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Big bang nucleosynthesis with a new neutron lifetime

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We show that the predicted primordial helium production is significantly reduced when new measurements of the neutron lifetime and the implied enhancement in the weak reaction rates are included in big-bang nucleosynthesis. Therefore, even if a narrow uncertainty in the observed helium abundance is adopted, this brings the constraint on the baryon-to-photon ratio from BBN and the observed helium into better accord with the independent determination of the baryon content deduced from the WMAP spectrum of power fluctuations in the cosmic microwave background and measurements of primordial deuterium in narrowline quasar absorption systems at high redshift.

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I. INTRODUCTION

Big-bang nucleosynthesis (BBN) plays a crucial role in constraining cosmological models. It is essentially the only probe of physics in the early universe during the interval from $\sim 1 - 10^4$ sec in the radiation dominated epoch. As such, it is important to have accurate predictions of the light element abundances produced in this era.

The single unknown parameter for standard BBN is the baryon-to-photon ratio during the nucleosynthesis epoch. All light abundances are a simple function of this parameter. In this regard, it has been noted for some time [1–7] that the nucleosynthesis yields from the big bang are particularly sensitive to the neutron lifetime which affects BBN in two ways. For one, changing the neutron lifetime τ_n implies different weak reaction rates through the relation between the neutron lifetime and the weak coupling constant

$$\tau_n^{-1} = \frac{G_F^2}{2\pi^3}(1 + 3g_A^2)m_e^5\lambda_0, \tag{1}$$

where G_F is the Fermi coupling constant and g_A is the axial-vector coupling of the nucleon. The quantity m_e is the electron mass and λ_0 is the phase-space integral for neutron decay. To a good approximation, weak reactions cease once the weak reaction rate

$$\Gamma = (7/60)\pi(1 + 3g_A^2)G_F^2T^5, \tag{2}$$

becomes smaller than the Hubble expansion rate

$$H \approx [(8/3)\pi G\rho_\gamma]^{1/2}, \tag{3}$$

where $\rho_\gamma = (\pi^2/30)g_*T^4$ is the energy density in relativistic particles, and g_* the total number of effectively massless degrees of freedom at the relevant epoch.

Equating these two rates gives the freeze-out temperature, $T_f \approx 1$ MeV. Once weak reactions freeze out the ratio of the number of neutrons/protons remains fixed at the freeze-out value except for neutron decay. However, changing the neutron half life resets the temperature T_f at which weak reactions freeze out.

For example, a shorter lifetime for neutron decay means that the reaction rates remain greater than the Hubble expansion rate until a lower freeze-out temperature. This shifts the equilibrium neutron-to-proton ratio at freeze-out. To a good approximation this n/p ratio is just given by thermal equilibrium to be $n/p = \exp\{-\Delta m/T_f\}$, where Δm is the mass difference between the neutron and the proton. Since most of the neutrons remaining until the nucleosynthesis epoch at $t \sim 200$ sec are converted to ^{4}He, there is a simple approximate relation between the n/p ratio at freeze-out and the helium mass fraction from BBN

$$Y_p \approx 2n/(n + p) = 2(n/p)/(n/p + 1), \tag{4}$$

where n and p refer to the number densities of neutrons and protons, respectively. The other dependence of Y_p on the neutron lifetime simply comes from the fact that some neutrons can decay in the interval between weak freeze-out ($t \sim 1$ sec) and nucleosynthesis ($t \sim 200$ sec). Taken together, both of these effects imply that the shorter the neutron lifetime, the lower the predicted BBN helium abundance.

