV accelerator is also shown [12, 13, 14], as well as the energy region that can be investigated with an underground MegaVolt accelerator.

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

Deuterium is the most sensitive nuclide to η (or equivalently to the related baryon density $\Omega_b h^2$). Therefore it provides an independent measure of this parameter with respect to CMB experiments, which give the η value as it was after the recombination epoch, when the universe was some 400,000 years old [1, 2]. The most accurate measurement of baryon density is presently the one released by the PLANCK collaboration, $\Omega_{b,0}(CMB) = (2.205 \pm 0.028)/h^2$, where $\Omega_{b,0}$ is the present day baryon density of universe and h is the Hubble constant in units of 100 $km\ s^{-1}Mpc^{-1}$. On the other hand, the abundance of primordial deuterium has recently been measured with unprecedented precision, $10^5(D/H) = 2.53 \pm 0.05$ [2], improving the BBN-derived baryon density to $\Omega_{b,0}(BBN) = (2.22 \pm 0.03 \pm 0.08)/h^2$ [20]. The error terms reflect the uncertainties in, respectively, observed deuterium abundance and BBN calculation. The last is due to the uncertainties in the nuclear reaction rates used in BBN codes, and in particular the one related to the $D(p,\gamma)^3He$ cross-section. Therefore, even a modest reduction of the uncertainty of the $D(p,\gamma)^3He$ cross-section would make the precision of $\Omega_{b,0}(BBN)$ comparable to that of $\Omega_{b,0}(CMB)$ achieved by the PLANCK mission [21, 22]. For what concern the particle physics sector, D and ^4He abundances depends on the expansion rate of universe, therefore allow to bound the number of active neutrino families (and any other relativistic species) much better than with CMB alone [21, 22, 23]. Furthermore, unlike the CMB, The abundance of D and ^4He has the potential to probe a non-zero lepton asymmetry (neutrino degeneracy).
As discussed above, the accuracy of BBN constraints in cosmology and particle physics depends on the knowledge of the $D(p,\gamma)^3He$ cross-section. Figure 4 shows the S-factor data for this reaction. It is worth to point out that the precise low-energy data comes from underground measurements, by using a 50 kV accelerator [24]. The data at higher energies are much less accurate and show some tension with respect to theoretical models. In this concern, a measurement in the BBN energy range is mandatory, possibly with an underground accelerator. It is worth to point out that the existing 400 kV accelerator of LUNA can be used to measure the $D(p,\gamma)^3He$ S-factor up to $E_{cm} = 260\ keV$, with a substantial improvement of the calculated abundance of deuterium.

4. Conclusions

BBN theory represent a powerful tool to probe cosmology and standard model physics. In the age of "precision cosmology" we currently are, it is mandatory to improve the accuracy of BBN reactions, because they severely affects the uncertainty of calculations. This program must be be performed with facilities operating deep underground, to reduce the background induced by cosmic rays. To give an example, the muon and neutron fluxes inside the Gran Sasso Laboratory are reduced by a factor 10^6 and 10^3 with respect to the Earth's surface typical values, and the suppression of the γ-ray activity is a factor $10^2 - 10^5$, depending on the photon energy [25]. The $D(p,\gamma)^3He$ and $^2H(\alpha,\gamma)^6Li$ are of crucial importance to calculate the D and ^6Li isotopes and therefore to probe cosmology and particle physics. In this concern, a renewed study of $D(^3He,p)^4He$ and $^3H(^4He,\gamma)^7Li$ reactions, to respectively improve the calculation ^3He and ^7Li abundances, is also desirable.

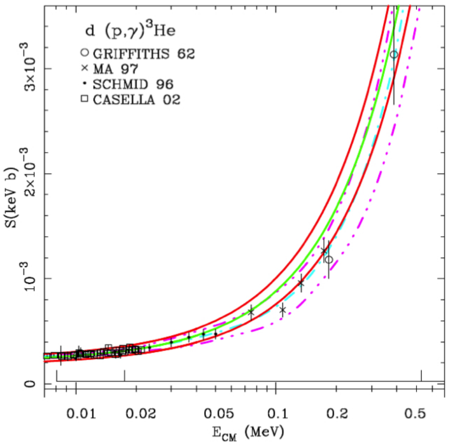

Figure 4. S-factor data for the reaction $D(p,\gamma)^3He$. the best-fit curve (dash-dot curves) and theoretical calculation (solid) are shown. All errors are shown as 2 σs.

References

[1] WMAP collaboration: arXiv:1212.5225v3 [astro-ph.CO] 4 Jun 2013.
[2] PLANCK collaboration: arXiv:1303.5076v1 [astro-ph.CO] 20 Mar 2013.
[3] P.D. Serpico et al., J. Cosmol. Astropart. Phys. 2004, 010 (2004).
[4] D.S. Leonard et al., Phys. Rev. C 73 045801 (2006).
[5] See proceedings of "Lithium in the Cosmos", 27-29 February 2012, Paris.
[6] A. Formicola et al., Nucl. Instr. and Meth. A 507 (2003) 609.
[7] M. Junker: "Experiences and Prospects of Nuclear Astrophysics in Underground Laboratories", proceedings of Nuclear Physics in Astrophysics VI, 19-24 May 2013, Lisbon.
[8] D. Bemmerer: "5 MeV underground accelerator in the Dresden Felsenkeller" , proceedings of Nuclear Physics in Astrophysics VI, 19-24 May 2013, Lisbon.
[9] A. Lemut: "The DIANA Underground Accelerator Facility", proceedings of Nuclear Physics in Astrophysics VI, 19-24 May 2013, Lisbon.
[10] F. Hammache et al., Phys. Rev. C 82, 065803 (2010), 1011.6179.
[11] F.E. Cecil, J. Yan, and C. S. Galovich, Phys. Rev. C 53, 1967 (1996).
[12] "Results of the first direct measurement of the $^2H(\alpha,\gamma)^6Li$ S-factor at Big Bang Energies", proceedings of Nuclear Physics in Astrophysics VI, 19-24 May 2013, Lisbon.
[13] C. Gustavino: "LUNA data on the $^2H(\alpha,\gamma)^6Li$ reaction and the Big Bang Nucleosynthesis", PoS(NIC XII)074 (2012).
[14] C. Gustavino: "The $^2H(\alpha,\gamma)^6Li$ experiment at LUNA", Proceedings of Int. Nucl. Phys. Conf., 2-7 june 2013, Florence, Italy.
[15] B.D. Fields, Annu. Rev. Nucl. Part. Sci. 61, 47 (2011).
[16] R.G.H. Robertson et al., Phys. Rev. Lett. 47, 1867 (1981).
[17] P. Mohr et al., Phys. Rev. C 50, 1543 (1994).
[18] J. Kiener et al., Phys. Rev. C 44, 2195 (1991).
[19] F. Hammache et al., Phys. Rev. C 82, 065803 (2010), 1011.6179.
[20] M. Pettini and R. Cooke: Mon. Not. R. Astron. Soc. 425, 24772486 (2012).
[21] K.M. Nollett and G.P. Holder: arXiv:1112.2683v1 [astro-ph.CO] 12 Dec 2011.
[22] R.J. Cooke et al.: arXiv:1308.3240v1 [astro-ph.CO] 14 Aug 2013.
[23] G. Steigman: arXiv:1208.0032v1 [hep-ph] 31 Jul 2012.
[24] C. Casella et al.: Nuclear Physics A 706 (2002) 203216.
[25] A. Caciolli et al., Eur. Phys. J. A 39, 179 - 186 (2009).