Big Bang Nucleosynthesis and neutrinos

F.L. Villante\(^1\) and A.D. Dolgov\(^2\)

\(^1\) Dipartimento di Fisica and Sezione INFN di Ferrara, Via del Paradiso 12, I-44100 Ferrara, Italy
\(^2\) ITEP, Bol. Cheremushkinskaya 25, 117218, Moscow, Russia

Abstract. We present a brief review of Big Bang Nucleosynthesis (BBN). We discuss theoretical and observational uncertainties in deuterium and helium-4 primordial abundances and their implications for the determination of important cosmological parameters. We present, moreover, some recent results on active-sterile neutrino oscillations in the early universe and on their effects on BBN.

1 Introduction

Big Bang Nucleosynthesis (BBN), as well known, is one of the solid pillars of the standard cosmological model. The theory predicts that relevant abundances of light elements, namely \(^2\)H, \(^3\)He, \(^4\)He and \(^7\)Li, have been produced during the first minutes of the evolution of the Universe. The predictions span about 9 orders of magnitude and are in reasonable agreement with observations. Theoretical calculations are well defined and very precise. The largest uncertainty arises from the values of cross-sections of the relevant nuclear reactions. Theoretical accuracy is at the level of 0.2% for \(^4\)He, 5% for \(^2\)H and \(^3\)He and 15% for \(^7\)Li. However, comparison of theoretical results with observational data is not straightforward because the data are subject to poorly known evolutionary effects and systematic errors. Still, even with these uncertainties, BBN permits to constraint important cosmological parameters and to eliminate many modifications of the standard model, thus allowing to derive restrictions on the properties of elementary particles and, in particular, of neutrinos.

In this paper, we briefly review the physics of BBN. In sect. 2 we introduce the essential parameters and inputs. In sect. 3 we summarize the present situation of observational data. In sect. 4 we discuss the determination of cosmological parameters. The last section is dedicated to BBN bounds on non-standard neutrinos and, specifically, to BBN and neutrino oscillations\(^1\).

2 The Physics of BBN

To understand primordial nucleosynthesis, we must follow in detail the histories of nucleons in the early universe. This is usually done by using numerical codes (among which the Fortran code by Wagoner \(^2\), updated by Kawano \(^3\)) has

\(^1\) In this paper, due to space limitation, we will consider only selected topics. For a complete review of the BBN bounds on neutrinos see ref.\(^1\).
Primordial nucleosynthesis occurs at temperatures $T \leq 1 \text{ MeV}$, which are small with respect to nucleon masses. At these temperatures, the number of nucleons is simply equal to the initial baryon asymmetry of the universe. It is useful to describe this quantity in terms of the present baryon to photon ratio:

$$\eta \equiv \frac{N_B - N_B^\text{FB}}{N_\gamma}.$$  \hspace{1cm} (1)

The parameter $\eta$ is simply related to the baryon density of the universe, being $\Omega_B h^2 = 3.7 \cdot 10^7 \eta$.

The neutron to proton ratio is controlled by the weak processes

$$n + e^+ \leftrightarrow p + \nu_e$$
$$n + \nu_e \leftrightarrow p + e^-$$
$$n \to p + e^- + \nu_e$$ \hspace{1cm} (2)

which interconvert neutron and proton. When the temperature $T$ of the universe is about 1 MeV, these reactions are fast enough to maintain neutron and proton in chemical equilibrium. The neutron abundance is thus given by:

$$X_n = \frac{n_n}{n_n + n_p} = \frac{1}{1 + \exp(\Delta m/T + \xi_e)}$$  \hspace{1cm} (3)
where $\Delta m = 1.29$ MeV is the neutron-proton mass difference and $\xi_e = \mu_e/T$ is the dimensionless chemical potential of electron neutrinos (in standard BBN $\xi_e$ is assumed to be negligible).

When the temperature $T$ drops below $T_f = 0.6 - 0.7$ MeV, the neutron-proton inter-conversion rate, $\Gamma_W \sim G_F^2 T^5$, becomes smaller than the expansion rate the universe, $H \sim \sqrt{g^* G_N T^2}$, where $g^*$ counts the total number of relativistic degrees of freedom of the early universe. The deviation of $g^*$ from the standard value, $g^* = 10.75$, is usually described in terms of an equivalent number of massless neutrinos $N_\nu \neq 3$ according to:

$$g_* = 10.75 + \frac{7}{4} (N_\nu - 3). \quad (4)$$

For temperatures $T \leq T_f$, chemical equilibrium can no longer be maintained. The neutron abundance $X_n$ evolves only due to neutron decay, according to $X_n = X_n(T_f) \exp(-t/\tau_n)$, where $\tau_n$ is the neutron lifetime. One should note that the “freeze-out” temperature $T_f$ scales as $T_f \propto g^*/6$ and thus is sensitive to the particle content of the early universe. The larger is $g_*$ (or equivalently $N_\nu$), the earlier is the freeze-out of the neutron abundance, at a higher value, and hence, the larger is the $^4$He abundance produced in BBN.

