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A new tension in the cosmological model from primordial deuterium?

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ABSTRACT
Recent measurements of the D(p,γ)^{3}He nuclear reaction cross-section and of the neutron lifetime, along with the reevaluation of the cosmological baryon abundance from cosmic microwave background (CMB) analysis, call for an update of abundance predictions for light elements produced during the big-bang nucleosynthesis (BBN). While considered as a pillar of the hot big-bang model in its early days, BBN constraining power mostly rests on deuterium abundance. We point out a new $\simeq 1.8\sigma$-tension on the baryonic density, or equivalently on the D/H abundance, between the value inferred on one hand from the analysis of the primordial abundances of light elements and, on the other hand, from the combination of CMB and baryonic oscillation data. This draws the attention on this sector of the theory and gives us the opportunity to reevaluate the status of BBN in the context of precision cosmology. Finally, this paper presents an upgrade of the BBN code `PRIMAT`.

Key words: primordial nucleosynthesis, baryon abundance, deuterium

INTRODUCTION

Big-Bang nucleosynthesis (BBN) has long been considered as one of the three historical pillars of the cosmological "Big-Bang" model, together with the expansion of the universe revealed by the Hubble diagram and the existence of a cosmic microwave background (CMB) of radiation. In the past decades, the accuracy of the measurements and analysis of these three cosmological probes have drastically improved and were complemented by many other observables, mostly based on the large scale structure of the Universe. As a consequence, the error bars on the cosmological parameters have significantly been improved and, as could have been anticipated, one starts to witness tensions between different probes.

This is in particular the case for the Hubble parameter H_0 that is measured to be 69.36 ± 0.54 km/s/Mpc [1] from the global fit of the CMB data (Planck Collaboration et al. 2020). This "low" value is to be contrasted with the higher value obtained from standard distance ladder, 73.4 ± 1.4 km/s/Mpc (Reid, Pesce & Riess 2019), or 73.3 ± 1.7 km/s/Mpc (Wong et al. 2020) from strong gravitational lensing effects on quasar systems. In such a situation, one first needs (1) to look for so-far negligible bias in the understanding of each data set, (2) reconsider some hypothesis of the cosmological model, such as the Copernican principle that assumes a spatially homogeneous and isotropic universe, or in this particular case the fluid limit since thin beams (Clarkson et al. 2012) do not propagate in the mean Friedmann-Lemaître (FL) spacetime, which can be at the origin of the misinterpretation of the cosmological parameters (Fleury, Dupuy & Uzan 2013). The interpretation of any observation requires to model the propagation of light and is thus tied with the whole cosmological model itself. To finish (3) one can consider new physics, since here the two discrepant values for H_0 correspond to data in the early and late universe; see e.g. Di Valentino et al. (2020) for a list of attempts.

As far as BBN is concerned, the theoretical computation rests on the hypothesis of a strictly spatially homogeneous and isotropic FL spacetime, which is thought to be a good approximation in the early radiation dominated universe in which density perturbations are still very small. The microphysics at play is particle and nuclear physics below 100 MeV that can be tested in accelerator. Today, several public (or not) numerical codes are able to predict the abundances of the light elements (Wagoner, Fowler & Hoyle 1967; Kawano 1992; Coc & Vangioni 2017; Pisanti et al. 2008; Consiglio et al. 2017; Arbey 2012; Arbey et al. 2020; Pitrou et al. 2018; Fields et al. 2020). Prior to WMAP, these predictions depended on two cosmological parameters, the total number

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[1] All error bars are stated with 1σ confidence intervals.

of relativistic degrees of freedom (or equivalently the effective number $N_{\rm eff}$ of neutrino families) and the number of baryons per photon η. This latter quantity is equivalent to specifying the baryon density $\Omega_{\rm b}h^2$, a parameter measured by other cosmological probes such as the CMB, with the relation (Pitrou et al. 2018)

$$\frac{\Omega_{\rm b}h^2}{0.0224} \simeq \left(\frac{\eta}{6.13197\times10^{-10}}\right)\left(\frac{T_{\rm CMB}}{2.7255\ {\rm K}}\right)^3 \times\left(\frac{1-1.759\times10^{-3}\frac{Y_{\rm P}}{0.2471}}{1-1.759\times10^{-3}}\right). \quad (1)$$

Prior to WMAP, these parameters were adjustable but they are now determined with high accuracy from the CMB analysis. A first method consists in fixing $\Omega_{\rm b}h^2$ from CMB and $N_{\rm eff}$ from particle physics (thus making BBN a parameter-free model) and assess the agreement between the predicted abundances and the measured ones. Alternatively, we can constrain $\Omega_{\rm b}h^2$ and $N_{\rm eff}$ from BBN (by confronting the predicted abundances which depend on these physical parameters, and the measured ones) and assess the agreement with the values determined by other probes.

Spectroscopic measurements of the abundances of helium-4, deuterium, helium-3 and lithium-7 allow for a comparison with the BBN theoretical predictions. While lithium-7 still exhibits a so-far unexplained discrepancy, see e.g. Molaro & Vangioni (2009, 2010); Fields (2011) for an extended debate, deuterium has been considered as a success of the model due to the agreement of BBN predictions, CMB constraints on $\Omega_{\rm b}h^2$ and observed primitive abundances. Recent measurements (Mossa et al. 2020b,a) of one of the key nuclear cross-section drives us to reconsider the robustness of this primordial deuterium success, and more largely of the status of BBN in the standard cosmological model.

1 BBN OVERVIEW

BBN predictions consist in abundances of light nuclei (deuterium, helium-3 and -4, lithium-7) that can be compared to spectroscopic measurements and to the trace abundances of heavier nuclei (Iocco et al. 2007; Coc, Uzan & Vangioni 2014), that cannot be measured but may influence the evolution of the first generation of stars. These nuclei are synthetized through nuclear reactions in an expanding universe and can take place only in a narrow window of time during which (1) the thermal bath of the universe has cooled enough for the light atomic nuclei, and foremost deuterium, not to be photo-dissociated, and (2) the density of baryonic matter is high enough for the number of collisions to be large enough. As such it rests on nuclear physics in an expanding homogeneous universe and has two free cosmological parameters, $N_{\rm eff}$ and η.