Regarding the neutron lifetime, it is of particular interest that a new and very accurate measurement of the neutron lifetime has recently been reported [8] using ultracold neutrons in a gravitational trap. There are several distinguishing features of this measurement. Among the most important are (1) that it involves the best-measured storage time (872 ± 1.5 sec) of neutrons in the trap; (2) the ability to measure the spectrum of the ultracold neutrons after they have been stored in the trap; and (3) an improvement in the coating of the traps which improves the reliability for the different geometries. These features are particularly important improvements because all measurements of the neutron lifetime involve an ambiguity between the neutron decay lifetime τ_n and the storage lifetime $\tau_{\rm storage}$ in the trap. To circumvent this, it is necessary to conduct a number of measurements with different storage lifetimes which can be then extrapolated to zero storage loss rate ($\tau_{\rm storage}^{-1} \to 0$) to determine the decay rate due to neutron decay alone. This is a source of considerable systematic error. The present result is a major improvement in previous extrapolations in that the neutron storage loss rate was not only accurately measured but was as much as a factor of 2 smaller than the best previous measurements, making the inferred neutron decay lifetime much less subject to systematic error. Indeed, the difference between the best-measured storage time and the inferred neutron lifetime is only 5 sec, whereas in the previous best measurements the extrapolation was made over an interval of 105 sec and therefore less reliable.

The neutron lifetime deduced by this method is significantly reduced to $878.5 \pm 0.7_{\rm stat} \pm 0.3_{\rm sys}$ sec. This value differs from the previous mean weighted world average of 885.7 ± 0.8 sec [9] by 6 standard deviations. It differs from the previous most precise result of $885.4 \pm 0.9_{\rm stat} \pm 0.3_{\rm sys}$ sec [10] by 4 standard deviations. Indeed, including the new result of Ref. [8] into deriving a new weighted mean world average according to the methods of the Particle Data Group [9] reduces the mean weighted world average by over 4 standard deviations to 881.9 ± 0.6 sec. More conservatively, however, this weighted mean uncertainty may not be appropriate due to the inconsistency among the data. A chi-squared minimization instead of a weighted mean gives a larger uncertainty of ± 1.6 sec, which we adopt here. This larger uncertainty and smaller lifetime together help to bring the primordial helium abundance into concordance with other determinations of the baryon-to-photon ratio as described below.

On the other hand, there are reasons to consider the new value by itself, independently of the previous measurements. In addition to the vast improvement in the present measurement, another aspect which lends particular credibility to this new result is the fact that when this new lifetime is used as a unitarity test of the Cabibbo-Kobayashi-Maskawa matrix [8], together with the current value of the β asymmetry in neutron decay [11], there is excellent agreement with the standard-model predictions. Such is not the case for the current world average [8].

If this new lower value for the neutron lifetime is adopted as a most extreme case, then this substantially reduces the expected ^{4}He abundance from primordial nucleosynthesis. This is particularly important for BBN cosmology as we now explain.

II. LIGHT-ELEMENT ABUNDANCES

One of the powers of BBN is that all of the light element abundances are determined in terms of a single parameter η_{10} which is the baryon-to-photon ratio in units of 10^{-10}. The crucial test of the standard BBN is, therefore, whether a single value of η_{10} can be found which reproduces all of the observed primordial abundances. The different light element abundances are determined by different means. This makes each determination an important independent check on BBN.

Primordial deuterium is best determined from its absorption line in high redshift Lyman α clouds. The average of measurements of six absorption line systems towards five quasi stellar objects gives [12] deuterium-to-hydrogen number abundance ratio (D/H) $\mathrm{D/H} = 2.78^{+0.44}_{-0.38} \times 10^{-5}$. This would imply a value of $\eta_{10} = 5.9 \pm 0.5$. This is an important result because it is also very close to the value $\Omega_b h^2 = 0.0224 \pm 0.0009$ ($\eta_{10} = 6.13 \pm 0.25$) deduced [13] from the WMAP independent determination of the baryon content at the epoch of photon last scattering. Because of the concordance of these two independent methods, the WMAP determination of η_{10} is generally accepted as the most accurate determination.

The primordial lithium abundance , on the other hand, is inferred from old low-metallicity halo stars. Such stars exhibit an approximately constant (''Spite plateau'') lithium abundance as a function of surface temperature. This is taken to be the primordial abundance. There is, however, some controversy [14,15] concerning the depletion of ^{7}Li on the surface of such halo stars and/or during the big bang itself [16]. For the present purposes we adopt the value from [17] $^7\mathrm{Li} = 1.23^{+0.68}_{-0.32} \times 10^{-10}$, where the errors are 95% confidence limits.

