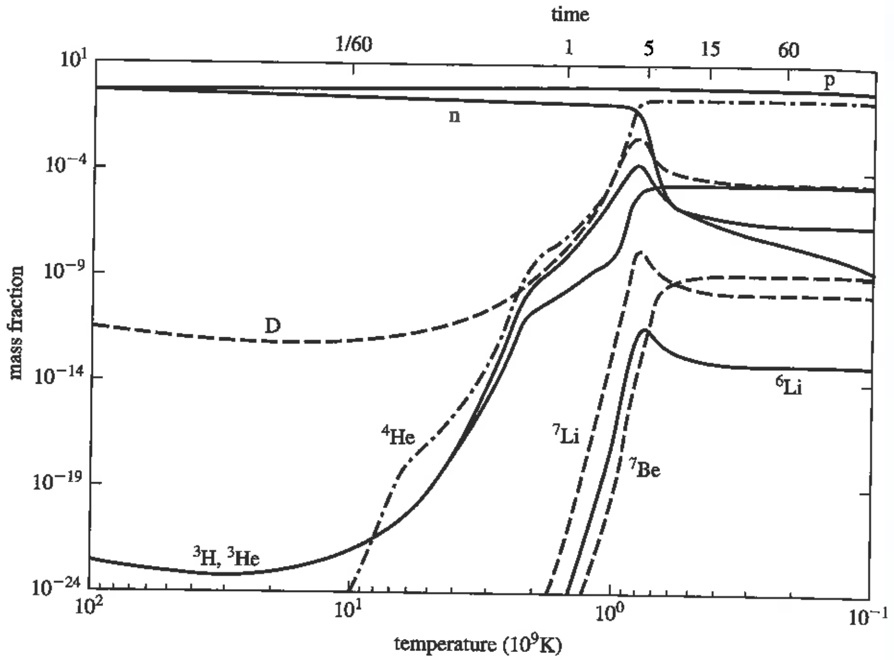

FIGURE 10.4 Mass fraction of nuclei as a function of time during the epoch of nucleosynthesis. A baryon-to-photon ratio of $\eta = 5.1 \times 10^{-10}$ is assumed.

significant amounts of ^{3}H, ^{3}He, and ^{4}He are formed. By the time the temperature has dropped to $T \sim 4 \times 10^8$ K, at $t \sim 10$ min, Big Bang Nucleosynthesis is essentially over. Nearly all the baryons are in the form of free protons or ^{4}He nuclei. The small residue of free neutrons decays into protons. Small amounts of D, ^{3}H, and ^{3}He are left over, a tribute to the incomplete nature of Big Bang Nucleosynthesis. (^{3}H later decays to ^{3}He.) Very small amounts of ^{6}Li, ^{7}Li, and ^{7}Be are made. (^{7}Be is later converted to ^{7}Li by electron capture: $^7\text{Be} + e^- \rightarrow {}^7\text{Li} + \nu_e$.)

The yields of D, ^{3}He, ^{4}He, ^{6}Li, and ^{7}Li depend on various physical parameters. Most importantly, they depend on the baryon-to-photon ratio η. A high baryon-to-photon ratio increases the temperature T_{nuc} at which deuterium synthesis occurs, and hence gives an earlier start to Big Bang Nucleosynthesis. Since BBN is a race against the clock as the density and temperature of the universe drop, getting an earlier start means that nucleosynthesis is more efficient at producing ^{4}He, leaving less D and ^{3}He as leftovers. A plot of the mass fraction of various elements produced by Big Bang Nucleosynthesis is shown in Figure 10.5. Note that larger values of η produce larger values for Y_p (the ^{4}He mass fraction) and smaller values for the deuterium density, as explained above. The dependence of the ^{7}Li density on η is more complicated. Within the range of η plotted in Figure 10.5, the direct production of ^{7}Li by the fusion of ^{4}He and ^{3}H is a decreasing function of η, while the indirect production of ^{7}Li by ^{7}Be electron capture is an increasing function of η. The net result is a minimum in the predicted density of ^{7}Li at $\eta \approx 3 \times 10^{-10}$.

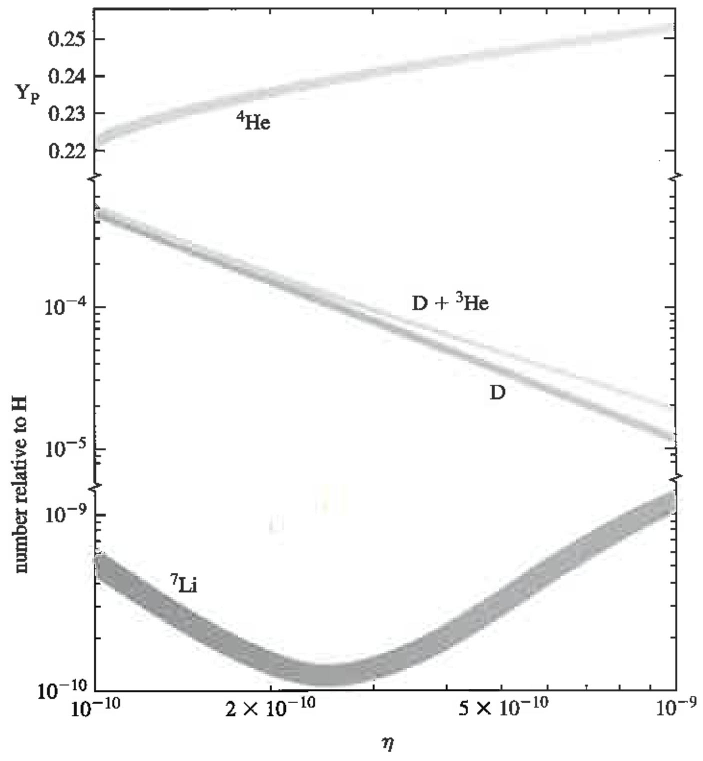

FIGURE 10.5 The mass fraction of ^{4}He, and the number densities of D, D+^{3}He, and ^{7}Li expressed as a fraction of the H number density. The width of each line represents the 95% confidence interval in the density.

Broadly speaking, we know immediately that the baryon-to-photon ratio can't be as small as $\eta \sim 10^{-12}$. If it were, BBN would be extremely inefficient, and we would expect only tiny amounts of helium to be produced ($Y_p < 0.01$). Conversely, we know that the baryon-to-photon ratio can't be as large as $\eta \sim 10^{-7}$. If it were, nucleosynthesis would have taken place very early (before neutrons had a chance to decay), the universe would be essentially deuterium-free, and Y_p would be near its maximum permissible value of $Y_{\max} \approx 0.33$. Pinning down the value of η more accurately requires making accurate observations of the *primordial* densities of the light elements; that is, the densities before nucleosynthesis in stars started to alter the chemical composition of the universe. In determining the value of η, it is most useful to determine the primordial abundance of deuterium. This is because the deuterium abundance is strongly dependent on η in the range of interest. Thus, determining the deuterium abundance with only modest accu-