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Simultaneous solution to the ^{6}Li and ^{7}Li big bang nucleosynthesis problems from a long-lived negatively charged leptonic particle

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The ^{6}Li abundance observed in metal-poor halo stars exhibits a plateau similar to that for ^{7}Li suggesting a primordial origin. However, the observed abundance of ^{6}Li is a factor of 10^3 larger and that of ^{7}Li is a factor of 3 lower than the abundances predicted in the standard big bang when the baryon-to-photon ratio is fixed by Wilkinson microwave anisotropy probe. Here we show that both of these abundance anomalies can be explained by the existence of a long-lived massive, negatively charged leptonic particle during nucleosynthesis. Such particles would capture onto the synthesized nuclei thereby reducing the reaction Coulomb barriers and opening new transfer reaction possibilities, and catalyzing a second round of big bang nucleosynthesis. This novel solution to both of the Li problems can be achieved with or without the additional effects of stellar destruction.

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I. INTRODUCTION

It has recently been pointed out (e.g., [1]) that the abundances of both ^{6}Li and ^{7}Li observed in metal-poor halo stars (MPHSs) are not in agreement with those predicted from standard big bang nucleosynthesis (BBN). Specifically, the ^{6}Li abundance as a function of metallicity exhibits a plateau similar to that for ^{7}Li in very metal-poor stars, suggesting a primordial origin for both isotopes. This ^{6}Li abundance plateau, however, is a factor of $\sim 10^3$ larger than that predicted by BBN. A less severe problem exists for ^{7}Li; the BBN value based upon the baryon-to-photon ratio fixed by the Wilkinson microwave anisotropy probe (WMAP) analysis [2] of the cosmic microwave background (CMB) is roughly a factor of 3 higher than is observed.

Moreover, a long-standing effort in cosmology has been the search for evidence of unstable particles that might have existed in the early universe. It is thus natural to ask whether the two lithium abundance anomalies might be a manifestation of the existence of such a particle. In this context, a number of possible solutions to the ^{6}Li problem have been proposed which relate the Li anomalies to the possible existence of unstable particles in the early universe [3]. This has been extended in several recent studies [4–9] to consider heavy negatively charged decaying particles that modify BBN, but in rather different ways. In these latter studies, the heavy particles, here denoted as X^-, bind to the nuclei produced in BBN to form X-nuclei. The massive X^- particles would be bound in orbits with radii comparable to those of normal nuclei. Hence, they would reduce the reaction Coulomb barriers thereby enhancing the thermonuclear reaction rates and extending the duration of BBN to lower temperatures.

Pospelov [4] suggested that a large enhancement of the ^{6}Li abundance could result from a transfer reaction involving an X^- bound to ^{4}He (denoted $^4\text{He}_X$), i.e. $^4\text{He}_X(d, X^-)^6$Li. Although this was an intriguing idea, Hamaguchi *et al.* [9] have recently pointed out via a more complete quantum mechanical calculation that Pospelov's estimate for the $^4\text{He}_X(d, X^-)^6$Li cross section was too large; this leads to too high a ^{6}Li abundance. Cyburt *et al.* [5] further motivated this hypothesis by identifying the X^- as the supersymmetric partner of the tau lepton, i.e., a stau, and considered X^- transfer reactions for ^{7}Li and ^{7}Be production, too. Although their calculation is based on a fully dynamical treatment of the recombination of nuclei with X^- particles and also of BBN, they used cross sections for all X^- transfer reactions involving ^{6}Li, ^{7}Li, and ^{7}Be that were too large, as we discuss below. Therefore, the calculated abundances are to be viewed with caution. Kaplinghat and Rajaraman [6] observed that the decay of an X^- when bound to ^{4}He would occasionally knock out a proton or neutron to produce ^{3}He or ^{3}H, thereby enhancing their abundances and the abundance of ^{6}Li through reactions with other primordial ^{4}He nuclei at higher energies. Kohri and Takayama [7] studied the recombination of nuclei with X^- particles, and suggested the possibility of solving the ^{7}Li problem. However, they did not carry out dynamical calculations involving recombination processes and BBN simultaneously. This forced them to introduce artificial parameters for the fractions of the captured nuclei, which turn out to be different from the fractions obtained by solving the recombination plus BBN

