Monte-Carlo Analysis of Big Bang Production of Beryllium and Boron

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Abstract
There is continued interest in the possibility that big bang nucleosynthesis may produce significant quantities of Be and B. In this paper we reevaluate the primordial abundances taking into account uncertainties in reactions rates. We discuss the implications for primordial nucleosynthesis, and for galactic cosmic ray spallation.

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1 Introduction

Big bang nucleosynthesis (BBN) has, for almost three decades, been the standard model for the production of the light elements ($^1$H, and $^4$He, with trace amounts of $^2$H, $^3$He and $^7$Li, see Walker et al., 1991; Copi, Schramm and Turner; 1994, Thomas et al. 1995). It is the absence of stable isotopes at masses five and eight which prevents the build-up of significant quantities of heavier species in the big bang. It is possible, however, that some small leakage may occur past this bottleneck, especially in models (such as baryon-inhomogeneous models) which contain regions with high neutron-to-proton ratios. Indeed, as was pointed out by Boyd and Kajino (1989) and by Malaney and Fowler (1989), detection of a primordial abundance of an element like $^9$Be could provide the much-needed test by which we may determine if there were significant inhomogeneities in baryon number in the early universe.

Recently, Thomas et al. (1993, hereafter TSOF) have calculated primordial abundances in the standard (homogeneous) model using a much expanded reaction network, with the aim of determining abundances of $^6$Li, $^9$Be and B. Their conclusions were that in spite of some uncertainties in the reaction rates leading to $^9$Be, it was unlikely that BBN would be able to produce Be or B in the quantities necessary to make detection possible. Furthermore, it has been shown (Thomas et al., 1994) that inhomogeneous models are unable to produce any more Be or B (than the standard, homogeneous, model) without violating the observed limits on the abundances of the light elements. It seems then, that not only is primordial $^9$Be unlikely to provide the desired litmus test between the two models, but it may not be observable under any model of BBN.

The current work on homogeneous production of Be and B is motivated by two recent developments. Data on $^9$Be in old, population II, halo dwarfs has been improving rapidly in the last few years. Indeed Boesgaard and King (1993) have suggested that we may be seeing the first sign of a plateau in the $^9$Be vs. metallicity data. Such a plateau would suggest that the primordial abundance had been discovered. In addition, TSOF concerned
themselves largely with uncertainties in the rates of reactions between Be and B and other heavier elements. While these reactions are certainly important, reactions among the light elements can also have a large effect on the abundances of LiBeB, even though the uncertainties are smaller. Since all species are produced from an initial state consisting only of protons and neutrons, by transforming these through the light elements into the heavier ones, all species are sensitive to rates of reactions between the light elements. In this paper, we reevaluate the abundances of $^6\text{Li}$, $^9\text{Be}$ and B using a monte-carlo technique to take into account the uncertainties in these reactions, and give 2-$\sigma$ uncertainties in the abundances.

2 Observations

The observational data on Be and B in metal-poor halo stars is summarized in figures 1 and 2. The Be data (Rebolo et al., 1988; Ryan et al., 1992; Gilmore, Edvardsson and Nissen, 1991; Gilmore et al., 1992; Boesgaard and King, 1993) shows a definite dependence on metallicity. (We use the usual astrophysical conventions, $[X] \equiv 12.0 + \log(X/H)$ and $[X/H] \equiv \log(X/H) - \log(X/H)_{\odot}$.) If the primordial abundance of $^9\text{Be}$ were within the range covered by the observations, one would expect to see a plateau as the metallicity goes to zero—i.e. the same $^9\text{Be}$ abundance over a range of metallicities. Figure 1 shows little, if any, evidence of a plateau, suggesting that the primordial value is below $[\text{Be}] = -1$. We can take $[\text{Be}] \geq -2$ to be a (very) safe lower limit on the observations.

The data on B is less abundant (Duncan, Lambert and Lemke, 1992; Edvardsson et al., 1994), however there again appears to be an increase in abundance with metallicity. We can safely take $[\text{B}] \geq -1$ as a lower limit on the observations.

There are currently only two observations of $^6\text{Li}$ in metal-poor halo stars (Smith, Lambert & Nissen, 1993; Hobbs & Thorburn, 1994). These show $^6\text{Li}$ at a few percent of total Li ($^6\text{Li}/H \sim \text{a few} \times 10^{-12}$).
3 Results

The theoretical predictions come from a monte-carlo calculation generating 1000 data points for each value of $\eta$. The code is based on the original code of Wagoner (1967; Wagoner, Fowler & Hoyle, 1969). The reaction network has been updated since then; our network is based on that in Thomas et al. (1994). Smith et al. (1993) have summarized the uncertainties in the light element reaction rates. We adopt their values, with the exception that we use the latest world average for the neutron lifetime (Particle Data Group, 1994), $\tau_n = 887.0 \pm 2.0$. The calculation is for standard BBN—homogeneous, with three light neutrino species.

Figure 3 shows primordial abundances (number densities relative to hydrogen) for $^6$Li, $^9$Be, $^{10}$B, $^{11}$B and for the sum of all species with $A \geq 12$. For each species two-sigma bounds are shown. The dip in the $^{11}$B curve is due to the fact that it can be produced directly (for low $\eta$) or as $^{11}$C (for high $\eta$) which then $\beta$-decays to $^{11}$B. It is worth noting that the uncertainty in $^9$Be and $^{10}$B is approximately the same as that due to the uncertainty in the rate of $^7$Li(t,n)$^9$Be (TSOF), although we note that this rate has been measured (Brune et al., 1991).

