Solar neutrino constraints on the BBN production of Li

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Using the recent WMAP determination of the baryon-to-photon ratio, $10^{10}\eta=6.14$ to within a few percent, big bang nucleosynthesis (BBN) calculations can make relatively accurate predictions of the abundances of the light element isotopes which can be tested against observational abundance determinations. At this value of η, the ^{7}Li abundance is predicted to be significantly higher than that observed in low metallicity halo dwarf stars. Among the possible resolutions to this discrepancy are (1) ^{7}Li depletion in the atmosphere of stars, (2) systematic errors originating from the choice of stellar parameters—most notably the surface temperature, and (3) systematic errors in the nuclear cross sections used in the nucleosynthesis calculations. Here, we explore the last possibility, and focus on possible systematic errors in the $^3\mathrm{He}(\alpha,\gamma)^7\mathrm{Be}$ reaction, which is the only important ^{7}Li production channel in BBN. The absolute value of the cross section for this key reaction is known relatively poorly both experimentally and theoretically. The agreement between the standard solar model and solar neutrino data thus provides additional constraints on variations in the cross section (S_{34}). Using the standard solar model of Bahcall, and recent solar neutrino data, we can exclude systematic S_{34} variations of the magnitude needed to resolve the BBN ^{7}Li problem at the $\gtrsim$95% C.L., or more strongly, depending on the Li observations used. Additional laboratory data on $^3\mathrm{He}(\alpha,\gamma)^7\mathrm{Be}$ will sharpen our understanding of both BBN and solar neutrinos, particularly if care is taken in determining the absolute cross section and its uncertainties. Nevertheless, it is already clear that this ''nuclear fix'' to the ^{7}Li BBN problem is unlikely; other possible solutions are briefly discussed.

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I. INTRODUCTION

The recent all-sky, high-precision measurement of microwave background anisotropies by Wilkinson Microwave Anisotropy Probe (WMAP) [1] has opened the possibility for new precision analyses of big bang nucleosynthesis (BBN). Until now, one could use the predictions of standard BBN [2,3] for the abundances of the light element isotopes, D, ^{3}He, ^{4}He, and ^{7}Li and compare those results with the observational determination of those isotopes and test the concordance of the theory. If concordance is found, the theory is also able to predict the value of the baryon-to-photon ratio, η. Indeed, concordance is found, so long as a liberal estimation of systematic uncertainties are included in the analysis. The accuracy of the predicted value of η from BBN alone based on likelihood methods [4–7] is modest: $\eta_{10}=5.7^{+1.0}_{-0.6}$ when D, ^{4}He, and ^{7}Li are used, and $\eta_{10}=6.0^{+1.4}_{-0.5}$ when using D alone, where $\eta_{10}=10^{10}\eta$. This pales in comparison with the recent WMAP result of $\Omega_B h^2=0.0224\pm0.0009$ which is equivalent to $\eta_{10,\mathrm{CMB}}=6.14\pm0.25$. This result is the WMAP best fit assuming a varying spectral index and is sensitive mostly to WMAP alone (primarily the first and second acoustic peaks) but does include CBI [8] and ACBAR [9] data on smaller angular scales, and Lyman α forest data (and 2dF redshift survey data [10]) on large angular scales.

If we use the WMAP data to fix the baryon density, we can make quite accurate predictions for the light element abundances. At this density, we can make a direct comparison [11] between theory and observation as shown in Table I.

As one can see, the agreement between the predicted abundance of D/H and the observed value (based on the average of the 5 best determined quasar absorption system abundances [12–15]) is perfect. The comparison with ^{4}He is less good, as BBN predicts a mass fraction which is high compared to most observations [16–19]. The value in Table I is based on a combined analysis [18] which is close agreement with the recent observations of [19]. One should note that (1) the data of [16] alone give a higher value for the ^{4}He abundance $Y_p=0.242\pm0.002\pm0.005$, and (2) important systematic effects have been underestimated [20]. Among the most probable cause for a serious underestimate of the ^{4}He abundance is underlying stellar absorption. Whether or not

TABLE I. Light element abundances: BBN predictions and observations.

Element	Theory	Observation
D/H	$2.75^{+0.24}_{-0.19}\times10^{-5}$	$2.78\pm0.29\times10^{-5}$
^{4}He	$0.2484^{+0.0004}_{-0.0005}$	$0.238\pm0.002\pm0.005$
^{7}Li	$3.82^{+0.73}_{-0.60}\times10^{-10}$	$1.23^{+0.34}_{-0.16}\times10^{-10}$

this effect can account for the serious discrepancy now uncovered remains to be seen.

Clearly the key problem concerning the concordance of BBN theory and the observational determinations of the light element abundances is ^{7}Li. The primordial abundance of ^{7}Li is determined from the ''Spite plateau'' [21] in Li/H observed in low metallicity halo dwarf stars (extreme population II). The observed value is clearly discrepant with the BBN +WMAP prediction. The cause of the discrepancy may be:

Stellar depletion of ^{7}Li—however, the lack of dispersion in the observed data, make it unlikely that dispersion alone can account for the difference.

Stellar parameters—the determined ^{7}Li is sensitive to the assumed surface temperature of the star. However, to account for a discrepancy these large temperatures would have to be off by at least 500 K. This may not be reasonable.

The nuclear rates—this is the case we wish to explore here.

Of course, it is also possible that the ^{7}Li discrepancy is real, and points to new physics. However, it is our view that at present, the case for new physics is not compelling, though it certainly merits serious investigation. Furthermore, a firm rejection of the more ''prosaic'' possibilities we have outlined is a prerequisite which must be satisfied before we are driven to more radical and exciting new solutions. It is in this spirit that we investigate possible systematic errors in the BBN theoretical predictions for ^{7}Li.

Uncertainties in the nuclear reaction rates which determine ^{7}Li are dominated by $^3\mathrm{He}(\alpha,\gamma)^7\mathrm{Be}$. There has been concerted experimental and theoretical effort to understand this reaction, and indeed the cross section *shape* versus energy appears to be well understood [22]. However, a challenge to both experimental and theoretical work has been the determination of the absolute *normalization* of the cross section. This uncertainty propagates into an overall systematic error in the $^3\mathrm{He}(\alpha,\gamma)^7\mathrm{Be}$ rate.

We thus pose the following question. Independent of the quoted (or derived) laboratory uncertainties in $^3\mathrm{He}(\alpha,\gamma)^7\mathrm{Be}$, what is the maximum allowable amount that this rate can be adjusted? Of course, we are not completely free to adjust this rate, since this nuclear reaction occurs in the Sun and is in part responsible for the observed flux of solar neutrinos. Thus our goal is to use the standard solar model [23] as a constraint on the BBN nucleosynthesis rates. In order to reduce the predicted ^{7}Li abundance in Table I, to the observed one requires a reduction in the $^3\mathrm{He}(\alpha,\gamma)^7\mathrm{Be}$ by a factor of 0.27. We show that by using the concordance between the standard solar model and the observed flux of solar neutrinos, this is excluded at the 99.9999% C.L. At the 95% C.L., the largest reduction factor possible is 0.65. Thus, it is not possible to argue that the uncertainties in nuclear reactions are solely responsible for the ^{7}Li discrepancy.

