# Big-bang nucleosynthesis enters the precision era

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The last parameter of big-bang nucleosynthesis, the density of ordinary matter (baryons), is being pinned down by measurements of the deuterium abundance in high-redshift hydrogen clouds. When it is, the primeval abundances of the light elements D, $^3$He, $^7$Li, and $^4$He will be fixed. The first three will then become "tracers" in the study of Galactic and stellar chemical evolution. A precision determination of the $^4$He abundance will allow an important consistency test of big-bang nucleosynthesis and will sharpen nucleosynthesis as a probe of fundamental physics, e.g., the bound to the number of light neutrino species. An independent consistency test is on the horizon: a high-precision determination of the baryon density from measurements of the fluctuations of the cosmic background radiation temperature. [S0034-6861(98)01001-0]

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## GLOSSARY AND LIST OF SYMBOLS

**BBN** Big-bang nucleosynthesis, the sequence of nuclear reactions that led to the synthesis of the light elements D, $^3$He, $^4$He, and $^7$Li between 0.01 sec and 200 sec after the bang.

**CBR** The cosmic background radiation is the microwave echo of the big bang. It is blackbody radiation to a precision of 0.005% and has a temperature 2.7277 K ± 0.002 K.

**Chemical evolution** The change in chemical composition of (ordinary) matter due to the nuclear transformations that take place in stars and elsewhere.

**Cold dark matter** Dark matter particles that move very slowly (e.g., axions, neutralinos, or black holes).

**$g_*$** Counts the total number of spin states of all relativistic particle species. During BBN, $g_*=10.75$ for the standard scenario. See Appendix for more details.

**Hot dark matter** Dark matter particles that move very fast (e.g., neutrinos with mass in the range of 1 eV to 30 eV).

**H II region** Region of hot ($T\gg10^4$ K), ionized gas (mostly hydrogen and helium). H II regions are common within our own galaxy and other galaxies.

**$H_0$** Present value of the expansion rate (or Hubble constant). The expansion rate $H\equiv\dot{R}/R$, where $R(t)$ is the cosmic scale factor.

**Lyman-$\alpha$ (Ly-$\alpha$) cloud** A cloud of gas (mostly hydrogen) present in the early universe that is "seen" by its absorption of light (in the Lyman series) from even more distant quasars. The Lyman series begins with Ly-$\alpha$ at 1216 Å, continuing to the continuum limit at 912 Å.

**MACHO** Acronym for massive astrophysical compact halo object. Refers generically to stars too faint to be seen (of any mass) that might be the constituents of the baryonic dark matter, e.g., white dwarfs, neutron stars, black holes, brown dwarfs, or Jupiters. MACHOs can be detected by their gravitational lensing of bright stars.

**$N_\nu$** The number of neutrino species with mass much less than 1 MeV. In the standard model of particle physics all three neutrino species are massless and $N_\nu=3$. Sometimes $N_\nu$ is used to quantify the energy density in relativistic particles (other than photons and electron-positron pairs) at the time of BBN: $g_*=5.5+1.75N_\nu$.

**$\eta$** The ratio of nucleons (baryons) to photons (in the cosmic background radia-

[†]Deceased.

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| | tion), whose value is around $5\times10^{-10}$, and whose inverse is, up to a numerical factor, the specific entropy per nucleon. The fraction of critical density contributed by baryons is $\Omega_B h^2 = 3.64\times10^7\ \eta$. |
| Nonbaryonic dark matter | Measurements of the total matter density in the Universe exceed the BBN upper limit to that contributed by ordinary matter (baryons), indicating the presence of another form of matter (nonbaryonic). Possibilities for the nonbaryonic dark matter include elementary particles remaining from the earliest moments (e.g., axions, neutralinos, or massive neutrinos) and primordial black holes (formed before the epoch of BBN). |
| Peculiar velocity | Motion of a galaxy or other object over and above that due to the expansion of the universe. More precisely, velocity with respect to the cosmic rest frame. Peculiar velocities arise due to the inhomogeneous distribution of matter and can be used to determine the mean matter density. |
| T-Tauri phase | An unstable phase that stars like our sun go through just before they settle down to the main-sequence (hydrogen burning) phase. |
| $Y_P$ | The mass fraction of baryons converted to $^4$He during BBN. |
| $Z^0$ boson | Together with the $W^{\pm}$ bosons, the carriers of the weak force. The $Z^0$ mediates the neutral-current interaction and has a mass of $91.187\pm0.007$ GeV. |
| $\Omega_i$ | The fraction of the critical mass density contributed by species $i$; e.g., baryons $(i=B)$ or nonrelativistic matter $(i=M)$, which includes baryons and cold dark matter. |
| $\Omega_{\rm TOT}$ | The fraction of critical density contributed by all forms of matter and energy. A universe with $\Omega_{\rm TOT}<1$ has negatively curved spatial hypersurfaces, expands forever, and is said to be open; a universe with $\Omega_{\rm TOT}=1$ has flat spatial hypersurfaces, expands forever, and is open; and a universe with $\Omega_{\rm TOT}>1$ has positively curved spatial hypersurfaces, eventually recollapses, has finite volume, and is said to be closed. |

## I. FROM GAMOW TO KECK

Over the last two decades big-bang nucleosynthesis (BBN) has emerged as one of the cornerstones of the big bang, joining the Hubble expansion and the cosmic microwave background radiation (CBR) in this role. Of the three, big-bang nucleosynthesis probes the Universe to the earliest times, from a fraction of a second to hundreds of seconds. Since BBN involves events that occurred at temperatures of order 1 MeV, it naturally played a key role in forging the connection between cosmology and nuclear and particle physics that has blossomed during the past fifteen years (see, for example, Kolb and Turner, 1990).

It is the basic consistency of the predictions for the abundances of the four light elements D, $^3$He, $^4$He, and $^7$Li with their measured abundances (which span more than nine orders of magnitude) that has moved BBN to the cosmological centerstage. In its success, BBN has led to the most accurate determination of the mass density of ordinary matter.

Currenly, there is great excitement because we are on the verge of determining the baryon density to a precision of 20%, and ultimately to 5% or better, from measurements of the primeval deuterium abundance. When this occurs, BBN will enter a qualitatively new phase, an era of high precision. The consequences for cosmology are obvious: an accurate determination of the average density of ordinary matter in the Universe and a completion of the BBN story. The implications for astrophysics are just as important: fixing the baryon density fixes the primeval abundances of the light elements and allows them to be used as tracers in the study of the chemical evolution of the Galaxy and aspects of stellar evolution. Lastly, important limits to particle properties, such as the limit to the number of light neutrino species, can be further sharpened.

The BBN story (see, for example, Kragh, 1996) begins with Gamow and his collaborators, Alpher and Herman, who viewed the early Universe as a nuclear furnace that could "cook the periodic table." Their speculations, while not correct about the details of nucleosynthesis, led to the prediction of the microwave echo of the big bang, the cosmic background radiation. Key refinements include those made by Hayashi, who recognized the role of neutron-proton equilibration (see Appendix), and by Turkevich and Fermi, who pointed out that lack of stable nuclei of mass 5 and 8 precludes nucleosynthesis beyond the lightest elements. The framework for the calculations themselves dates back to the work of Alpher, Follin, and Herman and of Taylor and Hoyle, preceding the discovery of the 3K background, of Peebles and of Wagoner, Fowler, and Hoyle, immediately following the discovery, and the more recent work of our group of collaborators (Yang *et al.*, 1984; Walker *et al.*, 1991; Smith *et al.*, 1993; Copi *et al.*, 1995a, 1995b, 1995c) and of other groups around the world (Matzner and Rothman, 1982; Kurki-Sunio *et al.*, 1990; Pagel, 1991; Sato and Terasawa, 1991; Malaney and Mathews, 1993; Audouze, 1995; Hata *et al.*, 1995; Krauss and Kernan, 1995; Fuller and Cardall, 1996; Kernan and Sarkar, 1996).

The basic calculation, a nuclear reaction network in an expanding box, has changed very little. The most up to date predictions are shown in Fig. 1, and the physics of light-element nucleosynthesis is reviewed in the Ap-

