PRIMORDIAL NUCLEOSYNTHESIS REDUX

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ABSTRACT

The latest nuclear reaction cross sections (including the most recent determinations of the neutron lifetime) are used to recalculate the abundances of deuterium, ³He, ⁴He, and ⁷Li within the framework of primordial nucleosynthesis in the standard (homogeneous and isotropic) hot, big bang model. The observational data leading to estimates of (or bounds to) the primordial abundances of the light elements is reviewed with an emphasis on ⁷Li and ⁴He. A comparison between theory and observation reveals the consistency of the predictions of the standard model and leads to bounds to the nucleon-to-photon ratio, $2.8 \le \eta_{10} \le 4.0$ ($\eta_{10} \equiv 10^{10}n_B/n_\gamma$), which constrains the baryon density parameter, $\Omega_B h_{50}^2 = 0.05 \pm 0.01$ (the Hubble parameter is $H_0 = 50h_{50}$ km s⁻¹ Mpc⁻¹). These bounds imply that the bulk of the baryons in the universe are *dark* if $\Omega_{\text{TOT}} = 1$ and would require that the universe be dominated by nonbaryonic matter. An upper bound to the primordial mass fraction of ⁴He, $Y_p \le 0.240$, constrains the number of light (equivalent) neutrinos to $N_y \le 3.3$, in excellent agreement with the LEP and SLC collider results. Alternatively, for $N_y = 3$, we bound the predicted primordial abundance of ⁴He: $0.236 \le Y_p \le 0.243$ (for $882 \le \tau_n \le 896$ s).

Subject headings: abundances — early universe — elementary particles — nucleosynthesis

1. INTRODUCTION

It is well known that primordial nucleosynthesis provides a unique window on the early universe. Along with measurements of the cosmic background radiation (CBR), it constitutes one of the two crucial quantitative tests of the standard big bang cosmological model. Indeed, big bang nucleosynthesis (BBN) and the CBR, which have been related symbiotically since the early work of Gamow (1948) and Alpher & Herman (1949), provide complementary views of the early universe. The synthesis of the light elements is determined by events occurring in the epoch from ~ 1 to ~ 1000 s in the history of the universe when temperatures varied from $\sim 10^{10}$ K or higher ($\gtrsim 1$ MeV) to $\sim 10^9$ K or higher ($\lesssim 0.1$ MeV). Thus, the observed abundances offer a probe of the universe at epochs far earlier than those probed by the CBR ($t \sim 10^5$ yr; $T \sim 10^4$ K [~ 1 eV]). Without BBN, those early epochs would be denied our scrutiny. Through a detailed comparison of the predicted abundances with the observational data, cosmological models may be tested and constraints inferred on parameters of importance to cosmology (e.g., the universal density of baryons) and elementary particle physics (e.g., the number of species of light neutrinos).

The "standard" big bang model of cosmology is the simplest (i.e., it has the fewest adjustable parameters), based on the observed large-scale isotropy and homogeneity of the universe. Utilizing only the *known* particles (e.g., assuming three species of *light* neutrinos v_e , v_{μ} , v_{τ} ; $N_{\nu} = 3$) and assuming the correctness of general relativity, the nucleosynthesis predictions of the standard model depend on only one parameter, the ratio, η , of nucleons to photons ($\eta \equiv n_B/n_{\nu}$) (or, equivalently, the density of

⁵ School of Physics and Astronomy, University of Minnesota, Minneapolis, MN 55455, and LAPP, Annecy-le-Vieux, France. baryons, since n_{γ} is known from measurements of the CBR). The quantitative success of the standard model in accounting for the observed abundances of D, ³He, ⁴He, and ⁷Li, whose values span some nine orders of magnitude, has stimulated more detailed comparison of predictions with data. Among the goals of such comparisons, key is that of testing in detail the consistency of the standard model (i.e., is there a unique value of η such that the predicted abundances all agree with observations?). A related goal is to subject to the same detailed scrutiny alternative cosmological models (e.g., inhomogeneous nucleosynthesis), as well as variations on the standard model of particle physics (e.g., more species of light neutrinos and/or the existence of massive, unstable exotic particles).

Since Hayashi (1950) recognized the role of neutron-proton equilibration, the framework for big bang nucleosynthesis calculations has not varied significantly, The work of Alpher, Follin, & Herman (1953), Hoyle & Tayler (1964) and Zel'dovich (1965) preceding the discovery of the 3 K background, and of Peebles (1966) and Wagoner, Fowler, & Hoyle (1967) immediately following the discovery, and the more recent work in which some of us took part (Schramm & Wagoner 1977; Olive et al. 1981; Yang et al. 1984; Boesgaard & Steigman 1985; Kawano, Schramm, & Steigman 1988) all do essentially the same basic calculation. As for the calculation itself, the reaction network is relatively simple by the standards of, for example, explosive nucleosynthesis calculations in supernovae. The changes over the last 25 years are mainly in the input of more recent nuclear reaction rates. This paper follows that trend by providing the most recent update to the input reaction rates.

With the exception of the effects of elementary particle assumptions, to which we will return, the real excitement in BBN over the last 25 years has not been in redoing the calculation. Instead, the true action has been focused on understanding the evolution of the light-element abundances and using that information to infer powerful conclusions. In particular, in the 1960s, the main focus was on ⁴He, which has the virtue (and the weakness!) of being very insensitive to the

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baryon density (η) . The agreement between BBN predictions and observations provided support for the basic big bang model but did not significantly constrain the density. In fact, in the mid-1960s the other light isotopes (which are capable of giving density information) were assumed to have been made during the T Tauri phase of stellar evolution (Fowler, Greenstein, & Hoyle 1962), and so it was not appreciated that they too have cosmological significance. It was during the 1970s that BBN was developed fully as a tool for probing the universe. The possibility was in part stimulated by Ryter et al. (1970), who showed that the T Tauri mechanism for lightelement synthesis failed. Furthermore, deuterium abundance determinations improved significantly through solar wind measurements (Geiss & Reeves 1973; Black 1971) and the interstellar observations from the Copernicus satellite (Rogerson & York 1973). Reeves et al. (1973) argued for a cosmological origin of ²H (and ⁷Li) and were able to place a constraint on the baryon density excluding a universe closed by baryons alone. Subsequently, the ²H arguments were strengthened by Epstein, Lattimer, & Schramm (1976), who showed that no realistic astrophysical process, other than the big bang, could produce cosmologically significant amounts of 2 H. It was also interesting that the baryon density implied by BBN was in good agreement with the density inferred from the dark galactic halos (Gott et al. 1974).

By the late 1970s, a complementary argument (to ²H) had developed, using ³He. In particular, Rood, Steigman, & Tinsley (1976) argued that, unlike ²H, ³He was made in stars; thus, its abundance would increase with time. Since primordially synthesized ³He, like ²H, decreases monotonically with the cosmological baryon density (η), this argument could be utilized (Yang et al. 1984), in conjunction with measurements of ³He in the solar wind (Black 1971; Geiss & Reeves 1972) or in the interstellar medium (Wilson, Rood, & Bania 1983), to place a *lower* limit on the universal density of baryons. Since the bulk of the ²H was converted in stars to ³He, the constraint was quite restrictive (Yang et al. 1984).

It was interesting that the lower bound to η from ³He and the upper bound to η from ²H yielded the prediction that primordial ⁷Li be near its minimum of ⁷Li/H ~ 10⁻¹⁰, which was subsequently verified by the Population II Li measurements of Spite & Spite (1982a, b). This yielded the situation, emphasized by Yang et al. (1984), that the light-element abundances are consistent with BBN over nine orders of magnitude only if the cosmological baryon density is constrained to be ~5% of the critical density.

The other development of the 1970s for BBN was the explicit calculation of Steigman, Schramm, & Gunn (1977, hereafter SSG), showing that the number of neutrino generations, N_{y} , had to be small to avoid overproduction of ⁴He. Earlier work had noted a dependence of the primordial ⁴He abundance on the amount of the cosmological stress-energy in exotic particles (Hoyle & Tayler 1964; Shvartsman 1969; Peebles 1971) but had not explicitly calculated the quantity of interest to particle physics, N_{v} . To put this in perspective, one should remember that the mid-1970s also saw the discovery of charm and bottom quarks and the tau lepton, so that it seemed as if each new accelerator experiment led to the discovery of new particles. And yet cosmology argued against this "conventional" wisdom. Over the years the SSG limit on N_{y} has improved with better ⁴He abundance determinations, with neutron lifetime measurements, and with limits on the lower bound to the baryon density. For most of the 1980s, the SSG cosmological bound on N_v hovered at ~4 or less; just as LEP and SLC were accumulating data, N_v dropped below 4 (Kawano & Schramm 1989; Steigman 1989a; Pagel 1989a; Olive et al. 1990).

Because of the obvious importance of BBN, it is clearly important to carry out, periodically, a reevaluation using the latest reaction rates and latest abundance determinations. That is the purpose of this paper. In particular, many of the cross sections of relevance to the calculation of primordial nucleosynthesis have been reexamined. Of special importance for ⁴He, the neutron lifetime has been measured in a series of modern, high-accuracy experiments, leading to a slightly smaller (and much more accurate) value than has been employed in previous calculations. On the observational side, lithium has been measured in large numbers of metal-poor (Population II) stars, leading to increased confidence that the Population II lithium abundance is an indicator of the primordial abundance (Spite & Spite 1982a, b). Also, ⁴He has been studied in many metal-poor extragalactic H II regions, leading to an improved estimate of the primordial abundance of ⁴He. Furthermore, the LEP and SLC measurements of N_{y} (Jarlskog 1990; Mark II Collaboration 1989; L3 Collaboration 1989; ALEPH Collaboration 1989; OPAL Collaboration 1989; DELPHI Collaboration 1989; in subsequent citations "Collaboration" will be omitted) provide laboratory tests of the standard cosmological models as well as of the standard model of particle physics.

It is these new laboratory and observational data that motivate our detailed reexamination of big bang nucleosynthesis. For the most part we will confine our attention to the predictions of BBN within the context of the standard model, and to the comparison of these predictions with the observations. We will, however, briefly comment on alternative scenarios (inhomogeneous models; decaying massive particles). We will also explore the sensitivity of the standard model to the number of light neutrino species to see by how much N_{ν} can differ from the "standard" value $N_{\nu} = 3$; the cosmological and accelerator constraints are, in fact, complementary (Schramm & Steigman 1984).

As a preview of our results, we note that we find that the standard model predictions for the abundances of the light elements *are* in agreement with observations for the baryon-tophoton ratio in the restricted range $2.8 \leq \eta_{10} \leq 4.0$. This corresponds to a baryon fraction of the critical density $\Omega_B h_{50}^2 = 0.05 \pm 0.01$, where $\Omega_B \equiv \rho_B / \rho_c$ and $H_0 = 50h_{50}$ km s⁻¹ Mpc⁻¹. Thus, the universe fails to be "closed" by baryons by at least an order of magnitude. On the other hand, the lower bound to Ω_B suggests that most of the baryons in the universe are "dark" (i.e., $\Omega_B \geq \Omega_{LUM} \approx 0.007$). As for N_v , the uncertainty in the upper bound to Y_p is the greatest source of uncertainty in the SSG upper bound to the number of light neutrino species; for $Y_p \leq 0.240$ we find $N_v \leq 3.3$. Alternatively, for the allowed ranges of η and the neutron lifetime, and for the standard value $N_v = 3$, we predict that the primordial ⁴He mass fraction lies in the range $0.236 \leq Y_p \leq 0.243$.

