PHYSICAL REVIEW C VOLUME 56, NUMBER 2 AUGUST 1997

Nuclear reaction rates and primordial ^{6}Li

Kenneth M. Nollett,[1] Martin Lemoine,[2,3] and David N. Schramm[1,2,3]
[1]Department of Physics, Enrico Fermi Institute, The University of Chicago, Chicago, Illinois 60637-1433
[2]NASA/Fermilab Astrophysics Center, Fermi National Accelerator Laboratory, Batavia, Illinois 60510-0500
[3]Department of Astronomy and Astrophysics, Enrico Fermi Institute, The University of Chicago, Chicago, Illinois 60637-1433

(Received 16 December 1996)

We examine the possibility that big-bang nucleosynthesis (BBN) may produce nontrivial 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 $^{2}\mathrm{H}(\alpha,\gamma)^{6}\mathrm{Li}$ radiative capture reaction cross section. We also argue that present observational capabilities do not yet allow the detection of primeval ^{6}Li in very metal-poor stars of the galactic halo. However, if the critical cross section is very high in its plausible range and the baryon density is relatively low, 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.
[S0556-2813(97)02608-3]

PACS number(s): 26.35.+c, 25.45.−z, 26.45.+h, 98.80.Ft

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 30 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, η:$2.5\times10^{-10}<\eta<6\times10^{-10}$ (see, e.g., Ref. [2] and references therein). The fact that there is such a range of concordance, for abundances spanning more than 9 orders of magnitude, is taken as evidence that BBN gives a correct description of the origin of the light elements. This concordance interval also provides a measure of the baryonic contribution to the total mass density of the Universe, $0.01h^{-2}<\Omega_B<0.02h^{-2}$, as obtained from the constraints on η, and where h denotes the value of the Hubble constant in units of 100 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 η. 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 $T_{\mathrm{eff}}\sim6000$–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. 1). 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 [5–7].

At present, there have been only three relatively uncertain detections of ^{6}Li in such low-metallicity stars, one of them being marginal [8]. The metallicities of these stars where ^{6}Li has been observed, roughly $[\mathrm{Fe/H}]>-2$,[1] 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.

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 nonhomogeneous 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 pri-

---

[1] $[\mathrm{Fe/H}]=\log_{10}(\mathrm{Fe/H})-\log_{10}(\mathrm{Fe/H})_{\odot}$, where the subscript $\odot$ refers to abundances measured at the birth of the Sun.

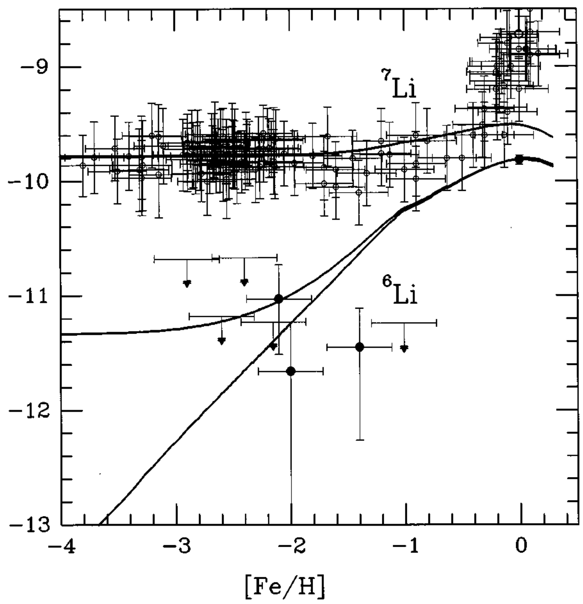

FIG. 1. Abundance vs metallicity. Open data points represent ^{7}Li abundances, the flat region at low metallicities being attributed to the primordial abundance of ^{7}Li. Solid data points represent ^{6}Li abundance measurements and triangles refer to upper limits. The solid curves bracket the possible primordial abundances of ^{6}Li and indicate the evolution of ^{6}Li with metallicity, assuming ^{6}Li evolves like ^{9}Be (see Ref. [41]). 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. [31], $(^6\mathrm{Li/H})_{\mathrm{BBN}} \sim 5\times10^{-12}$. The lower limit corresponds to $(^6\mathrm{Li/H})_{\mathrm{BBN}} \sim 10^{-14}$.

mordial 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 $^2\mathrm{H}(\alpha,\gamma)^6\mathrm{Li}$ 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 $[\mathrm{Fe/H}] < -3$, 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 $(^6\mathrm{Li/H}) \sim 10^{-14} - 10^{-12}$, would nonetheless 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, $^2\mathrm{H}(\alpha,\gamma)^6\mathrm{Li}$, which produces practically all of the ^{6}Li, and the ^{6}Li *destroying* reaction $^6\mathrm{Li}(p,\alpha)^3\mathrm{He}$. We examine below the current status of these reaction rates.

