IL NUOVO CIMENTO **39 C** (2016) 361
DOI 10.1393/ncc/i2016-16361-3

Colloquia: SEA2016

Some nuclear physics aspects of BBN

Alain Coc

Centre de Sciences Nucléaires et de Sciences de la Matière (CSNSM), CNRS/IN2P3, Univ. Paris-Sud, Université Paris–Saclay - F–91405 Orsay Campus, Orsay, France

received 28 November 2016

Summary. — Primordial or big bang nucleosynthesis (BBN) is now a parameter free theory whose predictions are in good overall agreement with observations. However, the ^{7}Li calculated abundance is significantly higher than the one deduced from spectroscopic observations. Nuclear physics solutions to this *lithium problem* have been investigated by experimental means. Other solutions which were considered involve exotic sources of extra neutrons which inevitably leads to an increase of the deuterium abundance, but this seems now excluded by recent deuterium observations.

Primordial nucleosynthesis is one of the three evidences for the big bang model, together with the universal expansion and the Cosmic Microwave Background radiation (CMB). While the relevant nuclear reaction rates have been determined by laboratory experiment, its last free parameter, the baryonic density of the Universe, is now precisely deduced from observations of the anisotropies of the CMB [1]. The calculated primordial abundances of ^{4}He, D, and ^{3}He are in good agreement with observations, but ^{7}Li abundance prediction is a factor of ≈ 3 higher than the one deduced from spectroscopic observations. Solutions to this problem (see [2] for a review) include stellar surface depletion of lithium [3], nuclear destruction during BBN or solutions beyond the standard model (*e.g.* [4]). This situation is shown in table I that displays the comparison between recent BBN calculations [5, 6] and observations [7-10]. (The small differences in the predicted values are mostly due to the choices of nuclear reaction rates.) This lithium problem is even more acute after recent deuterium observations have reduced the uncertainty on the primordial deuterium abundance [7] since most solutions to reduce BBN lithium production lead to an increase of deuterium.

It is fundamental to, first, investigate solutions to the lithium problem that can be tested by laboratory measurements, essentially in the nuclear sector. At the CMB deduced density, ^{7}Li is produced through the formation of ^{7}Be via the ^{3}He$(\alpha,\gamma)^7$Be reaction; ^{7}Be will much later decay to ^{7}Li. The destruction of ^{7}Be occurs through the ^{7}Be(n,p)^{7}Li(p,α)^{4}He channel which is limited by the scarcity of neutrons. Hence,

TABLE I. – *Primordial abundances compared to observations.*

	Coc *et al.* [5]	Observations	Cyburt *et al.* [6]
Y_p	0.2484 ± 0.0002	0.2449 ± 0.0040 [8]	0.24709 ± 0.00025
D/H ($\times 10^{-5}$)	2.45 ± 0.05	2.53 ± 0.04 [7]	2.58 ± 0.13
^{3}He/H ($\times 10^{-5}$)	1.07 ± 0.03	1.1 ± 0.2 [9]	1.0039 ± 0.0090
^{7}Li/H ($\times 10^{-10}$)	5.61 ± 0.26	$1.58^{+0.35}_{-0.28}$ [10]	4.68 ± 0.67

a peculiar attention should be paid to ^{7}Be destruction: either by a supplementary reaction that was overlooked in previous studies, or by an increased late-time neutron abundance.

A greater destruction of ^{7}Be by extra nuclear reactions have been proposed, the most promising was ^{7}Be(d,p)2α [11]: an increase of its rate by a factor of ≈ 100 would have solved the problem. Measurements of its cross section [12] at the Louvain-la-Neuve facility ruled out this possibility, but the existence of unknown resonances in the ^{7}Be+n, p, d, t, ^{3}He and ^{4}He channels was rapidly proposed (*e.g.* [13]). In particular, the existence of a relatively narrow state around 15 MeV in the compound nucleus ^{10}C formed by ^{7}Be+^{3}He or the existence of a state close to 8 MeV in the compound nucleus ^{11}C formed by ^{7}Be+^{4}He could help reduce the ^{7}Be production. However, a search [14] for missing levels in the relevant excitation energy regions of ^{10}C and ^{11}C, via the reactions ^{10}B(^{3}He,t)^{10}C and ^{11}B(^{3}He,t)^{11}C, respectively, did not find any new level. In addition, Coulomb barrier penetrability would prevent any resonance strength to be strong enough to have a significant effect on ^{7}Be destruction [15, 16]. The decay of ^{7}Be proceeds by electron capture; its lifetime could be shortened by the high electron density prevailing during BBN. Figure 1 shows that the electron density resulting from the $\gamma\gamma \leftrightarrow e^+e^-$ equilibrium is lower than at the solar center when ^{7}Be is formed ($T < 0.5$ GK) in BBN. This rules out the possibility that ^{7}Be lifetime could to be reduced to a value ($\sim 10^3$ s) such

