^{7}Be Charge Exchange between ^{7}Be^{3+} Ion and Exotic Long-lived Negatively Charged Massive Particle in Big Bang Nucleosynthesis

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A serious problem in big bang nucleosynthesis (BBN) is a discrepancy between primordial ^{7}Li abundance predicted in standard BBN (SBBN) model and those inferred from observations of metal-poor stars [1,2]. In SBBN, ^{7}Li is produced mostly as ^{7}Be, which transforms into ^{7}Li by electron capture in a late epoch. A ^{7}Be destruction can be caused by negatively charged massive particles X^- [3] with a large mass, $m_X \gg 1$ GeV, in BBN [4,5,6]. The X^- particles become bound to positively charged nuclides A, and form bound states A_X. ^{7}Be destruction proceeds via the recombination of ^{7}Be with X^- followed by $^7\mathrm{Be}_X + p \rightarrow {}^8\mathrm{B}_X + \gamma$ through both atomic [4] and nuclear [5] excited states of ^{8}B$_X$. In previous studies, only the radiative recombination of nuclides A and X^- [7] has been investigated. We, however, found that the nonradiative charge exchange reaction between ^{7}Be^{3+} and X^- contribute to the ^{7}Be$_X$ formation and the subsequent destruction.

The destruction of ^{7}Be$_X$ occurs at the temperature $T_9 \equiv T/(10^9\,\mathrm{K}) \sim 0.4$ [6]. The effective rate of ^{7}Be recombination with X^- through the ^{7}Be^{3+} ion is given by the product of the following three quantities: 1) the number ratio of ^{7}Be^{3+} to ^{7}Be^{4+}(=^{7}Be), 2) the formation rate of excited states $^7\mathrm{Be}^*_X$ via the reaction $^7\mathrm{Be}^{3+} + X^- \rightarrow {}^7\mathrm{Be}^*_X + e^-$, and 3) the probability that produced $^7\mathrm{Be}^*_X$ are converted to the ground state (GS), which is estimated by the ratio of the transition rate to the GS ^{7}Be$_X$ and the total reaction rate of the $^7\mathrm{Be}^*_X$.

The rate for ^{7}Be to recombine with e^- is much larger than the Hubble expansion rate. The number ratio of ^{7}Be^{3+} to ^{7}Be^{4+} is then the equilibrium value via the efficient reaction $^7\mathrm{Be}^{4+} + e^- \rightleftharpoons {}^7\mathrm{Be}^{3+} + \gamma$.

We estimated the thermal reaction rate of the charge transfer reaction $^7\mathrm{Be}^{3+} + X^- \rightarrow {}^7\mathrm{Be}^*_X + e^-$. We assume that the cross section roughly scales as the squared Bohr radius of ^{7}Be^{3+}. Excited states $^7\mathrm{Be}^*_X$ produced via the reaction experience bound-bound transitions of the spontaneous and stimulated emissions and the photo-absorption in the universe filled with the cosmic background radiation (CBR). These are the GS formation reactions.

The $^7\mathrm{Be}^*_X$ is destroyed via the following reactions: 1) collisional ionization by $e^\pm$, $^7\mathrm{Be}^*_X + e^\pm \rightarrow {}^7\mathrm{Be} + X^- + e^\pm$, 2) the charge exchange reaction, $^7\mathrm{Be}^*_X + e^- \rightarrow {}^7\mathrm{Be}^{3+} + X^-$, and 3) photoionization of $^7\mathrm{Be}^*_X$ by CBR. Reaction 1) is important while 2) and 3) are not.

Figure 1 shows a result of BBN calculation [8]. The effective recombination rates are derived as a function of temperature, and used in this calculation. Depending on the cross sections, abundance evolutions and the final abundances of ^{7}Be and ^{7}Be$_X$ is affected by the recombination of ^{7}Be with X^- through the ^{7}Be^{3+} ion.

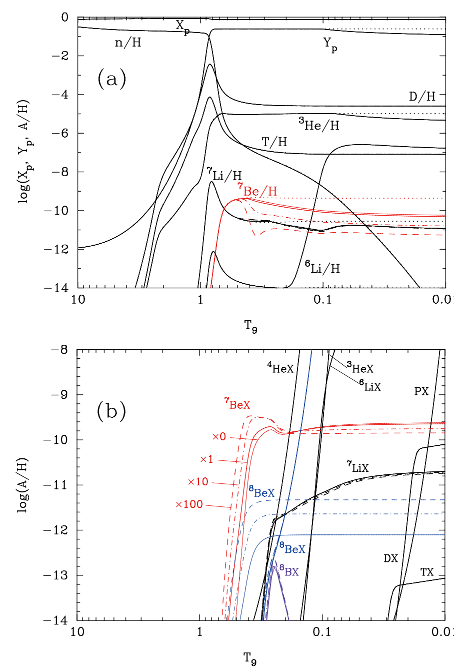

Figure 1: Abundances of normal nuclei (a) and X nuclei (b) as a function of T_9. X_p and Y_p are mass fractions of ^{1}H and ^{4}He, respectively, while other lines correspond to number abundances relative to that of ^{1}H. Thick lines correspond to the standard reaction rate for $^7\mathrm{Be}(e^-, \gamma)^7\mathrm{Be}^{3+}(X^-, e^-)^7\mathrm{Be}_X$, while thin solid, thick dot-dashed and dashed lines correspond to the cross sections of $^7\mathrm{Be}^{3+}(X^-, e^-)^7\mathrm{Be}^*_X$ multiplied by a factor of 0, 10 and 100, respectively. The dotted lines correspond to SBBN. This is reprinted from [8].

References

[1] Spite, F., Spite, M.: 1982, *A&A*, **115**, 357.
[2] Aoki, W., et al.: 2009, *ApJ*, **698**, 1803.
[3] Cahn, R. N., Glashow, S. L.: 1981, *Science*, **213**, 607.
[4] Bird, C., et al.: 2008, *Phys. Rev. D*, **78**, 083010.
[5] Kusakabe, M., et al.: 2007, *Phys. Rev. D*, **76**, 121302.
[6] Kusakabe, M., et al.: 2008, *ApJ*, **680**, 846.
[7] Dimopoulos, S., et al.: 1990, *Phys. Rev. D*, **41**, 2388.
[8] Kusakabe, M., et al.: 2013, *Phys. Rev. D*, **88**, 063514.