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EFFECTS OF NEUTRINO DEGENERACY ON THE PRIMORDIAL ABUNDANCES OF ${}^9\text{Be}$ AND ${}^{11}\text{B}$

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ABSTRACT

The primordial abundances of ${}^9\text{Be}$ and ${}^{11}\text{B}$ are calculated to investigate the effects of the lepton number asymmetry due to non-zero neutrino degeneracy. Within the permitted ranges of parameters obtained from the analysis of primordial abundances of light nuclei, ${}^4\text{He}$, D , ${}^3\text{He}$, and ${}^7\text{Li}$, ${}^9\text{Be}$ abundance is found to be indistinguishable from that of the standard BBN. However, ${}^{11}\text{B}$ abundance is found to be sensitive on the neutrino degeneracy.

Subject heading: early Universe—elementary particles—nucleosynthesis, abundances

1. INTRODUCTION

Big-Bang nucleosynthesis (BBN) provides valuable limits on cosmological and particle physics parameters through a comparison between the predicted and inferred primordial abundances of the light nuclei. The standard BBN (Steigman, Schramm, & Gunn 1977; Yang et al. 1984; Kolb & Turner 1990; Walker et al. 1991) provides the limits of the number of light neutrino species which is consistent with LEP experiment (LEP Collaborations 1992). Also the estimation of $\eta \sim 3 \times 10^{-10}$, or equivalently $\Omega_B h_0^2 \sim 0.05$, puts the possible limit of the baryonic dark matter in the Universe. However, given the uncertainties of the inferred abundances and the possible variations of the physics in the early Universe, which might be different from the standard procedure, the possible alternatives for the standard BBN has been studied in various contexts (Boesgaard & Steigman 1985; Schramm 1991); neutrino degeneracy (Olive et al. 1991; Kang & Steigman 1992), varying gravitational constant (Damour, Gibbons, & Taylor 1988; Accetta, Krauss, & Romanelli 1990), baryon inhomogeneity (Malaney & Fowler 1989; Boyd & Kajino 1989; Kajino & Boyd 1990), neutrino oscillation (Kobayashi, Lim, & Nojiri 1991; Kostelecky & Samuel 1993; Shi, Schramm, & Fields 1993) and primordial magnetic field (Turner & Widrow 1988; Magueijo 1994) in the early history of Universe. So far these analysis have been done mainly on the light element up to ${}^7\text{Li}$. But to clarify the possible variations more effectively, it is necessary to continue the analysis up to more massive elements like ${}^9\text{Be}$ and ${}^{11}\text{B}$. Actually the abundances of ${}^9\text{Be}$ and ${}^{11}\text{B}$ have been of interests for inhomogeneous BBN model (Malaney & Fowler 1989; Boyd & Kajino 1989; Kajino & Boyd 1990). It has been found that the abundances of ${}^7\text{Li}$ constrains strongly the inhomogeneous BBN and with this constraint the abundances of ${}^9\text{Be}$ and ${}^{11}\text{B}$ are indistinguishable from those of standard BBN (Thomas et al. 1993a,b). Recently the possibility of non-zero neutrino degeneracy (Olive et al. 1991; Kang & Steigman 1992) together with variation of gravitational constant (Damour, Gibbons, & Taylor 1988; Accetta, Krauss, & Romanelli 1990) has been studied (Kim, Kim, & Lee 1993) and it has been demonstrated that a rather wide range of η for the abundances of light elements, D , ${}^3\text{He}$, ${}^4\text{He}$ and ${}^7\text{Li}$, than in standard BBN is possible. Therefore, it is interesting to calculate the primordial abundances with non-zero neutrino degeneracy for comparison with the predictions of the standard BBN model. It

is particularly more interesting because of the fact that it becomes recently possible to observe ${}^9\text{Be}$ and ${}^{11}\text{B}$ abundances in extreme Pop.II stars with low Z (Ryan et al. 1990; Gilmore, Edvardsson, & Nissen 1991; Ryan et al. 1992; Duncan, Lambert, & Lemke 1992). Although these can be understood so being due to the cosmic ray spallation (Steigman & Walker 1992; Walker et al. 1993), the possibility for the new developments of observation of heavier element abundances is expected. In this paper, we will discuss in detail the role of varying G and non-zero neutrino degeneracies on the primordial abundances of ${}^9\text{Be}$ and ${}^{11}\text{B}$ and the possible range of η , using the extended reaction network to include the relevant reactions for ${}^9\text{Be}$ and ${}^{11}\text{B}$, for example, ${}^7\text{Li}(t, n){}^9\text{Be}$ (Brune et al. 1991), ${}^8\text{Li}(d, n){}^9\text{Be}$ (Malaney & Fowler 1989), ${}^9\text{Li}(p, n){}^9\text{Be}$ (Thomas et al. 1993a) and ${}^9\text{Be}(t, n){}^{11}\text{B}$ (Boyd et al. 1992). The new reaction network with 28 nuclei is composed of 103 reactions.

