Long Lived Charged Massive Particles and Big Bang Nucleosynthesis

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Abstract. We consider Big Bang Nucleosynthesis (BBN) with long lived charged massive particles. Before decaying, the long lived massive particles recombines with a light element to form a bound state like a hydrogen atom. We discuss the possible change of primordial light element abundances due to formations of such bound states.

Keywords: Big Bang Nucleosynthesis, Long Lived Massive Charged Particles

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INTRODUCTION

Under the remarkable triumph of cosmological standard model, the existence of dark matter has been well-established as one of the best evidence of new physics. Continuous efforts to identify what the dark matter is have been made in cosmological observations and collider experiments. In present stage, the only macroscopic phenomenon tell us the existence of dark matter, on the other hand, in future collider experiments and dark matter direct detection observations, the microscopic properties of dark matter may be understood, which has been one of the interesting targets for particle physicists.

Under several considerations on the extension of the standard model of elementary particle physics, a lot of candidates of dark matter has been proposed. In some scenarios as superWIMP dark matter [1], it is not necessary that the dominant component of matter during deeply radiation dominated universe is neutral and the relic is same as present observed relic density of dark matter. Actually the extremely long lived CHarged Massive Particle (CHAMP) have been well-motivated , for example, in scenarios of gravitino LSP [2] in the context of supersymmetric extension of particle standard model, and they may be the dominant matter in deeply radiation dominate era. Then the attractive candidate of such a long lived CHAMP may be stau NLSP which is a supersymmetric partner of tau lepton. If such long lived CHAMPS exist during BBN era, such a CHAMP may constitute a bound state with a light element and the formation of such bound states may modify nuclear reaction rates in BBN and eventually change light element abundances. The effects on light element abundances due to energy injections from late time decays have been performed assuming freely propagating decay particles [3]. On the other hand, in this paper, we consider new effects on BBN due to formation of such bound states which have not been discussed before [4].
TABLE 1. Table of the binding energies for the various nuclei in the case of $Z_C = 1$ given in Ref. [6]. For heavier elements than $^8\text{Be}$, the binding energies are given by the harmonic oscillator approximation.

| Nucleus(X) | binding energy (MeV) | atomic number |
|------------|----------------------|--------------|
| $p$        | 0.025                | $Z=1$        |
| $^2\text{H}$ | 0.050                | $Z=1$        |
| $^3\text{He}$ | 0.075                | $Z=1$        |
| $^3\text{He}$ | 0.270                | $Z=2$        |
| $^4\text{He}$ | 0.311                | $Z=2$        |
| $^6\text{Li}$ | 0.431                | $Z=2$        |
| $^6\text{Li}$ | 0.842                | $Z=3$        |
| $^7\text{Li}$ | 0.914                | $Z=3$        |
| $^7\text{Li}$ | 0.952                | $Z=3$        |
| $^7\text{Be}$ | 1.490                | $Z=4$        |
| $^8\text{Be}$ | 1.550                | $Z=4$        |
| $^{10}\text{B}$ | 2.210                | $Z=5$        |

CHAMP BIG BANG NUCLEOSYNTHESIS (CBBN)

When the temperature becomes higher than the binding energy of the bound state, the photo-destruction rate of bound states is rapid. Then only small fraction of bound states can be formed. But once the temperature becomes lower than the binding energy, the formation of bound states become efficient.

By using the detailed balance relation between the forward process $X + C \rightarrow \gamma + (X, C)$ and the reverse process $(X, C) + \gamma \rightarrow X + C$, and assuming SBBN processes are well decoupling, the Boltzmann equation for the capture reaction of a light element is,

$$ \frac{\partial}{\partial t} n_X + 3 H n_X \simeq -\langle \sigma v \rangle \left[ n_C n_X - n_{(C,X)} n_\gamma (E > E_{bin}) \right], \quad (1) $$

where $n_r(E > E_{bin}) \equiv n_r \frac{\pi^2}{2 \zeta(3)} \frac{m_X}{2 \pi T} \frac{3/2}{e^\frac{E_{bin}}{T}}$, $n_\gamma = \frac{2 \zeta(3)}{\pi} T^3$, $T$ is thermal temperature, $E_{bin}$ is a binding energy and $n_i$ is the number density of $i$ species. Then we can obtain the critical temperature that the formation of bound states dominate against the photo-destruction as follow [4].

