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PRIMORDIAL LITHIUM:
NEW REACTION RATES, NEW ABUNDANCES, NEW CONSTRAINTS

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Abstract

Newly measured nuclear reaction rates for $^3H(\alpha,\gamma)^7$ Li (higher than previous values) and $^7Li(p,\alpha)^4He$ (lower than previous values) are shown to increase the ^7Li yield from big bang nucleosynthesis for lower baryon to photon ratio ($\eta \lesssim 4 \times 10^{-10}$); the yield for higher η is not affected. New, independent determinations of Li abundances in extreme Pop II stars are in excellent agreement with the earlier work of the Spites and give continued confidence in the use of ^7Li in big bang baryon density determinations. The new ^7Li constraints imply a lower limit on η of 2×10^{-10} and an upper limit of 5×10^{-10}. This lower limit to η is concordant with that obtained from considerations of D + ^3He. The upper limit is consistent with, but even more restrictive than, the D bound. With the new rates, any observed primordial Li/H ratio below 10^{-10} would be inexplicable by the standard big bang nucleosynthesis. A review is made of the strengths and possible weaknesses of utilizing conclusions drawn from big bang lithium considerations. An appendix discusses the null effect of a factor of 32 increase in the experimental rate for the $D(d,\gamma)^4He$ reaction.

I. INTRODUCTION

Lithium has only recently begun to be used seriously in big bang nucleosynthesis studies. This delay was attributable to both the uncertainties in the estimates of production and destruction cross sections in the early calculations and the lack of determinations of (primordial) lithium abundances in extreme Pop II objects. During the last 10 years, both of these situations have improved markedly and further advancement on each of these fronts has occurred in the last few months. Thus, lithium is now able to take its place along side other big bang nucleosynthesis products and, as such, helps provide consistency for abundance predictions over 9 orders of magnitude (Yang et al. 1984; hereafter, YTSSO).

It is shown here that the newly determined rates and the independent verification of abundance data improve our confidence in the use of lithium as a big bang product as well as provide independent and possibly tighter constraints on the baryon to photon ratio η ($\equiv n_b/n_\gamma$) and thus on Ω_b ($\equiv \rho_b/\rho_{crit}$) than those obtained with D and ^{3}He. In particular, we will show that ^{7}Li can provide a lower bound on η comparable to that obtained from D + ^{3}He (YTSSO), furthering strengthening our confidence in the derived upper limit on the number of neutrinos from big bang nucleosynthesis (Steigman, Schramm, and Gunn 1974; YTSSO; Steigman, et al. 1986) since that number depends on a lower bound on η. Additionally, if lithium constraints are used, the upper limit on η is even more restrictive than that from deuterium considerations and can be used to set the constraint $\Omega_b < 0.08$ assuming $H_o > 50$ km s^{-1} Mpc^{-1} (YTSSO). Such a restrictive limit is on the verge of implying that non-baryonic matter is required to understand the virial mass of large clusters (see the discussion in Schramm and Steigman 1981).

Because of the potentially large payoff from ^{7}Li, it is important to carefully examine the effect of the new nuclear reaction rate measurements as well as the recent observations. Furthermore, with the new improvements in the physical data relevant to ^{7}Li, it is important to review again the caveats regarding the use of ^{7}Li to infer more than just concordance and to utilize the perspective of history to see why it has taken us so long for ^{7}Li to become cosmologically useful. The next section will thus be devoted to reviewing the history; section III, the effect of the new reaction rates; section IV, the current Population II abundance determinations; and section V summarizes the conclusions as well as presents the caveats regarding ^{7}Li. Appendix I will discuss how a new expermental value for D(d,γ)^{4}He, which was a factor of 32 larger than previous values, has no effect on the ^{7}Li yield.

II. HISTORY

When Wagoner, Fowler, and Hoyle (1967) first calculated lithium yields in big bang nucleosynthesis, there were several reasons why the results were not viewed as being important. One was that in the 1960's, it was generally thought that the light elements Li, Be, B, and D were all made in proto-solar processes (Fowler, Greenstein, and Hoyle 1962). Another was that the estimated big bang lithium production and destruction cross sections yielded ^{7}Li/H abundances of $\approx 4 \times 10^{-11}$ whereas observed ^{7}Li/H abundances were then all $\approx 10^{-9}$ (Cameron 1968).

