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A REEXAMINATION OF THE COSMOLOGICAL BOUND TO THE NUMBER OF NEUTRINO FLAVORS

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ABSTRACT

The predictions of the light element abundances produced primordially in the standard hot big bang cosmological model with three species of light neutrinos ($N_\nu = 3$) is consistent with current observational data. If additional species of light neutrinos exist, additional ^{4}He is produced primordially; consistency with observations of ^{4}He leads to an upper bound to N_ν which depends on the neutron half-life ($\tau_{1/2}$), the nucleon - to - photon ratio (or, equivalently, the primordial abundances of deuterium and helium-3) and the primordial mass fraction of ^{4}He (Y_p). We reexamine the bounds to these quantities and reconfirm that $N_\nu \lesssim 4.0$.

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INTRODUCTION

The upper bound to the number of neutrino flavors imposed by primordial nucleosynthesis[1)] is one of the most impressive of the connections between particle physics and astrophysics revealed in recent years. This bound exists because the amount of ^{4}He produced primordially increases with the addition of new species of particles which are relativistic during nucleosynthesis; too many light neutrinos leads to the production of too much helium-4. Observations, then, of ^{4}He can be used to place an upper bound on N_ν, the effective number of light neutrino species[2)],

$$N_\nu = \Sigma_F'(g_F/2)(T_F/T_\nu)^4 + 8/7\ \Sigma_B'(g_B/2)(T_B/T_\nu)^4. \quad (1)$$

In equation (1), F(B) are the fermion (boson) species which are relativistic at nucleosynthesis, T_F (T_B) are their temperatures, $g_F(g_B)$ are the number of helicity states and T_ν is the temperature of the "usual" (i.e.: e-, μ-, τ-) neutrinos ($g_\nu = 2$); the primes indicate that electrons and photons are excluded from the sums. For the usual neutrinos $N_\nu = \Sigma_F'(g_F/2) = 3$. Comparisons between the predictions of big bang nucleosynthesis and the derived abundances of the light elements (D, ^{3}He, ^{4}He, ^{7}Li) lead to the conclusion[2)] that the "standard" case $N_\nu = 3$ is consistent with all extant data; the data (barely) allows[2)] $N_\nu = 4$ (i.e.: $N_\nu \lesssim 4$).

This prediction[1,2)] of the "standard" hot big bang cosmology is close to being tested critically in accelerator experiments[3)]. Recent UA1 and UA2 $\bar{p}p$

collider data[3] suggest that the number of light neutrinos coupled to the Z^0 is limited to $N_\nu < 5.4 \pm 1.0$. For the connection between the laboratory and cosmological bounds, see reference 4. At the same time, there are phenomenological models based on E_6, motivated by the superstring which predict the existence of additional (right-handed) neutrinos which may be light[5]. These models are insensitive to the laboratory bounds (since the ν_R couple only through a new neutral gauge boson) but, they are severely constrained by the cosmological bound ($N_\nu \lesssim 4$). The viability of such models[5] relies crucially on the possibility of evading the cosmological bound (EENS, reference 5). With these important issues as motivation, we present here a critical reexamination of the cosmological bound to N_ν.

THE COSMOLOGICAL BOUND TO N_ν

The abundance of helium-4 produced primordially depends[2] on N_ν, on the nucleon-to-photon ratio η (at present, $n_N/n_\gamma = \eta$; $\eta_{10} \equiv 10^{10}\eta$) and, on the neutron half-life $\tau_{1/2}$ (in the following, $\tau_{1/2}$ is in minutes). The primordial mass fraction of ^{4}He predicted by numerical evolution of the "standard" hot big bang model[2] are well fit by[6]

$$Y_P = 0.230 + 0.011 \ln \eta_{10} + 0.013(N_\nu - 3) + 0.014\,(\tau_{1/2} - 10.6)\,. \qquad (2)$$

