4. BIG-BANG NUCLEOSYNTHESIS

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Among the successes of the standard big-bang model is the agreement between the predictions of big-bang nucleosynthesis (BBN) for the abundances of the light elements, D, ^{3}He, ^{4}He, and ^{7}Li, and the primordial abundances inferred from observational data (see [1–3] for a more complete discussion). These abundances span some nine orders of magnitude: ^{4}He has an abundance by number relative to hydrogen of about 0.08 (accounting for about 25% of the baryonic mass), while ^{7}Li, the least abundant of the elements with a big-bang origin, has a abundance by number relative to hydrogen of about $\sim 10^{-10}$.

4.1. Big-bang nucleosynthesis theory

The BBN theory matches the observationally determined abundances with a single well-defined parameter, the baryon-to-photon ratio, η. All the light-element abundances can be explained with η in the relatively narrow range $(2.8–4.5) \times 10^{-10}$, or $\eta_{10} \equiv \eta \times 10^{10} = 2.8–4.5$. (When possible systematic errors are allowed to take extreme values, the range becomes $\eta_{10} = 1.5–6.3$ [4]. We shall always quote this extreme range parenthetically following the best range.) Equivalently, this range can be expressed as the allowed range for the baryon mass density, $\rho_B = 1.9–3.1$ $(1.0–4.3) \times 10^{-31}$ g cm^{-3}, and can be converted to the fraction of the critical density, Ω.

The synthesis of the light elements was affected by conditions in the early Universe at temperatures $T \lesssim 1$ MeV, corresponding to an age as early as 1 s. At somewhat higher temperatures, weak-interaction rates were in equilibrium, thus fixing the ratio of the neutron and proton number densities. At $T \gg 1$ MeV, $n/p \approx 1$, since the ratio was given approximately by the Boltzmann factor, $n/p \approx e^{-Q/T}$, where Q is the neutron-proton mass difference. As the temperature fell, the Universe approached the point ("freeze-out") where the weak-interaction rates were no longer fast enough to maintain equilibrium. The final abundance of ^{4}He is very sensitive to the n/p ratio at freeze-out.

The nucleosynthesis chain begins with the formation of deuterium in the process $pn \to \mathrm{D}\gamma$. However, photo-dissociation by the high number density of photons ($n_\gamma/n_B = \eta^{-1} \sim 10^{10}$) delays production of deuterium (and other complex nuclei) well past the point where T reaches the binding energy of deuterium, $E_B = 2.2$ MeV. (The average photon energy in a blackbody is $\overline{E}_\gamma \approx 2.7\ T$.) When the quantity $\eta^{-1}\exp(-E_B/T)$ reaches about 1 (at $T \approx 0.1$ MeV), the photo-dissociation rate finally falls below the nuclear production rate.

The 25% fraction of mass in ^{4}He due to BBN is easily estimated by counting the number of neutrons present when nucleosynthesis begins. When the weak-interaction rates freeze-out at about $T \approx 0.8$ MeV, the n-to-p ratio is about 1/6. When free-neutron decays prior to deuterium formation are taken into account, the ratio drops to $n/p \lesssim 1/7$. Then simple counting yields a primordial ^{4}He mass fraction

$$Y_p = \frac{2(n/p)}{1+n/p} \lesssim 0.25 \; . \tag{4.1}$$

In the Standard Model, the ^{4}He mass fraction depends primarily on the baryon-to-photon ratio η, as it is this quantity that determines when nucleosynthesis via deuterium production may begin. But because the n/p ratio depends only weakly on η, the ^{4}He mass fraction is relatively flat as a function of η. The effect of the uncertainty in the neutron half-life, $\tau_n = 887 \pm 2$ s, is small. Lesser amounts of the other light elements are produced: D and ^{3}He at the level of a few times 10^{-5} by number relative to H, and ^{7}Li/H at the level of about 10^{-10}, when η is in the range 1 – 10 $\times 10^{-10}$.

When we go beyond the Standard Model, the ^{4}He abundance is very sensitive to changes in the expansion rate, which can be related to the effective number of neutrino flavors. This will be discussed below.