The primordial helium abundance is obtained by measuring extragalactic HII regions in low-metallicity irregular galaxies. Often in the past, the primordial helium abundance Y_p so deduced tended to reside in one of two possible values (a low value, e.g., $Y_p = 0.238 \pm 0.002 \pm 0.005$ [18] and a high value $Y_p = 0.2452 \pm 0.0015$ [19]). There is also, however, a current dilemma regarding the uncertainty in the observationally determined primordial helium abundance. Many recent evaluations (e.g., [19]) give a rather narrow range of abundance uncertainty. For our purposes we adopt the value of [19] as a representative result. On the other hand, the extent of systematic errors in these analyses is still being debated. Another recent study [20] has adopted a more conservative approach and concluded that correlations in various uncertainties could stretch the error in the inferred primordial abundance. Their representative analyses yields $Y_p = 0.249 \pm 0.009$ and they argue in favor of range of allowed values of $0.232 \le Y_p \le 0.258$.

While this is being sorted out, however, it has been deduced by several authors (cf. [16,21]) that the combined deuterium and WMAP constraints on the baryon-to-photon ratio implies that the primordial helium abundance should be $Y_p = 0.2484^{+0.0004}_{-0.0005}$ [21] or $Y_p = 0.2479 \pm 0.0004$ [16].

If we adopt the narrow helium abundance of [19] and the WMAP constraint of [21] there is, therefore, a possible

2–3σ discrepancy between the ^{4}He + ^{7}Li and the D + WMAP results. This dilemma with regards to BBN is depicted by dashed lines on Fig. 1.

One of course could (and probably should) disregard this dilemma if the uncertainty is as large as deduced in [20]. However, if this dilemma is real, then it may provide insight into new physics beyond the minimal BBN model, for example, brane-world effects [22], cosmic quintessence [23], time varying constants [24], etc. [4]. In this paper we point out an important result, however, that even if the most narrow uncertainty in the deduced primordial helium is adopted, then a significant portion of the discrepancy between BBN and the CMB results can be accounted for simply by adopting the new neutron lifetime.

