CNO and ^{6}Li from big-bang nucleosynthesis—Impact of unmeasured reaction rates

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Rates for a number of nuclear reactions not studied in the laboratory are crucial for predicting the outcome of big-bang nucleosynthesis. It is shown in the present investigation that the mass fraction of CNO elements produced in neutron-rich zones in inhomogeneous nucleosynthesis (other parameters fixed) spans almost 3 orders of magnitude depending on the unmeasured rate of $^8\mathrm{Li}(\alpha,n)^{11}\mathrm{B}$. The possibility of producing observable quantities of primordial ^{6}Li via $^3\mathrm{H}(^3\mathrm{He},\gamma)^6\mathrm{Li}$ is discussed for the first time, and finally it is reported that helium production through $^2\mathrm{H}(^2\mathrm{H},\gamma)^4\mathrm{He}$ is negligible in all nucleosynthesis scenarios, in spite of recent measurements increasing the low-energy rate by a factor 32.

I. INTRODUCTION

The agreement between observationally deduced and theoretically predicted amounts of primordial light nuclei (notably ^{4}He, ^{2}H, ^{3}He, and ^{7}Li) is usually considered a major triumph of the big-bang model as such, and in particular of the so-called standard big-bang nucleosynthesis (SBBN) scenario (see Ref. 1 for an excellent review). Within the SBBN scenario it is now possible to pin down the baryon-to-photon ratio of the Universe, η, to $1.2\times10^{-10}\leq\eta\leq6.4\times10^{-10}$, and to limit the number of long-lived, light neutrino flavors to less than 4 (Ref. 2).

Recently the constraints from SBBN have been somewhat relaxed in models taking into account the possible inhomogeneities in baryon density and corresponding inhomogeneities in the neutron-to-proton ratio during nucleosynthesis resulting from the quark-hadron phase transition at $T\approx100$ MeV (Refs. 3–7). If the observed abundance of ^{7}Li in Population II stars is taken to equal the primordial production, it seems difficult to reconcile these models with a flat $\Omega=1$ universe, as was initially hoped for, but even with $\Omega<1$ the inhomogeneous models could have interesting consequences.[8] For instance, it has been shown that the production of heavy nuclei ($A\geq12$) is increased significantly in neutron-rich zones, and it has even been speculated that such seed nuclei might absorb sufficient numbers of neutrons to allow primordial production of *r*-process elements.[3]

A detailed investigation of the latter possibility is hampered by the lack of knowledge of the properties of unstable, neutron-rich nuclei and even the production of "primary" heavy nuclei is disputed among the groups studying inhomogeneous nucleosynthesis. Part of the discrepancy is probably due to differences in input physics, and here differences in nuclear reaction rates can play an important role.

The present investigation explores the uncertainties in a few of the reaction rates entering big-bang nucleosynthesis (BBN) calculations and points out some possible observational consequences in order to further encourage the relevant observational programs and nuclear-physics experiments.

Of primary concern will be the unmeasured reaction $^8\mathrm{Li}(\alpha,n)^{11}\mathrm{B}$ that leads to a factor of 10^3 uncertainty in the amount of "heavy elements" ($A\geq12$) produced in neutron-rich regions. Upper and lower limits on the production are given, and the possibilities for observing the produced amounts of ^{12}C and ^{14}N are discussed.

Results are also reported on the inclusion of the (hitherto neglected) reaction $^3\mathrm{H}(^3\mathrm{He},\gamma)^6\mathrm{Li}$ in nucleosynthesis calculations. No low-energy measurements exist for the rate of this reaction. If existing high-energy measurements can be extrapolated to the interesting energy regime, the reaction is of minor importance for BBN. But since the ^{6}Li production is proportional to the low-energy reaction rate, interesting amounts of ^{6}Li may be produced in the big bang, in particular in the low-density SBBN model, should the low-energy rate turn out to exceed the extrapolated value.

Finally it is argued that ^{4}He production through $^2\mathrm{H}(^2\mathrm{H},\gamma)^4\mathrm{He}$ is negligible in all nucleosynthesis scenarios, in spite of recent measurements increasing the low-energy rate by a significant amount.

II. CNO PRODUCTION VIA $^8\mathrm{Li}(\alpha,n)^{11}\mathrm{B}$

The reaction $^8\mathrm{Li}(\alpha,n)^{11}\mathrm{B}$ is known to be crucial for the production of heavy elements in the big bang through the chain

$$^7\mathrm{Li}(n,\gamma)^8\mathrm{Li}(\alpha,n)^{11}\mathrm{B}(n,\gamma)^{12}\mathrm{B}(\beta)^{12}\mathrm{C}(n,\gamma)^{13}\mathrm{C}(n,\gamma)^{14}\mathrm{C}\ ,$$

but the short lifetime of the ^{8}Li nucleus (0.8 sec) has so far made cross-section measurements impossible. The problems involved are generic to many cross-section measurements of astrophysical importance, since many interesting reactions involve short-lived nuclei. Suggestions for overcoming these problems with the use of radioactive ion-beam techniques are presently under consideration, e.g., at CERN (Ref. 9) and at Livermore (Ref. 10).

