Bounds on long-lived charged massive particles from Big Bang nucleosynthesis

Karsten Jedamzik

Laboratoire de Physique Mathématique et Théorique, CNRS,
Université de Montpellier II, F-34095 Montpellier Cedex 5, France
E-mail: jedamzik@lpta.univ-montp2.fr

Received 9 November 2007
Accepted 7 February 2008
Published 10 March 2008

Online at stacks.iop.org/JCAP/2008/i=03/a=008
doi:10.1088/1475-7516/2008/03/008

Abstract. The Big Bang nucleosynthesis (BBN) process in the presence of charged massive particles (CHAMPs) is studied in detail. All currently known effects due to the existence of bound states between CHAMPs and nuclei, including possible late-time destruction of $^6$Li and $^7$Li, are included. The study sets conservative bounds on CHAMP abundances in the decay time range $3 \times 10^2 \, \text{s} \lesssim \tau_x \lesssim 10^{12} \, \text{s}$. It is stressed that the production of $^6$Li at early times $T \sim 10 \, \text{keV}$ is overestimated by a factor $\sim 10$ when the approximation of the Saha equation for the $^4$He bound state fraction is utilized. To obtain conservative limits on the abundance of CHAMPs, a Monte Carlo analysis with $\sim 3 \times 10^6$ independent BBN runs, varying the reaction rates of 19 different reactions, is performed. The analysis yields the surprising result that, except for small areas in the particle parameter space, conservative constraints on the abundance of decaying charged particles are currently very close to those of neutral particles. It is shown that, in the case that the rates of a number of heretofore unconsidered reactions may be determined reliably in the future, it is conceivable that the limit on CHAMPs in the early Universe could be tightened by orders of magnitude.

Keywords: big bang nucleosynthesis, cosmology of theories beyond the SM

ArXiv ePrint: 0710.5153
1. Introduction

Big Bang nucleosynthesis (BBN) has proven itself as a powerful tool in constraining the conditions of the early Universe and physics beyond the standard model. Thus bounds on a variety of hypotheses have been derived including, for example, modifications of gravity, baryon inhomogeneity, matter–antimatter domains, non-zero lepton chemical potentials and relic decaying particles. It has been recently realized that BBN may also place bounds on the abundance of charged, weak-scale mass particles existing during and after BBN. Though it had been noted already earlier that negatively charged, weak-scale mass particles (CHAMPs) form bound states with positively charged nuclei towards the end of BBN [1], it has only recently been put forward that this may impact considerably on the light element yields synthesized during BBN [2]–[4].

Here the most important proposed change is due to a cataclysm of reactions such as $^2$H + $^4$He $\rightarrow$ $^6$Li + $\gamma$ [2]. Other less important modifications, concerning constraints on CHAMPs, had also been considered [4]–[6]. Being of a quadrupole (E2) nature the $^2$H + $^4$He reaction has a very small rate (S factor: $10^{-8}$ MeV barn), thus yielding typically very little $^6$Li/$^1$H $\sim 10^{-14}$ in standard BBN. When the helium nuclei is in a bound state ($^4$He−X$^-$) the above reaction may be replaced by its photonless analog: $^2$H + ($^4$He−X$^-$) $\rightarrow$ $^6$Li + X$^-$, with a cross-section estimated orders of magnitude larger than that for the standard BBN $^6$Li-synthesizing process. Initial estimates for this enhancement factor were given at around $6 \times 10^7$ [2, 7]. It was argued that, since $\sim 1$ of all X$^-$ are within bound states with $^4$He at temperatures $T \lesssim 8$ keV (cf. figure 3), very small abundances of CHAMPs present at $t \approx 10^4$ s in the early Universe could already overproduce the $^6$Li isotope with respect to observations [8]. Assuming a (too restrictive) $^6$Li/$^1$H $\lesssim 2 \times 10^{-11}$ constraint, bounds as strong as $n_{X^-}/s \lesssim 2.5 \times 10^{-17}$, the CHAMP-to-entropy ratio, were derived. These bounds were subsequently weakened by one order of magnitude when a more proper evaluation of the rate for the $^2$H + ($^4$He−X$^-$) $\rightarrow$ $^6$Li + X$^-$ process [9] was derived. Such bounds have now been utilized by a number of groups to constrain, for example, abundances of supersymmetric staus $\tilde{\tau}$ in the early Universe [2, 7], [9]–[11].

