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Constraints on the Density of Baryons in the Universe [and Discussion]

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Constraints on the density of baryons in the Universe

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It is shown that not only does Big Bang nucleosynthesis provide an upper limit on the baryon density of the Universe, but if one takes into account arguments concerning the production of ^{3}He in stars, one can show that the ^{3}He plus deuterium abundance can also provide a lower limit on the baryon density of the Universe. The derived constraints are that the baryon:photon ratio, η, must be between 1.5×10^{-10} and 7×10^{-9} with a best fit between 3 and 6×10^{-10}. This small range for η has implications for our limits on numbers of neutrino types, for Big Bang baryosynthesis, and for arguments about the nature of the dark matter in clusters of galaxies. With reference to the dark matter, the derived baryon density for Big Bang nucleosynthesis corresponds very closely with the implied density of matter in binaries and small groups of galaxies. This implies that non-baryonic matter is not dominant by a large factor on scales as large as binaries and small groups of galaxies. It is also shown that the constraints on the lower limit on the baryon density constrain the lower limit on the primordial ^{4}He abundance. Consistency seems to be possible only if the primordial ^{4}He is between 23 and 25% by mass if there are three or four species of neutrinos.

1. Introduction

Big Bang nucleosynthesis has been shown to be one of the most powerful tools for exploring the nature of the early Universe (see Schramm & Wagoner (1977) and references therein). Of particular importance has been the demonstration that the limits on abundances of ^{4}He (see Yang *et al.* (1981) and references therein) and deuterium (Gott *et al.* 1976), and a review by Reeves (1974) can be used to determine an upper limit on the density of baryons in the Universe, or, more precisely, an upper limit on the ratio of baryons to photons in the Universe, $n_b/n_\gamma = \eta$. Steigman *et al.* (1977) showed that Big Bang nucleosynthesis can also be used to determine a limit on the number of neutrino species. However, this limit is sensitive to the lower bound on η as pointed out in detail by Olive *et al.* (1981*b*).

At one time it was thought that one could use the implied density of matter from the dynamics of binaries and small groups of galaxies to constrain a lower limit on the baryon density. This argument is now thrown into some question by the possibility that neutrinos may have mass and thus that they may be making up a considerable fraction of the implied matter density even in binaries and small groups. In addition to these arguments about limits on neutrino types, and also to resolving whether the dark matter is baryonic or non-baryonic, there is also the fact that grand unification theories have been shown to be very successful in determining η in the very early Universe in Big Bang baryosynthesis (see Fry *et al.* (1980) and Kolb & Wolfram (1980), and references therein). Thus, a precise value for η may have a role in distinguishing between different grand unified models. It will be shown in this paper that it is indeed possible to obtain a lower bound on η from Big Bang nucleosynthesis through the use of ^{3}He and deuterium and that this limit is consistent with the ^{7}Li abundance. I shall show that this limit places very narrow bounds on the allowed value for η, thus tightly constraining the neutrino limits to no more than four species. This constrains the baryon density to be not too different from the density implied by the dynamics of binaries and small groups, thus implying that on these and smaller scales, non-baryonic matter is not dominant by a very large factor. I shall also show that since the constraint on ^{3}He and deuterium appears to be so strong with regard to the lower limit on the baryon density that we begin to constrain a lower limit on the primordial ^{4}He abundance.

The lower limit argument will run as follows. It will be shown that ^{3}He is on average produced rather than destroyed in any normal generation of stars; thus, barring some very exotic and unknown type of star existing before the formation of the Galaxy, we can assume that the abundance of ^{3}He must on average remain the same or increase with time. Therefore, the amount of ^{3}He produced in the Big Bang should not exceed the currently observed values. Since deuterium, when it is destroyed in stars, primarily burns to ^{3}He, one needs to take into account that the primordial ^{3}He coming out of the Big Bang has had added to it a considerable fraction of the deuterium that was produced in the Big Bang in excess of the currently observed deuterium abundance. Thus the sum of the deuterium plus ^{3}He abundance, when applied to the Big Bang, will give us a constraint on the value of η. This paper will go through these arguments, showing how the abundances of deuterium and ^{3}He are determined and how they evolve in the galaxy with specific emphasis on these arguments. I shall also examine ^{7}Li and show that it gives answers consistent with the answers obtained from ^{3}He and deuterium, but it is unfortunately unable to place firm constraints. The consequences of the limits on η for the density parameter Ω of the Universe and the mass of the implied dark matter in clusters of galaxies will then be deduced. The consequences of limits of η for limits on neutrino types and limits and predictions on range of primordial ^{4}He will also be discussed. At the end, the best-fit model for deuterium, ^{3}He, ^{4}He, ^{7}Li, η, and number of neutrino species will be presented.