The predictions reach the percent-level accuracy on helium-4, in complete agreement with its observed value (Aver et al. 2020) $Y_{\rm P} = 0.2453\pm0.0034$. Note however that its order of magnitude was initially obtained (Alpher, Bethe & Gamow 1948; Alpher & Herman 1948) from back-of-the-envelope considerations, because it depends very mildly on η, and mostly on $\tau_{\rm n}$, $N_{\rm eff}$ (along with the Fermi and Newton constants, $G_{\rm F}$ and $G_{\rm N}$). It was an early and robust prediction of the standard cosmological model (Peebles 1966a,b) that allowed to claim that only 3 neutrino families existed (Yang et al. 1979), as was later confirmed by the LEP in 1990. But today, due to its mild dependence on η and the accuracy of its measurement, helium-4 is not competitive anymore in our era of precision cosmology to constrain the baryon density. The lithium-7 abundance still exhibits a factor ~ 3 discrepancy, that is usually discarded with modesty in cosmological studies that never take it into account. The consensus is that it cannot arise from the nuclear sector (Coc et al. 2014; Davids 2020; Iliadis & Coc 2020). Helium-3 is less constraining because, (1) since it is both produced and destroyed in stars, the evolution of its abundance in time is not very precise and (2) because there are only few observations in the Galactic disk (Bania, Rood & Balser 2002). Vangioni-Flam et al. (2003) have shown that these observations do not allow to set a strong constraint on the primordial baryon density due to the limited understanding of the chemical evolution of this isotope. To finish, deuterium is a very fragile isotope that can only be destroyed after BBN throughout stellar evolution. The most recent recommended observed value provided by Cooke, Pettini & Steidel (2018) is

$$\mathrm{D/H} = (2.527\pm0.030)\times10^{-5} \quad (2)$$

at a redshift $z\sim 2.5-3.1$.

It follows that among all light elements, deuterium is the most constraining since both its observational measurement and its theoretical prediction reach 1% accuracy. As can been seen from our previous analysis (Pitrou et al. 2018), it requires theoretical predictions and nuclear data to reach the 1% level so that great care should be paid to nuclear cross-sections affecting deuterium nucleosynthesis.

`PRIMAT` (Pitrou et al. 2018) computes directly the weak interaction rates, which interconvert neutrons and protons, including radiative corrections, finite nucleon mass effects, and neutrino spectral distortions, whereas `PArthENoPE` (Consiglio et al. 2017) and `AlterBBN` (Arbey et al. 2020) rely on a the fit given in Appendix C of Serpico et al. (2004). The differential equations governing the evolution of nuclear abundances are integrated in time (as also does `AlterBBN`), which differs from `PArthENoPE` which integrates equations in terms of the plasma temperature. Since ${\rm d}T/{\rm d}t$ can be obtained from the plasma continuity equation, both methods are of course equivalent. Since its release in 2018, a series of improvements have been included in `PRIMAT` :

- A refined treatment of neutrino decoupling, including neutrino oscillations and neutrino spectral distortions, has been included by using results from an external neutrino decoupling computation (Froustey & Pitrou 2020; Froustey, Pitrou & Volpe 2020);
- Pair production corrections to nuclear rates that otherwise produce a photon in the final state have been included for the most important reactions (Pitrou & Pospelov 2020);
- QED corrections at order e^3 have been taken into account in the plasma thermodynamics (Bennett et al. 2020b), whereas previously it was restricted to order e^2 corrections.

These three modifications have a very minor impact on $10^5\times\mathrm{D/H}$ as they shift it by 0.0015, −0.0021 and −0.0003 respectively. Only the first modification has a small impact on $Y_{\rm P}$ as it shifts it by 0.00005, the other two being completely subdominant.

Also, since the publication of Pitrou et al. (2018) there have been a series of updates on the values of the physical parameters. First concerning the cosmology, the value of $\Omega_{\rm b}h^2$ has been revised by the Planck 2018 release (Planck Collaboration et al. 2020) to

$$\Omega_{\rm b}h^2 = 0.02237 \pm 0.00015 \qquad \text{(CMB)} \tag{3}$$

for the CMB alone (instead of the previous 0.02225 ± 0.00016 from Ade et al. (2016)), and

$$\Omega_{\rm b}h^2 = 0.02242 \pm 0.00014 \qquad \text{(CMB+BAO)} \tag{4}$$

when combined with baryon acoustic oscillations (BAO) data (Alam et al. 2017). The value of the number of effective relativistic degrees of freedom is (Mangano et al. 2005; de Salas & Pastor 2016; Grohs & Fuller 2017; Escudero Abenza 2020; Akita & Yamaguchi 2020; Froustey, Pitrou & Volpe 2020; Bennett et al. 2020a)

$$N_{\rm eff} = 3.044 \tag{5}$$

for 3 neutrino families[2], taking into account the neutrino decoupling physics. This value is very robust and can be understood fully from the adiabatic transfer of averaged oscillations (ATAO) approximation (Froustey, Pitrou & Volpe 2020). This allows one to show that this prediction is insensitive to the type of neutrino mass hierarchy (normal or inverted) as it depends nearly exclusively on mixing angles. Also, since mixing angles are currently known with rather good precision, the propagation of uncertainty affects $N_{\rm eff}$ with $\pm 2 \times 10^{-5}$ only.

