Nuclear Reaction Rates and Primordial $^6$Li

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We examine the possibility that Big Bang Nucleosynthesis (BBN) may produce non-trivial amounts of $^6$Li. If a primordial component of this isotope could be observed, it would provide a new fundamental test of Big-Bang cosmology, as well as new constraints on the baryon density of the universe. At present, however, theoretical predictions of the primordial $^6$Li abundance are extremely uncertain due to difficulties in both theoretical estimates and experimental determinations of the $^2$H($\alpha, \gamma$)$^6$Li radiative capture reaction cross-section. We also argue that present observational capabilities do not yet allow the detection of primordial $^6$Li in very metal-poor stars of the galactic halo. However, if the critical cross section is towards the upper end of its plausible range, then improvements in $^6$Li detection capabilities may allow the establishment of $^6$Li as another product of BBN. It is also noted that a primordial $^6$Li detection could help resolve current concerns about the extragalactic D/H determination. 

$^{26.35.}\pm 0.26.44.\pm h,25.90.\pm k$

I. INTRODUCTION

The consistency of the observed light element abundances with the predictions of Big-Bang nucleosynthesis (BBN) is a fundamental source of evidence for a hot Big-Bang $^1$. Over the last thirty years, the abundances of the light isotopes $^2$H, $^3$He, $^4$He, and $^7$Li have all been found to be consistent with the primordial levels predicted by BBN over a fairly narrow range of the baryon-to-photon ratio of the universe, $\Omega_B h^2 < 0.01 < 0.02$, as obtained from the constraints on $\eta$, and where $h$ denotes the value of the Hubble constant in units of $100 \text{ km/s/Mpc}$. 

Inferring primordial abundances of elements is a tricky business, and it seems fair to say that at the present time, the constraints on the baryon density are limited by the systematic errors on the observed or inferred abundances $^2$. In this regard, an additional light isotope could further firm up BBN, and might provide new constraints on $\eta$. The only remaining candidate that could in principle be brought into the framework of homogeneous BBN is $^6$Li. $^6$Li has the next-highest predicted primordial abundance, after those species already understood in the BBN framework. (See Ref. $^3$.) Like beryllium and boron, present day $^6$Li is thought to be produced mostly by cosmic ray spallation in the galaxy $^4$. The meteoritic abundance of $^6$Li is certainly much higher (by a factor $\sim 100$) than even the most optimistic primordial abundance predicted by standard BBN. However, it is possible that the levels of this isotope in hot $T_{\text{eff}} \sim 6000$-6300 K, extreme low-metallicity halo stars (either main-sequence dwarfs or subgiants near the turn-off point) could reflect its primordial abundance. This would show up as a flattening of the curve of $^6$Li vs. metallicity at the point where the abundance of cosmic-ray-produced $^6$Li becomes comparable to the abundance of primordial $^6$Li (see Fig.$^4$). Such a situation appears to hold for $^7$Li, whose abundances in low-metallicity halo stars are uniform over a wide range of metallicities and a narrow range of temperatures, the so-called Spite plateau $^5$. 

At present, there have been only three relatively uncertain detections of $^6$Li in such low-metallicity stars, one of them being marginal $^5$. The metallicities of these stars where $^6$Li has been observed, roughly $\text{[Fe/H]} > -2$ $^6$, are unfortunately not low enough for any primordial component to be observable. However, as new data come in, and as new instruments that are able to reach lower metallicities and lower $^6$Li abundance levels eventually come on line, it is of interest to know what levels of primordial $^6$Li we might expect to see, and to what extent they could provide constraints on the baryon density.

$^1[\text{Fe/H}] = \log_{10} (\text{Fe/H}) - \log_{10} (\text{Fe/H})_\odot$, where the subscript $\odot$ refers to abundances measured at the birth of the Sun
FIG. 1. Abundance vs. Metallicity. Open data points represent \(^7\)Li abundances, the flat region at low metallicities being attributed to the primordial abundance of \(^7\)Li. Filled data points represent \(^6\)Li abundance measurements and triangles refer to upper limits. The solid curves bracket the possible primordial abundances of \(^6\)Li and indicate the evolution of \(^6\)Li with metallicity, assuming \(^6\)Li evolves like \(^9\)Be (see Ref. [3]). A primordial component of \(^6\)Li would show up as a flat region of the curve at low metallicity, as shown here for the upper limit derived from Ref. [30], \((^{6}\text{Li}/^{7}\text{Li})_{BBN} \sim 5 \times 10^{-12}\). The lower limit corresponds to \((^{6}\text{Li}/^{7}\text{Li})_{BBN} \sim 10^{-14}\).