When the temperature of the universe is equal to $T_N \simeq 0.06 - 0.07$ MeV neutrons and protons start to react each other to build up light nuclei. The exact value of $T_N$ depends on the baryon to photon ratio $\eta$. Only two body reaction are indeed important in BBN, such as $p(n, \gamma)^2H$, $^2H(p, \gamma)^3He$, $^3He(d, p)^4He$, etc. (see [10]). Deuterium must be produced in appreciable quantity before the other reactions can proceed at all. However, due to the large number of photons per baryon, photodissociation of deuterium is not suppressed until the temperature decreases well below the deuterium binding energy $B_d = 2.2$MeV. Following [5], one can see that the temperature $T_N$ below which deuterium production is favoured scales as $T_N \sim B_d/(15 - \ln \eta)$.

Once deuterium is formed, nucleosynthesis begins and light nuclei are produced rapidly. Essentially all available nucleons are quickly bound into $^4$He, which is the most tightly bound light nuclear species. In addition to $^4$He, substantial amounts of $^2$H, $^3$He and $^4$He are produced. No heavy elements ($A > 8$) are produced, due both to the fact that Coulomb-barrier suppression is very significant and to the absence of stable isotopes with $A = 5$ and $A = 8$. In fig.1 we show the light element abundances produced during BBN, as calculated by using the Kawano code [3], for $\eta$ between $10^{-10}$ and $10^{-9}$. The calculation of $^4$He abundance includes small corrections due to radiative processes at zero and finite temperature, non-equilibrium neutrino heating during $e^\pm$ annihilation, and finite nucleon mass effects [11,12].

Theoretical predictions are affected by uncertainties at the level of 0.2% for $^4$He, 5% for $^2$H and $^3$He and 15% for $^7$Li. These uncertainties are due to uncertainties in the weak rates (which are “normalized” to the measured neutron lifetime $\tau_n = 885.7 \pm 0.8$ s, see [5] for details) and in the values of the relevant nuclear reaction rates. They have been estimated by montecarlo or semi-analytical
methods [10,13]. Recently the nuclear data have been re-analyzed, leading to improved precision in the abundance predictions [14,15,16].

3 Observational Data

The abundances of light elements synthesized in the Big Bang have been subsequently modified through chemical evolution of the astrophysical environments where they are measured. The observational strategy is to identify sites which have undergone as little chemical processing as possible and rely on empirical methods to infer the primordial abundances. For example, measurements of deuterium are made in quasar absorption line systems (QAS) at high redshift; if there is a “ceiling” to the abundance in different QAS then it can be assumed to be the primordial value. The $^4$He abundance is measured in H II regions in blue compact galaxies (BCGs) which have undergone very little star formation. Its primordial value is inferred either by using the associated nitrogen or oxygen abundance to track the stellar production of helium, or by simply observing the most metal-poor objects. Closer to home, the observed uniform abundance of $^7$Li in the hottest and most metal-poor Pop II stars in our Galaxy is believed to reflect its primordial value. (We do not consider $^3$He whose post-BBN evolution is more complex.)

As observational methods have become more sophisticated, the situation has become more, instead of less, complex. Relevant discrepancies, of a systematic nature, have emerged between different observers. In the following, we give a brief summary of the present situation for deuterium and helium-4 (looking from outside by a non-expert). We refer to [7] for a more complete and up-to-date discussion.

**Deuterium**

Post-BBN evolution of deuterium (D) is simple. Deuterium is burnt in stars producing $^3$He. Any deuterium measurement provides thus a lower limit for the primordial D abundance and an upper limit for baryon density of the universe.

In recent years, measurements of deuterium have been made in quasar absorption line systems (QAS) at high redshift. These systems are presumably not contaminated by stellar processes and thus the observed deuterium should be close to the primordial one. Since deuterium isotope shift corresponds to velocity of only ($\sim 82$) km/sec, clearly QAS with simple velocity structure are needed for reliable determinations. Moreover, ionization corrections, possible “interlooper” etc. further increase systematic uncertainties.