In Sec. II, we detail the problem of BBN produced ^{7}Li. In Sec. III, we discuss the key nuclear reactions which contribute to the overproduction of ^{7}Li. We derive our constraints on these reactions using the observed flux of solar neutrinos in Sec. IV. A summary and discussion is given in Sec. V.

II. THE OVERPRODUCTION OF ^{7}Li

As noted in Table I, the BBN ^{7}Li abundance is predicted to be $3.82^{+0.73}_{-0.60}\times10^{-10}$ for $\eta_{10}=6.14\pm0.25$. This result [11] is based on a BBN calculation [7] using the NACRE Collaboration rates [25], which have been renormalized to minimize χ^2 and yield well defined uncertainties. Other calculations tend to give even higher values, e.g., $^7\mathrm{Li}/H=4.87^{+0.64}_{-0.60}\times10^{-10}$ [26]; $^7\mathrm{Li/H}=4.18\pm0.46\times10^{-10}$ [27]. These results differ due to the different nuclear data sets and procedures used to fit them and derive thermonuclear rates. The variations are thus a measure of *known* systematics in the ^{7}Li prediction. A new evaluation of nuclear reaction rates [28], takes into account the underlying nuclear systematics, finding a ^{7}Li abundance of $4.27^{+1.02}_{-0.83}\times10^{-10}$ for the WMAP baryon density. To be conservative we will adopt the first and lowest predicted ^{7}Li abundance.

The observed Li/H value in Table I reflects the inferred mean abundance in the atmospheres for a set of pop II stars. The analysis is that of [29], based on the data of [30]. The data sample consists of 23 very metal poor halo stars, with metallicities ranging from $[\mathrm{Fe/H}]=-2.1$ to -3.3. The data show a remarkably uniform abundance of Li and negligible dispersion about a tiny slope which is consistent with the production of some Li in galactic cosmic ray collisions (primarily $\alpha+\alpha$). Note that any galactic component of Li only compounds the BBN discrepancy.

The ^{7}Li value in Table I assumes that the Li abundance in the stellar sample reflects the initial abundance at the birth of the star; however, an important source of systematic uncertainty comes from the possible depletion of Li over the $\gtrsim$10 Gyr [31] age of the pop II stars. Stellar interiors can burn Li and alter its surface abundance. The atmospheric Li abundance will suffer depletion if the outer layers of the stars have been transported deep enough into the interior, and/or mixed with material from the hot interior; this may occur due to convection, rotational mixing, or diffusion. However, if mixing processes are not efficient, then Li can remain intact and undepleted in a thin outer layer of the atmosphere, which contains a few percent of the star's mass but is the portion of the star's material that is observable.

Standard stellar evolution models predict Li depletion factors which are very small (<0.05 dex) in very metal-poor turnoff stars [32]. However, there is no reason to believe that such simple models incorporate all effects which lead to depletion such as rotationally-induced mixing and/or diffusion. Current estimates for possible depletion factors are in the range $\sim$0.2–0.4 dex [33]. While the upper end of this range is close to the lower end of the required range for the depletion factor $\simeq$0.3–0.7 necessary to account for the difference in the BBN and observed abundance, depletion models typically predict the existence of star-to-star differences in observed Li abundances due to the range of stellar rotation and other intrinsic stellar properties to which the models have some sensitivity. As noted above, this data sample [30] shows a negligible intrinsic spread in Li leading to the conclusion that depletion in these stars is as low as 0.1 dex.

Another important source for potential systematic uncertainty stems from the fact that the Li abundance is not di-

rectly observed but rather, inferred from an absorption line strength and a model stellar atmosphere. Its determination depends on a set of physical parameters and a model-dependent analysis of a stellar spectrum. Among these parameters, are the metallicity characterized by the iron abundance (though this is a small effect), the surface gravity which for hot stars can lead to an underestimate of up to 0.09 dex if log g is overestimated by 0.5, though this effect is negligible in cooler stars. Typical uncertainties in log g are ± 0.1–0.3. The most important source for error is the surface temperature. Effective-temperature calibrations for stellar atmospheres can differ by up to 150–200 K, with higher temperatures resulting in estimated Li abundances which are higher by ~ 0.08 dex per 100 K. Thus accounting for a difference of 0.5 dex between BBN and the observations, would require a serious offset of the stellar parameters.

We note however, that a recent study [34] with temperatures based on Hα lines (considered to give systematically high temperatures) yields $^7\mathrm{Li/H} = (2.19^{+0.46}_{-0.38}) \times 10^{-10}$. These results are based on a globular cluster sample and do show considerable dispersion. A related study (also of globular cluster stars) gives $^7\mathrm{Li/H} = 2.29 \times 10^{-10}$ [35]. The difference between these results and the BBN value is just over 0.2 dex making it plausible that depletion may be responsible for the difference in these stars which show systematically high temperatures. It remains an open question why stars in a globular cluster—which are usually thought of as sharing a common origin site and epoch—seem to show a larger Li dispersion (and higher temperatures) than field halo stars whose evolution has not been so tightly related.

Finally, the remaining source of systematic uncertainty pertains not to the observations, but to the BBN calculation itself. Here we will limit ourselves to a discussion of those cross sections which have a bearing on the production of ^{7}Be, which is the dominant source of mass-7 at the high values of η consistent with the WMAP result.[1] As such, the principal cross section of interest is $^3\mathrm{He}(\alpha,\gamma)^7\mathrm{Be}$. Since we will also discuss this reaction in the context of solar neutrinos, we describe how $^7\mathrm{Be}(p,\gamma)^8\mathrm{B}$ affects BBN.

III. NUCLEAR RATES CONTRIBUTING TO BBN ^{7}Li PRODUCTION

Since our aim is to fix the ^{7}Li problem by changing nuclear reaction rates, it is important to understand how they do or do not impact primordial nucleosynthesis. We will start with the all-too-familiar $n(p,\gamma)d$ reaction and how it affects the light element yields. This will guide us when looking specifically at the other reactions. It is well known that nucleosynthesis in the early universe is delayed due to the deuterium bottleneck. It is important to understand how the deuterium bottleneck affects the abundances of the light elements. The delay being caused by the large number of photons relative to baryons, which makes the deuterium photo-destruction rates much larger than the production rates. At lower temperatures, about 70 keV, deuterium production proceeds and the burning into heavier nuclei occurs. Burning proceeds until the neutron fuel is depleted and the Coulomb barrier stops charged-induced reactions, happening at a temperature around 50 keV.