The calculated abundances of the light elements are shown in Fig. 4.1 as a function of η_{10}. The curves for the ^{4}He mass fraction, Y_p, bracket the range based on the uncertainty of the neutron mean-life, $\tau_n = 887 \pm 2$ s. The spread in the ^{7}Li curves is due to the 1σ uncertainties in nuclear cross sections leading to ^{7}Li and ^{7}Be which subsequently decays to ^{7}Li [4,5,6]. The uncertainties in the D and ^{3}He predictions are small and have been neglected here. The boxes show to the observed abundances, discussed below. Since the observational boxes line up on top of each other, there is an overall agreement between theory and observations for η_{10} in the range 2.8–4.5 (1.5–6.3).

4.2. Observations

Because stars produce helium as well as heavier elements, one must search for primordial helium in regions where stellar processing has been minimal, *i.e.*, in regions where abundances of elements such as carbon, nitrogen, and oxygen are very low. There are extensive compilations of observed abundances of ^{4}He, N, and O in many different extra-galactic regions of ionized H [7,8,9]. Extrapolating the ^{4}He abundances from the data leads to a observational estimate for Y_p of [10,11]

$$Y_p = 0.234 \pm 0.003 \pm 0.005 \; . \tag{4.2}$$

(Here and elsewhere, the first error is the statistical standard deviation, and the second systematic.) The large box in Fig. 4.1 bracketing the ^{4}He curves covers the range 0.223 to 0.245, where the half height is conservatively given as twice the statistical error plus the systematic error. There has been some debate on the size of systematic errors [4] and the dashed box is obtained using a larger systematic error of 0.01.

Observations for deuterium and ^{3}He abundances present larger problems. All deuterium is primordial [12], but some of the primordial