2. Abundances and evolution of ^{2}D, ^{3}He and ^{7}Li

Table 1 summarizes the current information on abundances of deuterium and ^{3}He, with ranges observed in the interstellar medium and the Solar System. The interstellar medium observations of deuterium are primarily those made with the Copernicus satellite by using the Lyman transition lines for deuterium compared with those for hydrogen. In addition, there are limits due to Weinrab (1962) and Cezarsky *et al.* (1973) from the 92 cm line of deuterium (which is equivalent to the 21 cm line of hydrogen). For the Solar System there are measurements of HD/H_2 in Jupiter with implied limits that are consistent with those from the interstellar medium (see Owen *et al.* 1980) and there are the limits from the solar wind measurements of ^{3}He where it is known that deuterium in the Sun has burnt to ^{3}He and so the ^{3}He in the solar wind can be used to set a limit on the primordial deuterium in the Sun (Geiss & Reeves 1971). In addition, there are the observations of Black on ^{3}He in meteorites showing which fraction of the He in the solar wind is primordial and thus implying indirectly the primordial deuterium of the Sun. For ^{3}He, there are the interstellar limits obtained by Wilson & Rood and there are the Solar System arguments mentioned by Black. For ^{7}Li there are the direct observations in many stars and there are the carbonaceous chondrite observations in the Solar System. As summarized by Audouze (1981), the ^{7}Li number fraction is probably *ca.* 10^{-9} or a mass fraction of *ca.* 5×10^{-9}. I shall not discuss in this section the ^{4}He abundances that were thoroughly discussed in Yang *et al.* (1979) and Olive *et al.* (1981 *b*); they will be reviewed briefly at the end of this paper when the implications for primordial ^{4}He are discussed.

Each of these light elements evolves in a somewhat different manner through the history of the galaxy. Deuterium is probably the simplest and it has been shown (arguments by Epstein *et al.* (1976), and references therein) that deuterium cannot be produced in significant amounts throughout the history of the galaxy without causing an overproduction of Li. In any normal stellar process, deuterium is destroyed with the initial burning, by the reaction $D + p \rightarrow {}^3He + \gamma$.

Table 1. Abundances of D and ^{3}He

(Note that some ratios are weighted averages of data.)

location	method	$10^5 \times$ abundance	source
D/H			
interstellar	Lyman lines	1–3	Rogerson & York
	92 cm line	$\lesssim 7$	Weinrab; Cesarsky *et al.*
Solar System	solar wind	~ 4	Geiss & Reeves
		2 ± 1	Black
	Jupiter HD/H_2	3 ± 2	Owen
^{3}He/H			
interstellar	direct	$\lesssim 5$	Rood, Wilson & Steigman
Solar System	meteorites	2 ± 1	Black

For a summary of ^{4}He abundance data see Yang *et al.* (1979).
Conclusion: $0.20 \leqslant Y_p \leqslant 0.25$, where Y_p is the primordial ^{4}He mass fraction.

It may be possible for there to have been some sort of exotic object, no longer seen today, that had such enormous temperatures that it breaks down everything to neutrons and protons, which are reconstructed to make deuterium when the temperature cools sufficiently rapidly that little else is produced. However, any such objects with enough energy to break down all heavy nuclei into nucleons would produce γ-rays and neutrinos. From limits on the γ-ray background and limits on the neutrino background, it can be shown that such processes would have had to have taken place at red shifts $z \gtrsim 100$ (see Epstein (1977) and Eichler (1978)).

As limits on neutrino fluxes improve with the proton decay experiments, etc. such hypothetical possibilities should be pushed back to higher red shifts and, it is hoped, out of existence. Thus, barring rather exotic loopholes, it appears that deuterium cannot be produced in significant amounts other than in the Big Bang and that deuterium has on the average been destroyed in star processing.

