Non-Standard Big Bang Nucleosynthesis Scenarios

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Abstract

A brief overview of non-standard big bang nucleosynthesis (BBN) scenarios is presented. Trends and results of the light-element nucleosynthesis in BBN scenarios with small-scale or large-scale inhomogeneity, the presence of antimatter domains, stable or unstable massive neutrinos, neutrino oscillations, neutrino degeneracy, or massive decaying particles are summarized.

Introduction

Light-element nucleosynthesis during the BBN epoch below cosmic temperatures $T \approx 1\text{MeV}$ contributes significantly to $^4\text{He}$, $^3\text{He}$ and $^7\text{Li}$ abundances and likely, to all of the $^2\text{H}$ abundance observed throughout the universe. BBN is a freeze-out process from nuclear statistical equilibrium such that light-element abundance yields are sensitively dependent on the cosmic conditions during the BBN era as well as the properties of neutrinos governing the freeze-out process from weak equilibrium. Calculations of abundance yields in a standard BBN scenario are performed under the assumptions of a universe homogeneous in the baryon-to-photon ratio, with massless neutrinos and vanishing neutrino chemical potentials, and in the absence of massive decaying particles or other degrees of freedom. For reviews on the physics of standard BBN see [1]. The purpose of this short article is to summarize results and trends in theoretical calculations of non-standard BBN scenarios where one of the above assumptions in standard BBN is relaxed. This summary is in no way intended to be complete neither in discussing all possible modifications to a standard BBN scenario nor in referencing the thousands of articles on non-standard BBN. I wish to apologize for including only certain key references due to the limited scope of these proceedings and for presenting my personal view of the field of non-standard BBN. For two excellent reviews on non-standard BBN the reader is referred to [2]. The determination of observationally inferred primordial abundance constraints, which represents possibly the most important branch of the field of big bang nucleosynthesis at present, will not be discussed here. In what follows, abundance yields in non-standard BBN will either be given in relation to abundance yields in standard BBN or in absolute values and shall be understood as indicative of approximate trends.

Non-Standard BBN

In the following a list of non-standard BBN scenarios, their respective modifications to standard BBN (hereafter; SBBN), as well as trends and results in these scenarios are given.

Inhomogeneity

The baryon-to-photon ratio $\eta$ is the one free parameter in SBBN. Any inhomogeneity in this quantity results in modified nucleosynthesis yields which depend on the typical amplitude
and spatial separation scale of inhomogeneities. Substantial changes in the abundance yields only result when $\delta \eta / \eta \gtrsim 1$.

**a) Inhomogeneity in the Baryon-to-Photon Ratio on Small Mass Scales:**

Fluctuations in $\eta$ which may arise on sub-horizon scales at earlier cosmic epochs as, for example, possibly during a first-order QCD transition or electroweak transition, result in a highly nonstandard BBN scenario. The nucleosynthesis in an environment with $\eta$-fluctuations is characterized by coupled nuclear reactions and hydrodynamic processes, such as baryon diffusion and late-time expansion of high-density regions. Fluctuations in $\eta$ persist down to the onset of BBN provided the mass of an individual high-density region exceeds $10^{-21} M_\odot$. One of the main features of such scenarios is the differential diffusion of neutrons and protons leading to the existence of neutron- and proton-rich environments. The trend in inhomogeneous BBN is the overabundant production of $^4$He when compared to SBBN at the same average $\eta$, nevertheless, there exists parameter space where less $^4$He than in SBBN is synthesized. Scenarios which don’t overproduce $^4$He typically have high $(^2\text{H}/\text{H}) \sim 1 - 2 \times 10^{-4}$ and high $(^7\text{Li}/\text{H}) \sim 10^{-9} - 10^{-8}$. Such BBN may agree with observational abundance constraints for fractional contributions of the baryon density to the critical density $\Omega_b$ about 2-3 times larger than in SBBN, but only in the seemingly unlikely advent of efficient $^7\text{Li}$ depletion in population II stars.