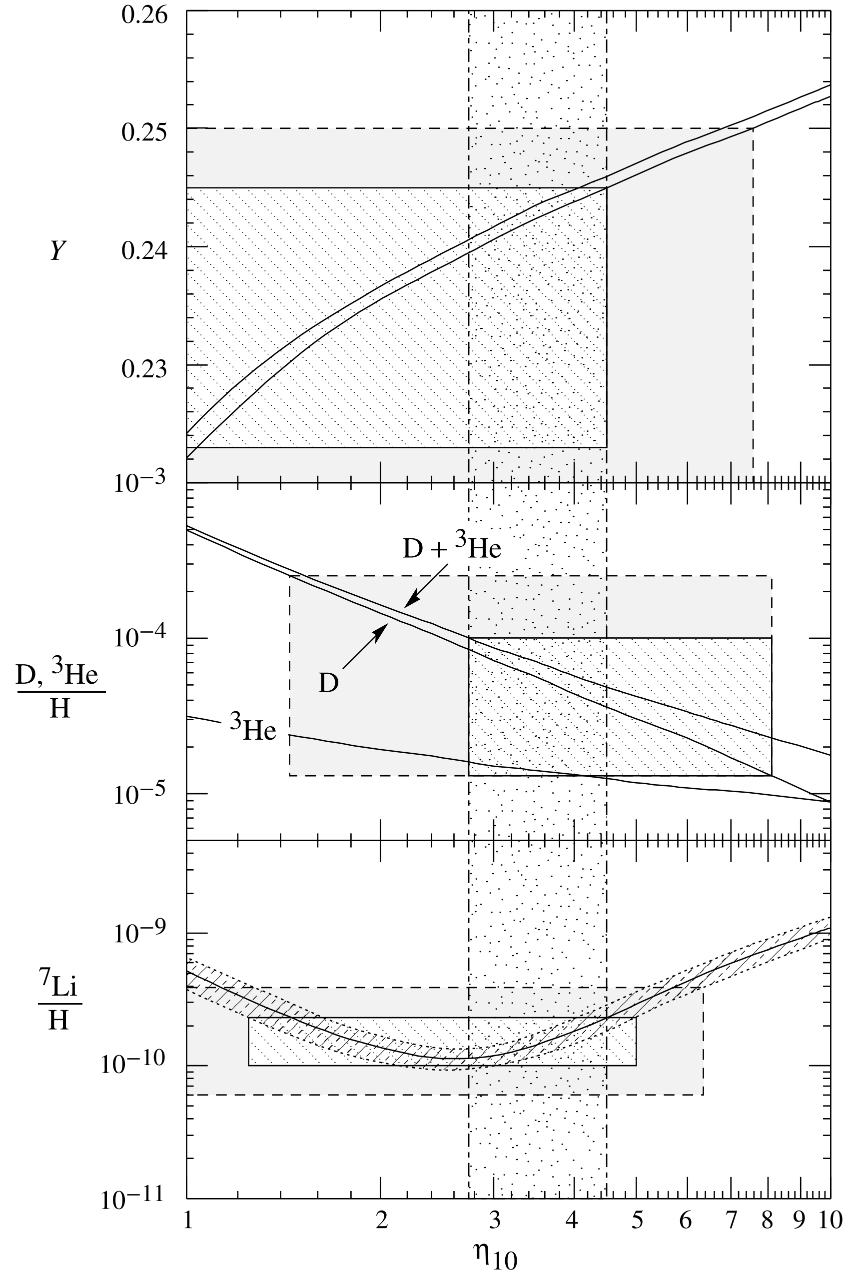

Figure 4.1: The abundances of D, ^{3}He, ^{4}He and ^{7}Li as predicted by the standard model of big-bang nucleosynthesis. Also shown by a series of boxes is the comparison between these predictions and the observational determination of the light element abundances. See text for details.

deuterium has been destroyed. Thus, as can be seen in the figure, the present deuterium abundance gives an upper limit to η. However, to get more information requires either an understanding of galactic chemical evolution of deuterium or a direct measurement of primordial deuterium. Even more problematical is ^{3}He: Not only is primordial ^{3}He destroyed in stars but it is very likely that low-mass stars are net producers of ^{3}He. Neither the galactic chemical evolution of ^{3}He nor the production of ^{3}He in stars is well understood.

It appears that D/H has decreased over the age of the galaxy. Samples obtained deep inside meteorites provide measurements of the true (pre)-solar system abundance of ^{3}He, while measurements on meteoritic near-surface samples, the solar wind, and lunar soil samples also contain ^{3}He converted from deuterium in the early pre-main-sequence stage of the sun. The best current values are [13]

$$\begin{aligned} \left(\frac{\mathrm{D} + {}^3\mathrm{He}}{\mathrm{H}}\right)_\odot &= (4.1 \pm 1.0) \times 10^{-5} \ , \\ \left(\frac{{}^3\mathrm{He}}{\mathrm{H}}\right)_\odot &= (1.5 \pm 0.3) \times 10^{-5} \ . \end{aligned} \tag{4.3}$$

The difference between these, $\mathrm{D/H} \approx (2.6 \pm 1.0) \times 10^{-5}$, is the pre-solar D abundance.

On the other hand, the present interstellar-medium abundance of D/H is [14]

$$\mathrm{D/H} = 1.60 \pm 0.09^{+0.05}_{-0.10} \times 10^{-5} \ . \tag{4.4}$$

It is this lowest value of D/H that provides the most robust upper bound on η, since D is only destroyed. It is shown (decreased by $2\sigma_{\rm stat} + \sigma_{\rm syst}$) as the lower side of the D and ^{3}He box in Fig. 4.1. If η_{10} is in the range 2.8–4.5 (1.5–6.3) then the primordial abundance of D/H is between 3.6–8 (2–25) $\times 10^{-5}$, and it would appear that significant destruction of deuterium has occurred. The upper side of the box in Fig. 4.1 comes from the upper limit on $(\mathrm{D} + {}^3\mathrm{He})_\odot$ under the assumption that at least 25% of a star's initial D + ^{3}He is returned to the interstellar medium [15].