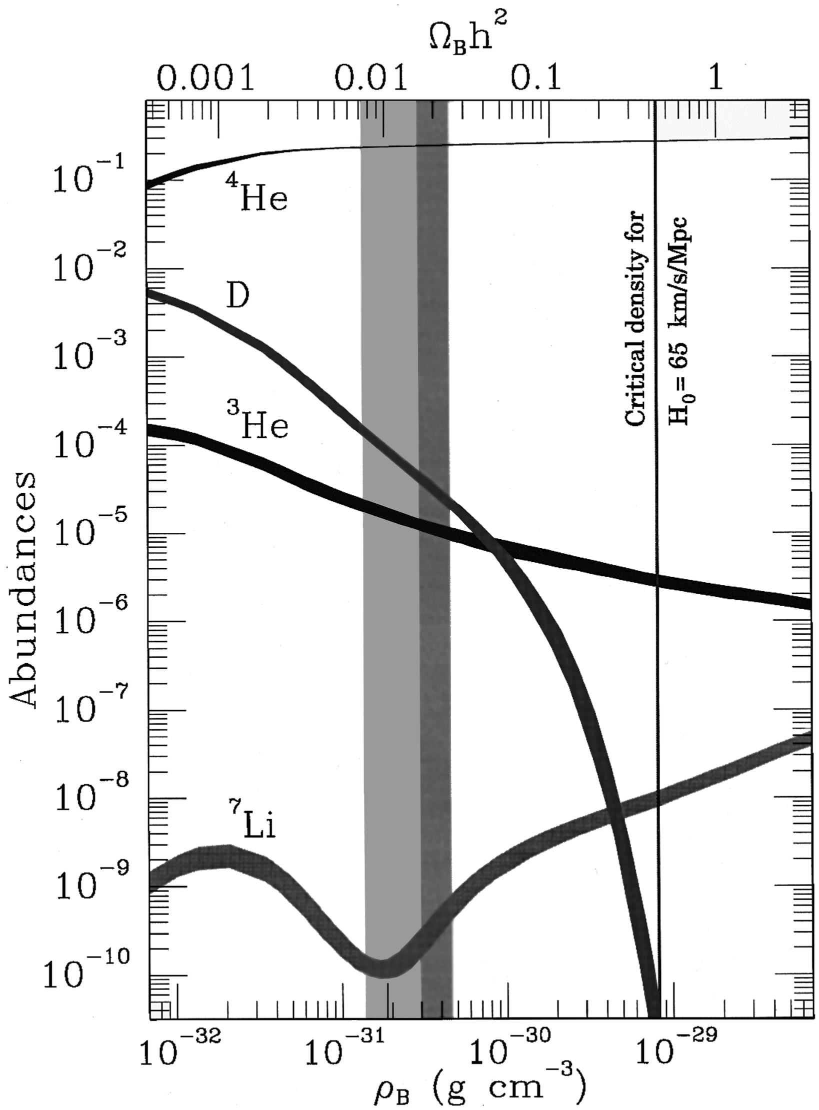


FIG. 1. Summary of big-bang production of the light elements ($^4$He abundance is mass fraction; others are number relative to hydrogen). The widths of the curves indicate the $2\sigma$ theoretical uncertainties, and the vertical band is the Copi *et al.* (1995b) consistency interval where the predicted abundances of all four light elements agree with their measured primeval abundances. The darker band in the consistency interval corresponds to Tytler *et al.*'s determination of the primeval deuterium abundance. Figure courtesy of K. Nollett.

pendix. The predictions of BBN are robust because essentially all input microphysics is well determined: The relevant energies, 0.1 to 1 MeV, are well explored in nuclear physics laboratories, and with the possible exception of $^7$Li, the experimental uncertainties have minimal impact (see Fig. 1 and Appendix).

Over the last 25 years the focus has been on understanding the evolution of the light-element abundances from the big bang to the present in order to test the BBN predictions for the *primeval* abundances. (Astronomers refer to the evolution of the elemental abundances due to the nuclear transmutations that occur in stars and elsewhere as "chemical evolution.") In the 1960s, the main focus was $^4$He, which is very insensitive to the baryon density. The agreement between the BBN prediction (lots of $^4$He production) and observations ($^4$He abundance of 25% to 30% is much greater than what stars can make, which is only a few percent) gave strong support to the big-bang model but gave no significant constraint to the baryon density.

During the 1960s, there was little cosmological interest in the other light elements, which are, in principle, capable of shedding light on the baryon density. This is because they were assumed to have been made during the T-Tauri phase of stellar evolution (Fowler *et al.*, 1962). That changed in the 1970s, and primordial nucleosynthesis developed into an important probe of the Universe. Ryter *et al.* (1970) showed that the T-Tauri mechanism for light-element synthesis failed. Furthermore, knowledge of the deuterium abundance improved significantly with solar-wind and meteoritic measurements (Black, 1971; Geiss and Reeves, 1972) and the interstellar medium (ISM) measurements made by the Copernicus satellite (Rogerson and York, 1973).

Reeves, Audouze, Fowler, and Schramm (1973) argued for a cosmological origin for deuterium. By exploiting the rapid decline in deuterium production with baryon density ($\propto 1/\rho_B^{1.7}$) they were able to place an upper limit to the baryon density which excluded a Universe closed by baryons. This was the beginning of the use of deuterium as a "cosmic baryometer," which should culminate in a determination of the baryon density to a precision of 5%. Their argument was strengthened when Epstein, Lattimer, and Schramm (1976) showed conclusively that no realistic astrophysical process could produce significant deuterium (most astrophysical processes destroy deuterium because it is so weakly bound), and thus the contemporary abundance leads to a firm upper limit to the baryon density.

In the late 1970s, attention turned to $^3$He. In part, this was to use deuterium to obtain a lower bound to the baryon density. In particular, it was argued that $^3$He, unlike D, is made in stars. During the pre-main-sequence stage any deuterium initially present is burnt to $^3$He, and low-mass stars are believed to produce additional $^3$He while on the main sequence. Thus the sum D+$^3$He should increase with time or at least stay constant (Yang *et al.*, 1984). This means current measurements of D + $^3$He limit the big-bang production, which in turn sets a lower limit to the baryon density.

This simple argument, while apparently qualitatively correct, fails in the details. For example, a recent measurement of $^3$He in the local interstellar medium (Gloeckler and Geiss, 1996) shows that D+$^3$He has been constant for the last 5 Gyr, contradicting the predicted increase due to $^3$He production by low-mass stars (over the past 5 Gyr galactic chemical evolution has been dominated by the action of low-mass stars). The chemical evolution of $^3$He is not fully understood; however, because the only stars that efficiently destroy $^3$He are massive and also make metals, the metallicity of the galaxy provides an upper limit to the amount by which D+$^3$He can decrease and thus a lower bound to the baryon density (Copi, Schramm, and Turner, 1995a; Scully *et al.*, 1996).

The abundances of D, $^3$He, and to a lesser extent $^4$He led to the prediction that the primeval $^7$Li abundance should be near its minimum, $(^7\text{Li/H}) \sim 10^{-10}$. This was verified by Spite and Spite (1982), who measured the $^7$Li abundance in the atmospheres of the oldest (Population II) stars in the halo of our galaxy. Their work was confirmed and extended by Hobbs, Thorburn, and others (Spite, Maillard, and Spite, 1984; Hobbs and Pilachowski, 1988; Rebolo *et al.*, 1988; Thorburn, 1994; Bonifacio and Molaro, 1997). An important question still remains: Does the $^7$Li abundance in these stars reflect the big-bang abundance, or could the $^7$Li abundance have been reduced by nuclear burning over the past 10 Gyr or so?

Three years ago the status of BBN was reviewed and summarized by Copi, Schramm, and Turner (1995b), who concluded: Within the uncertainties stemming from the chemical evolution of $^3$He and D, possible stellar depletion of $^7$Li, and systematic error in determining the primeval abundance of $^4$He, the abundances of the four light elements produced in the big bang are consistent with their BBN predictions provided that the fraction of critical density contributed by baryons is between $0.007h^{-2}$ and $0.024h^{-2}$ and the equivalent number of light neutrino species is less than 3.7. [The Hubble constant $H_0 = 100h$ km s$^{-1}$ Mpc$^{-1}$ enters because it fixes the critical density, $\rho_{\rm CRIT} = 3H_0^2/8\pi G = 1.88h^2 \times 10^{-29}$ g cm$^{-3}$; recent measurements seem to be converging on a value $h = 0.65 \pm 0.1$ (see, for example, Freedman, 1997)].

## II. KECK: THE GREAT LEAP FORWARD

As discussed above, it took a while to recognize the cosmic importance of deuterium and its role as the baryometer. Measuring the primeval deuterium abundance has taken even longer and required the advent of the 10 meter W.M. Keck Telescope and its HiRes spectrograph. However, it was worth the wait.

In 1976 Adams outlined how the deuterium abundance in a high-redshift hydrogen cloud could be measured (Adams, 1976). Distant hydrogen clouds are observed in absorption against even more distant quasars. Many absorption features are seen: the Lyman series of hydrogen and lines of various ionization states of carbon, oxygen, silicon, magnesium, and other elements (see Fig. 2). Because of the large hydrogen abundance, Ly-$\alpha$ is very prominent. In the rest frame Ly-$\alpha$ occurs at 1216 Å, so that for a cloud at redshift $z$, Ly-$\alpha$ is seen at $1216(1+z_{\rm cloud})$Å. The isotopic shift for deuterium is $-0.33(1+z)$Å, or expressed as a Doppler velocity, $-82$ km s$^{-1}$. Adams' idea was to detect the deuterium Ly-$\alpha$ feature in the wing of the hydrogen feature. (The same technique has been used to detect deuterium in the local interstellar medium, first by the Copernicus satellite and now by the Hubble Space Telescope.)

His proposal has much to recommend it: For $z \gtrsim 3$, Ly-$\alpha$ is shifted into the visible part of the spectrum and thus can be observed from Earth-based telescopes; "Ly-$\alpha$ clouds" are ubiquitous, with hundreds being seen along the line of sight to a quasar of this redshift, and judged by their metal abundance (anywhere from $10^{-2}$ of that seen in solar system material to undetectably small levels), these clouds represent nearly virgin samples of cosmic material. There are technical challenges: Because the expected deuterium abundance is small, D/H $\sim 10^{-5} - 10^{-4}$, clouds of very high column density, $n_H \gtrsim 10^{17}$ hydrogen atoms cm$^{-2}$, are needed; because hydrogen clouds are ubiquitous, the probability of another, low-column-density cloud sitting in just the right place to mimic deuterium—an interloper—is not negligible; many clouds have broad absorption features because of large internal velocities or complex velocity structure within the cloud; and to ensure sufficient signal-to-noise, bright quasars and large-aperture telescopes are a must (Webb *et al.*, 1991). Based upon his experience, Tytler has estimated that no more than one in thirty quasars has even a single cloud suitable for determining the primeval deuterium abundance.