The standard models of galactic evolution process about half the gas through stars (see, for example, Talbot & Arnett (1974) and Thuan *et al.* (1975)); with extreme models, up to 90% or down to 10% is processed. The unprocessed material is thus the origin of the deuterium that is now seen. In the processing of deuterium through a stellar generation, the gas that is returned to the interstellar medium will primarily have converted its deuterium to ^{3}He. Although in very massive stars some of the deuterium would have been burned on up to heavier elements, even in these stars some appreciable fraction, of the order of a quarter, of the primordial deuterium will be returned to the interstellar medium as ^{3}He, because these massive stars do shed a large fraction of their outer envelopes during main-sequence mass-loss phases. Low-mass stars, with masses less than about $6M_\odot$, shed most of their material in excess of $1.4\ M_\odot$ during some form of mass loss or planetary nebular phase on their way to yielding white dwarfs. There is evidence (Angel 1977) that there is a white dwarf in the Pleiades where there is a main sequence turn-off above 6 $M_\odot$. This shed material is put back into the interstellar medium without significant amounts of heavy elements and thus returns the primordial deuterium almost completely as ^{3}He. Stars in the intermediate region between about 6 and 10 $M_\odot$ will not return significant amounts of heavy elements to the interstellar medium, but will return a significant amount of ^{4}He. Thus in these stars a considerable fraction of the primordial deuterium will have been converted to ^{4}He rather than ^{3}He; however, even here, because of mass loss in the outer envelopes, there will be some primordial deuterium returned as ^{3}He, at least of the order of a quarter. Thus, regardless of the masses of the stars involved, it appears that more than about a quarter of all the primordial deuterium that has been processed through stars is returned as ^{3}He. I shall return to this point later.

Evolution of ^{3}He itself is somewhat more complex than deuterium since stars on the average will be producing ^{3}He rather than destroying it. As mentioned earlier, a considerable fraction of the primordial deuterium will have been converted to ^{3}He and injected into the interstellar medium, but in addition the proton–proton burning will produce ^{3}He, which outer zones of the star will not have burned up to ^{4}He. Yang *et al.* (1982) give the relative burning rates of the synthesis and destruction of ^{3}He and the equilibrium values for ^{3}He at different temperatures. They conclude, with Rood *et al.* (1976), that in any stellar population ^{3}He will be expected to be enhanced. Thus ^{3}He is enhanced rather than destroyed on average since the Big Bang.

The evolution of ^{7}Li is also non-trivial. It is known that ^{6}Li and ^{7}Li are produced by the interactions of cosmic rays with the interstellar medium throughout the history of the galaxy. Such interactions were pointed out by Reeves *et al.* (1970), and worked out in detail by Meneguzzi *et al.* (1971). ^{6}Li and ^{9}Be and ^{11}B can be understood in a reasonable, straightforward manner by attributing their origin to this cosmic-ray production process. It is also known from cross-section measurements and from direct observation in the cosmic rays that spallation production of ^{7}Li and ^{6}Li is in a ratio of *ca.* 2 when one takes into account that both ^{7}Be and ^{7}Li eventually end up as ^{7}Li. Such processes would therefore only produce a ^{7}Li:^{6}Li ratio of the order of 2, whereas the observed ^{7}Li:^{6}Li ratio is approximately 12. Therefore, more ^{7}Li has been produced than can be made in cosmic ray spallation. It is possible that this additional ^{7}Li was produced in the Big Bang. However, one cannot rule out the possibility that there has been additional production of ^{7}Li in stars, and in fact some red giants do seem to show appreciable Li abundances. At times this has been attributed to production of Li *in situ* by processes such as that proposed by Cameron & Fowler (1971), although the details of such processes seem to have difficulty due to problems of convective burning and the relative ease of destroying Li. It is known that ^{6}Li cannot be produced easily in the stars nor in the Big Bang since it is a somewhat more fragile nucleus than ^{7}Li; thus the production of ^{6}Li by spellation throughout the galaxy must gradually yield over the history of the galaxy an abundance equal to the present ^{6}Li abundance. The equation

$$^6\mathrm{Li/H} = (\rho\sigma f/\omega)(1-\mathrm{e}^{-\omega t})$$

can therefore be written, where ω is the astration factor and t is the age of the galaxy, f is the cosmic ray flux, and ρ is the interstellar density of carbon, nitrogen and oxygen nuclei. The abundance equation for ^{7}Li can be written

$$^7\mathrm{Li/H} = (\rho\sigma f/\Omega)(1-\mathrm{e}^{-\omega t}) + {}^7\mathrm{Li}_{\mathrm{Big\ Bang}}\,\mathrm{e}^{-\omega t}.$$

As shown by Reeves *et al.* (1970), ^{6}Li/H is fitted approximately just by $\rho\sigma f t$, thus implying that $\omega t < 1$, and that ^{7}Li/H has increased on average since the Big Bang. However, the uncertainties in this statement are of the order of a factor of 2 or 3, and a factor of 2 or 3 astration stops one from using ^{7}Li to set lower limit constraints on the baryon density, as we shall see in the next section.

