Lithium-6: A Probe of the Early Universe

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It is well known that useful constraints on the abundance of relic particles decaying after the epoch of Big Bang Nucleosynthesis may be derived from a possible overproduction of ^{3}He and ^{2}H. These nuclides result from the photodisintegration of ^{4}He by γ-rays from an electro-magnetic cascade initiated by the decay of the out-of-equilibrium relic particles. I show that the products of the photodisintegration process (i.e. ^{3}H, ^{3}He) are energetic enough to synthesize ^{6}Li via non-thermal nuclear reactions on ^{4}He. The synthesized ^{6}Li/H ratio may be compared to ^{6}Li/H in metal-poor halo stars which, in the absence of stellar depletion of ^{6}Li, yields already with current observational data more than an order of magnitude stronger constraints on relic particle densities than considerations of overproduction of ^{3}He and ^{2}H. In the advent that a plateau in ^{6}Li/H ratios in metal-poor stars should be ever established, invaluable insight about the very early universe could be gained.

It is believed that most of the observed properties of the present universe originate from out-of-equilibrium conditions during brief periods in the evolution of the very early universe. These may result during cosmic phase transitions, an inflationary period followed by an era of reheating, and epochs of incomplete particle annihilation. During such eras the production of "unwanted" relics is also possible, and any observational constraint on relics is important in order to limit a plethora of proposed scenarios. Lindley [1] pointed out, that γ-rays present in the primordial plasma below redshift $z \lesssim 10^7$ may spoil the agreement between light element abundances synthesized during Big Bang nucleosynthesis (hereafter, BBN) and observationally inferred primordial abundance constraints due to the possible photodisintegration of ^{2}H. Similarly, possible overproduction of mass two and three elements concomitant with the photodisintegration of ^{4}He may result from γ-rays injected below redshift $z \lesssim 2\times 10^6$. Such arguments have since been used to constrain the abundances of a variety of relics, such as massive decaying particles [2], and radiating cosmic strings [3,4], among others. In this letter I point out, that electro-magnetic decay of relics after the BBN era leads also to efficient production of ^{6}Li [5].

Injection of energetic $e^{\pm}$ and γ-rays into the primordial plasma at high redshift induce an electro-magnetic cascade on the cosmic microwave background radiation (hereafter, CMBR) via pair production of γ-rays on CMBR photons, $\gamma + \gamma_{\rm bb} \to e^- + e^+$, and inverse Compton scattering of the produced pairs on the CMBR, $e^{\pm} + \gamma_{\rm bb} \to e^{\pm} + \gamma$. This cascade, rapid compared to the expansion time of the universe, is halted only when γ-ray energies fall below the threshold for pair production, i.e. for $E_\gamma < E_C \simeq m_e^2/2E_{\rm bb}$. The resulting spectrum of "breakout" (i.e. $E_\gamma < E_C$) photons is quite generic, independent of the details of the injection mechanism, and has been analyzed analytically and numerically [1,7,11,9,10]. The number of "breakout" photons per unit energy interval is well approximated by the following form [11]

$$n_\gamma(E_\gamma) \approx \begin{cases} K_0 (E_\gamma/E_X)^{-1.5} & \text{for } E_\gamma < E_X \\ K_0 (E_\gamma/E_X)^{-2} & \text{for } E_X < E_\gamma < E_C \\ 0 & \text{for } E_C < E_\gamma \end{cases} \tag{1}$$

where $E_C(z) \approx 4.7\times 10^7 z^{-1}$MeV, with z redshift, and $E_X(z) \approx 1.78\times 10^6 z^{-1}$MeV [9] represents a break in the spectrum. Here

$$K_0 \approx \frac{E_0}{E_X^2[2+\ln(E_C/E_X)]}\,, \tag{2}$$

is a normalization constant with E_0 the total energy in form of electro-magnetically interacting particles (i.e. $e^{\pm}$'s and γ's with energies well above E_C) injected by the decay. Subsequent interactions of the "breakout" γ-rays are dominated by processes on matter. The dominant process for energetic photons is Bethe-Heitler pair production on protons and helium, i.e. $\gamma + p\,(^4{\rm He}) \to p\,(^4{\rm He}) + e^- + e^+$. The cross section for this process is given by

$$\sigma_{BH}(E_\gamma, Z) \approx \frac{\alpha}{\pi}\sigma_{Th}\left(\frac{28}{9}\ln\left[\frac{2E_\gamma}{m_e}\right] - \frac{218}{27}\right)Z^2\,, \tag{3}$$

