Solving the cosmic lithium problems with primordial late-decaying particles

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\textbf{I. INTRODUCTION}

Standard Big-Bang nucleosynthesis (SBBN) is one of the most reliable and farthest reaching probes of early Universe cosmology, being based on the rigorously tested Standard Model of particle physics as well as basic principles of nuclear physics. Augmenting these principles with experimental data concerning nuclear reactions, we can precisely estimate the relative abundances of light elements (ALEs), particularly D, \(^{3}\)He, \(^{4}\)He, \(^{6}\)Li, and \(^{7}\)Li (relative to H) at the end of the "first three minutes" after the Big-Bang, as a function of the baryon-to-photon ratio \(\eta\). Consequently, SBBN has been instrumental in the realisation that baryonic matter constitutes only a small proportion of the total energy density of the Universe, hence providing further supporting evidence for the existence of dark matter. Utilising the value of \(\eta\) measured by the Wilkinson Microwave Anisotropy Probe (WMAP), \(\eta_{\text{WMAP}} = (6.10 \pm 0.21) \times 10^{-10}\) at the 68\% C.L.\textsuperscript{1}, the majority of theoretical predictions from SBBN are in excellent agreement with observational data. This is truly remarkable considering that the ALEs span many orders of magnitude from \(^{4}\)He/H\textasciitilde0.08 down to \(^{7}\)Li/H\textasciitilde10\(^{-11}\).

Despite the great success of SBBN, it has been noted that the prediction for the ratio of \(^{7}\)Li to H, \(-9.476 < \log_{10}(^{7}\text{Li}/\text{H}) < -9.322\) (obtained using \(\eta_{\text{WMAP}}\)), does not agree with current observations. Recently Bonifacio \textit{et al.}\textsuperscript{2} reported that \(\log_{10}(^{7}\text{Li}/\text{H})_{\text{obs}} = -9.90 \pm 0.09\), confirming the results of Ryan \textit{et al.}\textsuperscript{3} \(\log_{10}(^{7}\text{Li}/\text{H})_{\text{obs}} = -9.91 \pm 0.10\). Even the less stringent observational result \(-9.63 \pm 0.06\) of Melendez and Ramirez (MR)\textsuperscript{4} exceeds the SBBN prediction at 2\(\sigma\). This is the "\(^{7}\)Li problem". It has been often argued that the \(^{7}\)Li abundance would be smaller than the SBBN value due to depletion in stars\textsuperscript{5,6}. However, a quite uniform \(^{7}\)Li abundance (the Spite plateau) observed in metal-poor stars is somewhat difficult to explain with such stellar depletion and, moreover, the recent detections by\textsuperscript{7} of more fragile isotope \(^{6}\)Li in some of these stars provide evidence against stellar depletion.

The observations of\textsuperscript{8,9} that some metal-poor stars have the isotopic ratio \(^{6}\)Li/\(^{7}\)Li of a few percent not only sharpened the \(^{7}\)Li problem but also elucidated the "\(^{6}\)Li problem". Since the \(^{6}\)Li abundance predicted in SBBN is very small (\(^{6}\)Li/\(^{7}\)Li\textasciitilde3.3 \times 10^{-5}\) for \(\eta_{\text{WMAP}}\), it is usually considered to be produced later through cosmic ray nucleosynthesis, but it is also known that the conventional processes are not sufficient for the observed abundance. This \(^{6}\)Li problem was exacerbated by\textsuperscript{10} who found a relatively metallicity-independent abundance of \(^{6}\)Li which is in contrast to the prediction of the cosmic ray synthesis scenario. In particular, a high abundance \(^{6}\)Li/\(^{7}\)Li = 0.046 \pm 0.022 observed in the very metal-poor star LP 815–43 with [Fe/H] = −2.74, is very hard to obtain. Unconventional scenarios to enhance \(^{6}\)Li are investigated, for example, in\textsuperscript{11,12,13} but they cannot solve the \(^{7}\)Li problem in any case.

