CLNS 07/1996

Extremely Long-Lived Charged Massive Particles as A Probe for Reheating of the Universe

Fumihiro Takayama

Institute for High Energy Phenomenology, Cornell University, Ithaca, NY 14853, USA

We discuss the impact of Charged massive particle Big Bang Nucleosynthesis (CBBN) on a low reheating temperature model in the case that extremely long lived CHArged Massive Partucles(CHAMPs) existed in the early Universe. If the mass of the CHAMP is within collider reach and it's lfetime longer than 10^4sec, the comparison between CBBN prediction and observed ^{6}Li abundances may indicate a low reheating temperature without relying on details of the decay properties. Even if the CHAMP mass is outside the reach of colliders, the cosmological considerations may provide a non-trivial hint for the existence of such very heavy long-lived CHAMPs from the late Universe if the daughter particles are the dominant component of the present dark matter.

PACS numbers: 95.35.+d, 11.10.Kk, 12.60.-i

INTRODUCTION

We are living in an interesting time for particle physics. The Large Hadron Collider (LHC) experiment will start this year and may show exciting results soon. Also recent significant developments of cosmological and astrophysical observations have improved our knowledge of particle physics.

The fact that the large fraction of matter in the Universe is not accounted for by standard model particles motivates further considerations for the role of hypothetical particles in the early Universe and the connection to collider physics. Recent theoretical studies have shown the possibility of extremely long lived CHArged Massive Particles(CHAMPs) [1–9]. The search for CHAMPs and the determination of it's properties may be an exciting challenge for future collider experiments and cosmological observations.

Under continuous efforts in the past decade, the Standard Big Bang Nucleosynthesis(SBBN) theory has been well established to precisely predict the primordial light element abundances [10] and may be used as a probe to find or constrain new physics beyond the standard model in the late time Universe [11–19, 21]. As recent papers have pointed out [14–19], if an extremely long-lived CHAMPs existed in the early Universe, such a CHAMP might constitute a bound state with a light element after/during BBN era and modify the SBBN prediction of light element abundances. This might constrain the number density of long lived CHAMPs depending on the lifetime.

The cosmological constraints on thermally frozen long lived CHAMPs have been discussed [5, 6, 20]. In most of these papers, the standard cosmology after the freeze out of CHAMPs was assumed. In standard cosmology, the relic density $\Omega_C \sim m_C^2$ and the number density $n_C \sim m_C$ where m_C is mass of the CHAMP, which implies severe constraint for heavier mass. Recent analysis showed that the entire mass region may be disfavored by BBN if the lifetime is longer than 10^4sec [15]. [1] On the other hand, above BBN constraints may not exclude the possibility of the discovery of CHAMPs with lifetime $> 10^4$sec. The violation of the above constraints does not necessarily mean contradictions but may indicate an evidence of additional new physics or lack of understanding of astrophysics. From this point of view, the importance of search for extremely long lived massive particles in supersymmetric theory with a gravitino LSP was also discussed [5].

In this paper, we discuss a possible impact of the discovery of extremely long lived CHAMPs on a specific scenario beyond standard cosmology. We focus on a low reheating temperature model as the possibility of the non-standard Universe and extract constraints on the theoretical parameters. We calculate the relic density of CHAMPs frozen during/after reheating and estimate the CBBN prediction of primordial ^{6}Li abundance by using recent estimation of the nuclear reaction rate [18] and without assuming the Saha equation for bound state formation of a CHAMP and a ^{4}He. We will find that the CBBN prediction of ^{6}Li is sensitive to the number density of CHAMPs and lifetime around $10^3 - 10^4$sec, and the comparison between observed ^{6}Li and the CBBN prediction can impose a relevant constraint on the reheating temperature, which may potentially become a severe restriction on inflation models or models of late time entropy production [24].