YTSSO[2] have adopted $10.4 \lesssim \tau_{1/2}(\text{min.}) \lesssim 10.8$ and conclude from a comparison of prediction and observations of the abundances of D, ^{3}He and ^{7}Li that it is likely that $4 \lesssim \eta_{10} \lesssim 7$ although a somewhat larger range

($3 \lesssim \eta_{10} \lesssim 10$) is still consistent with the data. As a result, for the "standard" case $N_\nu = 3$, the mass fraction of primordial ^{4}He is predicted to lie in the range: (0.239) $0.242 \lesssim Y_P \lesssim 0.254$ (0.258), in excellent agreement with the range allowed by the observational data (YTSSO). For $N_\nu = 4$, the lower bound to Y_P, corresponding to $\eta_{10} \gtrsim 3$ and $\tau_{1/2} \gtrsim 10.4$ minutes, $Y_P \gtrsim 0.252$ (the more precise numerical result is $Y_P \gtrsim 0.253$; YTSSO), requires that Y_P is at the upper end of its allowed range (YTSSO).

It is difficult to determine η directly from observational data since it is not known how much of the "dark" matter in the Universe is nucleonic. Therefore, it is preferrable to eliminate the η dependence from equation (2). Since the predicted primordial abundances of deuterium and helium-3 depend sensitively on η (and on N_ν), η may be replaced by the corresponding dependence of Y_P on $y_{23P} \equiv [(D + {}^3He)/H]_P$, the primordial abundance (by number relative to hydrogen) of deuterium plus helium-3.[6)]

$$Y_P = 0.243 + 0.014[(N_\nu - 3) + (\tau_{1/2} - 10.6)] - 0.018 \log (10^4 y_{23P}). \qquad (3)$$

Y_P and y_{23P} are, in principle, derivable from observational data and, along with a knowledge of $\tau_{1/2}$, such data can be used to predict N_ν.

$$N_\nu = 3 + (10.6 - \tau_{1/2}) + (Y_P - 0.243)/0.014 + 9/7 \log(10^4 y_{23P}). \qquad (4)$$

In practice, however, there are - inevitably - uncertainties in the values of Y_P, y_{23P} and $\tau_{1/2}$ derived from observational and experimental data. Below, we review the current status of the relevant data and derive the allowed range of N_ν, concentrating on the upper bound to N_ν.

THE NEUTRON HALF-LIFE

In their reviews of the data, YTSSO and, more recently, Boesgaard and Steigman[6)] conclude that $\tau_{1/2}$ lies in the range 10.4 - 10.8 minutes. In a survey of nuclear reactions, Filipone[7)] suggests $\tau_{1/2}$ = 10.4 ± 0.2 min. The direct measurements[8)] of the neutron half-life range from $\tau_{1/2}$ = 10.13 ± 0.09 (Bondarenko et al.), to $\tau_{1/2}$ = 10.61 ± 0.16 (Christensen et al.), to $\tau_{1/2}$ = 10.82 ± 0.20 (Byrne et al.). Since the result with the highest claimed accuracy is the most discrepant, it seems safest to take a straight (rather than weighted) average,

$$\tau_{1/2}\,(\text{direct}) = 10.52 \pm 0.09 \text{ min.} \tag{5}$$

Another approach to determining the neutron half-life is to measure the ratio $\lambda = |G_A/G_V|$ in neutron decay[9]. Using the more recent result of Bopp et al[9)] ($\tau_{1/2}$ = 10.37 ± 0.07 min.), we derive for an unweighted average,

$$\tau_{1/2}\,(\text{indirect}) = 10.49 \pm 0.07 \text{ min.} \tag{6}$$

A weighted average of the indirect data yields $\tau_{1/2} = 10.44 \pm 0.05$ minutes. If we combine the direct and indirect determinations, we find

$$\tau_{1/2} \text{ (all data)} = 10.51 \pm 0.06 \text{ min.} \tag{7}$$

Had we taken a weighted average of all the data, the high weight of the results of Bondarenko et al[8] leads to a smaller neutron half-life: $\tau_{1/2} = 10.40 \pm 0.04$ minutes.

