Latest model calculation of big bang nucleosynthesis catalyzed by a long-lived massive particle

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In standard big bang nucleosynthesis (BBN) with the baryon-to-photon ratio inferred from WMAP, ^{7}Li is produced mostly as ^{7}Be (Fig. 1a, dashed lines). Subsequently, ^{7}Be is transformed into ^{7}Li by electron capture. A problem of standard BBN is a discrepancy between the predicted and observed abundances of $^{(6\text{ and})\,7}$Li[1]. One of solutions is catalysis reactions by negatively charged massive particles X^-s[2]. We solve numerically the nonequilibrium nuclear and chemical reaction network for this X^--catalyzed BBN[2] with improved reaction rates derived from rigorous quantum many-body calculations[3]. We adopt all of their rates, and choose their $^7\mathrm{Be}_X(p,\gamma)^8\mathrm{B}_X$ rate for an infinite X^- mass case.

Figure 1 shows a result of BBN calculation[4]. The X^- particles recombine with ^{7}Be at $T_9 \sim 0.5$. The $^7\mathrm{Be}_X$ (Fig. 1b) is then destroyed by the $^7\mathrm{Be}_X(p,\gamma)^8\mathrm{B}_X$ reaction, primarily through the atomic excited state of $^8\mathrm{B}_X$[5], and secondarily through the atomic ground state $^8\mathrm{B}^*(1^+, 0.770\,\mathrm{MeV})_X$ composed of the $^8\mathrm{B}^*(1^+, 0.770\,\mathrm{MeV})$ nuclear excited state and an X^-[6]. At $T_9 \sim 0.1$, the X^-particles bind to ^{4}He. Then, the reaction $^4\mathrm{He}_X(d,X^-)^6\mathrm{Li}$ operates, and ^{6}Li and $^6\mathrm{Li}_X$ (after the recombination) are produced. Neutral X-nuclei, i.e., p_X, d_X, and t_X, mainly react with ^{4}He nuclei to lose their X^-s leaving $^4\mathrm{He}_X$. The abundances are, therefore, kept low. Their nuclear reactions are thus not important.

The $^8\mathrm{Be}_X(p,\gamma)^9\mathrm{B}_X$ reaction through the $^9\mathrm{B}^{*a}_X$ atomic excited state is weak because its resonance energy is large [3]. The resonant $^8\mathrm{Be}_X(n,X^-)^9\mathrm{Be}_X$ reaction through the state $^9\mathrm{Be}^*(1/2^+, 1.684\,\mathrm{MeV})_X$ is not likely to operate since the state is estimated to be not a resonance but a bound state located below the $^8\mathrm{Be}_X+n$ threshold[3].

We assume that the present cold dark matter (DM) was partly produced by the decay of $X^\pm$ particles, i.e., $Y_{\mathrm{DM}} \geq Y_X$. Using the WMAP-CMB constraint on the cold DM density and the X^- abundance needed for a solution to the Li problems, a limit on the mass m_{DM} is derived. Comparing this mass to the suggested allowed region, e.g., $40\,\mathrm{GeV} < m_{\mathrm{DM}} < 200\,\mathrm{GeV}$ from the CDMS experiment, implies that only an X^- particle which decays via the weak interaction can have existed with sufficient abundance to reduce the ^{7}Li produced in BBN (see Fig. 6 of [2] for this case).

In this revised model there is no signature in the abundances of nuclei heavier than Be. We predict that the primordial ^{9}Be abundance in the allowed parameter region is negligible, $^9\mathrm{Be/H} < O(10^{-25})$, and far less than the most stringent upper limit of $^9\mathrm{Be/H} < 10^{-14}$[7]. $^9\mathrm{Be}_X$ is destroyed through the process $^9\mathrm{Be}_X(p, {}^6\mathrm{Li})^4\mathrm{He}_X$ [2]. Another isobar, i.e., $^9\mathrm{B}_X$ can be produced without experiencing the decays. The decay of the X^-, however, induces reactions $^9\mathrm{B}_X \rightarrow p + {}^8\mathrm{Be} + $ (decay products) since the ^{9}B is unstable to the proton decay. The ^{9}Be production through $^9\mathrm{B}_X$ is, thus, not possible

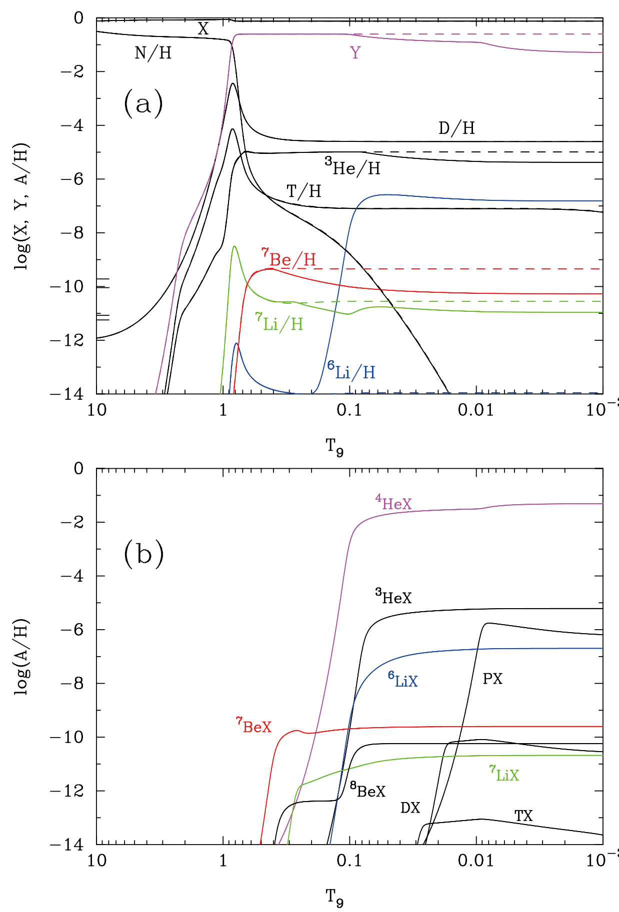

Figure 1: Abundances of normal (a) and X-nuclides (b) as a function of temperature $T_9 \equiv T/(10^9\,\mathrm{K})$. The parameters are the abundance ratio of X to baryon $Y_X \equiv n_X/n_b = 0.05$ and the lifetime $\tau_X = \infty$. This is reprinted from[1].

References

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