LOW REHEATING TEMPERATURE AND THE RELIC ABUNDANCE OF CHAMPS

Here we consider the CHAMP production during/after reheating of the Universe. It is believed that the reheat-

[1] For the lifetime $> 7 \times 10^6$sec, this conclusion may be changed once CHAMPs are captured by protons [14]

ing of the Universe result from the thremalization of the decay products from the decay of coherent oscillations of a scalar field after the energy dominated the Universe. [2] The reheating temperature is defined by

$$\Gamma_\phi = \sqrt{\frac{4\pi^3 g_*(T_{\rm RH})}{45}}\frac{T_{\rm RH}^2}{M_{\rm pl}}, \quad (1)$$

where Γ_ϕ is the decay rate of scalar field ϕ, $g_*(T)$ is the number of massless degree of freedom at temperature T and $M_{\rm pl} = 1.2 \times 10^{19}$GeV. In this paper, we call *Low* reheating temperature scenario in which the most of decays of scalar field ϕ occur after freeze-out of CHAMPs. The importance of particle productions during reheating era and the difference from standard radiation dominated universe in thermally frozen non-relativistic particles was discussed in [25–27]. We estimate the relic density of heavy charged species as a function of the mass and reheating temperature. [3]

We consider a simple reheating model described by the following equations [25].

$$\begin{aligned}
&\frac{d\rho_\phi}{dt} + 3H\rho_\phi = -\Gamma_\phi\rho_\phi \\
&\frac{d\rho_R}{dt} + 4H\rho_R = \Gamma_\phi\rho_\phi + <\sigma v> 2 < E_C > [n_C^2 - n_{\rm EQ}^2] \\
&\frac{dn_C}{dt} + 3Hn_C = - <\sigma v> [n_C^2 - n_{\rm EQ}^2] \quad (2)
\end{aligned}$$

where H is Hubble parameter, $< E_C >\sim \sqrt{m_C^2 + (3T)^2}$, $\rho_C = m_C n_C$ and ρ_ϕ, ρ_R are energy density of ϕ field and radiation.[4] Here we assumed that CHAMPs annihilate into radiation or the particles in final state rapidly convert into radiation. The Hubble parameter is

$$H^2 = \frac{8\pi}{3}\frac{1}{M_{\rm pl}^2}(\rho_C + \rho_\phi + \rho_R) \quad (3)$$

As the initial condition, we use

$$\rho_\phi = \frac{3}{8\pi}M_{\rm pl}^2 H_I^2, \quad \rho_R = \rho_C = 0 \quad (4)$$

The initial Hubble parameter H_I is taken significantly early before the completion of reheating at Γ_ϕ^{-1} and the freeze out of CHAMP. In this paper, we do not consider more complicated cases of reheating after inflation and assume that this is the last reheating of the Universe. But notice that $\rho = \rho_C = 0$ may not be always satisfied if this reheating occurs after the Universe went through radiation dominated once as a result of earlier reheating. [5]

We are interested in the production of non-relativistic particles during/after reheating. [6] In this paper, we will use the analytical solution for thermally frozen CHAMP relic density of the above differential equations [25].

The particle freeze out may be classified into two cases, the case that chemical equilibrium is not established before the freeze out, and the case that chemical equilibrium is established. The annihilation cross section determines which of the two cases applies. Since we are interested in production of CHAMPs, the minimal coupling would be the coupling with a photon. Assuming s-wave processes dominates, we have

$$<\sigma_{\rm ann} v> = \frac{4\pi\alpha^2}{m_X^2}\gamma \quad (5)$$

where we take $\gamma = 1$. Chemical equilibrium during reheating era is established before freeze out if

$$\begin{aligned}
\frac{T_{\rm RH}}{m_C} &> 1\times 10^{-6} \\
&\times\gamma^{-1/2}\sqrt{\frac{2}{g}[\frac{g_*(T_*)}{g_*(T_{\rm RH})^{1/2}}][\frac{m_C}{10^2{\rm GeV}}]^{1/2}} \quad (6)
\end{aligned}$$

This condition follows from $n_X^{\rm Max} > n_{\rm eq}(T_*)$ where $T_* = 4m_C/17$ for s-wave corresponds to the temperature at which most of the production take place [25]. Notice that for the thermal freeze-out during reheating, the typical freeze-out temperature may be $O(10)\times m_C$. So if the reheating temperature normalized by m_C, $T_{\rm RH}/m_C \sim O(10^{-3})$, the chemical equilibrium in CHAMPs will be established even for heavy CHMAPs with $m_C \sim 10^7$GeV.