A. The reaction $^6\mathrm{Li}(p,\alpha)^3\mathrm{He}$

The low-energy ($100 \text{ keV} < E < 1000$ 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 ($E < 100$ 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}Li ions, that the reaction takes place. (See Ref. [11] for a detailed discussion.) In the case of $^6\mathrm{Li}(p,\alpha)^3\mathrm{He}$, this corresponds to energies of $E \sim$ 75–410 keV at a temperature of 10^9 K at the beginning of BBN or $E \sim$ 30–80 keV at a temperature of 10^8 K, when the ^{6}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:

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

where E is energy, σ is the reaction cross section, and E_g is the Gamow energy,

$$E_g = 2\mu\pi^2 e^4 Z_1^2 Z_2^2/\hbar^2, \tag{2}$$

for reactants of reduced mass μ 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 $^6\mathrm{Li}(p,\alpha)^3\mathrm{He}$ reaction rate using a new polynomial fit to the experimental S factor between 100 and 1000 keV. (See Table I and Fig. 2.) In addition, we present the S factor curve corresponding to the rate found in the compilation of Harris *et al.* [12]. Following Engstler *et al.* [10], we use only the data above 100 keV [13–20,10] 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 $^2\mathrm{H}(\alpha,\gamma)^6\mathrm{Li}$

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 [21–29] vary over a factor of about 8 at 200 keV (c.m.). Experimental measurements are difficult because of the extremely small

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

Reaction	Rate, $\langle N_A \sigma v \rangle$ (cm^3 s^{-1})		2σ error	Source
^{2}H$(\alpha,\gamma)^6$Li	$1.79\times10^3 T_9^{-2/3}\exp(-7.429/T_9^{1/3})(1+0.056T_9^{1/3})$ $+9.71\times10^1 T_9^{-3/2}\exp(-8.251/T_9)$	$T_9<3.2$	Extreme Upper Limit	Present work
	$3.01\times10^1 T_9^{-2/3}\exp(-7.429/T_9^{1/3})$ $\times(1+0.056T_9^{1/3}-4.85T_9^{2/3}+8.85T_9$ $-0.585T94/3-0.584T95/3)$ $+9.71\times10^1 T_9^{-3/2}\exp(-8.251/T_9)$	$T_9>3.2$		
^{6}Li$(p,\alpha)^3$He	$3.39\times10^{10} T_9^{-2/3}\exp[-8.415/T_9^{1/3}-(T_9/5.50)^2]$ $\times(1+0.0495T_9^{1/3}-0.087T_9^{2/3}-0.030T_9$ $-0.0055T_9^{4/3}-0.0048T_9^{5/3})$ $+1.33\times10^{10} T_9^{-3/2}\exp(-17.793/T_9)$ $+1.29\times10^9 T_9^{-1}\exp(-21.820/T_9)$		15%	Present work
^{6}Li$(n,\alpha)^3$H	$2.54\times10^9 T_9^{-3/2}\exp(-2.39/T_9)$		—	Caughlan and Fowler [a]
^{3}He$(t,\gamma)^6$Li	$2.21\times10^5 T_9^{-2/3}\exp(-7.720/T_9^{1/3})$ $\times(1+2.68T_9^{2/3}+0.868T_9+0.192T_9^{4/3}$ $+0.174T_9^{5/3}+0.044T_9^2)$		—	Fukugita and Kajino [b]
^{6}Li$(n,\gamma)^7$Li	5.10×10^{-3}		—	Malaney and Fowler [c]
^{4}He$(nn,\gamma)^6$He	$4.04\times10^{-12} T_9^{-2}\exp(-9.585/T_9)(1+0.138T_9)$		—	Caughlan and Fowler
^{6}He$\rightarrow e+{}^6$Li	0.859		—	Malaney and Fowler
^{6}Li$(p,\gamma)^7$Be	$6.69\times10^5 T_{9a}^{5/6} T_9^{-3/2}\exp(-8.413/T_9^{1/3})$		—	Caughlan and Fowler
^{9}Be$(p,\alpha)^6$Li	$2.11\times10^{11} T_9^{-2/3}\exp[-10.359/T_9^{1/3}-(T_9/0.520)^2]$ $\times(1+0.040T_9^{1/3}+1.09T_9^{2/3}+0.307T_9$ $+3.21T_9^{4/3}+2.3T_9^{5/3})$ $+4.51\times10^8 T_9^{-1}\exp(-3.046/T_9)$ $+6.70\times10^8 T_9^{-3/4}\exp(-5.16/T_9)$		—	Caughlan and Fowler
^{6}Li$(\alpha,\gamma)^{10}$B	$4.06\times10^6 T_9^{-2/3}\exp[-18.790/T_9^{1/3}-(T_9/1.326)^2]$ $\times(1+0.22T_9^{1/3}+1.54T_9^{2/3}+0.239T_9$ $+2.20T_9^{4/3}+0.869T_9^{5/3})$ $+1.91\times10^3 T_9^{-3/2}\exp(-3.484/T_9)$ $+1.01\times10^4 T_9^{-1}\exp(-7.269/T_9)$		—	Caughlan and Fowler
^{6}Li$(d,n)^7$Be	$1.48\times10^{12} T_9^{-2/3}\exp(-10.135/T_9^{1/3})$		—	Malaney and Fowler
^{6}Li$(d,p)^7$Li	$1.48\times10^{12} T_9^{-2/3}\exp(-10.135/T_9^{1/3})$		—	Malaney and Fowler
^{9}Li$(p,\alpha)^6$He	$1.03\times10^{11} T_9^{-2/3}\exp(-8.533/T_9^{1/3})$		—	Thomas *et al.* [d]