2. ELECTRON NEUTRINO DEGENERACY AND GRAVITATIONAL CONSTANT IN BIG BANG NUCLEOSYNTHESIS

One of the important factors in nucleosynthesis is the expansion rate of the Universe which competes with weak and strong interaction rates. The expansion rate of the Universe is measured by the Hubble parameter:

$$H^2 = \left(\frac{\dot{R}}{R}\right)^2 = \frac{8\pi}{3}G\rho_{tot}, \quad (1)$$

where R is the cosmic scale factor and the gravitational constant G might be different from the present value G_0 . One can see that a larger value of G results in a faster expansion rate. Assuming that the light particles other than photons, electrons and neutrinos were decoupled earlier such that their contributions to the total energy density can be neglected, ρ_{tot} depends mainly on the number of neutrino species and neutrino degeneracies (Olive et al. 1991; Kang & Steigman 1992). In this work we fix the number of neutrino species to be three (Walker et al. 1991; LEP Collaborations 1992). Since the product $G(t)\rho_{tot}$ enters into the expression for the expansion rate, the effect of changing ρ_{tot} due to the degeneracies of neutrino seems to be simply equivalent to redefining G . It is the case for degeneracies of muon- and tau-neutrino the effects of which are only on the energy density. On the other hand, the degeneracy of electron neutrinos affects also the weak interaction rate for nucleons such that it

affects strongly the neutron to proton density ratio. Therefore the effect of electron neutrino degeneracy can not be simply absorbed by redefining G and we have essentially two parameters for the expansion rate, G/G_0 and $\xi_e = \mu_{\nu_e}/T$. The neutron mean life time which determines weak interaction rate is taken to be $889.1 \pm 2.1 \text{ sec}$ (Hikasa et al. 1992). One more important parameter in nucleosynthesis is the baryon to photon ratio η which strongly affects the nuclear reaction rate. Now we have, in this work, three parameters η , G/G_0 and ξ_e , whereas only one parameter η is used in standard BBN.

3. THE RESULTS AND THE DISCUSSIONS

We calculate the possible ranges of three parameters, G , ξ_e and η which are consistent with the primordial abundances of light element up to ${}^7\text{Li}$. The inferred abundances of light nuclei from the observational data are those found in Ref. (Smith, Kawano, & Malaney 1993):

$$\begin{aligned} 0.21 &\leq Y_p \leq 0.24 \\ 1.8 \times 10^{-5} &\leq X_D \\ X_D + X_{{}^3\text{He}} &\leq 9.0 \times 10^{-5} \\ 1.1 \times 10^{-10} &\leq X_{{}^7\text{Li}} \leq 2.3 \times 10^{-10}, \end{aligned} \quad (2)$$

where Y_p is the mass fraction of ${}^4\text{He}$ and X refers to number density relative to hydrogen. To see the deviations from the standard BBN, we calculate the possible ranges of ξ_e and η in Fig. 1(a) and of G/G_0 and η for $\xi_e = 0.0$ in Fig. 1(b). For the standard BBN with $\xi_e = 0.0$ and $G = G_0$, the allowed ranges of $\eta_{10} (\eta = \eta_{10} \times 10^{-10})$, $2.4 \leq \eta_{10} \leq 3.3$, can be read in Fig. 1 (a) or (b). Within this permitted range of η_{10} , the abundances of ${}^9\text{Be}$ and ${}^{11}\text{B}$ are calculated as

$$\begin{aligned} 1.0 \times 10^{-18} &\leq {}^9\text{Be}/H \leq 2.7 \times 10^{-18} \\ 3.9 \times 10^{-18} &\leq {}^{11}\text{B}/H \leq 2.2 \times 10^{-17}. \end{aligned} \quad (3)$$

With zero electron-neutrino degeneracy (Fig. 1(a)), the ratio of baryon to photon, η_{10} , and the possible variation of G from G_0 can be estimated within the present observational limit, Eq. (2) :

$$\begin{aligned} 2.381 \leq \eta_{10} \leq 4.468 \\ 0.689 \leq G/G_0 \leq 1.036. \end{aligned} \quad (4)$$