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fully dynamically. A new resonant reaction $^7\mathrm{Be}_X(p,\gamma)^8\mathrm{B}_X$ has recently been proposed by Bird *et al.* [8] that destroys $^7\mathrm{Be}_X$ through an atomic excited state of $^8\mathrm{B}_X$, and the present study identifies another effect in this reaction that might also destroy ^{7}Be. Thus there has been a great deal of recent progress in X^- catalyzed BBN in three important aspects: the simultaneous description of recombination and ionization processes of X^- particles with nuclei in the description of BBN, use of updated reaction rates involving the *X*- nuclei, and inclusion of new resonant processes by which ^{7}Be is destroyed. No previous calculation has involved all of these effects in a single dynamical calculation of BBN in order to study their effects on the ^{6}Li and ^{7}Li problems.

In this paper, we present the results of a thorough dynamic analysis of the effects of X^- particles on BBN. The important difference from previous works is, first, that we carried out a fully dynamical BBN calculation by taking account of the recombination and ionization processes of X^- particles by normal and *X*-nuclei as well as the many possible nuclear reactions among them. Second, the reaction rates on normal and *X*-nuclei used in the present study are based on quantum mechanical calculations of the cross section like those of Hamaguchi *et al.* [9], which we believe to be correct. Third, we have not only included the important ^{7}Be destruction mechanism identified by Bird *et al.* [8], but have identified another potentially important destruction mechanism involving the reaction channel $^7\mathrm{Be}_X + p \rightarrow {}^8\mathrm{B}^*(1^+, 0.770\ \mathrm{MeV})_X \rightarrow {}^8\mathrm{B}_X + \gamma$ which has the potential to destroy $^7\mathrm{Be}_X$ via capture through the 1^+ nuclear excited state of ^{8}B. We show that when all these effects are included, the single hypothesis of the existence of the X^- particle provides a remarkable solution to both the ^{6}Li and ^{7}Li abundance anomalies. We can then use this constraint to place interesting limits on the X^- relic abundance and its decay lifetime and mass.

II. MODEL

We assume that the X^- particle is leptonic and of spin 0, consistent with its identification as the supersymmetric partner of a lepton. The X^- would be thermally produced at an earlier epoch together with X^+. Their small annihilation cross section allows a significant abundance to survive to the BBN epoch. The mass and decay lifetime of the X^- is ultimately constrained by WMAP and the present BBN study. Only the X^- can bind to nuclei and the X^+ remains inert during BBN. The binding energies and the eigenstate wave functions of the *X*-nuclei were calculated by assuming uniform finite-size charge distributions of radii $r_0 = 1.2A^{1/3}$ fm for nuclear mass number A [10]. When the X^- abundance is very high, some nuclei can bind two X^- particles, such as $^3\mathrm{He}_{XX}$ and $^4\mathrm{He}_{XX}$. In that case their binding energies were calculated using a variational calculation with a trial wave function for *X*-nuclides bound to one X^- particle, analogous to the case of the H_2^+ ion.

Thermonuclear reaction rates (TRRs) for all reactions that might take place in X^- catalyzed BBN, including the X^- transfer reaction suggested in [4] and X^- decay, were added to the BBN network code. See Kusakabe *et al.* [11] for details on the calculations. These were corrected for the modified nuclear charges and the effective mass resulting from the binding of one or two X^- particle(s). If the X^- decayed at some later stage, they would be expected to destroy some fraction of the nuclei to which they had become bound during BBN. However, that fraction would be small [6,12]. We found that the inclusion of the *X*-nuclei $^8\mathrm{Be}_X$ and $^8\mathrm{Be}_{XX}$ (both are bound) results in a leakage of the nuclear reaction flow out of the light nuclei or *X*-nuclei to produce slightly heavier $A \geq 9$ nuclei. This might be an additional BBN signature resulting from binding the X^- particles. We determined most thermonuclear reaction rates involving the *X*-nuclei by taking account of the lowered Coulomb barriers and modified reduced masses. However, as discussed below, there are a number of reactions that require careful additional considerations.