**b) Inhomogeneity in the Baryon-to-Photon Ratio on Large Mass Scales:**

When the baryonic mass within a typical fluctuation exceeds ($M \gtrsim 10^{-12} M_\odot$), baryon diffusion and hydrodynamic processes during the BBN era are of no significance such that BBN abundance yields may be given by an average over the SBBN abundance yields of separate regions at different $\eta$. For non-linear fluctuations exceeding the post-recombination Jeans mass $M \gtrsim 10^5 M_\odot$, which may exist in primordial isocurvature baryon (PIB) models for structure formation, early collapse of high-density ($\eta$) regions is anticipated. The nucleosynthesis yields of collapsing regions may be excluded from the primordial abundance determination if either dark objects form or significant early star formation in such high-density regions occurs. If only low-density regions contribute to the observable primordial abundances, characteristic average abundance yields for scenarios designed to possibly agree with observationally inferred primordial abundances are: $(^2\text{H}/\text{H}) \sim 1 - 3 \times 10^{-4}$, $(^7\text{Li}/\text{H}) \sim 5 \times 10^{-10} - 2 \times 10^{-9}$, and $^4$He mass fraction $Y_p \approx 0.22 - 0.25$ at a total $\Omega_b \lesssim 0.2$ (i.e. including possible dark objects), larger than inferred from a SBBN scenario. One feature of such models is the prediction of fairly large intrinsic spatial variations in the primordial abundances, which may be observationally tested by $(^2\text{H}/\text{H})$ determinations in Lyman-limit systems. These models may only agree with observationally inferred abundance limits when there are no fluctuations below $M \lesssim 10^5 M_\odot$ and collapse efficiencies of high-density regions are large.

**c) Matter/Antimatter Domains:**

A distribution of small-scale matter/antimatter domains in baryon-asymmetric universes (i.e. where net $\eta \neq 0$) may result from electroweak baryogenesis scenarios. If the baryon (antibaryon) mass in individual domains is $\gtrsim 10^{-21} M_\odot$ the BBN process in such scenarios is characterized by differential diffusion of neutrons (antineutrons) and protons (antiprotons) which causes a preferential annihilation of antimatter on neutrons. When annihilation of antimatter occurs before significant $^4$He synthesis ($T \gtrsim 80$keV) but after weak freeze-out ($T \lesssim 1$MeV) a modest to substantial reduction of $Y_p$ results. When annihilations occur mainly
after $^4$He synthesis the dominant effect is significant production of $^3$He and $^2$H [8], with $^3$He/$^2$H ratios likely to be in conflict with observational constraints.

**Non-standard Neutrino Properties**

The BBN process may be approximated as the incorporation of all available neutrons into $^4$He nuclei at a temperature $T \approx 80$keV. The neutron abundance at this temperature, and hence the final $^4$He mass fraction $Y_p$, may be increased with respect to a SBBN scenario due to an increased expansion rate of the universe during the BBN era. An increased expansion rate raises the neutron-to-proton ratio (hereafter; n/p) at weak freeze-out and reduces the time for neutron decay to decrease the n/p ratio between weak freeze-out and significant $^4$He synthesis. We will refer to this effect as the “expansion rate effect”. In addition, the n/p ratio at $T \approx 80$keV may be either decreased or increased by introducing additional electron- and/or anti-electron neutrinos into the plasma. In SBBN it is assumed that the left-handed neutrino and right-handed antineutrino seas of three massless, stable neutrino flavors $\nu_e$, $\nu_\mu$, and $\nu_\tau$ are populated and that neutrino chemical potentials do vanish. Modifications of these assumptions usually result in either the expansion rate effect or additional (anti) electron neutrinos, or both. The principal effect of such modifications is to change the $^4$He abundance, and to a less observationally significant degree the abundances of other light-element isotopes.

a) **Massive, long-lived $\tau$-neutrinos:**

Neutrinos are considered massless and long-lived in the context of BBN for neutrino masses $m_\nu < 100$keV and lifetimes $\tau_\nu > 10^3$s (see b), however, possible photodisintegration). A massive, long-lived $\tau$-neutrino leads to the expansion rate effect since the contribution to the total energy density from the rest mass of $\tau$-neutrinos continually increases as the universe expands between weak freeze-out and $^4$He synthesis, possibly even resulting in matter domination during the BBN era. BBN with massive, long-lived $\tau$ neutrinos and for experimentally allowed $\nu_\tau$-masses therefore results in increased $^4$He and useful limits on the allowed mass of a long-lived $\tau$-neutrino have been derived [9].