Then, concerning the microphysics the new neutron decay constant reported by Zyla et al. (2020) is

$$\tau_{\rm n} = 879.4 \pm 0.6\,{\rm s} \tag{6}$$

which is very close to $\tau_{\rm n} = 879.5 \pm 0.8\,{\rm s}$ used in Pitrou et al. (2018), but with an even smaller error bar. It was historically used to bypass the uncertainty about the quark mixing angle $V_{\rm ud}$ and the nucleon axial coupling constant g_A in the prefactor $V_{\rm ud}^2(1+3g_A^2)$ which enters the weak interaction rates expressions, thanks to the relation

$$\tau_{\rm n} = \frac{2\pi^3\hbar}{\lambda_0 G_{\rm F}^2 V_{\rm ud}^2(1+3g_{\rm A}^2)(m_{\rm e}c^2)^5}\,, \tag{7}$$

with $\lambda_0 \simeq 1.75434$ (Cooper et al. 2010; Pitrou et al. 2018). Note that from the recent values[3] $V_{\rm ud} = 0.97420 \pm 0.00028$ and $g_{\rm A} = 1.2756 \pm 0.0013$, we would infer from (7) that $\tau_{\rm n} = 879.4 \pm 0.5\,{\rm s}$, hence increasing the confidence in the determination (6).

BBN also notably depends on the value of the Newton constant $G_{\rm N}$ and Fermi constant $G_{\rm F}$ and we rely on their latest CODATA values (Mohr et al. 2018) as well as for all fundamental constants (the sensitivity to these constants has been estimated in works related to the constraints on their possible variations, see e.g. Coc et al. (2007); Uzan (2003, 2011)).

Finally, the nuclear network has been updated to take into account the results of new experiments or analyses as summarized in Table 1. None of these changes brings any relief to the cosmological lithium problem (Iliadis & Coc 2020). The reference for the other, unchanged reaction rates, can be found in Coc et al. (2012); Pitrou et al. (2018).

The change in the ^{7}Be(n,p)^{7}Li rate is mainly responsible for the small decrease of Li/H. The Rijal et al. (2019) experiment put the ^{7}Be(d,p)2α rate on firmer ground but brings no change in our Li/H predictions (Coc & Davids 2019). The rates from the re–analyses of the ^{3}H(d,n)^{4}He and ^{3}He(d,p)^{4}He reactions lead to a small change in the ^{3}He/H prediction. To finish, and that will be the focus of our present analysis, a new reaction rate for the D(p,γ)^{3}He reaction (Mossa et al. 2020b) has recently been published. This is a long awaited and major progress for BBN.

2 DEUTERIUM NUCLEOSYNTHESIS

Except for ^{4}He, differences in modern BBN codes are explained by differences in adopted reaction rates. Hence, to compare our results with others, one first needs to compare reaction rates. The production of deuterium mostly depends on 4 nuclear reactions. Deuterium is produced through ^{1}H(n,γ)^{2}H, the cross-section of which is obtained from an effective field theory computation (Ando et al. 2006), reliable at the 1%-level and in perfect agreement with the existing few experimental data (see e.g. Fig. 1 in Coc (2013)). It is then involved in 3 nuclear reactions D(p,γ)^{3}He, D(d,n)^{3}He and D(d,p)^{3}H. These reactions are the main sources of nuclear uncertainty for the prediction of the primordial deuterium abundance. The sensitivity (Coc & Vangioni 2010) to these reaction rates are

$$\begin{aligned}\frac{\Delta({\rm D/H})}{\rm D/H} &= -0.32\frac{\Delta\langle\sigma v\rangle_{{\rm D(p,\gamma)^3He}}}{\langle\sigma v\rangle_{{\rm D(p,\gamma)^3He}}} \\ \frac{\Delta({\rm D/H})}{\rm D/H} &= -0.54\frac{\Delta\langle\sigma v\rangle_{{\rm D(d,n)^3He}}}{\langle\sigma v\rangle_{{\rm D(d,n)^3He}}} - 0.46\frac{\Delta\langle\sigma v\rangle_{{\rm D(d,p)^3H}}}{\langle\sigma v\rangle_{{\rm D(d,p)^3H}}}.\end{aligned} \tag{8}$$

It is clear that a percent accuracy on the predictions, as required by the data, implies to reach a percent level accuracy on the cross-sections. Since none of them have resonances, their determination boils down to the accurate modeling of the slowly varying energy dependent S-factor and to a precise determination of their absolute scale.

2.1 Reaction rate evaluations

To derive reaction rates and uncertainties, there are two main approaches in the literature. Either one empirically fits both the energy dependence and scale so as to follow closely the data, or one uses theoretical energy dependences from nuclear physics models and only determine the absolute normalisation. Different approaches have also been considered in the treatment of uncertainties, frequentist versus bayesian with different treatments of systematic uncertainties. However, it has been shown that given the same datasets and

[2] This recent reference value (Froustey, Pitrou & Volpe 2020) is lower than the previously admitted 3.046 of e.g. Mangano et al. (2005) or the improved value 3.045 of de Salas & Pastor (2016), essentially due to the inclusion of $\mathcal{O}(e^3)$ QED corrections in the plasma equation of state, following Bennett et al. (2020b).

[3] We use the PDG2020 (Zyla et al. 2020) value for $g_{\rm A}$, but the PDG2018 (Tanabashi et al. 2018) value for $V_{\rm ud}$ since the PDG2020 value for $V_{\rm ud}$ is lower and slightly incompatible with the unitarity of the CKM matrix.

Table 1. References of the reaction rates in PRIMAT 2018 (Pitrou et al. 2018) and their updated values in PRIMAT 2021.

Reaction	PRIMAT 2018	PRIMAT 2021
D(p,γ)^{3}He	Iliadis et al. (2016)	**LUNA** Mossa et al. (2020b)
^{3}H(d,n)^{4}He	Descouvemont et al. (2004)	de Souza et al. (2019)
^{3}He(d,p)^{4}He	Descouvemont et al. (2004)	de Souza, Iliadis & Coc (2019)
^{7}Be(n,p)^{7}Li	Descouvemont et al. (2004)	de Souza et al. (2020)
^{7}Be(d,p)2α	Caughlan & Fowler (1988)	Rijal et al. (2019)

fitting functions, those different methods lead to the same results for the three reactions. For instance the frequentist (Coc et al. 2015) and bayesian Iliadis et al. (2016) D(p,γ)^{3}He rates are almost identical (see next section). Similarly, Eqs. (3.49)–(3.51) from Serpico et al. (2004) were tested in Coc et al. (2015) leading to very similar rates and uncertainties. Hence, the differences in reaction rates obtained from different groups come from the selection of datasets and the choice of fitting function.

