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PRIMORDIAL LITHIUM: KECK OBSERVATIONS IN M92 TURNOFF STARS

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ABSTRACT

We present new Keck I/HIRES observations at $R = 45{,}000$ (=3 pixels) of seven stars near the turnoff of the old, metal-poor globular cluster M92. In three of these stars, we have signal-to-noise ratios (S/Ns) of 40 pixel^{-1}, and in the other four, the S/N is near 20. The Li abundance in star 18 is high compared with the halo field-star plateau and is similar to that in the remarkable Li-rich halo field star BD +23°3912. In addition to the high Li abundance in star 18, there is a dispersion in Li abundance in our seven stars covering the full range of a factor of 3.

We have attempted to determine whether the excess Li in star 18 is due to less than average Li depletion in this star from an even higher initial abundance, as predicted by the Yale rotational models, or whether it is due to the extraordinary action of Li production mechanisms in the material that formed this star. We have found no convincing evidence that favors Li production: (1) Stars 18, 21, and 46 have identical Ba abundances, which argues against Li production carrying an *s*-process signature. (2) These three stars have indistinguishable Ca, Cr, Fe, and Ti, which argues against supernova Li production. (3) We discuss ν-process production of Li and find no convincing observational evidence for this from the strengths of the Mg, Ca, and Fe lines. (4) The similarity in age of these cluster stars argues against cosmic-ray Li production that requires age differences of gigayears.

The most likely explanation for the Li dispersion is differential Li depletion from a (possibly significantly) higher primordial Li abundance due to differences in the initial angular momentum in each star followed by spin-down; the most rapid rotators destroy the most Li, whereas the initially slower rotators preserve more Li.

Subject headings: globular clusters: individual (M92) — stars: abundances — stars: interiors

1. INTRODUCTION

Lithium (Li) is an element of great importance in the study of stellar interiors, stellar evolution, Galactic chemical evolution, and cosmology. Knowledge of the primordial Li abundance (hereafter Li_p) can test models of big bang nucleosynthesis (BBN) and thereby constrain cosmological parameters such as the universal baryonic density, Ω_b, and the number of neutrino families. The standard model of BBN has enjoyed the remarkable success of predicting abundances for the light isotopes (^{2}H, ^{3}He, ^{4}He, and ^{7}Li) that, in a general sort of way, are close to the observed or inferred primordial abundances, giving values for each isotope of nearly the same universal baryon density (Boesgaard & Steigman 1985; Deliyannis et al. 1989; Walker et al. 1991). However, detailed testing of standard BBN and the resulting implications for cosmology still await a confident and precise determination of the primordial abundances of the light elements.

The avenue for determining Li_p accurately requires understanding what processes have modified the Li abundances observed in field halo stars. Spite & Spite (1982) and many subsequent studies have shown that halo dwarfs and subgiants with $6300 \geq T_{\mathrm{eff}} \geq 5600$ K exhibit a nearly uniform plateau of Li abundances near $A(\mathrm{Li}) = 12 + \log N(\mathrm{Li})/N(\mathrm{H}) = 2.1$, and that cooler halo dwarfs and subgiants have depleted their Li relative to this plateau. It is often conjectured that the plateau represents the unaltered Li_p; however, stellar and/or Galactic processing may mean that the average Li abundance observed today in halo stars is *not* the primordial value (Ryan et al. 1996).

Li is destroyed easily by (p, α)-reactions at only a few million degrees, so that already when stars arrive on the zero-age main sequence, Li survives in only the outermost few percent (by mass) of the stellar interior. Standard models (that ignore diffusion, rotational mixing, mass loss, and magnetic fields) reproduce the general features of the observations with little ^{7}Li depletion in the plateau (Deliyannis, Demarque, & Kawaler 1990). Until recently, the derived ("low") Li_p values provided constraints on Ω_b that were similar to those derived from estimates of the primordial abundances of the other light elements; this is somewhat suggestive of the existence of nonbaryonic dark matter in galactic halos and larger scales, although it is far

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from definitive. However, recent determinations of D in the directions of quasars (Songaila et al. 1994; Tytler, Fan, & Burles 1996) may be discrepant with low Li_p.

Consistency in standard BBN might still be possible if Li_p were higher. Indeed, more advanced stellar models that include the effects of rotationally induced mixing resulting from angular momentum loss and resulting transport can significantly deplete the surface Li abundance (Deliyannis 1990; Pinsonneault, Deliyannis, & Demarque 1992; Chaboyer & Demarque 1994—collectively referred to as the Yale rotational models) such that $Li_p \sim 3.0$ ("high" Li_p) would be inferred. The implied Ω_b is not a unique function of Li_p. High Li_p can imply either a low Ω_b or a high Ω_b of standard BBN, with drastically different implications for dark matter. The low Ω_b version would require nonbaryonic dark matter in galactic halos or in clusters of galaxies, whereas the high Ω_b version might require little or none.

Alternatively, a high Li_p could perhaps be pointing to the necessity for including inhomogeneities or other additional physics in BBN, which could well have different implications for dark matter. Regardless, it is clearly important to ascertain an accurate Li_p value. This requires realistic stellar models and, in particular, knowledge of interior transport processes that might affect halo star photospheric Li abundances.

The Yale rotational models can potentially be tested through their prediction that a small Li dispersion should result at a given $T_{\rm eff}$ as a consequence of, for example, differences in the initial angular momentum. In their scrutiny of the halo star Li data in the color–equivalent width plane, Deliyannis, Pinsonneault, & Duncan (1993) found some evidence for such a small Li dispersion. Thorburn (1994) reached the same conclusion using new Li observations. Ryan et al. (1996) provide specific examples of very metal poor stars of apparently similar $T_{\rm eff}$ having a factor of 2 difference in Li abundance. Li dispersions are also observed in cool open cluster dwarfs (for example, Hyades [Thorburn et al. 1993] and Praesepe [Soderblom et al. 1993]). What is particularly striking in these examples are the direct comparisons of spectra that show all other lines canceling, except for the Li lines, which leave a residual. Further support of the models (and the idea that Li depletion depends on the angular momentum history) comes from the larger than normal Li abundances in short-period binaries in a variety of stellar populations (Ryan & Deliyannis 1995; unfortunately, no suitable binaries in the $T_{\rm eff}$ range of the Li plateau are yet known). Strong support for the models comes from the combination of Li and Be data (Deliyannis & Pinsonneault 1993; Deliyannis 1995; Stephens et al. 1997). However, a Li dispersion in the *field-star* halo Li data can also possibly be consistent with Galactic Li production coupled with a dispersion in the halo age-metallicity relation (Thorburn 1994). At this time, the degree to which Galactic enrichment and stellar depletion have each contributed to altering Li_p is still unclear. Discriminating diagnostics are sorely needed.

One diagnostic requires us to scrutinize the Li-rich halo stars for signatures of Li production mechanisms. The relevance of the remarkable halo star BD $+23°3912$ (King, Deliyannis, & Boesgaard 1996, hereafter KDB96) is discussed in § 4.3. Another excellent diagnostic, which is the focus of this study, involves reducing or even eliminating the dispersion in the halo age-metallicity relation. This can be achieved by observing relatively unevolved stars near the main-sequence turnoff in globular clusters, which have the same or similar mass, luminosity, age, temperature, and (presumably) initial composition. A Li dispersion found for relatively unevolved stars of the same $T_{\rm eff}$ within a given globular cluster, as opposed to in a field-star sample, would more likely the result of differing degrees of stellar depletion from a higher initial Li abundance, since differential Li enrichment within the cluster would be less likely. Comparison of Li in different globular clusters could allow investigation of the effects of parameters such as age and metallicity. It is now possible to obtain high-resolution ($R \sim 50,000$) spectra of 18th magnitude near-turnoff stars in globular clusters using the Keck I 10 m telescope and the efficient HIRES echelle spectrograph.