Thomas et al. [9] have examined the BBN predictions for the primordial abundance of \(^6\)Li. These authors have not discussed in detail, however, the extremely large uncertainties on this prediction, as they were mainly concerned with both homogeneous and non-homogeneous nucleosynthesis yields of beryllium and boron. Predictions of primordial abundances are made by numerically integrating rate equations for nuclear reactions that occurred during the first few minutes of the Big Bang, and for \(^6\)Li, the uncertainties on the yields are directly related to uncertainties on the input reaction rates. Therefore, we first examine the status of relevant cross-section measurements and identify the chief sources of uncertainty. We then discuss the prediction of the \(^6\)Li primordial abundance, and we examine to what extent primordial \(^6\)Li could be observed. We argue that even in the most optimistic case, this observation is not within reach of present instrumental capabilities, but must be subjected to future techniques. In particular, we discuss how a direct measurement of the \(^2\)H(\(\alpha, \gamma\))\(^6\)Li radiative capture cross-section, at the low energies where this reaction takes place during BBN, \(E \sim 60 - 400\) keV, could have a profound impact on the predictions. In fact, the present uncertainty on the \(^6\)Li yield is so large that even if \(^6\)Li were detected in very metal-poor stars, at metallicities of about \([\text{Fe/H}] < -3\), this would not allow a sensible constraint on the baryonic density parameter. However, an eventual measurement of the primordial \(^6\)Li abundance, at a predicted level \((^{6}\text{Li}/^{7}\text{Li})_{BBN} \sim 10^{-14} - 10^{-12}\), would in any case provide another fundamental test of modern cosmology.

II. REACTION RATES

The primordial abundance of \(^6\)Li is determined almost entirely by the rates of two reactions. These reactions are radiative capture of deuterium on alpha particles, \(^2\)H(\(\alpha, \gamma\))\(^6\)Li, which produces practically all of the \(^6\)Li, and the \(^6\)Li destroying reaction \(^6\)Li(\(p, \alpha\))\(^3\)He. We examine below the current status of these reaction rates.
A. The reaction $^6\text{Li}(p, \alpha)^3\text{He}$

The low-energy ($100 \text{ keV} < E < 1000 \text{ keV}$) cross-section for this reaction is sufficiently well-known that recent work \[10\] has concentrated on determining the effects of electron screening in the experimental target at extremely low energies ($E < 100 \text{ keV}$) via comparison with the higher-energy cross section. The energy range that concerns us here is the range in which the peaks of the Coulomb barrier penetration factor and of the Maxwell-Boltzmann thermal velocity distribution overlap significantly at BBN temperatures. It is in this range, where there is a population of protons with enough thermal energy to penetrate the Coulomb barriers of the $^6\text{Li}$ ions, that the reaction takes place. (See Ref. \[11\] for a detailed discussion.) In the case of $^6\text{Li}(p, \alpha)^3\text{He}$, this corresponds to energies of $E \sim 75 – 410 \text{ keV}$ at a temperature of $10^9 \text{K}$ at the beginning of BBN or $E \sim 30 – 80 \text{ keV}$ at a temperature of $10^8 \text{K}$, when the $^6\text{Li}$ abundance has stabilized.

For purposes of fitting curves to experimental cross-section data and integrating them to obtain reaction rates, it is customary to use the astrophysical S-factor, defined by removing the Coulomb barrier factor and a geometric factor from the cross section:

$$S(E) = E\sigma(E) \exp\left[-\left(E_g/E\right)^{1/2}\right],$$

where $E$ is energy, $\sigma$ is the reaction cross section, and $E_g$ is the Gamow energy,