In the next section we review the changes of relevance to BBN of the nuclear reaction rates and the neutron lifetime. Since the nuclear and weak reaction rate uncertainties are now much reduced, it is important to include finite temperature effects and radiative corrections in calculating the ⁴He abundance (Dicus et al. 1982; Johansson, Perussuti, & Skagerstam 1982; Saleem 1987). Then we present the results of our calculations and emphasize any residual uncertainties. The observational data on D, ³He, ⁴He, and ⁷Li are reviewed and, for the

latter two isotopes, updated. We try, as far as is possible, to derive from the data 95% confidence level (CL) ranges allowed for the primordial abundances (or, bounds thereof) of the light elements. Then these 95% CL limits are compared with the predicted abundances to derive bounds on η and N_{ν} . These same 95% CL limits are also used to explore the consistency of alternative scenarios of BBN. Finally, we summarize our results.

2. NUCLEAR REACTION RATES

The calculation of the standard BBN production of D, ³He, ⁴He, and ⁷Li proceeds in two distinct stages. The first involves the competition between the expansion rate of the universe $[t^{-1} = 2H$, where $H^2 = (8\pi/3)G\rho$] and the rate of the weak interactions responsible for the interconversion of neutrons and protons $(ne^+ \leftrightarrow p\bar{v}_e, nv_e \leftrightarrow pe^-, \text{ and } n \leftrightarrow pe^-\bar{v}_e)$. The second stage involves the interplay between the expansion rate and the nuclear reactions that synthesize complex nuclei. For $T \gtrsim 1$ MeV, the $n \leftrightarrow p$ rates are greater than the expansion rate, and the neutron-to-proton ratio traces its equilibrium value

$$(n/p) = \exp\left(-Q/T\right) , \qquad (1)$$

where $Q \equiv (m_n - m_p)c^2 = 1.293$ MeV. When the universe cools below ~1 MeV, the $n \leftrightarrow p$ rates are less than H and (n/p)"freezes out," decreasing only slowly owing to neutron decay and residual e^{\pm} , v_e , and \bar{v}_e collisions until the onset of nucleosynthesis. The high photon-to-baryon ratio, coupled with the relatively low binding energies per nucleon of the light nuclei, inhibits the buildup of significant abundances of more complex nuclei until $T \leq 100$ keV. In particular, the formation of the various light elements proceeds by a two-body reaction network that flows through weakly bound nuclei such as deuterium. The equilibrium abundance of D does not become significant until $T \leq 100$ keV, at which point nearly all the available neutrons are quickly processed into the most tightly bound of the light nuclei, ⁴He. A small amount of ⁷Li is made by further reactions on ⁴He—a point we address in more detail in § 4. The absence of stable nuclei at A = 5 and A = 8, coupled to the low densities of nuclei and nucleons (ensuring that two-body reactions are dominant) and to a neutron-toproton ratio less than unity, make it difficult, in the standard model, to synthesize nuclei beyond mass 5. The small leakage to ${}^{7}\text{Li}/{}^{7}\text{Be}$ is prevented from extending beyond mass 8 by the rapid destruction of mass-7 nuclei by reactions with protons. Leakage to heavier nuclei can occur in regions of high neutron densities which are not found in the standard model but which could be present in inhomogeneous models (Applegate, Hogan, & Scherrer 1988; Terasawa & Sato 1989; Kawano, Fowler, & Malaney 1990).

The calculated abundance of primordial ⁴He is most sensitive to the ratio (n/p) at the onset of nucleosynthesis and therefore depends crucially on the weak interaction rate. The weak $n \leftrightarrow p$ rates can be expressed in terms of the neutron decay rate τ_n^{-1} , and thus increasing (decreasing) τ_n raises (lowers) the "freeze-out" temperature and increases (decreases) the yield of ⁴He. Prior to the very recent measurements of τ_n , the errors introduced in the overall normalization of the $n \leftrightarrow p$ rates because of the uncertainty in τ_n led to uncertainties in the primordial ⁴He yield which were much greater than those introduced by approximating the temperature (T_y) dependence of the tree-level $n \leftrightarrow p$ rates with analytic fits. The much

improved accuracy of the τ_n measurements now requires a more careful evaluation of the $n \leftrightarrow p$ (Olive et al. 1990, hereafter OSSW). This was first discussed by Dicus et al. (1982), and we have adapted their prescription as follows: (1) The $n \leftrightarrow p$ rates are integrated numerically for each T_{y} step with an explicit calculation of the neutrino temperature required for the phase-space dependence and the appropriate Coulomb corrections to the tree-level interactions are included. (2) We verify at several values of (η, τ_n, N_v) that the corrections to the primordial ⁴He mass fraction, ΔY_p , due to the inclusion of radiative corrections, electron self-mass effects, and $e^+e^$ heating of v_e , are less than 0.0001 in magnitude ($\Delta Y_p \leq$ ± 0.0001), whereas step (1) contributes $\Delta Y_p \simeq -0.0023$. To make a full exploration of parameter space possible, we turn off step 2 and conclude that for fixed τ_n the uncertainty in the predicted Y_p due to the weak interaction sector is 0.0002 or less. Typically $Y_p \sim 0.24$, and so this amounts to better than 0.1% accuracy, whereas 2 σ variations in τ_n lead to ~1% uncertainties in the predicted Y_p . These latter changes are the same order as those found in going from an analytic fit to the $n \leftrightarrow p$ rates to the numerical evaluation of the Coulomb-corrected tree-level rates.

The primordial yields of D, ³He, and ⁷Li are most sensitive to the competition between the nuclear reaction rates and the expansion rate H. Increasing the nucleon number density increases the temperature at which D has an appreciable equilibrium abundance, increases the efficiency of forming ⁴He, and, thus, decreases the primordial abundances of D and ³He while increasing that of ⁴He. Thus, $y_{2p} \equiv (D/H)_p$ and $y_{3p} \equiv$ $({}^{3}\text{He/H})_{p}$ decrease with increasing η , while the ${}^{4}\text{He}$ mass fraction V tion Y_p increases with η . The predicted ⁷Li abundance has a similar coupling to the nuclear reaction rates, but it is slightly more complicated and we delay our discussion of its specific behavior for the moment. Obviously, the individual reaction rates for each link in the reaction network are crucial to the predicted yields of D, ³He, and ⁷Li. We have updated the standard reaction network (31 links up to and including nuclei of mass number 7) using the most recent rate compilations of Caughlan and Fowler (1988, hereafter CF). For the purposes of comparison we discuss our updated version relative to the network used by Kawano, Schramm, & Steigman (1988, hereafter KSS). Except for ⁴He(t, γ) and ⁷Li(p, α), the KSS network was based on the standard compilations of rates, up to and including Harris et al. (1983). The CF rates differ significantly from those used by KSS at only five links, which we list below in Table 1.

For this comparison, the ratio of rates from CF and KSS are taken at a temperature characteristic of nucleosynthesis, 80 keV ($T_9 \equiv T_y/10^9$ K = 0.9). Following tradition, CF uses the astrophysical S-factor to parameterize the energy dependence

TABLE 1

COMPARISON	OF	CF	AND	KSS	RATES
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Reaction	CF/KSS	Source		
$D(d, n)^{3}$ He	1.3	Krauss et al. 1987; FCZ75 ^a		
D(d, p)T	1.3	Krauss et al. 1987; FCZ75		
${}^{4}\text{He}(t, \gamma)^{7}\text{Li}$	0.8	Langanke 1986; Kajino 1986; Schröder et al. 1987		
$^{7}L(p, \alpha)^{4}He$	1.1	Rolfs & Kavanaugh 1986		
7 Be(<i>n</i> , <i>p</i>) 7 Li	0.8	Koehler et al. 1988; FCZ75		

^a Fowler, Caughlan, & Zimmerman 1975.

of the cross section

$$\sigma(E) \equiv \frac{S(E)}{E} \exp\left[-\left(\frac{E_{\rm C}}{E}\right)^{1/2}\right],\tag{2}$$

where $E_{\rm C}$ is the Coulomb barrier penetration factor and S(E) is related to actual data by a Taylor series expansion about E = 0,

$$S(E) \simeq S(0) + \frac{dS}{dE} \bigg|_{E=0} E + \frac{1}{2} \frac{d^2S}{dE^2} \bigg|_{E=0} E^2$$

Changes in the D(d, n) and D(d, p) reactions are based on the data of Krauss et al. (1987). For the D(d, x) reactions, KSS use the compilation of Fowler, Caughlan, & Zimmerman (1975). The CF rate for ⁴He(t, γ)⁷Li is based on the analysis of Langanke (1986) and Kajino (1986), both of which suggest a smaller S(0) than that derived by KSS using the data of Schröder et al. (1987) alone. CF analyze the data of Rolfs & Kavanaugh (1986) on ⁷Li(p, α)⁴He and find that, for applications to primordial nucleosynthesis, S(E) is larger than KSS calculate from the same data.

The rate for ⁷Be(n, p)⁷Li used in KSS is based on the analysis of Bahcall & Fowler (1969, hereafter BF). BF used detailed balance to convert ⁷Li(p, n) data (Gibbons & Macklin 1959) into ⁷Be(n, p) cross sections, which they then fitted in the standard way (see eq. [2]). Recently Koehler et al. (1988) made direct measurements of ⁷Be(n, p), from 25 MeV to 13.5 keV, which are ~10 times more precise and result in rates which are 60%-80% of BF over the range $T_9 = [0.1, 1]$. The CF rate for ⁷Be(n, p) reflects the new measurements and is therefore smaller than that of KSS.

Recently, Krauss & Romanelli (1990, hereafter KR) have studied the effects on the predicted yields of primordial nucleosynthesis of $\pm 2 \sigma$ (where KR choose, from their analysis of the data, a "reasonable" 1 σ error for a reaction rate) variations in the weak $n \leftrightarrow p$ rates and in nine of the more important nuclear reaction rates. In this section we compare our network with theirs; we discuss the results of our calculations later. The reactions rates varied by KR and their adopted fractional 1 σ uncertainties are $D(p, \gamma)$ (16%), $p(n, \gamma)$ (10%), D(d, n) (10%), D(d, p) (10%), T(d, n) (10%), ${}^{3}He(\alpha, \gamma)$ (6%), ${}^{4}He(t, \gamma)$ (18%), ⁷Li(p, α) (8%), and ⁷Be(n, p) (10%). Except for the last three reactions, the reference point of the KR variation is the KSS network. This difference makes comparison of the two networks difficult because the central values of the D(d, n) and D(d, p) rates have changed by more than 1 σ_{KR} , based on the CF analysis of the Krauss et al. (1987) data. Excluding these two and the last three, the KR network adopts the same central values as ours, fixed on CF. It also appears that the central values adopted by KR for T(α , γ), ⁷Li(p, α) and ⁷Be(n, p) are consistent with those suggested by CF; i.e., the $T(\alpha, \gamma)$ rate is smaller than that used by KSS, the ⁷Li(p, α) rate is larger, and Be(n, p) is smaller.