TABLE II. BBN ^{7}Li sensitivities to the top 15 reaction rates and other parameters, given in terms of the logarithmic derivatives of the predicted ^{7}Li abundance with respect to each rate or parameter. $^7\mathrm{Li}/^7\mathrm{Li}_0 = \Pi_i R_i^{\alpha_i}$, where R_i represents a reaction or parameter, relative to its fiducial value. The reaction $^7\mathrm{Be}(p,\gamma)^8\mathrm{B}$ is completely negligible, with its logarithmic derivative about $\alpha_{17} \sim -10^{-6}$.

Reaction/Parameter	Sensitivities (α_i)
$\eta_{10}/6.14$	$+2.04$
$n(p,\gamma)d$	$+1.31$
$^3\mathrm{He}(\alpha,\gamma)^7\mathrm{Be}$	$+0.95$
$^3\mathrm{He}(d,p)^4\mathrm{He}$	-0.78
$d(d,n)^3\mathrm{He}$	$+0.72$
$^7\mathrm{Be}(n,p)^7\mathrm{Li}$	-0.71
Newton's G_N	-0.66
$d(p,\gamma)^3\mathrm{He}$	$+0.54$
n decay	$+0.49$
$N_{\nu,eff}/3.0$	-0.26
$^3\mathrm{He}(n,p)t$	-0.25
$d(d,p)t$	$+0.078$
$^7\mathrm{Li}(p,\alpha)^4\mathrm{He}$	-0.072
$t(\alpha,\gamma)^7\mathrm{Li}$	$+0.040$
$t(d,n)^4\mathrm{He}$	-0.034
$t(p,\gamma)^4\mathrm{He}$	$+0.019$
$^7\mathrm{Be}(n,\alpha)^4\mathrm{He}$	-0.014
$^7\mathrm{Be}(d,p)2^4\mathrm{He}$	-0.0087

While the bottleneck is in place, neutrons and protons remain at their weak freeze-out values, except for the occasional n-decay, and deuterium at its equilibrium value. The other light element abundances exist in a quasistatic equilibrium, being determined by various algebraic combinations of the important thermonuclear reaction rates [36–38],

$$\dot{X}(t) = J(t) - X(t)\Gamma(t) \tag{1}$$

$$X_{\mathrm{QSE}}(t) = J(t)/\Gamma(t), \tag{2}$$

where $J(t)$ is the sum of all source reaction rates and $\Gamma(t)$ is the sum of all sink reaction rates, for a particular abundance $X(t)$. Thus, we can see that reactions that dominate $J(t)$ and $\Gamma(t)$, determine the final abundance predictions until these nuclear reactions freezeout due to the Coulomb barrier and neutron fuel depletion. Table II lists the most important reactions and fundamental parameters that determine the primordial ^{7}Li abundance. Additionally, the table shows the ^{7}Li sensitivities to each rate or parameter, in agreement with [6]. One can see that the most important reaction that directly creates or destroys ^{7}Li (or rather ^{7}Be, and subsequently ^{7}Li)

[1] At $\eta_{10} = 6.14$, the production ratio is $^7\mathrm{Be}/^7\mathrm{Li} = 10.8$. Of course, the ^{7}Be eventually suffer electron capture and decay to ^{7}Li before hydrogen recombination and long before incorporation into pop II stars.

is the reaction $^3\mathrm{He}(\alpha,\gamma)^7\mathrm{Be}$ (S_{34}).[2] The reactions $n(p,\gamma)d$, $^3\mathrm{He}(d,p)^4\mathrm{He}$, $d(d,n)^3\mathrm{He}$, and $d(p,\gamma)^3\mathrm{He}$ are important in determining the deuterium, ^{3}He and ^{4}He abundances, and thus the source and sink rates that determine ^{7}Li. We mention here the nonimpact of the reaction $^7\mathrm{Be}(p,\gamma)^8\mathrm{B}$ (S_{17}) only because we will discuss this particular reaction later in this paper. This reaction is suppressed rather strongly by the Coulomb potential between the ^{7}Be and proton. It is this fact that no significant abundance of heavier elements is produced during primordial nucleosynthesis. The time required to form such elements is too long compared with the 350 second epoch of nucleosynthesis in the early universe.

The question of interest to us here, is which of these reactions can be altered to enhance or diminish the ^{7}Be (^{7}Li) abundance and be consistent with observational constraints. We wish to choose a reaction for which ^{7}Li has a large sensitivity, as well as large enough uncertainties to question its absolute normalization. The $^3\mathrm{He}(\alpha,\gamma)^7\mathrm{Be}$ reaction meets this criteria, both strongly influencing the ^{7}Li prediction and having large enough uncertainties in the nuclear data to let its absolute normalization float.

The determination of the BBN light element yields is from [7], where new normalizations and errors to the NACRE [25] rates important for primordial nucleosynthesis have been assigned. For $^3\mathrm{He}(\alpha,\gamma)^7\mathrm{Be}$, the BBN calculation uses the renormalized NACRE rate $S_{34}^{OLD}(0)=0.504\pm0.0534$ keV b. Other compilations yield higher values, with the original NACRE value $S_{34}^{NAC}(0)=0.54\pm0.09$ keV b [25] and the Adelberger $S_{34}^{ADL}(0)=0.53\pm0.05$ keV b [24]. One can see that these compilations will yield ^{7}Li values about 7% larger than [7], if the $S(E)$ shapes are assumed to be the same. Given this reaction, we now address how much this reaction must change to meet concordance with the light element observations. As discussed above, there are two sets of ^{7}Li observations we can try to match by renormalizing the $^3\mathrm{He}(\alpha,\gamma)^7\mathrm{Be}$ reaction. Using the ^{7}Li measurements of a metal poor globular cluster [35] would require a change of

$$\left.\begin{aligned} S_{34}^{NEW}(0)&=0.267\ \text{keV b}\\ \Delta S_{34}/S_{34}&=-0.47\end{aligned}\right\}\ \text{globular cluster Li.} \tag{3}$$

Using the ^{7}Li measurements of metal poor stars in the galactic halo [29] would require a change of

$$\left.\begin{aligned} S_{34}^{NEW}(0)&=0.136\ \text{keV b}\\ \Delta S_{34}/S_{34}&=-0.73\end{aligned}\right\}\ \text{halo star Li.} \tag{4}$$

As one can see, shifts in the $^3\mathrm{He}(\alpha,\gamma)^7\mathrm{Be}$ cross section as large as that necessary to produce $S_{34}^{NEW}(0)$ are strongly excluded given the cited uncertainties for this reaction. Although adjustments in the nuclear cross sections of this size are unlikely given the stated experimental errors, one could worry that additional systematic effects are present, particularly given the difficulties in establishing the absolute normalization for this reaction. As stated in the Introduction, these rates in particular can be bounded by another means. In the next section, we will determine the maximum possible downward adjustment to S_{34} which is consistent with solar neutrino fluxes.

The effect of changing the yields of certain BBN reactions was recently considered by Coc et al. [27]. In particular, they concentrated on the set of cross sections which affect ^{7}Li and are poorly determined both experimentally and theoretically. In many cases however, the required change in cross section far exceeded any reasonable uncertainty. Nevertheless, it may be possible that certain cross sections have been poorly determined. In [27], it was found for example, that an increase of either the $^7\mathrm{Li}(d,n)2\,^4\mathrm{He}$ or $^7\mathrm{Be}(d,p)2\,^4\mathrm{He}$ reactions by a factor of 100 would reduce the ^{7}Li abundance by a factor of about 3.

