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Solution to Big-Bang nucleosynthesis in hybrid axion dark matter model

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ABSTRACT

Following a recent suggestion of axion cooling of photons between the nucleosynthesis and recombination epochs in the Early Universe, we investigate a hybrid model with both axions and relic supersymmetric particles. In this model we demonstrate that the ^{7}Li abundance can be consistent with observations without destroying the important concordance of deuterium abundance.

1. Introduction

Low-metallicity halo stars exhibit a finite ^{7}Li abundance, suggesting the primordial origin of ^{7}Li [1]. However, the amount of ^{7}Li needed to be consistent with the cosmic microwave background observations [2] is significantly more than ^{7}Li observed in old halo stars [3]. Even though ^{7}Li can be both produced and destroyed in stars, old halo dwarf stars are thought to have gone through little nuclear processing. However, for an alternative scenario see [4]. Recent improvements in the observational and experimental data seem to make the discrepancy worse [5,6]. One possible solution is to invoke either nuclear physics hitherto excluded from the Big-Bang Nucleosynthesis (BBN) [7,8] or new physics such as variations of fundamental couplings [9,10], and particles not included in the Standard Model [11–44]. If a relic long-lived charged particle (X^-) existed in BBN epoch, it binds to ^{7}Be to form ^{7}Be$_X$ which is destroyed by proton capture reaction through both atomic [42] and nuclear [37] excited state of ^{8}B$_X$. This scenario provides one solution to the lithium problem since a ^{7}Be destruction in BBN epoch leads to an overall reduction of primordial ^{7}Li abundance. However, model parameters, i.e., the lifetime and abundance of X^-, must be fine-tuned in order to escape from an overproduction of ^{6}Li [30]. The abundance of X^- must be higher than that of baryon (e.g. Refs. [38,40]). Such a high abundance is, however, referred with caution [30]. Effects of massive neutral relic particles on BBN were also extensively studied [11–29], which will be explained later in detail.

More recently an alternative solution to the lithium puzzle was proposed. Since the last photon scattering occurs after the end of the nucleosynthesis, one can search for a mechanism for the cooling of photons before they decouple. It was suggested that dark matter axions could form a Bose–Einstein condensate (BEC) [45,46]. Such a condensate would cool the photons between the end of BBN and epoch of photon decoupling, reducing the baryon-to-photon ratio WMAP infers, as compared to its BBN value [47]. An alternative mechanism for such a cooling is resonant oscillations between photons and light abelian gauge bosons in the hidden sector [48]. There are two *prima facie* problems with the axion BEC-photon cooling hypothesis: it overpredicts primordial deuterium (D) abundance as well as the effective number of neutrinos. Even though D is easy to destroy, one does not expect the sum of abundances of D and ^{3}He to change significantly in the course of cosmic evolution [49]. Hence it is important to find a parameter region in which predicted abundances of D and ^{7}Li are consistent with observations. In this Letter we demonstrate the existence of such a parameter region using a model with axions and massive relic particles.