Before presenting the results of our calculations, we turn to a brief discussion of the latest results of the neutron lifetime.

3. NEUTRON LIFETIME

From the previous discussion, it is clear that the nucleosynthetic yields, and, in particular, the predicted abundances, depend on the competition between the expansion rate of the universe and the weak interaction rate. Since the matrix element is the same for all $n \leftrightarrow p$ reactions, we can follow Wagoner (1973) and scale all variations in the weak interaction

rate to a variation in the neutron mean life. Prior to the measurement of Bondarenko et al. (1978) of $\tau_n = 877 \pm 8$ s, the standard value was that of Christensen et al. (1972), $\tau_n = 918$ \pm 14. The effects on primordial nucleosynthesis of a possibly low neutron half-life were explored in detail by Olive et al. (1981), where limits on quantities such as $\eta(\Omega_B)$ and N_{ν} were given for $\tau_n = 918$ s ($\tau_{1/2} = 10.61$ minutes) as well as $\tau_n = 877$ s $(\tau_{1/2} = 10.13 \text{ minutes})$ (the Bondarenko et al. 1978 value was later revised to the higher value of 881 ± 8 in Bondarenko 1982) and the even higher value found by Byrne et al. (1980) of $\tau_n = 937 \ (\tau_{1/2} = 10.82 \text{ minutes})$. We note that this latter value has recently been withdrawn (Particle Data Group [PDG] 1990). Because of its large deviation from the other measurements, the Bondarenko et al. (1978) measurement had generally not been included in "world averages" (cf. PDG 1982). Only later, when recent measurements began to support lower values for τ_n , has the Bondarenko result been included. The 1984 and 1986 "world averages" by the Particle Data Group gave $\tau_n = 898 \pm 16$ s ($\tau_{1/2} = 10.37$ minutes) and $\tau_n = 896 \pm 10$ s ($\tau_{1/2} = 10.35$ minutes), respectively. (The latter included the measurements of Kosvintsev, Morozov, & Terekhov 1988, $\tau_n = 903 \pm 13$, and Last, Arnold, & Döhner 1988, $\tau_n = 876$ ± 21.)

Recently, a very accurate measurement of the neutron lifetime has been reported by Mampe et al. (1989), who used a glass storage container coated with Fomblin oil. This container has a very low probability for leakage $[(2-3) \times 10^{-5}/$ bounce at room temperature] for ultracold neutrons with kinetic energies $E_n \leq 10^{-7}$ eV. The measured mean lifetime in this experiment is $\tau_n = 887.6 \pm 3$ s. Combining this result with the previous ones, removing the Byrne et al. (1980) result, replacing the Bondarenko et al. (1978) measurement with the recently revised value of $\tau_n = 891 \pm 9$ s (Spivak 1988), and including the very recent results of Paul et al. (1989; $\tau_n = 887$ ± 10 s) and Kossakowski et al. (1989; $\tau_n = 878 \pm 30$ s) leads to a new "world average" of $\tau_n = 888.6 \pm 3.5$ s.

For our calculations we have chosen the 95% CL range: $882 \le \tau_n \le 896$ s (10.19 $\le \tau_{1/2} \le 10.35$ minutes). Although we have not included the very recent results of Byrne et al. (1990), 893.6 ± 5.3 s, they are in good agreement with the value adopted here. Including this measurement would raise the world average to 889.6 ± 2.9 .

4. RESULTS

Figure 1*a* displays the abundance of ⁷Li relative to that of H (by number) as a function of the baryon-to-photon ratio in units of 10^{-10} , $\eta_{10} \equiv 10^{10} n_B/n_y$, for $882 \le \tau_n \le 896$ s, for 3 (solid curve) and 4 (dashed curve) light neutrino species. Note that, unlike D, ³He, and ⁴He, ⁷Li is not a monotonic function of η ; it has a minimum at $\eta_{10} \sim 3$. The ⁷Li trough is due to the competition between the production and destruction of mass 7 nuclei: ${}^{4}\text{He}(t, \gamma)^{7}\text{Li} \leftrightarrow {}^{7}\hat{\text{Li}}(p, \alpha)^{4}\text{He}$ (yielding an abundance that decreases with increasing η) competes with ³He(α , γ)⁷Be \leftrightarrow ⁷Be(e, v_e)⁷Li (yielding an abundance that increases with increasing η). In addition, there is a mass 7 leak at high η where ⁷Be(n, p) reactions convert ⁷Be to the more fragile ⁷Li, which can be destroyed by ⁷Li(p, α). In Figure 1b we compare the ⁷Li as a function of η_{10} for the current network based on CF (solid curve) to the pre-CF network of KSS (dashed curve). The net effect of using the CF results is to decrease the low- η^{7} Li branch [the change is dominated by the decrease in ⁴He(t, α)⁷Li, and the increase in ⁷Li(p, α)⁴He] and to increase the high- η ⁷Li branch [here changes in $D(d, n)^3$ He



FIG. 1.—(a) Predicted abundance (ratio, by number, to hydrogen) of ⁷Li as a function of the baryon-to-photon ratio ($\eta_{10} = 10^{10}\eta$) for $N_v = 3$ (solid curve) and 4 (dashed curve). The width of the $N_v = 3$ curve corresponds to the 95% CL range of the neutron lifetime ($882 \le \tau_n \le 896$ s). The $N_v = 4$ dashed line is for $\tau_n = 889$ s. (b) Predicted abundance (ratio, by number, to hydrogen) of ⁷Li as a function of the baryon-to-photon ratio ($\eta_{10} = 10^{10}\eta$) for $N_v = 3$ and $\tau_n = 889$ s. The solid curve represents results of this work, and the dash-dot curve is the KSS result.

and ⁷Be(n, p)⁷Li dominate] relative to the KSS calculations. Relative to the central values of the KR code, we would expect a slight low- η ⁷Li increase [due to D(d, p)³H] and a slight increase at high η [due to D(d, n)³He] because of the changes in the rates in going from KSS to CF. A direct comparison does show a very small increase in the extreme low- η ⁷Li branch and the high- η ⁷Li branch.

We pause here to comment on the residual uncertainties in the predicted ⁷Li abundance due to uncertainties in the nuclear cross sections that constitute the big bang reaction network. KR have shown, using Monte Carlo techniques with 1 σ variations in the reaction rates, that the predicted abundance of ⁷Li is uncertain by ~40% at the 2 σ level. Although the KR central values do not completely agree with ours, we estimate that our predicted abundance of ⁷Li should also be accurate to 40% at the 2 σ level. This uncertainty is particularly important for the high- η branch, since we will use the comparison of the observed primordial ⁷Li abundance with the big bang ⁷Li prediction to constrain the baryon-to-photon ratio from above.

In Figure 2*a* we display the abundances of D, ³He, and D + ³He relative to H (by number) as a function of η_{10} for $N_{\nu} = 3$ and $882 \le \tau_n \le 896$ s (the dashed line shows D + ³He for $N_{\nu} = 4$ and $\tau_n = 889$ s). In Figure 2*b* we compare our new results ($N_{\nu} = 3$) with those of the KSS network. There is a very small decrease relative to KSS (and the central values of KR) due to the increase in D(*d*, *n*) and D(*p*, *n*). Over most of the range $1 \le \eta_{10} \le 10$, the predicted deuterium abundance is well fitted by

$$10^5 y_{2p} = 46\eta_{10}^{-5/3} . \tag{3}$$



FIG. 2.—(a) Predicted abundances (ratios, by number, to hydrogen) of D, ³He, and their sum as a function of η . The dashed curve is the sum D + ³He for $N_{\nu} = 4$. The thicknesses of the solid $N_{\nu} = 3$ curves correspond to the 95% CL range of the neutron lifetime ($882 \le \tau_n \le 896$ s); the $N_{\nu} = 4$ dashed curve is for $\tau_n = 889$ s. (b) As in Fig. 1b, but for D, ³He, and their sum.



FIG. 3.—(a) Primordial mass fraction of ⁴He, Y_p , as a function of η . The thicknesses of the two bands $N_y = 3$ and 4 represent the 95% CL range of the neutron lifetime. (b) As in Fig. 1b, but for the primordial mass fraction of ⁴He, Y_p .

We note that the thickness of the abundance curves reflects the adopted range of uncertainty in τ_n .

Figure 3a shows the primordial mass fraction of ⁴He, Y_p , as a function of η_{10} for $N_v = 3$ and 4 and $\tau_n = 889 \pm 7$ s. The dependence of Y_p on N_v can be understood as follows. The universe at the time of primordial nucleosynthesis is radiationdominated by photons, electron-positron pairs, and light $(\leq MeV)$ neutrinos. Recall that the expansion rate H is proportional to $\rho^{1/2} \simeq (\rho_{\gamma} + \rho_e + \rho_{\gamma})^{1/2}$, so that increases in the number of light neutrinos lead to an increase in *H*. An increase in H means that $n \leftrightarrow p$ interactions freeze out earlier when (n/p)is larger, resulting in the increase of Y_p with N_y . It is useful to fit the primordial ⁴He yield to the free parameters of the model: η , τ_n , and N_v . Over the range $3 \le \eta_{10} \le 10$, Y_p is well fitted (to within ± 0.001) by

$$Y_p = 0.228 + 0.010 \ln \eta_{10} + 0.012(N_v - 3) + 0.185 \left(\frac{\tau_n - 889}{889}\right),$$
(4a)

or, in terms of the neutron half-life (in minutes),

$$Y_p = 0.228 + 0.010 \ln \eta_{10} + 0.012 (N_v - 3) + 0.017 (\tau_{1/2} - 10.27) .$$
(4b)

Notice that (for η_{10} and N_v fixed), the 95% CL uncertainty in $\tau_n, \pm 7$ s, contributes only $\leq \pm 0.0014 \ (\leq \pm 0.6\%)$ to the uncertainty in Y_p . Alternatively, if Y_p and η_{10} are fixed, the 95% CL uncertainty in τ_n contributes $\sim \pm 0.12$ or less ($\leq 4\%$) to the uncertainty in N_{y} .

In Figure 3b we compare the KSS predictions (dashed curve) with our new results for $\tau_n = 889$ s and $N_y = 3$. The difference between our results and KSS for ⁴He is due to two sets of changes. Our code integrates the weak rates numerically and includes an explicit calculation of the neutrino temperature (see our earlier discussion) rather than approximating these corrections to Y_n by uniformly reducing the numerical fit by the average amount found by Dicus et al. (1982). Our code also uses the updated (CF) reaction network rather than that used by KSS. In particular, the increases of the D(d, n) and D(d, p)

rates increase the ⁴He production. The total change due to both effects can be written as $\Delta Y \equiv Y_{WSSOK} - Y_{KSS} = \Delta Y_{CF} + \Delta Y_{weak} \simeq 6 \times 10^{-4} + 5 \times 10^{-4} \simeq 1.1 \times 10^{-3}$ (where WSSOK = this paper). For comparison, note that the 2 σ uncertainty in τ_n leads to $\Delta Y = \pm 1.4 \times 10^{-3}$.