It was not until the early 1970's that this picture began to change. On the theoretical side, it was realized that proto-solar processes did not have sufficient energy available to do the job (Ryter et al. 1970). It was also realized that although Be, B, and ^{6}Li could be made via cosmic ray spallation (Reeves, Fowler, and Hoyle 1970), cosmic rays failed for ^{7}Li since they produced ^{7}Li/^{6}Li ≈ 2 rather than the observed meteoritic value of ^{7}Li/^{6}Li ≈ 12. Thus, either the big bang or some other stellar process (Cameron and Fowler 1971) was needed. Furthermore, galactic evolution considerations (Reeves, Audouze, Fowler, and Schramm 1973) began to increase the significance of the big bang yields of D and ^{7}Li. On the experimental side, new cross section measurements increased big bang nucleosynthesis ^{7}Li yields, raising them by a factor of ≈ 3 (Schramm and Wagoner 1977, see Spinka et al. 1971 for ^{7}Li(p,α)^{4}He). The ^{7}Li was still only observed in Pop I stars and in the interstellar medium so that the high η required to fit the ^{7}Li observations appeared to be inconsistent with the lower η values required for the other light elements (Wagoner 1972).

It was in the early 1980's that the role of ^{7}Li in big bang nucleosynthesis finally fell into place. Spite and Spite (1982a,b) found that the Pop II ^{7}Li/H abundance was $\approx 10^{-10}$, an order of magnitude lower than the Pop I abundance. Such a ^{7}Li abundance fell near the minimum in the big bang ^{7}Li production curve (see figure 1) and gave reasonable agreement with the η limits as implied by D, ^{3}He, and ^{4}He (YTSSO). This then led to a truly dramatic achievement: complete concordance of the predicted abundances of all light elements over a range of values from ≈ 0.1 (^{4}He/H) to $\approx 10^{-10}$(^{7}Li/H) within a narrow allowed range in η.

However, YTSSO as well as Boesgaard and Steigman (1985) in their recent review were cautious about the use of ^{7}Li. This caution derived both from the fact that the nuclear cross sections used for ^{7}Li yields had the largest uncertainties of any in big bang nucleosynthesis and from concern over the abundance determinations which involved a number of considerations. At the time of YTSSO, only the Spites' data existed for Pop II abundances. The higher Pop I abundances implied significant ^{7}Li production over the history of the galaxy by some still undetermined mechanism (Audouze, et al. 1983). In addition, while the Spites' observations of ^{7}Li in Pop II stars all saturated at the same abundance for high surface temperature (high mass) stars, there was the nagging problem that stellar evolution studies did not easily explain such an effect. It is true that lower surface temperature (lower mass) stars have deeper convective zones and so would be expected to destroy all their primordial ^{7}Li via ^{7}Li(p,α)^{4}He reactions. But, since even the Sun shows ^{7}Li destruction, it is not clear why Pop II stars less massive than the Sun would not have convective zones deep enough to destroy ^{7}Li. Since the saturation effect indicates that for a whole range of masses, Pop II stars have the same ^{7}Li abundance, the Spites concluded that the convective zones were not deep enough to destroy the ^{7}Li and the ^{7}Li observed was primordial, undepleted in abundance since the Big Bang. It is not very surprising that stellar evolution theory does not predict such an effect since the depth of the surface convective zone is one of the most uncertain aspects of stellar modeling. For even our well studied Sun, the standard models fail to yield a sufficient depth of convection to explain the observed ^{7}Li depletion.

Pop III stars — if there was such a stellar population — provide another possible loophole in the ^{7}Li abundance argument. Conceivably, ^{7}Li may have been depleted by some generation of stars which existed prior to the Pop II stars. However, since D is even more fragile than ^{7}Li, such a depletion can be constrained using the present abundance of D as well as the fact that D is first burned to ^{3}He (YTSSO). The ^{7}Li/D ratio is useful since since cycling through the stars will only increase this ratio. A higher primordial ^{7}Li would require an even higher primordial D which is only possible at lower values of η. Although this further strengthens the upper limit on η and on Ω_b, it leaves a lower bound on η unconstrained by ^{7}Li. Since D + ^{3}He already yields a lower bound to η (YTSSO), the bound from ^{7}Li is complementary.

The recent Pop II abundance observations of Beckman, Rebolo, and Molaro (1986; hereafter BRM) and Hobbs and Duncan (1986; hereafter HD) lend new support to the Spites' pioneering work, but still leave the stellar and galactic evolution questions unresolved.