b) **Massive, unstable $\tau$-neutrinos:**

The effects of decaying $\tau$ neutrinos on the light-element nucleosynthesis [11] sensitively depend on the decay products. One distinguishes between (i) decay into sterile particles, in particular, particles which interact neither weakly with nucleons interchanging neutrons and protons nor electromagnetically with the ambient plasma (e.g. $\nu_\tau \rightarrow \nu_\mu + \phi$, where $\phi$ is a weakly interacting scalar), (ii) decay into sterile and electromagnetically interacting particles (e.g. $\nu_\tau \rightarrow \nu_\mu + \gamma$), and (iii) decay into (anti) electron neutrinos and sterile particles (e.g. $\nu_\tau \rightarrow \nu_e + \phi$) [12]. For decay channel (i) and $\tau_\nu > 1$s increased $^4$He mass fraction results due to the expansion rate effect which, nevertheless, is weaker than for long-lived $\tau$-neutrinos since the energy of the (massless) decay products redshifts with the expansion of the universe. In contrast, for lifetimes $\tau_\nu \lesssim 1$s and $m_\nu \gtrsim 10$MeV it is possible to reduce the $Y_p$ since effectively the distributions of only two neutrino flavors are populated [13]. Decay channel (ii) would have interesting effects on BBN but is excluded by observations of supernova 1987A for $\tau_\nu \lesssim 10^4$s. For decay via channel (iii) additional (anti) electron neutrinos are injected into the plasma and their effect depends strongly on the time of injection [14]. When injected early ($\tau_\nu \sim 1$s), the net result is a reduction of $Y_p$ [15] since weak freeze-out occurs at lower temperatures. In contrast, when injected late ($\tau_\nu \sim 10^2 - 10^3$s) the resulting non-thermal electron neutrinos...
affect a conversion of protons into neutrons, yielding higher \(Y_p\) and/or higher \(^2\text{H}\) depending on injection time. It had been suggested that a scenario with late-decaying \(\nu_\tau\) via channel (iii) may result in the relaxation of BBN bounds on \(\Omega_b\) by a factor up to ten \([14]\), nevertheless, this possibility seems to be ruled out now by the current upper laboratory limit on the \(\nu_\tau\)-mass. For life times \(\tau_{\nu_\tau} \gtrsim 10^3\)s, modifications of the light-element abundances after the BBN era by photodisintegration of nuclei may result (cf. radiative decays).

c) Neutrino oscillations:
Neutrino oscillations may occur when at least one neutrino species has non-vanishing mass and the weak neutrino interaction eigenstates are not mass eigenstates of the Hamiltonian. One distinguishes between (i) flavor-changing neutrino oscillations (e.g. \(\nu_e \leftrightarrow \nu_\mu\)) and (ii) active-sterile neutrino oscillations (e.g. \(\nu_e \leftrightarrow \nu_s\)). Here \(\nu_s\) may be either the right-handed component of a \(\nu_e\) (\(\nu_\mu, \nu_\tau\)) Dirac neutrino, or a fourth family of neutrinos beyond the standard model of electroweak interactions. In the absence of sterile neutrinos and neutrino degeneracy, neutrino oscillations have negligible effect on BBN due to the almost equal number densities of neutrino flavors. When sterile neutrinos exist, neutrino oscillations may result into the population of the sterile neutrino distribution, increasing the energy density, and leading to the expansion rate effect. The increased \(Y_p\) has been used to infer limits on the neutrino squared-mass difference – mixing angle plane \([14]\). In the presence of large initial lepton number asymmetries (see neutrino degeneracy) and with sterile neutrinos, it may be possible to reduce \(Y_p\) somewhat independently from the detailed initial conditions, through the dynamic generation of electron (as well as, \(\mu\) and \(\tau\)) neutrino chemical potentials \([17]\).

Neutrino Degeneracy
It is possible that the universe has net lepton number. Positive net cosmic lepton number manifests itself at low temperatures through an excess of neutrinos over antineutrinos. If net lepton number in either of the three families in the standard model is about ten orders of magnitude larger than the net cosmic baryon number BBN abundance yields are notably affected. Asymmetries between the \(\nu_\mu\) (\(\nu_\tau\)) and \(\bar{\nu}_\mu\) (\(\bar{\nu}_\tau\)) number densities result in the expansion rate effect only, whereas asymmetries between the \(\nu_e\) and \(\bar{\nu}_e\) number densities induce a change in the weak freeze-out \((n/p)\) ratio as well. Since the expansion rate effect leads to increased \(^4\text{He}\) production \(\nu_\mu\) (\(\nu_\tau\)) degeneracy may be constrained. However, one may find combinations of \(\nu_\mu\), \(\nu_\tau\), and \(\nu_e\) chemical potentials which are consistent with observational abundance constraints for \(\Omega_b\) much larger than that inferred from SBBN \([18]\). Nevertheless, such solutions not only require large chemical potentials but also an asymmetry between the individual chemical potentials of \(\nu_e\) and \(\nu_\mu\) (\(\nu_\tau\)). Asymmetries between the different flavor degeneracies may be erased in the presence of neutrino oscillations.