To reiterate, since the predicted primordial abundances of D, ³He, and ⁷Li depend mainly on the nucleon abundance η , a comparison with the observed abundances of D, ³He, and ⁷Li will lead to bounds on the allowed range of η . In contrast, the predicted ⁴He mass fraction varies very slowly (only logarithmically) with η but does depend on τ_n and N_{ν} . Given the experimentally allowed (95% CL) range for τ_n , coupled with the range of η determined from D, ³He, and ⁷Li, the observations of ⁴He can be used to constrain N_{y} . In anticipation of these comparisons, we first turn to a discussion of the observations.

5. OBSERVATIONAL DATA

Crucial to testing the standard model, and to constraining nonstandard models, are the abundances of the light elements derived from the observational data. Furthermore, to test the theoretical predictions requires that the primordial abundances be extracted from the observations. Thus, any intrinsic observational uncertainties will be compounded by the uncertainties due to galactic chemical evolution. In the following we collect and review the best current data and, to the extent possible, try to infer 95% CL (~2 σ) bounds to the primordial abundances of D, ³He, ⁴He, and ⁷Li. Whenever possible, we will rely on model-independent bounds rather than claim a more stringent constraint which is model-dependent.

5.1. Deuterium and ³He

At relatively low temperatures ($\sim 6 \times 10^5$ K), deuterium is destroyed by (p, γ) reactions. Thus, any D which is cycled through stars will be completely burned away. Also, since D is so weakly bound, it is difficult to produce deuterium in significant quantities (i.e., comparable to the observed abundance) in any astrophysical environment (Epstein et al. 1976). As a result, a (virtually) model-independent assumption is that the primordial deuterium abundance is no smaller than the present, or the No. 1, 1991

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presolar, D abundance. Therefore, we will concentrate on deriving a *lower bound* to the primordial D abundance.

The extensive data on atomic hydrogen in the interstellar medium (ISM) was reviewed by Boesgaard & Steigman (1985). Comparing the D and H column densities for some two dozen lines of sight in the local ISM (≤ 1 kpc) reveals a linear $N_{\rm D}$

wersus $N_{\rm H}$ relation which corresponds to [D]_{ISM} = 7.2 ± 0.2 [here and below we use the notation [X] = 12 + log ($N_{\rm X}/N_{\rm H}$)]. Since the presolar D abundance should represent a sample

of the ISM 4.5 Gyr ago (when, it is reasonable to expect, less D would have been destroyed), we will bound the primordial D abundance with the presolar D abundance. However, since the Sun destroyed any initial deuterium during its pre-main-sequence evolution, we must infer the presolar D abundance indirectly. Indeed, since presolar D is burned to ³He via (p, γ) reactions, the solar ³He abundance should have increased from its presolar value. Thus, we need to compare "old" and "new" samples of ³He. The meteorites provide the sites for such a comparison. The smallest ³He abundances are found in the carbonaceous chondrites (CC), which provide a sample of the most primitive solar system material. The ³He/⁴He ratio derived from this sample (Frick & Moniot 1977; Eberhardt 1978) is

$$10^4 (y_3/y_4)_{\rm CC} = 1.52 \pm 0.04$$
 . (5)

(Here and subsequently, we use the notation $y_{\rm X} = N_{\rm X}/N_{\rm H}$.)

In contrast, higher ${}^{3}\text{He}/{}^{4}\text{He}$ ratios are found in gas-rich meteorites (GRMs) (Jeffrey & Anders 1970), lunar soil and breccias (Black 1972), and the solar wind (Geiss et al. 1970).

$$10^4 (y_3/y_4)_{\rm GRM} = 4.03 \pm 0.19$$
 . (6)

Following Black (1971) and Geiss & Reeves (1972), we identify the CC ³He abundance with the presolar ³He abundance, and the GRM abundance with the *sum* of presolar D plus ³He:

$$10^4 (y_{23}/y_4)_{\odot} = 4.03 \pm 0.19$$
, (7a)

$$10^4 (y_3/y_4)_{\odot} = 1.52 \pm 0.04$$
. (7b)

Therefore, we may infer that the presolar D abundance is equal to

$$10^4 (y_2/y_4)_{\odot} = 2.51 \pm 0.23$$
 (8)

We still need to know the solar ⁴He abundance $(y_{4\odot})$. The only direct observations are those of Heasley & Milkey (1978), who found in solar prominences $y_{4\odot} = 0.10 \pm 0.025$; for a solar metallicity $Z_{\odot} = 0.02$, this corresponds to $Y_{\odot} = 0.28 \pm 0.05$ for the helium mass fraction. Recent solar models (Bahcall & Ulrich 1988; Turck-Chièze et al. 1988) are consistent with this value and suggest a smaller range, $y_{4\odot} = 0.10 \pm 0.01$ ($Y_{\odot} = 0.28 \pm 0.02$), which we shall adopt here. Thus, our "95% CL" (~2 σ) ranges for presolar D and ³He are

$$1.8 \le 10^5 y_{2\odot} \le 3.3$$
, (9a)

$$1.3 \le 10^5 y_{3\odot} \le 1.8$$
, (9b)

$$3.3 \le 10^5 y_{23\odot} \le 4.9$$
 (9c)

In particular, we will require that the primordial abundance of D satisfy

$$y_{2n} \ge y_{20} \gtrsim 1.8 \times 10^{-5}$$
 (10)

Having bounded y_{2p} from *below*, we turn to the question of an *upper* bound. Any primordial D should either reside in the ISM (if it has not been cycled through stars) or have been destroyed. But deuterium is burned to ³He, and *some* ³He survives stellar processing (Yang et al. 1984, hereafter YTSSO). Therefore, although attempting to estimate how much D has been destroyed is model-dependent, the evolution of D plus ³He is less so. Dearborn, Schramm, & Steigman (1986) have estimated the survival fraction of ³He to be $g_3 \equiv N_{3f}/N_{23i} \approx \frac{1}{4} - \frac{1}{2}$, and YTSSO utilized a simplifed "one-cycle" approximation to Galactic evolution to derive

$$y_{23p} \le y_{23\odot} + (g_3^{-1} - 1)y_{3\odot} . \tag{11}$$

The inequality arises, in part, because of the neglect of ³He *production* in low-mass stars (Iben 1967a, b; Rood 1972). Using the upper bounds in equations (9b) and (9c) and taking $g_3 \ge \frac{1}{4}$, we find $10^5 y_{23p} \le 10$, consistent with the original bound of YTSSO.

However, we can be more realistic. In OSSW we replaced the "one-cycle" approximation with an "instantaneous recycling" approximation (IRA) which accounts for material that has been through more than one generation of stars. Again neglecting possible production of ³He (and possible infall), it can be shown that

$$X_{p} y_{23p} < A_{\odot}^{(g_{3}-1)} y_{23\odot} X_{\odot} , \qquad (12)$$

where $A_{\odot} \equiv X_{2\odot}/X_{2p}$ is the deuterium "astration" factor. To avoid overproduction of the heavy elements requires (Pagel 1989a) $A_{\odot} \gtrsim \frac{1}{3}$. To find an upper bound to $y_{23\odot} X_{\odot}$, note that $y_{4\odot} X_{\odot} = Y_{\odot}/4 \le 0.075$, so that with $g_3 \ge \frac{1}{4}$ and the upper bound on $(y_{23}/y_4)_{\odot}$ from equation (7a) we have,

$$X_n y_{23n} \le 7.5 \times 10^{-5} . \tag{13}$$

Note that the $Y_p \leq 0.25$ ($X_p \gtrsim 0.75$), equation (13) is consistent with the bound on y_{23p} derived from equation (11).

5.2. ⁷Li

The cosmological significance of ⁷Li increased enormously with the discovery (Spite & Spite 1982a, b) of lithium in halo (Population II) stars. This discovery has subsequently been confirmed by many observers who have detected lithium in several dozen metal-poor Population II stars. These Population II stars, if sufficiently warm ($T \gtrsim 5500$ K), have apparently not depleted their surface lithium (see Fig. 4), in contrast to Population I stars (e.g., the Sun) of similar temperatures. Thus, Spite & Spite (1982a, b) were led to suggest that these very old Population II stars provide a fair sample of the lithium abundance present during the early evolution of the Galaxy. The higher Population I lithium abundance then requires a production source(s), and Type II supernovae have recently been suggested (Dearborn et al. 1989; Woosley et al. 1990) as a possible site; an alternative source of lithium could be the super-Li-rich red giants (Smith & Lambert 1989) if this material is ejected into the interstellar medium.

This most natural hypothesis (primordial \approx Population II) finds support in the "Li plateau." In Figure 4 we show [Li] = 12 + log (Li/H) as a function of $T_{\rm eff}$ for the most metalpoor Population II stars ([Fe/H] ≤ -1.3). For the 35 stars with $T_{\rm eff} \geq 5500$ K, all abundances lie in the range $1.84 \leq [\text{Li}] \leq 2.32$ with a mean value of [Li] = 2.08 and a 1 σ scatter about the mean of ± 0.12 . This scatter is entirely consistent with the observational uncertainties, which range from ± 0.1 to ± 0.2 . Also shown in Figure 4 are those cooler (T < 5500 K) metal-poor stars which display the depletion pattern familiar from the Population I stars. The "plateau" for

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FIG. 4.—⁷Li abundance ([Li] = $12 + \log (\text{Li}/\text{H})$) in the most metal-poor ([Fe/H] ≤ -1.3) Population II stars as a function of T_{eff} . The filled diamonds are upper limits to Li. The crosshair shows the representative errors in [Li] and T_{eff} .

the warmer stars is very narrow in comparison to the range in [Li] for the cooler stars.

In Figure 5 we show the variation of [Li] with [Fe/H]; note the separation between the "warm" ($T_{\rm eff} > 5500$ K) stars and the "cool" ($T_{\rm eff} < 5500$ K) stars. In choosing our sample, which is detailed in Table 2, we have restricted attention to the

"extreme" Population II stars (i.e., most metal-poor). As is well known (e.g., Rebolo, Molaro, & Beckman 1988), as [Fe/H] increases, the [Li] versus [Fe/H] relation shows increasing dispersion (see Fig. 6). That [Li] increases with [Fe/H] can be understood as a consequence of lithium production during the course of Galactic evolution. That [Li] also



FIG. 5.—⁷Li abundance [Li] as a function of [Fe/H] for all stars with [Fe/H] ≤ -1.3 . The squares are the warmer (\geq 5500 K), and the circles are the cooler (\leq 5400 K) stars. The filled circles are for upper limits to Li; the filled squares are for upper limits to Fe; the filled diamonds are for upper limits to Li and Fe.