Since the commissioning of the HiRes spectrograph on the first Keck telescope, a number of deuterium detections and tentative detections, as well as upper limits and lower limits to the deuterium abundance—not all consistent with one another—have been reported (Carswell *et al.*, 1994; Songaila *et al.*, 1994, 1997; Carswell *et al.*, 1996; Rugers and Hogan, 1996; Wampler *et al.*, 1996; Webb *et al.*, 1997). A confusing situation is now becoming clear. Tytler and his collaborators (Tytler, Fan, and Burles, 1996; Burles and Tytler, 1996; Burles, 1997) have made a strong case for a primeval deuterium abundance of $(\text{D/H})_P = (3.2 \pm 0.3) \times 10^{-5}$, based upon

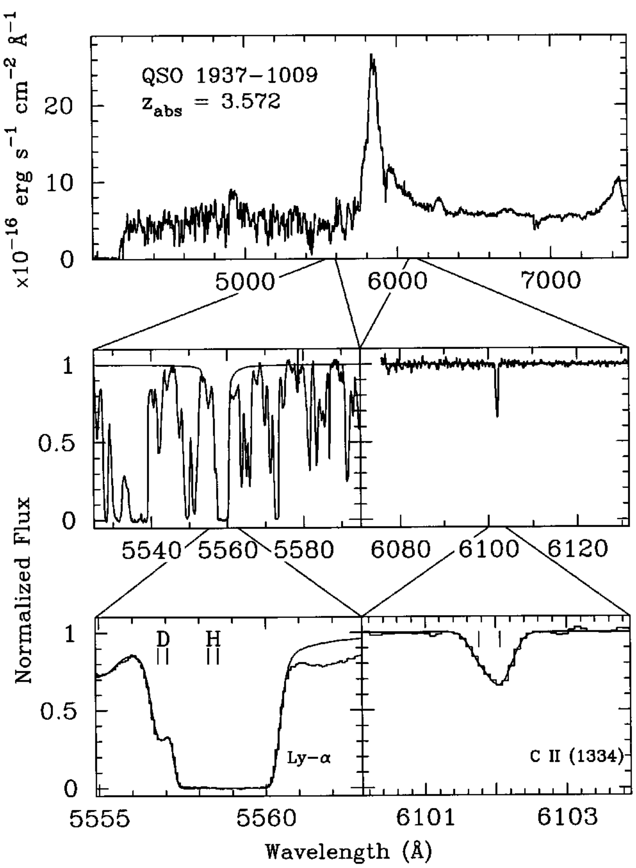


FIG. 2. Spectra of quasar Q1937-1009. Top panel: Low-resolution spectrum taken with the Shane three-meter telescope at Lick Observatory. The prominent feature at 5850 Å is Ly-$\alpha$ emission from the quasar. The depression shortward of 4200 Å is Lyman-continuum absorption from the deuterium cloud at $z=3.572$. The hundreds of absorption lines (Ly-$\alpha$ forest) are due to individual hydrogen clouds along the line of sight. Middle and bottom panels: Keck HiRes spectra of Q1937-1009. Middle panel shows the deuterium cloud lying within the resolved Ly-$\alpha$ forest (left) and the singly ionized carbon line due to the deuterium cloud lying in isolation. Bottom panel shows the model fit to the Ly-$\alpha$ lines of the two deuterium and hydrogen components (resolved by their metal lines). Figure courtesy of S. Burles.

detections in four clouds. The two best detections are a cloud at redshift 3.572 along the line of sight to quasar Q1937-1009 (see Fig. 2) and a cloud at redshift 2.504 along the line of sight to quasar Q1009+2956 (the other detections are a cloud at redshift 2.6032 toward Q1251 +3644 and a cloud at redshift 2.9102 toward Q1759 +7539). The metal abundances in these clouds are around $10^{-3}$ of solar, so that any depletion of deuterium due to stellar processing should be negligible (see, for example, Jedamzik and Fuller, 1997). In addition, they have observed the clouds for which others had claimed a much higher abundance, and, with better data, they have shown that the absorption features are not due to the deuterium (Tytler, Burles, and Kirkman, 1996).

It would be premature to conclude that the value of the primeval deuterium abundance has been settled or that all potential systematic errors are fully understood and taken into account. For example, because the hydrogen Ly-$\alpha$ feature is so saturated, it is the hydrogen abundance, not the deuterium abundance, that is most difficult to determine (see Cowie, 1997); in addition, there is usually more than one velocity component within the cloud, which complicates the analysis. The case for $(\mathrm{D/H})_P=(3.2\pm0.3)\times10^{-5}$ will be made very firm when a few more clouds of similar deuterium abundance are found. (Conversely, the case could fall apart.) Both Keck and Hubble Space Telescope observations are ongoing. The UV capability of the Hubble Space Telescope allows a search at lower redshift where there are fewer clouds and the problem of interlopers mimicking deuterium is less severe.

## III. THE BARYON DENSITY AND ITS COSMIC IMPLICATIONS

To be definite and to allow for possible systematic uncertainty, we take as a provisional primeval deuterium abundance $(\mathrm{D/H})_P=(3.2\pm0.6)\times10^{-5}$. This pegs the baryon density at $(3.6\pm0.7)\times10^{-31}\ \mathrm{g\,cm^{-3}}$, or as a fraction of critical density, $\Omega_B=(0.02\pm0.004)h^{-2}$. This lies near the high end of the pre-Keck BBN concordance interval and narrows the BBN interval for the baryon density considerably. (The above estimate includes theoretical uncertainty of about 15%; for our adopted error bar, the deuterium measurement still dominates the error budget. Soon, that will no longer be the case. The key nuclear uncertainties are cross-section measurements for D + D $\rightarrow p+{}^3\mathrm{H}$ and $n+{}^3\mathrm{He}$, which could be improved.)

This big-bang determination of the baryon density is consistent with other, independent methods: (1) The density of baryons in gas at redshifts between two and four is constrained by the measured Ly-$\alpha$ opacity of the ubiquitous hydrogen clouds previously discussed, and the baryon density inferred by this method is $\Omega_{\mathrm{gas}}\simeq(0.01-0.02)h^{-2}(h/0.65)^{1/2}$ (Meiksin and Madau, 1993; Rauch *et al.*, 1997; Weinberg *et al.*, 1997). (2) Most of the baryons in clusters of galaxies exist in the form of hot x-ray-emitting gas. Assuming that galaxy clusters represent a fair sample of material in the Universe, the cluster baryon fraction, which is determined from x-ray measurements to be $f_B=(0.07\pm0.007)h^{-3/2}$ (White *et al.*, 1993; Evrard, 1997), can be used to infer the universal baryon density $\Omega_B$ from the matter density $\Omega_M$:

$$\frac{\Omega_B}{\Omega_M}=f_B\Rightarrow\Omega_B h^2=(0.017\pm0.002)(h/0.65)^{1/2}(\Omega_M/0.3). \tag{1}$$

(3) The height of the Doppler peak in the angular power spectrum of cosmic background radiation temperature fluctuations depends on the baryon density (see Fig. 3 and Sec. VI); while the data do not yet determine the baryon density very precisely, they are consistent with the BBN value.

Next, consider the implications of the nucleosynthesis determination of the baryon density. First and foremost,

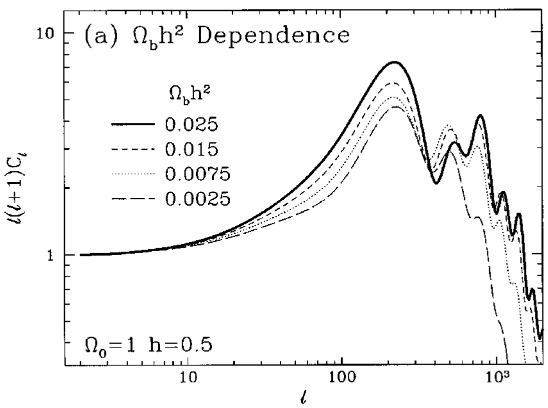


FIG. 3. Dependence of the angular power spectrum of cosmic background radiation anisotropy on baryon density for a cold dark matter universe. All models are normalized to have $l(l+1)C_l=1$ for $l=2$. Figure courtesy of Martin White.

it is the linchpin in the case for the two dark matter problems central to astrophysics and cosmology.

(1) The big-bang determination, together with measurements of the total amount of matter, provides firm evidence for nonbaryonic dark matter (see Fig. 4). Dynamic measurements of the density of matter that clusters based upon galaxy-cluster mass determinations, measurements of peculiar velocities, and the frequency of gravitational lensing, indicate that $\Omega_M$ is at least 0.3 (Dekel, 1994; Bahcall *et al.*, 1995; Dekel *et al.*, 1996; Willick *et al.*, 1997); nucleosynthesis puts the baryonic contribution at a value far below, $(0.05\pm0.01)(0.65/h)^2$. Particle physics provides three compelling candidates for the nonbaryonic matter: a very light axion (mass $\sim 10^{-5}$ eV); a light neutrino species [mass $\sim\mathcal{O}(10\text{ eV})$]; and the lightest supersymmetric particle (neutralino of mass 30 GeV to 500 GeV). That most of the matter is nonbaryonic receives additional support: No model of structure formation without nonbaryonic dark matter is consistent with the measured temperature fluctuations of the cosmic background radiation. While nonbaryonic dark matter is the driving force in structure formation, a baryon density this large means that baryons may also leave their imprint on the process, for example, by helping to produce the great walls separated by $\sim 100h^{-1}$ Mpc (Einasto, 1997; Eisenstein *et al.*, 1997). [For further discussion of nonbaryonic dark matter and structure formation, see Dodelson *et al.* (1996).]