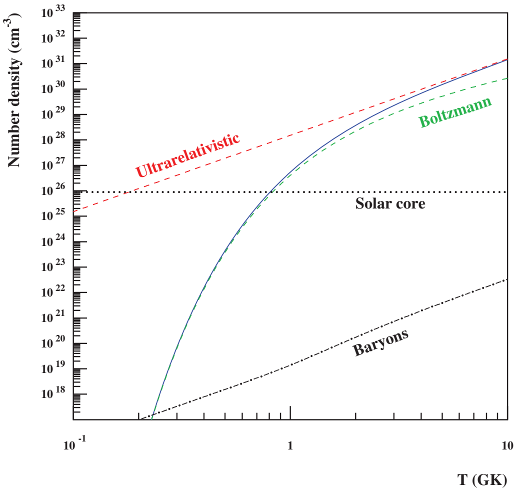

Fig. 1. – The electron number density during BBN, from $\gamma\gamma \leftrightarrow e^+e^-$, (solid line) compared to ultra–relativistic and classical limits (dashed lines), solar core (dotted line) and BBN baryon number (dash-dotted line) densities.

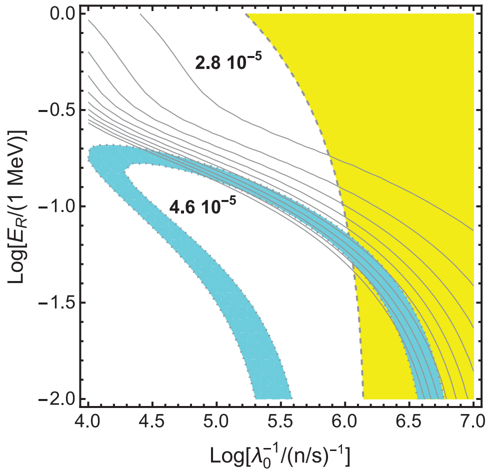

Fig. 2. – Regions in the two parameters space of the model of resonant relic particle annihilations [21] that are in agreement with ^{4}He (dashed line, yellow) [8] and ^{7}Li (dotted line, cyan) [10]. The solid lines indicates the prediction of deuterium abundance $D/H = (2.8–4.6) \times 10^{-5}$ but the observations [7] lie outside of the frame.

that it impacts BBN, nor that electron screening may be relevant. It is clear now that all extra ^{7}Be destructing reactions are inefficient to solve the lithium problem. However, a few reactions rates [^{3}He$(\alpha,\gamma)^7$Be [17] and ^{7}Be(n,p)^{7}Li] can have an impact on lithium BBN production and hence to the degree of depletion needed through other means. In particular, the ^{7}Be(n,pγ)^{7}Li channel was not considered in previous evaluations [18].

Another scenario would be to take advantage of an increased *late-time* neutron abundance so that more ^{7}Be is destroyed by ^{7}Be(n,p)^{7}Li(p,α)α (with no effect on ^{4}He because of timing). These exotic models involve mirror neutrons, relic particle decay or annihilation as extra neutron sources. The hypothesis of mirror matter aims at restoring global parity conservation [19] by postulating a mirror world with the same particles but opposite parities that would, except for neutral particles, only interact gravitationally with our own world (see [20] and reference therein). For some values of the parameters of the models, oscillations between mirror and ordinary neutrons could be the origin of this late neutron injection [21]. Exotic particles produced earlier than BBN could decay or annihilate [22, 23] with neutrons among other products. In fig. 2 are shown the results from a model in which relic particles annihilate in a resonant way, producing neutrons (*i.e.* $\chi + \chi \to \mathrm{n} + \ldots.$) that are thermalized by the ambient plasma. The parameters of the models are the resonance energy (E_R) and the combination (λ_0) of the abundance of relic particle and annihilation rate. There is a region (lower right corner) where both ^{4}He and ^{7}Li calculated abundances agree with observations [8, 10], but at the expense of deuterium overproduction: D/H observations [7] lie outside (upper right corner) of the frame. Compatibility with deuterium is only achieved for D/H values in the range [$(3.8–4.6) \times 10^{-5}$], well outside observational limits [7] (table I). This increase of the deuterium abundance associated with neutron injection result from the unavoidable product of the ^{1}H(n,γ)^{2}H reaction, that, in view of the recent D/H observations rules out a solution that involves extra neutron sources. Few solutions beyond the Standard Model that do not suffer from this drawback are left, *e.g.* [24].