Recently, I have shown that there are several changes to the ‘naive’ picture of synthesis of $^6$Li in the presence of CHAMPs [12]. First, ($^4$He−X$^-$) bound states may be destroyed during the electromagnetic cascades induced by the decay of CHAMPs, rendering $^6$Li...
production in some parts of parameter space much less efficient. More importantly, when
CHAMPs are still present at times $t \gtrsim 10^6$ s Big Bang nucleosynthesis enters a second
phase of Coulomb-unsuppressed reactions on bound states between charge $Z = 1$ nuclei
and a CHAMP. It has been shown that reactions such as $^6\text{Li} + (^1\text{H} - \text{X}^-) \to ^4\text{He} + ^3\text{He} + \text{X}^-$, $^7\text{Be} + (^1\text{H} - \text{X}^-) \to ^8\text{B} + \text{X}^-$, etc, are capable of completely destroying any previously
synthesized $^6\text{Li}$ and $^7\text{Li}$. This is possible in particular at somewhat higher CHAMP-to-
entropy $Y_X = n_X/s$ ratios. In order to estimate the efficiency of such destruction, not only
was it required to estimate the cross sections for such $^6\text{Li}$ and $^7\text{Li}$ destroying reactions,
but also those of CHAMP exchange reactions such as $(^1\text{H} - \text{X}^-) + ^2\text{H} \to ^1\text{H} + (^2\text{H} - \text{X}^-)$, capable of significantly reducing the $^1\text{H}$ bound state fraction. Altogether 19 reactions of
significant importance for the late-time nucleosynthesis $t \gtrsim 10^6$ s have been identified.
The rates for all these reactions were determined in the Born approximation. Concerning
details on the BBN with CHAMPs at late times, the importance of particular reactions
and their evaluation, the reader is referred to the original paper [12]. Unfortunately,
the Born approximation is not a particularly good approximation for determining rates
of these 19 important reactions for CHAMP BBN, leaving significant uncertainty in the
BBN yields with late decaying $\tau_x \gtrsim 10^6$ s CHAMPs.

Given the above, it seems very premature to rule out CHAMPs in the early Universe
simply by their production of $^6\text{Li}$ at $T \approx 8$ keV. In this paper constraints on the
abundances on CHAMPs are derived which take full account of all the above-mentioned
extra physics previously neglected. Here constraints will be placed for two different decay
time regimes, for $3 \times 10^2$ s $\lesssim \tau_x \lesssim 5 \times 10^5$ s in section 2, where the important rates are relatively well known, and for $5 \times 10^5$ s $\lesssim \tau_x \lesssim 10^{12}$ s in section 3, where a Monte Carlo
analysis is employed to derive conservative limits. It will be seen that constraints change
by large factors with respect to those previously given, particularly for long CHAMP
decay times.

2. Constraints on CHAMPS with intermediate lifetimes

In the next two sections constraints from BBN on the existence of CHAMPs in the
erly Universe are presented. Such constraints get increasingly more uncertain as the
lifetime $\tau_x$ of a CHAMP increases. For $\tau_x \lesssim 3 \times 10^2$ s CHAMPs have almost no
impact on BBN beyond those of their injection of electromagnetically and hadronically
interacting particles during their decay. Such constraints have already been discussed in
detail in the literature and the reader is referred to, for example, [13] for details.
For $3 \times 10^2$ s $\lesssim \tau_x \lesssim 5 \times 10^5$ s constraints are still fairly reliable and depend mostly
on the $^2\text{H}(^4\text{He} - \text{X}^-, \text{X}^-)^6\text{Li}$ rate. Since this one has been determined beyond the Born
approximation [9] and is most likely known to within a factor of three, limits should also
be known up to such a factor. It has been found numerically that other reactions, such as
$^3\text{H}(^4\text{He} - \text{X}^-, \text{X}^-)^7\text{Li}$ and $^3\text{He}(^4\text{He} - \text{X}^-, \text{X}^-)^7\text{Be}$, play less of a role in setting constraints
at early times, even in the case that their rates significantly exceed those determined in
the Born approximation.

1. The effects of annihilation of $\text{X}^-$ with $\text{X}^+$ in $\text{X}^- - \text{X}^+$ bound states forming to some degree [5] are subdominant
compared to those of the decay itself.
Figure 1. Limits on the primordial CHAMP-to-entropy ratio $Y_x = n_X/s$ (with $n_X/s = Y_x/2$) for CHAMPS with intermediate lifetimes. Shown are constraint lines for CHAMPS of mass $M_x = 1$ TeV and a variety of hadronic branching ratios $B_h = 10^{-5}$–$1$, as labeled in the figure. Solid (red) lines correspond to the conservative limit $^{6}\text{Li}/^{7}\text{Li} < 0.66$, whereas dashed (blue) lines correspond to $^{6}\text{Li}/^{7}\text{Li} < 0.1$. It is seen that only for CHAMPS with $B_h \lesssim 10^{-2}$ do the effects of bound states become important. For smaller decay times $\tau_x$ the limits on CHAMP abundances are virtually identical to those on the abundance of neutral relic decaying particles [13].