As noted by Pospelov [4], reactions in which an X^- particle is transferred can be very important in circumventing some normally inhibited reactions, especially the $^4\mathrm{He}_X(d, X^-)^6\mathrm{Li}$ reaction. Its rate could be orders of magnitude larger than that of the $^4\mathrm{He}(d,\gamma)^6\mathrm{Li}$ reaction, which is suppressed due to its occurrence through an electric quadrupole transition. Hamaguchi *et al.* [9] have recently carried out a theoretical calculation of the cross section for $^4\mathrm{He}_X(d, X^-)^6\mathrm{Li}$ in a quantum three-body model. Their value was about an order of magnitude smaller than that of [4]. This difference can be attributed to the use of an exact treatment of quantum tunneling and a better nuclear potential. We, therefore, adopt the result of [9] in the present study.

Cyburt *et al.* [5] estimated astrophysical S-factors for the $^4\mathrm{He}_X(t, X^-)^7\mathrm{Li}$, $^4\mathrm{He}_X(^3\mathrm{He}, X^-)^7\mathrm{Be}$, $^6\mathrm{Li}_X(p, X^-)^7\mathrm{Be}$, and other reactions by applying a scaling relation [4], $S_X/S_\gamma \propto p_\mathrm{f}a_0/(\omega_\gamma a_0)^{2\lambda+1}$. Here, S_X and S_γ are the S-factors for the X^- transfer and radiative processes, respectively, a_0 is the X^- Bohr radius of $^4\mathrm{He}_X$ or $^6\mathrm{Li}_X$, p_f is the linear momentum of the outgoing ^{7}Li or ^{7}Be in the X^- transfer reactions, and ω_γ is the energy of the emitted $\lambda = 1$ (electric dipole) photon in the radiative capture. However, the reaction dynamics are important to these results.

^{4}He, ^{6,7}Li, and ^{7}Be occupy an s-wave orbit around the X^- particle (assuming the X^- particle to be much heavier than these nuclei). The ^{6}Li nucleus is an $\alpha + d$ cluster system in a relative s-wave orbit, while the $A = 7$ nuclei are $\alpha + t$ and $\alpha + {}^3$He cluster systems in relative p-wave orbits. This difference in the orbital angular momentum will produce a critical difference in the reaction dynamics between the $^4\mathrm{He}_X(d, X^-)^6\mathrm{Li}$ and the $^4\mathrm{He}_X(t, X^-)^7\mathrm{Li}$, $^4\mathrm{He}_X(^3\mathrm{He}, X^-)^7\mathrm{Be}$, and $^6\mathrm{Li}_X(p, X^-)^7\mathrm{Be}$ reactions.

Specifically, the latter three reactions must involve $\Delta l = 1$ angular momentum transfer. In order to conserve total angular momentum, the outgoing ^{7}Li and ^{7}Be in the final state must therefore occupy a scattering p-wave orbit from the X^- particle, leading to a large hindrance of the overlap matrix for the X^- transfer processes. Thus, a realistic quantum mechanical calculation results in much smaller S_X-factors than those estimated in [5]. Therefore, in the present study, the above three reaction processes were found to be negligible and were therefore omitted.

Bird *et al.* [8] suggested that the $^7\mathrm{Be}_X(p,\gamma)^8\mathrm{B}_X$ resonant reaction could destroy $^7\mathrm{Be}_X$ through an atomic excited state of $^8\mathrm{B}_X$. They also proposed that a charged weak-boson exchange reaction $^7\mathrm{Be}_X \to {}^7\mathrm{Li} + X^0$ followed by $^7\mathrm{Li}(p,\alpha)^4\mathrm{He}$ could destroy $A = 7$ nuclides. We included only the former resonant reaction in the present study, although we confirmed their assertion on the weak process as will be discussed in a separate paper.