$$E_g = 2\mu\pi^2e^4Z_1^2Z_2^2/h^2,$$

for reactants of reduced mass $\mu$ and atomic number $Z_1$ and $Z_2$. (See Ref. \[11\].) The S-factor is particularly convenient for fitting because it is often a much slower function of $E$ than the cross section is. (For the procedure used to derive a reaction rate from the astrophysical S-factor, see Ref. \[11\].) We have computed a new analytic expression for the $^6\text{Li}(p, \alpha)^3\text{He}$ reaction rate using a new polynomial fit to the experimental S-factor between 100 and 1000 keV. (See Table \[1\] and Fig. \[2\].) In addition, we present the S-factor curve corresponding to the rate found in the compilation of Harris \textit{et al.} \[12\]. Following Engstler \textit{et al.} \[10\], we use only the data above 100 keV \[13,14,15,16,17,18,19,20\] in the fit to avoid the effects of electron screening. Unlike their fit, ours includes their data in addition to previous
data. Our reaction rate is lower than that of Harris et al. by a factor of about 15%. Treating all errors as statistical in our least-squares fit to the cross-section data gives a 1σ error of 5% in overall normalization (based on the fitting error at 100 keV, an energy relevant to BBN). An estimated 2σ error of 15% includes all of the lowest data points except those of Fiedler and Kunze [15], which were not used in the fit, and which seem to be normalized differently from the rest of the data. We will use this rather extreme estimate to determine upper limits on the $^6$Li yield. From this estimate, we still find the uncertainty in this reaction rate to be insignificant in comparison to uncertainties in the main $^6$Li-producing reaction rate. (See below.)

B. The reaction $^2$H($\alpha$, $\gamma$)$^6$Li

In contrast, the low-energy cross section for radiative capture of a deuteron by an alpha particle to form $^6$Li is almost completely unknown. Theoretical calculations (refs. [21,22,23,24,25,26,27,28]) vary over a factor of about ten. Experimental measurements are difficult because of the extremely small cross sections involved: electric dipole radiation is strongly suppressed because the nearly equal charge-to-mass ratios of the deuteron and alpha particle give the $d + \alpha$ system a very small dipole moment in all cases. This requires the radiative capture to proceed mostly via electric quadrupole radiation, and thus mostly through the $d$-wave portion of the incoming wavefunction.

To date, there have been three experiments to directly measure cross-sections for $d + \alpha$ radiative capture. The only recent direct measurement of the nonresonant cross section, used in the current standard low-energy extrapolation [24], is that of Robertson et al. [24], who measured the reaction cross section at center-of-mass energies of 1–3.5 MeV. The experiment of Mohr et al. [25] concentrated on the $J^\pi = 3^+$ resonance at 711 MeV. By contrast, the energies relevant to $^6$Li production in the big bang are in the range 30 – 400 keV. The recent experiment of Cecil et al. [30], has determined an upper limit (at 90% confidence level) for the cross section at 53 keV. Unfortunately, this limit is much higher than any current theoretical estimate of the cross section at 53 keV, so the actual reaction rate may be much lower – by a factor of fifty or so – than the limit implied by this measurement. (See Fig.3.)

![Fig. 3. d–$\alpha$ Capture S-factor. A selection of measured and inferred astrophysical S-factors for the reaction $^2$H($\alpha$, $\gamma$)$^6$Li is shown. In order of decreasing low-energy S-factor, the calculations are from Coulomb-breakup measurements of Kiener et al. [32], and the models of Mohr et al. [24], Ryzhikh et al. [26], and Typel [23]. The 53 keV upper limit is from Cecil et al. [30], and all other points are from Robertson et al. [24]. The data of Mohr et al. (not shown) are concentrated at the top of the 711 keV resonance.](image-url)
In recent years, an attempt has been made to get around the difficulty of measuring very small radiative-capture cross sections by studying Coulomb breakup of the product nucleus as an inverse reaction [31,32,33]. In this scheme, $^6\text{Li}$ nuclei are Rutherford-scattered off some high-Z nucleus. Some of these scattered nuclei are broken up into a deuterons and alpha particles by the electric-field gradient of the heavy nucleus. This process has been treated as the absorption of a virtual photon, and thus as an inverse radiative capture [31]. However, a number of difficulties arise in treating the data [30,34] which produce additional uncertainties in this approach, mostly because contributions from the various partial waves are not the same in Coulomb breakup as they are in radiative capture. One group [33] reports anomalous angular dependence in the data. The cross sections inferred from the breakup measurements of Kiener et al. [32] are significantly higher than any of the theoretical estimates, perhaps suggesting interference from the nuclear force, even at small scattering angles, or perhaps supporting a higher than anticipated low-energy cross section.