When deriving constraints the following conservative observationally determined limits on the light element abundances are adopted:

\begin{align}
Y_p &< 0.258 \\
1.2 \times 10^{-5} &< ^2\text{H}/\text{H} < 5.3 \times 10^{-5} \\
^3\text{He}/^2\text{H} &< 1.52 \\
8.5 \times 10^{-11} &< ^7\text{Li}/\text{H} < 5 \times 10^{-10} \\
^6\text{Li}/^7\text{Li} &< 0.66 (0.1).
\end{align}

Here $Y_p$ denotes the helium mass fraction. The observations behind these limits are discussed in further detail in [13]. It should be noted here that the frequently used bound $^6\text{Li}/^3\text{H} \lesssim 2 \times 10^{-11}$ is too stringent. $^6\text{Li}$ may be destroyed during the lifetime of a Population II star. In fact, if the current discrepancy between standard BBN predicted $^7\text{Li}/^3\text{H} \approx 4.5 \times 10^{-10}$ and Pop II star observed $^7\text{Li}/^3\text{H} \approx 1.25 \times 10^{-10}$ is resolved by a factor of 2–3 stellar $^7\text{Li}$ destruction, as claimed for example in [14], then $^6\text{Li}$ is destroyed by at least the same factor. This would yield an upper limit close to $^6\text{Li}/^3\text{H} \lesssim 4 \times 10^{-11}$, or $^6\text{Li}/^7\text{Li} \lesssim 0.1$. However, since $^6\text{Li}$ is more fragile than $^7\text{Li}$ it may, in principle, be destroyed by much larger factors than $^7\text{Li}$, as shown in a number of stellar evolution studies [15]. A conservative limit of $^6\text{Li}/^7\text{Li} \lesssim 0.66$ (corresponding approximately to $^6\text{Li} \lesssim 2.7 \times 10^{-10}$) was therefore applied in [13].

In figures 1 and 2 constraints on decaying CHAMPS with intermediate lifetimes are presented. In both figures results are shown for a variety of hadronic branching ratios $B_h$. 
Bounds on long-lived charged massive particles from Big Bang nucleosynthesis

Figure 2. Same as figure 1, but for $M_x = 100$ GeV.

Figure 3. Fraction of CHAMPs $f_X$ which are bound to $^4$He as a function of temperature for (a) the approximation by the Saha equation, thin-dashed (green) and (b) full numerical integration of the rate equation, thin-solid (red). Also shown is the product of $f_X$ with the rate $\langle \sigma v \rangle$ for the $^6$Li producing reaction $^2$H($^4$He–X−, X−)$^6$Li, simply denoted as ‘rate’ and in arbitrary units, for both cases (a) thick-dashed (green) and (b) thick-solid (red). The figure illustrates that $^6$Li production at $T \approx 8$ keV due to bound states is overestimated by a factor $\sim 10$ when the approximation of the Saha equation is utilized.

with figure 1 showing results for $M_x = 1$ TeV, and figure 2 for $M_x = 100$ GeV. In order to derive these constraints the rate for $^2$H($^4$He–X−, X−)$^6$Li as given in [9] has been utilized. It is seen that, for large hadronic branching ratio ($B_h \gtrsim 0.01$ for $M_x = 1$ TeV and $B_h \gtrsim 0.1$ for $M_x = 100$ GeV) constraints depend almost linearly on $B_h$ and are not different from those for neutral particles. This seems somewhat surprising, due to the advocated
power [2, 9] of helium–CHAMP bound states to produce $^6$Li. Nevertheless, it is known that $^6$Li is also produced abundantly by hadronic decays during that time [13, 16], and this $^6$Li source is more important than that of $^2$H$(^4$He–$X^-$, $X^-)^6$Li at large $B_h$. The efficiency of $^2$H$(^4$He–$X^-$, $X^-)^6$Li has, in any case, been overestimated in some papers [9, 10]. $^6$Li production here is given by a convolution of two exponentials: (a) the exponentially rising $^4$He–$X^-$ bound state fraction at $T \sim 10$ keV and (b) that due to a Coulomb barrier exponentially decreasing reaction rate. This leads to the bulk of the $^6$Li production in a very narrow temperature interval $8$ keV $\gtrsim T \gtrsim 6$ keV. References [9] and [10] assumed the applicability of the Saha equation for the $^4$He bound state fraction (though earlier studies [2]–[5, 7] did not). Numerical integration shows that the formation of appreciable bound state fractions is slightly delayed when compared to the Saha equation, since the recombination rate is of the same order as the Hubble rate. This may be seen in figure 3. This slight difference results in approximately one order of magnitude less $^6$Li production, due to the convolution of exponentials. Very recently, the same observation has also been made in [17] utilizing the set of Boltzmann equations relevant for $^6$Li production via $^4$He–$X^-$ bound states as given in [18]. Conservative limits on CHAMPs in the intermediate decay time interval are thus weaker than initially thought. Here the weakening is due to a lower rate [9], the failure of the Saha equation and a too restrictive upper limit on the $^6$Li abundance. It is noted here that the photo-disintegration of $(^4$He–$X^-)$ bound states as noted in [12] is comparatively unimportant at small $Y_x$, such that further weakening of the limit on CHAMPs does not result. In any case, when $B_h \lesssim 10^{-2}$, bound-state-induced production of $^6$Li becomes dominant over hadronic production. Since this is the case for, for example, supersymmetric staus, bound state effects thus still remain very constraining in particular scenarios [2].