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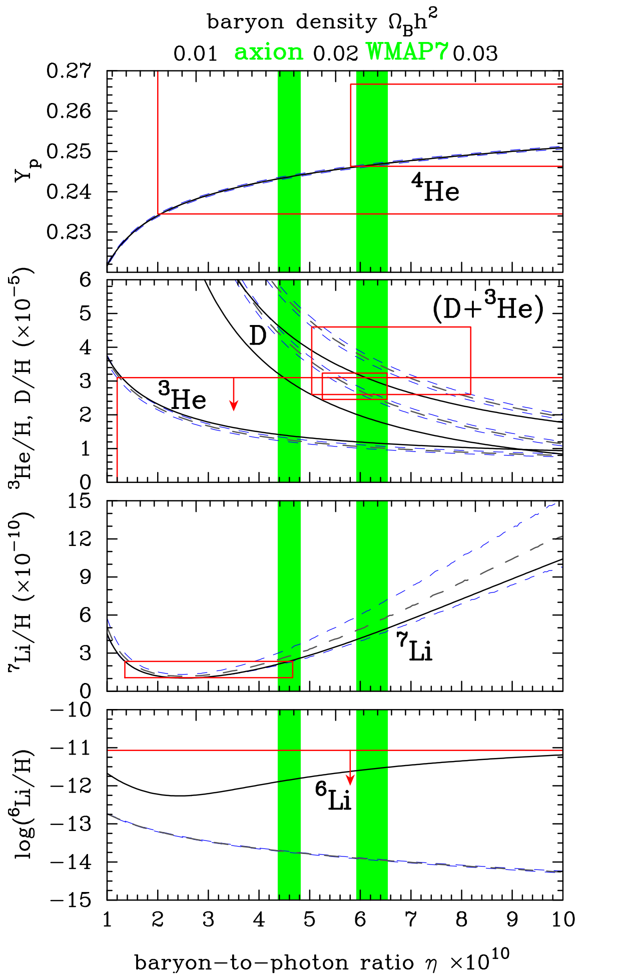

Fig. 1. Abundances of ^{4}He (mass fraction), D, ^{3}He, ^{7}Li and ^{6}Li (number ratio relative to H) as a function of the baryon-to-photon ratio η or the baryon energy density parameter $\Omega_B h^2$ of the universe. The thick dashed curves are for SBBN. The thin dashed curves around them show the regions of 95% C.L. in accordance with the nuclear reaction rate uncertainties. The boxes correspond to the adopted abundance constraints on the SBBN model. The vertical stripes represent the 2σ limits on $\Omega_B h^2$ or η for the SBBN model (taken from the constraint by WMAP [51] and labeled as WMAP7) and for the axion BEC model (labeled as axion). The solid curves are the results obtained with the long-lived decaying particle model with parameters fixed to $(\tau_X, \zeta_X) = (10^6\ \text{s},\ 2 \times 10^{-10}\ \text{GeV})$ (see text).

2. The hybrid model

We carried out BBN network calculations using Kawano's code [52,53] by including Sarkar's correction for ^{4}He abundances [54]. We checked our code against the publicly available code PArthENoPE 1.0 [55] with their uncertainties being included [56], and found that the differences in D, ^{3}He, and ^{7}Li abundances between two codes are less than 0.8%, and that for ^{4}He is less than 0.2%. JINA REACLIB Database V1.0 [57] is used for light nuclear ($A \leqslant 10$) reaction rates including uncertainties together with data [58–60]. Adopted neutron lifetime is $878.5 \pm 0.7_{\rm stat} \pm 0.3_{\rm sys}$ s [61] based on improved measurements [50]. Taking into account the uncertainties in these rates [57], we employ regions of 95% C.L. in our calculations.

We compare our results with the abundance constraints from observations. For the primordial D abundance, the mean value estimated from Lyman-α absorption systems in the foreground of high redshift quasi-stellar objects is $\log(\text{D/H}) = -4.55 \pm 0.03$ [62]. We adopt this value together with a 2σ uncertainty, i.e., $2.45 \times 10^{-5} < \text{D/H} < 3.24 \times 10^{-5}$. ^{3}He abundance measurements in Galactic HII regions through the 8.665 GHz hyperfine transition of ^{3}He$^+$ yield a value of $^3\text{He/H} = (1.9 \pm 0.6) \times 10^{-5}$ [63]. Although the constraint should be rather weak considering its uncertainty, we take a 2σ upper limit and adopt $^3\text{He/H} < 3.1 \times 10^{-5}$.

We also utilize a limit on the sum of primordial abundances of D and ^{3}He taken from an abundance for the protosolar cloud determined from observations of solar wind, i.e., $(\text{D} + {}^3\text{He})/H = (3.6 \pm 0.5) \times 10^{-5}$ [64]. This abundance can be regarded as constant at least within the standard cosmology since it is not affected by stellar activities significantly despite an effect of D burning into ^{3}He via ^{2}H$(p, \gamma)^3$He would exist [49].