As has been discussed, the "Lithium problems", too much \(^{7}\)Li and too little \(^{6}\)Li produced in the standard scenario, do not have an astrophysical solution in a complete manner at present.\textsuperscript{#1} In addition, the recent ob-

\textsuperscript{#1} Solutions by invoking not well measured reaction rates were investigated in\textsuperscript{11,13}, but without success at this stage.
servations seem to imply that stellar depletion of $^7\text{Li}$ is limited and that the metallicity dependence of $^6\text{Li}$ is only modest. These facts lead us to seek a solution to the Lithium problems by incorporating particle physics beyond the standard model. Specifically, we reinvestigate the effects on BBN predictions of late-decaying particles (LDPs) possessing a finite hadronic branching ratio. In the mid-eighties, Dimopolous, Esmailzadeh, Hall and Starkman (DEHS) showed that the mixed hadronic and electromagnetic decays of a massive particle at $t \sim 10^3\text{s}$ could reproduce the ratios of light elements $^{11,12}\text{Be}$ as then measured. In LDP nucleosynthesis, the products of particle decays scatter off the SBBN-produced light elements modifying the ALEs. Potentially, the modifications in the ALEs could eliminate the existing inconsistencies with current observations, since they predicted that a signature of such decays would be an anomalously high $^6\text{Li}$ to $^7\text{Li}$ ratio.

LDPs, which we call here $X$, appear in widely considered extensions to the standard model. For example, they are realised in supergravity models where the next-to-lightest sparticle (NLSP) decays into the lightest sparticle (LSP) with an extremely long lifetime (typically exceeding $\sim 1\text{ sec}$), owing to the Planck-mass suppression of its interactions. In these theories the most favoured candidate for $X$ would be a gravitino with a neutralino LSP, or a neutralino, a stau and a sneutrino as NLSPs with a gravitino LSP. These are but a few of the plethora of subtly varying possibilities. Many have been discussed and their effects rigorously investigated in studies conducted in the 1980’s $^{11,12,23,28}$, 1990’s $^{13,18,29}$, right up to recent times $^{13,18,30}$, with significant improvements being made at each stage (see also a text book $^{31}$ and references therein, and a recent partial reconfirmation in Ref. $^{32}$). Given the excellent agreement between SBBN and the measured (or inferred) abundances of $\text{D, } ^3\text{He and } ^4\text{He}$, the properties of LDPs are heavily constrained. Such constraints are valuable to theories beyond the standard model involving LDPs that are massive and weakly-interacting, which are difficult to study in collider experiments.

The purpose of this paper is to utilise the state-of-the-art model-independent analysis of LDP nucleosynthesis performed by Kawasaki, Kohri and Moroi (KKM) $^{13,14}$ (incorporating important improvements of the original DEHS analysis), to identify the parameter space that is consistent with current observations. That is, we determine the range of values such as hadronic branching ratio $B_\text{H}$, the lifetime $\tau_X$, and the primordial energy density of $X$ particles divided by primordial entropy density $Y_X$ that solves the Lithium problems while leaving the abundances of $\text{H, D, } ^3\text{He and } ^4\text{He}$ in agreement with observations. In addition we will reconfirm the original prediction of DEHS that a signature of the model is a high $^6\text{Li}/^7\text{Li}$ ratio, and note that this prediction is now in agreement with observational data. Fundamental particle physics models with LDPs would then need to lie within this allowed region of parameter space in order to solve the Lithium problems. Alternately, they might satisfy limits which have been presented elsewhere to ensure that they did not significantly change the ALEs, and look elsewhere for a solution of the Lithium problems.

In Sec. III we describe some key reactions in solving the Lithium problems. We carefully discuss how we can reduce uncertainties with regards the non-thermally produced abundance of $^7\text{Li}$ and $^7\text{Be}$ resulting from the $\alpha-\alpha$ collisions and make conservative predictions for the corresponding effects on the $^7\text{Li}$ abundance. In Sec. IV we summarise recent observational data which we try to explain by BBN with LDPs. We present our results in Sec. V and comment on the solution when some stellar depletion takes place in Sec. VI. We discuss our results in Sec. VI

