The New Hybrid BBN Model with the Photon Cooling, X Particle, and the Primordial Magnetic Field

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The Big bang nucleosynthesis theory accurately reproduces the abundances of light elements in the Universes, except for ^{7}Li abundance. Calculated ^{7}Li abundance with the baryon to photon ratio fixed by the observations of the cosmic microwave background (CMB) is inconsistent with the observed lithium abundances on the surface of metal-poor halo stars, and this problem is called "^{7}Li problem". Previous studies proposed to resolve this ^{7}Li problem include photon cooling (possibly via the Bose-Einstein condensation of a scalar particle), the decay of a long-lived X particle (possibly the next-to-lightest supersymmetric particle), or an energy density of a primordial magnetic field (PMF) [1,2].

We then used a maximum likelihood analysis to constrain the parameters of the X particles and the energy density of the PMF by the observed abundances of light elements up to Li (Fig. 1) [3].

As a result, we obtained allowed ranges for the X-particle parameters and find that the new hybrid model with a PMF gives the better likelihood than that without a PMF (Table 1:) [3].

We discussed the degeneracy between the parameters of the X particle and the PMF. Since the X particle parameters are mainly limited by the D and ^{7}\$Li abundances, while the PMF energy density is mainly limited by the ^{4}He abundance, we found that the parameters of the PMF and the X particle have no significant degeneracies [3].

We also discussed the effective number of neutrino species $N_{\rm eff}$ with our new hybrid model. Since the constraint on $N_{\rm eff}$ from the CMB observations is different from the $N_{\rm eff}$ value in our hybrid model which is consistent with the observed light elements, it is difficult to directly compare these two $N_{\rm eff}$ values. We will report a new limit on $N_{\rm eff}$ derived by taking into account analyses of both BBN and the CMB simultaneously in our future work [3].

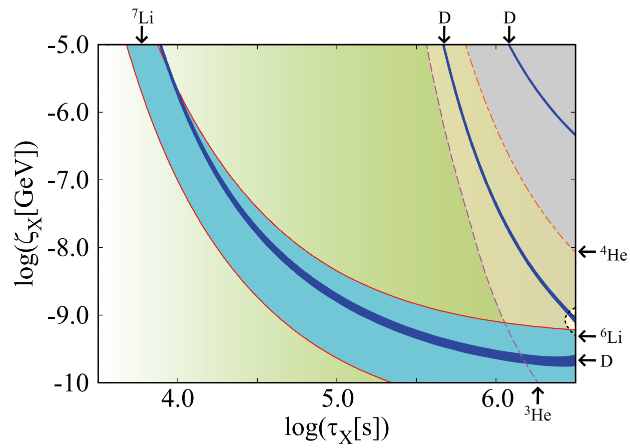

Figure 1: Allowed region in the (τ_X, ζ_X) plane by the observational constraints on the light element abundances for $\eta = 4.57 \times 10^{-10}$ and $B = 1.89\,\mu$G. The curves denote the allowed regions derived from observational limits on the primordial elemental abundances. The narrow dark band and the region bounded by the solid curves (color version: blue and aqua regions) show the 2σ (95 %) confidence limits determined from the observed abundances of D and ^{7}Li, respectively. Dashed, dot-dashed and dotted curves (color version: purple, orange and black curves) are the 2σ (95 %) confidence limits determined from the upper limits on the ^{3}He, ^{4}He and ^{6}Li abundances.

Table 1: Agreement with observed light element abundances for the four models considered here.

Model	γ-cooling	X	PMF	γ-cooling +X+PMF
Nuclide				
Y_p	✓	✓	✓	✓
D/H	-	✓	✓	✓
^{3}He/H	✓	✓	✓	✓
^{7}Li/H	?	-	-	✓
^{6}Li/H	✓	✓(high)	✓	✓(high)

References

[1] Yamazaki, D. G., Kusakabe, M.: 2012, *Phys. Rev. D*, **86**, 123006.
[2] Yamazaki, D. G., et al.: 2014, *Phys. Rev. D*, **90**, 023001.
[3] Yamazaki, Dai G., et al.: 2017, *Int. J. Mod. Phys. E*, **26**, 1741006.