[a] Reference [30].
[b] Reference [37].
[c] Reference [48].
[d] Reference [9].

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 wave function.

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 [30], 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 keV. 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.* [31] failed to observe the reaction, but 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, and since it results from measurement of background events only, it may be expected to say more about the experimental apparatus than about the reaction. Thus, the actual reaction rate is quite likely much lower—by a factor of 50 or so—than the limit implied by this measurement. (See Fig. 3.)

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 [32–34]. In this scheme, ^{6}Li nuclei are Rutherford scattered off some high-Z nucleus. Some of these scattered nuclei are broken up into 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 [32]. However, a number of difficulties arise in treating the data

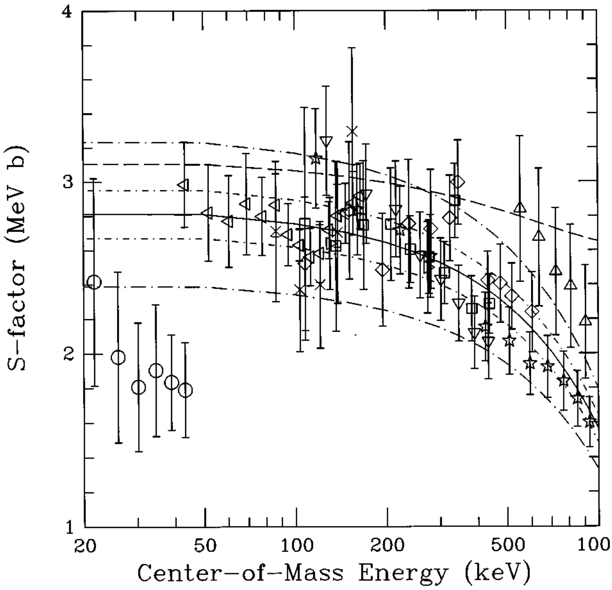

FIG. 2. ^{6}Li(p,α)^{3}HeS factor. Experimental data for the reaction are shown, along with our fit (solid line), "1σ" and "2σ" uncertainties in our fit (symmetrical dot-dashed lines), and the standard fit of Harris *et al.* [12] (long-dashed line). Data are those of ▷, Gemeinhardt [13]; ○, Fiedler and Kunze [15]; ◁, Spinka *et al.* [16]; □, Kwon *et al.* [14]; ◇, Shinozuka *et al.* [17]; ⋆, Elwyn *et al.* [18]; △, Marion *et al.* [19]; ×, Várnagy *et al.* [20]; and ▽, Engstler *et al.* [10].

