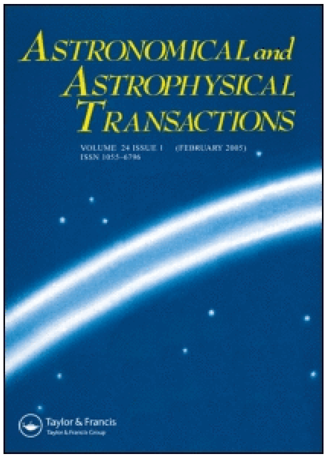


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# BARYON DENSITY IN ALTERNATIVE BIG BANG NUCLEOSYNTHESIS MODELS

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We present recent determinations of the cosmological baryon density $\rho_b$, extracted from different kinds of observational data. The baryon density range is not very wide and is usually interpreted as an indication for consistency. All other determinations give higher $\rho_b$ values than the standard big bang nucleosynthesis (BBN) model. The differences in the $\rho_b$ values from the BBN predicted value (the most precise today) may be due to the statistical and systematic errors in observations. However, they may be an indication of new physics. Hence, it is interesting to study alternative BBN models, and the possibility of resolving these discrepancies. We discuss alternative cosmological scenarios: a BBN model with decaying particles (m of the order of megaelectronvolts; $\tau$ of the order of seconds) and a BBN with electron-sterile neutrino oscillations, which permit us to relax BBN constraints on the baryon content of the Universe.

Keywords: Cosmology; Baryon density; Big bang nucleosynthesis

## 1 INTRODUCTION

Usually, the small range of values for the baryon density, from different kinds of observation, is interpreted as an indication for consistency. However, the differences may be a signature of new physics. As standard big bang nucleosynthesis (SBBN) provides the most stringent constraints on the baryon density, we consider it appropriate to discuss its modifications and to obtain the baryon density range in alternative big bang nucleosynthesis (ABBN) models.

We discuss two ABBN models, namely big bang nucleosynthesis (BBN) with decaying particles and BBN with electron-sterile $\nu_e \leftrightarrow \nu_s$ neutrino oscillations. We present the results of the numerical analysis for $^4$He production in these ABBN models. The first model leads to overproduction or underproduction of $^4$He, depending on the model's parameters, while the second always leads to $^4$He overproduction. We reanalyze the constraints on the baryon density, following from $^4$He, and show that ABBN may permit a wider range for the baryon density; the lower bound of it is determined by BBN with oscillations, while the upper bound is estimated from the BBN model with decaying particles.

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## 2 BARYON DENSITY FROM DIFFERENT OBSERVATIONS

SBBN provides one of the most precision determinations of the baryon density, corresponding to the epoch when the Universe was a few minutes old. This probe of the baryon density is based on the observational data of four light elements: D, $^3$He, $^4$He and $^7$Li. The required agreement between the predicted and extracted from observations primordial abundances of the elements measures the baryon content of the Universe. The broad agreement range is (Fields and Sarkar, 2000) $0.0095 \leqslant \Omega_b h^2 \leqslant 0.023$, where $\Omega_b = \rho_b/\rho_{crit}$ and h is the Hubble parameter in units of 100 kilometre per second per megaparsec.

Primordial deuterium (D) measurements towards low-metallicity quasar absorption systems (Lyman limit systems (LLSs)) at very high $z \approx 3$ provide the precision determination (Burles et al., 2001): $\Omega_b h^2 = 0.0189 \pm 0.0019$. Light elements are consistent with this value except for $^7$Li, which needs a depletion factor greater than 2. [D]/[H] measurements in metal-poor damped Lyman $\alpha$ (DLA) systems (Odorico et al., 2001) give lower values than LLSs (Pettini and Bowen, 2001): $\Omega_b h^2 = 0.025 \pm 0.001$. These imply that $Y_p = 0.249$ and $^7$Li abundance $[LI]/[H] = 6.0 \times 10^{-10}$, which are larger than observed for He in extragalactic regions (Izotov arid Thuan, 1998) and Li in old halo stars (Bonifacio and Molaro, 1997), deepening the Li problem (Ryan et al., 2000; Burles et al., 2001). $^7$Li and D likelihood analysis provides $\Omega_b h^2 = 0.015 \pm 0.003 (2\sigma)$ (Coc et al., 2002).

We do not know why the D measurements in LLSs differ from those of DLA systems and which is the reliable D value. How can we explain the difference between the high $^4$He and especially $^7$Li values, predicted from the baryon density obtained from D measurements (the most precise known measurements), and the extracted from observations He and Li values?

An alternative determination of the baryon density, corresponding to the several hundred thousands years old Universe, was provided from measurements of the anisotropy of the cosmic microwave background (CMB) by BOOMERANG (Bernardis et al., 2002; Netterfield et al., 2002). MAXIMA (Stompor et al., 2002) and DASI (Pryke et al., 2002) experiments: $\Omega_b h^2 = 0.022 \pm 0.003$, which is slightly larger than the BBN value and light-elements determinations. However, is the consistency between BBN- and CMB-predicted values of the baryon density really so perfect?