3. Constraints on CHAMPs with long lifetimes

When the lifetimes exceed $\tau_x \gtrsim 5 \times 10^5$ s it becomes substantially more difficult to place reliable limits. This is due to a large number of CHAMP-induced reactions becoming important at $T \lesssim 1$ keV, in particular all Coulomb-unsuppressed nuclear reactions shown in tables II and III of [12], as well as the CHAMP exchange reactions shown in table IV of that paper. This comprises a total number of 19 reactions. Though all rates have been determined numerically in the Born approximation in [12], as the Born approximation is likely to fail badly, results become uncertain. In order to still arrive at a reliable result one is thus forced to perform a Monte Carlo analysis, varying all ill-determined reaction rates within conservative ranges. This has been done in the present paper. In particular, the Born approximation values of the rates given in [12] (shown in figures 3 and 4, as well as in tables III and IV of that paper) have been taken as benchmarks. For each reaction a random generator determined a factor $f_i$ with which the benchmark rate was multiplied. These factors were generated with a probability distribution flat in logarithmic space, and between values $1/f_{\text{cut}} \leq f_i \leq f_{\text{cut}}$. For the reaction rate dependence conservatively chosen as $f_{\text{cut}}$, the reader is referred to Table VII of [12]. For each point in parameter space, i.e. for $Y_x$ and $\tau_x$, this procedure was repeated 1000 times in order to arrive at 1000 different randomly chosen sets for the 19 ill-determined reaction rates. For each realization of reaction rates an independent BBN calculation was then performed and compared to the observational constraints.
Figure 4. Likelihood areas in the CHAMP-to-entropy ratio $Y_X$—CHAMP lifetime $\tau_X$ (in seconds) plane for bound state BBN to obey the observational constraints on light element abundances, equation (1). Results of a Monte Carlo analysis varying 19 ill-determined reaction rates randomly (see text for details) which significantly impact BBN yields at late times $\tau_x \gtrsim 10^6$ s are shown. From bottom to top, the areas show likelihoods: >99% lightest shade (yellow), 95%–99% (green), 80%–95% (purple), 20%–80% (red), 5%–20% (light blue), 1%–5% (black) and <1% (dark blue), respectively, for CHAMP BBN to respect observational constraints. No effects of electromagnetic and hadronic cascades due to the CHAMP decay have been taken into account (cf. figure 5). The Monte Carlo analysis presented in this figure employs $\sim 1.5 \times 10^6$ independent BBN calculations.

One may wonder if 1000 realizations for the reaction rates are actually sufficient for sampling the, a priori, complicated probability space. After all, even only adopting two values for each reaction rate, a large rate and a small rate, already yields $2^{19} \approx 5 \times 10^6$ different possibilities for sets of reaction rates. For a few individual points in $Y_x$ and $\tau_x$, I have therefore generated $10^5$ different realizations of rate combinations. Comparison with the results from only 1000 realizations shows that the simulation with 1000 realizations may be trusted approximately to the 1% level (i.e. <10 BBN runs passing or failing observational constraints). This is true since, at an individual point in the $Y_x-\tau_x$ plane, results mostly only depend on a number $\sim 4$–6 of rates, with all other rates being less important. Which rates are most important for the BBN yields, however, depends on the location in the $Y_x-\tau_x$ plane. For example, at large $Y_x$ (and $\tau_x$) results depend sensitively on the reactions: $^3\text{H}(^4\text{He}-X, X)^7\text{Li}$, $^6\text{Li}(^4\text{He}-X, X)^4\text{He} + ^3\text{He}$ and $(^4\text{He}-X) + ^2\text{H} \rightarrow ^1\text{H} + (^3\text{He}-X)$ (and to a lesser degree $^7\text{Be}(^4\text{He}-X, X)^8\text{B}$, $^4\text{He}(^3\text{He}-X, X)^7\text{Li}$ and $(^1\text{H}-X) + ^4\text{He} \rightarrow ^1\text{H} + (^4\text{He}-X)$), whereas for small $Y_x$ (still large $\tau_x$) they depend mostly on reactions $^4\text{He}(^2\text{H}-X, X)^9\text{Li}$, $(^1\text{H}-X) + ^2\text{H} \rightarrow ^1\text{H} + (^2\text{H}-X)$ and $(^1\text{H}-X) + ^4\text{He} \rightarrow ^1\text{H} + (^4\text{He}-X)$ (and to a lesser degree $(^3\text{He}-X) + ^4\text{He} \rightarrow ^2\text{H} + (^4\text{He}-X)$).