[31,35] 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 who examines $d+\alpha$ capture this way [34] reports anomalous angular dependence in the data. The cross sections inferred from the breakup measurements of Kiener *et al.* [33] 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.

Theoretical treatments of the reaction meet with two chief difficulties. The first derives from uncertainty in the asymptotic normalization of the ^{6}Li wave function in the α-d channel. This is crucial for calculating radiative-capture matrix elements because most of the overlap between the incoming scattering state and the ^{6}Li ground state is in the asymptotic part of the ^{6}Li wave function (outside ~4 fm) [29]. The calculations of Mukhamedzhanov *et al.* [29] and of Ryzhikh *et al.* [26] have been particularly careful about the asymptotic normalization, which is a quantity of more general interest than just as an ingredient for radiative capture calculations [36], and has been derived by various indirect methods to within claimed errors of about 5% [29]. Authors whose methods do not take this information into account have asymptotic normalizations dictated by their potential models. The second major difficulty in theoretical treatment of this reaction is the anomalously small dipole contribution to the reaction measured by Robertson *et al.* above 1 MeV [24]. As mentioned above, the nearly equal charge-to-mass ratios of the alpha particle and deuteron make the dipole operator very small. However, Robertson *et al.* found it to be smaller than expected, a result which has remained true, to varying degrees, in comparison with all subsequent models. The source of this anomalous behavior is not known, so its possible continuation into the low-energy region where the dipole transition is likely more important cannot be predicted. Previous work on extrapolating to low energy has been split between those authors who assume that this behavior will go away at lower energy (as Robertson *et al.* [24] and Mukhamedzhanov *et al.* [29] do) and those who renormalize their dipole operators to match the smaller dipole contribution measured by Robertson *et al.* above 1 MeV (as Ryzhikh *et al.* [26] and Typel *et al.* [23] do). All these authors agree that the dipole contribution to the cross section is less than about 50% of the total at low energy. While predictions vary (at their most extreme) by almost an order of magnitude below the 711 keV resonance, they are all in reasonable agreement with the nonresonant data above 1 MeV as well as with the resonant data of Mohr *et al.* [25].

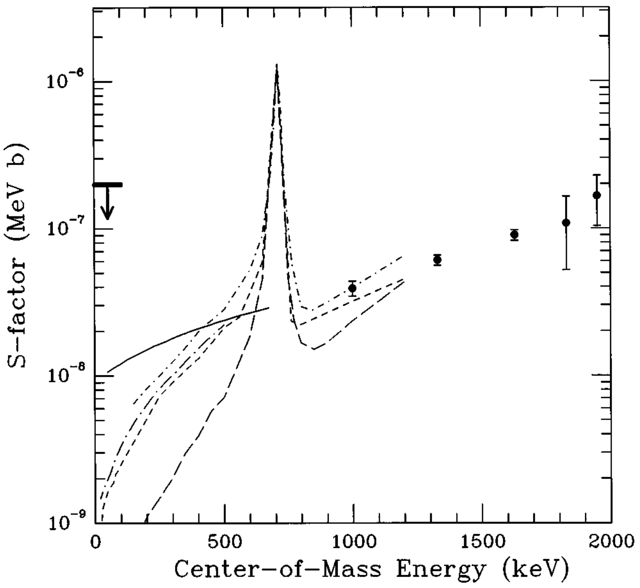

FIG. 3. d-α capture S factor. A selection of measured and inferred astrophysical S factors for the reaction ^{2}H(α,γ)^{6}Li is shown. In order of decreasing low-energy S factor, the calculations are from Coulomb breakup measurements of Kiener *et al.* [33] (solid curve), and the models of Mohr *et al.* [25] (short dash-dotted), Mukhamedzhanov *et al.* [29] (long dash-dotted) Ryzhikh *et al.* [26] (short dashed), and Typel [23] (long dashed). The 53 keV upper limit is from Cecil *et al.* [31], 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.