A major difficulty, for those three reactions is that only a few experimental datasets were obtained by precision experiments dedicated to BBN (e.g. (Mossa et al. 2020b) for D(p,γ)^{3}He or Leonard et al. (2006) for D(d,n)^{3}He and D(d,p)^{3}H). Many datasets lack sufficient documentation concerning the scale (systematic) error. This is the main criteria used by Coc et al. (2015); Iliadis et al. (2016); Gómez Iñesta, Iliadis & Coc (2017) to exclude datasets. In several cases, the scale error is not evaluated or only the combined, statistical and systematic uncertainties are given so that the corresponding datasets are also put aside. Details on this selection are given in Coc et al. (2015); Iliadis et al. (2016); Gómez Iñesta, Iliadis & Coc (2017).

The other issue concerns the S–factor fitting function. One option is to use polynomial (e.g. Serpico et al. (2004); Cyburt (2004)) or splines (e.g. Nollett & Burles (2000)), but choosing the correct polynomial degree is difficult. A higher degree provides a better fit, but can introduce artificial structures. This is why many evaluations introduce some phenomenological (e.g. R–matrix in Descouvemont et al. (2004) or Potential Model from Xu et al. (2013)) or even theoretical prejudices (e.g. *ab initio* model of Neff (2011)). In previous works, (e.g. Pitrou et al. (2018)), we had chosen this latter option, since *ab initio* S–factors were available for the three reactions (Marcucci et al. 2005; Arai et al. 2011).

Finally, the D(p,γ)^{3}He, D(d,n)^{3}He and D(d,p)^{3}H adopted rates in Pitrou et al. (2018) result from bayesian analyses (Iliadis et al. 2016; Gómez Iñesta, Iliadis & Coc 2017). They have the advantage of not being limited to gaussian distributions and to be able to take into account systematic uncertainties in a simple way (Iliadis et al. 2016) (see also de Souza et al. (2019); de Souza, Iliadis & Coc (2019); de Souza et al. (2020) concerning other reactions). However, note that for the D(p,γ)^{3}He rate we use the latest LUNA rate by Mossa et al. (2020b) (see below).

2.2 The D(p,γ)^{3}He rate

This reaction rate has long been a subject of controversy. As displayed in Fig. 23 of Pitrou et al. (2018) (updated in Fig. 1 below), there was a scarcity of experimental data in the region of interest for BBN.

In their evaluations, Coc et al. (2015) and Iliadis et al. (2016) used the theoretical S–factor from Marcucci et al. (2005) re-normalized (e.g. a factor of 0.9900±0.0368 in Coc et al. (2015)) to a selection of experimental data. Other authors (Cyburt 2004; Descouvemont et al. 2004) have preferred the alternative option that follows closely the experimental data points, resulting in a lower S–factor at BBN energies, mainly driven by the Ma et al. (1997) data (see Fig. 1). The widely used NACRE–II (Xu et al. 2013) compilation relies for this reaction on a potential model, adjusted to experimental data, but gives little details. The NACRE–II (Xu et al. 2013) compilation was designed to be conservative i.e. their S–factor limits were supposed to encompass almost all existing data, in order to be sure that the real S–factor is within the limits. The problem became more acute with the publication of an improved theoretical S–factor by Marcucci et al. (2016), lying above the previous one of Marcucci et al. (2005); see Fig. 1. Very recently, this cross–section, of the most important reaction for deuterium destruction, has been measured, first at the Joižef Stefan Institute of Ljubljana by Tišma et al. (2019), then at the LUNA, Gran Sasso underground laboratory (Mossa et al. 2020b) (see Fig. 1). Those experiments explored the energy range relevant to BBN. In particular, the LUNA data points span the range $E_{\rm cm}$ = 32–263 keV, and have very small error bars.

From these experiments, one can deduce that

- the LUNA data (Mossa et al. 2020b) confirm, in the BBN range, the energy dependence and magnitude of the S–factor calculated by Marcucci et al. (2005) (Fig. 1),
- the new data (Tišma et al. 2019; Mossa et al. 2020b) do not confirm the low S–factor from Ma et al. (1997) that, previously drove down the fitted S–factors (Descouvemont et al. 2004; Cyburt 2004),
- does not confirm the higher theoretical S–factor from Marcucci et al. (2016), and
- the LUNA data lies in between the S–factor limits derived by Coc et al. (2015) and, not shown on the Figure, those subsequently obtained by a more sophisticated (Bayesian) analysis by Iliadis et al. (2016).

Consequently, the rate (Iliadis et al. 2016) used by Pitrou et al. (2018) will need only minor revision (Moscoso *et al.*, in preparation), and confirm the deuterium tension, first observed by Coc et al. (2015); Pitrou et al. (2018). Indeed, Fig. 2 compares the rate Iliadis et al. (2016) previously used by Pitrou et al. (2018) with the new rates recently derived from Eq. (2) and (3) in Mossa et al. (2020b), in agreement with their Table 1. In the BBN temperature range, the new rate is mostly within the limits of the previously adopted ones. Fields et al. (2020) use the D(p,γ)^{3}He rate from NACRE–II (Xu et al. 2013) as a baseline, but also consider those from Coc et al. (2015) (very close to the one Iliadis et al. (2016) used in PRIMAT; see Fig. 2) and the high theoretical rate of Marcucci et al. (2016). Few details