II. REACTIONS

The reaction which is most significant in reducing the net $^7\text{Li}$ abundance is the neutron capture of $^7\text{Be},$ $^7\text{Be} + n \to ^7\text{Li} + p$, where the neutron is non-thermally produced in the hadronic decay resulting from the hadronic decay of a LDP. Subsequently, $^7\text{Li}$ can be destroyed by thermal protons through the process $^7\text{Li} + p \to 2^4\text{He}$. For relatively high baryon to photon ratios, $\eta \gtrsim 3 \times 10^{-10}$, the cosmic $^7\text{Li}$ abundance at much later times is mainly generated through electron capture by primordial $^7\text{Be}$. This is because primordial $^7\text{Li}$ (but not $^7\text{Be}$) is destroyed by the above thermal process involving $p$ capture. However, if large numbers of the non-thermal neutrons are emitted (e.g. by LDP decay) at the appropriate time, then the primordial $^7\text{Be}$ abundance can be converted to $^7\text{Li}$ sufficiently early to be destroyed through thermal proton capture. This mechanism was originally identified by Jedamzik in his pioneering work $^{13}$ for the first time and studied further in detail by $^{16,17,18,33}$ (For other mechanisms to reduce the $^7\text{Li}$ abundance beyond the standard model, see also $^{35,36,37,38,39,40}$).

The competing constraints on the properties of LDPs ultimately come from preventing the overproduction of $\text{D and } ^6\text{Li}$. These elements are also non-thermally produced during the evolution of the LDP hadronic shower. $\text{D}$ is directly produced through the spallation of $^4\text{He}$ by energetic nucleons, while $^6\text{Li}$ is mainly produced through the scattering of energetic (shower) $^4\text{He}$ off the background $^3\text{He}$ (and also $^7\text{Be}$). Such energetic $^4\text{He}$ and $^3\text{He}$ are produced through the destruction of the background $^4\text{He}$ within the LDP hadronic shower.

Both $^7\text{Li}$ and $^7\text{Be}$ can also be non-thermally produced in a manner similar to $^6\text{Li}$. If $^4\text{He}$ are produced during the evolution of the LDP hadronic shower through $p/n + ^4\text{He} \to p/n + ^4\text{He} + \pi^0$ (due to energetic shower nucleons), then energetic $^4\text{He}$ can collide with background $^4\text{He}$ and produce $^7\text{Li}$ and $^7\text{Be}$ (and also $^6\text{Li}$, although this is subdominant compared to the $^4\text{He}$ and $^4\text{He}-^4\text{He}$ processes $^{11,12,14}$). These non-thermal pro-
duction mechanisms were studied in detail in [13, 14], in order to constrain the properties of the LDPs, and also applied to solve the $^7\text{Li}$ problem with some audacious approximations in [16]. However, only if we adopt milder observational constraints on $^7\text{Li}$ (as in [13, 14]), can we ignore the intricacies of these production processes.

Unfortunately, there is a severe lack of experimental data on the energy distribution of the $^4\text{He}$ in the final state of $\alpha$-$\alpha$ inelastic scattering in the relevant energy regime. This energy distribution is essential in order to accurately compute the abundance of non-thermally produced $^7\text{Li}$ and $^7\text{Be}$. By making reasonable approximations for the energy of the scattered $^4\text{He}$, inferred from experimental data on similar processes involving collisions of energetic heavy ions, and utilising the theoretical properties of quantum chromodynamics (QCD), some of the current authors have investigated these non-thermal processes [14, 16]. The constraints on the abundance of hadronically-decaying LDPs from predictions of the abundance of $^7\text{Li}$ and $^7\text{Be}$ were not significantly affected by these approximations, since the authors considered relatively generous observational constraints.

However, for our purposes it is essential to more precisely calculate the abundances of these elements. In particular, a slight overestimation of the production of $^7\text{Li}$ and $^7\text{Be}$ may counterbalance their depletion by neutron capture, resulting in a worse fit to the more stringent data now available. Therefore we must reconsider the above ambiguities in order to better estimate the non-thermally produced $^7\text{Li}$ and $^7\text{Be}$ abundances.