The reaction rate is given in standard form (in $\mathrm{cm^3s^{-1}mole^{-1}}$) as

$$N_A\langle \sigma v\rangle = 7.851\times 10^{6}(1+\delta_{12})^{-1}T_9^{-2/3} \times \left[\frac{Z_1Z_2}{A}\right]^{1/3} e^{-\tau}S \ , \quad (1)$$

where

$$\tau = 4.248\left[\frac{Z_1^2Z_2^2A}{T_9}\right]^{1/3} \quad (2)$$

with N_A being Avogadro's number, σ the reaction cross section, v the relative velocity of reacting nuclei, Z_1 and Z_2 the nuclear charges, A the reduced atomic mass, and T_9 the temperature in units of 10^9 K. S is the astrophysical S factor in units of keV barn [assumed constant in Eq. (1)], given at the energy E by

$$S(E) = E\sigma(E)\exp\left[0.989Z_1Z_2\left[\frac{A}{E(\text{MeV})}\right]^{1/2}\right] . \quad (3)$$

In the case ^{8}Li$(\alpha,n)^{11}$B it has been common to adopt a constant S factor of 3.3×10^6 keV barn, corresponding to a reaction rate of $3.41\times 10^{13}T_9^{-2/3}\exp(-19.49/T_9^{1/3})$ (Ref. 11). Malaney and Fowler[6] have suggested a value which is almost a factor of 3 larger. Unfortunately there are no published presentations of the analyses underlying these rate estimates. As stated already there are no measurements, even at higher energies, to guide the estimations. Furthermore, there are no obvious reactions with measured rates to compare with [for instance, the mirror reaction ^{8}B$(\alpha,p)^{11}$C is unmeasured as well since the lifetime of ^{8}B is comparable to that of ^{8}Li]. There are several examples in the literature of reactions where rates have changed by large factors, even in cases with existing high-energy measurements. [E.g., a factor of 20 for ^{11}B$(n,\gamma)^{12}$B and a factor 32 for ^{2}H$(^2$H$,\gamma)^4$He, just to mention two reactions discussed elsewhere in this paper.] Variations by 1 to 2 orders of magnitude around the theoretically estimated rates for ^{8}Li$(\alpha,n)^{11}$B does therefore not seem unrealistic.

This introduces major uncertainties in the prediction of heavy-element production since it turns out that the outcoming mass fraction of CNO elements (primarily ^{12}C and ^{14}C, which decays to ^{14}N in 5730 years) for rates near the theoretical estimates is almost proportional to the reaction rate in the narrow temperature regime near $T_9=1$, where most nuclei form. Thus varying the rate by a factor of 30 around the Malaney and Fowler estimate[6] leads to a span of more than 2 orders of magnitude in CNO production.

To investigate the range of possibilities the rate for ^{8}Li$(\alpha,n)^{11}$B has been varied by tuning the S factor and the outcome of big-bang nucleosynthesis calculated as a function of neutron fraction in the simple two-zone inhomogeneous model used by several authors.[12] Apart from changes in the S factor one might consider inclusion of resonance terms. However, since nucleosynthesis takes place in a fairly restricted temperature regime, changing the S factor is an easier and sufficiently accurate way of probing parameter space.

The two-zone model assumes that the Universe with present average baryon density Ω (in units of the critical density) was divided into high- and low-density regions as a consequence of the quark-hadron phase transition, with the high-density regions occupying a volume fraction f_V prior to nucleosynthesis. The ratio of densities in these regions after weak-interaction freezeout is denoted by R. When nucleosynthesis sets in at $T_9\approx 0.9$ neutrons have diffused to fill space uniformly, whereas the charged protons are assumed to stay in the density peaks. Thus nucleosynthesis takes place in high-density, proton-rich peaks [superscript (p) in the following] and in low-density, neutron-rich volumes [superscript (n)]. The scales involved are such that presently observed objects (e.g., stars) consist of mixtures of nuclei formed in peaks and troughs.