Until more accurate data is available, it is reasonable to adopt: $10.4 \leq \tau_{1/2} \text{ (min.)} \leq 10.6$. With $\tau_{1/2} \gtrsim 10.4$ minutes, equation (4) becomes

$$N_\nu \, (\tau_{1/2} \gtrsim 10.4) \lesssim 3 + (Y_P - 0.240)/0.014 + 9/7 \log(10^4 y_{23P}). \tag{4'}$$

Note that if we had chosen a lower bound to $\tau_{1/2}$ of 10.3 rather than 10.4 minutes, the change in (4') would have been to increase 3 to 3.1.

THE PRIMORDIAL HELIUM ABUNDANCE

From an extensive review of the literature, YTSSO concluded that there were no contradictions with the primordial helium abundance lying in the range: $0.23 - 0.24 \lesssim Y_P \lesssim 0.25 - 0.26$. Although YTSSO noted that Kunth's[10] data on ^{4}He in blue compact galaxies suggested $Y_p < 0.254$, they cautioned against taking the third significant figure too seriously. After a similar exhaustive review, Boesgaard and Steigman[6] decided that all high quality data are consistent with $Y_P = 0.24 \pm 0.02$. They[6] noted that systematic - not statistical - uncertainties dominate the determination of Y_p. Following the lead of Pagel[11] and Steigman[12], Boesgaard and Steigman[6] used the data of Kunth and Sargent[13] to derive: $Y_p = 0.239 \pm 0.015$; this is consistent with the earlier estimate of YTSSO that $Y_p \lesssim 0.254$.

Recent work has suggested somewhat lower values for Y_p. In an extremely detailed study of the metal-poor object I ZW 18, Davidson and Kinman[14] derive $Y(IZW18) \simeq 0.21 - 0.24$ but, they caution that the uncertainties in deriving Y_p from observations of a single object are large ($\gtrsim 0.01$). Pagel[15] studies the helium versus oxygen correlation in highly ionized, low metal abundance (to minimize the corrections for unobserved neutral helium and for stellar produced helium) HII regions. Pagel[15] derives $Y_p = 0.235 \pm 0.004$. We have no quarrel with the central value of Y_p found by Pagel[15] however, we do believe the estimate of the uncertainty is unrealistically small. In a recent attempt to better extrapolate to the primordial abundance of ^4He, Steigman, Gallagher and Schramm[16] have studied the correlation between helium and carbon. They[16] derive $Y_p = 0.235$ in agreement with Pagel[15].

In sum, the best current data suggests $Y_p \simeq 0.24$ with an uncertainty (ΔY_p) which may be as small as ± 0.01 but which could be as large as ± 0.02. This conclusion is in complete accord with that of YTSSO. We emphasize that since systematic effects most likely dominate the uncertainties, the above estimates of ΔY_p are not to be regarded as a standard deviation. Rather, we simply conclude that - at present - the data is consistent with (0.22) $0.23 \lesssim Y_p \lesssim 0.25(0.26)$. Although we favor the narrower range (0.23 - 0.25), the more conservative range (0.22 - 0.26) cannot be entirely excluded. Although we emphasize that third decimal place accuracy is likely illusory, for an upper bound to N_ν, we will assume that $Y_P \lesssim 0.254$.

$$N_\nu(\tau_{1/2} \geq 10.4,\ Y_P \lesssim 0.254) \lesssim 4 + 9/7\ \log(10^4 y_{23P}). \qquad (4'')$$