$$ T_c \simeq \frac{E_{bin}}{40}. \quad (2) $$

The binding energies for each bound states are shown in Table 1. We can find that the bound state formation for heavier elements may occur in earlier time. Such bound state may cause some modification of nuclear reaction rate in BBN and cause changes on light element abundances.

Next we investigate the effects on BBN due to bound state formations. We consider the thermal freeze out of light element abundances in CBBN and here we simply ignore the effects of possible high energy injections due to the late decay of CHAMPs, which
FIGURE 1. Prediction of $^7\text{Li}/\text{H}$ (upper panel) and $^6\text{Li}/^7\text{Li}$ (lower panel) as a function of $\eta$. The red (blue) band is for Case B-I (Case B-II) in CBBN. Here we assumed $n_C/n_\gamma = 3.0 \times 10^{-11}$ and the instantaneous capture of CHAMPs. The Case B-I means that $E_{\text{CM}} = (\mu_{ab}/\mu_{(aC)b})E_{\text{bin}} + E_0$ in a process $(a,C) + b \rightarrow (c,C) + d$ where we take $E_0$ to be the Gamow’s peak energy for collisions between two charged elements, and to be $3T/2$ for collisions between a nucleus and a neutron. The Case B-II means that we take $E_{\text{CM}} = E_{\text{bin}} + E_0$ as the CM energy of processes and ten times larger value of the p-wave part of the cross section of $^7\text{Be}(n,\alpha)^4\text{He}$ than that in the standard BBN code. It is showed that the modification by a factor of ten on the p-wave partial cross section of $^7\text{Be}(n,\alpha)^4\text{He}$ does not change the SBBN prediction (Case B–I) but must be important in CBBN (Case B–II).

may provide the initial condition to consider such late decay phenomenon if the decay occurs enough after the decoupling of the BBN processes. In our estimation, we also assume the instantaneous captures for each light elements at $T_c = E_{\text{bin}}/40$. We evaluated the modifications of nuclear reaction rate from the SBBN values [4]. Once bound states were formed, an incident charged nucleus can penetrate the weakened Coulomb field and collide with the bound nucleus relatively rapidly. Also in SBBN, the kinetic energy of light elements is governed by thermal temperature, but after formation of bound states, the kinetic energy of bound light elements is the binding energy of bound states, which does not depend on thermal temperature and even at low temperature, the nuclear reaction may be proceed with relatively large CM energy.

In SBBN, abundances of all light elements are completely frozen until $T \sim 30\text{keV}$. Since $T_c$ is 24keV for $^7\text{Li}$ and 38keV for $^8\text{Be}$, which is almost the end of SBBN, the formations of bound states may change their abundances. On the other hand, for lighter elements than $^6\text{Li}$, since the efficient captures occur only at below 10 keV, the change of nuclear reactions can not recover the processes at such a low temperature. This conclusion will be hold if the difference from our estimation of nuclear reaction rate is not significant[6].

In Fig.1, we plot the theoretical prediction of $^7\text{Li}/\text{H}$ (upper panel) and $^6\text{Li}/^7\text{Li}$ (lower panel) as a function of $\eta$. The SBBN predictions are plot by the green bands.

1 In [5], bound state effects that we have not considered here have been examined.
CONCLUSION

We discussed the effects on BBN due to the formation of bound states with a CHAMP. Such extremely long lived CHAMPs can be trapped and the detail properties can be examined in near future collider experiments [7]. Also some considerations on CHAMP catalysis fusion [8] may be interesting to understand the effect on nuclear reactions due to bound state formations.

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