The high-density, proton-rich peaks are characterized at nucleosynthesis by density parameter $\Omega^{(p)}$ and neutron fraction $X_n^{(p)}$ given by

$$\Omega^{(p)} = X_n\Omega + (1-X_n)\frac{\Omega R}{f_V(R-1)+1} \ , \quad (4)$$

$$X_n^{(p)} = X_n\Omega/\Omega^{(p)} \ . \quad (5)$$

Similarly the low-density, neutron-rich regions are characterized by

$$\Omega^{(n)} = X_n\Omega + (1-X_n)\frac{\Omega}{f_V(R-1)+1} \ , \quad (6)$$

$$X_n^{(n)} = X_n\Omega/\Omega^{(n)} \ . \quad (7)$$

In these expressions X_n is the mean fraction of all nucleons in the form of neutrons at the onset of nucleosynthesis. Since this is a calculable parameter ($X_n\approx 0.15$), it is worth noticing the inverse relation between $\Omega^{(i)}$ and $X_n^{(i)}$. The baryon-to-photon ratio in zone (i), which is the decisive factor in nucleosynthesis calculations together with the neutron fraction, is simply given by

$$\eta^{(i)} = 4.245\times 10^{-9}T_{2.7}^{-3}\Omega h_0^2\frac{1}{X_n^{(i)}} \ , \quad (8)$$

where $T_{2.7}$ is the present background radiation temperature in units of 2.7 K, and h_0 is the present Hubble parameter in units of 100 km s^{-1}Mpc^{-1}. (The actual value of $\eta^{(i)}$ is somewhat larger before and during electron-positron annihilation. These effects are consistently included in the results given below.)

After calculating the produced mass fraction of element j in the two different environments, the final observable (mixed) mass fraction is

$$\bar{X}_j = \frac{f_VX_j^{(p)}\Omega^{(p)} + (1-f_V)X_j^{(n)}\Omega^{(n)}}{\Omega} \ . \quad (9)$$

The simple two-zone model gives a fair representation of the actual events if the typical distance between proton-rich peaks is small compared to the distance over which neutrons can diffuse from weak-interaction freezeout to the onset of nucleosynthesis, and if the proton-rich peaks are so extended and/or dense, that back diffusion of neutrons to the proton-rich peaks plays a minor role. Nucleon diffusion is not self-consistently included in the present calculations, but this should be of