In our exhaustive study of additional processes related to ^{6}Li, ^{7}Li, and ^{7}Be destruction, we found that the reaction channel which proceeds through the 1^+, $E^* = 0.770 \pm 0.010$ MeV nuclear excited state of ^{8}B via $^7\mathrm{Be}_X + p \to {}^8\mathrm{B}^*(1^+, 0.770\ \mathrm{MeV})X \to {}^8\mathrm{B}_X + \gamma$ could also destroy some $^7\mathrm{Be}_X$, and that the destruction processes $^6\mathrm{Li}_X(p,{}^3\mathrm{He})^4\mathrm{He}_X$, $^7\mathrm{Li}_X(p,\alpha)^4\mathrm{He}_X$ might also be significant.

Our calculated binding energies of the X^- particle in $^7\mathrm{Be}_X$ and $^8\mathrm{B}_X$ are, respectively, 1.488 and 2.121 MeV. Adopting these values without any correction to the energy levels of the nuclear excited states of $^8\mathrm{B}_X$, this 1^+ state of $^8\mathrm{B}_X$ is located near the particle threshold for the $^7\mathrm{Be}_X + p$ separation channel. Thus, the $^7\mathrm{Be}_X(p,\gamma)^8\mathrm{B}_X$ reaction can proceed through a zero-energy resonance of $^8\mathrm{B}_X^*$. However, the measured energy uncertainty of the 1^+ state of ^{8}B is ± 10 keV, and moreover, the excitation energy of this level is very sensitive to the model parameters used to calculate the binding energies of the X-nuclei. Even such a small uncertainty of the resonance energy as 10–100 keV would dramatically change the TRR because the BBN catalyzed by the X-nuclei proceeds at effective temperatures as low as $T_9 \sim 0.1$. Taking account of the uncertainties associated with the 1^+ resonance energy, E, from the $^7\mathrm{Be}_X + p$ separation threshold, we found that $E \approx 30$ keV maximizes the TRR. This threshold energy would be achieved when, for example, the uniform charge radii are 2.2955 fm for $^7\mathrm{Be}_X$ and 2.4564 fm for $^8\mathrm{B}_X$, respectively. This resonant reaction is potentially as effective as $^7\mathrm{Be}_X + p \to {}^8\mathrm{B}_X^{*a} \to {}^8\mathrm{B}_X + \gamma$ in destroying ^{7}Be. However, the charge radii we have adopted tend to be smaller than the measured charge radii, and this might overestimate the binding energies of X^-. If a more realistic calculation were performed, the resulting binding energies might shift this 1^+ excited state upward, which would diminish the effect of this destruction process. In addition, the transition through this state would be E2 or M1, which might also weaken its effect. Even in this case, though, the atomic resonance $^8\mathrm{B}_X^{*a}$ [8] plays the important role in destroying $^7\mathrm{Be}_X$.

Since it is important to know precisely when during BBN the X^- particles become bound to nuclei, and what their distribution over the BBN nuclei would be [7] at any time, it is necessary to consider the thermodynamics associated with binding the X^- particles. We thus included both recombination and ionization processes for X^- particles in our BBN network code and dynamically solved the set of rate equations to find when the X-nuclei decoupled from the cosmic expansion.

Regarding the thermonuclear reaction rates, we note that since the mass of the X^- particle m_X is assumed to be $\gtrsim$ 50 GeV, the reduced mass for the $X^- + A(N,Z)$ system can be approximated as $\mu_X \equiv m_A m_X/(m_A + m_X) \approx m_A$, rendering the thermonuclear reaction rate for the first recombination process $A(X^-,\gamma)A_X$ [7] to be $\langle\sigma_r v\rangle_X \approx 2^9\pi\alpha Z^2(2\pi)^{1/2}/(3\exp(4.0))E_{\mathrm{bind}}/(\mu_X^2(\mu_X T)^{1/2}) \propto m_A^{-2.5}$, where α is the fine structure constant. This rate is almost independent of m_X. However, the rate for the second recombination process $A_X(X^-,\gamma)A_{XX}$ is dependent upon m_X, i.e., $\langle\sigma_r v\rangle_{XX} \approx 2^9\pi\alpha(Z-1)^2 \times (2\pi)^{1/2}/(3\exp(4.0))E_{\mathrm{bind}}/(\mu_{XX}^2(\mu_{XX}T)^{1/2}) \propto m_X^{-2.5}$. This arises because $\mu_{XX} \equiv m_{AX}m_X/(m_{AX} + m_X) \approx m_X/2$. Since m_X is assumed to be much larger than the mass of the light nuclei $m_X \gg m_A$, the rate for the second or higher-order recombination process is hindered.