The results of the present Monte Carlo analysis are shown in figures 4 and 5. Also shown are the likelihood areas in the $Y_X-\tau_X$ plane by different shading (coloring).
Figure 5. As figure 4 but including the effects of electromagnetic cascades during \(X\) decay, assuming that a fraction \(f_{EM} = 1\) of the particle’s rest mass (taken as \(m_X = 100\) GeV) is converted into electromagnetically interacting particles. The hadronic branching ratio was set to \(B_h = 0\). The dashed line shows the analogous limit for neutral relics.

that >99%, 95% – 99%, 80% – 95%, 20% – 80%, 5% – 20%, 1% – 5% and <1% of all randomly generated models at the same \(Y_X\) and \(\tau_X\) obey the observational constraints. Note that the CHAMP-to-entropy ratio \(Y_X\) is easily converted to \(\Omega_X\), the fractional contribution of the \(X\) particle to the present critical density, if it had not decayed, via \(\Omega_X \equiv \frac{\sqrt{\tau_X}}{h^2} = 2.73 \times 10^{11} Y_X \left(\frac{m_X}{1\text{ TeV}}\right)\), where \(h\) is the present Hubble constant in units of 100 km s\(^{-1}\) Mpc\(^{-1}\). Note also that in all constraint figures \(Y_x\) denotes the total CHAMP-to-entropy ratio, assuming that only half of all CHAMPs are negatively charged. Whereas figure 4 shows results when the CHAMP decay is not associated with electromagnetic- or hadronic-energy release, figure 5 assumes a 100% electromagnetic CHAMP decay and the associated electromagnetic cascade nucleosynthesis. It is evident from figure 4 that, when only the effects of bound states are taken into account but not injection of energy during the decay, the probability distribution is extremely flat. In particular, whereas one still finds a small fraction of models which fail for \(Y_x\) as low as \(\sim 10^{-19}\) only at \(Y_x \gtrsim 10^{-12}\) one may exclude CHAMP BBN at the >99% confidence level. Conservatively, and in the absence of more reliable rates, even \(Y_x\) as large as \(10^{-12}\) may thus not be reliably ruled out. This is five orders of magnitude less stringent than the initial claim [2]. Note, however, that such large \(Y_x\) may only be (conservatively) acceptable for invisible, mass-degenerate or stable CHAMPs, associated with very little (or no) injection of electromagnetically interacting energy (i.e. high-energy \(\gamma\)’s and \(e^\pm\)’s). This may be seen from figure 5, where for larger lifetimes \(Y_x \gtrsim 10^{-15}\) is ruled out at the >99% level. Here models are ruled out principally due to violating the \(^3\text{He}/^2\text{H}\) upper limit due to \(^4\text{He}\) photodisintegration. This fact is essentially not changed by the \(X\) particle being charged, as may be seen by inspection of the results in [13] for neutral decaying particles or by the dashed lines in figure 5, which show the analogous limit for neutral particles. Immediately
Bounds on long-lived charged massive particles from Big Bang nucleosynthesis

Figure 6. Isocontours of $^6\text{Li}/^7\text{Li} = 0.66$ solid (red), and $^6\text{Li}/^7\text{Li} = 0.1$ dashed (blue), in the CHAMP-to-entropy $Y_x$-CHAMP lifetime $\tau_x$ plane for rates determined in the unreliable Born approximation [12]. The present figure is not supposed to be utilized for limiting CHAMP abundances. It is rather for illustrative purposes, showing the possible importance of the $^4\text{He} + (^2\text{H}-\text{X}^-) \rightarrow \text{X}^- + ^6\text{Li}$ reaction to further tighten limits on long-lived CHAMPS by orders of magnitude due to late-time $^6\text{Li}$ production. A hadronic branching ratio of $B_h = 0$ has been assumed.