Massive Decaying Particles
The out-of-equilibrium decay or annihilation of long-lived particles (\(\tau \gtrsim 0.1\)s), such as light supersymmetric particles, as well as non-thermal particle production by, for example, evaporating primordial black holes or collapsing cosmic string loops, during, or after, the BBN era may significantly alter the BBN nucleosynthesis yields \([19]\). The decays may be classified according to if they are (i) radiative or (ii) hadronic, in particular, whether the electromagnetic or strong interactions of the injected non-thermal particles are most relevant.
a) Radiative decays:
Electromagnetically interacting particles (i.e. $\gamma$, $e^\pm$) thermalize quickly in the ambient photon-pair plasma at high temperatures, such that they usually have little effect on BBN other than some heating of the plasma. In contrast, if radiative decays occur at lower temperatures after a conventional BBN epoch, they result in a rapidly developing $\gamma$-$e^\pm$ cascade which only subsides when individual $\gamma$-rays of the cascade do not have enough energy to further pair-produce $e^\pm$ on the ambient cosmic background radiation. The net result of this cascade is a less rapidly developing $\gamma$-ray background whose properties only depend on the total amount of energy released in electromagnetically interacting particles and the epoch of decay. At temperatures $T \lesssim 5\text{keV}$ the most energetic $\gamma$-rays in this background may photodissociate deuterium, at temperatures $T \lesssim 0.5\text{keV}$ the photodisintegration of $^4\text{He}$ becomes possible. Radiative decays at $T \approx 5\text{keV}$ may result in a BBN scenario with low $^2\text{H}$ and low $^4\text{He}$ if an ordinary SBBN scenario at low $\eta$ is followed by an epoch of deuterium photodisintegration $[20]$. Radiative decays at lower temperatures may produce significant amounts of $^2\text{H}$ and $^3\text{He}$. Nevertheless, this process is unlikely to be the sole producer of $^2\text{H}$ due to resulting observationally disfavored $^3\text{He}/^2\text{H}$ ratio. The possible overproduction of $^3\text{He}$ and $^2\text{H}$ by the photodisintegration of $^4\text{He}$ has been used to place meaningful limits on the amount of non-thermal, electromagnetically interacting energy released into the cosmic background. These limits may actually be more stringent than comparable limits from the distortion of the cosmic microwave background radiation $[21]$.

b) Hadronic decays:
The injection of hadrons into the plasma, such as $\pi^\pm$'s, $\pi^0$'s and nucleons, may affect light-element nucleosynthesis during, or after, the BBN era and by the destruction and production of nuclei. In general, possible scenarios and reactions are numerous. If charged hadrons are produced with high energies below cosmic temperature $T \lesssim \text{keV}$ they may cause a cascade leading to the possibility of photodisintegration of nuclei (see radiative decays). Through charge exchange reactions the release of about ten pions per nucleon at $T \approx 1\text{MeV}$ results in a significant perturbation of weak freeze-out and increased $Y_p [22]$. A fraction of only $\sim 10^{-3}$ antinucleons per nucleon may cause overproduction of $^3\text{He}$ and $^2\text{H}$ through antinucleon -- $^4\text{He}$ annihilations. It is also conceivable that the particle decaying carries baryon number such that the cosmic baryon number is created during the BBN era. A well-studied BBN scenario is the injection of high-energy ($\sim 1\text{GeV}$) nucleons created in hadronic jets which are produced by the decay of the parent particle $[23]$. If released after a conventional BBN era these high-energy nucleons may spall pre-existing $^4\text{He}$, thereby producing high-energy $^2\text{H}$, $^3\text{H}$, and $^3\text{He}$ as well as neutrons. Such energetic light nuclei may initiate an epoch of non-thermal nucleosynthesis. It was found that the nucleosynthesis yields from a BBN scenario with hadro-destruction/production and photodisintegration may result in abundance yields independent of $\eta$ for a range in total energy injection, and half-life of the decaying particles. Nevertheless, such scenarios seem to produce $^6\text{Li}$ in conflict with observational constraints.

Other Modifications to BBN
There are many other variants to a standard big bang nucleosynthesis scenario which have not been mentioned here. These include anisotropic expansion, variations of fundamental constants, theories other than general relativity, magnetic fields during BBN, superconducting cosmic strings during BBN, among others. The influence of many, but not all, of those
scenarios on BBN is due to the expansion rate effect. Studies of such variants is of importance mainly due to the constraints they allow one to derive on the evolution of the early universe.

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