For the non-chemical equilibrium production, the present time relic density of CHAMPs is [7]

$$\Omega_C^{NT(Low)}h^2 = 0.13\times(\frac{g}{2})^2[\frac{g_*(T_{\rm RH})^{1/2}}{g_*(T_*)}]^3[\frac{10^3 T_{\rm RH}}{m_C}]^7\gamma \quad (7)$$

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[2] In similar way, we also could consider the case of particle gravitational production due to expansion of the Universe during inflation. [23]

[3] The constraint on stable CHAMPs from heavy isotope search was discussed in similar set up. [28]

[4] Here the kinetic equilibrium for CHAMPs and radiations is assumed.

[5] Also we do not consider the significant amount of decays of ϕ directly into hidden particles like gravitinos which has very small coupling with Standard Model parties. If the decay of such hidden particles happen after freeze out of CHAMP and has a branch into CHAMPS, We may expect additional contributions to the CHAMP relic. Also we assume that such component of hidden particle does not dominate the energy density of the Universe.

[6] In early stage of reheating, heavy particle may be relativistic. but if the cross section is suppressed by their own mass scale, they may keep thermal equilibrium until they become non-relativistic. So in this paper, we do not consider the relativistic decoupling, which might happen in gravitational relic like gravitino, KK graviton.

[7] Implicitly we assume that $H(T_*) < \Gamma_\phi$ for non-equilibrium case and $H(T_F) < \Gamma_\phi$ for equilibrium case, where T_* is decoupling temperature and T_F is freeze out temperature.

For the chemical equilibrium production, the final relic abundance is approximately given by $< \sigma_{\rm ann} v > n_C^{eq} = H(T_F)$ and by taking account of the dilution of frozen relic until the reheating complete. Notice that $T \sim a^{-3/8}$ during reheating, so that $a(T_{\rm RH})^3/a(T_F)^3 = (T_F/T_{\rm RH})^8$ [25]. Then,

$$\Omega_C^{TH(Low)} h^2 = 3.3 \times 10^{-8} [\frac{g_*(T_{\rm RH})^{1/2}}{g_*(T_F)}] \frac{T_{\rm RH}^3 {\rm GeV}^{-2}}{\gamma m_C x_F^{-4}} \quad (8)$$

The freeze-out temperature is fixed by the solution of $< \sigma_{\rm ann} v > n_C^{eq}(T_F) = H(T_F)$.

$$x_F = \ln[\frac{6\pi g}{\sqrt{10}\pi^2} \frac{g_*(T_{\rm RH})^{1/2}}{g_*(T_F)} \frac{M_{\rm pl} T_{\rm RH}^2}{m_C^3} \alpha^2 \gamma x_F^{5/2}] \quad (9)$$

Here we implicitly assume that the maximum temperature is higher than the freeze out temperature, which may constrain the initial energy density of ϕ field. This case reduces to known thermal freeze out formula within a few 10 percent differences if we take the limit $T_{\rm RH} = T_F$. That is, in this limit, eliminating dilution,

$$\Omega_X^{TH} h^2 \simeq 4.2 \times 10^{-8} [\frac{1}{g_*(T_F)^{1/2}}] \frac{m_C^2 {\rm GeV}^{-2}}{\gamma x_F^{-1}} \quad (10)$$

$$x_F = \ln[\frac{3\sqrt{5} g}{\sqrt{2}\pi^2} \frac{1}{g_*(T_F)^{1/2}} \frac{M_{\rm pl}}{m_C} \alpha^2 \gamma x_F^{1/2}] \quad (11)$$

CHAMP BIG BANG NUCLEOSYNTHESIS (CBBN)

Next we consider the impact of CBBN for the number density of CHAMPs. Recently it has been pointed out that the bound state formation of a CHAMP and a light element at lower temperature of the binding energy may change the nuclear reaction rates of BBN and eventually change the light elements abundance from SBBN [14, 15, 17]. Especially Pospelov pointed out that because of the strong electro-magnetic field due to the bound CHAMP, CBBN may has significant changes in the nuclear reaction rates from SBBN's for radiative processes which are highly suppressed in SBBN [15]. The CBBN nuclear reaction rate for ^{6}Li production has recently been evaluated by the use of the state-of-the-art coupled channel method [18]. We use the reaction rate here. for $T < 100$keV,

$$< \sigma_{^6{\rm Li}}^{CBBN} v > = 3.4 \times 10 \times {\rm GeV}^{-2} \times (1 - 0.34(\frac{T}{10^9{\rm K}}))(\frac{T}{10^9{\rm K}})^{-2/3} e^{-5.33(\frac{T}{10^9{\rm K}})^{1/3}} \quad (12)$$