 TABLE 2

 Lithium in Metal-poor Halo Stars

Star	T _{eff} (K)	[Fe/H]	[Li]	References*
G64-12	6267	-3.5	2.19	HP, RBM, SSPC
LP 608–62	6250	-2.7	2.20	HD
HD 84937	6226	-2.1	2.11	SS, HD, B
HD 74000	6223	-1.8	2.16	SS
BD 3°740	6190	-2.9	2.12	HP, RMB
BD 72°94	6160	-1.8	2.22	RMB
BD 34°2476	6119	-2.3	2.14	SS, HP
BD 20°3603	6019	-2.3	2.10	SS, HD
BD 26°2606	5980	<-2.2	2.24	RMB
BD 42°2667	5950	-1.7	2.12	RMB
BD - 10°388	5950	-2.2	2.18	RMB
HD 16031	5929	-2.2	2.03	SMS
BD 21°607	5929	-1.6	1.98	SMS
BD 26°3578	5914	-2.4	1.84	SMS, HD
BD 9°352	5870	-2.2	2.12	RMB
HD 108177	5869	-1.9	2.00	SS
HD 166913	5861	-1.8	2.17	ŝŝ
HD 160617	5861	-1.6	2.20	ŝŝ
BD 17°4708	5850	-1.9	1 94	HD RMB
BD 59°2723	5830	-1.6	1.95	RMB
HD 94028	5827	-1.7	2 10	SS HD
BD 2°3375	5820	< -2.5	2.10	RMB
HD 201891	5818	-1.3	1.98	SS. HD. RMB
HD 194598	5808	-1.6	20	SS, TID, TRUD
HD 134169	5797	-1.6	2.0	SS HD
BD 2°4651	5794	-2.3	1.92	SMS
HD 19445	5789	-2.1	2 07	SS HD RMB
HD 219617	5784	-1.4	2.18	SS HD RMB
BD 29°2091	5670	-2.1	2.10	RMB
BD 4°4551	5670	-1.7	1.88	RMB
HD 189558	5662	-1.3	2.04	SMS
BD 23°3912	5658	-1.5	2.36	SMS RMB
G238-30	5600	- 3.0	1 84	HP
HD 140283	5591	-2.4	2.06	SS HD RMB
HD 132475	5550	-1.6	2.00	RMB
HD 64090	5363	-1.8	1 16	SS HD RMB
HD 188510	5297	-1.8	1 43	SS, HD, RHD
BD 66°268	5240	< -2.5	<11	RMB
HD 211998	5200	-15	1.1	SS
$BD = 0^{\circ}4470$	5200	-14	1.04	SMS
HD 128279	5180	_23	<10	DDK
BD 38°4955	5080	-25	< 1.0	RMB
HD 103095	5070	-14	< 0.45	SS HD
HD 25329	4842	-18	< 0.43	SMS
HD 122563	4400	_27	< -0.4	HD
1120 122303	7700	- 4.1	< 0. 4	

^a References: $B \equiv Boesgaard 1985$; $BRM \equiv Beckman$, Rebolo, Molaro 1986; $DDK \equiv Deliyannis$, Demarque, & Kawaler 1990; $HD \equiv Hobbs \&$ Duncan 1987; $HP \equiv Hobbs \&$ Pilachowski 1988; $RMB \equiv$ Rebolo, Molaro, & Beckman 1988; $SMS \equiv$ Spite, Maillard, & Spite 1984; $SS \equiv$ Spite & Spite 1986; $SSPC \equiv$ Spite et al. 1987.

decreases with [Fe/H] is most likely due to stellar destruction of lithium occurring in warmer stars as the metallicity increases. To obtain a good sample of the oldest stars, in which both these effects are absent or, at least, minimized, we restrict our attention to the most metal-poor Population II stars ([Fe/ H] ≤ -1.3). Our sample (with the exception of our cool stars) is almost the same as the "Group A" stars of Deliyannis, Demarque, & Kawaler (1990), who require [Fe/H] ≤ -1.3 , $V_{LSR} \geq 160 \text{ km s}^{-1}$, and $T_{eff} \geq 5500 \text{ K}$.

That the plateau is so narrow (i.e., its dispersion is consistent with observational uncertainty) supports the original claim of Spite & Spite (1982a, b) that the lithium observed in the hotter Population II dwarfs is a measure of the primordial abundance. For the 35 stars with $T_{eff} \ge 5500$ K, the weighted (by the quoted uncertainties for [Li] in each observation) mean value is

$$\langle [Li] \rangle = 2.08 \pm 0.07$$
, (14)

where the dispersion is the 2σ error in the mean.

There still remains the question whether the observed lithium in those (Population II) stars provides a fair sample of the lithium abundance in the nearly primordial gas out of which these stars formed. That is, could lithium have been depleted during the evolution of even the warmer ($T \gtrsim 5500$ K), extreme Population II ([Fe/H] ≤ -1.3) stars? Although Vauclair (1988) suggests the depletion could be important, detailed calculations of Deliyannis et al. (1990) suggest otherwise. From their standard main-sequence isochrones which yield the best fit to the data, Deliyannis et al. (1990) conclude that the plateau stars are essentially undepleted in lithium, and they derive an upper limit (2 σ) of [Li] \leq 2.21. Although their nonstandard isochrones which allow diffusion yield poorer, but acceptable, fits to the lithium data, Deliyannis et al. (1990) still conclude that very little lithium depletion is allowed: [Li] $\leq 2.36 (2 \sigma)$. Including the nonstandard diffusion models, Deliyannis et al. (1990) find, for the 95% CL range of the pre-Population II lithium abundance,

$$2.04 \le [Li] \le 2.36$$
 . (15)

Since, however, the "best-fit" isochrones of Deliyannis et al. (1990) are consistent with very little lithium depletion, we adopt here the observationally determined "plateau" value for the bound to the primordial abundance. In subsequent comparisons we will take for the "95% CL" upper bound

$$[Li] \le 2.15$$
 . (16)

5.3. ⁴He

Finally, we turn to the most abundant element (after hydrogen) to emerge from the early universe. The abundance of ⁴He has been determined from observations of young stars, old stars, planetary nebulae and Galactic and extragalactic H II regions (cf. Boesgaard & Steigman 1985). Since helium is so abundant, it can be observed throughout the universe, and its abundance can be determined more accurately than that of any of the other light elements. However, since (many) stars generate their energy by burning hydrogen to helium, the primordial abundance of ⁴He has been contaminated by the debris of Galactic evolution. Therefore, to better approach the uncontaminated primordial abundance, it is best to restrict attention to helium observations in metal-poor environments. That means concentrating on extragalactic H II regions.

Helium is observed in H II regions via its recombination radiation. For detailed discussions of the observational techniques—and their uncertainties—see Davidson & Kinman (1985), Davidson, Kinman, & Friedman (1989), and Pagel & Simonson (1989). Here we only comment on two of the potential problems. Since helium is revealed via its recombination radiation, neutral helium is invisible. Thus, it is necessary either to use a theoretical model of the H II region to estimate the He I contribution or, as is more common, to restrict attention to hotter, higher excitation H II regions and to neglect the He I contribution. It is not always easy to estimate the uncertainty associated with this neglect, and, indeed, Dinerstein & Shields (1986) have shown that, under special circumstances, it could be substantial. Another difficulty in deriving accurate 60



FIG. 6.—⁷Li abundance [Li] as a function of [Fe/H] for all stars with $T_{eff} \ge 5500$ K (cf. Rebolo et al. 1988). The filled symbols are for upper limits to Li.

helium abundance estimates is that, for high-temperature and -density H II regions, collisonal excitation may compete with radiative transitions in determining the populations of excited states in ionized helium (Ferland 1986). To correct for this effect it is necessary to determine the electron density (and temperature), which is not always easy to do (Pagel 1988). Further, the initial estimate of this effect (Ferland 1986) was too large by ~50% to a factor of 2 (Péquignot, Baluteau, & Grunwald 1988; Berrington & Kingston 1987; Clegg 1987). Although the correction is typically only a few percent, the uncertainty in the correction is of comparable size.

In Table 3 we list the abundance of ⁴He, C, N, O derived from observations of the most metal-poor extragalactic H II regions. This table is largely taken from Pagel's (1988) compilation, updated by the newer data of Pagel & Simonson (1989). Pagel's data set contains 33 metal-poor extragalactic H II regions, including those studied by Kunth & Sargent (1983). Pagel (1988) reanalyzed the original data, starting from the spectral line strengths and using a common set of atomic data. To Pagel's data set we have added three additional H II regions: I Zw 18, NGC 5471, and CG 1116+51; I Zw 18 is the most metal-poor H II region yet observed. Further, for the oxygen and nitrogen abundances in the SMC, we adopted the results of Dufour, Schiffer, & Shields (1985, hereafter DSS) and Peimbert, Peña, & Torres-Peimbert (1986, hereafter PPT-P). We also included the DSS value for O/H in NGC 2363. The helium mass fractions (Y) have, in general, been corrected by Pagel (1988) for collisional excitation, but Pagel has assumed that the possible neutral helium contribution can be ignored. Also, in using the ⁴He/H ratios to infer Y, the heavy-element mass fraction, Z, has been ignored. In Figures 7-10 we plot Y as a function of the oxygen, nitrogen, and carbon abundances and of the N/O ratio.

Even for these low-metal abundance H II regions, it is still necessary to correct for the evolution of ⁴He. Peimbert & Torres-Peimbert (1974) originally suggested correlating Y with O/H, and, until very recently, this has remained the most frequent approach to deriving the primordial helium mass fraction. The helium/oxygen data set is, indeed, strongly correlated; for the 36 data points the linear correlation coefficient is r = 0.55, which would have a probability P < 0.001 if they were drawn from an uncorrelated parent population (Bevington 1969). A linear fit to the data in Table 3 (using the errors listed in the table) which minimizes χ^2 yields

$$Y = 0.226 \pm 0.005 \pm (1.6 \pm 0.4) \times 10^{2} (\text{O/H}) .$$
(17)

This fit has a reduced χ^2 of 0.57.

However, despite the small value of the reduced χ^2 , it is our opinion that some of the error estimates in Table 3 may be unrealistically small and could give excess weight to a handful of H II regions. As an example, doubling the error estimate (for Y) for T1214–227 increases the intercept in equation (17) to 0.228 ± 0.005 , and excluding this H II region entirely results in $Y_p = 0.229 \pm 0.005$. Recently, Davidson et al. (1989) have paid special attention to estimating errors in their very careful study of I Zw 18. Because of their conservative error estimate, $\sigma_Y = \pm 0.016$, this most metal-poor H II region has relatively little weight in our linear Y versus O/H fit. To attempt to correct for this possible inequity, we have also analyzed the data by assigning an equal uncertainty, which we have arbitrarily chosen to be $\sigma_Y = \pm 0.009$, to all entries in Table 3. With this prescription we now find [for $0.14 \le 10^4$ (O/H) ≤ 2.15]

$$Y = 0.229 \pm 0.004 + (1.3 \pm 0.3) \times 10^{2} (\text{O/H}) .$$
(18)

The reduced χ^2 of this fit is 0.95.