In tab. 1 we give the results of recent deuterium determinations in QAS [17,18,19,20,21,22,23]. An estimate of primordial deuterium abundance can be obtained from the weighted mean of data in tab. 1. It should be noted, however, that the dispersion among the different determinations is not consistent with errors in the single measurements (see [21] for detailed discussion). We will use, in the following, the value $D/H = 2.78^{+0.44}_{-0.38} \times 10^{-5}$ given in [21], which is the weighted mean of the log $D/H$ values given by [17,18,19,20,21]. The quoted
error is the $1\sigma$ error in the mean, given by the standard deviation of the five log D/H values divided by $\sqrt{5}$. This error is used instead of the usual error in the weighted mean, in order to take into account the “anomalous” dispersion of deuterium data.

Table 1. Deuterium abundance in quasar absorption line systems at high red-shift (see [21] for details).

| $z$  | 2.504 | 3.572 | 2.536 | 2.076 | 2.526 | 3.025$^a$ |
|------|-------|-------|-------|-------|-------|----------|
| $10^5(D/H)$ | $3.98^{+0.59}_{-0.67}$ | $3.25 \pm 0.3$ | $2.54 \pm 0.23$ | $1.65 \pm 0.35$ | $2.42^{+0.35}_{-0.25}$ | $3.75 \pm 0.25$ |

$^a$ This system was first analyzed by [23] with the result $D/H = (2.24 \pm 0.67) \times 10^{-5}$. The quoted value is from [22].

**Helium-4**

As a result of stellar processing, $^4$He is produced, increasing its abundance above the primordial value, together with “metals”, such as nitrogen, oxygen and other elements heavier than $^4$He, which are not produced in BBN. The observed $^4$He abundance provides thus an upper bound to the primordial one, $Y_p$.

Helium observations are done in H II regions in blue compact galaxies (BCGs) which have undergone very little star formation (at present $\sim 100$ H II regions have been studied for their helium content). In order to infer the primordial value $Y_p$, one extrapolates to zero metallicity ($Z = 0$) the observed relation between helium ($Y$) and metals ($Z$). This is usually done using by nitrogen ($N$) or oxygen ($O$) as metallicity tracers. Alternatively, one can simply average helium abundances in most metal poor objects.

The present situation is that independent determinations of $Y_p$ have a statistical errors at the level of $1 - 2\%$ but differ among each others by about $\sim 5\%$. In particular, by using independent data sets, Olive and Steigman [24] and Olive et al. [25] have obtained $Y_p = 0.234 \pm 0.003$, while Izotov et al. [26] and Izotov and Thuan [27] have found $Y_p = 0.244 \pm 0.002$.

The discrepancy between different determinations is possibly related to different description of the complex physical processes acting in H II regions. Several sources of systematic uncertainties may, in fact, affect the helium determination at a level comparable or larger than the reported statistical errors, like e.g. the evaluation of the ionization correction factor (which is related to how much neutral helium is in the object under scrutiny), of the temperature correction factor, of underlying stellar absorption, etc. (see [28] for a review).

As discussed in the next section, it is extremely important to have a better determination of the $^4$He primordial abundances and a reliable estimate of the total (statistical + systematic) associated error. For our estimates, we will use the central values for $Y_p$ reported above ($Y_p = 0.234$ and $Y_p = 0.244$), and the
4 Cosmological parameters from BBN

The deuterium abundance \( \frac{D}{H} = 2.78^{+0.44}_{-0.38} \times 10^{-5} \) can be used to determine the baryon density of the universe. As discussed in [21], the quoted value corresponds to \( \eta = 5.9 \pm 0.5 \times 10^{-10} \) (in standard BBN) or, equivalently, to \( \Omega_B h^2 = 0.0214 \pm 0.0020 \). The error budget is dominated by the observational uncertainties which are about a factor 3 larger than uncertainties in theoretical prediction.

The obtained value for \( \Omega_B h^2 \) has to be compared with independent determination of the baryon density of the universe. In particular with the result \( \Omega_B h^2 = 0.0224 \pm 0.0009 \) given in [29] which is obtained from a combined fit to the cosmic microwave background (CMB) and large scale structure (LSS) data. The agreement of these two independent determinations is extremely important because they rely on completely different physical phenomena (which occurred at different time during the evolution of the universe). We note that CMB (and LSS) are presently more accurate than BBN in determining the baryon density of the universe.

