Solution to Big-Bang Nucleosynthesis in Hybrid Axion Dark Matter Model

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The primordial ^{7}Li abundance predicted in standard big bang nucleosynthesis (BBN) model for the baryon-to-photon number ratio η determined from the cosmic microwave background observations is significantly more than those observed in old halo stars [1,2]. Recently a new solution to the lithium puzzle was proposed, which is a mechanism for the cooling of photons in the epoch between the end of BBN and the last photon scattering. An axion, one of candidates for the dark matter could form a Bose-Einstein condensate (BEC) and may have cooled the photons in the epoch [3]. The baryon-to-photon ratio would then be smaller in BBN epoch ($\eta = 4.6\times10^{-10}$ [3]) than that measured by WMAP ($\eta = 6.2\times10^{-10}$ [4]). In the cooling model, however, the deuterium (D) abundance and the effective number of neutrinos are too high although the ^{7}Li abundance agrees with observations.

Nonthermal photons can be generated through electromagnetic energy injections by the radiative decay of long-lived particles after the BBN epoch. Long-lived particles are motivated by particle physics beyond the standard model. These nonthermal photons can photodisintegrate background light elements. Effects of energy injection depend on two parameters. One is $\zeta_X = (n_X^0/n_\gamma^0)E_{\gamma 0}$ where (n_X^0/n_γ^0) is the number ratio of the decaying particle X and the background radiation before the decay of X, and $E_{\gamma 0}$ is the energy of photon emitted at the radiative decay. The other is τ_X, the lifetime of X.

We calculated BBN in a hybrid axion and decaying exotic relic particle model in which the axion cools the photons and the particle produces nonthermal photons to eliminate the high D abundance in the original axion BEC model. We compared results with observational constraints on primordial nuclear abundances.

We also utilize a limit on the sum of primordial abundances of D and ^{3}He taken from an observational abundance for the protosolar cloud, i.e., (D+^{3}He)/H=$(3.6\pm0.5)\times10^{-5}$ [5]. 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 [6]. We thus showed that the constraint on (D+^{3}He)/H abundance excludes the original axion BEC model.

We found a narrow parameter region in which calculated abundances of all nuclides including D and ^{7}Li are simultaneously in ranges of adopted observational constraints. We conclude that the present model eliminates the main drawback of the original axion BEC model by reducing primordial D abundance via ^{2}H$(\gamma, n)^1$H reaction, where γ's are nonthermal photons. We note that the decaying X particle model with the WMAP η value cannot resolve the ^{7}Li problem by itself [7].

Figure 1 shows a result of a BBN calculation in our hybrid model [8]. The small difference at $T_9 \gtrsim 0.06$ observed between solid and dashed lines is caused by difference between initial η values. At $0.06 \gtrsim T_9 \gtrsim 7\times10^{-3}$, effects of ^{2}H$(\gamma, n)^1$H are seen in the decrease of D and the increase of n abundances. We find a slight decrease in ^{7}Be abundance caused through reactions ^{7}Be$(\gamma, ^3$He$)^4$He, ^{7}Be$(\gamma, p)^6$Li, and ^{7}Be$(\gamma, 2pn)^4$He. The second reaction increases the ^{6}Li abundance. Finally, at $T_9 \lesssim 7\times10^{-3}$, when the abundance of long-lived X particle is already less than 3 % of the initial abundance, effect of ^{4}He photodisintegration is to increase ^{3}H and n abundances.

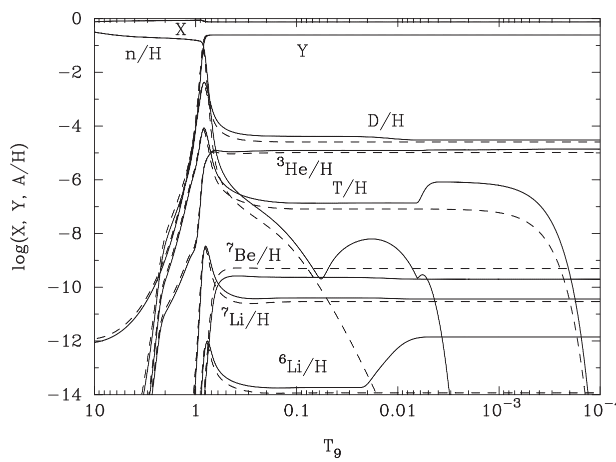

Figure 1: Mass fractions of H and ^{4}He (X_p and Y_p, respectively) and number ratios of other nuclides relative to H as a function of $T_9 \equiv T/(10^9\ \mathrm{K})$. Solid lines show the abundances in the hybrid model with the parameters $(\tau_X, \zeta_X)=(10^6\ \mathrm{s}, 2\times10^{-10}\ \mathrm{GeV})$ which predict primordial abundances consistent with all observations. The dashed lines show the standard BBN prediction. This is reprinted from [8].

Reference

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