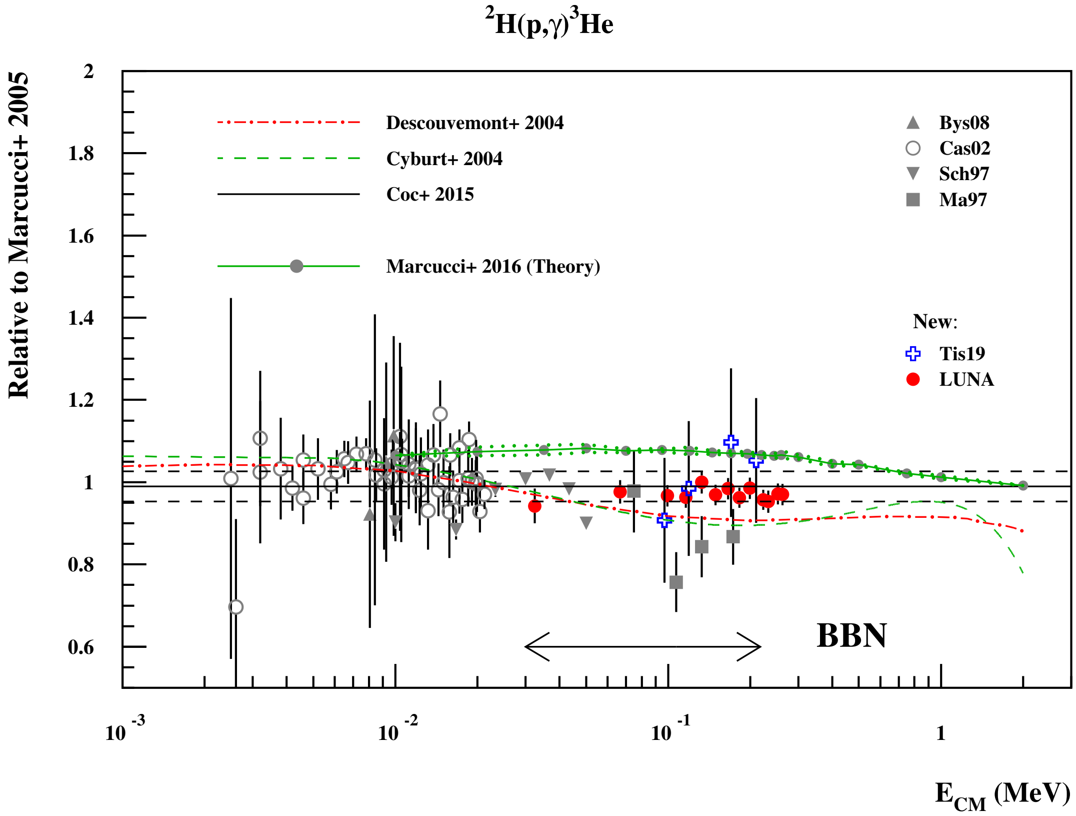

Figure 1. Theoretical and experimental S–factor, normalized to the Marcucci et al. (2005) theoretical one. Data in grey point "Bys08" (Bystritsky et al. 2008), "Ca02" (Casella et al. 2002), "Sch97" (Schmid et al. 1997) and "Ma97" (Ma et al. 1997), are those used in our previous calculations (Coc et al. 2015; Iliadis et al. 2016; Pitrou et al. 2018). Blue points (Tišma et al. 2019) and red points (LUNA Mossa et al. (2020b)) are new. Compared to Fig. 23 of Pitrou et al. (2018), only datasets that were used in Coc et al. (2015); Iliadis et al. (2016) are displayed. Curves are the S–factor used in previous BBN calculations (see text).

are given in NACRE–II on the evaluation of the D(p,γ)^{3}He rate, but it is found to be significantly lower than the one used in `PRIMAT` and has wider limits. Hence, its use by Fields et al. (2020) is expected to lead to a higher D/H prediction.

To take into account the new experimental data we use the Mossa et al. (2020b) rate, derived from their Eq. (2) and (3), making comparison with other works easier.

2.3 The D(d,n)^{3}He and D(d,p)^{3}H rates

As reminded in Eq. (8), two other reactions are important for deuterium destruction: D(d,n)^{3}He and D(d,p)^{3}H. For these reactions, `PRIMAT` relies on the rates evaluated by Gómez Iñesta, Iliadis & Coc (2017), based on the theoretical, *ab initio* energy dependences from Arai et al. (2011) re-normalized to a selection of experimental data, using bayesian techniques. Fields et al. (2020) use instead the NACRE–II rates based on a DWBA model adjusted to experimental data. However, as for D(p,γ)^{3}He, few details are available in NACRE–II on the evaluation of experimental data, and rate uncertainties. Contrary to the D(p,γ)^{3}He reaction, several recent experimental studies have investigated both D(d,n)^{3}He and D(d,p)^{3}H cross sections at BBN energies (Krauss et al. 1987; Brown & Jarmie 1990; Greife et al. 1995; Leonard et al. 2006). These are all direct measurements that are in good agreement with the theoretical cross section obtained by Arai et al. (2011) as can be seen in Fig. 3. It displays the ratio of D(d,n)^{3}He over D(d,p)^{3}H S–factors, allowing to evaluate the coherence of the data because this ratio is essentially governed by the Coulomb interaction, and as such is weakly dependent of the nuclear model. The theoretical curve (Arai et al. 2011) (not a fit) reproduces the directly measured data, including the Schulte et al. (1972) at high energy, above the BBN range. Reaction rates based on a re–normalization of the Arai et al. (2011) S–factor to the experimental data of Krauss et al. (1987); Brown & Jarmie (1990); Greife et al. (1995); Leonard et al. (2006) were obtained by Coc et al. (2015) and Gómez Iñesta, Iliadis & Coc (2017) analyses. These four experimental studies were selected because they all provide both statistical and systematic uncertainties. In particular the most recent direct experiment (Leonard et al. 2006) provides an error matrix and quote a scale error as low as 2%±1%. Both uncertainties were considered separately by Coc et al. (2015), using a classical analysis, and by Gómez Iñesta, Iliadis & Coc (2017) with a Bayesian analysis that, in particular treats systematic uncertainties as priors. Resulting reaction rates were found to differ by less than 0.2% and we adopt the Gómez Iñesta, Iliadis & Coc (2017) rate. The D(d,n)^{3}He and D(d,p)^{3}H rates used in the LUNA BBN calculations (Mossa