3. Big Bang nucleosynthesis constraints on η

Before going into the various constraints, I shall mention some changes that have been made in the reaction rates and a discussion of the uncertainties in these reaction rates as well as other uncertainties. Various new data on reaction rates have been used. However, the only ones that seem to make a significant effect concern Li production. There is also an unpublished coulomb screening correction reported by E. W. Kolb that may shift ^{4}He down by less than about 0.004.

Table 2. Uncertainties of primordial nucleosynthesis as a function of uncertain reaction rates†

(For $N_L = 3$ and $\tau_{\frac{1}{2}}(n) = 10.61$ min.)

reaction	σ/σ_0	$\eta = 10^{-10}$ X_2	X_3	X_7	$\eta = 10^{-9}$ X_2	X_3	X_7
p (n, γ) d	1.1	93	101	91	99	101	109
	0.9	108	100	110			
d (d, n) ^{3}He	1.1	96	103	101	95	101	105
	0.9	104	97	99			
d (d, p) t	1.1	96	95	102	95	98	100
	0.9	104	105	98			
t (d, n) ^{4}He	1.1	100	100	91	100	100	100
	0.9	100	100	110			
^{3}He (d, p) ^{4}He	1.1	100	99	100	100	93	93
	0.9	100	101	100			
^{4}He (t, γ) ^{7}Li	1.1	100	100	110	100	100	100
	0.9	100	100	90			
^{4}He (^{3}He, γ) ^{7}Be	2.0	100	100	102	100	100	196
	0.5	100	100	98			
^{7}Li (p, ^{4}He) ^{4}He	2.0	100	100	38	100	100	99

† Y is not changing more than 1% for the above changes of cross sections.

Since 1973 there have been some improvements in the reaction rates that affect the production of the heavy elements from Big Bang nucleosynthesis. Using these improved reaction rates we calculated the abundances of elements up to ^{12}C and found that new abundances of ^{4}He, D, and ^{3}He have remained the same to within *ca.* 1%, but X_7 has increased by about a factor of 3. The reasoning behind the change in X_7 is as follows. As the Universe expands from the singularity the temperature drops. At about 10^{10} K, the expansion rate becomes greater than the weak interaction rates, so thermal equilibrium between neutrons and protons no longer holds, and the n/p ratio is frozen out. As the temperature drops below *ca.* 10^9 K (1 GK), nucleosynthesis takes place. (There is a slight dependence of η on this, which is why the ^{4}He abundance rises slightly with increasing η.) Deuterium is formed by the reaction, n(p, γ)^{2}H and subsequently the heavier elements are synthesized from this element. At $T \approx 0.7$ GK, tritium is produced by ^{2}H(d, p)^{3}H and is eventually converted into ^{4}He by ^{3}H(d, n)^{4}He. At the same time, a very small amount of ^{7}Li is also produced by ^{4}He(t, γ)^{7}Li.

The new reaction rate of $^3H(d, n)^4He$ is one third as fast in this temperature region so that three times more tritium is available for the ^7Li synthesis.

Table 2 shows how much the Big Bang nucleosynthesis calculations are uncertain depending on the experimental uncertainties of the most critical reaction rates. Cross sections were varied by about one σ estimation. X_2 and X_3 have uncertainties less than 10%, but X_7 is not calculable to better than a factor of 2. Estimation of the primordial X_7^9, 1.1×10^{-8}, which is also uncertain by a factor of 2, is more than 10 times that of the Big Bang production (figure 1) in the range $1.3 \times 10^{-10} \lesssim \eta \lesssim 6 \times 10^{-10}$ from X_2, X_3 and Y. Even allowing a factor of 2 uncertainty to the calculation and the observations, the Big Bang production is still too small to account for the observations. The rest of the ^7Li is from galactic cosmic-ray spallations, $X_7^{\text{g.c.s.}} \approx 6 \times 10^{-9}$, from red giants, or from novae. This can be confirmed by γ-ray observations in the near future.