below the constraint line already between 20 and 80% of all models yield acceptable abundance yields. This parameter space is thus currently not ruled out. However, it is conceivable that constraints on CHAMPs may be significantly tightened in the future to values possibly as low as $Y_x \lesssim 10^{-17} - 10^{-18}$, in the case rates for the important reactions $^4\text{He}(^2\text{H}-\text{X}^-, \text{X}^-)^6\text{Li}$, $(^1\text{H}-\text{X}^-) + ^2\text{H} \rightarrow (^2\text{H}-\text{X}^-) + ^1\text{H}$ and $(^1\text{H}-\text{X}^-) + ^4\text{He} \rightarrow (^4\text{He}-\text{X}^-)$ are determined, and contrive to yield unacceptably large $^6\text{Li}$ at low $Y_x$. Here it is noted that the by far most important $^6\text{Li}$ producing reaction, potentially leading to such stringent constraints, is $^4\text{He}(^2\text{H}-\text{X}^-, \text{X}^-)^6\text{Li}$ rather than $^2\text{H}(^4\text{He}-\text{X}^-, \text{X}^-)^6\text{Li}$, yielding the bulk of the $^6\text{Li}$ at temperatures $T \lesssim 1$ keV and not $T \approx 6-8$ keV. Important here is the CHAMP exchange reaction $(^1\text{H}-\text{X}^-) + ^2\text{H} \rightarrow (^2\text{H}-\text{X}^-) + ^1\text{H}$ which may continuously produce $(^2\text{H}-\text{X}^-)$ bound states (cf. [12] for more detail). This trend may be seen in figure 6, where $^6\text{Li}/^7\text{Li}$ isocontours are shown for a CHAMP with $B_h = 0$, and when the Born approximation for all rates is utilized. It is seen that for a $\tau_x \gtrsim 10^6$ s factor $\sim 1000$ more $^6\text{Li}$ is synthesized than for $\tau_x \lesssim 10^6$ s.

It is evident from figures 4 and 5 that the probability distributions only flatten significantly for CHAMP lifetimes $\tau_x \gtrsim 5 \times 10^5$ s. For $10^5$ s $\lesssim \tau_x \lesssim 5 \times 10^5$ s the probability passes from $>99\%$ observationally acceptable models to $<1\%$ observationally acceptable models within one decade of $Y_x$. This is because for shorter $\tau_x$ possible late-time destruction of $^6\text{Li}$ and $^7\text{Li}$ may not yet be efficient due to large $(^1\text{H}-\text{X}^-)$ bound state fractions only forming at $T \lesssim 1$ keV. Up to $\tau_x \lesssim 5 \times 10^5$ s one may therefore approximately use the bounds on CHAMPS as given in section 2. When $\tau_x \gtrsim 5 \times 10^5$ s late-time processing (destruction) of $^6\text{Li}$, $^7\text{Li}$ and $^2\text{H}$ may occur efficiently. For long lifetimes it is thus proposed
to use only the constraint imposed by possible $^3\text{He}/^2\text{H}$ overproduction. This constraint is not affected by bound states and the uncertainties in reactions including bound states. The $^3\text{He}$ isotope is special in that it may not be destroyed without destroying $^2\text{H}$ as well. This is because the reaction $^3\text{He}(^1\text{H}–\text{X}^–, \text{X}^–)^4\text{Li}$ is endothermic and other reactions not involving $^2\text{H}$ nuclei are Coulomb-suppressed. It is thus conservative to use the $^3\text{He}/^2\text{H}$ constraint, in particular, since there are other $^2\text{H}$ destroying (but not producing) reactions within bound state nucleosynthesis. This translates into using the constraints given in [13] for $B_h = 0$ (and shown by the dashed curve for $\tau_x \gtrsim 10^6$ s in figure 5). Since the fraction of rest mass $f_{\text{EM}}$ which is converted to electromagnetic interacting energy has been assumed $f_{\text{EM}} = 1$ for $B_h = 0$ in the figures of [13], the constraint has to be rescaled accordingly, when neutrino losses are significant, or close to mass degeneracy between mother and daughter particle exists. Finally, in the window $5 \times 10^5$ s $\lesssim \tau_x \lesssim 3 \times 10^6$ s one may apply an additional constraint, stronger than that due to $^3\text{He}/^2\text{H}$ overproduction. From figures 4 and 5 it is found that for $Y_x \gtrsim 3 \times 10^{-14}–10^{-13}$ only $\lesssim 1\%$ of all models are observationally acceptable.