It is clear from the conflicting theoretical curves that a reliable determination of the reaction rate for $d + \alpha$ radiative capture will require a direct cross section measurement below the $J^\pi = 3^+$ resonance. While the cross section was too small to be measured at 53 keV (an alpha particle energy of 160 keV), the expected cross section should exceed this limit slightly higher in the range of energies $\sim 50 – 400$ keV relevant to BBN (alpha bombarding energies of $\sim 150 – 1200$ keV) so that it can be measured in similar experiments. In the absence of any evidence to allow a decision between the various theoretical and experimental extrapolations, we will use a few representative results to see how large a spread is allowed. It should be kept in mind that these cross-sections are only representative values selected from the literature, where it is difficult to choose between conflicting results. (Note, for example, that in the same paper where they calculate one of the cross sections used here, Ryzhikh et al. [26] also obtain significantly different results by expanding the $^6\text{Li}$ ground state in different sets of basis functions.) We will also use the Cecil et al. [30] value as an extreme upper limit, setting the nonresonant S-factor constant at the 53 keV limit of $2 \times 10^{-7}$ MeV b for energies below the 711 keV resonance.

Using the measurement of the resonant cross section due to Mohr et al., [25], we also present a new value of the contribution to the reaction rate from the 711 keV resonance. Using the methods described in [11], the resonant contribution is

$$N_A \langle \sigma v \rangle_{\text{Resonant}} = 97.1 T_9^{-3/2} \exp(-8.251/T_9)$$

(3)

This is a fairly small change from the customary value, given in Robertson et al., [24] and it does not have a significant effect on the rate at BBN temperatures or on the BBN $^6\text{Li}$ yields.

FIG. 4. BBN Reaction Network. The lower portion of the BBN reaction network used here, which is identical to that of Ref. [9]. Reactions producing or destroying $^6\text{Li}$ are indicated by thick lines.
C. Other \( ^6\)Li reactions

Eleven other reactions in the BBN reaction network involve \( ^6\)Li (see Table I and Fig. 4). However, neither removing these reactions (individually) from the reaction network nor augmenting them by large factors changes the final \( ^6\)Li abundance by more than one tenth of a percent. The effect of any uncertainty in these rates is certainly swamped by the uncertainties in the rates of the more crucial reactions discussed above, so we pass over them. Note, in particular, the reaction \( ^3\)He\((^3\)H, \(\gamma\))\( ^6\)Li, which has generally been omitted from BBN studies, has only a very small effect on the \( ^6\)Li yield [36], so its uncertainty was safely ignored.

III. PRIMORDIAL ABUNDANCE (\( ^6\)Li/H)

We predicted \( ^6\)Li yields for various values of the relevant reaction rates using Kawano’s version [36] of the standard nucleosynthesis code and the full network of Thomas et al [9]. We were particularly interested in establishing upper limits for the primordial \( ^6\)Li abundance to determine whether it is possible in principle for primordial \( ^6\)Li to contribute a significant fraction of the \( ^6\)Li abundance at low metallicity.

A. Predictions and uncertainties

The uncertainty in the primordial abundance of \( ^6\)Li depends only weakly on the \( ^6\)Li-destroying proton capture reaction considered in section II A above. Holding all other rates at their standard values, a 20% increase in this rate decreases the \( ^6\)Li yield by 10%; a 20% decrease in this rate increases the \( ^6\)Li yield by \( \sim \) 30%. As discussed above, the 2\( \sigma \) uncertainty in this reaction rate is probably less than 20%. Therefore, uncertainties in this reaction rate have at most a small role to play in determining the possibility of observing primordial \( ^6\)Li.

![Graph](https://via.placeholder.com/150)

FIG. 5. Predicted Abundances. Abundances relative to hydrogen generated from the BBN network of figure 4, with the concordance interval in \( \eta \) of Copi et al. [2] indicated by vertical dashed lines. The top curve is the predicted \( ^7\)Li abundance. The several other solid curves are results for \( ^6\)Li based on the Kiener et al. [12] Coulomb-breakup measurements and the calculations of Mohr et al. [27], Robertson et al. [21] (the “standard” rate), Ryzhikh et al. [20], and Typel, et al. [23], in decreasing order. The dashed curve is derived from the experimental limit of Cecil et al. [30].
The dependence of the $^6\text{Li}$ yield on normalization of the $d + \alpha$ radiative capture rate is very nearly linear at all values of the normalization. Given the wide range of predictions for the reaction rates and the extreme upper limit from [3], there is a wide range of possible $^6\text{Li}$ yields. Depending on the low-energy extrapolation used, the maximum possible primordial ratio of $^6\text{Li}$ to $^7\text{Li}$ varies from 0.01% ($^6\text{Li}/^7\text{Li} = 1.4 \times 10^{-14}$) to 0.18% ($^6\text{Li}/^7\text{Li} = 2.4 \times 10^{-13}$), while the extreme upper limit on this ratio derived from the Cecil et al. limit on the $d + \alpha$ cross section and our lower limit on the $^6\text{Li}(p,\alpha)^3\text{He}$ cross section is as high as 3.7%; see Fig. 3. The maximum always occurs at $\eta \simeq 2 \times 10^{-10}$, the extreme low end of the concordance interval allowed by standard BBN [2]. These results are in agreement with those of Ref. [4], who found an upper limit on the primordial ratio $^6\text{Li}/^7\text{Li} < 0.2\%$ in all cases they considered.