The best-fit value of $\eta$ is currently the subject of some debate, and will be discussed in detail in a future paper (Thomas et al., 1995). For further detail see, for example, Walker et al. (1991), Copi, Schramm and Turner (1994), Krauss and Kernan (1994). Here, we will simply defer any discussion and assume that $\eta_{10} \equiv 10^{10} \times \eta$ is somewhere between 1 and 10, with a best value around 3 (Walker et al. 1991). The relevant abundances are then those shown (with two-sigma errors) in table 1.

$^9$Be takes its largest value at $\eta_{10} = 1$. Here, it is at least two orders of magnitude below the smallest observed abundance in figure 1. The uncertainty in the predicted abundance is not enough to make up this difference. It is conceivable that $^9$Be might reach the observed levels for sufficiently small $\eta$ (TSOF), but this would imply a $^4$He abundance much lower than that observed in extragalactic HII regions. In addition, the excess $^7$Li
produced would be a problem for models of halo stars, since the $^7$Li would have to be depleted to the level of the observations found on the Spite plateau. Meanwhile, at such low $\eta$, $^2$H and $^3$He would be driven up to a value which would require a complete change in our understanding of galactic chemical evolution.

The $^{10}$B abundance is consistently lower than that of $^{11}$B. Since observations are sensitive only to total B abundance this allows us to concentrate on $^{11}$B. At $\eta_{10} = 3$, $^{11}$B is close to its minimum value of $\sim 10^{-18}$. Its largest value ($\sim 10^{-15}$, for $\eta_{10} \sim 10$) is still two orders of magnitude below the observations. Once again, the uncertainty in the predicted abundance has no significant effect on this conclusion. The abundance does increase with $\eta$ (TSOF), but like the solution to $^9$Be above, this causes difficulties reconciling the light element abundances with observations. High values of $\eta$ overproduce both $^7$Li and $^4$He.

The $^6$Li abundance at $\eta_{10} = 3$ is a factor of 100 lower than the observations. We can reduce this discrepancy by going to a lower value of $\eta$, but again this underproduces $^4$He and overproduces $^7$Li. Worse still, this scenario would require significant depletion of $^7$Li in population II stars and this implies depletion of $^6$Li (Brown & Schramm, 1988). Thus, the $^6$Li discrepancy reappears.

It seems fairly conclusive then, that the primordial abundances of $^6$Li, $^9$Be and B are significantly lower than the current set of observations, and are likely to remain out of reach for the foreseeable future. Given the correlation between Be/B abundances and

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**TABLE 1**

Abundances

| Element       | $\eta_{10} = 1$            | $\eta_{10} = 3$            | $\eta_{10} = 10$           |
|---------------|----------------------------|----------------------------|-----------------------------|
| $^6$Li/H      | $(1.6 \pm 0.2) \times 10^{-13}$ | $(3.2 \pm 0.5) \times 10^{-14}$ | $(5.0 \pm 1.0) \times 10^{-15}$ |
| $^9$Be/H      | $(8.5 \pm 6.0) \times 10^{-17}$ | $(1.6 \pm 0.9) \times 10^{-18}$ | $(4.0 \pm 2.0) \times 10^{-20}$ |
| $^{10}$B/H    | $(2.2 \pm 1.0) \times 10^{-19}$ | $(1.2 \pm 0.1) \times 10^{-19}$ | $(8.0 \pm 1.5) \times 10^{-21}$ |
| $^{11}$B/H    | $(6.6 \pm 3.6) \times 10^{-18}$ | $(1.3 \pm 1.0) \times 10^{-17}$ | $(1.3 \pm 0.5) \times 10^{-15}$ |
| $(A \geq 12)/H$ | $(6.1 \pm 3.0) \times 10^{-15}$ | $(2.4 \pm 1.1) \times 10^{-14}$ | $(6.3 \pm 2.8) \times 10^{-14}$ |
metallicity, this comes as no great surprise. It is likely that the observed abundances are due to processes in the early galaxy, such as cosmic ray spallation of the interstellar medium. Cosmic rays are believed to be responsible for the abundances of $^6\text{Li}$, $^9\text{Be}$, $^{10}\text{B}$ and $^{11}\text{B}$ in population I stars (Walker, Mathews and Viola, 1985). The same mechanism acting on population II stars can produce significant amounts of Li, while remaining consistent with the observed Be abundances (Steigman and Walker, 1992) and with a minimal set of assumptions it is possible to reproduce the observed abundances of LiBeB (Walker et al., 1993).

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Figure Captions

[1.] Observations of Be in halo dwarfs, as a function of metallicity. Data is taken from Rebolo et al., 1988 (RMAB); Gilmore et al., 1991 (GEN); Gilmore et al., 1992 (GGEN); Ryan et al., 1992 (RNBD); Boesgaard & King, 1993 (BK).

[2.] Observations of B in halo dwarfs, as a function of metallicity. Data is taken from Duncan et al., 1992 (DLL); Edvardsson et al., 1994 (EGJ).

[3.] Big Bang Nucleosynthesis abundances (number densities, relative to hydrogen) of $^6\text{Li}$, $^9\text{Be}$, $^{10}\text{B}$, $^{11}\text{B}$ and the sum of all species with $A \geq 12$. Dashed lines show 2-σ bounds.
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