H II REGION ABUNDANCES⁸

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H II Region	10 ⁶ O/H	10 ⁷ N/H	10 ⁶ C/H	Y
I Zw 18	14 ± 2	4 ± 1	5.5 ± 4	0.234 ± 0.016
Tol 65	33 ± 4	5 ± 1		0.224 ± 0.014
T1214-227	40 ± 3	10 ± 7		0.224 ± 0.008
CG 1116 + 51	48 ± 6	9 ± 4		0.251 ± 0.018
T1304-353	49 ± 6	20 ± 7		0.233 ± 0.014
POX 186	52 ± 8	24 ± 7		0.244 ± 0.013
C1543+091	57 ± 5	21 ± 7		0.240 ± 0.012
UM 461	66 ± 5	17 ± 5		0.233 ± 0.007
POX 120	70 ± 5	32 ± 4		0.247 ± 0.013
POX 105	73 ± 15	30 ± 3		0.228 ± 0.014
NGC 2363	85 ± 8	28 ± 3	24 ± 4	0.230 + 0.014
SMC	87 + 13	26 + 5	14 + 4	0.242 + 0.007
POX 4	89 + 5	34 + 3		0.237 + 0.006
T1304-386	92 + 6	60 + 4		0.253 + 0.009
POX 139	95 + 9	32 + 3		0.255 + 0.011
C1148-2020	96 + 8	34 + 3		0.240 + 0.007
POX 4NW	98 + 12	17 + 4		0.228 + 0.017
F30	99 + 7	44 + 3		0.237 ± 0.016
POX 108	102 + 8	52 + 7		0.233 ± 0.009
NGC 4861	104 + 10	16 + 7	19 + 10	0.230 ± 0.015
CS 0341 – 4045E	110 + 10	27 + 8		0.244 + 0.018
NGC 5471	112 + 14	52 + 15	38 + 30	0.242 + 0.007
UM 439	114 + 8	38 + 6		0.225 ± 0.020
Tol 35	128 + 13	34 + 4		0.257 + 0.016
II Zw 40	128 ± 9	71 ± 4		0.251 + 0.009
II Zw 40	130 ± 6	76 ± 8		0.251 ± 0.009
NGC 5253A	137 ± 15	110 ± 15		0.262 + 0.007
II Zw 70	140 + 15	41 + 5		0.246 + 0.020
Tol 35	141 ± 12	55 + 4		0.257 + 0.011
T0633-415	144 ± 2	59 ± 9		0.248 + 0.009
POX 36	156 ± 15	43 ± 4		0.239 + 0.018
NGC 6822V	158 ± 20	40 ± 10		0.244 + 0.012
NGC 6822X	180 ± 20	30 ± 10		0.253 ± 0.012
Tol 3	185 ± 14	77 ± 5		0.250 ± 0.010
Tol 3	193 ± 18	73 ± 8	•••	0.250 ± 0.013
LMC	215 + 15	80 + 20	63 ± 16	0.252 ± 0.009

^a The data in this table were obtained from Davidson et al. 1989, Dinerstein & Shields 1986, Dufour Shields, & Talbot 1982, Dufour, Garnett, & Shields 1988, Pagel et al. 1986, Pagel 1988, Pagel & Simonson 1989, Peimbert & Torres-Peimbert 1974, Peimbert et al. 1986, Rosa & Mathis 1987, and Torres-Peimbert, Peimbert, & Fierro 1989.

An alternative approach to Y_p would be to restrict attention to the most metal-poor of the H II regions. The mean of the ⁴He mass fraction for these objects would then provide an upper bound to the primordial abundance: $Y_p \leq \langle Y \rangle$. For example, for the 20 H II regions with $10^4(O/H) \leq 1.0$, $\langle Y \rangle = 0.237 \pm 0.004$; for the 10 H II regions with 10⁴(O/ H) $\leq 0.8, \langle Y \rangle = 0.236 \pm 0.005.$

Although a linear Y versus O/H relation is simplest (fewest adjustable parameters), it is far from clear that it is "physical" (Steigman, Gallagher, & Schramm 1989). The reason is that oxygen is produced only by massive stars ($\gtrsim 12 M_{\odot}$), while ⁴He is contributed by all stars ($\gtrsim 2 M_{\odot}$). Since nitrogen and carbon are produced in intermediate-mass stars, it might be expected that N and/or C would correlate better with helium (Pagel, Terlevich, & Melnick 1986; Steigman et al. 1989). Indeed, the Y versus N/H data set has a linear correlation coefficient r = 0.63 (very highly correlated; $P \leq 10^{-4}$). The linear fit (with $\sigma_{\gamma} = \pm 0.009$) which minimizes χ^2 yields

$$Y = 0.231 \pm 0.003 + (2.8 \pm 0.7) \times 10^{3} (N/H)$$
. (19)

The reduced χ^2 of this fit is 0.81. If instead of equal errors in Y we had used the quoted errors (Table 3), we would have found

$$Y = 0.230 \pm 0.004 + (3.0 \pm 0.7) \times 10^{3} (\text{N/H}) .$$
 (20)

For this latter fit the reduced χ^2 is 0.41.

For the 20 H II regions with $10^{6}(N/H) \le 3.4$, the mean helium abundance is $\langle Y \rangle = 0.239 \pm 0.004$; for the 10 H II regions with $10^{6}(N/H) \le 2.4, \langle Y \rangle = 0.234 \pm 0.005$.

To test the robustness of the Y versus N/H correlation, we have divided the data into nine overlapping bins (in N/H), each containing eight H II regions. We have then chosen the second and third lowest values of Y in each bin and compared Y with $\langle N/H \rangle$, the average nitrogen abundance for that bin. For the second-ranked correlation we find r = 0.97 and $\Delta Y/$ $\Delta \langle N/H \rangle = 3.3 \times 10^3$, in agreement with equations (19) and (20). For the third-ranked correlation, r = 0.93 and $\Delta Y/$ $\Delta \langle N/H \rangle = 2.9 \times 10^3$. These comparisons suggests that the correlations found earlier are not an artifact of a systematic bias in the data (B. J. T. Jones 1990, private communication; Hawkins 1980).

There are only six extragalactic H II regions with carbon abundances determined. Further, since UV and optical observations (made with different telescopes, detectors, etc.) are required to derive the carbon abundance, carbon abundances are quite uncertain. Nonetheless, since it would be very valuable to correlate Y with C/H (Steigman et al. 1989), we show the existing data in Figure 9. This data set has a correlation

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 10^6 O/H FIG. 7.—⁴He mass fraction, Y, observed in extragalactic H II regions vs. observed oxygen abundance (see Table 3)

coefficient r = 0.75. A linear fit to the data (with $\sigma_{\gamma} = 0.009$) yields [for $0.6 \le 10^{5}$ (C/H) ≤ 6.3]

γ

$$Y = 0.230 \pm 0.007 + (3.1 \pm 2.2) \times 10^{2} (C/H) .$$
 (21)

The reduced χ^2 of this fit is 0.47.

N/O. In Figure 10, Y is plotted against N/O. The data have We have also looked for a possible correlation of Y with

a correlation coefficient of r = 0.43 ($P \approx 0.01$) and a twoparameter fit, with a reduced χ^3 of 1.03, is $Y = 0.227 \pm 0.005 + (0.42 \pm 0.12)$ N/O. Finally, for general information, we show in Figure 11 the N/O ratio versus O/H; this comparison has a correlation coefficient of only r = 0.14.

To summarize, our linear fits of Y (with $\sigma_Y = 0.009$) and O, N, C have led to the following estimates of the primordial



10⁷ N/H

FIG. 8.—⁴H mass fraction, Y, observed in extragalactic H μ regions vs. observed nitrogen abundance (see Table 3)



10⁶ C/H

FIG. 9.—⁴He mass fraction, Y, observed in extragalactic H II regions vs. observed carbon abundance (see Table 3)

helium abundance:

O:
$$Y_p = 0.229 \pm 0.004$$
, (22a)

N:
$$Y_p = 0.231 \pm 0.003$$
, (22b)

C: $Y_p = 0.230 \pm 0.007$. (22c)

The above are all consistent with $Y_p = 0.23 \pm 0.01$. The real question is, what is the true uncertainty in this estimate? Can

we determine the third decimal place in the bounds to Y_p ? A corollary question is, what should we take as the "95% CL" upper limit to the primordial abundance of helium? Until the many possible systematic effects (ionization corrections, collisional excitation corrections, nonlinear detectors, etc.) are sorted out, these questions are difficult to answer quantitatively, especially if we want Y_p to 3 significant figures. In subsequent comparisons with the predicted abundance, we will



FIG. 10.—⁴He mass fraction, Y, observed in extragalactic H II regions vs. observed ratio of nitrogen to oxygen

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10⁶ O/H Fig. 11.—The ratio N/O vs. O/H

choose the upper bound $Y_p \le 0.240$, keeping in mind that the uncertainty in this upper bound may be of the order of ± 0.005 .

6. COMPARISON WITH THE STANDARD MODEL

We are now in a position to confront the predictions of the standard model ($N_v = 3$, $882 \le \tau_n \le 896$) with the observational data. Initially, we will examine D, ³He, and ⁷Li to see whether there is a range of baryon densities (i.e., η -values) for which the predictions are in concordance with our adopted 95% CL bounds to the primordial abundances. Then we will turn to ⁴He, where a comparison between theory and observations will permit us to bound the effective number of light neutrinos, N_v .

The meteoritic data have provided a lower bound to the deuterium abundance in the presolar nebula ($y_2 \ge 1.8 \times 10^{-5}$), which, since D is only destroyed, bounds the primordial abundance from below ($y_{2p} \ge y_{2\odot}$). To satisfy this bound (see Fig. 2) requires

D:
$$\eta_{10} \le 6.8$$
. (23)

The same meteoritic data, coupled to estimates of the ³He survival fraction (Dearborn et al. 1986), permitted us to place an upper bound on the sum of the primordial abundances of D plus ³He ($10^5y_{23p} \le 10$; $10^5X_py_{23p} \le 7.5$). This bound is satisfied (see Fig. 2) for

D + ³He:
$$\eta_{10} \ge 2.8$$
. (24)

Next, we turn to ⁷Li. From our discussion of the observations of Population II stars, we have adopted a 95% CL upper limit: $[Li]_p \leq 2.15$. This limit is, indeed, consistent (see Fig. 1) with the abundances predicted for η in the range allowed by the D and ³He abundances ($2.8 \leq \eta_{10} \leq 6.8$). However, the lithium constraint by itself selects a somewhat different range for η . For CF (see Fig. 1b), [Li] ≤ 2.15 is satisfied when

Li(CF):
$$1.9 \le \eta_{10} \le 3.3$$
. (25)

If, however, we allow for the 40% residual uncertainty in lithium production, this range extends to

$$1.6 \le \eta_{10} \le 4.0$$
 . (26)

Until the residual uncertainties in the predicted lithium abundance are reduced further, we will adopt $1.6 \le \eta_{10} \le 4.0$ as the ("95% CL") range consistent with the Population II lithium abundances.

