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Reaction rate for destruction of ^{7}Li and primordial nucleosynthesis

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The rate for destruction of ^{7}Li via deuteron-induced reactions is reexamined and is found to be appreciably larger than that previously used in primordial nucleosynthesis codes over most of the temperature region of interest. Numerous calculations were run to determine the significance of the new rate; it was found to change the predicted ^{7}Li abundance by not more than 20% over the parameter space examined.

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I. INTRODUCTION

Calculations of the light element production in the early Universe generally employ the "standard" big-bang model, which assumes a high-entropy, radiation-dominated Friedmann cosmology. In addition, they usually assume a homogeneous distribution of the baryonic matter [1]. In some scenarios for the early Universe, however, subhorizon baryon number fluctuations may develop [2]. The abundance yields computed in models of these baryon-inhomogeneous universes [3–5] may be considerably different from those found in the homogeneous models. Light element yields in primordial nucleosynthesis thus provide diagnostics of the degree of baryon inhomogeneity in the early Universe.

Because of its particular sensitivity to baryon inhomogeneity, the primordial ^{7}Li yield is one of the more important of these diagnostics. In inhomogeneous nucleosynthesis models, ^{7}Li is generally overproduced compared with the yield in the homogeneous models. Moreover, the overproduction increases with the degree of inhomogeneity [3–5]. Unless late-time dissipation of primordial baryon-number fluctuations [6] or galactic destruction mechanisms [7] can destroy significant amounts of ^{7}Li, the primordial ^{7}Li yield constrains baryon inhomogeneity to be small in the early Universe [8].

The abundance of ^{7}Li is determined from a balance between the reactions which produce it and those which destroy it. In order to have confidence in our predictions of the primordial ^{7}Li yield, we must therefore use accurate rates for both types of reactions. The rate for one set of destruction reactions, the $^7\mathrm{Li}+d$ reactions, that has been used in primordial nucleosynthesis codes involves only a direct term [9]. However, resonances are known to dominate the low-energy interactions between ^{7}Li and d. We have thus reexamined the reaction rates pertinent to those two nuclei. The $^7\mathrm{Li}+d$ reactions may be of importance in the baryon-inhomogeneous models because ^{7}Li and d coexist in the low-density regions of these models and the d abundance can be large.

Section II deals with our considerations in deriving the reaction rate for $^7\mathrm{Li}+d$ reactions. Section III presents a series of calculations of predictions of primordial nucleosynthesis using the new rate, and Sec. IV gives our conclusions from this study.

II. DERIVATION OF THE REACTION RATE FOR ^{7}Li DESTRUCTION REACTIONS

The low-energy resonances associated with interactions between ^{7}Li and d, one at 280 keV and the other at 600 keV, have been studied by a variety of authors, and will be discussed individually below. In addition to the reaction rate contributions from them, a direct term is also needed. This is also discussed below.

A. The 280-keV resonance

Recent experiments have determined all the information about this resonance that is necessary to calculate its contribution to the $^7\mathrm{Li}+d$ destruction rate. In calculating the contribution to the reaction rate, the narrow resonance formula [10],

$$\langle \sigma v \rangle = \left[\frac{2\pi}{\mu k T} \right]^{3/2} \hbar^2 \frac{2J_R+1}{(2J_1+1)(2J_2+1)} \times \frac{\Gamma_d(\Gamma_n+\Gamma_p+\Gamma_\alpha)}{\Gamma} \exp(-E_R/kT) , \qquad (1)$$

can be used. In this expression, Γ_d represents the partial width of the resonance for deuteron decay, while the other partial widths represent the widths for decay by neutrons, protons, or α particles. J_R, J_1, and J_2 are the spins of the resonance and entrance channel particles, respectively, E_R is the resonance energy, μ is the entrance channel reduced mass, T is the temperature, and $\hbar$ and k are Planck's and Boltzmann's constants.

