Decaying neutrino and a high cosmological baryon density

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**Abstract**

The low second acoustic peak in the recent Boomerang data may indicate a cosmological baryon density which is larger than allowed by standard big bang nucleosynthesis. We show that the decay of the tau-neutrino: \( \nu_\tau \rightarrow \nu_e + \phi \), where \( \nu_e \) is the electron neutrino and \( \phi \) is a scalar, essentially can assure agreement between BBN calculations and light element observations for a large baryon density.

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1 Introduction

The Boomerang experiment recently measured the angular power spectrum of the cosmic microwave background up to \( l = 600 \) \cite{1}. Accordingly to what is expected for a flat Universe, the data show a peak in the power spectrum at \( l = 197 \pm 6 \). At the same time, however, the data seem to indicate that the second acoustic peak is rather low \cite{2}, which may be an indication of a high baryon number \cite{3} (see also \cite{4,5}) (say e.g. \( \Omega_b h^2 \sim 0.03 \), where \( h \) is the Hubble constant in units 100 km s\(^{-1}\) Mpc\(^{-1}\)). This simple conclusion, however, immediately leads to disagreement with the well established Big Bang Nucleosynthesis (BBN), which predicts \( \Omega_b h^2 \approx 0.019 \pm 0.0024 \) \cite{6}. Although this discrepancy is still very preliminary, it is interesting to investigate specific models which can reconcile BBN with a high baryon density.

The problem is the following. In the standard BBN scenario there is only one free parameter, namely the baryon to photon number ratio, \( \eta = n_B/n_\gamma \), which is related to the baryon density according to \( \eta \simeq 2.68 \cdot 10^{-8} \Omega_b h^2 \). Observationally \( \eta_{10} = \eta \cdot 10^{10} \) has long been known to be in the interval \( 1 \lesssim \eta_{10} \lesssim 10 \), and the recent deuterium measurements favor \( \eta_{10} \approx 5 \). When one increases \( \eta_{10} \) the helium abundance increases slightly while the deuterium abundances decreases rapidly:

\[
\eta_{10} \uparrow \quad \text{implies} \quad Y_{\text{He}} \uparrow \quad \text{and} \quad D/H \downarrow \quad \text{(1)}
\]

It is then clear that a high baryon number leads to a too low deuterium prediction and a too high helium-4 value. Now, with a lower deuterium abundance one must seek a method of

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increasing the deuterium, to achieve agreement with observations. This is easily found; one could simply increase the effective number of massless degrees of freedom. For two different values of $\eta$ one can achieve the same deuterium abundance by varying the energy density (expressed through $\Delta N_{\text{eff}} = N_{\text{eff}} - 3$). According to [7], the needed $\Delta N_{\text{eff}}$ is roughly:

\[
\Delta N_{\text{eff}} \approx \frac{1}{0.03} \cdot \log_{10} \left( \frac{\eta_2}{\eta_1} \right)
\]

and we thus see, that if $\eta_{10}$ is 7 (9) instead of 5, then we need additional energy density corresponding to 5 (8.5) extra neutrinos. Increasing the energy density (which effectively corresponds to adding new particles), however, also affects the helium abundance. An increase in $N_{\text{eff}}$ correspond to a variation $\Delta Y_{\text{He}} \approx 0.013\Delta N_{\text{eff}}$ in the helium abundance and the observational data leave room for not more than one extra neutrino. We thus conclude that even if one can make deuterium calculations agree with observations by increasing $N_{\text{eff}}$, then the helium predictions will be in strong disagreement with observations. The goal of this Letter is to point out a specific model, which may solve this apparent problem.