Deuterium may have been detected in high-redshift, low-metallicity quasar absorption systems [16,17,18]. These measured abundances should represent the primordial value, but, they are not entirely consistent: One [16] gives $\mathrm{D/H} \approx 1.9\text{–}2.5 \times 10^{-4}$ while the other [17] gives $\mathrm{D/H} \approx 1\text{–}2 \times 10^{-5}$. Most recently, measurements in three absorption systems show consistent values of D/H around $10^{-4.0\pm0.25}$ [18] and corresponds to a value of η in good agreement with that discussed in the previous section. The upper limit on D/H from the first observation is shown by the dashed box in Fig. 4.1. As one can see, the corresponding value of Y_p (at the same value of η as inferred by the observation of a high D/H) is in excellent agreement with the data. ^{7}Li is also acceptable at this value as well. However, due to the still somewhat preliminary status of this observation, it is premature to use it to fix the primordial abundance. A high value for the D abundance would require an even greater degree of D destruction over the age of the galaxy. The lower measurement for D/H is problematic for both ^{4}He and ^{7}Li and requires that systematics all work in the same direction to give a marginal overlap with this data.

Finally, we turn to ^{7}Li. In old, hot, population-II stars, ^{7}Li is found to have a very nearly uniform abundance. For stars with a surface temperature $T > 5500$ K and a metallicity less than about 1/20th solar (so that effects such as stellar convection may not be important), the abundances show little or no dispersion beyond that consistent with the errors of individual measurements. Much data has been obtained recently from a variety of sources, and the best estimate for the mean ^{7}Li abundance and its statistical uncertainty in halo stars is [19](the estimate of the systematic uncertainty discussed below is our own)

$$\mathrm{Li/H} = (1.6 \pm 0.1^{+0.4+1.6}_{-0.3-0.5}) \times 10^{-10} \ . \tag{4.5}$$

The first error is statistical, and the second is a systematic uncertainty that covers the range of abundances derived by various methods. The box in Fig. 4.1 corresponds to these errors (as before, with a half height of $2\sigma_{\rm stat} + \sigma_{\rm syst}$). The third set of errors in Eq. (4.5) accounts for the possibility that as much as half of the primordial ^{7}Li has been destroyed in stars, and that as much as 30% of the observed ^{7}Li was produced in cosmic ray collisions rather than in the Big Bang. These uncertainties are shown by the dashed box in Fig. 4.1. Observations of ^{6}Li, Be, and B help constrain the degree to which these effects play a role [20,21,22].

4.3. A consistent value for η

For the Standard Model of BBN to be deemed successful, theory and observation of the light element abundances must agree using a single value of η. We summarize the constraints on η from each of the light elements. From the ^{4}He mass fraction, $Y_p < 0.240$ (0.245–0.250), we have $\eta_{10} < 2.9$ (4.5–7.6) as a 2σ upper limit (the highest values use possible systematic errors up to their extreme range). Because of the sensitivity to the assumed upper limit on Y_p, the upper limit on η from D/H, is still of value. From $\mathrm{D/H} > 1.3 \times 10^{-5}$, we have $\eta_{10} < 8.1$.

The lower limit on η_{10} comes from the upper limit on D + ^{3}He and is $\eta_{10} \gtrsim 2.8$ if one ignores ^{3}He production. We stress, however, that the upper limit on D + ^{3}He depends critically on models of galactic chemical evolution, which are far from being understood, and that one of the two measurements of D/H in quasar absorption systems indicates that $\eta_{10} \sim 1.5$.

Finally, ^{7}Li allows a broad range for η_{10} consistent with the other elements. When uncertainties in the reaction rates and systematic uncertainties in the observed abundances are both taken into account, ^{7}Li allows values of η_{10} between 1.3–5.0 (1–6.3). The resulting overall consistent range for η_{10} becomes 2.8–4.5 (1.5–6.3). These bounds on η_{10} constrain the fraction of critical density in baryons, Ω_B, to be

$$0.010 < \Omega_B h_0^2 < 0.016 \ \ (0.005 < \Omega_B h_0^2 < 0.023) \tag{4.6}$$

for a Hubble parameter, h_0, between 0.4 and 1.0. The corresponding range for Ω_B is 0.01–0.10 (0.005–0.14).