In a study by Zijderhand *et al.* [11] it was found that $\Gamma_d=86\pm18$ eV, $\Gamma_n+\Gamma_\alpha=380\pm50$ eV, $\Gamma=490\pm50$ eV,

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and therefore, that Γ_p is negligible. Thus, this resonance contributes a reaction rate of

$$N_A\langle\sigma v\rangle = 1.71\times10^6 T_9^{-3/2} \times\exp(-3.246T_9^{-1})\ \mathrm{cm^3\,s^{-1}\,mol^{-1}}\ . \qquad (2)$$

B. The 600-keV resonance

This resonance is a broad resonance, so the broad resonance formula must be used as the prescription for its contribution to the reaction rate, and that contribution must be calculated numerically. The broad resonance cross section is given [10] by

$$\sigma(E)=\sigma_R\frac{E_R}{E}\frac{\Gamma_d(E)}{\Gamma_d(E_R)}\frac{\Gamma_i(E)}{\Gamma_i(E_R)}\frac{(\Gamma_R/2)^2}{(E-E_R)^2+[\Gamma(E)/2]^2}\ , \qquad (3)$$

where σ_R is the cross section at E_R and Γ_R is the width the resonance would have if its energy-dependent factors were taken to be their values at $E=E_R$. In this expression, the most important energy-dependent quantity is the barrier penetrability, which must be taken into account explicitly for Γ's, especially when they involve charged particles. Γ_i are the partial widths for decay of the resonance into neutrons, protons, or alpha particles; all three must be included to determine the total cross section for destruction of ^{7}Li via this resonance.

Studies of the ^{7}Li(d,p) and ^{7}Li(d,n) reactions [12,13] were used to estimate the value for Γ to be 200 keV, and the ratio of Γ_n to Γ_p to be 420 mb (assuming isotropy) to 110 mb at the peak of the resonance. Studies [14] of the ^{7}Li(d,α) reaction through this resonance suggest that the resonant yield is appreciably smaller than that for ^{7}Li(d,n), so Γ_α has been neglected in comparison to Γ_n. In any event, that partial width would have been included in the Γ_n measurement. The cross section for this reaction was calculated numerically, then inserted into the general expression [10] for the thermonuclear reaction rate

$$\langle\sigma v\rangle=\left[\frac{8}{\pi\mu}\right]^{1/2}\frac{1}{(kT)^{3/2}}\int_0^\infty\sigma(E)E\exp(-E/kT)dE \qquad (4)$$

to determine the contribution from each of the possible decay channels to the reaction rate. The resulting reaction rate was then fitted with a polynomial expansion to give, for the rate due to the 600-keV resonance,

$$N_A\langle\sigma v\rangle=1.49\times10^{10}T_9^{-3/2}\exp(-4.0894T_9^{-1}) \times[0.0257T_9^{-1}+2.6314T_9^{-2/3} -4.1929T_9^{-1/3}-2.1241+4.1136T_9^{1/3}]\ \mathrm{cm^3\,s^{-1}\,mol^{-1}}\ . \qquad (5)$$

C. Nonresonant component

An appreciable nonresonant component apparently exists for ^{7}Li$+d$ reactions; the contribution to the reaction rate from such processes can be calculated from the expression [10]

$$\langle\sigma v\rangle=\left[\frac{2}{\mu}\right]^{1/2}\frac{\Delta}{(kT)^{3/2}}S(E_0)\exp(-3E_0/kT)\ , \qquad (6)$$

where $S(E_0)$ is the astrophysical S factor evaluated at E_0, the peak of the Gamow window, $\Delta=(4/3^{1/2})(E_0kT)^{1/2}$, and

$$E_0=[(2\mu)^{1/2}\pi e^2Z_1Z_2kT/2\hbar]^{2/3}\ ,$$

where Z_1 and Z_2 are the charge numbers of the entrance channel interacting nuclei. The only parameter which

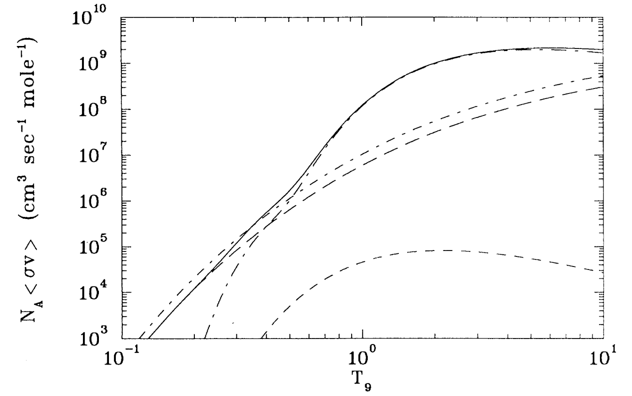

FIG. 1. The thermonuclear reaction rate for destruction of ^{7}Li via ^{7}Li$+d$ reactions. The solid curve shows the present result, with the various components indicated as the short-dashed curve (contribution of 280-keV resonance), long-dashed curve (nonresonant contribution), and long-dash-dotted curve (contribution of 600-keV resonance). The short-dash-dotted curve, which is seen to exceed the present result only at low values of T_9, is the rate used [9] in previous primordial nucleosynthesis calculations.