III. NEW CROSS SECTIONS AND BIG BANG PRODUCTION OF ^{7}LI

During the big bang mass 7 is produced directly as ^{7}Li for low ($\lesssim 3\times10^{-10}$) values of η and as ^{7}Be for higher values which e^-–captures to form ^{7}Li. For low η, the production is dominated by the ^{3}H$(\alpha,\gamma)^7$Li reaction and destruction by ^{7}Li(p,α)^{4}He. At higher η, ^{3}He$(\alpha,\gamma)^7$Be begins to dominate production and ^{7}Be(n,α)^{4}He becomes important for destruction because the high coulomb barrier inhibits charged particle reactions.

Recently, both destruction and production reaction cross sections which dominate at low η have been remeasured and have undergone revisions in the direction favoring higher production. The ^{7}Be production rates are unchanged; as such, the high η yields remain fixed (see figure 1). Rolfs and Kavanaugh (1986) have shown that the measured cross section for ^{7}Li(p,α)^{4}He is lower at low energies than previous extrapolations had indicated. In particular, the factor S(0) which is the cross section at zero energy with the coulomb barrier factor removed is found to be 52$\pm$8 KeV-barns compared to 65 KeV-barns in previous studies (see Rolfs and Kavanaugh 1986). However, since the new data are consistent with previous data at higher energies and since big bang nucleosynthesis occurs at finite temperature (kT $\approx$ 100 KeV), this new reduction does not change the yield significantly. The situation is different for ^{3}H$(\alpha,\gamma)^7$Li. Here, Schröder et al. (1986) have found a factor of 2 increase in S(0). While the new data at higher energy data are indeed consistent with previous work, there results a factor of $\approx$ 1.5 increase in ^{7}Li production for kT $\approx$ 100 KeV.

Although nucleosynthesis of lithium occurs at kT $\approx$ 100 KeV, the effective reaction energy for the particles involved is about three times higher due to the importance of the coulomb barrier between the incoming particles. The effective reaction energy is the position of the maximum of the product of the coulomb penetration factor and of the Maxwell-Boltzmann distribution and is given by

$$E \approx \begin{cases} 250(kT_{100})^{2/3}\text{KeV}, & \text{for } ^7\text{Li(p},\alpha)^4\text{He} \\ 300(kT_{100})^{2/3}\text{KeV}, & \text{for } ^3\text{H}(\alpha,\gamma)^7\text{Li} \end{cases}$$

in which kT_{100} is the kT of the Maxwell-Boltzmann distribution in units of 100 KeV (see Wagoner 1968).

Using the new reaction rates, we have reevaluated the primordial production of lithium. The results are shown in figure 1. In particular, notice that ^{7}Li/H $= 0.9 \times 10^{-10}$ is the new minimum value (the minimum in YTSSO was 0.7×10^{-10}). Notice also that a given ^{7}Li/H ratio now yields a higher lower bound on η. The yields have been calculated for a neutron half-life of 10.5 min (see discussion in Steigman et al. 1986). However, variation in the neutron half-life has little effect on Li production.

IV. LITHIUM ABUNDANCES IN POP II STARS

Recently, two groups (BRM and HD) have independently studied lithium in extreme Pop II stars and they have both checked and extended the Spites' pioneering work. Not only do all three groups agree on the saturation of the abundances but with a larger pool of objects examined, have found that the effect persists for even the most extreme Pop II stars such as G64-12 (Rebolo, Beckman, and Molaro 1986; hereafter RBM). Some stars were studied by all three groups with similar results, showing the reproducibility of the data as well as providing a measure of the small intrinsic scatter.

BRM obtain ^{7}Li/H $= 1.2\pm0.3 \times 10^{-10}$ for their sample of 22 Pop II dwarfs with temperatures $T_{eff} >$ 5500 K. For the very extreme Pop II star G64-12 with $T_{eff} = 6350$ K, v = 440 km/s, and [Fe/H] = -3.5, they (RBM) find ^{7}Li/H $= 1.7\pm.6 \times 10^{-10}$. HD also obtain ^{7}Li/H $= 1.2\pm0.3 \times 10^{-10}$ for 23 halo stars with $T_{eff} \geq 5600$ K. Twelve of their stars with more extreme properties: [Fe/H] $\leq$ -1.4 and v $>$ 160 km/s, are consistent with the rest. Their most extreme star LP608-62 with [Fe/H] = -2.7 and v = 430 km/s and $T_{eff} = 6250$ K yielded ^{7}Li/H $= 1.6\times10^{-10}$.