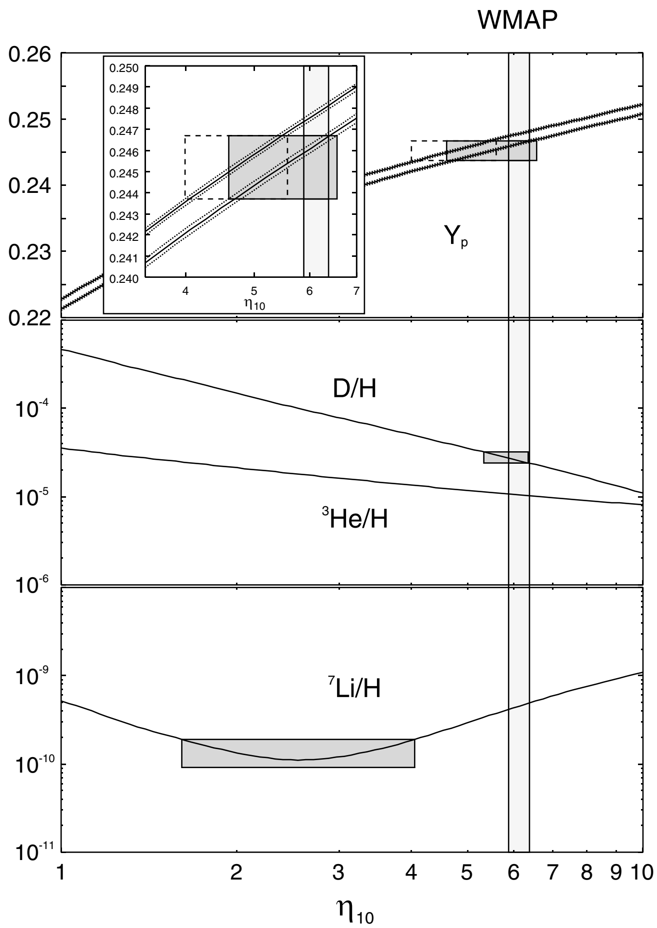

FIG. 1. Predicted BBN light element abundances vs the baryon-to-photon ratio η_{10} in units of 10^{-10}. These are compared with the observationally inferred [16] primordial abundances (horizontal lines) and the independent determination of η_{10} from the WMAP results (light shaded region). The top box shows the primordial helium abundances. The inset shows an expanded view of Y_p near the allowed region. The banded regions indicate the range of predicted Y_p due to the neutron lifetime uncertainty. The upper lines are based upon the previous world average $\tau_n = 885.7 \pm 0.8$ sec. The lower lines are based upon the new measured value of $\tau_n = 878.5 \pm 0.8$ sec. The previously allowed η_{10} values (shown by the dashed open box) shifts to the dark shaded box if the new neutron lifetime is adopted.

III. RESULTS

For illustration of the implications of the new value for the neutron lifetime, we have made calculations of standard homogenous big bang nucleosynthesis for three values of the neutron lifetime. These are (1) the previous world average (885.7 ± 0.8 sec); (2) the new world average (881.9 ± 1.6 sec) which includes the new measurement of Ref. [8]; and (3) the newest lower value of [8] ($878.5 \pm 0.7 \pm 0.3$ sec).

The benchmark code used for the present illustration is the standard big bang nucleosynthesis code originally developed by Wagoner [1] and made user friendly by Kawano [25]. This code is available for public download [26]. The reaction rates and uncertainties are those adopted in [5]. Although newer reaction rate compilations and uncertainties have been evaluated [6,7,27], this code is readily available and adequate for the benchmark comparison of interest here.

Figure 1 compares the primordial nucleosynthesis yields based upon both the previously adopted world average with the yields based upon the new neutron lifetime measurement and its uncertainty. The inset shows an expanded view of the primordial helium abundance for η_{10} values near those allowed by the various observational constraints.

From this figure it is clear that the primary effect of altering the neutron lifetime is to lower the primordial helium abundance prediction. The uncertainty in the predicted Y_p is indicated by parallel bands on the figure. The uncertainty remains nearly the same with the new lifetime because the uncertainty in the new neutron lifetime is nearly the same as that of the previous world average. Though not shown on this figure, the uncertainty in predicted Y_p increases by a factor of ≈ 1.5 if the larger error ($\pm$ 1.6 sec) in the new world average is adopted.

The effect on other light elements is so small ($\lesssim 1\%$) as to be indiscernible from the line widths on the figure. The key point of Fig. 1 is that now the primordial helium abundance required for the baryon-to-photon ratio given in the WMAP and/or D/H quasi stellar objects absorption line results reduces from $Y_p = 0.2479 \pm 0.0006$ to $Y_p = 0.2463 \pm 0.0006$ when using the new value for new neutron lifetime. For comparison, incorporating the new lifetime measurement into a new mean world average would require $Y_p = 0.2470 \pm 0.0009$. These two later values overlap (within 1σ) with the uncertainty of even the narrower of the observationally inferred helium abundance [19] of $Y_p = 0.2452 \pm 0.0015$.

Alternatively, the η_{10} values implied by an observed helium abundance of $Y_p = 0.2452 \pm 0.0015$ are $5.5 \pm$

0.9 for the new lifetime or 5.1 ± 1.1 for the new weighted mean lifetime as compared to 4.8 ± 0.8 based upon the previous world average. These are to be compared with the WMAP + D/H determination of $\eta_{10} = 6.13 \pm 0.25$. Hence, even with this small correction to the neutron lifetime, and adopting a narrow range for the observational uncertainty in Y_p, the implied η_{10} value for either the new lifetime or new weighted average now overlaps the value required by the WMAP and D/H analysis. This significantly further constrains nonstandard models for BBN [4,28] and strengthens the viability of standard BBN as a probe of cosmology.