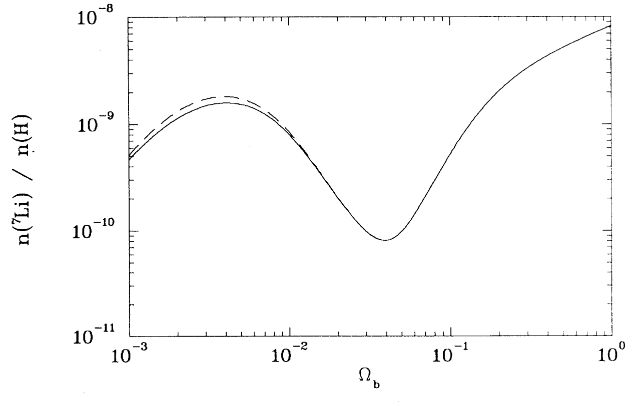

FIG. 2. Production of ^{7}Li in the homogeneous models of primordial nucleosynthesis as a function of the baryonic density Ω_b, given as the fraction of the critical density. The solid curve shows the ^{7}Li production using the ^{7}Li$+d$ destruction rate given in this paper, while the dashed curve shows the result of using the rate of Caughlan and Fowler [9].

TABLE I. Abundances of light nuclides in inhomogeneous models with different $^7\mathrm{Li}+d$ destruction rates. $\Omega_b=1.0$. Note that all calculations assumed the fraction of the space in the inhomogeneous models in the high-density regions was 0.25, the separation distance between high-density regions was 100 m. The predicted abundances for ^{2}H, ^{3}He, and ^{4}He were the same to three significant figures for either ^{7}Li destruction rate.

R	$n(^2\mathrm{H})/n(\mathrm{H})$	$n(^3\mathrm{He})/n(\mathrm{H})$	$X(^4\mathrm{He})$	$n(^7\mathrm{Li})/n(\mathrm{H})$	
				Old	New
1.0×10^{0}	0.91×10^{-9}	4.02×10^{-6}	0.269	8.22×10^{-9}	8.22×10^{-9}
1.0×10^{1}	3.07×10^{-9}	4.18×10^{-6}	0.270	1.17×10^{-8}	1.17×10^{-8}
1.0×10^{2}	2.92×10^{-7}	3.76×10^{-6}	0.271	4.03×10^{-8}	4.03×10^{-8}
1.0×10^{3}	5.04×10^{-6}	2.61×10^{-6}	0.273	5.81×10^{-8}	5.81×10^{-8}
1.0×10^{4}	1.94×10^{-5}	5.37×10^{-6}	0.261	4.97×10^{-8}	4.79×10^{-8}
1.0×10^{5}	2.05×10^{-5}	5.55×10^{-6}	0.258	4.95×10^{-8}	4.78×10^{-8}
1.0×10^{6}	2.06×10^{-5}	5.56×10^{-6}	0.258	4.95×10^{-8}	4.78×10^{-8}

needs to be evaluated to estimate the nonresonant contribution is $S(E_0)$; this was done by examining the $^7\mathrm{Li}(d,n)$ and $^7\mathrm{Li}(d,p)$ data [12,13] above the low-energy resonances. The values obtained for $S(E)$ for $^7\mathrm{Li}(d,p)$ and $^7\mathrm{Li}(d,n)$ were found to be fairly constant from 1.6 to 2.0 MeV, and were found to sum to about 1.7×10^4 keV b over that region. Thus this value was assumed for $S(E_0)$. The contribution to the reaction rate for the nonresonant processes, then, is

$$N_A\langle\sigma v\rangle=1.66\times10^{11}T_9^{-2/3}\times\exp(-10.254T_9^{-1/3})\ \mathrm{cm^3\,s^{-1}\,mol^{-1}}\ . \quad (7)$$

The total thermonuclear reaction rate for destruction of ^{7}Li is the sum of the terms given in Eqs. (2), (5), and (7). It is shown in Fig. 1, where it is also compared to the rate of Caughlan and Fowler [9], which is presently in many of the primordial nucleosynthesis codes.