The ideal cluster for such an investigation is M92 because it is one of the closest with near-zero reddening, as well as one of the oldest and most metal poor known. Stetson & Harris (1988) and Demarque, Deliyannis, & Sarajedini (1991) derive an age of 16 to -17 Gyr, and Sneden et al. (1991) find $[\mathrm{Fe/H}] = -2.24 \pm 0.06$. We have previously reported initial results on Li in four M92 stars based on one night of observations in 1994 July (Deliyannis, Boesgaard, & King 1995, hereafter DBK95). There we reported differences in the Li abundances of three otherwise apparently identical M92 subgiants[4] and argued against cosmic-ray, supernova, and asymptotic giant branch (AGB) star Li production as the source of these differences. This suggested that differing Li depletion histories were the cause of the Li dispersion, consistent with the predictions of the rotational stellar models that imply a large value of Li_p.

We have obtained three additional nights of Keck/HIRES observations of M92 subgiants in 1995 July. The purpose of these was to increase our signal-to-noise ratio (S/N) on the three stars observed before and to obtain data for additional stars in order to increase our sample size. Here we report the additional data and combine it with our earlier observations. Our updated and new Li abundances are given in § 3, and the results are discussed in § 4.

2. OBSERVATIONS AND DATA REDUCTION

Near the turnoff of M92, the Li I λ6707.8 resonance doublet increases in strength with lower $T_{\rm eff}$ and is virtually independent of gravity. Thus, in order to detect possible differences in the Li line strengths, we chose (in DBK95) to observe stars slightly cooler than the turnoff itself, because they presumably have stronger Li lines. Further evolved stars (as opposed to cooler dwarfs) are also brighter, further facilitating the observations. At the same time, we stayed well away from the onset of Li dilution (near $B-V \sim 0.57$) as defined empirically from slightly more evolved field stars, which reflects the post-turnoff deepening of the convection zone (Deliyannis et al. 1990; Ryan & Deliyannis 1995), by choosing three stars with $B-V \sim 0.49$. The possibility that M92 might be reddened by $E(B-V) = 0.02 \pm 0.01$ further ensures that our stars have not yet begun dilution. These stars are photometrically identical and should have nearly

[4] We employ the technical term "subgiants" to distinguish stars that are evolved past the bluest point of the turnoff from those that are below that point; in fact, our "subgiants" are very close to the turnoff, still very much on the horizontal part of the subgiant region. To avoid confusion, we stress that others use the term "subgiants" differently, to refer to stars that are still further evolved, at the base of the giant branch or even as high up (on the giants branch) as the level of the horizontal branch.

identical masses. We report additional observations of these three stars (with higher S/Ns) and find a Li dispersion among them. We also report here the observations of three more stars (at lower S/Ns): a fourth star at identical $B-V$, a star with just slightly lower $B-V$, and a star with just slightly higher $B-V$ (to check on dilution). Figure 1 shows the color-magnitude diagram (CMD) of M92 using data

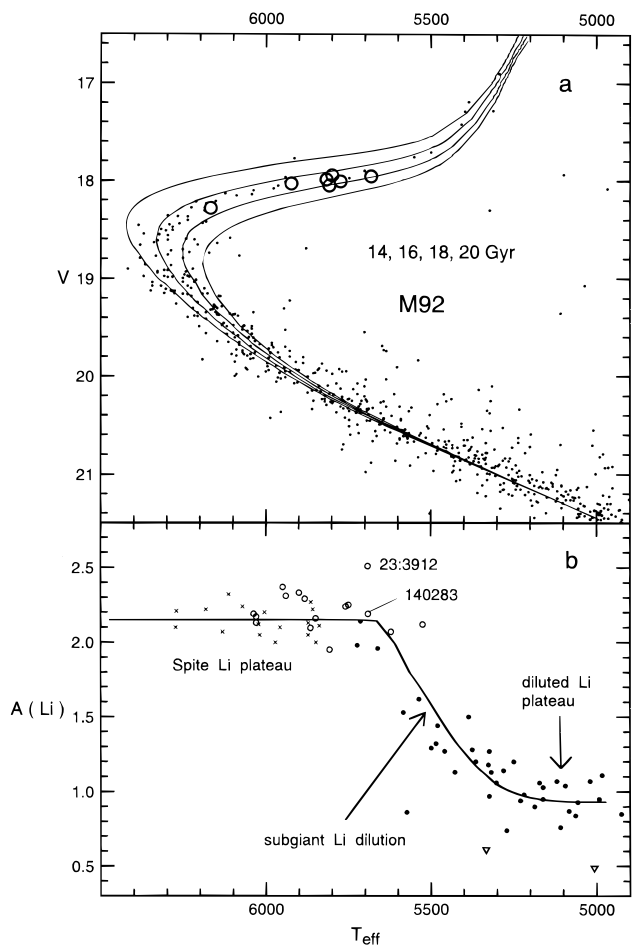

FIG. 1.—(*a*) CMD of the turnoff region of M92 based on the data of Stetson & Harris (1988), with the isochrones of Demarque et al. (1991). The open circles denote the program stars. For the M92 data, $E(B-V) = 0.02$ has been assumed, and the $(B-V)$–T_{eff} relation of T94; for the isochrones, $E = 0.03$ was assumed (which is within the allowed error). (*b*) Field halo star Li abundances, on a consistent scale as (*a*) (see text). The crosses (dwarfs and possible subgiants) and filled circles (subgiants) are from the data of Pilachowski et al. (1993), as reanalyzed by Ryan & Deliyannis (1995). For the open circles (possible and probable subgiants), Li equivalent widths have been averaged from the literature, and Li abundances derived here (see Fig. 4 and text). The solid line shows the subgiant dilution predictions of Deliyannis et al. (1990).

from Stetson & Harris (1988) and Yale isochrones (Demarque et al. 1991) and indicates the locations of the stars we have observed. Figure 1*b* shows subgiant Li data on a consistent scale (see § 3.3): a very clear pattern of subgiant Li dilution is evident. It is also clear that our four M92 "identicals" are hotter than the onset of field-star dilution.

High-resolution ($R \sim 45{,}000$) echelle spectrographic observations were made of six stars in M92 near $V = 18$ at the Keck I telescope on 1995 July 4, 5, and 6 (UT). The HIRES spectrograph is described by Vogt et al. (1994). The spectrograph setup was similar to the "blue" configuration described in DBK95. The wavelength coverage (with some interorder gaps) was 4430–6865 Å. Table 1 lists the stars observed, the sum of the exposure times on each star on each night, the total exposure time for all the nights on a given star, and the empirical S/N per pixel of the co-added spectra in the Li region. This table includes the information for the night of 1994 July 30 also. On each night, there were exposures of a Th-Ar comparison lamp, 20 quartz flat-field frames, and at least 20 bias frames. During the run, exposures were taken of the asteroid Ceres and of the Moon to obtain a solar spectrum with the same instrument and configuration. A spectrum was also obtained of HD 140283 to compare with the M92 stars.

Reduction of the HIRES data involved the use of both general IRAF tasks as well as IRAF packages specifically designed to process echelle spectra. Preparing the raw, two-dimensional spectra for aperture extraction required (1) the removal of the overscan region, (2) bias or "zero" frame subtraction, and (3) division by a flat field. Multiple quartz lamp and zero-second exposures obtained each night were processed and combined to produce a nightly flat field and bias frame, respectively, which were applied to the science images. A single pass by the IRAF COSMICRAYS task successfully excised severe cosmic-ray strikes from the images without affecting the spectra. Contamination of the stellar signal by background light appeared to be insignificant. The two-dimensional scattered light plateau was modeled using the APSCATTER routine, and the fit revealed that $\leq 1\%$ of the stellar signal was due to background contamination. Therefore, this plateau was not removed from the data. Intraorder contamination, or signal dilution by overlapping echelle orders, also proved to be inconsequential for the 100 pixels separation between neighboring orders that greatly exceeded the projected length (~ 30 pixels) of the 7″ slit. Following the above preprocessing steps, the two–dimensional spectra were aperture-extracted and placed on a linear wavelength scale.