For comparision, remember that Spite and Spite also obtained ^{7}Li/H $\approx 1.1\times10^{-10}$ which was supported by Spite, Mailard, and Spite (1984). The good agreement between the work done in the Canary Islands (BRM), the work at MacDonald, Lick, and Kitt Peak (HD), and the work of the Spites at the French-Canada Telescope in Hawaii shows the reproducibility of the results. Within the stated uncertainties, all groups are in excellent agreement. The observational results from each of the groups are plotted in figure 1.

V. CONCLUSIONS AND CAVEATS

HD caution that this concordant value from Pop II should be viewed as a lower bound on the primordial ^{7}Li/H as it is conceivable that some depletion may have occurred before even the extreme Pop II stars formed.

However, they do note that "there is no observational or theoretical evidence" for depletion. In addition, such a depletion would not account for the Pop I and Pop II ^{7}Li abundances if metalliticy independence of the depletion process is inferred from the observed metalicity independence of Pop II ^{7}Li/H values. If we assume Pop II = primordial, we may combine the new yields with the concordant observations to derive new bounds to η (see figure 1). The one σ upper limit of $(^7\text{Li/H}) \lesssim 1.5 \times 10^{-10}$ yields a lower bound on η of $\approx 2 \times 10^{-10}$ and an upper bound of $\approx 5 \times 10^{-10}$ but ^{7}Li can conceivably be depleted prior to Pop II formation so that higher primordial ^{7}Li/H values are not categorically ruled out. However, ^{7}Li depletion would be accompanied by D depletion. Since D is destroyed at a lower temperature, the primordial ratio of ^{7}Li/D will increase. YTSSO used this argument to show that the Spites' measurements yield an upper limit of $\eta \lesssim 7\times10^{-10}$. Since the Spites' measurements are now confirmed and the yields are unchanged at high η, the upper limit argument is unaffected. On the low η side, the bound from ^{7}Li is completely consistent with the lower bound on η obtained from D + ^{3}He (YTSSO, Steigman et al. 1986). This lower bound is needed to limit the number of neutrino types. In fact, if the ^{7}Li constraint on $\eta (\eta \gtrsim 2 \times 10^{-10})$ is used instead of the D + ^{3}He constraint ($\eta > 3 \times 10^{-10}$), the limit on the number of neutrino families changes by less than 1/2 of a family.

The baryon to photon ratio is related to the density parameter $\Omega_b (= \rho_b/\rho_{crit})$ by

$$\Omega_b = 3.53 \times 10^{-3} h_o^{-2} \left(\frac{T_o}{2.7K}\right)^3 \eta_{10}$$

in which the Hubble constant H is stated in units of 100h_o km s^{-1} Mpc^{-1}. Present observational data suggests h_o in the range $0.5 \leq h_o \leq 1$; however, values as low as 0.4 cannot be ruled out. T_o is the present temperature of the microwave background radiation, and the baryon to photon ratio is η for which $\eta_{10} = 10^{10}\eta$. Using the background temperature limits of 2.73±0.04 (Partridge 1985, Meyer and Jura 1984) and $h_o = 1/2$, the upper limit on η of 7×10^{-10} from the ^{7}Li/D argument corresponds to an upper limit on Ω_b of $\lesssim 0.11$. The upper limit on η of 5×10^{-10} from ^{7}Li alone corresponds to an upper limit on Ω_b of $\lesssim 0.08$. If the dynamical arguments on the virial masses of clusters of galaxies could ever show conclusively that $\Omega > 0.11$, then there would be a strong case for the necessity for non-baryonic matter (Schramm and Steigman 1981). Unfortunately, current virial mass arguments do not yet have the accuracy of the big bang nucleosynthesis arguments.

APPENDIX I

The $D(d,\gamma)^4He$ Reaction

While examining the effect of newly measured reaction rates, we also looked at the role that the recent increase of the astrophysical S(0) factor for $D(d,\gamma)^4He$ by a factor of 32 (Barnes, et al. 1986) would have on big bang nucleosynthesis. The effect is completely negligible due to the fact that the competing channels D + p and D + n destroy D very much faster and ^3H + p, ^3He + n, and ^3He + ^3He produce ^4He very much faster. Thus, this dramatic increase in the D + D reaction rate has no effect on the calculated yields of any of the light elements.