IV. THE SUN AS A NUCLEAR LABORATORY

The $^3\mathrm{He}(\alpha,\gamma)^7\mathrm{Be}$ reaction plays a crucial role not only in BBN ^{7}Li synthesis, but also in solar neutrino production. In particular, this reaction is responsible for the creation of ^{7}Be, which will then either (1) produce a monoenergetic neutrino via electron capture $^7\mathrm{Be}(e^-,\nu_e)^7\mathrm{Li}$, or (2) produce ^{8}B via radiative capture of a proton, $^7\mathrm{Be}(p,\gamma)^8\mathrm{B}$. The branching between these paths determines the solar ^{8}B abundance and thus directly sets the flux of ^{8}B neutrinos. SNO (as well as Super-K) are sensitive exclusively to these neutrinos. Furthermore, SNO measures directly the total ^{8}B neutrino flux, with no assumptions about mixing [39]. They find:

$$\phi_8=[5.21\pm0.27(\text{stat})\pm0.38(\text{syst})]\times10^6\ \ \text{cm}^{-2}\ \ \text{s}^{-1}, \tag{5}$$

where this is determined with no assumed shape of the^{8}B energy spectrum. This flux thus offers a constraint on the $^3\mathrm{He}(\alpha,\gamma)^7\mathrm{Be}$ reaction, as follows.

The standard solar model of Bahcall [40] can be used to predict the solar neutrino fluxes that can be observed by experiments. These fluxes depend upon various solar parameters, such as the luminosity, the chemical abundances, and nuclear fusion cross sections. In fact, the neutrino flux uncertainties are dominated by the cross section errors. Provided by [40], simple scalings between neutrino fluxes and these cross sections robustly describe the SSM predictions. The^{8}B neutrino flux scaling is:

$$\phi_8\propto S_{11}^{-2.6}S_{33}^{-0.4}S_{34}^{0.81}S_{17}^{1.0}S_{e7}^{-1.0}. \tag{6}$$

Here, the S's are the astrophysical S-factors, except for S_{e7}. The S_{e7} reaction is the electron capture rate on^{7}Be. One usually takes some nuclear rate compilation and uses the S-factors to evaluate the neutrino flux given these scalings.

[2]The S-factor is defined by the cross section: $S(E)=\sigma(E)E\exp(8\pi^2\alpha Z_1Z_2/v)$. The last term is the Coulomb penetration factor, in which Z_i are the charges of the incoming nuclei and v their relative velocity.

TABLE III. Shown are the results from the nuclear fusion rate compilations.

Reaction	Adelberger [24] (keV b)	NACRE [25] (keV b)
$p(p,e^+\nu_e)^2$H	$S_{11}=4.0\times10^{-22}(1.0\pm0.007^{+0.020}_{-0.011})$	$S_{11}=3.94\times10^{-22}(1.0\pm0.05)$
^{3}He(^{3}He,2p) ^{4}He	$S_{33}=5.4\times10^3(1.0\pm0.074)$	$S_{33}=5.18\times10^3(1.0\pm0.06)$
^{3}He(α,γ) ^{7}Be	$S_{34}=0.53(1.0\pm0.09434)$	$S_{34}=0.54(1.0\pm0.167)$
^{7}Be(p,γ) ^{8}B	$S_{17}=0.019(1.0^{+0.21}_{-0.11})$	$S_{17}=0.021(1.0\pm0.11)$
^{7}Be(e^-,ν_e) ^{7}Li	$S_{e7}=5.6\times10^{-9}(1.0\pm0.02)$ s^{-1}	N.A.

Two such nuclear compilations are from Adelberger *et al.* [24] and the NACRE Collaboration [25]. Their determinations relevant for this work are shown in Table III.

For these scalings to be useful, we must normalize the relation in Eq. (6) to the flux predicted for some fiducial set of *S*-factors. Two such normalizations are provided in [23], which presents SSM predictions using both the Adelberger et al. [24] and NACRE [25] rate compilations (Table III):

$$\phi_{8,0}^{\mathrm{ADL}}=5.05\times10^6\ \ \mathrm{cm}^{-2}\ \ \mathrm{s}^{-1} \tag{7}$$

$$\phi_{8,0}^{\mathrm{NAC}}=5.44\times10^6\ \ \mathrm{cm}^{-2}\ \ \mathrm{s}^{-1}. \tag{8}$$

These normalizations are both in excellent agreement with the observed flux [Eq. (5)], which affirms the basic soundness of the SSM and thus motivates our use of the Sun as a nuclear laboratory.

On the other hand, note that the differences between the flux predictions in Eqs. (7) and (8) are still significantly *smaller* than one predicts applying the scaling Eq. (6) to the set of *S*-factors in Table III. This discrepancy traces back to the nature of the SSM and in particular, to its boundary conditions. Specifically, a SSM calculation is required to match the present solar luminosity and radius at the present age. Given these fixed constraints, a change in nuclear rates and hence energy generation in turn forces a compensating change in solar structure [41]. Indeed, it was found [23] that the central density and particularly the central temperature are both lower in the NACRE case; these *lower* the ^{8}B flux, partially offsetting the increases due to higher reaction rates. Thus, we can view the different Adelberger and NACRE predictions as a measure of systematics due to nonlinearities in the SSM calculation. Consequently, we will use both in what follows to see what impact these effects have on our constraints. It is important to note that these issues of boundary conditions do not invalidate the use of the scalings in Eq. (6) for S_{34} (or S_{17}), because these reactions are part of the PP-II and PP-III chains; they do not participate in of the PP-I chain which dominates solar energy generation and hence feeds back into solar structure.

Our strategy is thus to use the SNO measurements of the ^{8}B neutrino flux and the SSM to constrain S_{34}. This is accomplished via the scalings in Eq. (6). A complication is that these scalings also depend on other reactions, none of which are significant for BBN, and all of which are better measured than ^{3}He(α,γ) ^{7}Be. This approach amounts to the extreme case in which we ignore *all* of the hard-won laboratory and theoretical information on S_{34}, using only solar neutrino data as well as constraints on other reactions, S_{17}. This can be viewed as providing independent information about S_{34}, or as a test of the systematics in the normalization, which is a salient feature for the BBN ^{7}Li problem. Our results will thus use the Sun to provide new and independent limits on the systematics of S_{34}. We will derive these using both approximate analytical methods and more accurate numerical methods.