The nightly Th-Ar calibration frames contained hundreds of reference features from which a dispersion solu-

TABLE 1

M92 OBSERVING LOG

Star	V	$B-V$	July 30 (hr min)	July 4 (hr min)	July 5 (hr min)	July 6 (hr min)	Total (hr min)	S/N
M92:18..........	17.975	0.486	1 30	5 15	...	...	6 45	36
M92:21..........	17.943	0.490	1 30	...	...	3 45	5 15	41
M92:34..........	17.954	0.518	...	...	1 15	1 35	2 50	19
M92:46..........	18.048	0.488	1 04	...	4 30	...	5 34	43
M92:60..........	18.029	0.462	...	...	1 30	1 00	2 30	15
M92:80..........	18.278	0.410	1 34	...	...	...	1 34	16
M92:350	18.004	0.497	...	1 45	...	0 41	2 46	19
HD 140283......	7.24	0.490	...	0 03	...	...	0 03	475

tion for each individual order was created. The wavelength rectification was based upon a first-order cubic spline fitted to the calibration lines with rms residuals typically hovering around 0.002 Å. The linearized dispersion of the 29 orders increased slowly with wavelength from 0.0307 Å pixel^{-1} at 4460 Å (order of 1) to 0.0474 Å pixel^{-1} at 6860 (order of 29) with the 6707.8 Å Li order, aperture 28, set to a scale of 0.0465 Å pixel^{-1}. A typical calibration line near Li spanned approximately 3.25 pixels (FWHM), so the operating resolution for the observing run was roughly 45,000. Multiple exposures of a single star acquired on one or more nights were co-added. We determined radial velocities from a sample of fairly strong lines for the 1995 spectra and from the Li I line for the 1994 spectra. The measured velocities agreed very well from the 2 years for stars 21 and 46 (to within 4 km s^{-1}), but they differed by 14 km s^{-1} for star 18. The resolution of the spectra is 6.8 km s^{-1}. The possibility exists that star 18 has a variable radial velocity and is perhaps an SB1.

The Li region of the three stars that have S/Ns near 40 are shown in Figure 2. These are the sum of the spectra obtained in 1994 and 1995. It is clear from this figure that the Li line in star 18 is stronger than those in the other two stars, by a factor of about 2 (see below). Figure 3 shows the Li region in the three newly observed stars where the S/Ns are about 20.

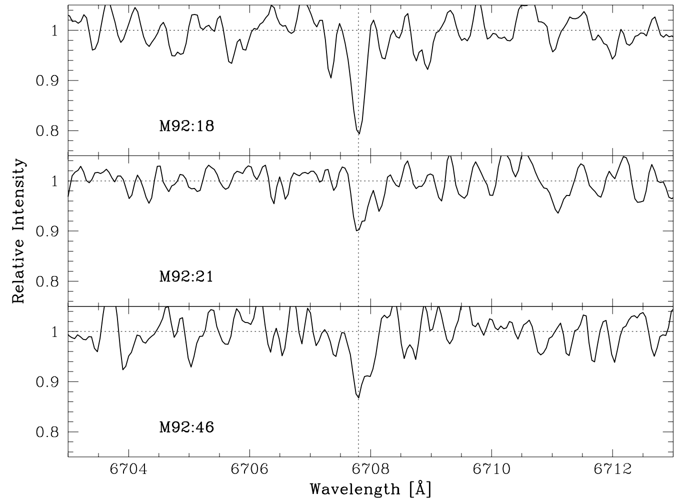

FIG. 2.—Spectra in the Li region of the three stars for which we have S/N values of ~40. The Li line is shown by an arrow and is clearly stronger in star 18 than in the other two stars.

3. ANALYSIS AND ABUNDANCES

3.1. Li *Equivalent Widths*

The equivalent widths of the Li I doublet were measured using the Gaussian fits in the IRAF SPLOT package. For the spectra with S/Ns of 40, we did a boxcar smoothing of three. For the others, a boxcar smoothing of five was used. These measures were made independently by two of us; our results were in agreement to better than 1.6 mÅ. Poisson (photon noise) and continuum 1 σ errors were determined using the approximations from Cayrel (1988) and McWilliam et al. (1995), respectively. Table 2 shows the photon noise error ($\sigma_{\rm ph}$), continuum error ($\sigma_{\rm co}$), and quadrature sum ($\sigma_{\rm qu}$). For the Poisson error, a measured FWHM of 6 pixels was used. For star 80, we adopt the 2 σ upper limit of DBK95.

We point out here that the Li equivalent widths are different in these otherwise similar stars by a factor of 2 or more when we compare stars 18 and 34 with stars 21 and 46. When we compare the stars for which we have the highest S/Ns, we find that Li is stronger in star 18 than in star 21 by a factor of 2.4, and in star 46 by a factor of 2.1. These differences would appear to be statistically significant. First, in terms of just photon noise, star 18 is 8.8 σ

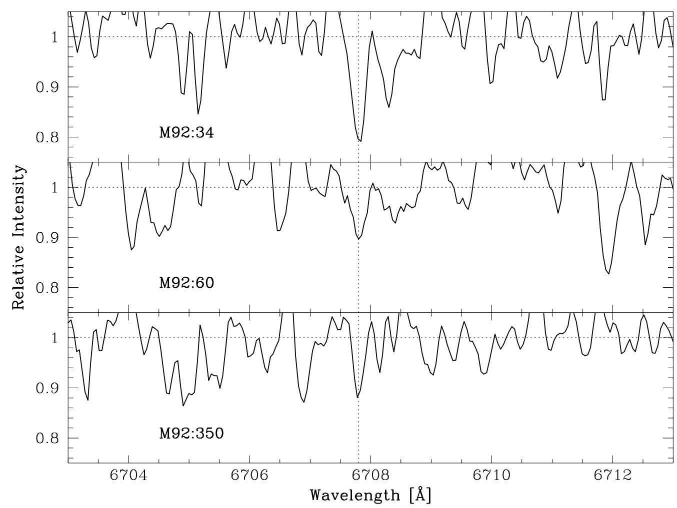

FIG. 3.—Spectra in the Li region of the three stars for which we have S/N values of ~20.