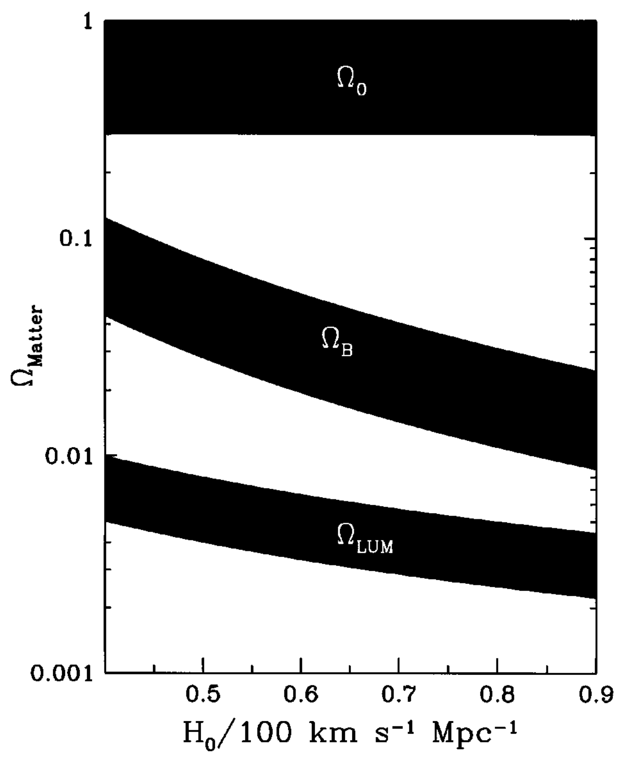


FIG. 4. Summary of knowledge of the matter density $\Omega_M$. The lowest band is luminous matter, in the form of bright stars and associated material; the middle band is the pre-Keck big-bang nucleosynthesis concordance interval; the upper region is the estimate of the total matter density based upon dynamic methods (galaxy-cluster mass determinations, galaxy peculiar velocities, and gravitational lensing). The gaps between the bands illustrate the two dark matter problems: most of the ordinary matter is dark and most of the matter is nonbaryonic.

(2) The BBN determination also implies that most of the baryons are in a form yet to be identified. Stars and closely related material ("luminous matter") contribute less than 1% of the critical density, $\Omega_{\rm LUM}\simeq 0.003h^{-1}$ (see, for example, Bahcall *et al.*, 1995); since this is almost a factor of ten lower than the BBN determination of the baryon density, it follows that most of the baryons are not optically bright, i.e., they are "dark." The fraction of critical density in gas at redshifts of two to four and in gas at the time of formation of clusters, redshifts one or less, is consistent with the nucleosynthesis value for the baryon density; this suggests that the bulk of the "dark" baryons are in the form of diffuse, hot gas. In clusters, this is clear—most of the baryons are in the hot intracluster gas that shines brightly in the x-ray region of the spectrum. Individual galaxies have shallower potential wells, and the gas would have a temperature of only around $10^5$ K, making it difficult to detect. There is some evidence, e.g., absorption of quasar light by singly ionized helium, for diffuse, intergalactic gas (Bi and Davidsen, 1997). While most of the dark baryons are likely to be found in the form of diffuse, hot gas, some fraction of the dark baryons, perhaps 10%, could be in the form of dark stars (or MACHOs), e.g., white dwarfs, neutron stars, brown dwarfs, and so on. There is evidence from microlensing that dark stars may comprise a portion of the halo of our own galaxy (Alcock *et al.*, 1996; Gates *et al.*, 1996; Renault *et al.*, 1996).

(3) Turning a previous argument around, if one accepts the baryon density based upon the primeval deuterium abundance, the cluster baryon fraction can be used to infer the matter density:

$$\Omega_M=\Omega_B/f_B=(0.30\pm0.1)(0.65/h)^{1/2}. \qquad (2)$$

Taken at face value, this implies that the matter density, while much larger than the baryon density, is far from unity. (This technique is not sensitive to a smooth component such as vacuum energy, and it does not preclude $\Omega_{TOT}=1$ with $\Omega_{VAC}\sim 0.65$; see, for example, Krauss and Turner, 1995.) However, important assumptions underlie the determination of the cluster baryon fraction: the gas is supported by its thermal motions only and not by magnetic fields or bulk motion; the gas is not clumped; and clusters provide a fair sample of matter in the Universe. If any one of these assumptions is not valid, the cluster gas fraction would be lower and the estimate for $\Omega_M$ correspondingly higher. There is some evidence that this may be the case: cluster masses determined by gravitational lensing appear to be systematically larger than those determined by x-ray measurements (Kaiser, 1996; Fischer and Tyson, 1997), perhaps by as much as a factor of two.

## IV. NUCLEAR COSMOLOGY CLARIFIES GALACTIC CHEMISTRY

Because most abundance measurements are made here and now, chemical evolution has always been an important issue for BBN. In order to extrapolate contemporary abundances to primordial abundances the use of stellar and Galactic chemical-evolution models is unavoidable. The difficulties are well illustrated by $^3$He: generally the idea that the sum D+$^3$He is constant or slowly increasing seems to be true, but the details, e.g., a predicted increase during the last few Gyr, are inconsistent with the $^3$He abundance measured in the local interstellar medium.

The pinning down of the baryon density turns the tables around. Primeval abundances become fixed and comparison with contemporary abundances can be used to reveal the details of stellar and Galactic chemical evolution. Nuclear physics in the early Universe provides tracers to study Galactic chemistry! For the sake of illustration we continue to use our provisional baryon density, $(3.6\pm 0.7)\times 10^{-31}$ g cm$^{-3}$, and remind the reader that conclusions could change if the value for the primeval deuterium abundance changes.

Beginning with deuterium, our assumed primeval abundance, D/H $=(3.2\pm 0.6)\times 10^{-5}$, is about a factor of two larger than the present interstellar medium abundance nearby, D/H $=(1.5\pm 0.1)\times 10^{-5}$, determined by Hubble Space Telescope observations (Linsky *et al.*, 1993; Linsky and Wood, 1996; Piskunov *et al.*, 1997) and comparable to a recent tentative detection of deuterium in the outer part of the Galaxy through the 92-cm hyperfine transition of atomic deuterium, (D/H) $=(4\pm 1)\times 10^{-5}$ (Chengalur *et al.*, 1997). This could imply little nuclear processing over the history of the Galaxy and/or significant infall of primordial material into the disk of the Galaxy. The metal composition of the Galaxy, which indicates significant processing of Galactic material through stars, together with the suggestion that even more metals may have been made and ejected into the intergalactic medium (this occurs in clusters of galaxies), means that the first possibility alone is unlikely. If the Chengalur *et al.* detection is confirmed, it suggests less stellar processing of material in the outer parts of the galaxy, which is consistent with most models of Galactic chemical evolution. More intriguing is the fact that the inferred abundance of deuterium in the presolar nebula, D/H $=(2.6\pm 0.4)\times 10^{-5}$ (Black, 1972; Bodmer *et al.*, 1995; Geiss, 1997) is very close to the primeval value. This could indicate less processing in the first 8 Gyr of Galactic history than in the past 5 Gyr (contrary to conventional models of galactic chemical evolution) or, alternatively, a decreasing rate of infall and/or a change in the distribution of stellar masses.

Moving on to $^3$He, the primeval value corresponding to our assumed deuterium abundance is $^3$He/H $\simeq 1.3\times 10^{-5}$. The presolar value, measured in meteorites and more recently in the outer layer of Jupiter, is $^3$He/H $=(1.2\pm 0.2)\times 10^{-5}$ (Black, 1972; Bodmer *et al.*, 1995; Geiss, 1998), which is comparable to the primeval value. The present value in the local interstellar medium, $^3$He/H $=(2.1\pm 0.9)\times 10^{-5}$, is about twice as large as the primeval value (Gloeckler and Geiss, 1996). Likewise, the $^3$He abundance measured in ten or so ionized gas clouds (H II regions) within the Galaxy, ($^3$He/H) $\simeq 1.5^{+1.0}_{-0.5}\times 10^{-5}$ (Rood *et al.*, 1998), is about twice the primeval value. On the other hand, the $^3$He abundance seen in several planetary nebulae is a factor of ten higher (Rood *et al.*, 1998), which supports the idea that some stars make significant amounts of $^3$He.

The primeval sum of deuterium and $^3$He, $[(\mathrm{D}+{}^3\mathrm{He})/\mathrm{H}]_P=(4.5\pm 0.7)\times 10^{-5}$, is close to that determined for the presolar nebula, $(3.8\pm 0.4)\times 10^{-5}$, and for the present interstellar medium $(3.7\pm 1)\times 10^{-5}$. This indicates little net $^3$He production beyond the burning of deuterium to $^3$He. This conflicts with conventional models for the evolution of $^3$He, which predict a significant increase in D+$^3$He due to $^3$He production by low-mass stars, as well as unconventional models, in which $^3$He is efficiently burned, which predict a sharp decrease in D + $^3$He. The constancy of D+$^3$He might actually be a coincidence: In models put forth to explain certain isotopic anomalies ($^{18}$O/$^{16}$O and $^{12}$C/$^{13}$C) in interstellar material (Charbonnel, 1995; Wasserburg *et al.*, 1995), $^3$He is produced during the main-sequence phase and then destroyed during post-main-sequence evolution. While empirical evidence supports the idea that the D+$^3$He remains roughly constant, as Yang *et al.* (1984) suggested, there is as yet no clear theoretical understanding of why this is so.