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 ~50–400 keV relevant to BBN (alpha lab energies of ~150–1200 keV) so that it can be measured in similar experiments. In the absence of any experimental evidence to allow a decision between the various theoretical and experimental extrapolations, we have calculated ^{6}Li yields using some representative published cross sections. The results of

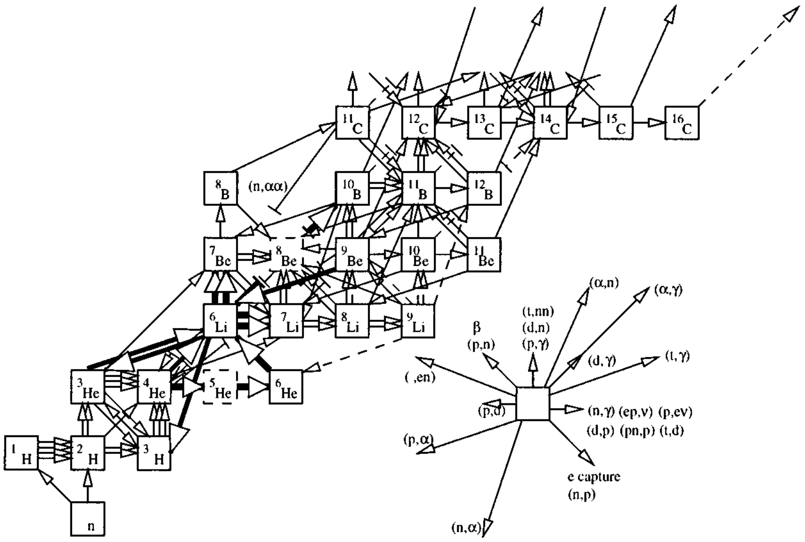

FIG. 4. BBN reaction network. The lower portion of the BBN reaction network used here, which is identical to that of Ref. [9]. Reactions producing or destroying ^{6}Li are indicated by thick lines.

Ryzhikh *et al.* [26] and of Mukhamedzhanov *et al.* [29] deserve special attention for their careful treatment of the asymptotic ^{6}Li wave function (see above), but the size of the low-energy dipole contribution in particular remains very uncertain even in these treatments. We will also use the Cecil *et al.* [31] upper limit for the unobserved low-energy cross section as an extreme upper bound. Simply scaling up the expected energy dependence below 700 keV would result in very high cross sections in conflict with the measurements of Mohr *et al.*, so we take as the extreme upper limit for the nonresonant S factor below the 711 keV resonance a constant value at the 53 keV limit of 2×10^{-7} MeV b. This does not represent a realistic energy dependence for the cross section, it is a cross section everywhere higher than expected on the basis of theoretical considerations (see Fig. 3), and it is (probably) not based on any observation of reaction products. However, it is certainly true that the cross section could not possibly be larger, and this is the lowest limit we can set easily with existing data.

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

$$N_A\langle\sigma v\rangle_{\mathrm{resonant}}=97.1T_9^{-3/2}\exp(-8.251/T_9). \qquad (3)$$

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}Li yields.

C. Other ^{6}Li reactions

Eleven other reactions in the BBN reaction network [9] 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 [37], 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 [38] 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 reaction ^{6}Li(p,α)^{3}He considered in Sec. 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 2σ 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.

The dependence of the ^{6}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 lack of low-energy cross-section measurements, there is a wide range of possible ^{6}Li yields. Depending on the low-energy extrapolation used, the maximum possible primordial ratio of ^{6}Li to ^{7}Li varies from 0.01% (^{6}Li/H$=1.4\times10^{-14}$) to 0.18% (^{6}Li/H$=2.4\times10^{-13}$), while the extreme upper limit on this ratio derived as described in Sec. II B from the Cecil *et al.* limit on the $d+\alpha$ cross section and our lower limit on the ^{6}Li(p,α)^{3}He cross section is as high as 3.7%; see Fig. 5. The maximum always occurs at $\eta\simeq2\times10^{-10}$, the extreme low end of the concordance interval allowed by standard BBN [2]. These results are in agreement with those of Ref. [9], who found an upper limit on the primordial ratio ^{6}Li/