Thus, combining the constraints from D, ³He, and ⁷Li, we find that the predictions of the standard model are consistent with the observationally inferred primordial abundances (or, bounds thereof) for a very limited range of nucleon densities:

D, ³He, ⁷Li:
$$2.8 \le \eta_{10} \le 4.0$$
. (27)

For our comparison with ⁴He, we will restrict our attention to this concordant range.

For the standard model ($N_v = 3$, $882 \le \tau_n \le 896$) with η in the above range, the predicted ⁴He primordial mass fraction lies in the range (see Fig. 3)

$$0.236 \le Y_p^{\text{BBN}} \le 0.243$$
 . (28)

In our discussion of the data we noted that the observations were consistent with $Y_p^{obs} = 0.23 \pm 0.01$. Clearly, there is complete agreement between theory and observations. The standard model successfully accounts for the observed abundances of *all* the light elements.

Can we use the ⁴He data to bound the nucleon density? In principle, yes, but the logarithmic dependence of Y_p on η (see eq. [4]) requires a highly accurate upper bound to the ⁴He abundance, since

$$\Delta \eta_{10} \approx 1000 \eta_{10} \Delta Y_n \,. \tag{29}$$



FIG. 12.—Predicted abundances (by number) of D, D + ³He, and ⁷Li, and the ⁴He mass fraction as a function of η for $N_{\nu} = 3$ and $\tau_n = 889$ s for $0.1 \le \eta_{10} \le 100$. The vertical band delimits the range of η consistent with the observations.

Since $N_{\nu} \geq 3$ (assuming $m_{\nu\tau} \lesssim a$ few MeV; the inequality is because BBN is sensitive to particles which could be undetected at SLC and LEP) and $\tau_n \geq 882$, we see from equation (4) that

$$Y_p \ge 0.227 + 0.010 \ln \eta_{10} , \qquad (30)$$

so that, for $Y_p \le 0.240$, we find $\eta_{10} \le 4$. If, however, we choose for the observational upper bound to the primordial helium abundance $Y_p \le 0.245$ (0.235), this bound on the nucleon density changes to $\eta_{10} \le 6$ (2).

The above results are displayed in Figures 12 and 13, where the predicted abundances of all the light elements are shown (for $N_v = 3$, $\tau_n = 889 \pm 7$ s) along with the bands allowed by the observations. The range $2.8 \le \eta_{10} \le 4.0$ is consistent with all the data (for values of τ_n toward the *high* end of the allowed range, consistency with ⁴He requires that η be near the *low* end of its range). In the next section we will explore the consequences of this concordance and probe the viability of models which deviate from the standard model.

7. DISCUSSION

In this section we consider the consequences, for particle physics and cosmology, of the consistency of the standard model. Then we will examine alternative models for cosmological nucleosynthesis and test their consistency by comparing their predictions with the observational data.

7.1. The Standard Model

Since nucleon-to-photon ratio is (virtually) unaltered from the epoch of primordial nucleosynthesis to the present, the bounds (eq. [27]) on η translate into bounds on the current density of baryons,

$$n_B = \eta n_{\gamma} = 20.3 T^3 \eta \; (\text{cm}^{-3}) \; , \tag{31}$$



FIG. 13.—Predicted abundances (by number) of D, ³He, D + ³He, and ⁷Li, and the ⁴He mass fraction as a function of η for $N_{\nu} = 3$ and $882 \le \tau_n \le 896$ s. The 95% CL bounds on the abundances (see text) are shown. The vertical band delimits the range of η consistent with the observations.

where T is in kelvins. Comparing the baryon mass density $(\rho_B = M_N n_B)$ with the critical mass density $(\rho_c = 3H_0^2/8\pi G)$ yields

$$\Omega_B h_{50}^2 = 0.015 T_{2.75}^3 \eta_{10} , \qquad (32)$$

where $\Omega_B = \rho_B/\rho_c$, the present value of the Hubble parameter is $H_0 = 50h_{50}$ km s⁻¹ Mpc⁻¹, and the present cosmic background radiation temperature is $T = 2.75T_{2.75}$ K. Palazzi et al. (1990) find that all recent data at $\lambda \ge 1$ mm are consistent with $T = 2.78 \pm 0.01$ K. The new results from *COBE* (Mather et al. 1990), $T = 2.735 \pm 0.06$ K, have large residual uncertainties. They are, however, entirely consistent with the conclusions of Gush, Halpern, & Wishnow (1990), who find $T = 2.736 \pm 0.017$ K. The 95% CL range consistent with a weighted average of these data is 2.75 K $\le T \le 2.79$ K. For T in this range,

$$0.015\eta_{10} \le \Omega_B h_{50}^2 \le 0.016\eta_{10} . \tag{33}$$

For our allowed range of nucleon densities $(2.8 \le \eta_{10} \le 4.0)$, we obtain

$$0.04 \le \Omega_B h_{50}^2 \le 0.06 \ . \tag{34}$$

The uncertainty in the true value of the Hubble parameter prevents us from deriving an accurate estimate of Ω_B . It is not excluded that H_0 could be as low as ~40 km s⁻¹ Mpc⁻¹ (Sandage 1988; Steigman 1989b; Wheeler 1989). For $h_{50} \ge 0.8$,

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we bound Ω_B from *above*:

$$\Omega_B \le 0.10 . \tag{35}$$

At the other extreme, if we were to adopt $H_0 \le 100$ km s⁻¹ Mpc⁻¹, we would derive a *lower* bound,

$$\Omega_B \ge 0.01 \ . \tag{36}$$

However, within the context of the standard model (i.e., zero cosmological constant), a Hubble parameter as large as 100 km s⁻¹ Mpc⁻¹ is almost certainly excluded, since it corresponds to a "young" universe; $t_0 \leq H_0^{-1} \leq 9.8$ Gyr for $H_0 = 100$. Indeed, if we adopt the popular assumption ("naturalness/inflation") that $\Omega_{\text{TOT}} = 1$, then $t_0 = (2/3)H_0^{-1} \approx 13h_{50}^{-1}$ Gyr. For $t_0 \gtrsim 10$ (13) Gyr, the Hubble parameter is then bounded from above by $h_{50} \leq 1.3$ (1.0), and

$$\Omega_B \gtrsim 0.02 \ (0.04)$$
 . (37)

It is clear from the above that the universe fails to be "closed" by baryons by at least a factor of 10. If, indeed, $\Omega_{\text{TOT}} = 1$, nonbaryonic matter is required. However, our lower bounds to Ω_B strongly suggest that most of the nucleons in the universe are "dark." For example, if the mass-to-light ratio inferred from the *luminous* matter in galaxies (Faber & Gallagher 1979; Pagel 1989b) is typical of the matter throughout the universe,

$$\Omega_{\rm LUM} \lesssim 0.007 \ . \tag{38}$$

Comparing equations (34) and (38) reveals that at least a significant fraction of the nucleons in the universe are dark.

$$\Omega_B/\Omega_{\rm LUM} \gtrsim 6h_{50}^{-2} . \tag{39}$$

Is nonbaryonic matter *required*? Here the answer is less clear. The data on rich clusters and large-scale flows suggests $\Omega_{\rm TOT} \gtrsim 0.2 \pm 0.1$. It is very suggestive, but, we think, not yet mandatory, that the universe is dominated by nonbaryonic dark matter.

Another constraint which emerges from the consistency of the standard model is the upper bound on N_v . In Figure 14 we show in detail the predicted Y_p versus η relation for 882 s $\leq \tau_n \leq 896$ s. Y_p is shown for the standard model ($N_v = 3.0$) and for $N_v = 3.3$. Also indicated is the "95% CL" range of η_{10} ; the dashed line corresponds to the constraint $Y_p \leq 0.240$. A more detailed comparison between theory and observation reveals the bounds

$$Y_p \le 0.240; \quad N_y \le 3.3$$
 (40)

Notice that (cf. eq. [4]), for fixed Y_p and η_{10} , the uncertainty in the bound to N_v due to the uncertainty in the neutron lifetime is $\delta N_v = 0.017 \, \delta \tau_n \approx 0.12$. The BBN bounds to N_v are clearly sensitive to the precise value of the upper bound to Y_p derived from the observations; it would be very valuable to reduce the *uncertainty* in this upper bound. The upper bound to N_v also depends on the *lower* bound to η . This constraint on η was derived from the requirements that ³He not be overproduced when primordial D is burned in stars. Detailed modeling of the Galactic evolution of D and ³He would be very useful (Steigman & Tosi 1990). For example, if we were to employ the stronger constraint (YTSSO), $10^5 y_{23p} \leq 6$, then $\eta_{10} \geq 4$ and $Y_p > 0.240$. This would lower our upper bound to $N_v \leq 3.0$.

Although the current SSG bound (eq. [40]) on N_v is consistent with the new accelerator limits, $N_v = 3.10 \pm 0.09$ (ALEPH



FIG. 14.—Shaded bands are predicted ⁴He mass fractions vs. η for the neutron lifetime in the range $882 \le \tau_n \le 896$ s and $N_v = 3.0$ and 3.3. The dashed line is the upper bound, $Y_p = 0.240$. The vertical band is the 95% CL range in η derived from the D, ³He, and ⁷Li data.

1989; DELPHI 1989; L3 1989; OPAL 1989; Mark II 1989; Jarlskog 1990), it is worth noting that the cosmological and accelerator bounds are complementary (Schramm & Steigman 1984). Any lights (≤ 1 MeV) particles, regardless of their coupling to the Z⁰, are counted cosmologically. In contrast, the accelerator tests count even very massive particles ($\leq m_{Z^0}/2$), but only if they couple with full (nearly full) strength to the Z⁰. For example, in many extensions of the standard particle physics model there are, in addition to the usual three lefthanded neutrinos (v_e , v_{μ} , v_{τ}), three right-handed neutrinos which couple to a new, heavier Z' gauge boson. Our bound, $N_{\nu} \leq 3.3$, then restricts the Z' to be very heavy: $m_{Z'} \gtrsim 2$ TeV. This bound from BBN (which however, is model-dependent) exceeds the current accelerator limits (Collider Detector Facility [CDF] at Fermilab) on $M_{Z'}$ of $\gtrsim 400$ GeV.

Alternatively, our bound $N_{y} \leq 3.3$ can be used to constrain the properties (or existence!) of any new, superweakly interacting particles (Steigman, Olive, & Schramm 1979; Olive, Schramm, & Steigman 1981). To see this, recall that the "usual" weakly interacting particles (coupling with full strength to the Z^0 and/or W^{\pm}) decouple at a temperature of a few MeV. A more weakly interacting particle will decouple earlier, at a higher temperature. If the decoupling temperature, T_D , is sufficiently high ($\gtrsim 100$ MeV), these superweak particles will—by the epoch of nucleosynthesis—be diluted by the entropy produced in the decay and/or annihilation of heavy particle species (muons, pions, etc.; see Steigman et al. 1979). In Figure 15 we show the bound on N—the equivalent number of (two-component) light neutrinos-as a function of the decoupling temperature. Significant entropy production, and hence dilution, is associated with the quark-hadron transition. The two curves in Figure 15 show N versus T_D for two possible quark-hadron transition temperatures.