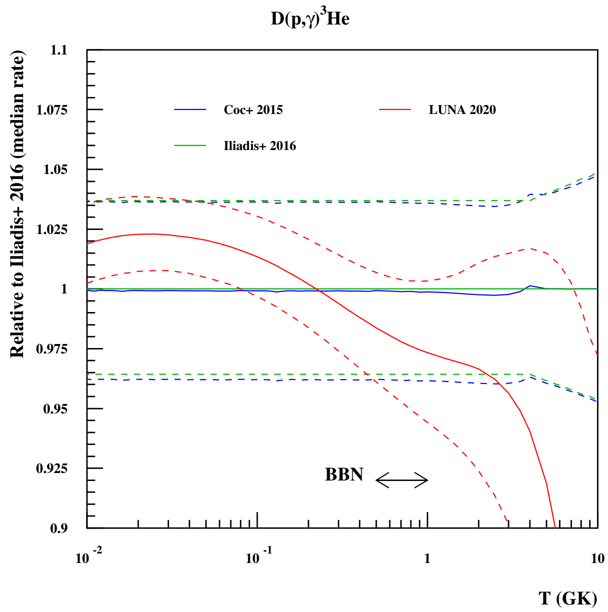

Figure 2. LUNA reaction rates (Mossa et al. 2020b) and uncertainties compared to the ones previously used (Coc et al. 2015; Iliadis et al. 2016). Rates labelled Coc+ 2015 are deduced from corresponding S–factors in Fig. 1, those labelled Iliadis+ 2016 are those used by Pitrou et al. (2018).

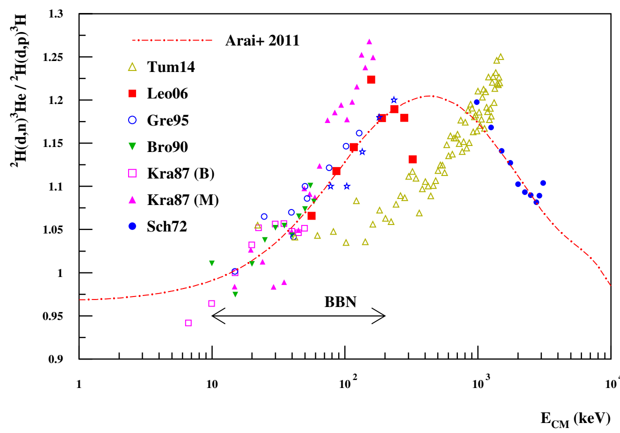

Figure 3. Ratio of the D(d,n)^{3}He over D(d,p)^{3}H cross sections. BBN, recent experimental data from direct measurements ("Kra87" (Krauss et al. 1987), "Bro90" (Brown & Jarmie 1990), "Gre95" (Greife et al. 1995), "Leo06" (Leonard et al. 2006) and "Sch72" (Schulte et al. 1972)) follows the theoretical predictions of Arai et al. (2011)). The indirect data from Tumino et al. (2014) follows a different trend.

et al. 2020b) are updated from the Consiglio et al. (2017); Serpico et al. (2004) evaluation including a minor contribution from the new data (Tumino et al. 2014) obtained by the (indirect) Trojan Horse Method. The main differences with the Gómez Iñesta, Iliadis & Coc (2017) analysis is that the latter applies stricter selection criteria on experimental data (e.g. only direct measurements with evaluation of systematic uncertainties) and uses theoretical guidance instead of polynomials.

In conclusion, our BBN results (Coc et al. 2015; Pitrou et al. 2018; Iliadis & Coc 2020) for D/H are in general lower than others, because we use different reaction rates for D(p,γ)^{3}He (previously Iliadis et al. (2016), but here, replaced by LUNA (Mossa et al. 2020b)), D(d,n)^{3}He, and D(d,p)^{3}H (Gómez Iñesta, Iliadis & Coc (2017)). In these evaluationsd (Iliadis et al. 2016; Gómez Iñesta, Iliadis & Coc 2017), first, only experimental datasets whose error budget (statistical *and* systematics) is available, are adopted. Next, whenever possible, theoretical guidance is considered. Other works may use smooth polynomial fits to the data, which is, in principle, another reasonable option. Finally, our adopted rates are obtained using Bayesian techniques because they allow for a rigorous inclusion of statistical *and systematic* sources of uncertainties. These choices have the advantage of being fully documented and simply stated. However, for this work, we use provisionally the Mossa et al. (2020b) rate.

3 CONSTRAINTS ON COSMOLOGICAL PARAMETERS FROM BBN

As mentioned above, there are two equivalent ways to look at the data. Either, we use BBN to constrain the only free cosmological parameter that affects the abundances, i.e. the baryonic density, and we then compare this measurement to the one by Planck (Planck Collaboration et al. 2020) (CMB or CMB+BAO), or we fix the baryonic density to its value determined by CMB analysis and compare the predictions of BBN under that hypothesis to spectroscopic data.

Figure 4 summarizes the predictions for BBN deuterium from the present analysis [using (Mossa et al. 2020b) for the D(p,γ)^{3}He rate, and Gómez Iñesta, Iliadis & Coc (2017) for the D(d,n)^{3}He and D(d,p)^{3}H rates] and the previous one by Pitrou et al. (2018), as well as the CMB constraint on η and the data by Cooke, Pettini & Steidel (2018).

In the first approach, we use BBN theory and spectroscopic observations to determine η, assuming that $N_{\rm eff}$ is fixed from particle physics, and compare to its CMB value by Planck (Planck Collaboration et al. 2020). Using the method described in section 6.2 of Pitrou et al. (2018), we estimate the posterior distribution of $\Omega_{\rm b}h^2$, given the observational constraints on ^{4}He and on D. The posteriors for CMB or BBN determinations of $\Omega_{\rm b}h^2$ are depicted on Fig. 4, and we obtain for BBN only

$$\Omega_{\rm b}h^2 = 0.02195 \pm 0.00022\,. \qquad (9)$$

This is a 1.6σ tension with CMB (3) and 1.84σ tension with CMB+BAO (4). The tension is higher when BAO are included, which is in general the case when more data are considered. Note also that BAO favour baryons compared to dark matter in the analysis.