The highly ionized intergalactic medium contains a substantial fraction of the baryons in the Universe at redshifts $z \approx 3$. Observations of the mean decrement and power spectrum of Lyman $\alpha$ forest (Rauch et al., 1997; Hu et al., 2001) indicate that $\Omega_b h^2 = 0.045 \pm 0.008$, assuming the estimate of the ionizing background, as found by recent measurements of a large escape fraction of ionizing photons from Lyman-break galaxies (Steidel et al., 2001).

Keeping in mind the possibility that all these determinations of the baryon density may not be mature enough and not so reliable as the BBN-predicted value, it is interesting to note that they all indicate a higher baryon density than the BBN value. So, it is worth studying the possibility of non-standard physics during BBN.

## 3 $^4$HE IN ALTERNATIVE BIG BANG NUCLEOSYNTHESIS MODELS

In SBBN the primordial production of the four light elements is calculated with great precision, assuming three neutrino flavours, zero lepton asymmetry and equilibrium neutrino number densities and energy distribution. The abundances of these elements are functions of only one parameter, namely the baryon-to-photon ratio $\eta = n_b/n_\gamma$. In ABBN models the allowed range of the baryon density is changed. Extensive reviews on ABBN have been given by Malaney and Mathews (1993) and Sarkar (1996). We discuss ABBN leading to higher baryon density values, as well as leading to lower than the BBN value. We present here the results of the first stage of our numerical analysis of these BBN models, dedicated to a detailed determination of $^4$He.

### 3.1 Big Bang Nucleosynthesis with Decaying Particles

ABBN with decaying particles has been studied and reported in the literature (Dolgov and Kirilova, 1988; Terasawa and Sato, 1988; Dolgov et al., 1997; 1999). The most interesting case is when the decay products include electron neutrinos. Then decays influence BBN, firstly, by changing the energy density and, secondly, by increasing the weak rates governing n–p transitions owing to the daughter products. We discuss a modification of the standard BBN with light ($m_x = 0$(MeV)) quasistable particles ($\tau_x \approx 1$ s), decaying into $\nu\bar{\nu}$. In the case when the decay products do not thermalize, they shift the proton–neutron freezing ratio and the abundance of the primordially produced light elements respectively (Dolgov and Kirilova, 1988). The direction of the shift depends on the concrete parameters of the model, $m_x$, $\tau_x$ and $T_F^x$, where $T_F^x$ is the freezing temperature of the decaying particles. In the case of He underproduction, the model with decaying particles allows us to extend the $\Omega_b h^2$ range to higher values up to $\Omega_b h^2 \leqslant 0.089$ (corresponding to 5% underproduction of He). So, ABBN with decaying light particles can reconcile BBN with a high baryon density.[1]

### 3.2 Big Bang Nucleosynthesis with Neutrino Oscillations

The effect of the flavour neutrino oscillations on BBN is negligible; therefore, we studied the case of active-sterile neutrino oscillations $\nu_e \leftrightarrow \nu_s$. We were especially interested in oscillations effective after the electron neutrino decoupling from the plasma (i.e. $\delta m^2 \leqslant 10^{-7}\,eV^2$).

Neutrino oscillations affect the BBN by bringing additional degrees of freedom into equilibrium, depleting the neutrino number densities $N_\nu$, distorting the neutrino spectrum and producing neutrino–antineutrino asymmetry (Kirilova and Chizhov, 2001a,b). Oscillations lead to a higher freezing temperature by weakening the weak interaction rates owing to neutrino spectrum distortion and depletion and hence to considerable He overproduction (Kirilova, 2001) of up to 32%.

The primordial He is a function of the oscillation parameters and of the baryon density. Consistency with the combined analyses of the oscillations data may be used to constrain oscillation parameters and to indicate the maximal allowed overproduction of $^4$He. Then the observational data on primordial $^4$He constrains the baryon density range. To constrain the oscillation parameters we chose $\delta Y_p/Y_p = 5\%$ $^4$He overproduction. Then the allowed baryon density in the discussed nucleosynthesis model with neutrino oscillations is $\Omega_b h^2 \geqslant 0.003$. The limit can be strengthened if D and $^7$Li data are taken into account.

Because of the higher freezing temperature, the D yield will increase owing to the shorter time of its destruction. So, the observed $^4$He abundance in the case of oscillations requires a lower baryon density than in SBBN, while D measurements will be higher than the standard value.

## 4 CONCLUSION

In conclusion, in ABBN, relaxed cosmological constraints on the baryon content of the Universe based on $^4$He are $0.003 \leqslant \Omega_b h^2 \leqslant 0.089$. ABBN can probably resolve some of

[1] A similar model was considered (Hansen and Villante, 2000), which aimed to reconcile high baryonic indications of the early CMB anisotropy measurements with the BBN value. Their model allows agreement between BBN calculations of D and He with baryon density up to $\eta = 7$.

the discrepancies between standard BBN predictions and other data and reduce the tension between them in the case it persists.

Relaxed constraints on the baryon density may also be useful for chemical evolution models, for constraining new physics, etc.

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