Because $^6\text{Li}$ yields fall rapidly with increasing baryon density, $^6\text{Li}$ is potentially a very sensitive probe of the baryon density. However, a direct measurement of the $^2\text{H}(\alpha, \gamma)^6\text{Li}$ reaction cross section at low energy will be necessary before any such claims can be made. In the meantime, it is obvious that a detection of primeval $^6\text{Li}$ at a level consistent with the above estimations would provide a new piece of evidence for the consistency of BBN, and hence a fundamental cosmological test. While a precise baryon density determination from $^6\text{Li}$ is not possible without a better rate for $^2\text{H}(\alpha, \gamma)^6\text{Li}$, it is clear that a measurable primordial component of $^6\text{Li}$ would argue for a value of $\eta$ near the lower end of the allowed range. (See Fig. 3.) This is also the range of $\eta$ implied by the extragalactic deuterium measurements of Rutgers and Hogan [37], but it would be in conflict with the the lower D/H (higher $\eta$) values implied by the work of Tytler et al. [38].

The highest value of the $^6\text{Li}/^7\text{Li}$ ratio may allow something like the “Spite plateau” of $^7\text{Li}$ to exist for $^6\text{Li}$ at extremely low metallicities. It was argued in Ref. [38], that $^6\text{Li}/^7\text{Li}$ should scale as $^{16}\text{O}/^7\text{Li}$ all along the galactic evolution, taking into account the trends observed for $^9\text{Be}$. This means that the curve log($^6\text{Li}/^7\text{Li}$) vs. log($^6\text{Fe}/^7\text{Li}$) should have a slope unity in the halo phase, i.e. up to [Fe/H] $\simeq -1$, and a slope $\simeq 0$ during the disk phase $-1 < [\text{Fe}/\text{H}] < 0$ (see Fig. 4). Roughly speaking, since the meteoritic abundance of $^6\text{Li}$ is log($^6\text{Li}/^7\text{Li}$) $\simeq -10$. at [Fe/H] $\equiv 0$, one would expect the primordial $^6\text{Li}$ plateau to show up at [Fe/H] $\simeq -3$ if the primordial abundance is log($^6\text{Li}/^7\text{Li}$)$_p$ $\simeq -12$, at [Fe/H] $\sim -4$. if log($^6\text{Li}/^7\text{Li}$)$_p$ $\sim -13$, and so forth. We note that the lower values of the reaction rate would result in $^6\text{Li}$ yields so much lower than those expected from cosmic-ray spallation that they would not be observable even in the least-evolved stars. On the other hand, the extreme upper limit on the $d + \alpha$ cross section derived from the experiment of [30] corresponds to an upper limit of the primordial $^6\text{Li}$ abundance at about the level of previous detections.

### B. Observing primordial $^6\text{Li}$

It is extremely difficult to detect the absorption due to the presence of $^6\text{Li}$ in the photosphere of a metal-deficient star for the two following reasons: (i) the only resonant line of $^6\text{Li}$ at 6708Å is usually blended with that of $^7\text{Li}$ since the isotopic separation is of the same order or smaller than the typical width of the lines; (ii) $^6\text{Li}$ is strongly under-abundant compared to $^7\text{Li}$, especially at low metallicities where the abundance of $^7\text{Li}$ is constant, of the order of the meteoritic abundance of $^6\text{Li}$, and the $^6\text{Li}$ abundance goes down as the metallicity. The absorption of $^6\text{Li}$ can therefore be seen only as a slight asymmetry of the $^7\text{Li}$ absorption line profile.