In this paper, we do not include decay effects and only consider effects of the CBBN on ^{6}Li. Actually in the case of sufficiently low abundances enough compared to the present DM relic density, the impact on ^{6}Li due to the decays will not be significant [11]. In this paper, we consider the case that the number density is smaller than ^{4}He but larger than other light elements. Then we can simplify the discussion of the capture of CHAMPs, that is, essentially the important part is only the capture by ^{4}He. Since elements heavier than ^{4}He are extremely rare, if the number density $n_C/n_p > 10^{-10}$, we can safely ignore the captures by elements other than ^{4}He to evaluate the number density of bound state $(C, ^4{\rm He})$. [8]. After the capture by ^{4}He starts, the probability of CHAMP captures by elements lighter than ^{4}He is extremely small, and can be safely ignored until the capture of protons starts at $T = 0.6$keV ($t = 7.2 \times 10^6$ sec). Once proton capture starts, remaining free CHAMPs will be immediately captured by protons. In this paper, we do not consider the effect of the bound state with a proton which may have big impact on light element abundance including ^{6}Li. The approximation will be safe for the case of $\tau_C < 7 \times 10^6$sec. [9]

Assuming that the reheating temperature is high enough for thermal BBN to occur, we solve following equations.

$$\begin{aligned}
\frac{dn_{^4{\rm He}}}{dt} + 3Hn_{^4{\rm He}} &= \\
&- < \sigma_{\rm rec} v > (n_C n_{^4{\rm He}} - n_{(C,^4{\rm He})} \tilde{n}_\gamma) + \frac{1}{\tau_C} n_{(C,^4{\rm He})} \\
\frac{dn_C}{dt} + 3Hn_C &= \\
&- < \sigma_{\rm rec} v > (n_C n_{^4{\rm He}} - n_{(C,^4{\rm He})} \tilde{n}_\gamma) \\
&+ < \sigma_{^6{\rm Li}}^{CBBN} v > n_{(C,^4{\rm He})} n_D - \frac{1}{\tau_C} n_C \\
\frac{dn_{(C,^4{\rm He})}}{dt} + 3Hn_{(C,^4{\rm He})} &= \\
&< \sigma_{\rm rec} v > (n_C n_{^4{\rm He}} - n_{(C,^4{\rm He})} \tilde{n}_\gamma) \\
&- < \sigma_{^6{\rm Li}}^{CBBN} v > n_{(C,^4{\rm He})} n_D - \frac{1}{\tau_C} n_{(C,^4{\rm He})} \\
\frac{dn_{^6{\rm Li}}}{dt} + 3Hn_{^6{\rm Li}} &= < \sigma_{^6{\rm Li}}^{CBBN} v > n_{(C,^4{\rm He})} n_{\rm D} \\
\frac{dn_{\rm D}}{dt} + 3Hn_{\rm D} &= - < \sigma_{^6{\rm Li}}^{CBBN} v > n_{(C,^4{\rm He})} n_{\rm D} \quad (13)
\end{aligned}$$

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[8] The formation of bound state with heavier elements than ^{4}He uses only small fraction of CHAMP, but if the number density is not small relative to ^{4}He abundance, the bound state formation with heaveir elements might have some impact to evaluate the primordial abundance of such heavier elements through CBBN processes, for example, in ^{7}Li etc [14, 19]

[9] However the bound state formation with protons may decrease ^{6}Li through $^6{\rm Li}((p,C),\alpha)^3{\rm He}$ [14]. But the estimation assumed that the nuclear reaction does not have Coulomb suppression and the stability of bound sate during nuclear reaction, which may not be good approximation for proton because the Bohr radius of bound sate is large relative to typical nuclear size. For the other bound sate with D, T etc would only contribute the small production of ^{6}Li.