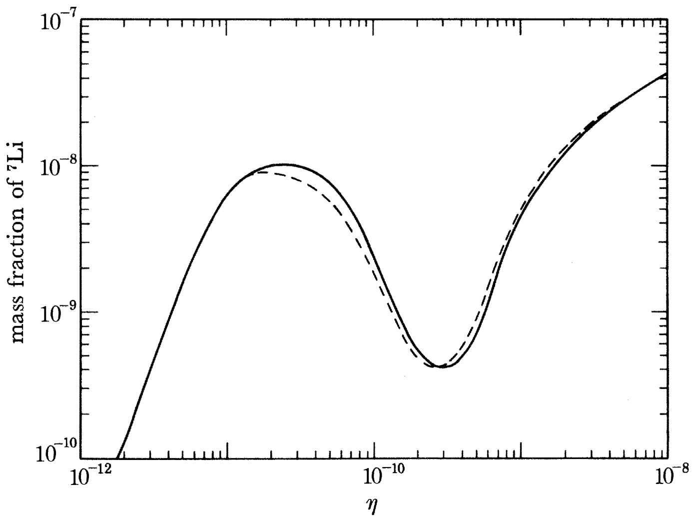

FIGURE 1. The mass fraction of ^7Li plotted against η for two and three neutrino species (from Yang *et al.* 1982).

Uncertainties in the neutron half-life were discussed in detail by Olive *et al.* (1981*b*). For the present I shall assume a half-life of 10.6 min with an uncertainty going from 10.4 to 10.8 min. An additional uncertainty is that of the degree of inhomogeneity in the Universe. We have assumed in our calculations no mixing of different density regions and thus each abundance corresponds uniquely to a density. Epstein & Petrosian (1975) showed the uncertainty in the deuterium limits from inhomogeneities to be small. We have also explored those variations for ^3He and D with regard to lower limits on η as well as the upper limits that Epstein & Petrosian used. At most, such variation can induce up to the order of a twofold uncertainty in any η value specified from the non-mixed situation. These variations occur because the D and ^3He abundances vary in a nonlinear manner so that different inhomogeneous regions have relative contributions that will not average in the same way as the mass density. One will produce an inhomogeneous mixture of variations because low-density regions contribute less material. Because the abundances do not rise arbitrarily rapidly in low-density regions, one cannot add arbitrarily large amounts of low-density material to compensate for the high-density material, which has no ^3He or D. Thus, only small variations, less than a twofold, arise as a result of averaging. These types of variations are assumed to be of an isothermal character because adiabatic variations retain the same η. However, it should be noted that if the regions ever mix, then one would have different regions in the Universe with different abundances, those corresponding to the η of that region.

Before going into the new constraints on the lower limit on η, I shall briefly review the upper limit constraints in the light of the uncertainties mentioned above. As pointed out by Yang *et al.* (1979), a reasonable upper limit on the ^{4}He abundances is *ca.* 25% by mass. Figure 2 shows the primordial He abundances plotted against η in the range of interest. Note that the limit at 25% by mass is exceeded for three neutrinos, even allowing for the uncertainty in the neutron half-life, by an η of 6×10^{-10}. This conclusion is not affected by the uncertainties in nuclear reaction rates. A similar result is obtained if we argue that the deuterium arising from the Big Bang must be greater than the deuterium observed in the interstellar medium.

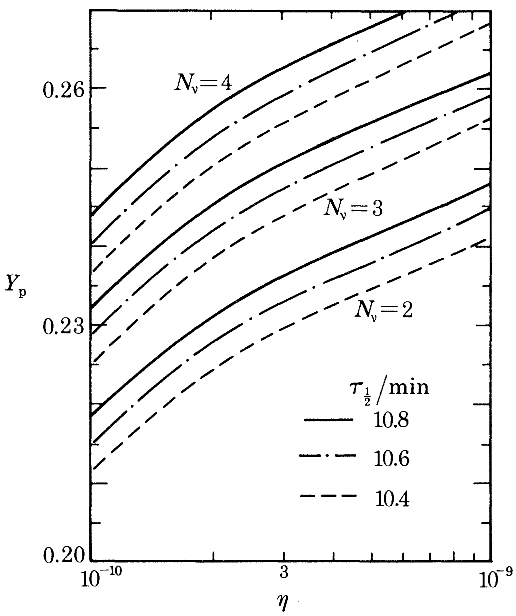

FIGURE 2. Primordial ^{4}He plotted against η for two, three and four two-component neutrinos (from Yang *et al.* 1982).