A. Analytic formalism and results

We can estimate the impact these rate compilations have on the neutrino flux, by doing linear error propagation as follows:

$$\left(\frac{\sigma_8}{\phi_8}\right)^2\approx\left(\frac{2.6\sigma_{11}}{S_{11}}\right)^2+\left(\frac{0.4\sigma_{33}}{S_{33}}\right)^2+\left(\frac{0.81\sigma_{34}}{S_{34}}\right)^2+\left(\frac{\sigma_{17}}{S_{17}}\right)^2+\left(\frac{\sigma_{e7}}{S_{e7}}\right)^2. \tag{9}$$

We find that the Adelberger and NACRE compilations predict $\sigma_8/\phi_8=0.19$ and $\sigma_8/\phi_8=0.22$ respectively using this linear approximation, adopting the average error when errors are asymmetric. With these results, we find that the error in the predicted flux is determined primarily by the S_{17}, S_{34} and S_{11} reactions.[3] With our ultimate aim of constraining S_{34}, we will have to treat at least the S_{17} and S_{11} uncertainties directly, in addition to the error in the solar neutrino flux measurement.

We can now use the scalings in Eq. (6) to estimate the likely value of S_{34} and its uncertainty, based on the SNO observations (5),

$$\frac{S_{34}}{S_{34,0}}=\left(\frac{S_{11}}{S_{11,0}}\right)^{3.21}\left(\frac{S_{33}}{S_{33,0}}\right)^{0.49}\left(\frac{S_{17}}{S_{17,0}}\right)^{-1.23}\left(\frac{S_{e7}}{S_{e7,0}}\right)^{1.23}\left(\frac{\phi_8}{\phi_{8,0}}\right)^{1.23} \tag{10}$$

where we use the Bahcall et al. results [Eqs. (7) and (8)] for the Adelberger and NACRE reaction complications (the $S_{i,0}$) to determine the flux normalization. In the extreme case in which *all* of the small mismatch between predicted and observed fluxes is attributed to S_{34}, we expect a shift of $S_{34}/S_{34}^{ADL}=1.04$ and $S_{34}/S_{34}^{NAC}=0.95$ using the purely Adelberger and NACRE rate compilations, respectively; the

[3]The other *S*-factors making only small contributions to the overall error budget, as their already small relative errors are suppressed in the overall variance, as seen in Eq. (9).

smallness of these shifts just restates the success of the SSM in light of the SNO observations.

If we adopt the scaling laws and propagate the errors according to the usual rules, we have

$$\left(\frac{\sigma_{34}}{S_{34}}\right)^2 \approx \left(\frac{3.21\sigma_{11}}{S_{11}}\right)^2 + \left(\frac{0.49\sigma_{33}}{S_{33}}\right)^2 + \left(\frac{1.23\sigma_{17}}{S_{17}}\right)^2 + \left(\frac{1.23\sigma_{e7}}{S_{e7}}\right)^2 + \left(\frac{1.23\sigma_8}{\phi_8}\right)^2. \quad (11)$$

This gives a dispersion of $\sigma_{34}/S_{34}=0.24$ for both the NACRE and Adelberger compilations, again using the average error when they are asymmetric. These are much larger than the small shifts in the mean found in the above paragraph. Moreover, we see that to solve the BBN ^{7}Li problem with reaction rate uncertainties alone requires a $\sim 2\sigma$ change in S_{34} to bring BBN Li into agreement with the globular cluster data [Eq. (3)]. Using halo star data [Eq. (4)], the discrepancy increases to $\sim 4\sigma$. Thus we find that this solution to the ^{7}Li problem is, under the most conservative assumptions, excluded at $\sim$95% C.L. We now turn to numerical results which will confirm and better quantify this limit.

B. Numerical formalism and results

Our analytic discussion uses standard error propagation which is good only to first order, and assumes Gaussian errors as well as linearity. To explore this scenario more rigorously, we perform this calculation numerically, taking into account the non-Gaussian nuclear errors and nonlinear scalings. We set out to perform a Monte Carlo integration of an integral of the form:

$$\int \mathcal{L}_{SSM}(\vec{S},\phi_8)\mathcal{L}_{NUC}(\vec{S})\mathcal{L}_{SNO}(\phi_8)d\vec{S}d\phi_8, \quad (12)$$

where $\vec{S}$ is a set of reaction rates (such as the rates already listed) and ϕ_8 is the ^{8}B solar neutrino flux. $\mathcal{L}_{SSM}$, $\mathcal{L}_{NUC}$, and $\mathcal{L}_{SNO}$ are the likelihood distributions of the standard solar model given a reaction network and a solar neutrino flux, the reaction network given various rate compilations, and the total ^{8}B solar neutrino flux given by the SNO Collaboration.

In order to test the reliability and accuracy of this method, we first predict the total ^{8}B neutrino flux given a complete reaction network, using both the Adelberger and NACRE compilations and then compare to the predictions shown in the works of Bahcall *et al*. [23]. The integral we are performing is:

$$\mathcal{L}(\phi_8) = \int \mathcal{L}_{SSM}(\vec{S},\phi_8)\mathcal{L}_{NUC}(\vec{S})d\vec{S}. \quad (13)$$

A Monte Carlo integration uses one of the likelihood functions to draw random numbers and average the remaining function over those generated random numbers. For our case, we will generate random numbers for the independent reaction rates given by either the Adelberger or NACRE compilations. We combine statistical and systematic uncertainties by adding them in quadrature, since only the total uncertainty is needed for this analysis. We generate gaussian or piecewise Gaussian distributions for the reaction rates, depending on whether the quoted errors are symmetric or asymmetric about the most likely value. For each random draw of the reaction rates, we can calculate a solar neutrino flux, given the scalings shown in Eq. (6). Once a large sample of ϕ_8 is created, we can calculate its likelihood distribution. To summarize:

(1) $\mathcal{L}_{NUC}(\vec{S})$ generates reaction rates randomly.
(2) $\mathcal{L}_{SSM}(\vec{S},\phi_8)$ enforces the scalings in Eq. (6).
(3) The resulting sample of ϕ_8 is used to find $\mathcal{L}(\phi_8)$.

The normalization or best value and the errors are calculated separately. The flux values for Adelberger and NACRE, as given in Tables 7 and 9 in [23] are the standard solar model predictions for the neutrino fluxes, adopting each compilations best fit values, without marginalizing over the reaction network. The errors are then propagated separately, as described in [42] using the scalings already mentioned. The scalings are valid in determining the uncertainties to 10%. Thus, we will adopt the scalings shown in Eq. (6), normalized such that when a given compilation is used, we reproduce the values listed in [23]

$$\phi_8^{ADL} = 5.05\times 10^6 \left(\frac{S_{11}}{S_{11,0}^{ADL}}\right)^{-2.6}\left(\frac{S_{33}}{S_{33,0}^{ADL}}\right)^{-0.40} \times \left(\frac{S_{34}}{S_{34,0}^{ADL}}\right)^{0.81}\left(\frac{S_{17}}{S_{17,0}^{ADL}}\right)^{1.0}\left(\frac{S_{e7}}{S_{e7,0}^{ADL}}\right)^{-1.0} \quad (14)$$

$$\phi_8^{NAC} = 5.44\times 10^6 \left(\frac{S_{11}}{S_{11,0}^{NAC}}\right)^{-2.6}\left(\frac{S_{33}}{S_{33,0}^{NAC}}\right)^{-0.40} \times \left(\frac{S_{34}}{S_{34,0}^{NAC}}\right)^{0.81}\left(\frac{S_{17}}{S_{17,0}^{NAC}}\right)^{1.0}\left(\frac{S_{e7}}{S_{e7,0}^{ADL}}\right)^{-1.0}. \quad (15)$$

By using the Adelberger scaling relation to predict the NACRE scaling relation and vice versa, we can verify the accuracy of these fits. We find deviations from the relations listed above at the 8 or 9% level, thus we adopt an overall 10% systematic uncertainty in the predicted flux. Also, since the resulting distributions are non-Gaussian, we expect our marginalized best fit neutrino fluxes to be different from the neutrino flux determined by adopting only the best values of the reaction rates.

