Revised Big-Bang Nucleosynthesis with Exotic Dark Matter Particle: Detailed Quantum Mechanical Calculation

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We extensively reanalyze effects of an exotic long-lived negatively charged massive particle [1], i.e., X^-, on big bang nucleosynthesis (BBN). The BBN model with the X^- particle was suggested to explain the discrepancy between ^{6,7}Li abundances predicted in standard BBN model and those inferred from spectroscopic observations of metal-poor stars (e.g., [2]). In this model, ^{7}Be is destroyed via the recombination with X^- followed by radiative proton capture, i.e., $^7\mathrm{Be}(X^-,\gamma)^7\mathrm{Be}_X(p,\gamma)^8\mathrm{B}_X$ [3,4].

First, we study the effects of uncertainties in nuclear charge distributions for X-nuclei in BBN. We show that different charge distributions can result in resonant nuclear reaction rates that differ by significant factors through changes in resonance energy heights.

Second, we calculate precise rates for the radiative recombinations of ^{7}Be, ^{7}Li, ^{9}Be, and ^{4}He with X^-. We calculate nonresonant rates taking account of respective partial waves of scattering states and respective bound states. It is found that the finite sizes of nuclear charge distributions cause deviations in bound and continuum wave functions from those derived assuming that nuclei are point charges. We find that for a heavy mass, $m_X \gtrsim 100$ GeV, the transition, d-wave $\rightarrow$ 2P, is the most important recombination reaction for ^{7}Li and ^{7,9}Be with an X^- particle. This fact is completely different from the case of hydrogen-like electronic ions. As for ^{7}Be and ^{7}Li, bound states of the nuclear first excited states (^{7}Be* and ^{7}Li*) with X^- can operate as effective resonances. The resonant reaction rates are then also calculated.

Figure 1 shows rates for the nuclear recombination with X^- as a function of temperature $T_9 = T/(10^9\ \mathrm{K})$ for $m_X = 1000$ GeV. Curves correspond to the sums of nonresonant and resonant reaction rates. The new rates for ^{7}Be, ^{7}Li, and ^{9}Be are larger than the previous rates, while that for ^{4}He is smaller than the previous rate. Importantly, the ^{7}Be rate in the present study is more than 6 times larger than the existing rate. This improvement leads to a significantly better constraint on the X^- properties. The present rates for ^{7}Li and ^{9}Be are also significantly larger than the previous rates. The present ^{4}He rate is, on the other hand, not significantly different for temperatures $T_9 \lesssim 0.1$ where the recombination effectively proceeds.

Third, we suggest a new reaction for ^{9}Be production: the radiative recombination of ^{7}Li and X^- followed by the deuteron capture. This reaction can enhance the primordial ^{9}Be abundance which may be detectable in future observations of metal-poor stars.

We derive binding energies and mass excesses of X-nuclei, and rates and Q-values for β-decays and nuclear reactions involving the X^- particle. We calculate BBN and find that amounts of ^{7}Be destruction depend significantly on the charge distribution of the ^{7}Be nucleus.

Finally, the most realistic constraints on the initial abundance and the lifetime of the X^- are deduced. Parameter regions for the solution to the ^{7}Li problem are derived, and primordial ^{9}Be abundances in the parameter regions are also predicted.

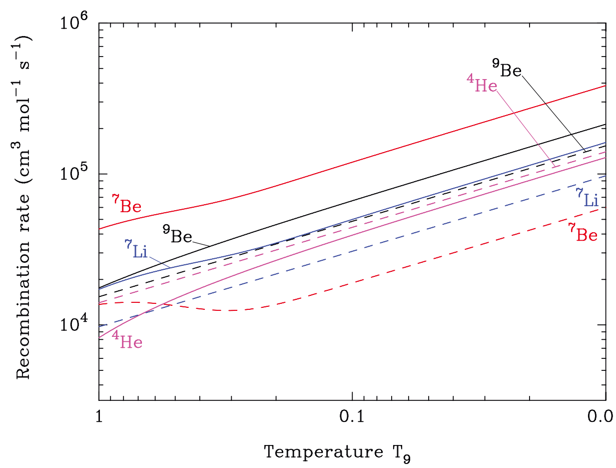

Figure 1: Total rates for nuclear recombination with X^- in the case of $m_X = 1000$ GeV as a function of temperature. Solid lines show the recombination rates derived in this study, while dashed lines show the rates adopted in the previous studies (e.g., [3,4]). This is reprinted from [5].

References

[1] Cahn, R. N., Glashow, S. L.: 1981, *Science*, **213**, 607.
[2] Aoki, W., et al.: 2009, *ApJ*, **698**, 1803.
[3] Bird, C., et al.: 2008, *Phys. Rev. D*, **78**, 083010.
[4] Kusakabe, M., et al: 2008, *ApJ*, **680**, 846.
[5] Kusakabe, M., et al.: 2014, *ApJS*, **214**, 5.