Finally, consider $^7$Li. The predicted primeval abundance, $^7$Li/H $=(4\pm 2)\times 10^{-10}$, is a factor of two to three larger than that measured in the atmospheres of Population II halo stars, $^7$Li/H $=(1.5\pm 0.3)\times 10^{-10}$. There are three things that, together or separately, could account for this. First, the abundance determinations in these old halo stars are sensitive to the model atmospheres used (the abundance is inferred from the absorption lines of neutral $^7$Li atoms, while most of the $^7$Li is ionized); this introduces an uncertainty that could be as large as 50%. Second, lithium could have been depleted in these old stars (see, for example, Pinsonneault *et al.*, 1992). The observation of $^6$Li in at least one Population II halo, which is much more fragile than $^7$Li, limits stellar deple-

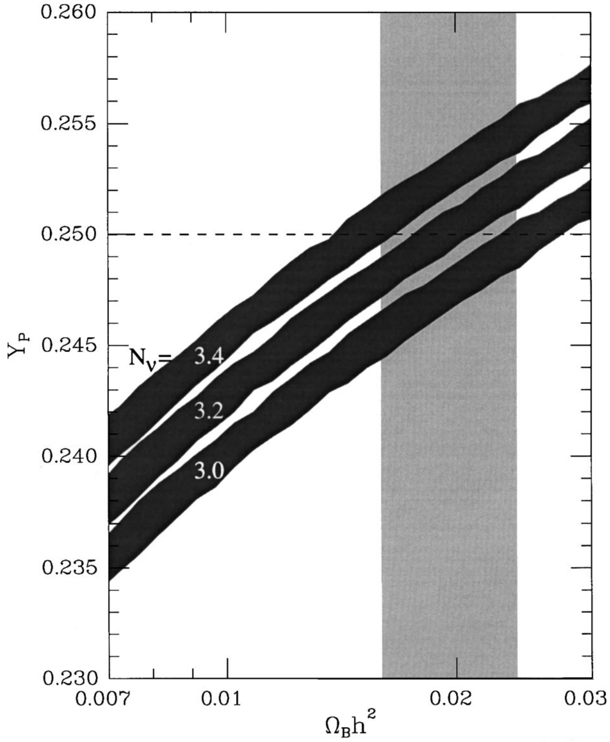


FIG. 5. $^4$He production for $N_\nu=3.0$, 3.2, and 3.4, where $N_\nu$ is the equivalent number of massless neutrino species. The vertical band indicates the baryon density consistent with $(D/H)_P = (3.2\pm0.6)\times10^{-5}$ and the horizontal line indicates a primeval $^4$He abundance of 25%. The widths of the curves indicate the two-sigma theoretical uncertainty. Figure courtesy of K. Nollett.

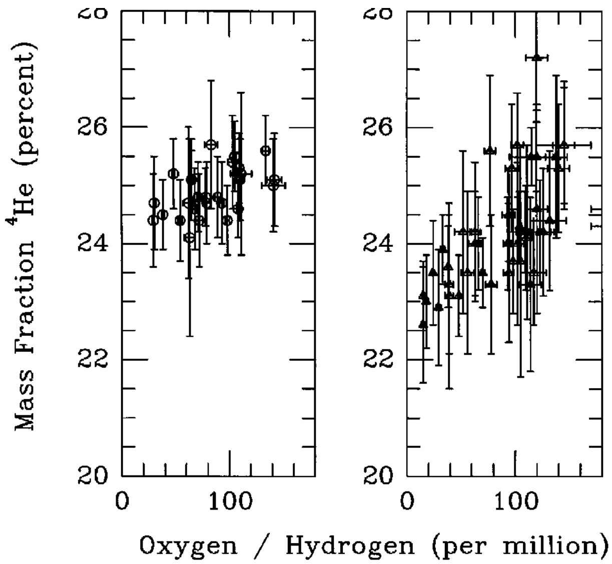


FIG. 6. Helium-4 abundance (mass fraction) in H II regions as a function of oxygen abundance (indicator of stellar processing and stellar $^4$He contribution) for two samples of metal-poor, dwarf emission-line galaxies. Right panel (triangles) is the sample analyzed by Olive and Steigman (1995); left panel (circles) is the new sample of Izotov *et al.* (1997).

tion to a factor of two or less (Lemoine *et al.*, 1997; for another view see Deliyannis and Malaney, 1995); further, the fact that the $^7$Li abundance in stars of different mass is at most weakly dependent upon mass also argues for a depletion of at most a factor of two or so (Vauclair and Charbonnel, 1995; Ryan *et al.*, 1996; Beckman and Rebolo, 1998). Finally, the theoretical uncertainty (due to nuclear cross sections) in the predicted $^7$Li abundance is significant (see Appendix and Fig. 1) and could, by itself, resolve the discrepancy.

The issue of stellar atmospheres can be addressed through both theoretical studies and observations. If depletion is important, high-quality observations of old halo stars (for example, by using the Keck telescope) should begin to reveal dispersion in the $^7$Li abundance due to the difference in stellar rotation rates and/or ages. The theoretical uncertainty can be narrowed by more precise measurements of two cross sections, $^3He+{}^4He\to{}^7Be+\gamma$ and $^3H+{}^4He\to{}^7Li+\gamma$; the first is also crucial to the solar neutrino problem. When the final details of the $^7$Li story are in, much should be revealed about the role of rotation and mixing in the evolution of stars.

## V. HELIUM-4: LOOSE END OR CONSISTENCY CHECK?

Helium-4 plays a different role and presents a different challenge. The primeval yield of $^4$He is relatively insensitive to the baryon density—pinning down the baryon density to 20% pegs its value to 1% precision (see Fig. 5). The chemical evolution of $^4$He is straightforward—the abundance of $^4$He slowly increases due to stellar production. The challenge is to determine the primeval abundance of $^4$He to a precision of 1% or better—few astrophysical quantities are measured this accurately. If this can be done, $^4$He will play a crucial role in the precision era.

Here is the present situation: Assuming our provisional value for the primeval deuterium abundance, the predicted primeval $^4$He abundance is $Y_P=0.248\pm0.002$ (including theoretical uncertainty; see Lopez and Turner, 1998). There have been two recent precision determinations of the primeval abundance of $^4$He. Both are based upon measurements of hydrogen and helium recombination lines detected from regions of hot, ionized gas (H II regions) found in metal-poor, dwarf emission-line galaxies. Analyzing one sample of objects and extrapolating to zero metallicity, Olive and Steigman (1995) infer $Y_P=0.232\pm0.003\,(\mathrm{stat})\pm0.005\,(\mathrm{sys})$ (also see Olive, Skillman, and Steigman, 1997). Using a new sample of objects, Izotov *et al.* (1997) infer $Y_P=0.243\pm0.003\,(\mathrm{stat})$. Both data sets are shown in Fig. 6. If Steigman and Olive are correct, there is significant discrepancy. On the other hand, if Izotov and his collaborators are correct, there is reasonable agreement.

This situation has fueled much debate. On one issue there is consensus: systematic error is the limiting factor at present. Much must be done to turn recombination-line strengths (what is measured) into a high-accuracy $^4$He abundance determination: corrections for doubly ionized $^4$He and neutral $^4$He have to be made; absorption by dust and by stars must be corrected for; and collisional excitation must be accounted for. On top of that, there are still (small) discrepancies in the input atomic physics, and extrapolation of the $^4$He to its primeval value (zero metallicity) must be made in the absence of a clear understanding of how the $^4$He abundance is related to stellar metal production. (Regarding the last point, because there are several post-big-bang sources of $^4$He, the relationship between $Y_P$ and metallicity is almost certainly not a single-valued function. This could make the simple regression techniques used unreliable.)

Olive and Steigman argue that the systematic error is no larger than $\Delta Y = \pm 0.005$, and their estimate of the primordial $^4$He abundance is discrepant (at three sigma) with the prediction based upon deuterium. Hata *et al.* (1995) have even gone so far as to argue for a BBN crisis (for another view see Copi, Schramm, and Turner, 1995c). Others, including Pagel, Skillman, Sasselov and Goldwirth, believe that at present the systematic error budget is larger—more like $\pm 0.01$ or larger—in which case the discrepancy is at most two sigma. And of course, the Izotov *et al.* (1997) value for $Y_P$ is reasonably consistent with the deuterium prediction.

Turning to the data themselves, the two samples are generally consistent, except for the downturn of the lowest metallicity objects, which is seen in the data analyzed by Olive and Steigman. Skillman (1998) has recently expressed concern about the use of the lowest-metallicity object, a dwarf galaxy known as IZw18, and Izotov and Thuan (1997) have shown that, for this object, underlying stellar absorption has caused the $^4$He abundance to be underestimated.

Visually, the data make a strong case for a primordial $^4$He abundance that is greater than 0.22 and less than about 0.25. To be more quantitative about the last statement and to derive very conservative upper and lower bounds to $Y_P$, we have carried out a nonparametric Bayesian analysis, which makes minimal assumptions about systematic error and the relationship between $Y_P$ and metallicity. We write the $^4$He abundance of a given object as $Y_i = Y_P + \Delta Y_i$. To obtain a lower bound to $Y_P$ we take a flat prior distribution for $\Delta Y_i$, $0 < \Delta Y_i < 1 - Y_P$, which accounts for the fact that stellar contamination increases the $^4$He abundance. To obtain an upper bound to $Y_P$ we take a different flat prior distribution, $-Y_P < \Delta Y_i < 0$, which accounts for possible systematic error that might lead to an underestimation of the $^4$He abundance. The likelihood distributions for the lower bound to $Y_P$ (first prior distribution) and for the upper bound (second prior distribution) are shown in Fig. 7. The 95% confidence intervals for the two bounds are

$$\text{Conservative lower limit:} \quad Y_P(\text{lower}) = 0.220^{+0.006}_{-0.012}$$
$$\text{Conservative upper limit:} \quad Y_P(\text{upper}) = 0.253^{+0.015}_{-0.005} \qquad (3)$$

This simple analysis with its minimal assumptions illustrates the strength of the case for a primeval $^4$He mass fraction between 22% and 25%. [Hogan *et al.* (1997) have very recently carried out a similar analysis, which is largely consistent with ours.]

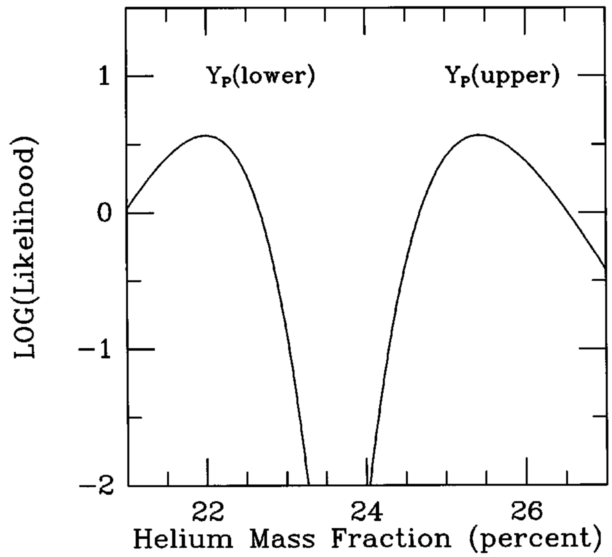


FIG. 7. Likelihood functions (unnormalized) for the conservative lower limit to $Y_P$ (left) and conservative upper limit to $Y_P$ (right). These results are based upon the H II regions in the sample analyzed by Olive and Steigman with metallicity O/H $\leq 10^{-4}$; qualitatively similar results obtain for different metallicity cuts and for the Izotov *et al.* (1997) sample.