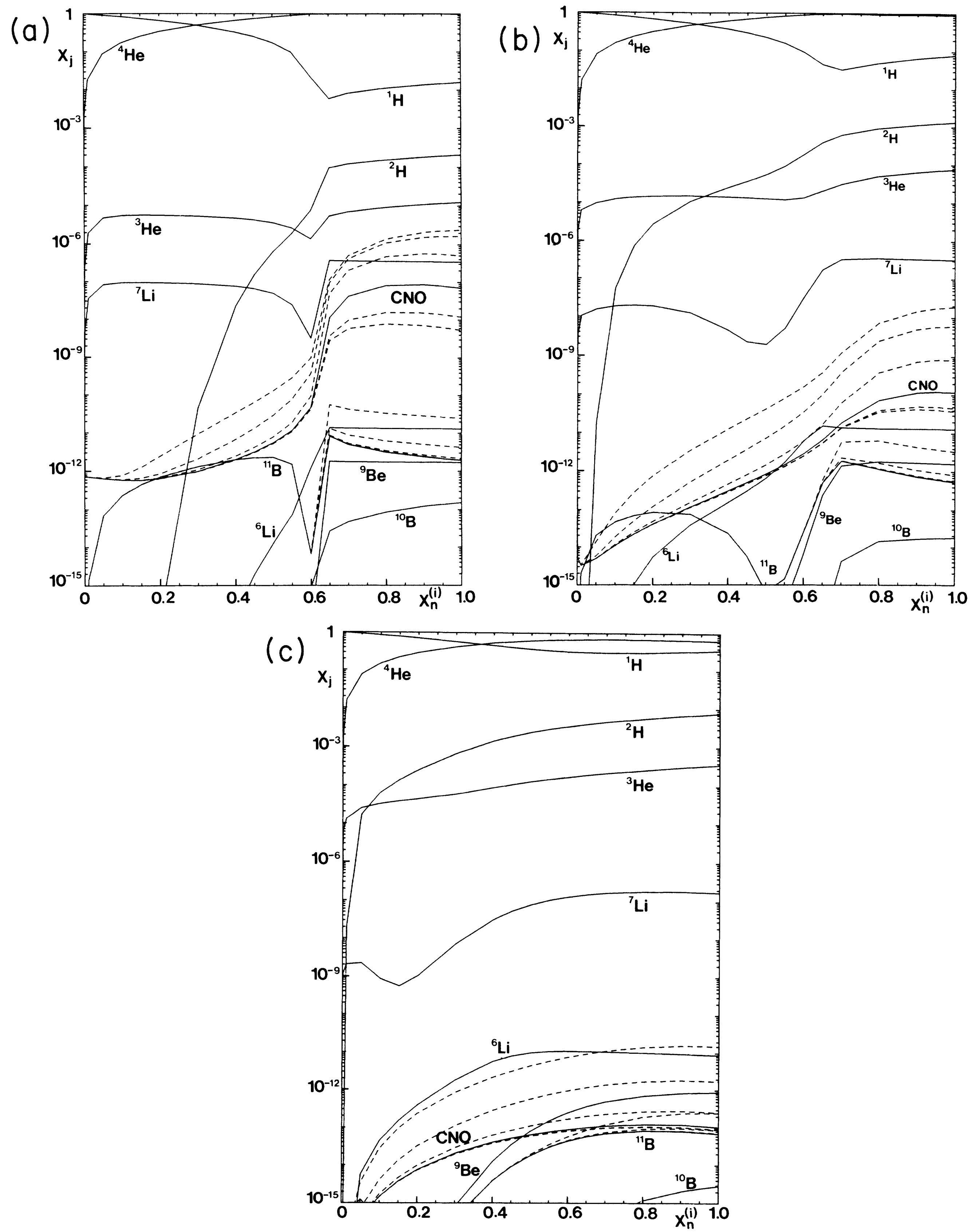

FIG. 1. Big-bang production of stable nuclei with $A \le 11$ and the sum of CNO elements ($12 \le A \le 16$) given as mass fractions X_j in zones with neutron fraction $X_n^{(i)}$. Figures 1(a), 1(b), and 1(c) are for $\Omega h_0^2 = 1$, 0.1, and 0.01, respectively. For CNO and ^{11}B curves are shown for ^{8}Li$(\alpha,n)^{11}$B reaction rates of 1000, 100, 10, 1, 0.1, and 0 times the "standard rate" discussed in the text. Rates are highest for the uppermost curves. Results for the standard rate are indicated by solid lines, for other rates by dashed curves.

minor importance for the conclusions, since the investigation is primarily concerned with CNO production in the neutron-rich zones, which is not significantly influenced by the late-time neutron diffusion back into proton-rich peaks. (Unless the characteristic length scales are so small, that neutron-rich zones lose significant fractions of their neutrons before nucleosynthesis begins; this would imitate a situation with lower $X_n^{(j)}$ and $\eta^{(j)}$, and hence lower CNO production. Details depend on the actual parameters involved.)

The nucleosynthesis calculations included 31 nuclei[13] with $A \leq 16$ and 121 reactions, expanding Kawano's[14] user-friendly version of the Wagoner code.[11] Rates were updated according to Caughlan and Fowler,[15] and except for a few unimportant three-body reactions all measured reaction rates involving only $A \leq 16$ nuclei were included from that compilation. In addition new measured rates for the important ^{8}Li-producing reaction $^7\mathrm{Li}(n,\gamma)^8\mathrm{Li}$ were taken from Wiescher, Steininger, and Käppeller,[16] and theoretically estimated rates involving ^{9}Li were taken from Malaney and Fowler.[6] Estimates for ^{6}Li plus ^{2}H, and ^{7}Li plus ^{2}H were taken from the latter reference as well, and so were updated rates for $^6\mathrm{Li}(n,\gamma)^7\mathrm{Li}$ and $^{11}\mathrm{B}(n,\gamma)^{12}\mathrm{B}$. Malaney and Fowler's rate for $^7\mathrm{Li}(n,\gamma)^8\mathrm{Li}$ was discarded in view of the new measurements reported in Ref. 16. Use of Malaney and Fowler's rate would in general *increase* the amount of heavy elements quoted below by a factor of 3. $^7\mathrm{Li}(^3\mathrm{H},n)^9\mathrm{Be}$ and $^9\mathrm{Be}(^3\mathrm{H},n)^{11}\mathrm{B}$, which have recently been shown to lead to an interesting increase in primordial ^{9}Be production, were included with the rates suggested by Boyd and Kajino.[17] Only one of the changes had a major impact on the conclusions of the present investigation, namely the significant decrease (by a factor 20) in the rate of $^{11}\mathrm{B}(n,\gamma)^{12}\mathrm{B}$, which caused a factor of 5–20 reduction in the production of $A \geq 12$ elements when compared with calculations using the rate from Wagoner[11] (yet another example of the uncertainties involved in estimates of nonstandard BBN outcomes).

Results of the calculations are illustrated in Fig. 1(a)–1(c), which show the final outcome of stable nuclei with $A \leq 11$ and the sum of CNO elements ($12 \leq A \leq 16$) (all given as mass fractions) in zones with varying values of $X_n^{(i)}$ for models with $\Omega h_0^2 = 1$, 0.1, and 0.01, respectively. In each figure curves for the CNO elements and for ^{11}B are shown for $^8\mathrm{Li}(\alpha,n)^{11}\mathrm{B}$ reaction rates of 0, 0.1, 1, 10, 100, and 1000 times the "standard choice" of $3.41\times 10^{13} T_9^{-2/3} \exp(-19.49/T_9^{1/3})$. (All other rates are kept fixed; apart from CNO only the ^{11}B results are influenced by the changing rate. The changes in ^{11}B are only visible for $X_n^{(i)} > 0.6$, and only for rates larger than 10 times the "standard value.") SBBN results correspond to $X_n^{(i)} = 0.15$.