2 A possible solution

As mentioned above, a low second peak in the CMB power spectrum may be explained by a high baryon number. In fig. 1 we present a CMB power spectrum together with the

![Figure 1: A comparison of the Boomerang data with theoretical predictions for 3 flat CDM models with varying $\Omega_b$. We have chosen values $h = 0.68, \Omega_{\text{tot}} = 1, \Omega_\Lambda = 0, Y_{\text{He}} = 0.24$. The various lines correspond to $\eta_{10} = 5$ (dash dotted), $\eta_{10} = 7$ (dashed) and $\eta_{10} = 9$ (solid). There is no scalar tilt, no tensors and we neglect reionization.](image)
Boomerang data with this figure we only want to illustrate that when varying $\Omega_b$ in a flat, CDM Universe ($\Omega_\Lambda = 0$) one gets a better agreement with a low second peak when $\Omega_b$ is high (this is well known, see e.g. refs. \[3, 4\]). In particular we find (for the chosen parameters) that $\eta_{10} = 9$ gives a power spectrum in visually rather fair agreement with the Boomerang data. Such a high baryon number could be in agreement with deuterium observations, if one at the same time allows for a large $N_{\text{eff}}$, however, both effects lead to a larger helium abundance, in disagreement with observations. Since we have used all the free parameters of BBN, we can only lower the helium predictions by introducing new physics.

The helium abundance is determined by the electron neutrinos, $\nu_e$, which govern the freeze-out of the $n - p$ reaction. In the standard BBN calculations it is assumed that the electron neutrinos have a Fermi Dirac thermal distribution. Any changes to the distribution function of the neutrino will alter the predicted abundances. As is well known (see e.g. \[10\]), if one adds neutrinos at the high energy tail of the distribution function, then the final helium abundance will be higher, whereas more low-energy $\nu_e$ will lower $Y_{\text{He}}$. Likewise more thermal $\nu_e$ will lead to a decrease in helium.

More $\nu_e$ could be achieved in several ways. If one has mixing between a massive tau-neutrino, $\nu_\tau$, and a muonic-neutrino, $\nu_\mu$, then the 3-body decay: $\nu_\tau \rightarrow \nu_\mu + \nu_e + \bar{\nu}_e$, would be possible. The lifetime for this decay would go like:

$$\tau_{\nu_\tau \rightarrow 3\nu} \approx \tau_\mu \left( \frac{m_\mu}{m_\nu_\tau} \right)^5 \sin^2 2\theta$$

where $\tau_\mu = 2.2 \cdot 10^{-6}$ sec and $m_\mu = 106$ MeV is the muon decay time and mass, and $\sin^2 2\theta$ is the mixing angle between the two neutrinos. For a big mixing angle and a mass of the tau-neutrino of the order 1 MeV, one gets a lifetime of the order $10^4$ sec, which would have very little influence on BBN. Recently was considered the possibility of adding a chemical potential both for the $\nu_e$ and for the $\nu_\tau$ in such a way, that BBN can have successful predictions even with large $\Omega_b$ \[4, 11\] (see also \[12\]). This is achieved by letting the degeneracy parameter $\xi_\nu_\tau \sim 1$ provide more energy density, and a positive $\xi_\nu_e \ll 1$ to lower the $n - p$ ratio. Also sources of Ly $\alpha$ resonance radiation (e.g. from hot stars or quasars), if present around $z \sim 1000$, could delay recombination and hence lead to a lower second peak \[13\].

Another possibility, which we will consider below, is the decay of a massive tau-neutrino into an electron neutrino and a scalar:

$$\nu_\tau \rightarrow \nu_e + \phi$$

where $\phi$ is light (or massless). This scalar boson could possibly be a Majoron \[14\], and the effect on nucleosynthesis of this decay was calculated accurately in ref. \[15\].

The power spectra were made with the CMBFAST code \[8\].

In refs. \[16, 17\] was considered the effects of both this decay $\nu_\tau \rightarrow \nu_e + \phi$ and also $\nu_\tau \rightarrow 3\nu_e$ on all light elements for a heavy and longliving $\nu_\tau$.\[5\]

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\[3\]

\[4\]

\[5\]
effects of this decay on BBN are the following. First, because the tau-neutrino is massive, it will contribute more to the energy density of the Universe, leading to a slightly increased deuterium abundance. For long lifetimes the mass effect of the $\nu_\tau$ may boost the energy density of the Universe corresponding to up to $\Delta N_{\text{eff}} = 7$ extra neutrinos (see fig. 1a in [15]).