III. RESULTS

The evolution of the BBN abundances when X^- particles are included exhibits some particularly notable features. During the nucleosynthesis epoch, the abundances for ^{6}Li, ^{7}Li, and ^{7}Be assume their normal BBN values until the temperature reaches $T_9 \sim 0.5$–0.2. Below that temperature the X^- particles bind to the heaviest nuclides, ^{7}Li and ^{7}Be. When the abundance ratio, Y_X, of X^- particles to baryons is larger than 0.1, these nuclides are then partially destroyed by reactions that would have previously been inhibited by the Coulomb barrier. At around $T_9 = 0.1$, the X^- particles are captured onto ^{4}He. Then a new round of X-nuclei nucleosynthesis occurs. In particular, the reaction $^4\mathrm{He}_X(d,X^-)^6\mathrm{Li}$ produces normal ^{6}Li nuclei with an abundance which is orders of magnitude above that from standard BBN. An interesting feature is that the ^{6}Li formed in this way is not easily destroyed by the $^6\mathrm{Li}(p,\alpha)^3\mathrm{He}$ reaction, the dominant ^{6}Li destruction reaction in BBN, because the X^- transfer reaction restores the charge to ^{6}Li. Hence, the Coulomb barrier is too high at this temperature for its destruction resulting in a large $^6\mathrm{Li}/^7\mathrm{Li}$ abundance ratio.

The final calculated abundances of the mass 6 and 7 nuclides, however, depend strongly on the assumed X^- abundance. At high X^- abundance levels, more than one X^- capture can occur. Although the abundance of these multiple X^- bound particles is too small to significantly contribute to BBN, they nevertheless interact readily since their Coulomb barriers are greatly reduced. This is especially true of charge-neutral $^4\mathrm{He}_{XX}$. To clarify the nucleosynthesis yields, we have thus made a study in which the X^- abundance Y_X was varied over a wide range.

In Fig. 1 we show contours of an interesting region in the decay lifetime τ_X vs Y_X plane. Curves are drawn for constant lithium abundance relative to the observed value in MPHSs, i.e., d(^{6}Li) $= {}^6\mathrm{Li}^{\mathrm{Calc}}/{}^6\mathrm{Li}^{\mathrm{Obs}}$ (solid curves) and d(^{7}Li) $= {}^7\mathrm{Li}^{\mathrm{Calc}}/{}^7\mathrm{Li}^{\mathrm{Obs}}$ (dashed curves) for several values of the stellar depletion factor "d". The adopted abundances are $^7\mathrm{Li/H} = (1.23^{+0.68}_{-0.32}) \times 10^{-10}$ [13] and $^6\mathrm{Li/H} = (7.1 \pm 0.7) \times 10^{-12}$ [1]. Shaded regions for the d(^{6}Li) $= 1$ and d(^{7}Li) $= 1$ curves illustrate the 1σ uncertainties in the adopted observational constraints based upon the dispersion of the observed plateaus. We also show curves for stellar depletion factors of d(^{7}Li) $= 2, 3$ and d(^{6}Li) $= 4, 25$. Since ^{6}Li is more fragile to stellar processing than ^{7}Li [14], its possible depletion factors could be larger than those for ^{7}Li.