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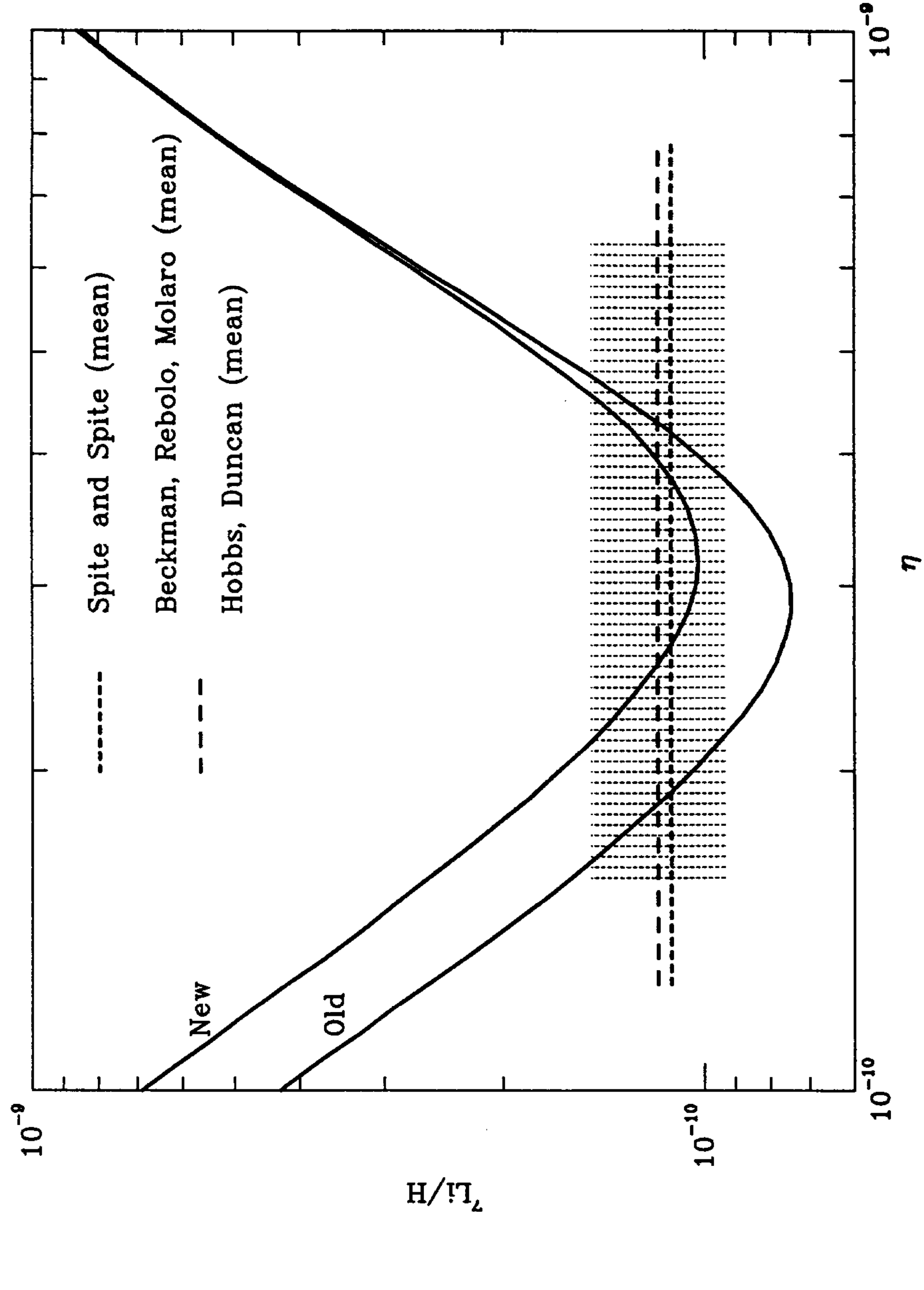
FIGURE CAPTION

Figure 1

The $^7Li/H$ abundance produced in big bang nucleosynthesis; the "old" yields are from the reaction rates used in YTSSO and the "new" yields incorporate the newly measured $^7Li(p,\alpha)^4He$ and $^3H(\alpha,\gamma)^7Li$ cross sections. The mean values of Spite and Spite (1982), Beckman, Rebolo, and Molaro (1986), and Hobbs and Duncan (1986) are shown (the latter two are completely concordant). The shaded area indicates the 1 σ uncertaintly in the data of Beckman et al. and Hobbs and Duncan.

Figure 1



Spite and Spite (mean)
Beckman, Rebolo, Molaro (mean)
Hobbs, Duncan (mean)
New
Old
η
10^{-10}
10^{-9}
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^{7}Li/H