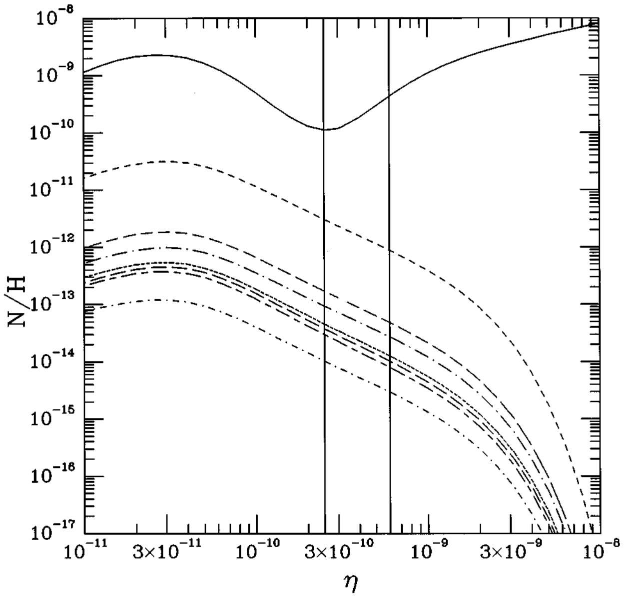

FIG. 5. Predicted abundances. Abundances relative to hydrogen generated from the BBN network of Fig. 4, with the concordance interval in η of Copi *et al.* [2] indicated by vertical solid lines. The solid curve at the top is the predicted ^{7}Li abundance. All other curves are ^{6}Li abundances derived from the various calculated and measured $d+\alpha$ cross sections. The top dashed curve is based on the current extreme upper experimental limit, as described in this paper. The remaining curves, in decreasing order, are from the Kiener *et al.* [33] Coulomb breakup measurements (dashed line), and the calculations of Mohr *et al.* [25] (long dash-dotted), Robertson *et al.* [24] (the ''standard'' rate; short-dashed line), Mukhamedzhanov *et al.* [29] (medium dashed), Ryzhikh *et al.* [26] (long-short dashed), and Typel, *et al.* [23] (short dash-dotted).

^{7}Li$<0.2\%$ in all cases they considered.

Because ^{6}Li yields fall rapidly with increasing baryon density, ^{6}Li is potentially a very sensitive probe of the baryon density. However, a direct measurement of the ^{2}H$(\alpha,\gamma)^6$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}Li at a level consistent with the above estimations, while very unlikely on the basis of existing cross-section data, would provide a new piece of evidence for the consistency of BBN, and hence a fundamental cosmological test. Although a precise baryon density determination from ^{6}Li is not possible without a better rate for ^{2}H$(\alpha,\gamma)^6$Li, it is clear that a measurable primordial component of ^{6}Li would argue for a value of η near the lower end of the allowed range. (See Fig. 5.) This is also the range of η implied by the extragalactic deuterium measurements of Rugers and Hogan [39], but it would be in conflict with the lower D/H (higher η) values implied by the work of Tytler *et al.* [40]. Current trends toward low D/H would imply a high η and hence low ^{6}Li/H even for unexpectedly high BBN production of ^{6}Li.

The highest values of the ^{6}Li/^{7}Li ratio may allow something like the ''Spite plateau'' of ^{7}Li to exist for ^{6}Li at extremely low metallicities. It was argued in Ref. [41] that ^{6}Li/H should scale as ^{16}O/H all along the galactic evolution, taking into account the trends observed for ^{9}Be. This means that the curve ln(^{6}Li/H) vs ln(Fe/H) should have a slope unity in the halo phase, i.e., up to [Fe/H]$\simeq -1$, and a slope ~ 0 during the disk phase $-1<$[Fe/H]<0 (see Fig. 1). Roughly speaking, since the meteoritic abundance of ^{6}Li is $\log_{10}(^6\mathrm{Li/H}) \sim -10$ at [Fe/H]$\equiv 0$, one would expect the primordial ^{6}Li plateau to show up at [Fe/H]$\simeq -3$ if the primordial abundance is $\log_{10}(^6\mathrm{Li/H})_p \sim -12$, at [Fe/H]$\sim -4$ if $\log_{10}(^6\mathrm{Li/H})_p \sim -13$, and so forth. We note that the expected values of the crucial reaction rate would result in ^{6}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 extremely high upper limit on the $d+\alpha$ cross section allowed by the present lack of a direct low-energy measurement corresponds to an upper limit of the primordial ^{6}Li abundance at about the level of previous detections.