In the previous treatment [14, 16], there was a tendency for the estimated energy of the final state $^4\text{He}$ to be larger than the equipartition distribution in the center-of-mass (CM) system. This was because the authors used theoretical properties of quantum chromodynamics (QCD) to extrapolate results from high-energy experiments to lower energies until the extrapolation became kinematically inconsistent. However, whenever we include non-standard processes, such as the aforementioned non-thermal $\alpha$-$\alpha$ collisions, into the standard calculations, it would be better to adopt most conservative approximations than does not result in such an overestimate of the kinetic energy of the final state $^4\text{He}$. Hence, we conservatively chose a (smaller) value of the $^4\text{He}$ kinetic energies between the experimentally-suggested QCD prediction [12] and the equipartition value in the CM system. For non-relativistic $\alpha$-$\alpha$ collisions this tends to give smaller energies for the scattered $^4\text{He}$, reducing the resulting abundance of Li and Be. To understand the significance of these processes, we also investigated scenarios without the $\alpha$-$\alpha$ collisions.

III. OBSERVATIONAL CONSTRAINTS ON LIGHT ELEMENT ABUNDANCES

Our theoretical ALEs must be compared against the observational constraints on the abundances of D, $^4\text{He}$, $^6\text{Li}$ and $^7\text{Li}$. The errors presented here are 1 $\sigma$ errors unless otherwise stated. The subscripts “p” and “obs” refer to the primordial and observational values, respectively. The abundance of $^3\text{He}$ does not play any significant role in our conclusions.

With regard to the mass fraction of $^4\text{He}$, recently two groups reported new values of $Y_p$ [43, 44] by adopting quite new $^4\text{He}$-emissivity data [43]. Izotov, Thuan and Stasinska reported two values, $Y_p$(IZS1) = 0.2472±0.0012 and $Y_p$(IZS2) = 0.2516±0.0011 [44] by using old and new $^4\text{He}$-emissivity data, respectively. Note that $Y_p$(IZS2) at face value excludes the SBBN prediction ($\approx 0.2484$) even with various theoretical errors ($\approx 0.0004$). We artificially incorporate a larger error into the value of $Y_p$(IZS2), to investigate conservative bounds, and call it “IZS3”, $Y_p$(IZS3) = 0.2516±0.0040, where the larger error 0.0040 was adopted according to a discussion in [46]. The possibility of these kinds of large errors was also discussed in [46].

We adopt the following two deuterium abundances, $\text{Low}(D/H)_{\text{obs}} = (2.82 ± 0.26) \times 10^{-5}$ as a most-recently reported value of the weighted mean [47], and the more conservative value, $\text{High}(D/H)_{\text{obs}} = (3.98_{-0.67}^{+0.50}) \times 10^{-5}$ [45].

As was discussed in Sec. II we will compare both milder and more stringent constraints on $^7\text{Li}/H$: $\log_{10}(^7\text{Li}/H)_{\text{obs}} = -9.63 ± 0.06$ (MR) [4], and $\log_{10}(^7\text{Li}/H)_{\text{obs}} = -9.90 ± 0.09$ (Bonifacio et al.) [2, 3].

For the $^6\text{Li}$ abundance, we adopt $^6\text{Li}/^7\text{Li} = 0.046 ± 0.022$, which was recently observed in the very metal-poor star LP 815-43 with [Fe/H] = $-2.74$ [7]. Again note that the value of $^6\text{Li}/^7\text{Li}$ calculated in SBBN ($\approx 3.3 \times 10^{-5}$) does not agree with this constraint.

IV. RESULTS

Let us first summarise the basic framework of our study. We describe the properties of the LDP, which we call $X$, using only the following generalised parameters: $E_{\text{vis}}$, the (averaged) energy emitted in the form of visible particles (an invisible particle may also be emitted in some cases); $\tau_X$, the lifetime of $X$; $B_n$, the branching ratio for $X$ decay channels directly resulting in hadron production; the primordial abundance of $X$, which we parameterise using the “yield variable” $Y_X = n_X/s$, which is defined at a cosmic time $t \ll \tau_X$. Here, $n_X$ is the number density of $X$ while $s$ is the total entropy density. We know that the influence of unobservable decay products (e.g. neutrinos) has a negligible effect in our calculations (see [27, 33, 34] and references therein).