The value of \( \eta \) deduced from deuterium can be used, in standard BBN, to predict the abundance of the other elements and to compare with observations. Following [21], one obtains \( Y_p = 0.2476 \pm 0.0010, ^3\text{He}/H = 1.04 \pm 0.06 \times 10^{-5} \) and \( ^7\text{Li}/H = 4.5 \pm 0.9 \times 10^{-10} \). It is evident that there is tension between the quoted values and the observational results. The “predicted” abundance for \(^4\text{He}\) is higher than the “high” helium value of Izotov et al. [26,27]. Moreover, the “predicted” \(^7\text{Li}\) abundance is a factor 2-3 larger with respect to the present observational results [30]. The origin of these differences has to be clarified. They could be due to systematic errors in the measurements or to evolutionary effects (e.g. \(^7\text{Li}\) depletion) or they could be a real indication for non-standard effects in BBN.

In particular, the present D and \(^4\text{He}\) data seems to favour an equivalent number of neutrino families \( N_\nu \leq 3 \). In order to understand the present situation, it is useful to combine the deuterium value \( \frac{D}{H} = 2.78^{+0.44}_{-0.38} \times 10^{-5} \), with the “low” helium abundance, \( Y_p = 0.234 \pm 0.005 \), or with the “high” helium abundance, \( Y_p = 0.244 \pm 0.005 \). The error \( \Delta Y_p = 0.005 \) is the “estimated” systematic error in \(^4\text{He}\) measurements (see above). If we fit these data in the plane \((\eta, N_\nu)\) following [31], we obtain the bound \( N_\nu = 2.3 \pm 0.5 \) (1\(\sigma\)) in the first case, and \( N_\nu = 2.8 \pm 0.5 \) (1\(\sigma\)) in the second. In both cases, the central values are below three, even if the errors are large enough to allow for the standard value \( N_\nu = 3 \).

The described results clearly indicate that a large number of effective neutrinos is disfavoured. One can conclude, in principle, that an upper bound on the number of extra neutrinos, \( \delta N_\nu \equiv N_\nu - 3 \), is \( \delta N_\nu \leq 0.3 \). It is clear, however, that the situation is quite delicate. The error \( \Delta N_\nu = 0.5 \) is completely dominated by systematic error in \(^4\text{He}\) measurements. For this reason, we believe that, at present stage, a more safe upper bound on the number of extra neutrinos is \( \delta N_\nu \leq 1 \). Hopefully in the near future we will be able to derive a stronger limit.
Other physical parameters which can be bounded by BBN are the chemical potentials of different neutrino species, $\mu_a$ where $a = e, \mu, \tau$. The possible role of neutrino degeneracy in BBN was noted already in [34] and then discussed in a number of papers. A non vanishing chemical potential for $\nu_e$, $\nu_\mu$ or $\nu_\tau$ would increase the neutrino contribution to the energy density and can be described as an increase in $N_\nu$. An additional (and dominant) effect exists for electron neutrinos which directly participate in n-p interconversion reactions. A non vanishing $\mu_e$ would shift the equilibrium between neutrons and protons, see eq. (3), with large effects on light elements production.

Several analysis have been made of the BBN limits on neutrino chemical potentials. A recent analysis which include also CMB data [35] concludes:

\[-0.01 < \xi_e < 0.2 \quad (5)\]
\[|\xi_{\mu,\tau}| < 2.6 \quad (6)\]

where $\xi_a = \mu_a/T$ are the dimensionless chemical potentials. For further implications and for a discussion of the case in which both $N_\nu$ and $\xi_e$ are free to vary see [36].

## 5 BBN and neutrino oscillations

Effects of neutrino oscillations on BBN are much different if only active neutrinos are mixed, if only one active and one sterile neutrino are mixed or if we consider the more “complete” case of mixing between three active and one sterile neutrino.

### 5.1 Mixing between active neutrinos

If neutrinos are in thermal equilibrium with vanishing chemical potentials, mixing between active neutrinos does not introduce any deviation from standard BBN results. The situation is more interesting if neutrinos are degenerate. In particular, it was shown recently [37] that, for the mixing parameters which explain the solar neutrino problem [32] ($\delta m^2_{sol} = 7.3 \cdot 10^{-5} \text{eV}^2$ and $\tan^2 \theta_{sol} = 0.4$) and the atmospheric neutrino anomaly [33] ($\delta m^2_{atmo} = 2.5 \cdot 10^{-3} \text{eV}^2$ and $\tan^2 \theta_{atmo} \approx 1$), asymmetries in the muonic and/or tauonic neutrino sectors would produce, through oscillations, an asymmetry into the electronic neutrino sector. This means that, in presence of oscillations, the restrictive bounds on the chemical potential of electron neutrinos applies to all neutrino flavours. It is thus possible to obtain the restrictive bound:

\[|\xi_a| < 0.1 \quad (7)\]

valid for any flavour [37].
5.2 Mixing between one active and one sterile neutrino