for $1 \ll E_\gamma/m_e \ll \alpha^{-1}Z^{-1/3}$, where α is the fine structure constant, σ_{Th} the Thomson cross section, m_e the electron mass, and $Z=1$ for protons and 2 for helium. For example, at $E_\gamma \approx 80$MeV one finds $\sigma_{BH} \approx 5.7\,$mb for Bethe-Heitler pair production on protons. The pairs created suffer inverse Compton scattering on CMBR photons and generate a secondary generation of γ-rays which, nevertheless, is much softer than the "breakout" photons whose initial spectrum is given by Eq. (1).

Energetic γ-rays may also photodisintegrate ^{4}He, i.e. $\gamma + {}^4{\rm He} \to {}^3{\rm H}\,({}^3{\rm He}) + p\,(n)$, provided their energies are above the threshold for this process, $E^{th}_{\gamma^4{\rm He}} = 19.81\,$MeV for production of ^{3}H (which decays into ^{3}He) and $20.58\,$MeV for direct production of ^{3}He. Here the cross sections for the production of ^{3}H and ^{3}He are almost equal. Deuterium may also result from the photodisintegration process but with production typically suppressed by a factor of ten compared to that of ^{3}He [9,4]. Whereas production of ^{3}He during the photodisintegration of ^{4}He is negligible for photons with $E_\gamma > E_C$ due to the efficiency of pair production on CMBR photons, a small fraction of "breakout" photons photodisintegrate rather than Bethe-Heitler pair produce. Thus at redshift $z \lesssim 2\times 10^6$ when $E_C \gtrsim 20\,\mathrm{MeV}$ cosmologically significant production of ^{3}He may result. The total number of ^{3}H nuclei produced by "breakout" photons is given by the contribution from photons with different energies, E_γ,

$$N_{^3\mathrm{H}} = \int_{E^{th}_{\gamma^4\mathrm{He}}}^{E_C} \mathrm{d}E_\gamma \frac{\mathrm{d}N_{^3\mathrm{H}}}{\mathrm{d}E_\gamma}\,, \tag{4}$$

where

$$\frac{\mathrm{d}N_{^3\mathrm{H}}}{\mathrm{d}E_\gamma} \approx \frac{n_{^4\mathrm{He}}\,\sigma_{^4\mathrm{He}(\gamma,p)^3\mathrm{H}}(E_\gamma)\,n_\gamma(E_\gamma)}{n_p\,\sigma_{BH}(E_\gamma,1) + n_{^4\mathrm{He}}\,\sigma_{BH}(E_\gamma,2)}\,, \tag{5}$$

and with $n_{^4\mathrm{He}}$, n_p helium and proton density, respectively. Eq. (5) is essentially a computation of the probability $P_{\gamma\mathrm{He}}$ that a photon will photodisintegrate, given that its typical life time towards pair-production is $\tau_{BH} \approx (c\sigma_{BH}n_p)^{-1}$. It applies for $P_{\gamma\mathrm{He}} \ll 1$ and when τ_{BH} is smaller than the Hubble time at the epoch of the cascade, which is the case for $z \gtrsim 10^3$

It is important to realize that the photodisintegration process leaves an initially non-thermal distribution of daughter nuclei, which may participate in non-thermal nuclear reactions. In fact, if only a small fraction of the produced energetic ^{3}H and ^{3}He may further react via $^3\mathrm{H}\,(^3\mathrm{He}) + {}^4\mathrm{He} \to {}^6\mathrm{Li} + n\,(p)$, overproduction of ^{6}Li may result. This reaction has energy threshold of $E^{th}_{^6\mathrm{Li}} = 4.80$ MeV for synthesis of ^{6}Li by ^{3}H nuclei and 4.03 MeV by ^{3}He nuclei and thus is of no importance during the BBN freeze-out where thermal nuclear reactions take place. The cross section for $^3\mathrm{He}(\alpha,p)^6\mathrm{Li}$ has been measured at $32 + 3\,\mathrm{mb}$ at $28\,\mathrm{MeV}$ energy (in the lab frame) [12], where the first contribution is from production of ^{6}Li in the ground state and the second is into the second excited state of ^{6}Li (which decays into the ground state). The cross section for ^{3}H is expected to be almost the same due to symmetry considerations. Unfortunately, there seems to be no further experimental data for this reaction. Theoretical calculations of nuclear reactions within seven-nucleon systems [13] may reproduce the experimental data and suggest that the cross section is almost energy independent between threshold and $E_{^3\mathrm{H}} \approx 35$ MeV. In contrast, ^{6}Li production during BBN has to proceed mainly via a reaction absent of an energy threshold, $^2\mathrm{H} + {}^4\mathrm{He} \to {}^6\mathrm{Li}$, with cross section in the $10 - 100$ nb range, a factor $\sim 10^6$ below that for $^3\mathrm{H}(\alpha,n)^6\mathrm{Li}$. BBN yields of ^{6}Li are therefore generically low $10^{-14} \lesssim (^6\mathrm{Li}/^1\mathrm{H}) \lesssim 10^{-13}$ [14], with considerable uncertainty remaining due to ill-determined reaction rates. Non-thermal ^{3}H and ^{3}He may also react on ^{4}He to form ^{7}Li and ^{7}Be, nevertheless, synthesis of ^{7}Li is less efficient than that of ^{6}Li due to a smaller cross section of ~ 0.1 mb for $E_{^3\mathrm{H}} \sim 1$ MeV.