The variation in the helium abundance does not follow directly from the increase in the energy density. This is because for helium the energy distribution of the decay products (the $\nu_e$) play a relevant role. In particular, for a wide range of values for $m$ and $\tau$, the net effect could be a decrease in the helium abundance as seen in fig. 2, and described in ref. [15]. Specifically we find, that by choosing a mass, $m_{\nu_\tau}$, of a few MeV, and a lifetime, $\tau$, of a few seconds, one has both more relativistic energy density than provided with 3 normal neutrinos, and at the same time the helium abundance is lowered substantially. For e.g. $m = 4$ MeV and $\tau = 2$ sec, we see that $Y_{\text{He}}$ is lowered by $\sim 10\%$, which for what concerns helium production correspond to $\Delta N_\nu \approx -1$ [5]. A region in the ($m_{\nu_\tau}$, $\tau_{\nu_\tau}$)-parameter space even provides one with such a low helium abundance that there is freedom to add two sterile neutrinos (see small lifetimes on fig. 2), which can increase the deuterium abundance further, if needed.

The two regions in ($m_{\nu_\tau}$, $\tau_{\nu_\tau}$)-parameter space described above, namely the long lifetime

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5The data used in fig. 2 are taken from the web site [http://tac.dk/~sthansen/decay/](http://tac.dk/~sthansen/decay/).

6Let us for the reference clarify that $\Delta N_{\text{eff}}$ parameterizes the change in energy density, whereas $\Delta N_\nu$ describes the change in primordial helium-4.
region \((\tau > \text{few sec})\) in which deuterium is increased \((\Delta N_{eff} > 0)\), and the \(\Delta N_\nu < 0\) region in which helium is decreased (see fig. 2) only partially overlap. This means that the region where one can both decrease helium and at the same time increase deuterium is fairly small. With an approximate analysis, where we optimize \(\Delta N_{eff} - \Delta N_\nu\) in the overlap region and use eq. 2, it seems only possible to allow for \(\eta_{10}\) smaller than 7. It is interesting to note, that in this overlap region the decaying neutrino also leads to a decrease in the amount of lithium, which will be needed to conform with lithium observations.

Let us mention that late decaying \(\nu_\tau\) with \(m > 3.6\) MeV may also produce high energy \(\nu_e\), which further can increase the deuterium abundance through the reaction: \(\nu_e + p \rightarrow n + e^+\). This effect become more efficient for high \(\eta\).

Finally, it is worth mentioning that the Boomerang data together with BBN deuterium arguments can give a fairly interesting upper limit on \(\eta\). It was found in ref. [19] from the Boomerang data that even when allowing \(\Omega_b\) to vary within a large region one gets a 2\(\sigma\) bound on the relativistic energy density, \(N_{eff} < 13\). Now, using eq. (2) one can translate this into a bound on \(\eta\), namely \(\eta_{10} < 12.5\). This translation is not quite safe for two reasons. First, in [19] \(\Omega_b h^2\) was only allowed to vary up to 0.03 (\(\eta_{10} = 9\)) which is smaller than the bound just found and hence the extrapolation to \(\eta_{10} < 12.5\) is strictly speaking not justified and second, the formula in eq. (2) is approximate. It could be interesting to do a careful analysis.

3 Conclusion

We have shown, how a specific model with a decaying massive tau-neutrino can make BBN calculations for the light element abundances agree with the observations in a Universe with as high baryon number as \(\eta_{10} = 7\). Such a high baryon number may be needed to explain a lower second peak in the CMB power spectrum as seen in the recent Boomerang data.

The scenario with a high \(\Omega_b\) naturally predicts a high 3\textsuperscript{rd} peak, and can hence easily be excluded by future CMB observations. On the other hand, should the future CMB experiments find a high 3\textsuperscript{rd} peak, then one must distinguish between the various models. One can distinguish a high \(\Omega_b\) scenario from the delayed recombination picture suggested in ref. [13], since high \(\Omega_b\) will lower the diffusion damping, and hence the 3\textsuperscript{rd} peak should be higher in this case than in the models proposed in [13]. Distinguishing between a decaying neutrino and a chemical potential [9] is more difficult, and one would probably need refined observations of other light elements like helium-3 and lithium.

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