PRIMORDIAL DEUTERIUM AND HELIUM - 3

In a low density Universe less helium-4 but considerably more deuterium and somewhat more helium-3 are synthesized[2)]. Observations of interstellar and solar system deuterium (for a summary and references see ref. 6) provide a lower bound to the primordial abundance: $y_{2P} = (D/H)_P \gtrsim 1\text{-}2\times10^{-5}$. Detailed models of chemical evolution are required to estimate how much of the primordial deuterium may have been destroyed in the course of galactic evolution. Most models[17)] suggest destruction by no more than a factor of 2-3. If, indeed, $y_{2P} \lesssim 3y_{2obs} \lesssim 6\times10^{-5}$, then[2)] $y_{3P} \lesssim 1.5\times10^{-5}$ and $y_{23P} \lesssim 7.5\times10^{-5}$. With this value in equation(4") we derive an upper bound of $N_\nu \lesssim 3.8$.

Some models of chemical evolution[18)], however, suggest the possibility that much more primordial deuterium may have been destroyed. The analysis of the survival of helium-3 (YTSSO and reference 19) provides a valuable constraint on such extreme models. The point is that when deuterium enters a star it is burned to helium-3 but, in the course of stellar evolution, not all the helium-3 is destroyed. Therefore, in addition to the "normal" production of ^{3}He synthesized by incomplete H-burning in low mass stars[20], the present (or, presolar) abundance of ^{3}He will have received a contribution from that ^{3}He which came from prestellar D and which survived stellar burning. As YTSSO have shown, the present (or, presolar) abundances of D and ^{3}He provide a constraint on the sum of the primordial abundances,

$$y_{23P} < y_2 + g_3^{-1} y_3, \tag{8}$$

where g_3 is the fraction of ^{3}He surviving stellar evolution. YTSSO estimated that $g_3 \gtrsim 1/4 - 1/2$ and, using solar system abundances, derived the constraint: $y_{23P} \lesssim 6.2\text{-}10 \times 10^{-5}$. Support for this bound is provided by the more detailed analysis of Dearborn, Schramm and Steigman[19] who found that if attention is restricted to relatively massive stars ($M > 8M_\odot$) - which are hotter and, therefore, destroy more ^{3}He - $g_3 \gtrsim 0.22$. For $M \gtrsim 3M_\odot$, g_3 increases to $\gtrsim 0.4$. With the constraint that $10^4 y_{23P} \lesssim 0.6 - 1.0$, the upper bound to the number of species of light neutrinos (or, their equivalent) becomes

$$N_\nu \lesssim 3.7 - 4.0. \tag{4'''}$$

DISCUSSION

In our reexamination of the relevant laboratory and observational data we have reaffirmed the conclusion[2] that, at most, one extra species of light neutrino (or, its equivalent) is permitted by considerations of primordial nucleosynthesis: $N_\nu \lesssim 4$. In achieving this bound we have adopted $\tau_{1/2} \gtrsim$ 10.4 min., $Y_P \lesssim 0.254$ and, $10^4 y_{23P} \lesssim 1$. In stark contrast to our conclusion, EENS claim that N_ν as large as 5.5 or even 6 is permitted by the data. Here, we trace the sources of this contradiction.

Instead of considering all the laboratory data[8,9], EENS derive a lower limit of $\tau_{1/2} > 10.2$ min. from the results of Bopp et al[9] ($\tau_{1/2} = 10.37 \pm 0.07$ min.) and Bondarenko et al[8] ($\tau_{1/2} = 10.13 \pm 0.09$ min.) alone, despite the fact that these two results differ by ~ 3 σ. If we had chosen $\tau_{1/2} \gtrsim 10.2$ min. (instead of $\tau_{1/2} \gtrsim 10.4$ min.), our bound would have increased (from $N_\nu \lesssim 4.0$) to $N_\nu < 4.2$.

For an upper bound to the primordial abundance of ^{4}He, EENS adopt $Y_P <$ 0.26. In our discussion we have chosen $Y_P \lesssim 0.254$ but have emphasized the danger of trusting the third significant figure. Although we believe that current data strongly suggests $Y_P \lesssim 0.25$, we agree that Y_P as large as 0.26 can probably not be entirely excluded at present. If we had chosen $Y_P \lesssim 0.260$ (and $\tau_{1/2} > 10.2$ min.) our bound would have increased to $N_\nu \lesssim 4.6$.