A procedure very similar to this has been very recently applied by [17] to derive a lower limit on the gaugino mass parameter $m_{1/2}$ in the constrained minimal supersymmetric standard model (CMSSM) when the gravitino is the lightest supersymmetric particle (LSP). This study considered only the catalyzed reaction $^2\text{H} + (^3\text{He}–\text{X}^–) \rightarrow ^6\text{Li} + \text{X}^–$ for intermediate lifetimes of the next-to-LSP (NLSP), arguing that even without the $^6\text{Li}$ bound long NLSP lifetimes were already ruled out previously by the $^3\text{He}/^2\text{H}$ upper limit. Since in the parameter space under investigation the NLSP is the stau, which has small hadronic branching ratio, the conclusion for $\tau_x \lesssim 5 \times 10^5$ s is thus not expected to change much when the present results are used. Using the results of the Monte Carlo analysis shown in figures 4 and 5 typical stau-to-entropy ratios $Y_x \gtrsim 10^{-13}$ should also be disallowed for $5 \times 10^5$ s $\lesssim \tau_x \lesssim 3 \times 10^6$ s due to $^6\text{Li}$ overproduction and for $\tau_x \gtrsim 3 \times 10^6$ s due to $^3\text{He}/^2\text{H}$ overproduction, rendering the conclusions of [17] likely unchanged.

### 4. Conclusions

In this paper the results of a detailed study of constraints on charged massive particles $X^–$ from Big Bang nucleosynthesis was presented. It was pointed out earlier that bound states between $^4\text{He}$ and negatively charged $X^–$ may lead to the efficient catalytic production of $^6\text{Li}$ at $T \approx 6–8$ keV [2]. Recently I have shown [12] that BBN with CHAMPs enters a second phase of nucleosynthesis at $T \lesssim 1$ keV, capable of destroying all previously synthesized $^6\text{Li}$. Altogether 19 reactions important for late-time BBN were identified. When these processes are included in the analysis, drastic changes concerning limits on the existence of CHAMPs when compared to those previously derived [2, 7, 9]–[11] are obtained.

Limits on the existence of CHAMPs during and after BBN are derived in two different decay time ranges. For very short lifetimes $\tau_x \lesssim 3 \times 10^2$ s limits are independent of the decaying particle being charged, or not. In the range $3 \times 10^2$ s $\lesssim \tau_x \lesssim 5 \times 10^5$ s the important rates (i.e. $^2\text{H}(^4\text{He}–\text{X}^–, \text{X}^–)^6\text{Li}$) are relatively well determined [9], such that a Monte Carlo analysis may be avoided. It is stressed that the approximation of the $^4\text{He}$ bound state fraction by the Saha equation leads to a factor $\sim 10$ overestimate in the synthesized $^6\text{Li}$ abundance. Due to substantial reaction rate uncertainties a full
Monte Carlo analysis had to be performed to obtain reliable and conservative bounds in the decay time range $5 \times 10^9 \text{s} \lesssim \tau_x \lesssim 10^{12} \text{s}$. It was found that, when a number of reaction rates are large, and when electromagnetic energy injection is absent, baryon-to-entropy ratios $Y_x$ as large as $\gtrsim 10^{-12}$ may be observationally acceptable. On the other hand, in the case a number of reaction rates are determined more precisely, in particular the rates for $^4\text{He}(^2\text{H}–X^-)\rightarrow(^1\text{H}–X^-)\rightarrow(^1\text{H}–X^-)\rightarrow(^4\text{He}$, it may be conceivable that limits on long-lived CHAMPs are improved by orders of magnitude, with the CHAMP-to-entropy ratio possibly constrained to be below $10^{-17}$–$10^{-18}$. A prescription is given for how to place conservative limits on CHAMPs, given current reaction rate uncertainties.

The final result of this study is somewhat surprising. When electromagnetic- and hadronic-energy release is included, and within the reaction rate uncertainties, conservative limits on charged decaying particles are no stronger than those on neutral particles. The exception here is the decay time range $10^3$–$3 \times 10^6 \text{s}$ but only when the hadronic branching ratio is small $B_h \gtrsim 10^{-2}$–$10^{-1}$, as is the case for supersymmetric staus.

**Acknowledgments**

I acknowledge helpful discussions with M Asplund, S Bailly, O Kartavtsev, K Kohri, A Korn, G Moulata, M Pospelov, J Rafelski, G Starkman, F Steffen, V Tatischeff and T Yanagida.