* * *

I am indebted to my collaborators on these topics: Pierre Descouvemont, Stéphane Goriely, Faïrouz Hammache, Christian Iliadis, Keith Olive, Patrick Petitjean, Maxim Pospelov, Jean-Philippe Uzan, and especially to Elisabeth Vangioni.

REFERENCES

[1] Planck Collaboration XIII, (Ade P. A. R., *et al.*), arXiv:1502.01589 [astro-ph.CO].
[2] Fields B. D., *Annu. Rev. Nucl. Part. Sci.*, **6** (2011) 47.
[3] Richard O., Michaud G. and Richer J., *Astrophys. J.*, **619** (2005) 538.
[4] Yamazaki D. G., Kusakabe M., Kajino T., Mathews G. J. and Cheoun M.-K., *Phys. Rev. D*, **90** (2014) 023001.
[5] Coc A., Petitjean P., Uzan J.-Ph., Vangioni E., Descouvemont P., Iliadis C. and Longland R., *Phys. Rev. D*, **92** (2015) 123526.
[6] Cyburt R. H., Fields B. D., Olive K. A. and Yeh T.-H., *Rev. Mod. Phys.*, **88** (2016) 015004.
[7] Cooke R., Pettini M., Jorgenson R. A., Murphy M. T. and Steidel C. C., *Astrophys. J.*, **781** (2014) 31.
[8] Aver E., Olive K. A. and Skillman E. D., *J. Cosmol. Astropart. Phys.*, **07** (2015) 011.
[9] Bania T., Rood R. and Balser D., *Nature*, **415** (2002) 54.
[10] Sbordone L., Bonifacio P., Caffau E. *et al.*, *Astron. Astrophys.*, **522** (2010) A26.
[11] Coc A., Vangioni-Flam E., Descouvemont P., Adahchour A. and Angulo C., *Astrophys. J.*, **600** (2004) 544.
[12] Angulo C., Casarejos E., Couder M., Demaret P., Leleux P., Vanderbist F., Coc A., Kiener J., Tatischeff V., Davinson T., Murphy A. S., Achouri N. L., Orr N. A., Cortina-Gil D., Figuera P., Fulton B. R., Mukha I. and Vangioni E., *Astrophys. J. Lett.*, **630** (2005) L105.
[13] Chakraborty N., Fields B. D. and Olive K. A., *Phys. Rev. D*, **83** (2011) 063006.
[14] Hammache F., Coc A., de Séréville N., Stefan I., Roussel P., *et al.*, *Phys. Rev. C*, **88** (2013) 062802(R).
[15] Kirsebom O. S. and Davids B., *Phys. Rev. C*, **84** (2011) 058801.
[16] Broggini C., Canton L., Fiorentini G. and Villante F. L., *J. Cosmol. Astropart. Phys.*, **6** (2012) 30.
[17] deBoer R. J., Görres J., Smith K., Uberseder E., Wiescher M., Kontos A., Imbriani G., Di Leva A. and Strieder F., *Phys. Rev. C*, **90** (2014) 035804.
[18] Hayakawa S. *et al.*, these proceedings.
[19] Lee T. D. and Yang C.-N., *Phys. Rev.*, **104** (1956) 254.
[20] Berezhiani Z., Comelli D. and Villante F. L., *Phys. Lett. B*, **503** (2001) 362.
[21] Coc A., Pospelov M., Uzan J.-P.h. and Vangioni E., *Phys. Rev. D*, **90** (2014) 085018.
[22] Olive K. A., Petitjean P., Vangioni E. and Silk J., *Mon. Not. R. Astron. Soc.*, **426** (2012) 1427.
[23] Kusakabe M., Cheoun M.-K. and Kim K. S., *Phys. Rev. D*, **90** (2014) 1045009.
[24] Goudelis A., Pospelov M. and Pradler J., *Phys. Rev. Lett.*, **116** (2016) 211303.