In Fig. 2 the neutron fraction is fixed at $X_n^{(i)} = 0.95$, and the element production is shown as a function of $\eta^{(i)}$. According to Eq. (8), $\Omega h_0^2 \approx 2.24\times 10^8 \eta^{(i)}$ in the two-zone model, but the results are more generally applicable, since $\eta^{(i)}$ and $X_n^{(i)}$ are the the parameters that determine the outcome.

One notes immediately from the figures that the production of CNO elements is very sensitive to the rate for $^8\mathrm{Li}(\alpha,n)^{11}\mathrm{B}$, being almost proportional to the reaction

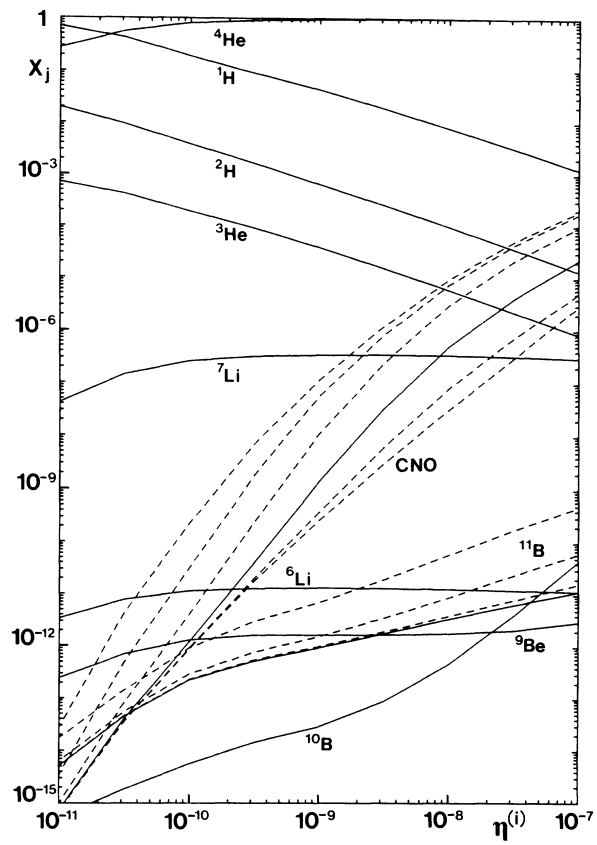

FIG. 2. Element production in mass fractions as a function of baryon-to-photon ratio $\eta^{(i)}$ for zones with fixed neutron fraction $X_n^{(i)} = 0.95$. Dashed and solid lines are as in Fig. 1. Very similar results are obtained for other choices of $X_n^{(i)} \gtrsim 0.75$.

rate in very neutron-rich regions for rates close to the standard choice. The total outcome varies by about a factor 1000. Most of the possible range for CNO production is spanned by varying the rate from 0.1 to 100 times the standard choice (a factor of 30 on each side of Malaney and Fowler's estimate). As discussed above this variation seems within the uncertainties involved in theoretical rate estimations for an unmeasured reaction.

Depending on the rate the maximal production of CNO elements in neutron-rich regions for $\Omega h_0^2 = 1$ lies between mass fractions of $8\times 10^{-9} \leq X_{\mathrm{CNO}} \leq 3\times 10^{-6}$ (with 9×10^{-8} for the "standard rate"). For $\Omega h_0^2 = 0.1$ the corresponding numbers are $5\times 10^{-11} \leq X_{\mathrm{CNO}} \leq 3\times 10^{-8}$, ($1\times 10^{-10}$ for the standard rate), and for $\Omega h_0^2 = 0.01$, $1\times 10^{-13} \leq X_{\mathrm{CNO}} \leq 3\times 10^{-10}$, ($1\times 10^{-13}$). The CNO production may thus vary by 3 orders of magnitude for given values of Ωh_0^2 and $X_n^{(i)}$. Using Wagoner's rate for $^{11}\mathrm{B}(n,\gamma)^{12}\mathrm{B}$ all of the above values are increased by factors between 5 and 20; most for low Ωh_0^2.