TABLE 2

TEMPERATURES, EQUIVALENT WIDTHS, AND Li ABUNDANCES

Star	$(B-V)_0$	σ	$T_{\rm eff}$	σ	W_λ	$\sigma_{\rm ph}$	$\sigma_{\rm co}$	$\sigma_{\rm qu}$	log N(Li)	σ	NLTE log N(Li)
M92:18	0.466	0.016	K93 5959	66	59.3	4.9	4.9	6.9	2.57	0.06	2.55
			C83 5817	70					2.45	0.08	2.45
M92:21	0.470	0.006	K93 5943	25	25.0	3.9	4.8	6.2	2.06	0.09	2.07
			C83 5800	26					1.96	0.09	1.99
M92:34	0.498	0.026	K93 5830	105	50.4	9.3	10.6	14.1	2.36	0.14	2.37
			C83 5681	108					2.22	0.14	2.25
M92:46	0.468	0.025	K93 5951	102	28.7	4.1	6.2	7.4	2.17	0.04	2.18
			C83 5808	108					2.04	0.11	2.07
M92:60	0.442	0.017	K93 6058	70	40.8	12.3	13.0	17.9	2.42	0.18	2.41
			C83 5923	77					2.30	0.18	2.30
M92:80	0.390	0.016	K93 6275	68	<22	11	...	...	<2.23	0.30	<2.21
			C83 6168	78					<2.16	0.30	<2.15
M92:350......	0.476	0.015	K93 5918	61	28.8	9.3	7.1	11.7	2.13	0.18	2.14
			C83 5774	65					2.01	0.18	2.04

above star 21 (star 21 is 7.0 σ below star 18); a χ^2 test suggests that there is less than a 0.000000022 probability of obtaining the measured equivalent widths by chance with the given errors if the real equivalent widths are identical. For star 18 versus star 46, star 18 is 7.5 σ above star 46 (star 46 is 6.2 σ below star 18); here the probability is still only 0.0000015 that this could happen by chance. In the case of the quadrature sum (assumption of uncorrelated errors) of the Poisson and continuum errors, the probabilities that the stars' real equivalent widths are the same still remain quite small: $P = 0.00022$ for 18 versus 21 and 0.0025 for 18 versus 46. In the case of the linear sum of Poisson + continuum (completely correlated errors), the probabilities still remain small, being 0.0073 and 0.031, respectively.

Since stars 21 and 46 both appear to have weaker Li features than star 18, we can also compare their weighted average, which is 26.7 ± 2.8 mÅ, with the weighted average of star 18. Here too, it is quite improbable that star 18 and the average of stars 21 and 46 have the same real Li equivalent width: $P = 0.000000021$ for Poisson error alone, $P = 0.000091$ for quadrature sum, and $P = 0.0050$ for linear sum. We can now confirm at a higher confidence level our original finding in DBK95 that star 18 has a stronger Li line than either star 21 or star 46.

3.2. *Equivalent Widths and Error Estimates*

In addition to the Li line measurements, we present measurements of lines of other elements that might conceivably be correlated with Li production in evolved stars; we need to investigate alternative sources of differential Li enhancement in the M92 subgiant 18 (see § 4.3). The measured widths explore the possibility that M92:18's Li excess results from either the neutrino process operating in Type II supernovae or contamination by the ejecta of AGB stars. Several neutral and/or singly ionized lines of Ca, Cr, Fe, Mg, and Ti are available in the low orders of the HIRES data and serve as tests of explosive nucleosynthesis in Type II supernovae. Samples of these spectra are shown in Figure 4. The equivalent widths of these features are listed in Tables 3 and 4, as are a handful of singly ionized barium lines. Excessively strong Ba II lines can be the result of photospheric pollution by material jettisoned into the intercluster medium by AGB stars or by mass transfer.

It was found that IRAF's SPLOT routine using Gaussian fits became increasingly fallible and uncertain as the line strength diminished; therefore, an alternate means of estimating the equivalent width of a poorly defined or noisy feature was required. We calculated the flux in weak lines using SPLOT's "e" feature, which performs a simple pixel summation after subtraction of a user-defined continuum. Unmeasurable or otherwise unrecognizable lines buried within the noise were assigned upper limits. These maximal widths represent the width a 3 σ detection would have, given the noise of the spectral order in which the feature resides. For detected lines, a Poisson 1 σ error (using a 4 pixels measured FWHM, i.e., smaller than that for the Li doublet) and a 1 σ continuum error, calculated as above, were added in quadrature and are listed in Tables 3 and 4.

3.3. *Temperatures*

Temperatures for the M92 stars are anchored to those of field halo stars, as determined by Deliyannis et al. (1997, hereafter DBKD97) and Thorburn (1994, hereafter T94). DBKD97 derived effective temperatures for 37 halo dwarfs

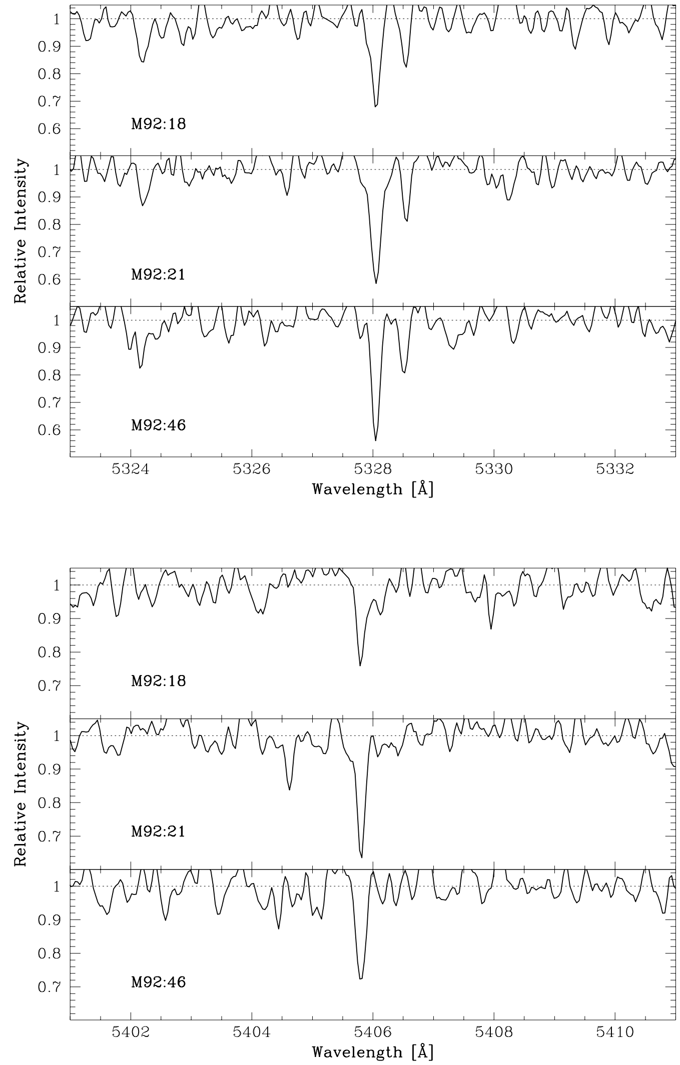

FIG. 4.—Spectra showing Fe lines of the three stars with the higher S/N observations in two different orders. The arrows point to the Fe lines.

and subgiants using $b-y$, $R-I$, and $V-K$ colors, for both a "hot" $T_{\rm eff}$ scale of King (1993, hereafter K93) and a "cool" $T_{\rm eff}$ scale of Carney (1983, hereafter C83). Reddenings were explicitly taken into account, as was a slight dependence on metallicity (for the K93 scale). $T_{\rm eff}$ for subgiants and possible subgiants (listed in DBK95) in Figure 5 (discussed below) have been taken directly out of DBKD97 or have been derived similarly. It turns out that there is excellent agreement between the $T_{\rm eff}$ derived in this manner and those from the halo Li study of T94 (most stars in this study have [Fe/H] < -2): using the C83 scale, for nine stars in common, the mean difference is only -1.2 K (in the sense of T94 and DBKD97). We therefore assume that the $T_{\rm eff}$ scale of T94 based on $B-V$ is consistent with the "cool" $T_{\rm eff}$ scale of DBKD97 based on $b-y$, $R-I$, and $V-K$ (not surprisingly, since both are based on C83), at least for [Fe/H] < -2, where the dependence of $B-V$ on [Fe/H] is minor. Figure 5 (see § 4.1) shows Li equivalent widths from the extensive compilation of Ryan et al. (1996). For 70 stars in common between Ryan et al. (1996) and T94, the T94 $T_{\rm eff}$ are 16 K higher, on average. For consistency, we have thus raised the $T_{\rm eff}$ from Ryan et al. by 16 K.