4.4. Beyond the Standard Model

Limits on particle physics beyond the Standard Model come mainly from the observational bounds on the ^{4}He abundance. As discussed earlier, the neutron-to-proton ratio is fixed by its equilibrium value at the freeze-out of the weak-interaction rates at a temperature $T_f \sim 1$ MeV, with corrections for free neutron decay. Furthermore, freeze-out is determined by the competition between the weak-interaction rates and the expansion rate of the Universe,

$$G_F{}^2 T_f{}^5 \sim \Gamma_{\rm wk}(T_f) = H(T_f) \sim \sqrt{G_N N}\, T_f{}^2 \ , \tag{4.7}$$

where N counts the total (equivalent) number of relativistic particle species. The presence of additional neutrino flavors (or of any other relativistic species) at the time of nucleosynthesis increases the energy density of the Universe and hence the expansion rate, leading to a larger value of T_f, n/p, and ultimately Y_p. It is clear that just as one can place limits [23] on N, any changes in the weak or gravitational coupling constants can be similarly constrained.

In the Standard Model, the number of particle species can be written as $N = 5.5 + \frac{7}{4} N_\nu$; 5.5 accounts for photons and $e^\pm$; and N_ν is the number of (massless) neutrino flavors. The helium curves in Fig. 4.1 were computed assuming $N_\nu = 3$, and the computed ^{4}He abundance scales roughly as $\Delta Y_{\rm BBN} \approx 0.012$–$0.014\ \Delta N_\nu$. Clearly the central value for N_ν from BBN will depend on η. If the best value for the observed primordial ^{4}He abundance is 0.234, then, for $\eta_{10} \sim 1.7$, the central value for N_ν is very close to 3. For $\eta_{10} > 2.8$ the central value for N_ν is less than 2.5. However, because of the uncertainties in the abundances, and thus in η, the upper limit on N_ν is more important here than the central value of N_ν. A straightforward propagation of errors leads to a 2σ upper limit of about 3.1 (3.5) on N_ν when systematic errors are included [10,24]. Other prescriptions, which involve renormalization of the probability distributions when the central value of N_ν falls below 3, give even higher upper limits to N_ν [25].

The limits on N_ν can be translated into limits on other types of particles or particle masses that would affect the expansion rate of the Universe just prior to nucleosynthesis. In some cases, it is the interaction strengths of new particles which are constrained. Particles with less than full weak strength interactions contribute less to the energy density than particles that remain in equilibrium up to the time of nucleosynthesis [26].

We close with a simple example. Suppose there exist three right-handed neutrinos with only right-handed interactions of strength $G_R < G_F$. The standard left-handed neutrinos are no longer in equilibrium at temperatures below ~ 1 MeV. Particles with weaker interactions decouple at higher temperatures, and their number density ($\propto T^3$) relative to neutrinos is reduced by the annihilations of particles more massive than 1 MeV. If we use the upper bound $N_\nu < 3.1$, then the three right-handed neutrinos must have a temperature $3(T_{\nu_R}/T_{\nu_L})^4 < 0.1$. Since the temperature of the decoupled ν_R's is determined by entropy conservation, $T_{\nu_R}/T_{\nu_L} = [(43/4)/N(T_f)]^{1/3} < 0.4$, where T_f is the freeze-out temperature of the ν_R's. Thus $N(T_f) > 100$ and decoupling must have occurred at $T_f > M_W$ (since in the Standard Model, $N(T > M_W) = 106.75$). Finally, the decoupling temperature is related to G_R by $(G_R/G_F)^2 \sim (T_f/3 \text{ MeV})^{-3}$, where 3 MeV corresponds to the decoupling temperature for ν_L. This yields a limit $G_R \lesssim 10^{-7}\ G_F$. Clearly these limits are strongly dependent on the assumed upper limit to N_ν; for $N_\nu < 3.5$, the limit on G_R is relaxed to $G_R < 0.002\ G_F$, since T_f is constrained only to be larger than the temperature corresponding to the QCD transition in the early Universe.

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