At the moment $^4$He is a loose end. Once the systematic uncertainties are under control, $^4$He has an important role to play in the high-precision era as a test of the consistency of BBN. Skillman and others are talking about a new assault on $Y_P$—putting together a larger, more homogeneous set of low-metallicity galaxies in order to better understand, and hopefully reduce, systematic error. Izotov has emphasized that the Keck and other large telescopes will be invaluable in testing assumptions about the modeling of H II regions and other underlying assumptions. $^4$He could turn out to be the loose end that unravels the BBN tapestry or it could provide an important consistency check. The ultimate resolution of $^4$He could even involve new physics—a short-lived tau neutrino of mass greater than a few MeV could lower the prediction for $Y_P$ by as much as $\Delta Y = 0.012$ by reducing the effective number of neutrinos to two (see Fig. 5)—but it is certainly premature to give this possibility much weight.

## VI. A NEW TEST OF THE STANDARD THEORY

Almost overnight, the discovery of the cosmic background radiation (CBR) transformed cosmology from the realm of a handful of astronomers to a branch of physics. Moreover, it was considerations of big-bang nucleosynthesis that led Gamow, Peebles, and others to predict the existence of the CBR (see, for example, Kragh, 1996). In the next decade, the CBR will likely return the favor by providing an important new check of big-bang nucleosynthesis.

The BBN test is part of a larger program to harvest the wealth of cosmological information encoded in the temperature fluctuations (anisotropies) of the CBR across the sky (see, for example, Bennett *et al.*, 1997). To date, CBR anisotropy has been detected on angular scales from 0.1° to 100° at the level of about 30 $\mu$ K. The CBR temperature fluctuations are most usefully described by their multipole decomposition,

$$\frac{\delta T(\theta,\phi)}{T}=\sum_{lm} a_{lm}Y_{lm}(\theta,\phi). \tag{4}$$

For a theory like inflation, where the underlying density perturbations that lead to the anisotropy are Gaussian, all information is encoded in the variance of the multipole amplitudes. (The multipoles are Gaussian distributed with zero mean, with the rms temperature difference between directions on the sky separated by angle $\theta$ given roughly by $\sqrt{l(l+1)C_l/2\pi}$ with $l\approx 180°/\theta$.) The angular power spectrum, $C_l \equiv \langle |a_{lm}|^2\rangle$, depends not only on the spectrum of density perturbations, but also upon cosmological parameters, including the baryon density.

The angular power spectrum, shown in Fig. 3, is characterized by a featureless (Sachs-Wolfe) plateau from $l=2$ to $l\sim 100$ and a series of (acoustic or Doppler) peaks and valleys from $l=200$ to $l\sim 2000$. For $l\gg 2000$ anisotropy is strongly damped by photon diffusion, which smears out anisotropy on smaller scales (see, for example, Hu and Sugiyama, 1995). The plateau arises due to differences in the gravitational potential on the last scattering surface (Sachs-Wolfe effect). The peaks and valleys develop due to photon-baryon acoustic oscillations driven by gravity, and their amplitudes and spacings depend upon the contribution of baryons to the matter density (see Fig. 3).

When the two new satellite experiments, NASA's MAP to be launched in 2000 and ESA's Planck to be launched in 2005, map the sky with angular resolution of 0.1°, they will determine the variance of about 2500 multipoles to an accuracy essentially limited by sky coverage and sampling variance. From this it should be possible to determine precisely a number of cosmological parameters, including (a) the total energy density ($\Omega_{\rm TOT}$) and the fraction of critical density contributed by matter ($\Omega_M$), a cosmological constant ($\Omega_\Lambda$), and neutrinos ($\Omega_\nu$); (b) the Hubble constant ($H_0$); (c) the power-law index of the spectrum of density perturbations ($n$) and deviation from an exact power law ($dn/d\ln k$); (d) the contribution of gravitational waves to CBR anisotropy; and (e) the baryon density ($\Omega_B h^2$). In particular, the baryon density should ultimately be determined to a precision of around 5% (Knox, 1995; Jungman *et al.*, 1996; Bond *et al.*, 1997; Zaldarriaga *et al.*, 1997).

Even before MAP flies, a host of balloon-borne and ground-based experiments (e.g., CBI, MAXIMA, DASI, VSA, BOOMERANG, Q/DMAP, and TOPHAT) will cover a significant fraction of the sky with angular resolution of less than one degree. These experiments may be able to delineate the first two or three acoustic peaks and thereby determine the baryon density to 25% or so.

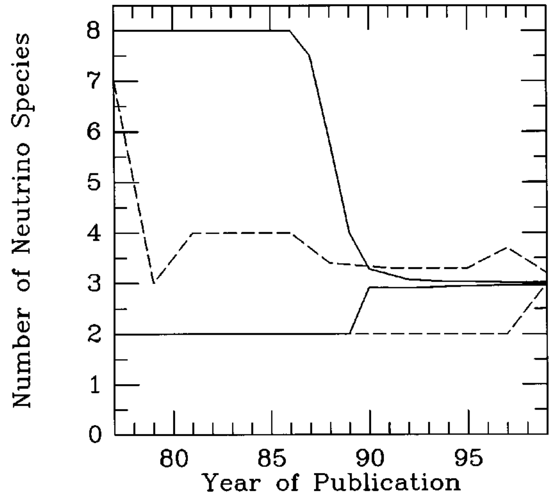


FIG. 8. Cosmological (dashed curve) and laboratory (solid curve) limits (95% C.L.) to the number of neutrino species as a function of publication date. The laboratory limits are from Denegri, Sadoulet, and Spiro (1990) and the Particle Data Group; the BBN limits are from papers published by Schramm and collaborators. A year 2000 cosmological limit of 3.1 neutrino species has been anticipated.

Certainly within a decade, and probably much sooner, there will be an independent, high-precision determination of the baryon density which is based on very different physics—gravity-driven, acoustic oscillations of the photon-baryon fluid when the Universe was around 300 000 years of age. If this determination of the baryon density agrees with that based upon big-bang nucleosynthesis it will be an impressive confirmation of the standard cosmology as well as of general relativity. (For further discussion about CBR anisotropy and its use in precision cosmology, see Bennett, Turner, and White, 1997.)

## VII. PROBING FUNDAMENTAL PHYSICS WITH NEW PRECISION

For almost two decades, big-bang nucleosynthesis has also been used as a powerful probe of fundamental physics, best illustrated by the BBN limit to the number of light neutrino species. Three neutrino types are now known, electron, muon, and tauon. There is no fundamental understanding of why there are three types (and not one or ten). Since there is one neutrino type for each pair of quarks, counting neutrinos is equivalent to counting quarks. The electron and muon neutrinos are known to be very light: $m_{\nu_e}\lesssim \mathcal{O}(10\ {\rm eV})$ and $m_{\nu_\mu}\lesssim 170$ keV. The current upper limit to the tau neutrino mass is 24 MeV. (For more about neutrinos, see Kayser *et al.*, 1989.)

In 1977 Steigman, Schramm, and Gunn argued that big-bang helium production set a limit of fewer than seven light neutrino species (Steigman *et al.*, 1977); by 1980 the limit had been refined to fewer than four neutrino species. Not until the $Z^0$ factories at SLAC and CERN came on line in 1989 did the laboratory limit become competitive (see Fig. 8). Today, the LEP determination based upon the shape of the $Z^0$ resonance stands at $N_\nu = 2.989 \pm 0.024$ (95% C.L.), a truly impressive achievement. [Denegri, Sadoulet, and Spiro (1990) have reviewed the history of "neutrino counting."]

While it is unlikely that the big-bang nucleosynthesis limit will ever achieve such precision, it will improve significantly when the baryon density is determined accurately. Moreover, the cosmological and laboratory limits are complementary: The neutrino limit based upon the shape of the $Z^0$ counts the number of particle species that are less massive than half the $Z^0$ mass, weighted by their coupling to the $Z^0$. BBN constrains the energy density contributed by relativistic particle species around the time of primeval nucleosynthesis and thus is sensitive to any particle species lighter than about 1 MeV. Historically, both have been expressed as a limit to the number of neutrino species.

The physics of the big-bang nucleosynthesis limit is described in the Appendix. In brief, the amount of $^4$He synthesized depends strongly upon the expansion rate at the time of BBN. In turn, it is determined by the energy density in relativistic particles, parametrized by the effective number of massless particle species,

$$g_* = \sum_{m \leq 1\,\mathrm{MeV}}^{\mathrm{Fermi}} g_i (T_i/T)^4 + \frac{7}{8} \sum_{m \leq 1\,\mathrm{MeV}}^{\mathrm{Bose}} g_i (T_i/T)^4, \qquad (5)$$

where $T_i$ is the temperature of species $i$. A species that interacts more weakly than neutrinos can have a lower temperature than the temperature of the electromagnetic plasma (see, for example, Kolb and Turner, 1990, or Steigman, Olive, and Schramm, 1979). The particles in the standard model contribute 10.75 to the sum, with each neutrino species contributing 1.75. To a lesser degree, $^4$He production depends upon the baryon density (see Fig. 5).

In the absence of precise knowledge of the baryon density and the measured primeval $^4$He abundance, setting a big-bang limit requires a lower limit to the baryon density and an upper limit to the value of the primeval $^4$He abundance. For more than a decade the lower limit to the baryon density was based upon the upper limit to the big-bang production of D+$^3$He (the shortcomings of which have been mentioned earlier). The upper limit to the primeval production of $^4$He was assumed to be 25% (and sometimes as low as 24%). Our provisional value of the primeval deuterium abundance pegs the baryon density to a precision of 20% at a value that is a factor of three above the previous lower limit.