For the primordial ^{4}He abundance, we adopt two different constraints from recent reports: $Y_{\rm p} = 0.2565 \pm 0.0051$ [65] and $Y_{\rm p} = 0.2561 \pm 0.0108$ [66] both of which are derived from observations of metal-poor extragalactic HII regions. Adding 2σ uncertainties leads to $0.2463 < Y_{\rm p} < 0.2667$ [65] and $0.2345 < Y_{\rm p} < 0.2777$ [66].

^{6}Li abundance of metal-poor halo stars (MPHSs), yields the upper limit of $^6\text{Li/H} = (7.1 \pm 0.7) \times 10^{-12}$ [3]. Adding a 2σ uncertainty, we adopt $^6\text{Li/H} < 8.5 \times 10^{-12}$.

For the ^{7}Li abundance, we adopt the limits $\log(^7\text{Li/H}) = -12 + (2.199 \pm 0.086)$ derived from recent observations of MPHSs in the 3D nonlocal thermal equilibrium model [67], i.e. $1.06 \times 10^{-10} < {}^7\text{Li/H} < 2.35 \times 10^{-10}$ (2σ).

Fig. 1 shows the abundances of ^{4}He ($Y_{\rm p}$; mass fraction), D, ^{3}He, ^{7}Li and ^{6}Li (number ratio relative to H) as a function of the baryon-to-photon ratio η or the baryon energy density parameter $\Omega_B h^2$ of the universe, where h is the Hubble constant in units of 100 km s^{-1} Mpc^{-1}. The thick dashed curves are the results of the standard BBN (SBBN) with a neutron lifetime of 878.5 ± 0.8 s. Thin dashed curves around them show regions of 95% C.L. from uncertainties in the nuclear reaction rates. The boxes represent adopted abundance constraints as summarized above. The vertical stripes correspond to the 2σ limits on $\Omega_B h^2$ or η. The values provided by WMAP [51] (labeled WMAP7) are

$$\Omega_B h^2 = 0.02258^{+0.00114}_{-0.00112} \qquad \eta = \left(6.225^{+0.314}_{-0.309}\right) \times 10^{-10}. \tag{1}$$

Values predicted by the BEC model (labeled axion) are smaller by a factor of $(2/3)^{3/4}$ at the BBN epoch [47]:

$$\Omega_B h^2 = 0.01666^{+0.00084}_{-0.00083} \qquad \eta = \left(4.593^{+0.232}_{-0.228}\right) \times 10^{-10}. \tag{2}$$

It can be seen that the adoption of the η value from WMAP leads to a ^{7}Li abundance calculated in the axion BEC model, which is in reasonable agreement with the observations. However, we lose the important consistency in D abundance. Ref. [47] noted that astronomical measurements of primordial D abundance can have a significant uncertainty as well as a possibility that D is burned by nonstandard stellar processes. Even if their assumption were true, stellar processes are not expected to change the sum of D and ^{3}He abundances [49]. As seen in Fig. 1, the constraint on $(\text{D} + {}^3\text{He})/\text{H}$ abundance seems to exclude the original axion BEC model. Ultimately, this model is viable only when the abundance of $(\text{D} + {}^3\text{He})/\text{H}$ is reduced through some exotic processes.

It is known that nonthermal photons can be generated through electromagnetic energy injections by the radiative decay of long-lived particles after the BBN epoch [12,17]. Long-lived particles which radiatively decay are motivated by physics beyond the standard model. Candidates of such particles include a neutralino decaying to gravitino through gravitational interaction and others [68]. These nonthermal photons can photodisintegrate background light elements [11,12,20,21,25,26]. We adopt the method of Ref. [26] to calculate the nonthermal nucleosynthesis, where we incorporated new thermal reaction rates as described above. In addition, we adopt updated reaction rates of ^{4}He photodisintegration [27] derived from the cross section data using precise