The distribution among the different CNO isotopes is illustrated in Fig. 3 (even though only one choice for the rate is shown, the relative distribution of isotopes is fairly independent of the $^8\mathrm{Li}(\alpha,n)^{11}\mathrm{B}$ rate). For all choices of Ωh_0^2 ^{12}C plays an important role with ^{13}C suppressed by a factor of 20–50. Only for Ωh_0^2 approaching 1 ^{12}C is dom-

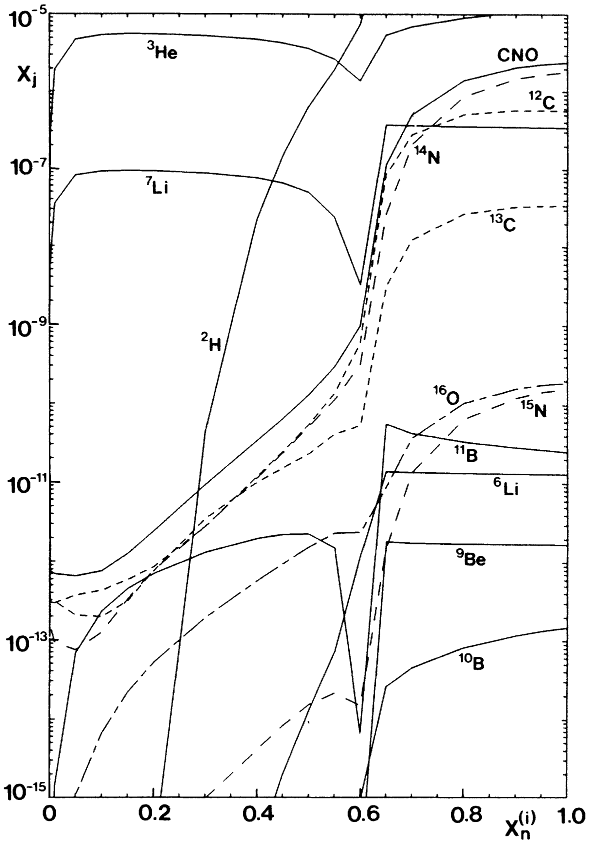

FIG. 3. Distribution of stable CNO isotopes produced for $\Omega h_0^2=1$ and a $^8\mathrm{Li}(\alpha,n)^{11}\mathrm{B}$ rate 1000 times the standard value in zones with neutron fraction $X_n^{(i)}$. The relative distribution of CNO elements is not strongly dependent on the rate for fixed Ωh_0^2. Changes may result from inclusion of reactions involving $A > 16$ nuclei.

inated by ^{14}N (originally produced as ^{14}C). Other stable isotopes (^{15}N and ^{16}O) are produced in amounts orders of magnitude smaller. This is a useful signature for comparison with observations, as discussed below, even though inclusion of $A > 16$ nuclei may change some of the results. (Kajino, Mathews, and Fuller[18] found that inclusion of reactions through the beta-unstable isotope ^{15}C could lead to 3 orders of magnitude increase in ^{15}N production, making it as abundant as ^{13}C. It has not been possible to reproduce this effect in the present investigation. Including the ^{15}C reactions listed by Wagoner[11] led to less than a factor-of-2 increase in ^{15}N. Inclusion of reactions through ^{16}N led to a similar increase in ^{16}O. These reactions are included in the curves shown.)

To compare with observations one should bear in mind that the observable mass fraction of a given element involves taking the mean of the production in a neutron-rich and a proton-rich zone as described in Eq. (9). The actual mixing depends on the choice of parameters R and f_V, ultimately calculable (at least in principle) from parameters of the quark-hadron phase transition. However if BBN involves zones with neutron fractions exceeding 0.65 (which are the interesting ones from the point of view of CNO production) ^{7}Li is overproduced unless the mixing reduces the mass fractions from neutron-rich zones by at least a factor of 40 (400) to fit ^{7}Li in Population I (II) stars. (A slightly smaller reduction may do for $\Omega h_0^2 < 0.1$.) Thus the final mass fraction of CNO for $\Omega h_0^2 = 1$ is at most between 2×10^{-10} and 10^{-7} (2×10^{-11} and 10^{-8}). For $\Omega h_0^2 = 0.1$ it is between 10^{-12} and 10^{-9} (10^{-13} and 10^{-10}), and for $\Omega h_0^2 = 0.01$ between 4×10^{-15} and 10^{-11} (4×10^{-16} and 10^{-12}).

The most metal-deficient star so far observed is the giant star CD-38245 with [Fe/H] $= -4.5$ (Ref. 19). The mass fractions of C and N in that star are approximately 10^{-7} (upper bound) and 10^{-6}, respectively, so even for the most optimistic choice of cross section this exceeds the largest possible "mixed" outcome from BBN by a factor 10 (Ref. 20). It does fall within the range of possible outcomes from neutron-rich zones, but it is hard to see how some stars could be formed exclusively from the neutron-rich troughs, though it has been speculated that sufficiently dense peaks might form invisible dark matter.[21] Interestingly the large N/C ratio observed in the star may be reproducible from the calculations, but the large abundance of oxygen in CD-38245 cannot be primordial. One may conclude that observation of the directly produced CNO nuclei require stars with even smaller [Fe/H] values. (This does not exclude the possibility that significant amounts of heavier elements in the star could result from the primordial r process suggested by Applegate, Hogan, and Scherrer[3].)