**References**

[1] De Rujula A, Glashow S L and Sarid U, 1990 *Nucl. Phys.* B 333 173 [SPIRES]

[2] Dimopoulos S, Eichler D, Esmailzadeh R and Starkman G D, 1990 *Phys. Rev.* D 41 2388 [SPIRES]

[3] Rafelski J, Sawicki M, Gajda M and Harley D, 1991 *Phys. Rev.* A 44 4345 [SPIRES]

[4] Pospelov M, 2006 *Preprint* hep-ph/0605215

[5] Kohri K and Takayama F, 2006 *Preprint* hep-ph/0605243

[6] Kaplinghat M and Rajaraman A, 2006 *Phys. Rev.* D 74 103004 [SPIRES]

[7] Bird C, Koopmans K and Pospelov M, 2007 *Preprint* hep-ph/0703096

[8] Jittoh T, Kohri K, Koike M, Sato J, Shimomura T and Yamanaka M, 2007 *Preprint* 0704.2914 [hep-ph]

[9] Cyburt R H, Ellis J R, Fields B D, Olive K A and Spanos V C, 2006 *J. Cosmol. Astropart. Phys.* JCAP11(2006)014 [SPIRES]

[10] Smith V V, Lambert D L and Nissen P E, 1993 *Astrophys. J.* 408 262 [SPIRES]

[11] Hobbs L M and Thorburn J A, 1997 *Astrophys. J.* 491 772 [SPIRES]

[12] Nissen P E, Asplund M, Hill V and D’Odorico S, 2000 *Astron. Astrophys.* 357 L49 [SPIRES]

[13] Kawasumi K, Kohri K and Moroi T, 2007 *Phys. Lett.* B 649 436 [SPIRES]

[14] Pradler J and Steffen F D, 2007 *Phys. Lett.* B 648 224 [SPIRES]

[15] Jedamzik K, 2007 *Preprint* 0707.2070 [astro-ph]

[16] Jedamzik K, 2006 *Phys. Rev.* D 74 103509 [SPIRES]

[17] Korn A J et al, 2006 *Nature* 442 657 [SPIRES]

[18] Pinsonneault M H, Steigman G, Walker T P, Narayanans K and Narayanan V K, 2002 *Astrophys. J.* 574 398 [SPIRES]

[19] Richard O, Michaud G and Richer J, 2005 *Astrophys. J.* 619 538 [SPIRES]

[20] Dimopoulos S, Esmailzadeh R, Hall J J and Starkman G D, 1988 *Astrophys. J.* 330 545 [SPIRES]

[21] Pradler J and Steffen F D, 2007 *Preprint* 0710.2213 [hep-ph]

[22] Takayama F, 2007 *Preprint* 0704.2785 [hep-ph]
Erratum

It has been recently put forward in [1], and subsequently confirmed in [2], through detailed computations of the most important reaction rates entering bound state nucleosynthesis, that late time $\tau \gtrsim 10^6$ s processing of light element abundances as envisioned possible by the present author [3] does not usually take place. This is mostly because of the abundance of proton–$X^-$ bound states staying small due to efficient exchange reactions transferring $X^-$ from $p$ to $^4\text{He}$, but also due to Coulomb barriers between $p$ and nuclei being only partially shielded when protons are in bound states. The Monte Carlo analysis as performed in sections 2 and 3 is therefore superfluous. Figures 4–6 of the paper are replaced by figure 1 in this erratum. It is cautioned, however, that for relatively large $Y_X > 2Y_{^4\text{He}}$ late time processing may still occur to some degree.

Figure 1. Limits on the primordial CHAMP-to-entropy ratio $Y_x = n_X/s$ (with $n_{X^-}/s = Y_x/2$) as a function of their lifetime $\tau_x$. Shown are constraint lines for CHAMPs of mass $M_x = 1$ TeV (left panel) and $M_x = 100$ GeV (right panel) and a variety of hadronic branching ratios $B_h = 10^{-5}$–$1$, as labeled in the figure. Solid (red) lines correspond to the conservative limit $^6\text{Li}/^7\text{Li} < 0.66$, whereas dashed (blue) lines correspond to $^6\text{Li}/^7\text{Li} < 0.1$. It is seen that only for CHAMPs with $B_h \lesssim 10^{-2}$ do the effects of bound states become important. For small decay times $\tau_x \lesssim 10^3$ s and large decay times $\tau_x \gtrsim 10^7$ s the limits on CHAMP abundances are virtually identical to those on the abundance of neutral relic decaying particles [4].

References

[1] Pospelov M, Pradler J and Steffen F D, Constraints on supersymmetric models from catalytic primordial nucleosynthesis of beryllium, 2008 J. Cosmol. Astropart. Phys. JCAP11(2008)020
[2] Kamimura M, Kino Y and Hiyama E, Big-bang nucleosynthesis reactions catalyzed by a long-lived negatively-charged leptonic particle, 2008 arXiv:0809.4772 [nucl-th]
[3] Jedamzik K, The cosmic $^6\text{Li}$ and $^7\text{Li}$ problems and BBN with long-lived charged massive particles, 2008 Phys. Rev. D 77 063524
[4] Jedamzik K, Big bang nucleosynthesis constraints on hadronically and electromagnetically decaying relic neutral particles, 2006 Phys. Rev. D 74 103509