Table 2 lists the $T_{\rm eff}$ for the M92 stars on each of the C83 and K93 scales, and 1 σ errors are listed in Table 2. For the

TABLE 3

M92 Equivalent Widths and 1 σ Errors

Species	Rest $\lambda\lambda$	M92:18	σ	S/N	M92:21	σ	S/N	M92:46	σ	S/N
Ti II	4501.28	43	5	27	48	7	27	35	6	26
Fe I	4528.63	47	4	27	56	4	27	47	4	26
Ba II	4554.04	<18	...	28	29	6	28	30	6	28
Ti II	4563.77	35	6	28	58	5	28	40	6	28
	4571.98	39	5	28	52	5	28	50	7	28
Fe II	4583.84	19	5	28	25	7	28	27	5	28
Mg I	4703.00	25	4	30	<18	...	30	10	3	29
Fe I	4871.33	16	3	32	29	4	32	15	3	31
	4890.76	23	4	32	24	6	32	23	5	31
	4891.50	30	5	32	44	4	32	29	5	31
	4919.00	29	4	32	40	4	32	23	6	31
	4920.51	49	5	32	56	3	32	47	9	31
Ba II	4934.09	25	5	33	28	6	32	22	5	31
Fe II	5018.45	38	6	33	52	5	33	40	4	32
Fe I	5171.61	22	5	34	27	5	34	22	4	33
Mg I	5172.70	94	5	34	90	6	34	85	6	33
	5183.62	122	5	34	101	6	34	120	6	33
Cr I	5208.43	25	4	34	36	5	34	28	3	33
Fe I	5227.19	52	5	35	50	6	34	56	5	34
	5232.95	34	5	35	45	7	34	58	6	34
	5269.55	62	5	35	58	5	34	67	7	34
	5328.05	49	4	36	60	5	35	63	4	34
	5328.54	25	4	36	26	4	35	28	5	34
	5397.14	46	4	36	50	4	36	38	4	35
	5405.78	46	5	36	51	4	36	49	7	35
	5429.78	43	4	36	58	3	36	51	5	35
	5434.53	54	6	36	70	7	36	42	5	35
	5455.62	46	5	37	53	4	36	59	4	36
	5615.66	26	3	37	28	4	36	26	3	36
Ba II	6141.73	19	5	39	15	6	38	8	3	37
Ca I	6162.18	33	6	39	38	7	38	39	5	37

C83 scale, $T_{\rm eff}$ have been determined using $B-V$ colors from Stetson & Harris (1988), the commonly adopted reddening of $E(B-V)=0.02$, and the T94 $(B-V)$–$T_{\rm eff}$ relation. For the K93 scale, $T_{\rm eff}$ have been derived using the relationship between the C83 and K93 scales from DBKD97. One sigma errors in $T_{\rm eff}$ have been propagated from the errors in the $B-V$ measures. An error of order 0.01 in $E(B-V)$ may affect systematically the $T_{\rm eff}$ of all M92 stars by approximately 50 K, and thus A(Li) by about 0.04 dex, but will have a negligible effect on the *relative* Li abundances. For Figure 1*b*, the field stars were placed on the same scale as the M92 stars as follows. $T_{\rm eff}$ for possible and probable subgiants (*open circles*, as defined in DBK95) are simply adopted as discussed above, and Li abundances are derived from Figure 5. For the other stars, data were taken from Pilachowski, Sneden, & Booth (1993) as reanalyzed by Ryan & Deliyannis (1995), and 22 K was added to their $T_{\rm eff}$ to account for a mean difference of 22 K between T94 and Ryan & Deliyannis (1995) for nine stars in common. The implied difference in A(Li) of almost 0.02 dex is negligible.

3.4. Li *Abundances*

Abundances have been determined from the measured equivalent widths of the Li doublet. Only the isotope of ^{7}Li was included. A microturbulence of 1.5 km s^{-1} was used following Magain (1989). The Li abundance is virtually independent of gravity. The Kurucz model atmospheres (R. L. Kurucz 1993, private communication) were used, and abundances were determined with both temperature scales. Possible corrections for non-LTE (NLTE) effects were calculated from Carlsson et al. (1994). These corrections are very small for these stars, typically 0.02 dex.

The LTE and NLTE abundances are also presented in Table 2 for both temperature scales. The 1 σ errors are determined from adding in quadrature the abundance errors due to the temperature errors and due to the equivalent width errors.

4. DISCUSSION

4.1. *High* Li *in Star 18*

Armed with twice the S/N that we had in DBK95 for each of the M92 stars 18, 21, and 46, we confirm at a higher confidence level that star 18 is Li-rich compared with stars 21 and 46, by approximately a factor of 2–3. Figure 5 shows the Li equivalent widths plotted against temperature (on the C83 $T_{\rm eff}$ scale) for our M92 stars and for halo field dwarfs and subgiants. This shows that the Li abundance in star 18 could be as high as that of the extraordinary Li-rich field halo star BD $+23°3912$ (§ 4.3). Since star 18 evolved from the turnoff relatively recently, it can be compared with field stars at the turnoff (the small crosses with $T_{\rm eff}$ approximately in the range 6200–6400 K in Fig. 5). These field stars appear to show a range in Li abundances. If this range is real, it could be due to either (1) Galactic Li enrichment or (2) differential Li depletion from a higher initial Li abundance, as predicted by the Yale rotational models. (Of course, both effects might have acted.) In the case of Li enrichment (1), star 18 can be compared with the turnoff field stars with the *lowest* Li abundances; in this case, star 18 contains approximately 0.6–0.7 dex more Li than those stars, and this extra Li (indeed, the majority of the Li in star 18) must be explained in terms of Li production mechanisms. We will argue in § 4.3 that evidence of such enrichment is lacking. In the case of Li depletion (2) from a higher

TABLE 4

M92 Equivalent Widths and 1 σ Errors

Species	Rest $\lambda\lambda$	M92:34	σ	S/N	M92:60	σ	S/N	M92:350	σ	S/N
Ti II	4501.28	54	8	15	41	7	14	<30	...	11
Fe I	4528.63	...	...	15	61	9	14	<30	...	11
Ba II	4554.04	49	9	15	...	...	15	<30	...	11
Ti II	4563.77	46	7	15	59	13	15	58	9	11
	4571.98	49	8	15	...	...	15	42	11	11
Fe II	4583.84	29	7	15	46	10	15	56	9	11
Mg I	4703.00	31	10	17	18	9	16	35	9	13
Fe I	4871.33	<30	...	18	41	11	18	35	8	16
	4890.76	...	...	18	16	7	18	38	9	16
	4891.50	47	9	18	<30	...	18	...	...	16
	4919.00	30	7	18	35	6	18	...	...	16
	4920.51	54	7	18	44	8	19	...	...	16
Ba II	4934.09	25	6	19	<30	...	20	<30	...	17
Fe II	5018.45	47	9	19	34	8	21	48	7	18
Fe I	5171.61	28	8	21	<30	6	21	30	8	19
Mg I	5172.70	126	10	21	120	11	21	98	8	19
	5183.62	125	10	21	140	10	21	119	9	19
Cr I	5208.43	...	...	21	35	10	21	<30	...	19
Fe I	5227.19	40	6	21	33	6	21	40	9	20
	5232.95	...	...	21	37	6	21	46	11	20
	5269.55	64	7	21	69	5	22	49	9	20
	5328.05	53	9	21	38	14	22	70	9	21
	5328.54	24	9	21	13	12	22	21	8	21
	5397.14	51	8	22	40	8	22	45	8	22
	5405.78	55	8	22	35	7	22	70	11	22
	5429.78	60	11	22	36	7	22	50	13	22
	5434.53	56	11	22	<30	...	22	56	14	22
	5455.62	38	10	22	40	9	22	51	6	22
	5615.66	<30	...	22	<30	...	23	<30	...	23
Ba II	6141.73	<30	...	24	23	9	23	<30	...	25
Ca I	6162.18	30	11	24	45	10	23	53	9	25

initial Li abundance, star 18 can be compared with turnoff field stars with the *highest* Li abundances; in this case, star 18 contains approximately 0.1–0.2 dex more Li than those stars. In the context of the Yale rotational models, star 18 would have had a slightly lower initial angular momentum compared with those stars. Note that if Li depletion is admitted as a possibility for some halo stars (e.g., the lower abundance turnoff stars compared with the higher abundance turnoff stars), then Li depletion, even significant Li depletion, must be admitted as a possibility for *all* halo stars.