The main point of this figure is that, independent of stellar destruction, it is possible to find a simultaneous solution to both the ^{7}Li overproduction problem and the ^{6}Li underproduction problem. This occurs in the parameter region $Y_X \approx 0.09$–0.6, $\tau_X \approx (1.6$–$2.8) \times 10^3$ s consistent with the suggestion of [8]. Assuming that the products of the decaying X^- particles are progenitors of the cold dark matter (CDM) particles, the WMAP-CMB observational constraint on $\Omega_{\mathrm{CDM}} = 0.2$ limits the mass of the X^-, i.e., $Y_X m_X \lesssim 4.5$ GeV and $m_X \lesssim 50$ GeV when we include the destruction reaction processes of $A = 7$ nuclide $^7\mathrm{Be}_X + p \to {}^8\mathrm{B}_X^{*a} \to {}^8\mathrm{B}_X + \gamma$ [8] and (assumed maximal value of the) $^7\mathrm{Be}_X + p \to {}^8\mathrm{B}^*(1^+, 0.770\ \mathrm{MeV})_X \to {}^8\mathrm{B}_X + \gamma$. When we include the destruction process $^7\mathrm{Be}_X \to {}^7\mathrm{Li} + X^0$ [8], these parameter ranges slightly change to $Y_X \approx 0.04$–0.1, $\tau_X \approx (1.8$–$3.2) \times 10^3$ s, and $m_X \lesssim 100$ GeV. Figure 2 illustrates the final calculated BBN yields as a function of baryon-to-photon ratio η for the case of $(Y_X, \tau_X) = (0.6, 1.6 \times 10^3\ \mathrm{s})$. This choice leads to ^{6}Li

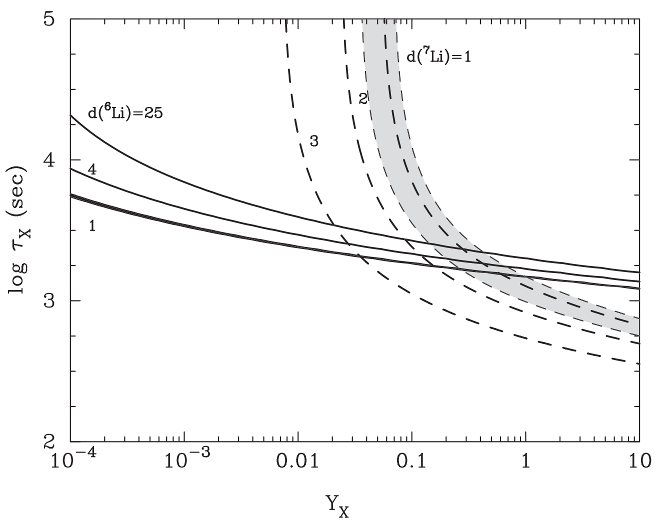

FIG. 1. Contours of constant lithium abundance relative to the observed value in MPHSs, i.e., d(^{6}Li) $= {}^6\mathrm{Li}^{\mathrm{Calc}}/{}^6\mathrm{Li}^{\mathrm{Obs}}$ (solid curves) and d(^{7}Li) $= {}^7\mathrm{Li}^{\mathrm{Calc}}/{}^7\mathrm{Li}^{\mathrm{Obs}}$ (dashed curves). The adopted abundances are $^7\mathrm{Li}/H = (1.23^{+0.68}_{-0.32}) \times 10^{-10}$ [13] and $^6\mathrm{Li}/H = (7.1 \pm 0.7) \times 10^{-12}$ [1]. Shaded regions for the d(^{6}Li) $= 1$ and d(^{7}Li) $= 1$ curves illustrate the 1σ uncertainties in the adopted observational constraints based upon the dispersion of the observed plateaus.