With $G/G_0 = 1.0$ in Fig. 1(b), the permitted ranges are found to be

$$\begin{aligned} 2.427 \leq \eta_{10} \leq 4.811 \\ -0.017 \leq \xi_e \leq 0.146. \end{aligned} \quad (5)$$

The maximum and minimum abundances of ${}^9\text{Be}$ and ${}^{11}\text{B}$ within the ranges of Eq. (4) and Eq. (5) are calculated respectively in Table I(a) and I(b). We can see from Eq. (3) and Table I that the abundance of ${}^9\text{Be}$ is not changing significantly from the standard BBN. On the other hand it is observed that the abundance of ${}^{11}\text{B}$ is very sensitive on the parameters and it varies over two orders of magnitude within the permitted range of parameters. Moreover, the maximum abundance of ${}^{11}\text{B}$ can be much larger than that of standard BBN. It is also interesting to note that the abundance of ${}^{11}\text{B}$ is being enhanced as η_{10} is increasing. To investigate the effects of η in detail, the allowed ranges of ξ_e and G/G_0 which are consistent with the abundances of light elements up to ${}^7\text{Li}$ are calculated for various η_{10} . For $\eta_{10} = 2.8, 5.0, 7.0$, and 10.0 , the results are shown in Table II. Within these four sets of possible ranges of parameters, the maximum and minimum abundances of ${}^9\text{Be}$ and ${}^{11}\text{B}$ are calculated in Table III and IV respectively. The abundances both of ${}^9\text{Be}$ and ${}^{11}\text{B}$ are observed to be roughly increasing as η is increasing. For ${}^9\text{Be}$, the rate of increasing is very small and it means that abundances of ${}^9\text{Be}$ is not so sensitive on the parameters ξ_e , G or η within the ranges which are consistent with the abundances of light elements. However, ${}^{11}\text{B}$ abundances are rapidly increasing as η being increased. The origin of this difference between the increasing rates of abundances with respect to the η can be traced back to their significantly different behaviour even with standard parameters, $G/G_0 = 1$ and $\xi_e = 0$, as shown in Fig. 2. While ${}^{11}\text{B}$ is increasing with η , ${}^9\text{Be}$ is decreasing. To understand the effects of the parameters more clearly, we show in Fig. 3 the abundances from the parameter sets (1): $\eta_{10} = 2.8, G/G_0 = 1.0, \xi_e = 0.0$, (2): $\eta_{10} = 2.8, G/G_0 = 1.0, \xi_e = 0.7$, (3): $\eta_{10} = 2.8, G/G_0 = 11.0, \xi_e = 0.7$ and (4): $\eta_{10} = 10.0, G/G_0 = 11.0, \xi_e = 0.7$, where (1) for the standard BBN and (4) from the fourth set in Table II. The parameter sets of (2) and (3) are included to see the effects

of increasing ξ_e and G/G_0 respectively from (1) to (4). From Table III and IV, we can see that the permitted values of G/G_0 and ξ_e are increasing with η . As ξ_e is increasing from (1) to (2), n/p gets smaller and the abundances becomes smaller as shown in Fig. 3. With increasing G/G_0 , the expansion rate, H , is increasing to enhance the abundances. It is because the nuclear reactions which destroy ${}^9\text{Be}$ and ${}^{11}\text{B}$ get frozen out earlier as the expansion rate is increasing. This increasing abundances from (2) to (3) can be seen also in Fig. 3. Finally from (3) to (4) with increasing η , the abundance of ${}^9\text{Be}$ is decreasing while ${}^{11}\text{B}$ is being enhanced. In other words, the net effects of G/G_0 and ξ_e barely balance the decreasing abundances of ${}^9\text{Be}$ such that it does not change as much as for ${}^{11}\text{B}$ within the permitted range of parameters.

4. SUMMARY

We have calculated the primordial abundances of ${}^9\text{Be}$ and ${}^{11}\text{B}$ to investigate the effects of non-zero neutrino degeneracy and possible variation of gravitational constant in the early Universe. The main effect of G variation is to change the expansion rate of Universe. The effects of neutrino degeneracies is to increase the energy density which accelerate the expansion of the Universe, while the degeneracy of electron neutrinos affects also the weak interaction rate. We calculate the permitted range of parameters, $\eta_{10}, G/G_0$, and ξ_e , which are consistent with the observational data of light elements up to ${}^7\text{Li}$. Within the permitted range of parameters, primordial abundances of ${}^9\text{Be}$ and ${}^{11}\text{B}$ are calculated using the extended reaction networks which includes the recently measured reactions. It is found that the abundance of ${}^9\text{Be}$ is almost same order of magnitude as in standard BBN. But ${}^{11}\text{B}$ abundances are considerably enhanced as we increase $\eta_{10}, G/G_0$ and ξ_e compared to that of standard BBN. This implies that ${}^{11}\text{B}$ abundances are sensitive enough to constrain the variations of gravitational constant and ξ_e .