Of course, one must still deal with the problem of ^{7}Li overproduction in BBN which will have to be resolved by ^{7}Li destruction, either within the big bang itself [16] or during subsequent stellar evolution [14,15]. We also emphasize that there is still additional uncertainty in the BBN production of helium and other light element abundances due to uncertainties in nuclear reaction rates, particularly the d(p, γ)^{3}He, d(d, n)^{3}He, d(d, p)^{3}H, and ^{3}He(a, γ)^{7}Be.

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[1] R. V. Wagoner, Astrophys. J. **179**, 343 (1973).
[2] D. N. Schramm and R. V. Wagoner, Annu. Rev. Nucl. Part. Sci. **27**, 37 (1977).
[3] J. Yang, M. S. Turner, G. Steigman, D. N. Schramm, and K. A. Olive, Astrophys. J. **281**, 493 (1984).
[4] R. A. Malaney and G. J. Mathews, Phys. Rep. **229**, 145 (1993).
[5] M. S. Smith, L. H. Kawano, and R. A. Malaney, Astrophys. J. Suppl. Ser. **85**, 219 (1993).
[6] K. M. Nollett and S. Burles, Phys. Rev. D **61**, 123505 (2000).
[7] R. H. Cyburt, Phys. Rev. D **70**, 023505 (2004).
[8] A. Serebrov *et al.*, Phys. Lett. B **605**, 72 (2005).
[9] Particle Data Group, Phys. Rev. D **66**, 010001 (2002); Particle Data Group, Phys. Lett. B **592**, 1 (2004).
[10] S. Arzumanov *et al.*, Phys. Lett. B **483**, 15 (2000).
[11] H. Abele *et al.*, Phys. Rev. Lett. **88**, 211 801 (2002).
[12] D. Kirkman *et al.*, Astrophys. J. Suppl. Ser. **149**, 1 (2003).
[13] C. L. Bennett *et al.*, Astrophys. J. Suppl. Ser. **148**, 1 (2003); D. N. Spergel, *et al.*, Astrophys. J. Suppl. Ser. **148**, 175 (2003).
[14] M. H. Pinsonneault, *et al.*, Astrophys. J. **527**, 180 (1999).
[15] S. Vauclair, in *Eleventh Cambridge Workshop on Cool Stars, Stellar Systems and the Sun*, edited by Ramon J. Garcia Lopez, Rafael Rebolo, and Maria Rosa Zapaterio Osorio, ASP Conference Proceedings, Vol. 223 (Astronomical Society of the Pacific, San Francisco, 2001) p. 227.
[16] A. Coc, *et al.*, Astrophys. J. **600**, 544 (2004).
[17] S. G. Ryan, *et al.*, Astrophys. J. **523**, 654 (1999).
[18] B. D. Fields and K. A. Olive, Astrophys. J. **506**, 177 (1998).
[19] Y. Izatov, *et al.* Astrophys. J. **527**, 757 (1999).
[20] K. A. Olive and E. D. Skillman, Astrophys. J. (to be published).
[21] R. H. Cyburt, B. D. Fields, and K. A. Olive, Phys. Lett. B **567**, 227 (2003).
[22] K. Ichiki, P. M. Garnavich, T. Kajino, G. J. Mathews, and M. Yahiro, Phys. Rev. D **68**, 083518 (2003).
[23] M. Yahiro, G. J. Mathews, K. Ichiki, T. Kajino, and M. Orito, Phys. Rev. D **65**, 063502 (2002).
[24] K. Ichikawa and M. Kawasaki, Phys. Rev. D **69**, 123506 (2004).
[25] L. Kawano, Fermilab Report No. FERMILAB-PUB-92-004-A, 1992.
[26] The Kawano BBN code is available at: http://www-thphys.physics.ox.ac.uk/users/SubirSarkar/bbn.html.
[27] P. Descouvemont *et al.*, At. Data Nucl. Data Tables **88**, 203 (2004).
[28] T. Kajino, and R. N. Boyd, Astrophys. J. **359**, 267 (1990).