Nonetheless, two detections of $^6\text{Li}$ have probably been achieved at metallicities [Fe/H] $\simeq -2.1$ and [Fe/H] $\simeq -1.4$, at a level $^6\text{Li}/^7\text{Li}$ $\simeq 5\%$. [5]. The main limiting factors for these detections were the signal-to-noise ratio and the spectral resolution achieved by the instruments. However, the accuracy of the measured value was limited equally by the noise in the observed spectrum (statistical error) and by the accuracy of the determination of the velocity broadening parameter (systematics), which defines the width of the lithium lines. This parameter, due to stellar rotation and macro-turbulent motions in the atmosphere, is constrained from the profile fitting of other lines, such as Fe and CaI. Therefore, in order to reach very low $^6\text{Li}/^7\text{Li}$ ratios in metal-poor stars, one has to considerably diminish the statistical noise, and, at the same time, to carefully control systematics.

Concerning the statistical accuracy, we note, as a reference, that the most precise measurement of the $^6\text{Li}/^7\text{Li}$ ratio was carried out in the star HD84937, of magnitude $m_V = 8.3$, in 1hr. integration time on the 2.7m McDonald Telescope and Coudé Spectrometer, at a resolving power $\lambda/\Delta\lambda = 1.25 \times 10^5$, yielding $^6\text{Li}/^7\text{Li}=5\%\pm2\%$ (statistical and systematics combined). The noise could be reduced by a factor of $\simeq 6$ for an integration time $\sim 20$hrs. on an instrument such as the 3.9m Anglo-Australian Telescope, assuming equal efficiencies for the spectrometers. On future telescopes such as one 8m reflector at the European Southern Observatory Very Large Telescope, using the UVES spectrograph, this factor could be brought up to $\simeq 12$ for 20hrs. integration time. However, this factor would not compensate for the difference of magnitude for a star at very low metallicities, since a factor of 12 allows one to achieve the same signal-to-noise ratio on a star 2.7 magnitudes higher. Indeed, HD84937 is a uniquely bright target; in the very metal-poor star survey by Beers, Preston & Shectman [34][44][45], we do not find any star brighter than $m_V = 13$, for [Fe/H] $<-3$ and a temperature of about $T_{eff} > 6000$ K, needed to ensure that $^6\text{Li}$ has not been depleted (i.e. destroyed and/or diluted) too much. This survey is not complete yet, and one may still hope to find a suitable
candidate. At the present time, however, the prospect of detecting $^6$Li at a level $^6$Li/$^7$Li $< 1\%$ does not seem realistic at metallicities [Fe/H] $< -3$. Only at the high values of $^6$Li/$^7$Li $\leq 3\%$ allowed by the present experimental upper limit on deuterium-alpha capture of [30], could even undepleted primeval $^6$Li be detected with present instruments. Regarding the systematics, it is unfortunately difficult to evaluate to what level these errors could be brought down. One would clearly have to increase the number of profiles studied to determine more accurately the theoretical line profile. In that frame, increasing the resolving power up to $\lambda/\Delta \lambda \sim 3 \times 10^5$ would help considerably, although an increase in spectral resolution is associated with a lower signal-to-noise ratio per resolution element.

IV. CONCLUSION

We examined possible $^6$Li abundances predicted by Big-Bang Nucleosynthesis, and discussed the uncertainties in these predictions. The latter arise primarily from the uncertainties in the rate of the $^2$H($\alpha, \gamma$)$^6$Li radiative capture reaction, which determines the final yield of $^6$Li. These uncertainties arise because this cross-section has never been measured directly at the relevant energies for Big-Bang production of $^6$Li, where the cross-section falls steeply with decreasing energy. Uncertainties in theoretical estimates amount to roughly a factor 10 on the yield of $^6$Li, and, as such, would preclude putting severe constraints on the baryonic density parameter $\Omega_B$ from $^6$Li alone, if a primeval component of $^6$Li were observed. The experimental upper limit of Cecil et al. [30] also allows the $^6$Li yield to be considerably higher than allowed by any of these estimates, so that any constraint on $\Omega_B$ from $^6$Li alone would be difficult to arrive at. However, since significant $^6$Li yields are favored by low baryon density and are strongly suppressed at high baryon density, regardless of the possible value of the production cross section, any detection of primordial $^6$Li would favor the low end of the current $\Omega_B$ range from BBN. This would favor higher primordial $D/H$ values. Thus, we emphasize that the detection of any primordial $^6$Li, to a level log($^6$Li/H) $\sim -14 \rightarrow -12$, as obtained from our present calculations, would provide a new fundamental test of Big-Bang nucleosynthesis, hence of modern cosmology, and it could help resolve the current debate over which value of the extragalactic deuterium-to-hydrogen ratio is representative of the primordial value.