We find remarkable agreement between our confidence intervals and those placed by Bahcall *et al.* [23]. Our results are summarized below, as well as in Fig. 1,

$$\phi_8^{ADL} = 5.09[1.0^{+0.20(0.44)}_{-0.16(0.29)}(\text{stat}) \pm 0.10(\text{syst})] \times 10^6 \ \text{cm}^{-2}\ \text{s}^{-1} \quad (16)$$

$$\phi_8^{NAC} = 5.19[1.0^{+0.25(0.53)}_{-0.21(0.38)}(\text{stat}) \pm 0.10(\text{syst})] \times 10^6 \ \text{cm}^{-2}\ \text{s}^{-1}, \quad (17)$$

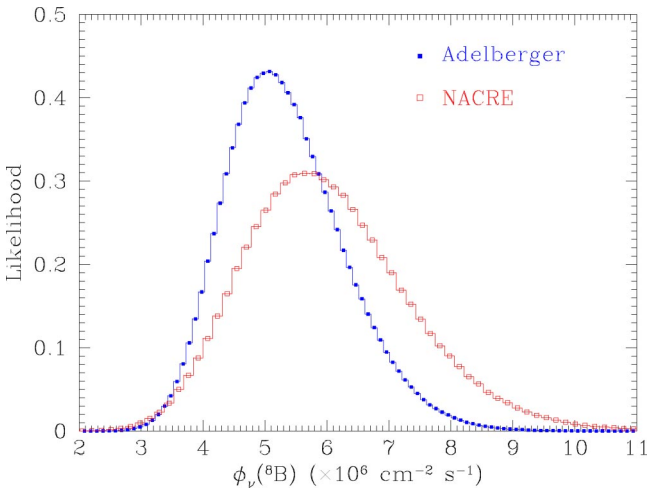

FIG. 1. Shown are the standard solar model predictions of the total ^{8}B neutrino flux. The binned likelihood based on the Adelberger (NACRE) rate compilation is plotted with solid (open) squares. The 10% systematic error has not been included here.

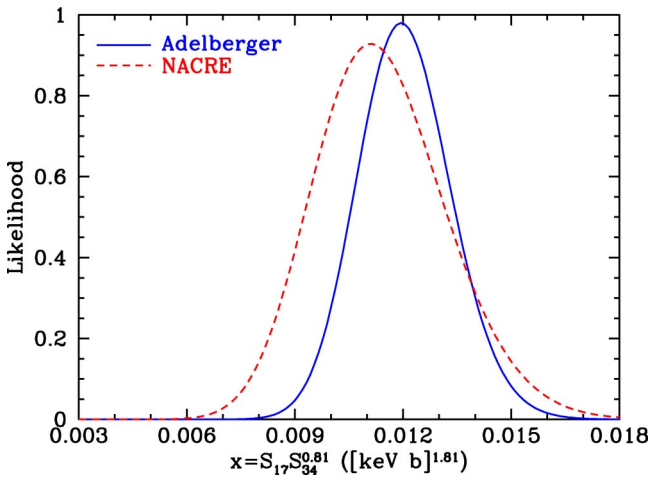

FIG. 2. Shown are the likelihood distributions of the parameter $x=S_{17}S_{34}^{0.81}$, given the subset of reactions from the Adelberger (solid) and NACRE (dashed) compilations respectively and the SNO Collaborations measurement of the solar ^{8}B neutrino flux. The 10% systematic uncertainty in the flux scalings has been included as Gaussian.

where the flux numbers listed are the most likely values for the Adelberger-based and NACRE-based compilations and their respective 68% (95%) confidence limits, as determined from the marginalized likelihood distributions. Notice that our most likely values are different than the fluxes determined by adopting the best values for the reaction rates. Because of this marginalization, shown explicitly in Eq. (13), the predicted flux will not necessarily follow the prescribed scalings. This shift in best values is due to the marginalization over the nonlinear scalings and asymmetric nuclear errors. Had the scalings been linear and additive, and all nuclear errors symmetric, no shift would have been seen. As one expected, NACRE has slightly inflated errors as compared to Adelberger. This is simply due to NACRE's overall larger rate uncertainties, as shown in our analytic work.

As discussed earlier, the solar neutrino flux depends primarily on the S_{17} and S_{34} reactions. The S_{33} and S_{e7} reactions have little impact on the results due to their small errors and the weak dependence of the flux on them. The S_{11} rate has negligible effect in the Adelberger compilation, but has significant impact in the NACRE compilation's results. NACRE's uncertainty for this rate is a factor of 2 larger than the Adelberger's compilation. Below we will use the differing results of these two compilations as a probe of the S_{11} error assignment.

Given the scalings in Eq. (6), we can use the SSM and the SNO measurement of the total ^{8}B neutrino flux to constrain these rates in the following combination: $x=S_{17}S_{34}^{0.81}$. As before, we will generate random numbers for the independent reaction rates given by either the Adelberger or NACRE compilations. However, we now fix S_{17} and S_{34} with various values of x. For each random draw of the reaction rates, we can calculate a solar neutrino flux, given the scalings shown in Eq. (6). With this flux, we then average $\mathcal{L}_{SNO}(\phi_8)$ over the sample to find the likelihood of a given x. To summarize:

(1) $\mathcal{L}_{NUC}(\vec{S})$ generates reaction rates randomly.
(2) $\mathcal{L}_{SSM}(\vec{S},\phi_8)$ enforces the scalings in Eq. (6).
(3) Calculate $\mathcal{L}(x)\equiv\langle\mathcal{L}_{SNO}(\phi_8)\rangle$.

Using the S_{11} and S_{33} from the Adelberger and NACRE compilations respectively and the S_{e7} from Adelberger compilation, and the SNO Collaborations constraint on the total ^{8}Bneutrino flux, we place the following constraints on x:

$$x^{ADL}=0.0119[1.0^{+0.16(0.35)}_{-0.14(0.25)}]\quad[\mathrm{keV\,b}]^{1.81} \tag{18}$$

$$x^{NAC}=0.0121[1.0^{+0.21(0.46)}_{-0.17(0.32)}]\quad[\mathrm{keV\,b}]^{1.81}, \tag{19}$$

where the most likely values, the 68% (95%) confidence intervals. The 10% systematic error has been included in the calculation and assumed to be Gaussian. These resulting likelihoods for x are shown in Fig. 2. The Adelberger and NACRE-based results agree quite well with each other. With differences mainly attributable to the larger error in S_{11} adopted by NACRE.