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TABLES

Table I(a). Maximum and minimum abundances of ${}^9\text{Be}/H$ and ${}^{11}\text{B}$ with $\xi_e = 0.0$

η_{10}	G/G_0	${}^9\text{Be}/H$	η_{10}	G/G_0	${}^{11}\text{B}/H$
4.040.....	0.689	$2.222 \times 10^{-19}(\text{min.})$	2.381.....	0.962	$3.592 \times 10^{-18}(\text{min.})$
2.493.....	1.036	$2.764 \times 10^{-18}(\text{max.})$	4.468.....	0.964	$1.012 \times 10^{-16}(\text{max.})$

Table I(b). Maximum and minimum abundances of ${}^9\text{Be}/H$ and ${}^{11}\text{B}$ with $G/G_0 = 1.0$

η_{10}	ξ_e	${}^9\text{Be}/H$	η_{10}	ξ_e	${}^{11}\text{B}/H$
4.811.....	0.146	$2.291 \times 10^{-19}(\text{min.})$	2.427.....	0.012	$3.729 \times 10^{-18}(\text{min.})$
2.450.....	-0.017	$2.758 \times 10^{-18}(\text{max.})$	4.811.....	0.146	$1.104 \times 10^{-16}(\text{max.})$

Table II. Allowed ranges of G/G_0 and ξ_e

η_{10}	$G/G_0(\text{min.})$	$G/G_0(\text{max.})$	$\xi_e(\text{min.})$	$\xi_e(\text{max.})$
2.8.....	0.311	1.34	-0.482	0.119
5.0.....	1.10	4.49	0.086	0.509
7.0.....	2.25	9.02	0.336	0.684
10.0....	4.82	19.0	0.536	0.846

Table III. Maximum and minimum abundances of ${}^9\text{Be}/H$

η_{10}	G/G_0	ξ_e	${}^9\text{Be}/H(\text{min.})$	G/G_0	ξ_e	${}^9\text{Be}/H(\text{max.})$
2.8.....	0.311	-0.393	2.081×10^{-19}	1.32	0.092	2.801×10^{-18}
5.0.....	1.10	0.167	2.429×10^{-19}	4.39	0.471	2.994×10^{-18}
7.0.....	2.25	0.420	2.475×10^{-19}	8.85	0.646	3.095×10^{-18}
10.0....	4.82	0.639	2.585×10^{-19}	18.6	0.805	3.158×10^{-18}

Table IV. Maximum and minimum abundances of ${}^{11}\text{B}/H$

η_{10}	G/G_0	ξ_e	${}^{11}\text{B}/H(\text{min.})$	G/G_0	ξ_e	${}^{11}\text{B}/H(\text{max.})$
2.8.....	1.34	0.119	4.920×10^{-18}	0.400	-0.407	1.981×10^{-17}
5.0.....	4.49	0.509	1.165×10^{-17}	1.20	0.086	1.391×10^{-16}
7.0.....	9.02	0.683	1.699×10^{-17}	2.45	0.336	3.003×10^{-16}
10.0....	19.0	0.846	2.320×10^{-17}	5.35	0.535	5.503×10^{-16}

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FIGURE CAPTIONS

Fig. 1. (a) Allowed ranges of η_{10} and G/G_0 with $\xi_e = 0.0$.

(b) Allowed ranges of η_{10} and ξ_e with $G/G_0 = 1.0$.

Fig. 2. The abundances of ${}^9\text{Be}$ and ${}^{11}\text{B}$ vs. η_{10} with $G/G_0 = 1.0$ and $\xi_e = 0.0$.

Fig. 3. The abundances of (a) ${}^9\text{Be}$ and (b) ${}^{11}\text{B}$ vs. temperature(T , MeV) for the parameter sets

- (1): $\eta_{10} = 2.8, G/G_0 = 1.0, \xi_e = 0.0$
- (2): $\eta_{10} = 2.8, G/G_0 = 1.0, \xi_e = 0.7$
- (3): $\eta_{10} = 2.8, G/G_0 = 11.0, \xi_e = 0.7$
- (4): $\eta_{10} = 10.0, G/G_0 = 11.0, \xi_e = 0.7$

FIG. 1(a)

FIG. 1(b)

FIG. 2

(a) ${}^9\text{Be}/\text{H}$

(b) ${}^{11}\text{B}/\text{H}$

FIG. 3