The kinetic energy transferred to the daughter ^{3}H and ^{3}He nuclei during the photodisintegration process is a simple function of photon energy, $E_{^3\mathrm{H}}(E_\gamma) = (E_\gamma - E^{th}_{\gamma^4\mathrm{He}})/4$, with negligible corrections of the order $(E_\gamma/m_p)^{1/2}$ depending on the angle between the outgoing particles, where m_p is proton mass. From this it may be seen that a γ-ray needs $E_\gamma \approx 40$MeV in order to produce a mass three nucleus sufficiently energetic to synthesize ^{6}Li. The main energy loss of energetic charged nuclei in the plasma is due to Coulomb scattering off electrons and plasma excitations. Energy loss due to these processes per unit path length traveled by the nuclei is given by [15]

$$\left(\frac{\mathrm{d}E}{\mathrm{d}x}\right)_C = \frac{Z^2\alpha}{v^2}\,\omega_p^2 \ln\left(\frac{\Lambda m_e v^2}{\omega_p}\right)\,, \tag{6}$$

where $\omega_p^2 = 4\pi n_e\alpha/m_e$ is the plasma frequency, n_e the electron density, v the velocity of the energetic nuclei, Z the charge of the nuclei, and Λ a factor of order unity. It is seen that ^{3}H nuclei loose their energy by a factor four slower than ^{3}He nuclei, and therefore dominate the production of ^{6}Li. Given the above it is possible to calculate the total ^{6}Li yield resulting from the energetic "breakout" photons. This is accomplished by a convolution over (a) the initial ^{3}H (^{3}He) energy which is given by the spectrum of the photodisintegrating photons Eq. (1), the energy-dependent relative reaction rates for ^{4}He photodisintegration and Bethe-Heitler pair production Eq. (5), and the relation between $E_{^3\mathrm{H}}$ and E_γ, and (b) the probability that a ^{3}H (^{3}He) nuclei of given initial energy synthesizes with ^{4}He to form ^{6}Li as it continuously looses energy by Coulomb interactions. This results in

$$N_{^6\mathrm{Li}} = \int_{E^{th}_{\gamma^4\mathrm{He}}+4E^{th}_{^6\mathrm{Li}}}^{E_C} \mathrm{d}E_\gamma \frac{\mathrm{d}N_{^3\mathrm{H}}}{\mathrm{d}E_\gamma} \times \int_{E^{th}_{^6\mathrm{Li}}}^{E_{^3\mathrm{H}}(E_\gamma)} \mathrm{d}E\, n_{^4\mathrm{He}}\,\sigma_{^3\mathrm{H}(\alpha,n)^6\mathrm{Li}} \left(\frac{\mathrm{d}x}{\mathrm{d}E}\right)_C . \tag{7}$$