Equivalently, the same analysis can be performed by assuming that the baryon density is determined from CMB+BAO (Planck Collaboration et al. 2020), and predict the theoretical expectation for the deuterium abundance. When estimating the theoretical uncertainty with a Monte-Carlo method, we vary on the uncertainty of nuclear rates, on the neutron lifetime, but also on the baryon abundance according to the CMB+BAO posterior. We then find the

Table 2. Predicted abundances compared to observations.

	Observations	Pitrou et al. (2018) $\tau_{\rm n} = 879.5(8)$ s, $100h^2\Omega_b = 2.2250\,(\pm 0.016)$ (e)	**This work** $\tau_{\rm n} = 879.4(6)$ s, $100h^2\Omega_b = 2.242\,(\pm 0.014)$ (f)
$Y_{\rm P}$	0.2453±0.0034(a)	0.24709±0.00018	**0.24721±0.00014**
D/H ($\times 10^{-5}$)	2.527±0.030 (b)	2.460±0.046	**2.439±0.037**
^{3}He/H ($\times 10^{-5}$)	<1.1±0.2 (c)	1.074±0.026	**1.039±0.014**
^{7}Li/H ($\times 10^{-10}$)	$1.58^{+0.35}_{-0.28}$ (d)	5.627±0.259	**5.464±0.220**

(a) Aver et al. (2020), (b) Cooke, Pettini & Steidel (2018), (c)Bania, Rood & Balser (2002), (d) Sbordone et al. (2010), (e) Ade et al. (2016), (f) CMB+BAO, Planck Collaboration et al. (2020)

theoretical expectation

$$(\mathrm{D/H}) = (2.439 \pm 0.037) \times 10^{-5}\,. \qquad (10)$$

Again, this has a 1.84σ tension with the measured value (2). This is expected since these two methods are different ways of doing the same thing.

DISCUSSION AND PERSPECTIVES

BBN theory has long been considered as a standard pillar of the big-bang model, despite the long-standing lithium-7 problem. In the current era of precision cosmology, its constraining power mostly rests on the prediction of the deuterium abundance since the accuracy of helium-4 data, and its mild dependence on the baryon density, do not make it a competitive probe anymore. As we argued, the agreement between data, theoretical BBN predictions and CMB constraints on the baryonic density requires to control the accuracy of the BBN computation at the percent level.

First, it follows that nuclear data are the crux in this debate. All existing codes differ from the difference of choices on the modelisation of the nuclear cross-sections, and not on weak rates since they differ by less than 0.2% between e.g. `PRIMAT` and `PArthENoPE` (Pisanti et al. 2008). It is important to control their accuracy at least at the percent level and to take into account the latest data. The recent release of the LUNA data confirms the S–factor and rate previously used in `PRIMAT` 2018 (Pitrou et al. 2018). We updated it to fully take into account these data and the code now also includes a series of refinements described in this article. Finally, because of the importance of the d+d reaction rates, in particular, the D(d,n)^{3}He one, further investigations are needed to reconcile Trojan Horse results (Tumino et al. 2014) with direct measurements.

Then, the second key issue concerns D/H measurements. Today it rests on the measurements of Cooke, Pettini & Steidel (2018). The primitive abundance of deuterium can be determined from the observation of DI and HI lines from neutral clouds (Damped Lyman-α systems, DLAs) at high redshift, located on the line of sight to background quasars. While progress has been done to obtain precise measurements, these remain very scarce. Because of this, each measurement has therefore an important impact on the determination of the primitive D/H abundance (i.e. the mean value) and its accuracy must be tested intensively. Indeed, both values and associated uncertainties remain debated (e.g. the remeasurement of the deuterium abundance at $z = 3.256$ by Riemer-Sørensen et al. (2015)). More observations are crucially needed not only to decrease statistical errors but also have the potential to reveal subtle systematics. While several thousands DLAs have been detected thanks to large spectroscopic surveys (e.g. Noterdaeme et al. (2012)), most of the background quasars are too faint for efficient selection of follow-up targets and precision measurements with current telescopes. Notwithstanding, there is still some room to detect new bright quasars and hence potentially useful DLAs. For example, the QUBRICS bright Quasar survey has recently identified 55 new high redshift quasars ($z > 2.5$) (Calderone et al. 2019; Boutsia et al. 2020). Alternatively, high-resolution optical spectrographs on the next generation of 30-m class telescopes will increase the number of accessible quasars and automatically the number of targets suitable for measuring D/H. For example, HIRES on the Extremely Large Telescope could increase the precision to 0.3% with a five-fold increase in sample size, provided its wavelength coverage extends enough to the blue (Maiolino et al. (2013) and Pasquier Noterdaeme, private communication).

With the existing D/H data (Cooke, Pettini & Steidel 2018), the updated nuclear network and the slight shift of the baryonic density determined by Planck-2018, we witness a $\simeq 1.8\sigma$-tension on the baryonic density between BBN and CMB+BAO or equivalently between the D/H abundance prediction assuming (CMB+BAO)-baryonic density and its spectroscopic measurement. This is indeed a mild warning but it sheds some light on the sector of the big-bang theory, indicating that it should be watched carefully, both on the nuclear and astrophysical data sides.