There are three possible effects on BBN created by mixing between active and sterile neutrinos. First is the production of additional neutrino species in the primeval plasma, leading to $N_{\nu} > 3$. The second effect is a depletion of the number density of electronic neutrinos which results in a higher neutron freezing temperature. Both these effects lead to a larger neutron-to-proton ratio and to more abundant production of primordial deuterium and helium-4 (for the details see e.g. review [1]). If mixing between active neutrinos is absent the second effect would manifest itself only in the case of $(\nu_e - \nu_s)$-mixing, if we neglect relatively weak depopulation of $\nu_e$ through the annihilation $\bar{\nu}_e \nu_e \rightarrow \bar{\nu}_\mu, \tau \nu_\mu, \tau$.

The third effect is a generation of large lepton asymmetry due to oscillations between active and sterile species [38]. However, this effect takes place only for very weak mixing, much smaller than the experimental bound and is not discussed in this paper.

The problem of active-sterile neutrino oscillation is quite complex and has been discussed in many papers starting from 1990 (a large list of references can be found in ref. [1]). The problem was recently re-considered in [39] both analytically and by solution of the complete system of integro-differential kinetic equations. Earlier derived bounds have been re-analyzed and significantly different results have been found in the resonance case.

The results of [39] are shown in Fig. 2. The effect on BBN is expressed in terms of variation of the effective number of neutrinos $\Delta N_{\nu}$. The upper panels are for the case of $\nu_\mu - \nu_s$ (or $\nu_\tau - \nu_s$) mixing, while the lower panels refer to the case of $\nu_e - \nu_s$ mixing. The obtained results clearly depend on the sign of the mass differences. For positive mass differences, $\delta m^2 > 0$ (left panels), sterile neutrino production occurs through non-resonant transitions. For $\delta m^2 < 0$ (right panels), one has instead resonant active-sterile transitions which result in much stronger bounds on the neutrino oscillation parameters. The solid lines in Fig. 2 correspond to numerical results, while the red dotted lines correspond to analytic approximate results. It is evident that an observational bound on extra neutrinos much better than unity, say $\delta N_{\nu} < 0.3$, could give very restrictive limits on active-sterile neutrino mixing. Unfortunately, the present observational bound $\delta N_{\nu} \leq 1.0$ is not accurate enough to put relevant constraints.

5.3 Three active and one sterile neutrinos

It is practically established now that all active neutrinos are mixed with parameters given by the Large Mixing Angle solution to solar neutrino problem ($\delta m^2_{\text{sol}} = 7.3 \cdot 10^{-5} \text{ eV}^2$ and $\tan^2 \theta_{\text{sol}} = 0.4$) and by atmospheric neutrino data ($\delta m^2_{\text{atmo}} = 2.5 \cdot 10^{-3} \text{ eV}^2$ and $\tan^2 \theta_{\text{atmo}} \approx 1$). Existence of fast transitions between $\nu_e$, $\nu_\mu$, and $\nu_\tau$ may noticeably change BBN bounds on mixing with sterile neutrinos, especially for small values of mass difference. In particular, due to

\footnote{In the notations of [39], $\delta m^2$ is positive if sterile neutrino is heavier than active neutrino, in the limit $\theta \rightarrow 0$.}
oscillations between active neutrinos, a deficit of $\nu_\mu$ or $\nu_\tau$ would be efficiently transformed into a deficit of $\nu_e$, leading to stronger bounds on active-sterile mixing. The effects of mixing between active neutrinos on the BBN bounds on a possible active-sterile admixture has been investigated in detail in \cite{39}.

6 Conclusion

Comparison of BBN theoretical results with observational data is not straightforward because the data are subject to poorly known evolutionary effects and systematic errors. Still, even with these uncertainties, BBN permits to constraint important cosmological parameters, like e.g. the baryon density $\Omega_B h^2$, the effective number neutrino families $N_\nu$, the neutrino degeneracy parameters $\xi_a$ etc. The present bound on the number of extra neutrinos species $\delta N_\nu$ is about unity and is not accurate enough to put relevant constraints on active-sterile neutrino mixing. If this limit could be reduced in the next future, say to $\delta N_\nu < 0.3$, very restrictive limits on active-sterile admixture could be obtained.

Fig. 2. BBN bounds on active-sterile neutrino mixing. See \cite{39} for details
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