Finally, we note that if the tau neutrino should prove very massive (e.g., $m_{\rm vr} \gtrsim 20$ MeV), it would not contribute to $N_{\rm v}$ and the "standard" model would have $N_{\rm v} = 2$. However, if $m_{\rm vr} \sim 10$ MeV, the tau neutrino could actually have a greater effect on the universal expansion rate at the epoch of nucleo-



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FIG. 15.—Bound on the equivalent number of two-component light neutrinos as a function of the decoupling temperature T_D . The two curves are for quark-hadron transition temperatures of 150 and 400 MeV.

synthesis, and the "effective" N_{ν} would, in this case, exceed 3 (Kolb & Scherrer 1982).

In YTSSO and in Boesgaard & Steigman (1985), the relic abundances of the light elements were used to constrain and/or exclude nonstandard cosmologies. Here we will consider two recent proposals: inhomogeneous nucleosynthesis (Applegate et al. 1988; Alcock, Fuller, & Mathews 1987) and nucleosynthesis initiated by the decay of a massive particle (Dimopoulos et al. 1988).

7.2. Inhomogeneous Nucleosynthesis

When the early universe cooled below ~ 200 MeV, the quark-hadron transition occurred. If this (or the related chiral symmetry breaking) is a first-order phase transition, the result might be a universe with large baryon inhomogeneities (Witten 1984; Crawford & Schramm 1982; Kaputsa & Olive 1988). At early times ($T \gtrsim 1$ MeV) neutrons and protons interconvert rapidly. However, for lower temperatures, neutrons and protons have "frozen out" and, since neutrons interact more weakly than protons with the e^{\pm} plasma, neutrons can diffuse much farther than protons, resulting in an inhomogeneous neutron-to-proton ratio. The result will be high-density, proton-rich regions, separated by low-density, neutron-rich regions. Nucleosynthesis in these regions is very different from that in the "standard" model and, initially, led to the hope that an $\Omega_B = 1$ universe might be reconciled with the observed abundances of the light elements (Applegate et al. 1988; Alcock et al. 1987). This hope has proved illusory (Kurki-Suonio et al. 1990). The problem is that nucleosynthesis begins earlier in the high-density regions, depleting them of free neutrons. The resulting neutron gradient drives a back diffusion of neutrons (Malaney & Fowler 1988), leading to the overproduction of ⁴He (Terasawa & Sato 1989; Kurki-Suonio & Matzner 1990). An associated problem is that mass 7 is produced in the highdensity, proton-rich regions (as ⁷Be) and in the low-density, neutron-rich regions (as ⁷Li), resulting in overproduction of primordial ⁷Li as well. The overproduction of ⁴He and ⁷Li has been further verified in the recent calculations of Mathews et al. (1990). Calculations which include back diffusion of neutrons suggest that the allowed range of nucleon-to-photon ratios is increased, in the inhomogeneous case, by at most a factor of 2 over that for the "standard" model.

7.3. Decaying Particles

The existence of a massive particle whose density dominates that of the relativistic particles present during BBN speeds up the universal expansion, resulting in abundances inconsistent with those observed. In particular, ⁴He is overproduced. If, however, when this hypothetical massive particle later decays, its hadronic decay products break up the previously synthesized nuclei and initiate a new round of nucleosynthesis, it may be possible to reproduce the observed abundances, even if $\Omega_{B} = 1$. This scenario has been investigated by Dimopoulos et al. (1988), who find that the uncertainties in the relevant nuclear reaction rates are sufficiently large that it is very difficult to make absolute abundance prodictions. As a result, this exotic scenario may not be easy to rule out (or in!). However, Dimopoulos et al. (1988) argue that they can predict abundance ratios (³He/D, ⁶Li/⁷Li) with greater certainty; this may well prove to be the Achilles heel of this model. In this scenario, more ³He than D is produced, and more ⁶Li than ⁷Li is produced. The absence of detectable ⁶Li (Pilachowski, Hobbs, & DeYoung 1989) argues against this scenario. Although the fact that ⁶Li is burned away in stars at a lower temperature than ⁷Li makes the interpretation of the data complicated, Brown & Schramm (1988) argue that the stars observed by Pilachowski et al. (1989) should not have destroyed ⁶Li if it was present when they formed. Perhaps more serious is the predicted high ³He/D ratio (Dimopoulos et al. 1988). In the course of Galactic chemical evolution deuterium is destroyed when interstellar gas is cycled through stars. In contrast, ³He is produced by low-mass stars (Iben 1967), and not all the initial ³He $(^{3}\text{He} + \text{D})$ is burned away in stars (Dearborn et al. 1986). The result is that the ratio ³He/D is expected to *increase* with time. For the solar system, $(y_3/y_2)_{\odot} \approx 0.6$, $(X_3/X_2)_{\odot} \approx 0.9$, arguing strongly that primordial D should exceed primordial ³He. Although the absence of firm predictions makes the decaying massive particle scenario a difficult target, the apparent problem with these isotope ratios renders this model an unlikely alternative to the standard model.

8. SUMMARY AND CONCLUSIONS

We have updated the BBN computer code to take account of new laboratory data and to follow more accurately the weak interactions crucial to a precise prediction of the ⁴He abundance. Of particular importance have been the recent highprecision determinations of the neutron lifetime (Mampe et al. 1989; Paul et al. 1989; Kossakowski et al. 1989; Byrne et al. 1990). The new "world average" of $\tau_n = 889 \pm 7 \text{ s}$ (95% CL) is significantly lower than the earlier values used by YTSSO ($\tau_n = 918 \pm 17 \text{ s}$; $\tau_{1/2} = 10.6 \pm 0.2 \text{ minutes}$) and leads (with all other parameters held fixed) to a *reduction* of $\Delta Y_p \sim 0.006$ in the predicted ⁴He mass fraction.

We reviewed the observational data, with particular attention paid to ⁷Li and ⁴He. The accumulating observations of ⁷Li in metal-poor Population II stars, especially the warmer ($\gtrsim 5500$ K) stars, lead to an accurate determination of the ⁷Li abundance [Li] = 2.08 ± 0.07. When comparison is made with the predictions of BBN in the standard model (with allowance for the uncertainties), we bound the baryon density: $1.6 \le \eta_{10} \le 4.0$. We note here that the solar system or Population I values of $[Li] \ge 3.0-3.3$ would require either very large or very small values of η , which would be inconsistent with the observed abundances of D, ³He and (for high η) ⁴He.

The lower bound to the primordial abundance of deuterium, $y_{2p} \gtrsim y_{2\odot} \gtrsim 1.8 \times 10^{-5}$, leads to an upper bound on the nucleon density, $\eta_{10} \leq 6.8$, which is consistent with, but weaker than, that already determined by the Population II lithium data. Of crucial importance to the BBN bound on N_{y} is the determination of a *lower* bound to η . Using the solar system abundances of D and ³He, along with two simple, complementary models for the Galactic evolution of D plus ³He (the two models yield the same bound to the primordial abundance), we bound D + ³He from above: $y_{23p} \leq 1.0$ $\times 10^{-4}$, which leads to $\eta_{10} \ge 2.8$ (for which [Li]_p ≥ 2.0 , in agreement with the Population II data).

Our bounds on the baryon density, $2.8 \le \eta_{10} \le 4.0$, then lead to constraints of importance to cosmology and elementary particle physics. For a cosmic background radiation temperature 2.75 $\leq T_{\gamma} \leq$ 2.79 K, the fraction of the critical density contributed by baryons is $\Omega_B = (0.05 \pm 0.01)h_{50}^{-2}$. For $H_0 \gtrsim 40$ km s⁻¹ Mpc⁻¹ (Sandage 1988; Steigman 1989b; Wheeler 1989), $\Omega_B \gtrsim 0.10$ and the universe fails, by a wide margin, to be "closed" by baryons. On the other hand, using the age of a flat universe to constrain H_0 (in the absence of a cosmological constant), $t_0 \gtrsim 10$ (13) Gyr implies $H_0 \lesssim 65$ (50) km s⁻¹ Mpc^{-1} , and a lower bound to the nucleon density is found: $\Omega_B \gtrsim 0.02$ (0.04). Comparison of this lower bound with estimates of the density of luminous matter in the universe suggests that at least a significant fraction of the nucleons in the universe are "dark" (i.e., $\Omega_B/\Omega_{LUM} \gtrsim 6h_{50}^{-2}$).

For the standard model $(N_v = 3)$ with $882 \le \tau_n \le 896$ s and $2.8 \le \eta_{10} \le 4.0$, we predict that primordial abundance of ⁴He should lie in the range $0.236 \le Y_p \le 0.243$. This prediction is consistent with our analysis of the metal-poor H II region data, which suggests that $Y_p = 0.23 \pm 0.01$. This consistency permits us to derive a reduced SSG upper bound to the number of equivalent, light neutrino species; for $Y_p \le 0.240$ we find $N_v \le$ 3.3. We note that if our lower bound on η were increased from $\eta_{10} = 2.8$ to $\eta_{10} = 4.0$, the "window" on N_v would be closed (for $Y_p \le 0.240$). Alternatively, if the observational bound on Y_p were reduced below 0.236, the standard model would require $N_{\nu} < 3$ (is ν_{τ} really light?). Thus, BBN is truly a falsifiable theory.

Primordial nucleosynthesis provides the only probe of the early evolution of the universe accessible to observational tests. The standard, hot big bang model has passed those tests with flying colors, leading to significant constraints of importance to cosmology and high-energy physics. The robustness of the standard model in accounting—with only one free parameter, the nucleon abundance—for the observed abundances of D, ³He, ⁴He, and ⁷Li, which span some nine orders of magnitude, is impressive. Alternative cosmologies (e.g., inhomogeneous, decaying massive particles), with more free parameters to vary, fail to achieve consistency with the data.

The current successes of standard BBN should not be a cause for complacency. Further observations of lithium in Population II stars, coupled with the modeling of the evolution of such stars would be of value in further constraining the range allowed for the primordial abundance of lithium. Models of the chemical evolution of the Galaxy which could lead to better bounds on the pregalactic abundances of deuterium and ³He would also be of great value. Such improvements in the estimates of the primordial abundances of D, ³He, and ⁷Li would provide ongoing checks of the consistency of the standard model; if, indeed, the standard model is correct, these improved bounds would help us "zero in" on the true nucleon abundance η . The primordial abundance of ⁴He is crucial to the consistency of standard BBN. Very careful, detailed studies of selected, extragalactic H II regions could be of great value in helping us get a handle on possible systematic errors (ionization corrections, collisional excitations, etc.). A firm and accurate (i.e., to the third significant figure) upper bound to Y_n could provide the key test of the standard model.

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