where $n_\gamma = 2\zeta(3)T^3/\pi^2$,

$$\tilde{n}_\gamma = n_\gamma \frac{\pi^2}{2\zeta(3)} (\frac{m_C}{2\pi T})^{3/2} e^{-E_{\rm bin}/T} \quad (14)$$

where we take the binding energy of ^{4}He to a CHAMP $E_{\rm bin}$ =311keV [22]. We use the following recombination cross section,

$$< \sigma_{\rm rec} v >= \frac{2^9 \pi \alpha Z^2_{^4{\rm He}} \sqrt{2\pi}}{2e^4} \frac{\tilde{E}_{\rm bin}}{m^2_{^4{\rm He}} \sqrt{m_{^4{\rm He}} T}} \quad (15)$$

where $\tilde{E}_{\rm bin} = \alpha^2 Z_C^2 Z^2_{^4{\rm He}} m_{^4{\rm He}}/2$ [22]. [10] For non-thermal photon emitted in the recombination process, we assume the rapid thermalization which would be valid in deeply radiation dominated Universe, that is, we always assume thermal distribution for photon and also kinetic equilibrium for all light elements.

We evaluate ^{6}Li abundance by use of the last equation assuming in eq(13) Saha type equation $n_{(C,{\rm He})} = n_C n_{^4{\rm He}}/\tilde{n}_\gamma$ and $n_C = n_C^{in} e^{-(t/\tau_C)}$ for number density of bound state until T = 10 keV, and connect to above a set of differential equations for temperature below 10 keV and numerically solved them. At T >10 keV, since the photo-destruction rate $< \sigma_{\rm rec} v > \tilde{n}_\gamma/H > 10^2$ and the bound state formation rate is also larger than the expansion rate of the Universe in the third equation of eq(13), the use of Saha equation would be a good approximation. Failure of Saha approximation may happen if $3H \sim < \sigma_{\rm ann} v > \tilde{n}_\gamma$, when the rate of bound state formation is faster than the expansion rate of the Universe. We also used SBBN value for the light elements as the initial values.

In Fig.1, we show contour plot of ^{6}Li abundance as a function of the lifetime and the number density of CHAMPs. Since the CBBN reaction rate D$((C,^4{\rm He}),\gamma)^6$Li rapidly decreases due to the Coulomb suppression, most of ^{6}Li production occurs from T = 10keV to a few keV. For CHAMP lifetime $\tau_C > 10^5$ sec. the ^{6}Li abundance is insensitive to τ_C.

In the last part of this section, we will make a few remarks. First, since CHAMPs would be metastable, high energy injections at late time due to the decays are expected and they could change the value of several light element abundances. But notice that the amount of the energy injection is in princeple independent from the number density, which can be constrained by our discussion. Of course, in specific models, the effects may not be negligible. On the other hand, the current good agreement with observation has disfavored large changes from SBBN predictions for D, ^{4}He. Since CBBN can not change D, ^{4}He abundances through D$((\alpha, C),\gamma)^6$Li, if we impose constraint from light elements other than ^{6}Li, our evaluation of CBBN production of ^{6}Li here still may provide correct prediction. Of course, the late time energy injection itself also can change ^{6}Li without any big change of other light elements if the energy release is large, which typically increasea ^{6}Li. The most stringent constraint is

$$\xi = Br_h \epsilon \frac{n_C}{n_\gamma} < 2 \times 10^{-13} {\rm GeV} \quad (16)$$

at $t = 10^5$sec assuming all energy release is hadronic [11], where ϵ is the hadronic energy due to the decay and Br_h is hadronic branching ratio of the decay. Roughly the above constraint implies that $n_C/n_H < 10^{-2}(100{\rm GeV}/\epsilon)(Br_h/10^{-3})^{-1}$. We do not expect a significant change for ^{6}Li abundance from our estimate in the region of Fig.1.

Next, if there is no significant charge asymmetry in the CHAMP sector, the positively charged and negatively charged CHAMPs can annihilate into two photons, W/Z or other SM particles. The energy release due to annihilation at T ~10keV was estimated as follow [19, 21].

$$\xi \sim 5 \times 10^{-13} {\rm GeV} (\frac{100{\rm GeV}}{m_C})^{1/2} (\frac{\frac{n_C}{n_H}}{0.01})^2 \quad (17)$$

Again comparing with $\xi < 2 \times 10^{-13} {\rm GeV}(Br_h/1.0)^{-1}$, this effect would be irrelevant in most of region of Fig.1.