Finally, we caution that the prospect of detecting $^6$Li in the atmospheric layers of a very metal-deficient star (pristine material), appears marginal with current instrumentation. With the present instruments available, and even for the larger instruments currently under construction, it seems that primordial $^6$Li could be detected, in stars with [Fe/H] $< -3$, only near the extreme upper error bar of the $d + \alpha$ reaction rate and the low end of the allowed baryon density, for which log($^6$Li/H) $\sim -12$. Clearly, measurements of the $d + \alpha$ cross section at relevant energies are crucial for deciding whether or not observational techniques should be pushed in this direction.

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TABLE I. Reaction rates that determine the primordial $^6\text{Li}$ abundance, roughly in order of importance. Errors have only been assessed for reactions determined to affect the final $^6\text{Li}$ abundance significantly.

| Reaction | Rate, $\langle \dot{N}_R \rangle$ (cm$^{-3}$s$^{-1}$) | $2\sigma$ Error | Source |
|----------|-------------------------------------------------|----------------|--------|
| $^4\text{He}(\alpha, \gamma)^7\text{Li}$ | $1.79 \times 10^9 T_9^{-3/2} \exp(-9.729/T_0^{1/3})$ | $T_9 < 3.1$ | Upper Present Work |
| $^4\text{Li}(p, \alpha)^7\text{He}$ | $3.91 \times 10^6 T_9^{-3/2} \exp(-1.192/T_0^{4/3})$ | $T_9 > 3.2$ | Limit |
| $^6\text{Li}(p, \alpha)^3\text{He}$ | $6.3 \times 10^8 T_9^{-3/2} \exp(-4.192/T_0^{3/2})$ | $15\%$ | Present work |
| $^6\text{Li}(n, \alpha)^3\text{H}$ | $2.54 \times 10^9 T_9^{-3/2} \exp(-2.39/T_0)$ | — | Caughlan and Fowler$^a$ |
| $^3\text{He}(t, \gamma)^6\text{Li}$ | $2.1 \times 10^9 T_9^{-2/3} \exp(-7.720/T_0^{1/3})$ | — | Fukugita and Kajino$^b$ |
| $^6\text{Li}(n, \gamma)^7\text{Li}$ | $5.10 \times 10^{-3}$ | — | Malaney and Fowler$^c$ |
| $^6\text{He}(n, \gamma)^7\text{He}$ | $4.04 \times 10^{-12} T_9^{-2} \exp(-9.585/T_0)$ | — | Caughlan and Fowler |
| $^6\text{He} \rightarrow c+^4\text{Li}$ | $0.859$ | — | Malaney and Fowler |
| $^6\text{Li}(p, \gamma)^7\text{Be}$ | $6.69 \times 10^5 T_0^{5/4} \exp(-8.413/T_0^{3/4})$ | — | Caughlan and Fowler |
| $^7\text{Be}(p, \alpha)^4\text{Li}$ | $2.11 \times 10^8 T_9^{-3/2} \exp(-10.359/T_0^{1/3} - (T_9/0.520)^2)$ | — | Caughlan and Fowler |
| $^6\text{Li}(\alpha, \gamma)^10\text{B}$ | $4.06 \times 10^3 T_0^{5/4} \exp(-18.790/T_0^{1/3} - (T_9/1.326)^2)$ | — | Caughlan and Fowler |
| $^6\text{Li}(d, n)^7\text{Be}$ | $1.48 \times 10^8 T_9^{-1/2} \exp(-10.135/T_0^{1/2})$ | — | Malaney and Fowler |
| $^6\text{Li}(d, p)^7\text{Li}$ | $1.48 \times 10^8 T_9^{-1/2} \exp(-10.135/T_0^{1/2})$ | — | Malaney and Fowler |
| $^6\text{Li}(p, \alpha)^3\text{He}$ | $1.03 \times 10^9 T_9^{-2/3} \exp(-8.533/T_0^{1/3})$ | — | Thomas et al.$^d$ |

$^a$Ref. 25
$^b$Ref. 35
$^c$Ref. 40
$^d$Ref. 5