Pinning down the baryon density improves the big-bang neutrino limit significantly. To illustrate, a recent Bayesian analysis assuming a primeval $^4$He abundance $Y_P = 0.242 \pm 0.003$ gave the following 95% credible intervals for $N_\nu$: $N_\nu = 3.0 - 3.7$, assuming the D+$^3$He lower bound to the baryon density, and $N_\nu = 3.0 - 3.2$, assuming $(\mathrm{D/H})_P = (2.5 \pm 0.75) \times 10^{-5}$ (Copi *et al.*, 1997; in both cases the prior $N_\nu \geqslant 3$ was enforced).

The determination of the baryon density from the primeval deuterium abundance will have a dramatic impact on the big-bang limit similar to the impact that the commissioning of the $Z^0$ factories had on the laboratory limit. When the baryon density is known to a precision of 5% and when the systematic uncertainties in the $^4$He abundance are reduced, an upper limit as precise as 3.1 neutrino species is possible (see Fig. 5). Together, the cosmological and laboratory neutrino limits work hand in hand to constrain new physics.

## VIII. CONCLUDING REMARKS

Big-bang nucleosynthesis is a cornerstone of the standard cosmology. Together with the cosmic background radiation it provides compelling evidence that the early Universe was hot and dense. This opened the door to the study of the earliest moments and helped to forge the symbiotic relationship between particle physics and cosmology. The inner space—outer space connection has led to very interesting and attractive ideas about the earliest moments, including inflation and cold dark matter. These ideas are now being tested by a host of experiments and observations and in the process a new window to fundamental physics is being opened (Turner, 1996).

For more than two decades BBN has also provided the best determination of the baryon mass density, which, in turn, has led to three important conclusions: baryons cannot provide the closure density; most of the baryons are dark; and most of the dark matter is nonbaryonic.

As we have tried to emphasize and illustrate, the pegging of the baryon density by a determination of the primeval deuterium abundance will advance BBN to a new, precision era. The scientific harvest to come is impressive: an accurate determination of a fundamental parameter of cosmology; light-element tracers to study Galactic and stellar chemical evolution; and new precision in probing fundamental physics. Finally, there are two important tests of BBN on the horizon: a check of the predicted primeval $^4$He abundance by new, more precise measurements and a comparison of the BBN value for the baryon density with that derived from CBR anisotropy.

## ACKNOWLEDGMENTS

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## APPENDIX: THE PHYSICS OF BIG-BANG NUCLEOSYNTHESIS

### 1. The ingredients

The synthesis of the light elements in the early Universe involves nuclear physics and elementary thermodynamics in "an expanding box" (the Universe) at temperatures between $10^9$ K and $10^{11}$ K (with an energy equivalent of $kT \sim 0.1$ MeV to 10 MeV) and matter den-

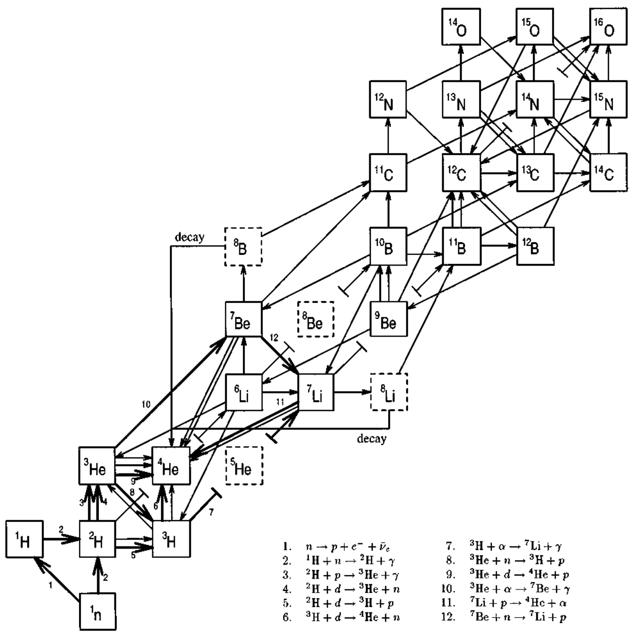


FIG. 9. The nuclear-reaction network used for BBN; the twelve most important reactions are listed. The broken boxes for mass 5 and 8 indicate that all nuclides of this mass are very unstable.

sities between $10^{-5}$ g cm$^{-3}$ and 10 g cm$^{-3}$. The important nuclear reactions are shown in Fig. 9.

The primary assumption underlying the standard scenario of BBN is the Friedmann-Robertson-Walker cosmological model. This solution of the Einstein equations is isotropic and homogeneous; the uniformity of the CBR temperature across the sky (to better than one part in $10^4$) as well as the success of the standard BBN scenario itself serve to validate this approximation. The Friedmann equation governs the rate of expansion,

$$H^2 = \frac{8\pi G \rho_{\rm TOT}}{3} \pm \frac{1}{R^2_{\rm curv}}, \qquad \text{(A1)}$$

where $R(t)$ is the cosmic scale factor and $H \equiv \dot{R}/R$. At the time of nucleosynthesis the energy density in radiation and other relativistic particles far exceeded that of matter. Further, the spatial curvature term, whose sign depends upon whether the Universe is positively curved and will ultimately recollapse (minus sign) or is negatively curved and forever expanding (positive sign) was unimportant. During BBN, $H^2 \approx 8\pi G\rho_{\rm R}/3$, the scale factor grew as $t^{1/2}$, and the temperature fell as $1/R(t)$, with $kT/1\ {\rm MeV} \sim 1/\sqrt{t/\ {\rm sec}}$.

Since a state of near-thermal equilibrium existed during BBN, the energy density in radiation can be written as

$$\rho_{\rm R} = g_* \frac{\pi^2}{30} \frac{k^4}{(\hbar c)^3} T^4. \qquad \text{(A2)}$$

The quantity $g_*$ counts the total number of spin degrees of freedom of the relativistic particles: 2 for photons + $2\times 2\times 7/8$ for electrons and positrons (the factor of 7/8 arises because electrons/positrons are fermions) $+2\times 7/8\times$ the number of neutrino species $N_\nu$ (neutrinos and antineutrinos come in only one spin state or, more precisely, one helicity state) for a total of $5.5+1.75N_\nu$. The expansion rate depends upon $g_*$ and $T$:

$$H^2 = g_* \frac{4\pi^3 G k^4}{45\hbar^3 c^5} T^4. \qquad \text{(A3)}$$

The results of BBN are determined by the matter density and nuclear matrix elements as well as the expansion rate. The matter density enters only through the (present) ratio of baryons to photons $\eta$; because the temperature of the cosmic background radiation is known so precisely, $T = 2.7277\ {\rm K} \pm 0.002\ {\rm K}$, $\eta$ and the baryon density (or the fraction of critical density contributed by ordinary matter) are directly related,

$$\rho_B = 6.84\times 10^{-22}\ {\rm g\ cm^{-3}}\,\eta,$$

$$\Omega_B h^2 = 3.64\times 10^7\,\eta. \qquad \text{(A4)}$$

The nuclear reactions relevant to BBN can be organized into two groups: those that interconvert neutrons and protons ($n + e^+ \leftrightarrow p + \overline{\nu_e}$, $p + e^- \leftrightarrow n + \nu_e$, $n \leftrightarrow p + e^- + \overline{\nu_e}$), and all others. The first group all depend upon the same matrix element and can be expressed in terms of the mean neutron lifetime $\tau_n$. The second group are determined by many different nuclear cross-section measurements; twelve are crucial (see Fig. 9).

In principle, then, the nuclear yields of BBN depend upon the baryon density, the mean neutron lifetime $\tau_n$, $g_*$ (or $N_\nu$), and twelve key nuclear cross sections. As recently as a decade ago, the uncertainties in $\tau_n$, several of the nuclear cross sections, the present temperature of the CBR, and the number of neutrino species meant that the outcome of the standard scenario of BBN depended upon many parameters. Precision measurements of the CBR temperature (by COBE), of the number of neutrino species, $N_\nu = 2.989\pm 0.012$ (by measurements of the decay width of the $Z^0$ boson made at CERN and at SLAC), and of the mean neutron lifetime, $\tau_n = 887\ {\rm sec} \pm 2\ {\rm sec}$ (by experiments using trapped, ultracold neutrons), along with improved determinations of some nuclear cross sections have reduced the standard BBN scenario to one parameter, the baryon density.

For the standard scenario, $N_\nu = 3.0$ and $g_* = 10.75$ and $\tau_n = 887$ sec. The only significant uncertainties are for the reactions $^3{\rm He} + {}^4{\rm He} \rightarrow {}^7{\rm Be} + \gamma$, $^3{\rm H} + {}^4{\rm He} \rightarrow {}^7{\rm Li} + \gamma$, and $p + {}^7{\rm Li} \rightarrow {}^4{\rm He} + {}^4{\rm He}$, which leads to about a 50% uncertainty in the predicted yield of $^7$Li. Interestingly enough, some of these same reactions are responsible for a significant portion of the uncertainty in the flux of high-energy neutrinos from the sun.

## 2. BBN 1-2-3

The two keys to understanding the synthesis of the light elements are the free-neutron fraction and the departures from thermodynamic equilibrium that occur. The neutron fraction is crucial because, unlike stars, in which the density of nucleons is higher and in which there is sufficient time for weak interactions to transmute protons to nuclei with neutrons (e.g., $p+p \rightarrow D+e^{+}+\nu_e$), in the early universe such reactions are impotent and the abundance of free neutrons determines the extent of nucleosynthesis. Departures from thermal equilibrium are crucial: If they did not occur, all nucleons would eventually end up in iron. The following is a quick synopsis of BBN; for more detailed treatments see Weinberg (1970), Kolb and Turner (1990), or Bernstein, Brown, and Feinberg (1989).