It is quite clear that the major discrepancy between our result and that of EENS is directly traceable to their choice of a very large value for y_{23P}: $y_{23P} < 50 \times 10^{-5}$ (to be compared to our bound of $y_{23P} <$ 6-10x10^{-5}). There are several serious problems and inconsistencies with the EENS choice of such a large value of y_{23P}. In adopting $y_{23P} < 5\text{x}10^{-4}$, EENS rely on the observation[21] of ^{3}He in the galactic HII region W3 (however, Rood et al[21] actually quote $y_3(\text{W3}) = 4\text{x}10^{-4}$). Recent reobservations of W3 and other sources[21] have led to a drastic revision of this result: $y_3(W3) \simeq 6\times10^{-5}$. Support, therefore, for the large value of y_{23P} chosen by EENS has, thus, evaporated. In any case, the EENS interpretation of the data[21] was internally inconsistent for the following reason. Large amounts of ^3He are not produced primordially for reasonable choices of parameters (for $\eta_{10} \gtrsim 1$, $y_{3P} \lesssim 4\times10^{-5}$). If, therefore, large abundances of ^3He were observed they must reflect stellar production[22] or, the burning of primordial deuterium. If stellar production dominates, the observations can not be used to derive the primordial abundance of ^3He. If destruction of primordial D were responsible for a large observed abundance of ^3He, the abundance of ^3He should also be very large elsewhere, but it is not. For example, the presolar abundance of ^3He is[6] $y_{3\odot} \simeq 1.4 \pm 0.4 \times 10^{-5}$ and, for the 14 HII regions (including W3) observed by Bania et al[21], $y_3 \lesssim 6\times10^{-5}$. To reconcile the EENS interpretation with <u>all</u> the observational data would force one to a very contrived two-step scenario in which first deuterium is burned to helium-3 and next, the ^3He is (almost) everywhere destroyed. Alternately, it might be assumed that where the observed abundance of ^3He is small, the reason is that the deuterium hasn't been burned to ^3He. In that case, most of the primordial D should have survived and the present abundance - in regions with a low abundance of ^3He - should be close to the primordial abundance. But, the presolar and interstellar abundances of deuterium[6] are also small, considerably smaller than the bound to y_{23P} adopted by EENS. In sum, where the primordial abundance of deuterium is very large, the presently observed abundances of deuterium and/or helium-3 should also be large, which is not the case. Should future observations reveal an object with a large abundance of ^{3}He, consistency with all the other data would point to stellar production[22]. Not only is the observational support for the large upper bound to y_{23P} favored by EENS now lacking, such a large primordial abundance inferred from a single object is untenable in light of all the other ^{3}He (and D) observations.

With our adopted upper bound of $y_{23P} < 1\times10^{-4}$, the limit to N_ν (for $\tau_{1/2} \gtrsim 10.4$ min., $Y_p \lesssim 0.254$) is (see eq. 4''') $N_\nu \lesssim 4.0$. If, following EENS, we were to use $\tau_{1/2} > 10.2$ min. and $Y_p \lesssim 0.260$ we would find $N_\nu \lesssim 4.6$.

The above bounds on N_ν constrain models[5] based on the superstring which predict the existence of additional light neutrinos. For example, three families of light, right-handed neutrinos[5] would increase N_ν by,

$$\Delta N_\nu = 3(T_\nu'/T_\nu)^4. \tag{9}$$

For $\Delta N_\nu \lesssim 1.0(1.6)$, $T_\nu'/T_\nu \lesssim 0.76(0.85)$ so that the "new" neutrinos (ν') must have decoupled earlier than the "usual" neutrinos (ν). The entropy transferred to the $e^\pm$ and γ subsequent to ν' decoupling is reflected in the ratio of the number of photons in a comoving volume at present ($N_{\gamma 0}$) to that at decoupling ($N_{\gamma d'}$)[23].

$$N_{\gamma 0}/N_{\gamma d}' = 11/4(T_\nu/T_\nu')^3 = 11/4(3/\Delta N\nu)^{3/4} \tag{10}$$

For $\Delta N_\nu \lesssim 1.0(1.6)$, $N_{\gamma o}/N_{\gamma d}{}' \gtrsim 6.3(4.4)$; from OSS[23] it follows that, $T_d{}' \gtrsim 150(100)$MeV.