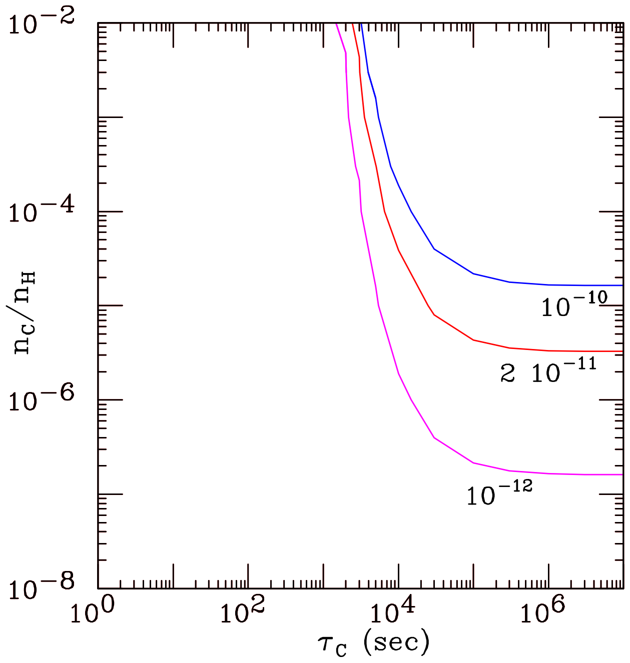

FIG. 1: Contour plot for ^{6}Li/H=10^{-10}, 2×10^{-11}, 10^{-12} as a function of lifetime and relic number density of CHAMPs

[10] In this estimation of recombination cross section, a point particle for ^{4}He is assumed and only capture into 1S state is considered. The estimation may have uncertainties from this assumption, the ignorace of the internal structure of nuclei and the contributions from captures into higher level, which directly reflct to the CBBN prediction.

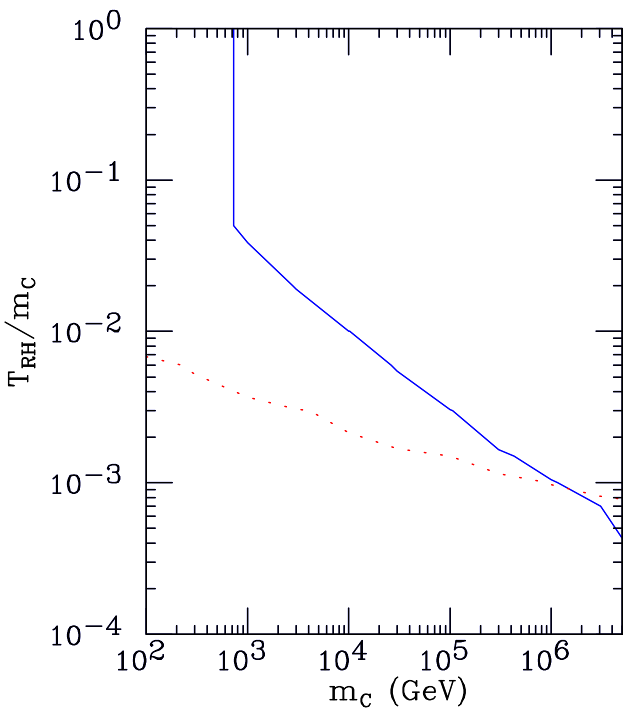

FIG. 2: Contour plot for the energy density $\Omega_C h^2 = 0.1$ (blue solid line) and the number density of CHAMPs $n_C/n_H = 3\times 10^{-6}$ (red dotted line) as a function of mass of CHAMPs and reheating temperature assuming specific reheating model of the Universe. We took $g_*(T_{\rm RH})/g_*(T_F)^{1/2} = 10$.

CONNECTING ^{6}LI WITH THE REHEATING TEMPERATURE

In our scenario, the primordial ^{6}Li abundance depends sensitively on the reheating temperature. In Fig.2, we show the contour plot for $\Omega_C h^2 = 0.1$ which correspond to the present dark matter relic density, and the contour plot for $n_C/n_H = 3\times 10^{-6}$ where the number density of CHAMPs with $\tau_C > 10^6$sec may explain the observed ^{6}Li abundance ^{6}Li/H $\simeq 2\times 10^{-11}$. It is well-known that the SBBN prediction of primordial ^{6}Li abundance$\sim O(10^{-14})$ is much below the observed value. For long lived CHAMP with $\tau_C > 10^6$sec, the ^{6}Li/H line may be a solution to explain the observed abundance of ^{6}Li by the primordial origin. A above the line, ^{6}Li may be over-produced and potentially can constrain the reheating temperature for $\tau_C > 10^6$sec. On the other hand, it will require the knowledge of the late time evoluntion of ^{6}Li from primordial era to present time. As we can see in Fig.1, if the lifetime is shorter than 10^4sec, the constraint significantly weakens. A discovery of CHAMPs with lifetime longer than 10^4sec at collider may put an upper bound of the reheating temperature.

