isotopic ratios for MPSs. These have been determined [18] and a high ^{6}Li abundance of ^{6}Li/H$\sim 6\times10^{-12}$ has been suggested. This is $\sim$1000 times higher than the standard BBN prediction. One should be cautious, however, in interpreting these results in that convective motion in stellar atmospheres could cause systematic asymmetries in the observed stellar line profiles and thereby mimic the presence of ^{6}Li [27]. Nevertheless, several MPSs, continue to exhibit high ^{6}Li abundances even after carefully correcting for the convection-triggered line asymmetries [28].

Be and B abundances have also observed in MPSs. ^{9}Be [29–34] and B [35–38] abundances appear to increase roughly linearly as the Fe abundance increases. The absence of a plateau in the abundances of Be and B at low metallicity, however, suggests that these elements are not of primordial origin.

Nonthermal nuclear reactions induced by the decay of exotic particles have been studied [39, 40] as a means to provide a cosmological solution to the Li problems. Nonthermal reactions triggered by the radiative decay of long-lived particles can produce ^{6}Li nuclides up to a level ~ 10 times larger than the observed level without causing discrepancies in abundances of other light nuclei or the CMB energy spectrum [40].

Another solution to the lithium problems of particular interest here is that due to the presence of negatively charged massive particles X^- [41–43] during the BBN epoch. They affect the nucleosynthesis in a different way [1–13]. The X^- particles become electromagnetically bound to positively charged nuclides with binding energies of $\sim O(0.1-1)$ MeV with the largest binding energies for heavier nuclei with larger charges. Since these binding energies are low, the bound states cannot form until late in the BBN epoch. At the low temperatures associated with late times, nuclear reactions are no longer efficient. Hence, the effect of the X^- particles is rather small. Interestingly, however, the X^- particles can catalyze the preferential production of ^{6}Li [1] along with the weak destruction of ^{7}Be [5, 6].

A large enhancement of the ^{6}Li abundance was first suggested [1] to result from an X^- bound to ^{4}He (denoted as ^{4}He$_X$). This enables the X^--catalyzed transfer reaction of ^{4}He$_X(d,X^-)^6$Li, whose cross section could be seven orders of magnitude larger than the corresponding BBN ^{4}He$(d,\gamma)^6$Li reaction. The cross section for this reaction, however, was calculated in a more rigorous quantum three-body model [4] and shown to be about an order of magnitude smaller than the estimate adopted in Ref. [1].

Additional enhancements in X^--catalyzed transfer reaction rates for the ^{4}He$_X(t,X^-)^7$Li, ^{4}He$_X(^3$He$,X^-)^7$Be, and ^{6}Li$_X(p,X^-)^7$Be reactions were assumed in Ref. [3]. The rates for those reactions are, however, not as greatly enhanced as that of the ^{4}He$_X(d,X^-)^6$Li because they involve a $\Delta l = 1$ angular momentum transfer and consequently a large hindrance of the nuclear matrix element [6]. This has been confirmed in recent detailed quantum many-body calculations [9].

The resonant ^{7}Be$_X(p,\gamma)^8$B$_X$ reaction through the first atomic excited state of ^{8}B$_X$ was suggested [5] as a means to reduce the primordial ^{7}Li abundance [51]. A rate for this reaction has been calculated in a rigorous quantum three body model [9], which roughly reproduces the value of Ref. [5] but is somewhat inefficient in destroying ^{7}Be$_X$. The resonant reaction ^{7}Be$_X$+p $\to^8$B*(1$^+$, 0.770 MeV)$_X$ $\to^8$B$_X$+γ through the atomic ground state of ^{8}B*(1$^+$,0.770 MeV)$_X$, i.e., an atom consisting of the 1^+ nuclear excited state of ^{8}B and an X^- particle has also been proposed [6] as a process for ^{7}Be$_X$ destruction. From a more realistic estimate of binding energies between nuclides and X^- particles [7], this resonant reaction was found to exist, but the resonance energy level is too high to efficiently destroy ^{7}Be$_X$.

The ^{8}Be$_X$+p $\to^9$B$^{*a}_X$ $\to^9$B$_X$+γ reaction through the ^{9}B$^{*a}_X$ atomic excited state of ^{9}B$_X$ has also been studied [7]. However this reaction was found to be not operative because its resonance energy is relatively large (see Table 2 of Ref. [7]). A resonant reaction ^{8}Be$_X(n,X^-)^9$Be through the atomic ground state of ^{9}Be*(1/2$^+$,1.684 MeV)$_X$, i.e., an atom composed of the 1/2+ nuclear excited state of ^{9}Be and an X^- particle, has also been suggested as a possible reaction to produce mass 9 nuclides [10]. Kamimura et al. [9], however, adopted a root mean square charge radius for ^{8}Be of 3.39 fm as a more realistic input. They then found that ^{9}Be*(1/2$^+$, 1.684 MeV)$_X$ is not a resonance but a bound state located below the ^{8}Be$_X$+n threshold. The resonant ^{8}Be$_X(n,X^-)^9$Be$_X$ reaction is thus not likely to contribute.

Neutral X-nuclei, i.e., p_X, d_X and t_X have also been suggested [8] as a means to produce and destroy Li and Be through two α-induced X^- stripping reactions $d_X(\alpha,X^-)^6$Li and $t_X(\alpha,X^-)^7$Li, and three p_X induced stripping reactions $p_X(^6$Li$,^3$He$\alpha)X^-$, $p_X(^7$Li$,2\alpha)X^-$ and $p_X(^7$Be$,^8$B$)X^-$. The result, however, relies on reaction rates calculated within the framework of the Born approximation, which is a poor approximation in this low-energy regime [9, 42]. The rates for those reactions and those for charge-exchange reactions of $p_X(\alpha,p)\alpha_X$, $d_X(\alpha,d)\alpha_X$ and $t_X(\alpha,t)\alpha_X$ have been calculated in a rigorous dynamical quantum many-body treatment in Ref. [9]. They found that the cross sections for the charge-exchange reactions were much larger than those of the nuclear reactions, and that the neutral bound states p_X, d_X and t_X were immediately changed to α_X before they could react with ambient nuclei. The late time production and destruction of Li and Be, therefore, do not significantly affect the BBN as shown in this letter.

The solution to the lithium problems in this catalyzed BBN model have been explored by solving the full Boltzmann equations for the recombination and the ionization of nuclides and X^- particles coupled to the nuclear reactions [6–8]. Constraints on specific supersymmetric models through the catalyzed BBN calculation have been obtained in Refs. [3, 11, 12, 44, 45].