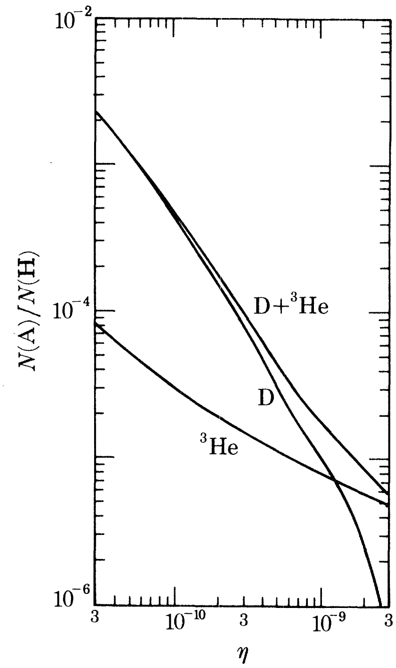

FIGURE 3. ^{3}He, D and (^{3}He + D) by number plotted against η for three neutrinos and $\tau_{\frac{1}{2}}$ = 10.6 min (from Yang *et al.* 1982).

Note that Big Bang deuterium production should be greater than the greatest value that for certain is observed in the interstellar medium, since it is possible to have lower values due to local higher rates of astration. Taking that as D/H = 2×10^{-5}, it yields an upper limit on η of 7×10^{-10}. Thus the deuterium and ^{4}He give consistent upper limits on η. Even allowing for inhomogeneities, this limit will not exceed 10^{-9}. This agreement on the upper limit on η is particularly impressive since D and ^{4}He have such different evolutionary histories.

The ^{7}Li result unfortunately does not yield a good lower limit on η, although it does give an upper limit consistent with that stated above. The ^{2}D, ^{3}He and ^{7}Li curves are almost unaffected by the uncertainties in neutron half-life or the number of neutrino species. From figure 1, ^{7}Li goes through a minimum in the region of interest and rises to a maximum at a somewhat lower η. Unfortunately, the present abundances with their uncertainties are not significantly below the maximum at 2×10^{-9}. As one takes into account the factor of 2 or 3 uncertainty in astration, one is not able to get a clear lower limit on η. However, on the upper end, even with these factors of 2 or 3 uncertainty, one does run into the problem of producing too much ^{7}Li in the Big Bang if $\eta > 3\times10^{-9}$. Although this is consistent with the D and ^{4}He limits, it is certainly not as strong a constraint as the ^{2}D or ^{4}He. As long as the ^{7}Li is consistent with an upper limit, it certainly tells us nothing at the lower end and does not appear to be a very valuable tool at present for constraining η.

Let us now consider the ^{3}He and deuterium with regard to the lower limit on η. Figure 3 is a plot of the ^{3}He and deuterium and the sum of ^{3}He and deuterium against η. Taking the ^{3}He by itself, and noting that there should not be more ^{3}He in the Big Bang than is currently observed because, as already argued, ^{3}He is on average destroyed, not produced, in stars, then the ^{3}He arising from the Big Bang must be less than about 5×10^{-5}; this constrains η to be greater than 4×10^{-11}. Constraints can be tightened significantly when the deuterium plus ^{3}He factor is taken into account, that is the fact that at least one-quarter of all deuterium produced in excess of the currently observed deuterium abundance has been converted to ^{3}He. With the present deuterium abundance of 2×10^{-5} and the present ^{3}He abundance of 5×10^{-5}, it is clear that the sum of deuterium plus ^{3}He cannot exceed 3×10^{-4}, or in other words, η must be greater than 1.5×10^{-10}. In this determination the weakest limits have been used to obtain the most conservative lower bound on η. If instead the more restrictive limits on ^{3}He of 2×10^{-5} are taken, then the sum of deuterium plus ^{3}He is constrained to be less than 1.6×10^{-4}, which restricts η to being greater than 3×10^{-10}. Thus it can be argued that a best fit to η is probably between 3×10^{-10} and 6×10^{-10}. It appears that this quantity is constrained to a rather high degree of accuracy. Even if possible uncertainties due to possible inhomogeneities, tc., are taken into account, the range of η is still confined to between 1.5×10^{-10} and 10^{-9}.

4. Consequences for the cosmological density

This parameter η, which comes out of the Big Bang, can now be converted to the cosmological density parameter Ω, defined as the density, ρ, divided by the critical density of the Universe, $\Omega \equiv \frac{8}{3}\rho\pi G/H_0^2$. The parameter Ω can be directly related to the fraction of the density of the Universe in the form of baryons, Ω_b, which can be shown to be equal to 3.3×10^7 $(T_0/2.7)^3\,\eta/h_0^2$, where h_0 is the Hubble constant in units of 100 km s^{-1} Mpc^{-1} and T_0 is the present absolute temperature of the background radiation. If h_0 is taken to be between $\frac{1}{2}$ and 1 and T_0 to be between 2.7 and 3, the range in η of 3–6×10^{-10} translates into a range in Ω_b of $0.01 \leqslant \Omega_b \leqslant 0.1$. This may be put into terms of mass:light ratios by using the critical mass:light ratio, that is the mass:light ratio that if true throughout the Universe and applied to the average luminosity density of the Universe would yield the mass density equal to critical density, $(M/L_{\text{crit}}) = 1400h_0 M_\odot/L_\odot$. The limit on η, coupled with ranges on T_0 and h_0 stated above, yield