III. EFFECT OF THE ^{7}Li DESTRUCTION RATE ON PRIMORDIAL NUCLEOSYNTHESIS

We now consider the effect of the new $^7\mathrm{Li}+d$ destruction rate on primordial nucleosynthesis. In the homogeneous models [1] the deuteron abundance is low enough, and the proton abundance high enough, that proton-induced reactions would constitute the dominant ^{7}Li destruction processes. That this is indeed true may be seen in Fig. 2, which shows the ^{7}Li abundance relative to hydrogen in the homogeneous models as a function of Ω_b, the ratio of the baryon density to the critical density of the Universe. These calculations were performed with the code described in Ref. [4] using a Hubble constant of 50 km/s Mpc, three light neutrino families, a neutron lifetime of 889 s [15], and a present microwave background temperature of 2.7 K. The dashed curve gives the results using the $^7\mathrm{Li}+d$ destruction rate in Ref. [9], while the solid curve gives the results derived from the new $^7\mathrm{Li}+d$ destruction rate presented in this paper. Only at low baryon density, where the deuteron abundance remains high throughout primordial nucleosynthesis, and where mass 7 u nuclei are in the form of ^{7}Li instead of ^{7}Be, is there significant destruction of ^{7}Li by deuterons and, consequently, any appreciable decrease in ^{7}Li production due to the new $^7\mathrm{Li}+d$ rate. We note that from the concordance among the observations of d, ^{3}He, ^{4}He, and ^{7}Li abundances, the lower limit on Ω_b is 0.02 [1]. Because the new $^7\mathrm{Li}+d$ rate only affects the ^{7}Li abundance for $\Omega_b<0.01$, the new rate has no effect on conclusions resulting from homogeneous model primordial nucleosynthesis.

In contrast to the homogeneous models, the inhomogeneous models [3–5] develop low-density, neutron-rich regions in which a high deuteron abundance can coexist with ^{7}Li and a low proton abundance. In such regions, we may expect considerable deuteron induced destruction of ^{7}Li. In the high-density regions, which are proton rich, ^{7}Li is produced as ^{7}Be. Its destruction mechanism is $^7\mathrm{Be}(n,p)^7\mathrm{Li}(p,\alpha)$, which is initiated by neutron back diffusion [5]. In general, the ^{7}Be yield in the high-density

TABLE II. Abundances of light nuclides in inhomogeneous models with different $^7\mathrm{Li}+d$ destruction rates. $\Omega_b=0.1$. Note that other parameters and results of the calculations are as in Table I.

R	$n(^2\mathrm{H})/n(\mathrm{H})$	$n(^3\mathrm{He})/n(\mathrm{H})$	$X(^4\mathrm{He})$	$n(^7\mathrm{Li})/n(\mathrm{H})$	
				Old	New
1.0×10^{0}	1.87×10^{-5}	1.06×10^{-5}	0.249	5.23×10^{-10}	5.23×10^{-10}
1.0×10^{1}	2.03×10^{-5}	1.06×10^{-5}	0.250	7.12×10^{-10}	7.12×10^{-10}
1.0×10^{2}	3.61×10^{-5}	9.50×10^{-6}	0.249	2.03×10^{-9}	2.03×10^{-9}
1.0×10^{3}	1.25×10^{-4}	1.40×10^{-5}	0.237	5.91×10^{-9}	5.45×10^{-9}
1.0×10^{4}	1.56×10^{-4}	1.66×10^{-5}	0.222	6.53×10^{-9}	5.68×10^{-9}
1.0×10^{5}	1.59×10^{-4}	1.69×10^{-5}	0.220	6.42×10^{-9}	5.58×10^{-9}
1.0×10^{6}	1.59×10^{-4}	1.69×10^{-5}	0.219	6.41×10^{-9}	5.57×10^{-9}

TABLE III. Abundances of light nuclides in inhomogeneous models with different ^{7}Li+d destruction rates. $\Omega_b = 0.01$. Note that other parameters and results of the calculations are as in Table I.

R	$n(^2\mathrm{H})/n(\mathrm{H})$	$n(^3\mathrm{He})/n(\mathrm{H})$	$X(^4\mathrm{He})$	$n(^7\mathrm{Li})/n(\mathrm{H})$	
				Old	New
1.0×10^0	8.18×10^{-4}	4.34×10^{-5}	0.212	8.42×10^{-10}	7.97×10^{-10}
1.0×10^1	8.33×10^{-4}	4.39×10^{-5}	0.211	9.18×10^{-10}	8.60×10^{-10}
1.0×10^2	1.10×10^{-3}	5.26×10^{-5}	0.189	2.03×10^{-9}	1.70×10^{-9}
1.0×10^3	1.18×10^{-3}	5.32×10^{-5}	0.148	1.39×10^{-9}	1.09×10^{-9}
1.0×10^4	1.14×10^{-3}	5.09×10^{-5}	0.137	8.55×10^{-10}	6.92×10^{-10}
1.0×10^5	1.13×10^{-3}	5.05×10^{-5}	0.136	7.90×10^{-10}	6.44×10^{-10}
1.0×10^6	1.13×10^{-3}	5.04×10^{-5}	0.136	7.83×10^{-10}	6.38×10^{-10}

regions will be unaffected by the ^{7}Li+d rate. The effect of the new deuteron-induced destruction rate on ^{7}Li in inhomogeneous models will thus depend on the relative contributions of the low- and high-density regions to the overall mass 7 yield.