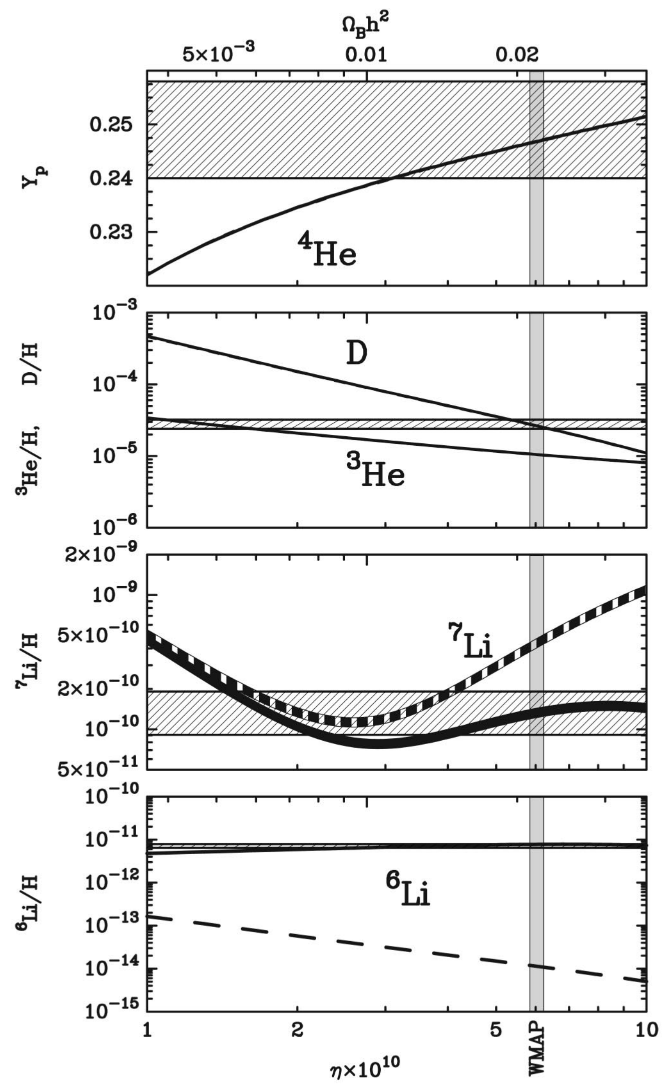

FIG. 2. Abundances of ^{4}He (mass fraction), D, ^{3}He, ^{7}Li, and ^{6}Li (by number relative to H) as a function of the baryon-to-photon ratio η or $\Omega_B h^2$. The dashed and solid curves are, respectively, the calculated results in the standard BBN and the X^- catalyzed BBN for the case of $(Y_X, \tau_X) = (0.6, 1.6 \times 10^3\ \mathrm{s})$. There is virtually no difference between the dashed and solid curves for ^{4}He, D, and ^{3}He. The band of theoretical curve for each nucleus displays 1σ limits taken from [15]. The hatched regions represent the adopted abundance constraints from [16] for ^{4}He, [17] for D, [13] for ^{7}Li, and [1] for ^{6}Li, respectively. The vertical stripe represents the $1\sigma \Omega_B h^2$ limits provided by WMAP [2].

and ^{7}Li abundances consistent with the observed values without stellar depletion. Note, though, that the same conclusion is reached if the destruction reaction through the ^{8}B(1^+) state is not included, so the general conclusion is robust.

IV. SUMMARY

In summary, we have investigated light-element nucleosynthesis during BBN taking into account the possibility of massive, negatively charged X^- particles which would bind to the light nuclei. When the chemical and kinetic processes associated with such particles are included in a BBN code in a fully dynamical manner, along with the reactions enabled by the X^- particles, the X^- particles are found to enhance the reaction rates in BBN, both by reducing the charge of the resulting X-nuclei, and by enabling transfer reactions of the X^- particles. X^- particles greatly enhance the production of ^{6}Li, primarily from the X^- transfer reaction $^4\mathrm{He}_X(d, X^-)^6\mathrm{Li}$. The ^{7}Li abundance, however, decreases when the X^- particle abundance is larger than 0.1 times the total baryon abundance. In this case, the ^{7}Li abundance decreases with the X^- particle abundance due to the inclusion of two resonance channels for $^7\mathrm{Be}_X(p, \gamma)^8\mathrm{B}_X$ through the nuclear and atomic excited states of $^8\mathrm{B}_X$. It was found to be important to predict precisely the binding energies and excited states of exotic X-nuclei in realistic quantum mechanical calculations. Both abundance ratios of $^6\mathrm{Li/H}$ and $^7\mathrm{Li/H}$ observed in MPHSs are obtained with an appropriate choice for the lifetime and abundance of the X^- particle. These observational constraints imply a lifetime and abundance roughly in the range of $\tau_X \sim 2 \times 10^3$ s and $Y_X \sim 0.1$. We deduce that this Y_X value requires that $m_X \sim 50$ GeV in order to guarantee that this abundance of X^- particles survives to the epoch of nucleosynthesis.

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