III. ^{6}Li PRODUCTION VIA $^3\mathrm{H}(^3\mathrm{He},\gamma)^6\mathrm{Li}$

In SBBN and in inhomogeneous nucleosynthesis models as well, ^{6}Li is only produced in rather insignificant amounts (mass fractions of 5×10^{-13} in SBBN, and up to 10^{-11} in neutron-rich zones in inhomogeneous models). The observed abundances of ^{6}Li are instead thought to be a consequence of cosmic-ray-induced spallation processes. However, one particular nonstandard BBN model[22] has tended to overproduce ^{6}Li.

It has been suggested by Rolfs[23] that the reaction $^3\mathrm{H}(^3\mathrm{He},\gamma)^6\mathrm{Li}$ might be important for a primordial production of ^{6}Li. This reaction has not been included in previous BBN calculations, and proper inclusion is hampered by lack of low-energy cross-section measurements. Such low-energy measurements are now being planned by Rolfs and co-workers.

From the existing high-energy measurements[24] one may deduce a ground-state capture cross section at a laboratory energy of 2 MeV of 45 μ barn, corresponding to an S-factor contribution of 0.51 keV barn (this should be considered as a lower limit of the S factor at center-of-mass energy 1 MeV). Assuming the S factor to be constant and neglecting all possible resonance terms, the reaction rate is given by Eq. (1) and the corresponding reverse-reaction rate can be found by standard procedures.[11] In fact the rate derived in this manner is consistent with the low-energy rate for $^3\mathrm{H}(^4\mathrm{He},\gamma)^7\mathrm{Li}$ given by Caughlan and Fowler.[15] Their reaction rate implies an S factor of 0.105 keV barn, and the corresponding value for $^3\mathrm{H}(^3\mathrm{He},\gamma)^6\mathrm{Li}$ would be expected to be four times larger due to the factor $(Z_1/A_1 - Z_2/A_2)^2$.

If low-energy measurements confirm these predictions, the inclusion of $^3H(^3He,\gamma)^6Li$ has only minor influence on primordial ^{6}Li production. This is illustrated in Fig. 4, which shows SBBN calculations for three neutrino flavors and a neutron half-life of 10.5 min (Ref. 25) as a function of the baryon-to-photon ratio η. The curves with and without the extra reaction are indistinguishable, except at low η, where the ^{6}Li mass fraction is increased by a factor 2.

If however the low-energy rate is significantly increased, for instance, due to resonances without counterparts in the $^3H(^4He,\gamma)^7Li$ case, interesting production of ^{6}Li may result. For reference, results are shown for S factors of 1, 10, 100, 1000, and 10 000 keV barn to probe parameter space (as argued previously varying the S factor is an easier but sufficiently accurate alternative to including specific resonance terms). Already for a rate 20 times the extrapolated lower bound discussed above, one obtains a factor of 10 increase in ^{6}Li production in a low-Ωh_0^2 universe, and for higher rates the outcoming ^{6}Li mass fraction is essentially proportional to the rate.

Recent observational[26] evidence suggests a primordial $^6Li/^7Li$ number ratio below 0.1, and theoretical considerations[27] certainly rule out a $^6Li/^7Li$ ratio above 3. The value 0.1 is exceeded for $\eta < 3\times10^{-10}$ if the reaction rate exceeds about 10^3 times the value extrapolated from high-energy measurements, but improved observational techniques would make it feasible to test primordial ^{6}Li production for smaller and more realistic rates. One may conclude that ^{6}Li could be produced in observable quantities in SBBN, provided that the rate for $^3H(^3He,\gamma)^6Li$ turns out to be higher than the value deduced above from high-energy measurements. Needless to say, low-energy experimental investigations of the reaction cross section, and improved observational limits on the amount of primordial ^{6}Li are mandatory for settling this issue.

In inhomogeneous scenarios ^{6}Li is primarily produced in neutron-rich regions (see Fig. 1). For $\Omega h_0^2 = 1$ the ^{6}Li mass fraction reaches 10^{-11} in neutron-rich zones without the $^3H(^3He,\gamma)^6Li$ reaction, and may increase to 10^{-10} for a very large rate. However this should be compared to a ^{7}Li production of 3×10^{-7}, so that the $^6Li/^7Li$ ratio is negligible. As expected from the SBBN results, ^{6}Li production is more efficient for lower Ωh_0^2, but it turns out that the $^6Li/^7Li$ ratio is highest for zones with neutron fraction near the homogeneous value of 0.15. Therefore the inhomogeneous models are generally less capable than the SBBN model to produce observable amounts of ^{6}Li.

