Primordial Abundances of $^6$Li, $^9$Be, and $^{11}$B with Neutrino Degeneracy and Gravitational Constant Variation

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Abstract

Recent measurements of deuterium abundances from QSO absorption spectra show two conflicting numbers, which differ by an order of magnitude. Allowing the neutrino degeneracy together with gravitational constant variation at the epoch of primordial nucleosynthesis, the implication of these observations on the $^6$Li, $^9$Be and $^{11}$B abundances will be discussed. Within the permitted ranges consistent with D, $^4$He and $^7$Li, we observe the strong $\eta$ dependence of $^{11}$B as in SBBN but no significant dependence of $^6$Li and $^9$Be on the baryon number density is observed. The predictions of $^6$Li and $^9$Be for low and high deuterium differ by an order of magnitude and predictions for $^{11}$B differ by several orders of magnitude at most and vary with $\eta$.

PACS numbers: 26.35.+c, 26.45.+h, 97.10.Cv, 97.10.Tk, 98.80.Ft

Typeset using REVTEX
The primordial abundances of the light nuclei has been considered as the important observables, which probe the physical environments of the early Universe in the frame work of hot Big-Bang cosmology [1]. One of the successes of the standard Big-Bang nucleosynthesis (SBBN) [2] is the determination of the baryon number density, $n_B$, which take part in the process of nucleosynthesis. Conventionally the baryon number density is expressed as the ratio to the photon number density, $\eta = n_B/n_\gamma$ [3]. It measures not only the degree of baryon number asymmetry [4] but also determines baryonic energy density of Universe, which puts the possible limit of the baryonic dark matter in the Universe. The ratio of the baryonic energy density ($\rho_B$) to the critical energy density ($\rho_c$), $\Omega_B(=\rho_B/\rho_c)$, can be written in terms of $\eta$ as $\Omega_B h^2_0 \sim 0.015 \eta_{10}$, where the Hubble parameter $H_0 = 50 h_0 km^{-1} Mpc^{-1}$ and $\eta_{10} = \eta \times 10^{-10}$.

Recent measurements of deuterium abundances from QSO absorption spectra [5,6] show two conflicting numbers which differ by an order of magnitude. Since the deuterium abundance is known to be very sensitive on the baryon number density in contrast to the $^4$He abundance in the range of interest, the implication of these two measurements is very important in determining the baryon number density. It is also well known that the heavier elements like $^9$Be and $^{11}$B are sensitive on the baryon number density, change of abundances by several orders of magnitude for $\eta = 1 - 10$. Recently, Nollet et al. [7] discussed that $^6$Li abundance is also very sensitive on the baryon number density, $\eta$, within the uncertainties of the nuclear reaction rates relevant to $^6$Li production. Hence these heavier elements are considered to be very useful in discussing the possible variations from SBBN, since some of the variations allow different ranges of baryon number density. For example, there has been some works on the $^9$Be and $^{11}$B with inhomogeneous baryon number density possibly due to the first order QCD phase transition [8]. In this work, we will consider the case with neutrino degeneracy [9] together with the gravitational constant variation [10] to investigate the implications of two distinct measurements of deuterium abundances on the primordial abundances of $^6$Li, $^9$Be and $^{11}$B.

In the radiation dominated era of early Universe, the evolution is described by the ex-
pansion rate $H$ which is defined as $H^2 = \frac{8\pi}{3} G \rho_{rad}$, where $G$ is the gravitational constant and $\rho_{rad}$ is the energy density of the light particles. In SBBN, photons, electrons and three light neutrinos are only considered. At BBN epoch, $T \sim 1MeV$, muon and tau ($m_\mu$ and $m_\tau \gg 1MeV$) have been already decayed away and their chemical potentials can be put to zero. Assuming the charge neutrality of the Universe the electron chemical potential can be also ignored, since $\mu_e/T$ should be of order $\mathcal{O}(\eta)$. However, there is presently no convincing theoretical or observational constraints on the neutrino degeneracies at the epoch of primordial nucleosynthesis [11] and we take it as parameters of the early environment of the Universe. Neutrino degeneracy increases $\rho_{rad}$ and therefore speeds up the expansion of the Universe. One can easily see also that the deviation of gravitational constant $G$ at the epoch of nucleosynthesis from the present value $G_0$ can also influence the expansion rate of the Universe and hence the standard BBN [12]. Since the effects of degeneracies of muon- and tau-neutrinos are only on the energy density, it can be effectively implemented as the variation of gravitational constant. The degenerate electron-neutrino not only increase $\rho_{rad}$ as muon- and tau-neutrinos but also it influences the weak interaction rates where electrons are involved. Hence the role of degenerate electron neutrinos cannot be simply absorbed in $G$ variation. In this work, we consider only electron-neutrino degeneracy together with the variation of gravitational constant, $G$, possibly due to the degenerate muon- and/or tau-neutrino or more fundamental origins [13]. The three light neutrinos are considered to be effectively massless during the nucleosynthesis and no neutrino oscillation is assumed.