B. Observing primordial ^{6}Li

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

Nonetheless, two detections of ^{6}Li have probably been achieved at metallicities [Fe/H]$\simeq -2.1$ and [Fe/H]$\simeq -1.4$, at a level ^{6}Li/^{7}Li$\simeq 5\%$ [8]. 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 macroturbulent motions in the atmosphere, is constrained from the profile fitting of other lines, such as Fe I and Ca I [8]. Therefore, in order to reach very low ^{6}Li/^{7}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}Li/^{7}Li ratio was carried out in the star HD84937, of magnitude $m_V=8.3$, in 1 h integration time on the 2.7 m McDonald Telescope and Coudé Spectrometer, at a resolving power $\lambda/\Delta\lambda = 1.25\times10^5$, yielding ^{6}Li/^{7}Li$=5\%\pm2\%$ (statistical and systematics combined) [8,42–44]. The noise could be reduced by a factor of $\simeq 6$ for an integration time ~ 20 h on an instrument such as the 3.9 m Anglo-Australian Telescope, assuming equal efficiencies for the spectrometers. On future telescopes such as one 8 m reflector at the European Southern Observatory Very Large Telescope, using the UVES spectrograph, this factor could be brought up to $\simeq 12$ for 20 h 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, and Shectman [45–47], we do not find any star brighter than $m_V = 13$, for [Fe/H]< -3 and a temperature of about $T_{\rm eff} > 6000$ K, needed to ensure that ^{6}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 the expected level ^{6}Li/^{7}Li$<1\%$ does not seem realistic at metallicities [Fe/H]< -3. Only at the very high values of ^{6}Li/^{7}Li$\sim 3\%$ allowed by the present lack of low-energy data for the deuterium-alpha capture cross section 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 Ω_B from ^{6}Li alone, if a primeval component of ^{6}Li were observed. The experimental upper limit on the unobserved low-energy cross section of Cecil *et al.* [31] also allows the ^{6}Li yield to be considerably higher than allowed by any of these estimates, so that any constraint on Ω_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 Ω_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 $\log_{10}(^6{\rm Li/H}) \sim -14 \rightarrow -12$, 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 for a much higher (by a factor of ~ 50) than expected $d+\alpha$ reaction rate and a relatively low baryon density, for which $\log_{10}(^6{\rm Li/H}) \sim -12$. 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.

ACKNOWLEDGMENTS

We would like to thank B. Fields, R. Wiringa, G. Ryzhikh, and R. G. H. Robertson for useful information, as well as D. Thomas for providing the code for the extended reaction network. This work was supported in part by the DOE, NASA, and the NSF at the University of Chicago, and by the DOE and NASA at Fermilab.

[1] P. J. E. Peebles, D. N. Schramm, E. L. Turner, and R. G. Kron, Nature (London) **352**, 769 (1991).
[2] C. J. Copi, D. N. Schramm, and M. S. Turner, Science **267**, 192 (1995).
[3] D. N. Schramm and R. V. Wagoner, Annu. Rev. Nucl. Sci. **27**, 37 (1977).
[4] H. Reeves, W. A. Fowler, and F. Hoyle, Nature (London) **226**, 727 (1970).
[5] F. Spite and M. Spite, Astron. Astrophys. **115**, 357 (1982).
[6] J. A. Thorburn, Astrophys. J. **421**, 318 (1994).
[7] M. Spite, P. François, P. E. Nissen, and F. Spite, Astron. Astrophys. **307**, 172 (1996).
[8] V. V. Smith, D. L. Lambert, and P. E. Nissen, Astrophys. J. **408**, 262 (1993).
[9] D. Thomas, D. N. Schramm, K. A. Olive, and B. D. Fields, Astrophys. J. **406**, 569 (1993).
[10] S. Engstler, G. Raimann, C. Angulo, U. Greife, C. Rolfs, U. Schröder, E. Somorjai, and B. Kirch, Z. Phys. A **342**, 471 (1992).
[11] C. E. Rolfs and W. S. Rodney, *Cauldrons in the Cosmos* (University of Chicago Press, Chicago, 1988).
[12] M. J. Harris, W. A. Fowler, G. R. Caughlan, and B. A. Zimmerman, Annu. Rev. Astron. Astrophys. **21**, 165 (1983).
[13] W. Gemeinhardt, D. Kamke, and C. von Rhöneck, Z. Phys. **197**, 58 (1966).
[14] J. U. Kwon, J. C. Kim, and B. M. Sung, Nucl. Phys. **A493**, 112 (1989).
[15] O. Fiedler and R. Kunze, Nucl. Phys. **A96**, 513 (1967).
[16] H. Spinka, T. A. Tombrello, and H. Winkler, Nucl. Phys. **A164**, 1 (1971).
[17] T. Shinozuka, Y. Tanaka, and K. Sugiyama, Nucl. Phys. **A326**, 47 (1979).
[18] A. J. Elwyn, R. E. Holland, C. N. Davids, L. Meyer-Schützmeister, F. P. Mooring, and W. Ray, Jr., Phys. Rev. C **20**, 1984 (1979).
[19] J. B. Marion, G. Weber, and F. S. Mozer, Phys. Rev. **104**, 1402 (1956).
[20] M. Várnagy, J. Csikai, J. Szabó, S. Szegedi, and J. Bánhalmi,

Nucl. Instrum. Methods **119**, 451 (1974).