To study the effect of the new ^{7}Li+d rate on inhomogeneous model primordial nucleosynthesis we have run several calculations within the inhomogeneous models, using the code described in Ref. [4]. The values used for the Hubble constant, the number of light neutrino families, the neutron lifetime, and the temperature of the microwave background were those described above. With the old and new ^{7}Li+d rates we have run models with R, the density contrast, varying from 1.0 to 1×10^6 and Ω_b having the values 0.01, 0.1, and 1.0. In all cases the separation between the centers of high-density regions was 100 m. This separation was chosen because it is the optimal one for neutron diffusion and shows the greatest variation in ^{7}Li production due to the different ^{7}Li+d reaction rates. The volume fraction f_v of the high-density region was 0.25 in all calculations.

In Table I we see that there is little sensitivity of the final ^{7}Li yield to the ^{7}Li+d destruction rate used. At low-density contrast (small R), the model is essentially homogeneous, and the results are close to those of the homogeneous models with $\Omega_b = 1.0$ (see Tables II and III). As is shown in Fig. 2, the new rate had no effect on a homogeneous model for $\Omega_b > 0.01$, and the low-contrast inhomogeneous models are no different. As R is increased, it would be expected that greater destruction of ^{7}Li would occur in low-density regions due to the higher abundance of deuteron. Playing against this effect, however, is the fact that for larger R, more and more of the mass 7 u production comes from ^{7}Be synthesized in the high-density regions. Since, as noted above, the ^{7}Be production is unaffected by the new rate, there is again little effect from the new rate.

For lower values of Ω_b the effect of the new rate becomes larger. Lower Ω_b leads to lower baryon densities in both the low- and high-density regions. This gives larger deuteron abundances and greater destruction by ^{7}Li+d. Nevertheless, the largest decrease in the ^{7}Li yield due to the new rate is around 20%. While 20% is a large enough effect to require the new rate to be used when great accuracy is needed, there is no need to make a change in any conclusions about nucleosynthesis in baryon-inhomogeneous universes [3–5].

IV. CONCLUSIONS

The inclusion of the resonances in the d + ^{7}Li processes increased the reaction rate for destruction of ^{7}Li in the temperature range from roughly $T_9 = 0.6$ to $T_9 > 10$, the range relevant to primordial nucleosynthesis. Therefore, all primordial nucleosynthesis calculations performed up to the present time, which have neglected the resonances in the ^{7}Li+d system, have underestimated the amount of deuteron-induced destruction of ^{7}Li that occurred during the big bang. Nevertheless, their inclusion has little effect on the primordial production of the light elements in the homogeneous models because, in the baryon density regimes of interest to the homogeneous model, the deuteron abundance is not high enough and the abundance of mass 7 u nuclei actually in the form of ^{7}Li is too low to effect much ^{7}Li destruction. Similarly the effect on ^{7}Li production in baryon-inhomogeneous primordial nucleosynthesis models is typically less than 20% because, although deuteron abundances can be high in the low-density regions in such models and the consequent ^{7}Li destruction large, the contribution of these regions to the overall ^{7}Li yield is small. Thus there is no need to change any conclusions previously made about primordial nucleosynthesis, although workers seeking accuracy in their estimates of the ^{7}Li yield from the big bang should use the ^{7}Li+d rate presented in this paper.

However, it should be noted that an important mass 7 u destruction process, late-time homogenization [5], has not been included in the present calculations. There are two reasons for this. First, it would mask the effects of changes in the ^{7}Li(d,n) and ^{7}Li(d,p) reaction rates, the primary result of the present paper. Second, there are sufficient uncertainties with that process, primarily as to the time at which it occurs, that its effects constitute a separate study in themselves. However, it should still be noted that late-time homogenization has the potential to destroy most of the mass 7 u nuclides which are produced in primordial nucleosynthesis.

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