For deuterium abundances, we take both high and low values from QSO observations. The low abundances of deuterium, $[D/H]=(1.7 - 3.5) \times 10^{-5}$ which is close to the ISM value, has been estimated by Tytler et al. [6], while higher abundance, $[D/H]=(1.5 - 2.3) \times 10^{-4}$ is obtained by Rugers et al. [5]. We take $0.226 \leq Y_p \leq 0.242$ for $^4$He and $0.7 \leq [^7\text{Li}/H] \times 10^{10} \leq 3.8$ for $^7\text{Li}$ [14]. We obtain the allowed ranges for $\eta_{10}$, $G$, and $\xi_e$ which are consistent with the
above observed abundances. The result is summarized in $\xi-e-G$ plot of Fig. 1. It shows a rather wide range of possible $\xi$ and $G$ for given $\eta_{10}$ (numbers in the shaded boxes for low deuterium abundances and empty boxes for higher abundances). And it also demonstrates clearly how these two distinct observations of D/H abundance predict the different ranges of $\eta$: smaller (larger) value of $\eta_{10}$ for high (low) deuterium abundance. One can see that upper bound on the baryon energy density with low deuterium abundance, $\Omega_B h^2 \leq 0.15(\eta_{10} = 10)$, is larger than that of standard BBN.

To see the implication of these two different ranges of $\eta$, we calculate the primordial abundances of $^6\text{Li}$, $^9\text{Be}$ and $^{11}\text{B}$ using these permitted sets of parameters obtained above from the observed abundances of D, $^4\text{He}$ and $^7\text{Li}$. In Fig. 2, the calculations of $^9\text{Be}$ abundance are shown. In SBBN, it decreases monotonically as $\eta$ increasing and is quite sensitive on $\eta$, which is the only parameter of SBBN. However, if we allow neutrino degeneracy and gravitational constant variation, we found that the predictions are not so sensitive on $\eta$. It is almost independent of $\eta$ both for high and low deuterium cases. For low deuterium case, the abundance is similar to that of SBBN with $\eta \sim 6$ and for high deuterium case the abundance is similar to that of SBBN with $\eta \sim 2$, whatever the value of $\eta$ is used in the permitted ranges of $\eta, G/G_0$ and $\xi$. This means that $^9\text{Be}$ does not constrain the $\eta$ any further as far as the parameter sets are consistent with D, $^4\text{He}$, and $^7\text{Li}$. However one can clearly see the differences in the abundance predictions with the low and high deuterium cases, which differ by an order of magnitude. Fig. 3 shows SBBN predictions of $^{11}\text{B}$ abundance which are changing rapidly with $\eta$. Allowing neutrino degeneracy and gravitational constant variation, the predictions of low and high deuterium cases are found to be quite different. With high deuterium, the sensitivity on $\eta$ get reduced as in $^9\text{Be}$ as far as the relevant parameters are confined to be consistent with abundances of D, $^4\text{He}$, and $^7\text{Li}$.

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1The variation of gravitational constant is chosen to be $G/G_0 = 0.1-6$ for numerical convenience, which is enough to see the dependences on the relevant parameters of the abundances.
For low deuterium case, however, the sensitivity on $\eta$ of $^{11}$B abundance is still clear as in SBBN within the permitted ranges of $\eta$. It is interesting to note that for $\eta_{10} \sim 2$ the predictions with low and high deuterium becomes similar. We include the reaction rates proposed by Nollet et al. into nuclear reaction chains \cite{10} to calculate the possible abundance of $^6$Li, which is monotonically decreasing by an order of magnitude in the range of interest as $\eta$ increases, as shown in Fig. 4. But the dependence on $\eta$ which is constrained to vary together with $G/G_0$ and $\xi_e$ is not the same as in SBBN. The abundance for low deuterium remains roughly fixed at the value of SBBN with $\eta \sim 6$ and at the SBBN value with $\eta \sim 2$ for high deuterium. They are differ by an order of magnitude but they show no $\eta$ dependence as for $^9$Be.

In summary, we calculate the abundances of $^6$Li, $^9$Be and $^{11}$B, using the permitted ranges of $\eta$ consistent with D, $^4$He and $^7$Li by allowing the neutrino degeneracy and gravitational constant variation. We investigate the implication of two different QSO measurements of deuterium abundances and the possible $\eta$ dependence on those heavier elements. Within the permitted ranges of $\eta$, $^6$Li and $^9$Be do not show any significant $\eta$ dependence. Within the allowed ranges obtained for high deuterium abundance, $^{11}$B show essentially no dependence on $\eta$. However, if we use the permitted ranges consistent to low deuterium abundance, $^{11}$B shows clearly the rapid dependence on $\eta$ as much as in SBBN. It is found that the predictions of the abundances of $^6$Li and $^9$Be with low and high deuterium abundance differ by an order of magnitude and predictions for $^{11}$B differ by several orders of magnitude at most. Therefore, the measurement of the heavier elements like $^6$Li, $^9$Be and $^{11}$B will provide us a valuable test of the neutrino degeneracy and gravitational constant variation proposed in this work and also be useful in resolving the issue of the two different QSO measurements of deuterium abundance.

Acknowledgements

This work is supported in part by Ministry of Education(BSRI 97-2441) and by Korea Science and Engineering Foundation (94-0702-04-01-3 and Center for Theoretical Physics at
Seoul National University).
REFERENCES


**Figure Captions**

Fig. 1. Allowed ranges of $\xi_e$ and $G/G_0$ [15]. Shaded boxes for low deuterium abundance and empty boxes for high deuterium abundance.

Fig. 2. The predictions of $^9$Be abundances; solid line for SBBN and shaded(empty) band for high(low) deuterium abundance.

Fig. 3. The predictions of $^{11}$B abundances; solid line for SBBN and shaded(empty) band for high(low) deuterium abundance.

Fig. 4. The predictions of $^6$Li abundances; solid line for SBBN and shaded(empty) band for high(low) deuterium abundance.