Since we are constraining x only, we cannot determine the S_{17} and S_{34} reactions uniquely. We require additional information. If a total $p-p$ or ^{7}Be neutrino flux measurement existed, we could in principle determine both cross sections. Since we are using the Sun to constrain systematic errors in the normalization of S_{34}, in an attempt to fix the BBN ^{7}Li problem, we will adopt various experimentally-determined values of S_{17} to place constraints on S_{34}. Once a value of S_{17} is adopted, we convolve the x likelihood distribution with the experimental S_{17} distribution to get our S_{34} likelihood.

Besides using the Adelberger and NACRE rate compilations for S_{17}, we also use two more recent determinations. We use the recommended values from Junghans *et al.* [43], and Davids and Typel [44]. The Junghans quoted value, $S_{17}=21.4\pm0.5(\mathrm{expt})\pm0.6(\mathrm{theor})$ eV b, is based on several direct capture data sets. The Davids and Typel value, $S_{17}=18.6\pm0.4(\mathrm{expt})\pm1.1(\mathrm{extrp})$ eV b, is based on both direct

TABLE IV. Shown are the constraints placed on S_{34} using reaction rates from various sources. Column 1 lists the adopted S_{17} constraint used, while columns 2 and 3 show the compilation used for the S_{11} and S_{33} reaction rates. The S_{34} numbers cited are the most likely values and their 68% (95%) confidence intervals.

Adopted S_{17} (eV b)	Adelberger-based [24]	NACRE-based [25]
Adelberger [24]		
$S_{17}=19.0^{+4.0}_{-2.0}$	$S_{34}=0.51^{+0.15(0.34)}_{-0.12(0.21)}$	N.A.
NACRE [25]		
$S_{17}=21.0\pm2.31$	N.A.	$S_{34}=0.51^{+0.17(0.38)}_{-0.12(0.22)}$
Junghans [43]		
$S_{17}=21.4\pm0.5(\text{expt})\pm0.6(\text{theor})$	$S_{34}=0.48^{+0.10(0.23)}_{-0.08(0.15)}$	$S_{34}=0.49^{+0.14(0.30)}_{-0.11(0.19)}$
Davids [44]		
$S_{17}=18.6\pm0.4(\text{expt})\pm1.1(\text{extrp})$	$S_{34}=0.57^{+0.13(0.30)}_{-0.11(0.19)}$	$S_{34}=0.59^{+0.17(0.39)}_{-0.13(0.24)}$

capture and Coulomb dissociation measurements, excluding the Junghans data set because it is systematically higher than the other data sets. Had the Junghans data been used, the value of S_{17} would lie between the two cited values. We will adopt the cited numbers, keeping in mind that the difference in their values are a measure of this systematic difference.

Our constraints in Table IV are based on the likelihood functions in Fig. 3. We find that

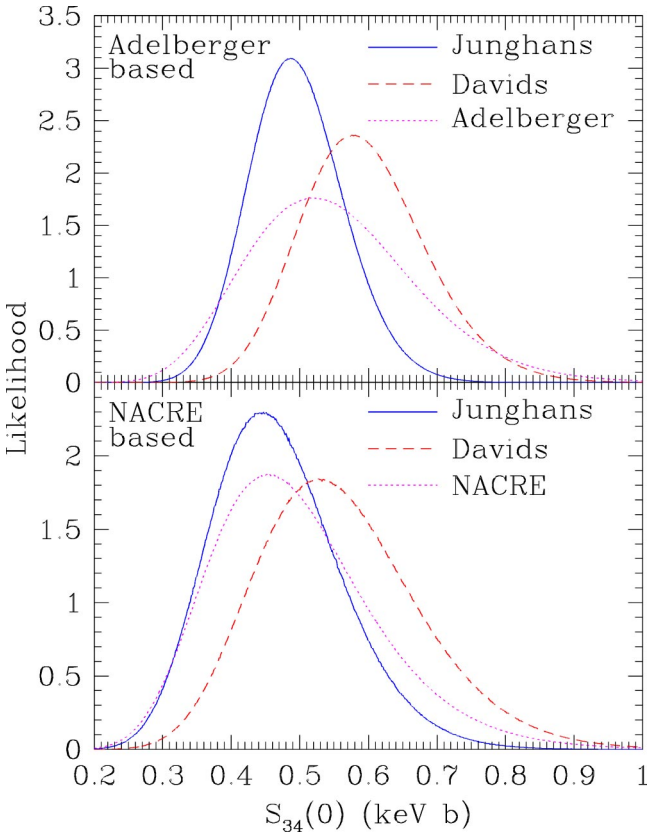

FIG. 3. Shown are the likelihood distributions of S_{34}, given S_{17} measurements listed in Table IV. The upper (lower) panel shows the results using the Adelberger (NACRE) compilation for the S_{11}, S_{33} and S_{e7} reactions. We have used values for S_{17} from Junghans [43] (solid), Davids [44] (dashed) and Adelberger [24] and NACRE [25] (dotted). Again, the 10% systematic uncertainty in the scalings has been included and assumed Gaussian.

$$S_{34}>0.35 \ \text{keV b} \tag{20}$$

at 95% C.L. for the case of the NACRE S_{17} value. Other choices give slightly higher limits, e.g., Adelberger with the Davids S_{17} gives $S_{34}>0.42$ keV b.

As shown in Table II, these limits on S_{34} place essentially identical limits to ^{7}Li production in BBN. One way to illustrate this is to fix the reaction normalization to its 95% C.L. limit of $S_{34}=0.35$ keV b, and then to propagate the other nuclear uncertainties in the BBN code [7] and convolve the predictions with the WMAP determination of the baryon density [1]. In this way, Eq. (20), along with the fiducial BBN theory results in Table I, demands that $(^7\text{Li/H})_{\text{BBN}}>2.72^{+0.36}_{-0.34}\times10^{-10}$. We see that allowing a 95% C.L. reduction in S_{34} still demands a Li abundance that is above the observed levels. Thus, pushing the systematic error on S_{34} does alleviate the BBN ^{7}Li problem somewhat, but cannot resolve it. A conventional solution still requires a combination of multiple $\gtrsim2\sigma$ effects to fix the problem—i.e., that ^{7}Li observations be systematically low, in addition to adopting the limits to nuclear systematics we have derived.

We can explore this possibility further by using the SSM-based S_{34} measures in the BBN calculation of Li (as in Fig. 3 and Table IV). By comparing to observations we can evaluate the overall agreement. This will of course depend both on the choice of nuclear data used to derived the S_{34} constraint, and on the choice of Li observations. In all cases the agreement is not good. The discrepancy is least bad for the case of NACRE-based SSM calculations with Junghans S_{17}, in conjunction with the higher, globular cluster Li. Here we find $\chi^2=2.75$, or a 1.66σ discrepancy. In this case, the combination of the most favorable data sets and stretching of errors leads to the mildest disagreement. Other combinations, however, give a much stronger disagreement: Aldelberger-based SSM with Junhans S_{17} and halo star Li give $\chi^2=13.29$ or a 3.65σ discrepancy.