$$14 < (M/L)_{\text{baryons}} < 72\,M_\odot/L_\odot.$$

It is interesting that this overlaps very well with the implied range for the mass:light ratios for galaxies as derived from binaries and small groups (see Rood 1978; Faber & Gallegher 1979; Peebles 1980). It also implies that if the amount of mass associated with the average light in the Universe is greater than the order of 72, then that mass cannot be nucleons. This is a point emphasized by Schramm & Steigman (1981) when they argue that the high mass:light ratios claimed for large clusters would imply non-baryonic matter, with the best guess for such matter being massive neutrinos. It should be also noted, though, that because the nucleons must make up a mass:light ratio of at least 14 throughout the Universe, the dark matter on a smaller scale, such as galaxies and binaries and small groups, has an appreciable if not complete baryonic component. The only place that may require there to be non-baryonic dark matter are the large clusters of galaxies. This location is particularly well fitted with the neutrino hypothesis since neutrinos can cluster easily on scales of large clusters of galaxies, as pointed out by Bond *et al.* (1980). However, they have great difficulty with clustering on a small scale, as demonstrated in the papers by Bond & Szalay (1981) and Sato (1981). Thus it may be that massive neutrinos can explain an exceptionally large mass:light ratios implied by large clusters, and the mass:light ratios of less than 100 are primarily due to baryons, although there may be some capturing of massive neutrinos and other non-baryonic manner on this scale too. It should be noted that it is more and more difficult to form galaxies with lower and lower values of Ω_b. A low-density Universe requires larger and larger perturbations to form galaxies, since galaxy formation could not begin until the Universe became matter-dominant. The fraction of the critical density in the form of neutrinos relative to the fraction from the nucleons is *ca.* $3 \times 10^{10} \sum m_\nu / \eta$. Thus our limits on η tell us that the Universe would be neutrino-dominated if the masses of neutrinos exceeded 1.5 eV.

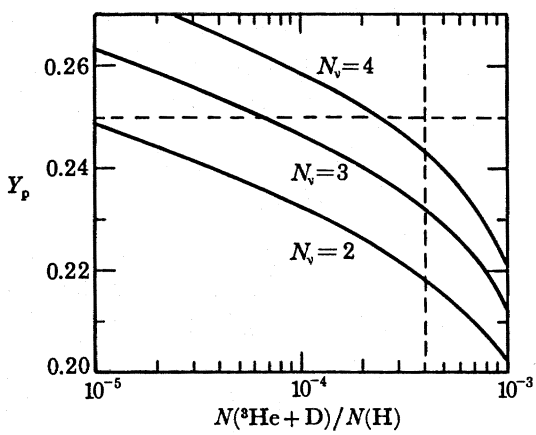

FIGURE 4. ^{4}He plotted against (^{3}He + D) for $\tau_{\frac{1}{2}}$ = 10.6 min, showing how ^{4}He is constrained to be between *ca.* 0.23 and 0.25 (from Yang *et al.* 1982).

5. Consequences for primordial He and numbers of neutrinos

It is important to note that the range of η derived above severely constrains the primordial He abundance and the number of neutrino types even with the uncertainties in the neutron half-life. This limit is at most four low-mass (less than about 1 MeV) two-component neutrino species, with three being a best fit because squeezing in the fourth required pushing all parameters to extreme limits. Thus all lepton families may have been discovered. This conclusion is quite similar to the results that Yang *et al.* (1979) obtained with a lower limit on the baryon density derived for binaries and small groups; however, as pointed out by Olive *et al.* (1981*b*), that limit was put into some question when it was pointed out that the mass implied by binaries and small groups may in fact have been dominated by non-baryonic matter. However, I have shown here that our limits on baryonic matter are quite consistent with that derived from binaries and small groups, so our limit on neutrino species is back to the same value. Thus if neutrinos are all long-lived and their masses are less than about 1 MeV, at most one more species of two-component neutrinos can be added, or the equivalent combination of other low-mass neutral particles (cf. Olive *et al.* 1981 *a*). It is very important that this will be testable in the laboratory when one finds the intermediate vector boson, since the Z^0 width is directly related to the number of neutrino species.