Several collider bounds on the mass of CHAMPs exist. On the other hand, the current most stringent constraint for CHAMP not decaying inside detector is 98 GeV at 95% CL from LEP at $\sqrt{s} = 209$GeV. [29] Currently there is no model-independent constraint through Drell Yan processes at Tevatron Run II. In LHC, the bound may be extended up to 700GeV for 100fb^{-1} for extremely long lived charged slepton in the supersymmetric Standard Model. [30] For the mass regions within collider reach, the ^{6}Li line suggests lower reheating temperature $T_{\rm RH} \sim$ a few GeV. The realization of such low reheating temperature may be a challenge for theoretical models of inflation. Low reheating temperature requires some hierarchy of two scales between initial amplitude of scalar field and the mass of scalar field or some fine tuning of couplings with SM particles.

For the mass region above the collider reach, if a such heavy CHAMP decays into highly degenerate neutral particle and constitutes most of the present dark matter, still there is interesting possibility. This possibility has been discussed in superWIMP dark matter scenario. [31] If heavy extremely long lived CHAMP keeps the tight coupling with baryon-photon fluid until it decays, the small scale power of primordial fluctuation of CHAMPs would be erased within the scale of sound horizon at the decay time, which has an impact on the small scale structure formation of the Universe. [32] To explain small scale problems, the lifetime $\sim 10^7$sec is preferred, where the CBBN ^{6}Li production may be expected. [11] To avoid large free streaming effects and additional cosmological constraints like CMB black body spectrum, tiny mass degeneracy may be favored, which means $\Omega_C h^2 \sim 0.1$ is the interesting region. We can find that such an interesting spot appears for $m_C \sim 10^6$GeV and $T_{\rm RH}/m_C \sim 10^{-3}$. Since the reheating temperature is O(TeV), the realization of leptogenesis scenario [34] may be possible for such heavy CHAMP regions, which face the difficulty with baryon number generation if the reheating happens after the ElectroWeak phase transition.

CONCLUSION

We considered extremely long-lived CHAMPs as a probe of the early Universe. Such CHAMPs could leave their trace in astrophysical observables. The primordial ^{6}Li abundance in CBBN could be sensitive to the number density of extremely long-lived CHAMPs for $T \sim 8$keV. Also, if the reheating temperature is below the mass of the CHAMPs, the relic abundance is also sensitive to the

[11] The rough estimation of the cut off scale is $\lambda \sim 0.265{\rm Mpc}\sqrt{\tau_C/{\rm year}}$.[33] Also the capture by ^{4}He will not disturb the discussion because the bound state would keep similar tight coupling with baryon-photon fluid to freely propagating case. Also since $n_C < n_{^4{\rm He}}$, the most of CHAMPs is captured by ^{4}He, so the conclusion may not be largely different from the case of no-capture.

reheating temperature.

If the CHAMP mass is within the future collider reach, since the lifetime and several parameters associated with the relic abundance can be measured at collider experiments, we will be able to estimate the relic density of CHAMPs as a function of the reheating temperature. The further understanding of CBBN and late time evolution of ^{6}Li from primordial era to present time may determine or constrain such a hidden parameter for collider experiments. Then the measurement of the decay properties and the lifetime of CHAMPs may be a big challenge in future experiments. [35]

Even if the mass range is outside of collider reach, still the existence of CHAMPs may leave a trace on the power spectrum of the primordial fluctuation if the CHAMP was the parent particle of the present superWIMP dark matter.

As one of the attractive possibilities, the search for superWIMP sector e.g in supersymmetric theory with a gravitino LSP or other stable superWeakly interacting superparticles is a very interesting target in future collider experiments and cosmological observations.

ACKNOWLEDGEMENTS

F.T would like to thank Csaba Csaki and Maxim Perelstein for reading the draft of this paper and making useful comments. This work is supported in part by the NSF grant PHY-0355005.

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