In our analysis, we calculate the primordial ALEs for a variety of different combinations of the above LDP model parameters, taking account of dissociation processes induced by the additional hadronic and electromagnetic interactions resulting from $X$ decays, as discussed in [13, 14], with some important modifications discussed in Sec. II. We assume that two jets are produced in each
hadronic decay of \( X \), each with an energy \( E_{\text{jet}} = m_X/2 \), with the hadronic branching ratio of \( X \) equal to \( B_h \). Here we set the mass of \( X \) to \( m_X = 1 \text{ TeV} \) and the energy converted into visible particles to \( E_{\text{vis}} = 2E_{\text{jet}} = m_X \). However, we conveniently find that even if we change \( m_X \), \( E_{\text{vis}} \) or \( B_h \), the constraints on \( B_h E_{\text{vis}} Y_X \) are not significantly altered for \( \tau_X \lesssim 10^6 \) sec. By comparing the results with the observations, we derived stringent constraints on both \( B_h E_{\text{vis}} Y_X \) and \( \tau_X \).

The shaded region indicates the part of parameter space that is consistent with observational 2\( \sigma \) constraints on the abundances of \(^4\text{He}(\text{ITS3})\), \(^7\text{Li} \) and \(^6\text{Li} \), where in (a) we omit the \( \alpha-\alpha \) collisions as discussed in Sec. VII whereas in (b) we include the \( \alpha-\alpha \) collisions. Two combinations of \( D \) and \(^7\text{Li} \) constraints are displayed: one using Low (D/H) and \(^7\text{Li}/\text{H} \) (MR), and a second using High (D/H) and \(^7\text{Li}/\text{H} \) (Bonifacio et al.). Note that only upper bounds on \( B_h E_{\text{vis}} Y_X \) are provided by the \( Y_p \) (ITS3) and D/H contours. We also note that, even if we adopted other observational bounds on \(^4\text{He} \), such as ITS1 and the values published in [43, 46], our results on the consistent region of parameter space would not be affected.

In both Fig. (a) and (b) (i.e. with and without the incorporation of \( \alpha-\alpha \) scattering), we identify a region of parameter space that agrees with all observational constraints, including those relating to \(^7\text{Li}/\text{H} \) and \(^6\text{Li}/\text{H} \). Even if we adopted the more stringent constraints claimed by Bonifacio et al., there still remains such an allowed region of parameter space if we adopt the High(D/H) result. Any differences in these observationally-consistent regions of parameter space in figures (a) and (b) should be interpreted as due to theoretical uncertainties in the hadron shower physics. Fortunately, such differences are minute.

The \(^6\text{Li} \) vs \(^7\text{Li} \) contour located at smaller \( \tau_X \) corresponds to the 2\( \sigma \) lower bound \(^6\text{Li} \geq \) 0.002. It has the unusual feature of being nearly perpendicular to the \( \tau_X \)-axis. This is because the non-thermally produced \(^6\text{Li} \) is uniformly destroyed by the standard thermal process \(^6\text{Li}(p, ^3\text{He})^4\text{He} \), whose reaction rate is a steeply falling function of cosmic temperature.

If we adopted a less-stringent lower bound, say \(^6\text{Li} \) \( \geq \) 6 \( \times \) \( 10^{-5} \) (note that SBBN predicts \(^6\text{Li} \) \( \geq \) 3 \( \times \) \( 10^{-5} \) for \( \eta = 6.1 \times 10^{-10} \)), it can explain \( Y_p \) (ITS2). In turn we may say that we require models where \(^6\text{Li} \) \( \geq \) 6 \( \times \) \( 10^{-5} \) in order to resolve the discrepancy between the \( Y_p \) (ITS2) measurement and the corresponding SBBN prediction.