If T_d is the temperature at which the usual (left-handed) neutrinos decouple and σ (σ') the ν (ν') cross section, then $T_d{}'$ and T_d are related by [23]

$$T_{d'}/T_d \simeq (g_{d'}/43/4)^{1/6}(\sigma/\sigma')^{1/3} \; , \tag{11}$$

Where $g_{d'}$ is the effective number of relativistic degrees of freedom at decoupling (i.e.: $\rho_{TOT}(T_d{}') = (g_d{}'/2)\; \rho_\gamma\; (T_d{}')$); for ν, g_d = 43/4). For the usual neutrinos, neutral current weak interactions lead to decoupling at[24] $T_d \simeq 3.5$ MeV. Thus, for $\Delta N_\nu \lesssim 1.0(1.6)$, $\sigma'/\sigma \lesssim 2.1\times10^{-5}$ (6.2×10^{-5}).

For the model of EENS, $\sigma'/\sigma = \alpha'/\alpha$ where $\sigma = \alpha T^2$. For $T_d \simeq 3.5$ MeV,$\alpha \approx 5.7\times10^{-11}$ GeV^{-4} so that our bounds $\Delta N_\nu \lesssim 1.0(1.6)$ correspond to $\alpha' \lesssim 1.2\times10^{-15}(3.5\times10^{-15})$ GeV^{-4}. In the EENS model the extra light neutrinos couple only through a new gauge boson Z'. Our limits on α' translate (see EENS) into lower bounds to the Z' mass: $M_Z{}' \gtrsim 500(400)$ GeV and to the ratio of Higgs vevs: $x/v \gtrsim 7(6)$.

SUMMARY

We have reexamined the cosmological bound to the number of equivalent species of light neutrinos provided by primordial nucleosynthesis. For the "standard" hot big bang model with $N_\nu = 3$, the observed abundances are best fit[6] by a nucleon-to-photon ratio in the range: $4 \lesssim \eta_{10} \lesssim 7$. In concert with our estimate from laboratory data[8,9] that the neutron half-life is in the range: $10.4 \lesssim \tau_{1/2} \lesssim 10.6$ minutes, the standard model predicts a primordial mass fraction of ^{4}He in the range: $0.239 \lesssim Y_P \lesssim 0.251$. The standard model predictions are, thus, consistent with the observed abundances[6].

Additional species of light neutrinos lead to additional production of primordial ^{4}He. N_ν is bounded from above if the predictions of big bang nucleosynthesis are to be consistent with the observed abundances of the light elements. For $\tau_{1/2} \gtrsim 10.4$ minutes, $Y_P \lesssim 0.254$ and $y_{23P} \lesssim 1\times10^{-4}$ we find: $N_\nu \lesssim 4.0$; at most, only <u>one</u> additional species of light (equivalent) neutrino is permitted. If, following EENS, we were to choose $\tau_{1/2} \gtrsim 10.2$ minutes and $Y_P \lesssim 0.260$, our bound would increase to $N_\nu \lesssim 4.6$. Each of these bounds is considerably more stringent than the estimate by EENS of $N_\nu \lesssim 5.5$-6. We have traced their excessively weak upper bound to the inconsistent value of y_{23P} adopted by EENS. Current laboratory and observational data, then, lead to the bound $N_\nu \lesssim 4.0$ This bound severely constrains models with additional species of light neutrinos.

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