Put another way, we can ask how far a "nuclear-only" BBN solution stretches our constraints on $^3\text{He}(\alpha,\gamma)^7\text{Be}$ systematics. We saw in Sec. III that for halo star observations to reflect the primordial ^{7}Li abundance requires that S_{34} be

systematically lowered, to 53% and perhaps 27% of its fiducial value [Eqs. (3) and (4), respectively], depending on the observational Li measure used. A reduction of $S_{34}^{\rm new} < 0.267$ keV b is excluded at the 99.5% C.L. for the NACRE case (and above for others in Table IV). A reduction of $S_{34}^{\rm new} < 0.136$ keV b is excluded at more than 99.9999% C.L. This restates our finding that the solar constraints on S_{34} remove this reaction as the main suspect in the ^{7}Li problem.

V. DISCUSSION AND CONCLUSIONS

The hot big bang cosmology has seen a great triumph in the agreement between the baryon density found by WMAP and the BBN value implied by the D/H ratio measured at high redshifts. However, this triumph is somewhat muted by the much poorer agreement between the primordial ^{7}Li value as predicted from BBN and the WMAP baryon density, and the observed values seen in halo stars. The predictions are at least a factor of 2 above the observations. This discrepancy impels a search for any possible systematic errors, which could either explain the mismatch, or if no systematics can be found, would reveal the true seriousness of the problem and a need for a more fundamental solution.

In this paper we have considered the effect of systematic errors in the nuclear reactions. In particular, we have focused on the ^{3}He$(\alpha,\gamma)^7$Be reaction, which is the sole important production channel of ^{7}Li at the WMAP baryon density. As such, systematic errors in this reaction have an immediate impact on the BBN ^{7}Li abundance. And indeed, while there has been extensive and careful work for this reaction, both fronts meet with technical difficulties which leave open the possibility for systematic errors in the absolute normalization of this rate.

Thus we have identified a new constraint on this reaction, coming from its influence on ^{7}Be and ^{8}B production in the Sun, and the associated ^{8}B solar neutrinos. The excellent agreement between the standard solar model and the total measured ^{8}B neutrino flux places demands that the underlying nuclear reactions cannot have large systematics. In particular, using the solar neutrino theory and observations, as well as some information on other reactions, notably ^{7}Be$(p,\gamma)^8$B, we find that S_{34} cannot be smaller than 65% of its fiducial value (e.g., NACRE or Adelberger). This limit is strong enough to exclude the ^{3}He$(\alpha,\gamma)^7$Be reaction as the dominant solution to the BBN ^{7}Li problem.

Other nuclear solutions to the ^{7}Li problem are logically possible but in fact unlikely. While many reactions are important for ^{7}Li production, the requirements that we not spoil agreement with D, and not (further) underproduce ^{4}He, leads us to focus on reactions which only affect ^{7}Li. Since we have shown that the production channel cannot be lowered sufficiently, we might hope to increase ^{7}Be destruction. This is done via the ^{7}Be$(n,p)^7$Li reaction, followed by ^{7}Li$(p,\gamma)2\,^4$He. The Sun does not constrain ^{7}Be$(n,p)^7$Li because the solar interior has a negligible neutron density. However, this reaction is nevertheless very well-studied because its inverse is a common laboratory neutron source. Since deuterium observations and CMB determinations suggest a baryon density on the high side, the destruction of ^{7}Li through the reaction ^{7}Li$(p,\gamma)2\,^4$He has negligible impact. Its mirror reaction, ^{7}Be$(n,\gamma)2\,^4$He, important on the higher baryon density side, is negligible compared to ^{7}Be$(n,p)^7$Li. Furthermore, ^{7}Li has a somewhat weaker dependence on the destruction cross section ($^7\mathrm{Li}_{\rm BBN} \propto S_{34}^{0.95} S_{n7}^{-0.74}$ [6]), so that the needed systematic error would be even larger than what we have considered for the production channel.

Thus nuclear solutions do not seem allowed by the current data. Of course, it remains possible that extremely large (factors $\gtrsim 100$) systematic errors lurk in otherwise negligible ^{7}Li production and destruction channels [27]. For these reasons, continued efforts to improve nuclear cross section experiments and theory (with particular attention to absolute normalizations and systematics) will reap benefits for BBN as well as solar neutrinos. Tighter experimental errors (including systematics) will reduce the BBN theoretical uncertainty budget, which will not only further clarify the seriousness of the ^{7}Li problem, but also allow for stronger constraints on astrophysics [11] when and if the ^{7}Li problem is resolved. In this respect, we particularly call attention to the ^{3}He$(\alpha,\gamma)^7$Be reaction, but also to ^{7}Be$(p,\gamma)^8$B, as they are undoubtedly linked through solar neutrinos. Determining a more accurate low-energy extrapolation in either of these reactions will impact the other through the solar neutrino constraint on the parameter $x = S_{17} S_{34}^{0.81}$.

Where, then, does the ^{7}Li problem stand? We have found nuclear reaction systematics are very unlikely to be the dominant source of the discrepancy. Of the remaining possibilities, the most conservative is that the problem is dominated by systematic errors in the observational ^{7}Li value. This could either be due to difficulties in the understanding the stellar parameters and in extracting the abundance from spectral lines, or from stellar evolution effects which deplete Li without introducing large dispersion in the Spite plateau. A similarly conventional solution would ascribe the ^{7}Li discrepancy to a combination of nuclear and observational systematics, both at the edge of what is currently allowed.

Finally, a more radical but intriguing possibility would be that new physics is required. If this is so, nature has been somewhat subtle in revealing this twist, as the perturbation to standard BBN has been small enough not to be noticed until now.[4] Nonstandard scenarios have already been proposed to alleviate the ^{7}Li problem by introducing new physics, e.g., by a late-decaying gravitino [45]. However, most of the scenarios require fine tuning, as one wishes to reduce ^{7}Li without spoiling the superb concordance between deuterium and the CMB.

In summary, we use solar neutrinos to remove the possibility of a solution to the ^{7}Li problem from the

[4] If so, this probably has been fortuitous for the development of cosmology. Had there always been large problems with standard BBN, one can imagine that this would have led to great skepticism about the viability of the hot big bang framework.

^{3}He$(\alpha,\gamma)^7$Be reaction, and thereby cast more doubt that the problem is due to nuclear systematics. By removing a possible resolution, we have both clarified the problem, and made it more acute. In our view, the most important arena now is the observations and astrophysics which lead to the primordial ^{7}Li inference. And while we continue to suspect that this is the likely solution, a parallel examination of nonstandard BBN scenarios is at this point not unwise.

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