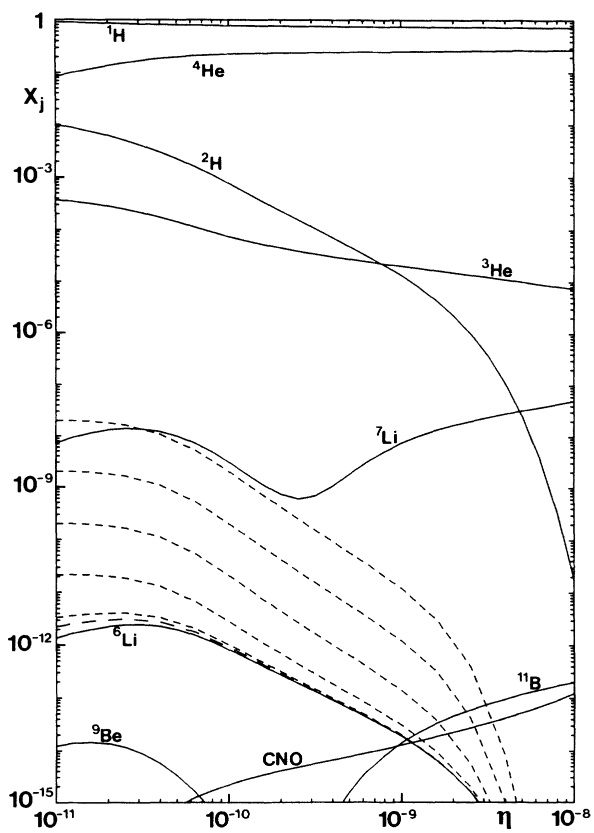

FIG. 4. SBBN element production as a function of baryon-to-photon ratio, η, related to Ωh_0^2 by $\Omega h_0^2 = 3.6\times10^7\eta$. Different curves for ^{6}Li correspond to astrophysical S factors for the reaction $^3H(^3He,\gamma)^6Li$ of 0 (solid line), 0.51 (long dashed), 1, 10, 100, 1000, and 10 000 (all short dashed) in units of keV barns.

IV. THE REACTION $^2H(^2H,\gamma)^4He$

The reaction $^2H(^2H,\gamma)^4He$ is an example that cross-section measurements at low energies may differ significantly from the high-energy expectations. In this case the newly measured rate[28] exceeded previous high-energy extrapolations by a factor 32. Even though the rate is still orders of magnitude smaller than rates for ^{2}H plus p or n it has been speculated that this direct channel to ^{4}He might give a measurable contribution to primordial helium. Kawano, Schramm, and Steigman[2] and Santos and Lin Yun[29] concluded that there was no calculable effect in SBBN, but the latter authors (as originally Barnes *et al.*[28]) mentioned that the reaction might be more important in inhomogeneous models.

I have tested this possibility for large ranges of parameters and conclude, that there is no measurable effect regardless of the choice of parameters. The explanation is the same as given for SBBN by Kawano and coworkers: ^{2}H plus p or n are orders of magnitude faster than $^2H+^2H$ for deuterium destruction, and ^3H+p, ^3He+n, and $^3He+^3He$ are much faster producers of ^{4}He.

V. DISCUSSION

It has been illustrated by means of examples that the uncertainty in nuclear reaction rates of importance for big-bang nucleosynthesis allows a large range of possible outcomes of CNO elements and perhaps also allows an observable primordial production of ^{6}Li. The main conclusions of the investigation were the following.

(a) Primordial CNO production in neutron-rich zones is very sensitive to the rate for $^8Li(\alpha,n)^{11}B$, in particular for rates near the theoretical estimates. Variation in the rate by a factor of 30 relative to the estimate from Ref. 6 leads to a range of more than 2 orders of magnitude in the CNO mass fraction. The total range is close to 3 orders of magnitude. These results were derived within a simple two-zone model, which does not incorporate late neutron diffusion out of the neutron-rich zones. For some parameters these effects would tend to lower the total production of CNO, as discussed earlier, but the relative variations in outcome as a function of reaction rate would still occur. The upper limits derived on CNO production by demanding sufficient mixing of neutron- and proton-rich outcomes of ^{7}Li should still hold.

(b) The reaction ^{3}H(^{3}He,γ)^{6}Li, not hitherto included in BBN calculations, has less than a factor-of-2 influence on the primordial production of ^{6}Li, if the S factor deduced above from old, high-energy cross-section measurements can be used at the relevant energies. However, the production of ^{6}Li in SBBN is proportional to the reaction rate in a low-baryon-density Universe, so observable amounts of primordial ^{6}Li could be produced if forthcoming low-energy cross-section measurements give a high rate.

(c) The reaction ^{2}H(^{2}H,γ)^{4}He is as negligible in inhomogeneous nucleosynthesis as it was previously shown to be in SBBN (Ref. 2 and 28).

The ultimate answer to these issues must await improved experiments of a very difficult nature and more detailed observations of the element content of very old stars. At the present time it is a warning that some inferences from big-bang nucleosynthesis should be taken with an appropriate grain of salt.[30]

ACKNOWLEDGMENTS

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