*0. Initial Conditions* ($kT \gtrsim$ *few MeV*). At temperatures above a few MeV ($T \gtrsim 10^{11}$ K), thermal equilibrium holds. The ratio of free neutrons to free protons assumes its equilibrium value,

$$\left(\frac{n}{p}\right) \approx \left(\frac{n}{p}\right)_{\rm EQ} = \exp(-Q/kT) \sim 1, \tag{A5}$$

where $Q$=1.293 MeV is the neutron-proton rest-mass energy difference.

The relative abundances of different nuclei is fixed by nuclear statistical equilibrium (NSE), with the mass fraction of nuclear species $A$,

$$X_A \propto (kT/m_N c^2)^{3(A-1)/2}\ \eta^{A-1}\ \exp(B_A/kT), \tag{A6}$$

where $B_A$ is the binding energy, $m_N c^2 \simeq 939$ MeV is the nucleon rest-mass energy, and other numerical factors of order unity have not been shown. While the binding-energy factor favors nuclei, the entropy factor, $\eta^{A-1}$, which arises due to the large number of photons per baryon (several billion) disfavors nuclei. (A simple way of seeing this is to think of the reaction photon + nucleus $\leftrightarrow$ $A$ nucleons; the large number of photons present drives equilibrium toward free nucleons.)

From the above equation one can estimate the temperature at which nuclei become favored over free nucleons:

$$X_A \sim \mathcal{O}(1) \quad \text{for } kT \sim \frac{B_A/(A-1)}{\ln(\eta^{-1}) + 1.5\ \ln(m_N c^2/kT)} \sim 0.3\ \text{MeV}. \tag{A7}$$

Because of the very high entropy, nuclei do not become thermodynamically favored until a temperature that is about a factor of 30 smaller than the binding energy per nucleon. If a state of thermodynamic equilibrium held during BBN, at a temperature not too much lower than this, all nucleons would end up in iron.

### a. Weak-interaction freezeout ($kT \sim 2$ MeV$-0.7$ MeV)

Weak interactions are responsible for keeping neutrinos in good thermal contact (through reactions like $e^{\pm}+\nu \leftrightarrow e^{\pm}+\nu$, $e^{+}+e^{-} \leftrightarrow \nu+\bar{\nu}$, and $\nu+\nu \leftrightarrow \nu+\nu$) and maintaining the equilibrium ratio of neutrons to protons ($n+e^{+} \leftrightarrow p+\bar{\nu}_e$, etc). At a temperature of around 2 MeV, energies and densities have dropped sufficiently so that neutrinos cease to interact (at these energies, weak-interaction cross sections vary as energy squared); thereafter, neutrino energies decrease as $1/R(t)$, which leads to neutrino distribution functions that continue to be of the Fermi-Dirac form, but with a temperature that falls precisely as $1/R(t)$. Since photons are heated slightly when the electron/positron pairs annihilate ($kT \sim m_e c^2/3 \sim 0.15$ MeV), the photon temperature eventually exceeds that of the neutrinos by a factor of $(11/4)^{1/3}$.

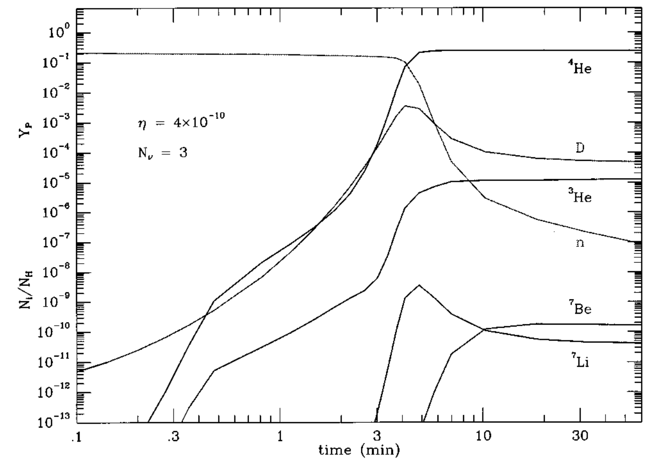


FIG. 10. The time evolution of the light-element abundances during BBN ($^4$He is given as mass fraction; the other elements are number relative to hydrogen). Note that $^7$Be decays to $^7$Li by electron capture.

The weak interactions that maintain the neutron-proton equilibrium cease to be effective for similar reasons, but at a slightly lower temperature ($kT \simeq 0.7$ MeV). Instead of decreasing exponentially with the falling temperature, the neutron-to-proton ratio freezes in at a value of around 1/6, decreasing to about 1/7 by the time of nucleosynthesis owing to neutrons capturing positrons and neutron decays. This reservoir of neutrons is the grist for the synthesis of the light elements.

### b. End of nuclear statistical equilibrium ($kT \simeq 0.5$ MeV)

At around this temperature the NSE mass fractions of D and $^4$He are each around $10^{-13}$; after this, the NSE value for $^4$He outstrips D and grows very rapidly. Production of $^4$He cannot keep up with demand; the D and $^4$He abundances rise together (D being overabundant compared to NSE and $^4$He being underabundant).

### c. BBN ($kT \simeq 0.07$ MeV)

By this temperature almost all the free neutrons have been incorporated into $^4$He. The mass fraction of $^4$He produced is thus

$$Y_P \approx \frac{2(n/p)}{1+(n/p)} \approx 0.25. \tag{A8}$$

The falling temperature and Coulomb barriers, as well as falling densities and the absence of stable nuclei with mass 5 or 8, prevent significant nucleosynthesis beyond $^4$He. Some D, $^3$He, and $^7$Li remain unburnt. The time evolution of the light-element abundances is shown in Fig. 10.

### 3. Variations on a theme

The sequence described above is the standard scenario of BBN. It is based upon our present understanding of fundamental physics and the minimum of additional assumptions. Over the past thirty years many variants of BBN have been explored, some motivated by new ideas in physics and some for the purpose of using the light-element abundances to constrain new physics and/or conditions in the early Universe. As it turns out, BBN is a "sensitive interferometer" for these purposes.

Variations on the standard scenario that have been studied include alternative theories of gravity (e.g., Jordan-Brans-Dicke theory); the possibility that the tau neutrino has a mass of 1 MeV or more and is unstable; the presence of inhomogeneity, anisotropy, or magnetic fields in the universe at the time of BBN; additional, new light particle species (e.g., neutrinos beyond the electron, muon, and tauon types); and large neutrino chemical potentials (see, for example, Yahil and Beaudet, 1976).

The last is related to an implicit assumption in the standard scenario: that the number of neutrinos is nearly equal to the number of antineutrinos (small net lepton number). Since the net lepton number per photon is proportional to neutrino chemical potential divided by temperature, this assumption is $|\mu_\nu/kT|\ll 1$. Beyond simplicity, the justification for such an assumption is the fact that the net baryon number per photon (which today is equal to $\eta$) is tiny, and the fact that baryon and lepton numbers will be comparable in size if the baryon number of the universe evolves dynamically due to particle interactions occurring during the earliest moments that do not conserve baryon number and matter/antimatter symmetry. Large lepton number, $|\mu_\nu/kT|\sim\mathcal{O}(1)$, affects BBN in two ways: (1) by changing the energy density in neutrinos; and (2) by changing the equilibrium neutron-to-proton ratio (electron-neutrino chemical potential only).

A great deal of attention has been given to the possibility that baryons might be distributed very inhomogeneously at the time of BBN, being highly concentrated in relatively isolated regions (see, for example, Applegate, Hogan, and Scherrer, 1987; Alcock, Fuller, and Mathews, 1987; Sato and Terasawa, 1991; Malaney and Mathews, 1993). Such inhomogeneity could arise if the transition from quark/gluon plasma to hadronic matter, which should take place at a time of around $10^{-5}$ sec, is a strongly first-order phase transition and occurs at a relatively low temperature (less than around 130 MeV). An inhomogeneity of this kind introduces two new parameters, the density contrast in the high-density regions and the separation of these regions. The late Willy Fowler (among others) hoped that this additional freedom would allow the same success of the standard scenario to be achieved with a sufficiently large baryon density to eliminate the need for nonbaryonic dark matter. As it turned out, the success achieved by the standard scenario could not be reproduced, let alone for a higher baryon density. Further, current numerical studies of the quark/hadron transition indicate that it is not strongly first order and that the transition temperature is well above 130 MeV.

In the end, consideration of inhomogeneity in the distribution of baryons served to constrain conditions in the early Universe (e.g., inhomogeneity produced by an earlier phase transition) and to further emphasize both the success and the robustness of the standard scenario (see, for example, Thomas *et al.*, 1994; Kurki-Sunio *et al.*, 1990).

### 4. Neutrino counting

The best known use of BBN in probing new physics is neutrino counting. Before the precision measurements of $N_\nu$ at SLAC and at CERN, BBN provided the best constraint on the number of neutrino species. Since there is one neutrino species per pair of quarks, this also constrained the number of quarks. Further, because BBN actually constrains the energy density of the Universe when the temperature was of the order of 1 MeV and because any particle species less massive than around 1 MeV which is in thermal equilibrium would contribute significantly to the energy density, the BBN constraint serves as a powerful probe of new physics.

During BBN the expansion rate of the Universe is determined by energy density in relativistic particles, and each additional neutrino species contributes 1.75 to the count of relativistic degrees of freedom $g_*$. The freezeout of the neutron-to-proton ratio is determined by a competition between the weak interactions that try to maintain equilibrium and the expansion and associated cooling of the Universe. More relativistic degrees of freedom means faster expansion and earlier freezeout; in turn, this leads to a larger neutron-to-proton ratio and more $^4$He (see Fig. 5). Overproduction of $^4$He is what constrains the number of neutrino species.

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