V. STELLAR DEPLETION

There is a possibility of late-time destruction of \(^6\text{Li} \) and \(^7\text{Li} \) in stars. Although we have argued in Sec. VII that the detections of \(^6\text{Li} \) in [49] show there is no stellar depletion, it can change for BBN with LDPs since \(^6\text{Li} \) can be produced so much relative to \(^7\text{Li} \) that the observed ratio \(^6\text{Li}/^7\text{Li} \) is reproduced even though the depletion takes place. In fact, we find an interesting solution for which the constraints on the abundance of \(^7\text{Li} \) claimed by Bonifacio et al. and Ryan et al. are compatible with the Deuteron abundance constraint, Low (D/H), with some stellar depletion.

According to [49], rotational mixing within halo stars results in the depletion of \(^7\text{Li} \), which can be parameterised by a depletion factor \( D_{\tau} \). The currently-observed \(^7\text{Li} \) abundance is then related to its primordial value by \( \log_{10}(7Li(\text{H})_p) = \log_{10}(7Li(\text{H})_{\text{obs}} + D_{\tau}) \). Because \(^6\text{Li} \) is more easily dissociated than \(^7\text{Li} \), the depletion factor associated with \(^6\text{Li} \), \( D_{\tau} = 2.5D_{\tau} \) [3]. Thus \( (6Li/7Li)_p = \)}
The most severe observational bounds can be satisfied. It lies within the range $1.5 \times 10^{-14} < B_h(E_{\text{vis}}/1\text{ GeV})Y_X < 3.0 \times 10^{-13}$ (where again $Y_X$ is the ratio of the primordial number density of LDPs divided by the entropy density) and $3.0 < \log_{10}(\tau_X/1\text{ sec}) < 3.8$ (with narrower ranges corresponding to observational constraints that are stronger than the most mild bounds discussed in this study). We derived the allowed regions in terms of the generalised parameters describing LDPs and converting them to some specific particle physics model parameters should be straightforward. This also means that the current study has independently confirmed the pioneering works $^{15, 17}$ by Jedamzik and his collaborators, with an improved treatment of some of the key reactions involved, as discussed in §II.

The scenario has the possibility of the nonthermal-production of cold/warm dark matter as one of the decay products of the $X$, which must be important for formations of small scale structures $^{17, 53, 54}$.

Finally, since we have a lower limit on $B_hE_{\text{vis}}Y_X$ to solve the Lithium problem, together with the constraint that the additional component of the energy density of the parent massive particle $X$ not to produce too much $^4\text{He}$, we can derive a lower limit on the hadronic branching ratio as $B_h > 10^{-8}$. The precise constraint $B_h > 10^{-8}$ originates from the relatively reasonable assumption that we allow one additional neutrino species which contributes (approximately 15% of the total) to the energy density at the freezeout temperature of nucleons $T = 0.1\text{ MeV}$.

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VI. DISCUSSION

We have investigated a scenario where late-decaying particles (LDPs) of lifetime $\tau_X \gtrsim 1\text{ sec}$, possessing a finite branching ratio into hadrons, $B_h$, and emitting visible particles of energy $E_{\text{vis}}$, are incorporated into the standard cosmological model. The scenario reaffirms the earlier prediction of DEHS that, as now observed, the $^6\text{Li}/^7\text{Li}$ abundance ratio is much larger than the SBBN predicted value. We find that this allows us to solve the so-called “Lithium problems”, while simultaneously remaining consistent with all other observational constraints on the abundances of light elements (ALEs) (within their 2 $\sigma$ error ranges). In other words, there exists a region of parameter space in which even the

\[ (^{6}\text{Li}/^{7}\text{Li})_{\text{obs}} \times 10^{1.5D_f}. \]

In Fig. 2 we plot results for the ALEs corresponding to $D_f = 0, 0.1,$ and 0.2. We see that the most severe experimental bounds on the abundance of $^7\text{Li}/H$ from Bonifacio et al. agree with the theoretical model for $D_f \gtrsim 0.2$, even if we adopt the Low (D/H) constraint.

FIG. 2. Results assuming stellar depletion. Here we have adopted the depletion factor $D_f = 0, 0.1,$ and 0.2 (thin line, moderate line, and thick line). We see that the most severe bounds on $^7\text{Li}$ agree with the theory with $D_f = 0.2$. The star symbol means the allowed region. Here we have included $\alpha + \alpha \rightarrow \text{Li}$ and Be processes.

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