It is also important to note how the above constraints on η constrain the primordial He abundance (see figure 4), with the observational limits at present giving values ranging from 0.20 to 0.25, with the most recent determination being 0.24 ± 0.01. It is clear that the lower limit constraint on η does not allow values of less than about 0.23 if there are three or more two-component neutrino species (see figure 4). (If the as yet unpublished coulomb corrections of Kolb are correct this may go as low as 0.225.) Only by constraining the τ neutrino to have a mass greater than *ca.* 1 MeV, and thus allowing only two light neutrinos, would lower values for the ^{4}He abundances be achievable. Ignoring this possibility, it can be said that the limits on η predict that the helium abundance should be the order of 23–25% by mass. It is interesting that the most recent measurement falls into that range. However, it is clear to us that future measurements need to be done here and that this is a most important prediction of the standard consistent Big Bang nucleosynthesis model. Even with altered uncertainties due to inhomogeneities this value of primordial abundance cannot be less than *ca.* 0.22. To go slightly lower than this requires the τ-neutrino mass to be greater than about 1 MeV; to go any lower than 0.21 requires very radical assumptions and calls into question basic arguments in this paper with regard to the ability of Big Bang nucleosynthesis to set a lower limit on the baryon density.

6. Summary

In this paper I have shown that Big Bang nucleosynthesis can not only set an upper limit on the baryon:photon ratio in the Universe, but can also set a lower limit through the use of ^{3}He and deuterium constraints. In particular we have shown that a best fit to the data seems to imply that η, the baryon:photon ratio, is between 3 and 6×10^{-10}, and even allowing the most conservative estimates on the input parameters η cannot be less than 1.5×10^{-10}. These limits imply that the baryon density of the Universe is comparable with the density of matter implied by binaries and small groups of galaxies, thus implying that these systems are probably baryon-dominated. These limits also give a limit on the number of neutrino species, allowing no more than four two-component neutrinos, with the best fit being three. Particularly important here is the ^{4}He abundance since my arguments constrain a lower limit on the primordial ^{4}He abundance of the order of 0.23 by mass. This primordial He abundance can be lowered slightly if it is shown that the τ neutrino has mass, but no standard model solution with a lower-limit constraint on η allows the primordial ^{4}He abundance to be less than 0.21. The power of Big Bang nucleosynthesis in constraining the standard Big Bang model has been able to make some very important predictions that are testable. The ^{4}He observations in the future will see whether or not primordial ^{4}He does lie within the allowed range or outside it. If it is outside it only in a few small regions, there may be local variations but it cannot on average from the whole Universe lie outside it without calling into serious question the arguments presented here. Of utmost importance in addition to the ^{4}He abundances are further determinations of the ^{3}He abundance in the interstellar medium, because that is what has been so powerful in determining the lower limit. In addition the future observation of extragalactic deuterium is needed to show that deuterium really is of cosmological origin. Finally let me re-emphasize the importance of the width of the Z^0.

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Discussion

M. J. Rees, F.R.S. (*Institute of Astronomy, Cambridge, U.K.*). A great deal hangs on the assumption that deuterium must have been produced in the Big Bang. Can one definitively exclude the alternative possibility that it might be produced by (for instance) a pregalactic generation of massive or collapsed objects at $z \gtrsim 100$, before the synthesis of the heavy elements?

D. N. Schramm. If ^{4}He is present, then too much Li will be produced via $2\,^{4}He \rightarrow {}^{7}Li + D$ under the deuterium-producing conditions. The one loophole is where energies are large enough for everything to be reduced to nucleons, then cool enough so that only $n + p \rightarrow D + \gamma$ follows. However, to reduce everything to nucleons will probably require energies that produce too many photons and too many neutrinos. Limits on the ν and γ background severley restricted this loophole.

R. J. Tayler (*Astronomy Centre, University of Sussex, U.K.*). In this discussion Dr Schramm did not mention the problem of reconciling the ages of galactic objects with values of the Hubble constant and deceleration parameter. Does this mean that he does not think that it is a worry or does he think it premature to discuss it at present?

D. N. Schramm. I believe that it is premature; the uncertainty in H_0 is still a factor of 2 and within that range concordance is possible.

R. J. Tayler. Does Dr Schramm agree that if $\Omega < 0.1$ the problem of ages may not be too great, but that if $\Omega \approx 1$ it is necessary that $H_0 \approx 50$ km s^{-1} Mpc^{-1}?

D. N. Schramm. Yes, the age concordance would require $H_0 \lesssim 70$ km s^{-1} Mpc^{-1}.

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