Molaro & Pasquini (1994) and Pasquini & Molaro (1996) have found Li in three turnoff stars in NGC 6397 that have log $N(\mathrm{Li}) = 2.28 \pm 0.10$, higher than the halo field-star plateau. The recent work of Pasquini & Molaro (1997) on 47 Tuc turnoff stars shows two stars with log $N(\mathrm{Li}) = 2.37 \pm 0.08$. They also find evidence for a dispersion in Li abundances in both clusters.

Figure 6 shows the Li abundances plotted against temperature (on the K93 T_{eff} scale) for the seven M92 stars. Star 18 at 5950 K has a significantly higher Li abundance than stars 21 and 46 at the same temperature. The dispersion in Li abundances in these otherwise identical stars is apparent.

4.2. Li *Dispersion*

As a further test of the reality of the Li dispersion between star 18 and stars 21 and 46, we have measured numerous lines of several species. Figure 7*a* shows a comparison between star 18 and star 46 of equivalent widths for Ba II, Ca I, Cr I, Fe I, Fe II, Mg I, and Ti II. There is good agreement between the two stars for all of those elements. This supports the supposition that these stars are identical (except for Li) as selected, previously based on their colors and position in the H-R diagram, and that the Li abundances differ. Figure 7*b* shows a comparison between star 18 and star 21. The equivalent widths in star 21 might be slightly stronger, consistent with the possibility that star 21 is up to 100 K cooler than star 18. (A comparison of only low-excitation, temperature-sensitive lines leads to a similar conclusion.) This is within the photometric errors. The possibility that star 21 is slightly cooler accentuates the stronger Li line in star 18 and would result in an even larger Li *abundance* difference between the two stars.

Taken at face value, the Li abundances in the slightly hotter star 60 and the slightly cooler star 34 appear to be intermediate to those of star 18 and stars 21, 46, and 350. The approximately normal Li abundance in star 34 also supports our conjecture that stars 18, 21, 46, and 350 are not cool enough to have started subgiant Li dilution.

4.3. Li *Production?*

In this section, we argue against the possibility that differential Li production within the cluster is responsible for the extra Li observed in star 18. There are at least three plausible Li production mechanisms: (1) the neutrino process in Type II supernovae (Woosley et al. 1990; Timmes, Woolsey, & Weaver 1995); (2) alpha + alpha production from cosmic rays interacting with, for example, the interstellar medium (ISM) (Steigman & Walker 1992; Prantzos, Cassé, & Vangioni-Flam 1993); and (3) the ^{7}Be transport process (Cameron & Fowler 1971) in AGB stars. We consider these in turn.

Models of core-collapse supernovae can produce enough ^{7}Li via the neutrino process so as to account for A–M of the

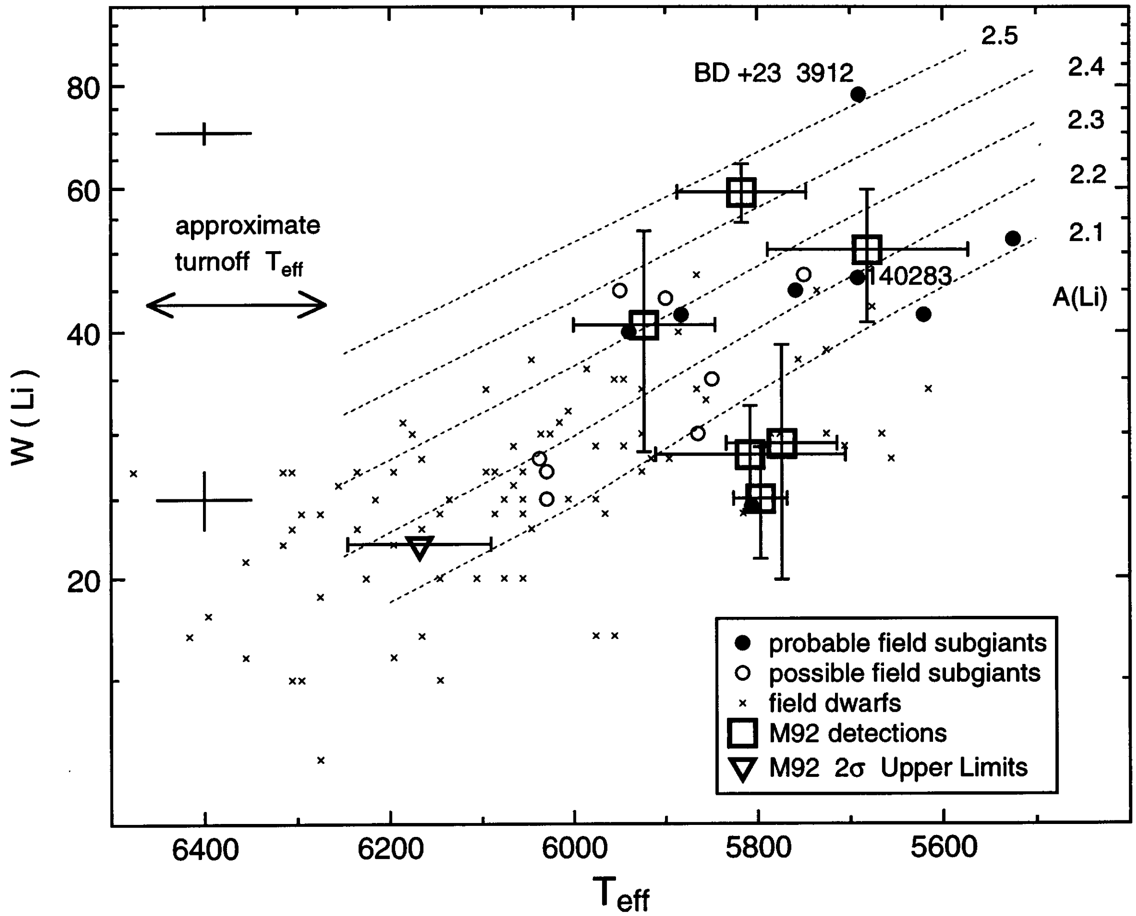

FIG. 5.—Li equivalent widths vs. T_{eff} for field metal-poor subgiants (*circles*), dwarfs (*small crosses*), and the M92 program stars (*squares*). For M92, 1 σ error bars are shown for T_{eff} (propagated from $B-V$) and W(Li) (photon noise). Typical errors are shown for the field stars at two different values of W(Li). The dotted lines indicate constant Li abundance, where $A(\mathrm{Li}) = 12 + \log [N(\mathrm{Li})/N(\mathrm{H})]$. The temperatures in this plot are from C83 and DBKD97 (see text).