It is worth mentioning that the Hubble constant tension has been interpreted as an early/late universe tension, while it shall maybe be seen as a thin/large beam tension (Fleury, Dupuy & Uzan 2013; Fleury, Larena & Uzan 2019a,b). This new emerging tension, to be confirmed by more BBN and large scale estimations of the baryonic density, is a primordial/late time tension, so that the CMB would be tied between two lever arms at redshifts of order $z \sim 1$ and $z \sim 10^8$. If confirmed, the status of BBN, with the lithium-problem and a mildly-constraining helium-4, would have to be reconsidered. Note also that unlike the cosmological lithium problem, this deuterium tension can be mitigated easily by invoking a small contribution from most models developed to solve the lithium problem as they overproduce deuterium (Albornoz Vásquez et al. 2012; Olive et al. 2012; Coc et al. 2014; Kusakabe, Cheoun & Kim 2014; Coc et al. 2015). To finish, note also that since BBN theory assumes a perfect FL geometry and since the spectroscopic data are located on our past light-cone at low redshift – and thus well inside the CMB sky – the Copernican principle could be at stake (Regis & Clarkson 2012; Dunsby et al. 2010).

With this new data, cosmology shows once more that

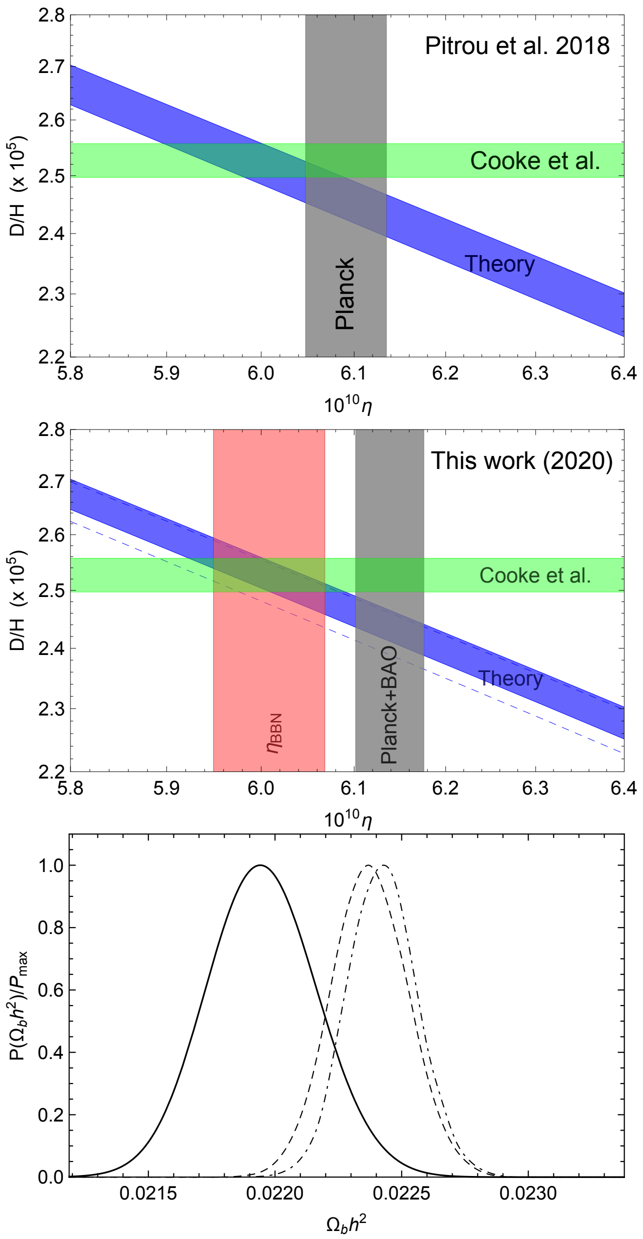

Figure 4. *Top:* D/H theoretical prediction (in blue), observation (in green) from Cooke, Pettini & Steidel (2018), and baryon abundance constraints from CMB (in gray), as reported in Pitrou et al. (2018). All ranges displayed are within 1σ standard deviation. *Middle:* Same quantities but the baryon density is updated from the CMB+BAO constraint by Planck Collaboration et al. (2020), and with the D/H theoretical predictions of this work. The dashed blue lines correspond to the theoretical range determined when using the D(p,γ)^{3}He rate of Iliadis et al. (2016) instead of the recent LUNA rate (Mossa et al. 2020b). *Bottom:* Posterior distribution of baryon density from BBN (this work) in solid line, from CMB only in dashed line, and from CMB+BAO in dot-dashed line (both from Planck Collaboration et al. (2020)). The correspondence between η and $\Omega_b h^2$ is given by Eq. (1).

precision cosmology should come with a cosmology of correctness (Uzan 2016) and that the new tensions we witness are some precursory signs of a more realistic model or just a transient that would disappear with future data with better accuracy and better controlled systematics.

NOTE ADDED

After this paper was submitted, two papers addressing the same topic as our current work were posted (Pisanti et al. 2020; Yeh, Olive & Fields 2020), confirming that differing conclusions can be traced to the data selection and analysis of D(d,n)^{3}He and D(d,p)^{3}H rates.

DATA AVAILABILITY

There are no new data associated with this article. The BBN code `PRIMAT` is freely available at `http://www2.iap.fr/users/pitrou/primat.htm`.

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ERRATUM

We take the opportunity of the new release of the BBN code `PRIMAT` to correct a few minor typos in Pitrou et al. (2018).

- In Eq. (53), there is an additional minus sign in front of 0.01452.
- In Eq. (61), the function $\mathcal{S}$ must be multiplied by the constant factor $\bar{s}_\gamma$, both in the numerator and the denominator.
- In Eq. (105), the numerical value for $\lambda_0^{\rm RC0}$ should be 1.75838.
- In Table 5, the first value in the RC+FM+WM+ID line (and which corresponds to $Y_{\rm P}$) should be 0.24710 instead of 0.24720.
- In Table 7, 10^{10} should be read instead of 10^5 for ^{7}Li multiplicative prefactor.
- In Table 8, theoretical abundance values and errors should be as reported in Table 2.
- In Eq. (B23), one must first read $g_\nu^{(2,0)}$ instead of g_ν in the first term, and in the fifth line $m_{\rm n}/m_{\rm p}$ must be replaced by $(m_{\rm n}/m_{\rm p})^{\pm 1}$.

These typos are corrected in the arXiv version of Pitrou et al. (2018).

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