[21] K. Langanke, Nucl. Phys. **A457**, 351 (1986).

[22] K. Langanke and C. Rolfs, Z. Phys. A **325**, 193 (1986).

[23] S. Typel, G. Blüge, and K. Langanke, Z. Phys. A **339**, 335 (1991).

[24] R. G. H. Robertson, P. Dyer, R. A. Warner, R. C. Melin, R. J. Bowles, A. B. McDonald, G. C. Ball, W. G. Davies, and E. D. Earle, Phys. Rev. Lett. **47**, 1867 (1981).

[25] P. Mohr, V. Kölle, S. Wilmes, U. Atzrott, G. Staudt, J. W. Hammer, H. Krauss, and H. Oberhummer, Phys. Rev. C **50**, 1543 (1994).

[26] C. G. Ryzhikh, R. A. Eramzhyan, and S. Shlomo, Phys. Rev. C **51**, 3240 (1995).

[27] N. A. Burkova, K. A. Zhaksibekova, and M. Zhusupov, Phys. Lett. B **248**, 15 (1990).

[28] R. Crespo, A. M. Eiró, and J. A. Tostevin, Phys. Rev. C **42**, 1646 (1990).

[29] A. M. Mukhamedzhanov, R. P. Schmitt, R. E. Tribble, and A. Sattarov, Phys. Rev. C **52**, 3483 (1995).

[30] G. R. Caughlan and W. A. Fowler, At. Data Nucl. Data Tables **40**, 283 (1988).

[31] F. E. Cecil, J. Yan, and C. S. Galovich, Phys. Rev. C **53**, 1967 (1996).

[32] G. Baur, C. A. Bertulani, and H. Rebel, Nucl. Phys. **A458**, 188 (1986).

[33] J. Kiener, H. J. Gils, H. Rebel, S. Zagromski, G. Gsottschneider, N. Heide, H. Jelitto, J. Wentz, and G. Baur, Phys. Rev. C **44**, 2195 (1991).

[34] J. Hesselbarth, S. Khan, T. Kihm, and K. T. Knöpfle, Z. Phys. A **331**, 365 (1988).

[35] S. B. Gazes, J. E. Mason, R. B. Roberts, and S. G. Teichmann, Phys. Rev. Lett. **68**, 150 (1992).

[36] L. D. Blokhintsev, V. I. Kukulin, A. A. Sakharuk, D. A. Savin, and E. V. Kuznetsova, Phys. Rev. C **48**, 2390 (1993).

[37] M. Fukugita and T. Kajino, Phys. Rev. D **42**, 4251 (1990).

[38] L. H. Kawano, Fermilab Report No. FERMILAB-PUB-88/34-A, 1988.

[39] M. Rugers and C. J. Hogan, Astron. J. **111**, 2135 (1996).

[40] D. Tytler, X.-M. Fan, and S. Burles, Science **381**, 207 (1996).

[41] M. Lemoine, D. N. Schramm, J. W. Truran, and C. J. Copi, Astrophys. J. **478**, 554 (1997).

[42] L. M. Hobbs and J. A. Thorburn, Astrophys. J. **428**, L25 (1994).

[43] P. E. Nissen, in *The Light Element Abundances*, edited by P. Crane (Springer-Verlag, Berlin, 1995), p. 337.

[44] P. E. Nissen, D. L. Lambert, and V. V. Smith, ESO Messenger **76**, 36 (1994).

[45] T. C. Beers, G. W. Preston, and S. A. Shectman, Astron. J. **90**, 2089 (1985).

[46] T. C. Beers, G. W. Preston, and S. A. Shectman, Astron. J. **103**, 1987 (1992).

[47] T. C. Beers, in *The Light Element Abundances*, edited by P. Crane (Springer-Verlag, Berlin, 1995), p. 145.

[48] R. A. Malaney and W. A. Fowler, Astrophys. J. **345**, L5 (1989).