Population I Li abundance. This assumes that Li_p was low; of course, if Li_p were high, supernova Li production may have contributed negligibly compared with Li_p. We must point out that, to date, evidence for supernova Li production remains elusive. We now ask what other abundance signatures might manifest themselves if the ν-process had acted to produce the larger Li abundance seen in star 18. This was investigated using the Woosley & Weaver (1995, hereafter WW95) hydrodynamic massive supernovae calculations. Employing their calculated ejected masses from their $Z = 0.01, 10^{-4}, 0.0\ Z_{\odot}$ grids, we estimated abundance changes from the process of adding enriched supernova (SN) material from a given model that yielded a 0.4 dex increase in the Li abundance from $\log N(\mathrm{Li}) = 2.1$ for an assumed 0.8 $M_{\odot}$ star with $X = 0.75$. We consider the elements Mg, Ca, and Fe because massive supernovae produce nontrivial amounts of these elements and because these elements' features appear in our spectra. The resulting increases in the abundances of Mg, Ca, and Fe produced by the same models were calculated from the relative ejected masses assuming solar abundances from Anders & Grevesse (1989) and the M92 abundances derived from our spectra as presented in King et al. (1997). We note from the outset that (i) the Ca line strengths of stars 18, 21, and 46 are in very good agreement that is well within the errors, and (ii) on average, the Fe line strengths seem, if anything, *smaller* in star 18 than in star 21, and in agreement for stars 18 and 46. Thus, we can recognize a priori that there is absolutely no observable evidence from the Fe and Ca features in our spectra for SN enrichment in star 18 relative to 21 and 46. The same also appears true from our measured Ti, Cr, and Ba features.

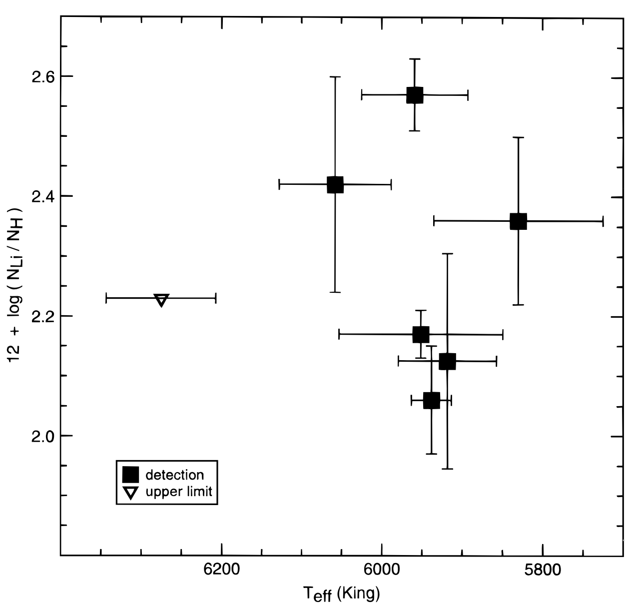

FIG. 6.—Lithium abundances for all seven M92 program stars. The temperature scale is from K93 (see text).

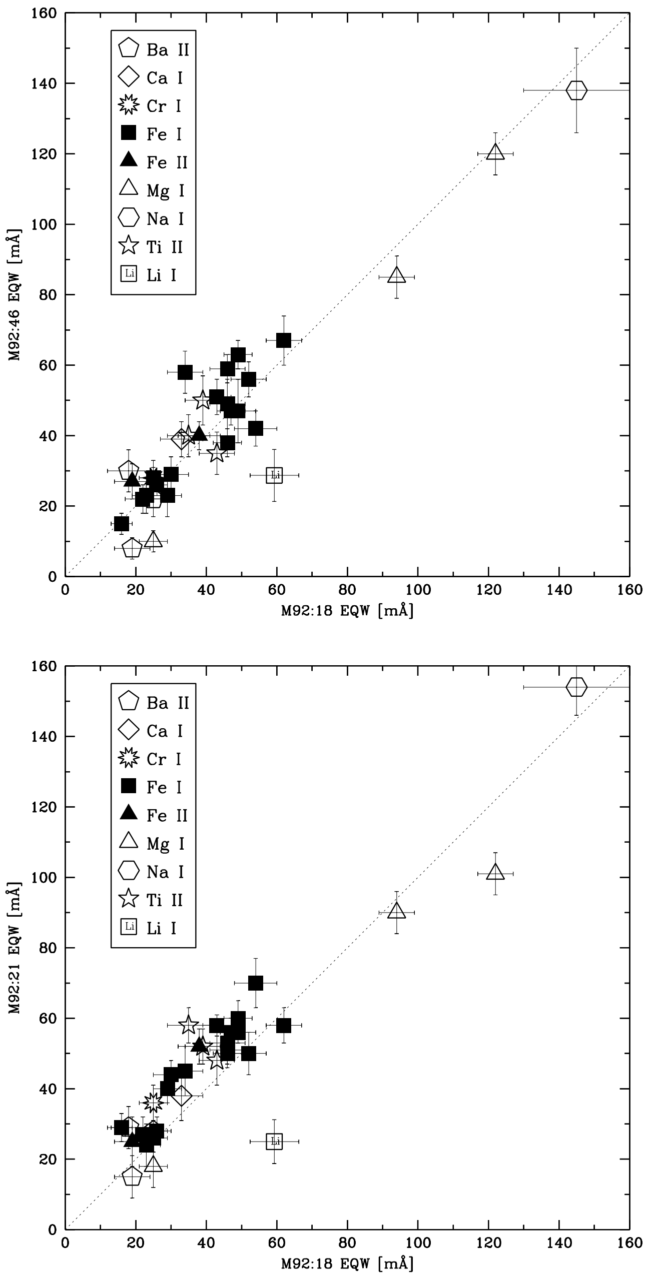

FIG. 7.—Equivalent widths of the Li line and of lines of several other species in star 18 vs. star 46 (*upper panel*) and star 18 vs. 21 (*lower panel*). The other species show no anomalies in line strengths. The filled symbols (Fe I and II) show this clearly. The offset of the equivalent widths in star 21 compared with star 18 (in the sense that the lines are systematically stronger in star 21 than in star 18) may indicate that the temperature in star 21 is cooler than in star 18, by as much as 100 K.

We find that the vast majority of the WW95 models explaining the excess in Li in star 18 due to SN production would lead to Mg abundance enhancements in star 18 that are greater than a factor of 10 (and often orders of magnitude larger). The line strengths in Table 3, and the plots of these in Figures 7*a* and 7*b*, show that this is clearly not observed. Two of the $Z = 0$ models, WW95's Z18A and Z20A, are more interesting. These $\sim$18 and $\sim$20 $M_\odot$ models allow the excess Li in star 18 to be produced by the neutrino process while only predicting a factor of $\sim$2 enhancement in this star's Mg abundance and completely negligible enhancements of other elements (Ca, Ti, Cr, Fe) present in our spectra. Inspection of Table 3 and Figures 7*a* and 7*b* indicates some possibility that star 18 exhibits stronger Mg lines than star 21 or star 46. However, any possible line-strength difference is not satisfyingly clear. Two of the Mg I lines' equivalent widths are identical to within the errors for stars 18 and 46, while one of the Mg I line's strength is statistically indistinguishable for star 18 versus star 21. Given that half of the possible comparisons show no statistical difference, and given the quality of the extant data, independent higher S/N spectra seem necessary to reach secure conclusions. In the meantime, while we have difficulty believing a statistical claim of a factor of 2 difference in our stars' Mg abundance, it is difficult to exclude this in the definitive manner required.

We also find that some of the higher mass $Z = 10^{-4}$ and 0.0 $Z_\odot$ WW95 models (U35A, U40A, Z25A, Z30A, Z35A, and Z40A) can synthesize Li without any measurable effect on the other abundances our spectra can address. Three important notes concerning these models are in order. First, in the case of the latter two models, the Li yields indicate that multiple SNs having these model characteristics would be required to produce the anomalous Li in (only) our one star; this might seem to be a somewhat remarkable circumstance. Second, models of the same mass and metallicity but incorporating other assumptions (WW95's analogous "B" and "C" models) produce relatively copious amounts of Mg that, despite the current uncertainties in the observations, are clearly excluded; thus, the degree to which these models correspond to real stars is an important issue. Third, there is a question of whether metal-poor stars of these masses undergo SN explosions and release their products into the surrounding environs. Until some of these issues can be addressed, we can only say that it remains conceivable that ν-process production might occur without any observational signatures in the elements we can survey in our spectra. Thus, observationally excluding the action of the ν-process may be quite difficult.

In sum, while there is no clear direct evidence of the ν-process having altered the abundances in star 18, our Mg I line strengths might conceivably be consistent with a small star-to-star difference that could be accommodated by existing massive SN models that also produce Li. However, we do not regard this observational evidence as very convincing. Independent observations of higher quality would be of great interest because of the astrophysical significance of testing the ν-process. Possibly a more important issue is that if some of the extant SN models investigated here are in fact representative of real stars, then detectable observational signatures of the ν-process on other species present in our spectra may not exist. One possible attack on such a frustrating obstacle would be observations of a variety of elements in numerous near-turnoff stars of other globular clusters. Until such efforts are completed, the effect of ν-process enrichment on globular cluster Li abundances remains an open issue despite the absence of convincing evidence consistent with its operation.

Energetic alpha particles interacting with alpha particles in the ISM can in principle create significant quantities of Li, even exceeding the abundance level of the Spite plateau. T94 suggested that this mechanism could create a Li dispersion in the field halo dwarfs. However, this mechanism operates on a timescale of gigayears and thus would require a significant age spread among the field halo stars. While an age spread of a few to several gigayears is possible for field stars, the presumed coevality of our M92 stars argues against this mechanism as the source of the excess Li in star 18. Conceivably, it might be of interest to investigate whether there are relevant circumstances under which cosmic rays can produce Li on a very short timescale.

In contrast to the above mechanisms, it has been known for quite some time that a small fraction of AGB stars produce significant amounts of Li (Smith & Lambert 1989, 1990). All known metal-poor examples and nearly all Population I examples are also overabundant in *s*-process elements. In fact, the metal-poor stars are *markedly* overabundant (for extended discussion of the data and their relevance to halo stars, see KDB96). However, not only is star 18 *not* overabundant in Ba, the Ba line strengths in star 18 are indistinguishable from those of star 21 (and 46). This argues against a Li production mechanism carrying an *s*-process signature as the source of the excess Li in star 18.

As in DBK95, we have argued against all three Li production mechanisms as the source of the extra Li in star 18. The higher S/N achieved in this study and the measurements of numerous lines have enabled us to carry these arguments further and to strengthen them in the present study. While we still cannot absolutely rule out the possibility of prestellar Li variations or of Li contamination from the sources discussed here or even more exotic sources, a more likely explanation for the high Li in star 18 is differential stellar Li depletion from an even higher initial abundance. Such differential Li depletion is a natural consequence of the Yale models.

4.4. *Relevance of the Remarkable Halo Star BD +23°3912*

Studying Li in field halo stars provides a complementary means to test for Li enrichment and/or stellar Li depletion. Of relevance here is the halo subgiant BD +23°3912, which may be a field analog of M92 star 18. Just like star 18, BD +23°3912 is clearly overabundant in Li relative to other field halo subgiants and dwarfs (Fig. 5). Coincidentally, it also has an identical evolutionary state as star 18, although it is somewhat more metal rich ([Fe/H] = −1.41 [K93 scale] or −1.53 [C83 scale]; DBKD97).

We have recently completed an investigation of Li production signatures in this star (KDB96). *All* elemental abundances observed either by us or by others were found to be normal in this star, except Li. These include C, O, Na, Al, Y, Zr, and Ba, and the upper limits for La, Nd, and Sm are consistent with normal abundances. The normality of the *s*-process abundances argues against Li production carrying an *s*-process signature (such as that carried by all known Li-rich metal-poor AGB stars). The low ratio of $^{6}Li/^{7}Li$ of less than 0.15 argues against cosmic-ray Li production. Finally, since BD +23°3912 is a field star, we could not employ the same test of supernova Li production as we employed here, namely, to compare it with other cluster members. Instead, future studies can potentially search for direct signatures of the neutrino process in BD +23°3912, such as ^{11}B or F.

4.5. *Microscopic Diffusion*

As discussed by Deliyannis et al. (1990), dredge-up of diffused Li in cluster subgiants can provide a test of microscopic diffusion. While it might be tempting to conclude that star 18 shows just such evidence favoring diffusion, diffusion acting alone should not produce a Li dispersion, as observed when comparing star 18 with stars 21 and 46. Such a dispersion is more consistent with the predictions of models with differing degrees of Li depletion from a higher initial Li abundance, such as the Yale rotational models (for additional discussion and for the relevance of BD +23°3912 to diffusion, see KDB96).

5. SUMMARY AND CONCLUSIONS

We have presented observations of seven stars near the turnoff of the old, metal-poor globular cluster M92, taken with the Keck I HIRES spectrograph at $R = 45,000$ (=3 pixels). We have found that star 18 has a Li abundance that is a factor of 2–3 larger than that in stars 21 and 46. We have also found evidence for a dispersion in the Li abundances of three otherwise identical stars, and they were intended to check this finding at higher S/N, to add three more stars to the sample, and to investigate possible Li production mechanisms in more detail.

The high Li abundance in star 18 could be due to either less than average Li depletion from an even higher initial abundance, as predicted by the Yale rotational models, or the extraordinary influence of Li production mechanisms in the material that formed this star (or both). If there has been no Li depletion, then star 18 must be compared with field turnoff stars having the lowest Li abundances; star 18 is 0.6–0.7 dex more Li rich than such stars. In this case, all that extra Li (as well as the higher Li abundances in other field halo stars) must be ascribed to Li production. If, on the other hand, there has been (possibly significant) Li depletion from a higher initial Li abundance, then star 18 can be compared with turnoff stars with the highest Li abundances. The Li abundance in star 18 is comparable to that in the extraordinary Li-rich field halo star BD +23°3912, and only 0.1–0.2 dex larger than other field halo stars with the apparently next highest Li abundances. These stars could have formed with lower than average initial angular momenta. It is potentially possible to distinguish between Li depletion and Li production by searching for Li production signatures. Their absence would favor Li depletion.

The possibility of a significant age spread among field halo stars leads to ambiguities about the possible effects of Li production (DBK95; T94). We have chosen to investigate a uniform-age, presumably uniform initial composition sample of stars to minimize these ambiguities. The uniform age of our M92 stars argues against cosmic-ray production mechanisms requiring age differences of gigayears as the source of the extra Li in star 18. The similarity of Ca, Cr, Fe, Ti, and Ba between stars 18, 21, and 46 argues against supernova Li production. We have examined the possibility of ν-process production of Li but find no observationally convincing concomitant evidence in the line strengths of Mg, Cr, and Fe. Finally, the normal Ba in star 18 argues against a Li production mechanism carrying an *s*-process signature, such as is observed in metal-poor Li-rich AGB stars. Thus, we have found no convincing evidence that favors Li production as the source of the extra Li in star 18. Although it is possible, in principle, to imagine other (possibly unlikely) Li production scenarios, a more attractive explanation for star 18 at present is less than average Li depletion from a still higher primordial abundance.

We have discussed the similarity in the Li abundances of star 18 and BD +23°3912 (KDB96), which provides complementary information as a field-star analog. As in star 18, no evidence has yet been found that Li production is responsible for the extra Li in BD +23°3912, and in fact the absence of their signatures specifically argues against cosmic-ray Li production and AGB Li production (carrying an observable *s*-process signature).

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