Figure 1 shows the synthesized ^{6}Li yield as a function of redshift per MeV of electro-magnetically interacting energy injected by the decay of relics. The calculation uses Eq. (1) - (7), as well as a ^{4}He photodisintegration cross section $\sigma_{^4\mathrm{He}(\gamma,p)^3\mathrm{H}} \approx 0.8\,\mathrm{mb}\,(E_\gamma/40\,\mathrm{MeV})^{-2.9}$ applicable for $E_\gamma \gtrsim 40$ MeV [16]. The cross section for $^3\mathrm{He}(\alpha,p)^6\mathrm{Li}$ is taken to be energy-independent in the energy range of interest at a value of 38 mb, as suggested by the experimental determination and theoretical calculations. Given this one finds that the contribution to the total yield of ^{6}Li is peaked for "breakout" photon energies of $E_\gamma \approx 70-80$ MeV, resulting in ^{3}H and ^{3}He nuclei with energy $E_3 \approx 15-20$ MeV, close to the energy where the cross section for ^{3}He$(\alpha,p)^6$Li has been determined. The calculation presented takes also account of two further effects. Tritium nuclei are unstable with half life $\tau_{^3\mathrm{H}} = 12.33$ y, such that for redshifts below $z \lesssim 10^4$ tritium nuclei may decay while still energetic enough to synthesize ^{6}Li [17]. An additional source of ^{6}Li is due to the photodisintegration of ^{7}Li. This has been included and results in ^{6}Li production for redshifts $z \gtrsim 10^6$, as evident from the figure [18]. At redshifts $10^6 \gtrsim z \gtrsim 5\times 10^5$ the ^{6}Li yield may be somewhat uncertain due to the neglect of $\gamma\gamma$ scattering [20] in the spectrum Eq. (1) [9].

Dimopoulos *et al.* [6] have shown that ^{6}Li is also synthesized in hadronic showers generated by the *hadronic* decay of relics. Yields are dependent on the number and energy of injected baryons in the decay, which are sensitive to the mass and the initial decay products of the relic. They estimate a production of $\sim 5\times 10^{-11}$ of ^{6}Li for hadronic decay of a particle with mass $M_X \approx 1$ TeV. This is comparable to the yield from electro-magnetic cascades for redshifts below 10^6, but may dominate ^{6}Li production at higher redshifts. Note that the ^{6}Li yield presented here is virtually independent of decay mode, as it only depends on the fraction of relic energy converted into electro-magnetically interacting energy. This fraction is typically of order unity except for the case of "invisible" decays.

The abundance of ^{6}Li has been determined for the presolar nebula at ^{6}Li/H $\approx 1.5\times 10^{-10}$, and within the atmospheres of hot, low-metallicity, Population II, halo stars. A number of authors have claimed detections of the ^{6}Li/^{7}Li ratio in the star HD 84937 [21,22], with the most recent observation yielding ^{6}Li/^{7}Li $= 0.052 \pm 0.019$. Furthermore, a ^{6}Li detection has also been claimed for the star BD 26 3578 [22] at ^{6}Li/^{7}Li $= 0.05\pm 0.03$. Both stars have metallicity of approximately [Fe/H] ≈ -2.3, and belong to the Spite plateau of constant ^{7}Li/H ratios, believed to reflect the primordial ^{7}Li abundance. Recently, the first observational determination of ^{6}Li/^{7}Li ratios in the far more metal-rich ([Fe/H] ≈ -0.6) galactic disk stars HD 68284 and HD 130551 has been claimed [23]. Coincidentally, both stars have ^{6}Li/^{7}Li ≈ 0.05 with ^{7}Li/H ratios only slightly elevated from the Spite plateau. Given the value of the Spite plateau ^{7}Li/H $\approx 1-2\times 10^{-10}$, one finds ^{6}Li/H $\approx 5-10\times 10^{-12}$, for both, halo and disk stars.

Whereas the origin of ^{7}Li in hot, low-metallicity halo stars is known to be primordial, ^{6}Li, as well as the isotopes ^{9}Be, ^{10}B (and some fraction of ^{11}B), are believed to originate from spallation (p, α + CNO $\to$ LiBeB) and fusion ($\alpha+\alpha \to$ Li) reactions of cosmic rays on interstellar gas. The abundances of these elements are expected to generically increase with increasing metallicity, since metallicity represents a measure of the total "action" of galactic supernova shock generated cosmic rays, up to the time of the formation of the star. There is controversy as to the detailed composition of the cosmic rays responsible for LiBeB production. In order to explain an observed linear relationship of Be versus Fe (which is contrary to what is expected from "standard" cosmic rays with roughly interstellar composition at the time of the supernova), observationally allowed, but so far unknown, populations of metal-enriched cosmic rays have been postulated [24]. Alternatively, it has been argued that if variation of O/Fe ratios with metallicity are taken into account, the observational data of LiBeB may be reproduced [25].

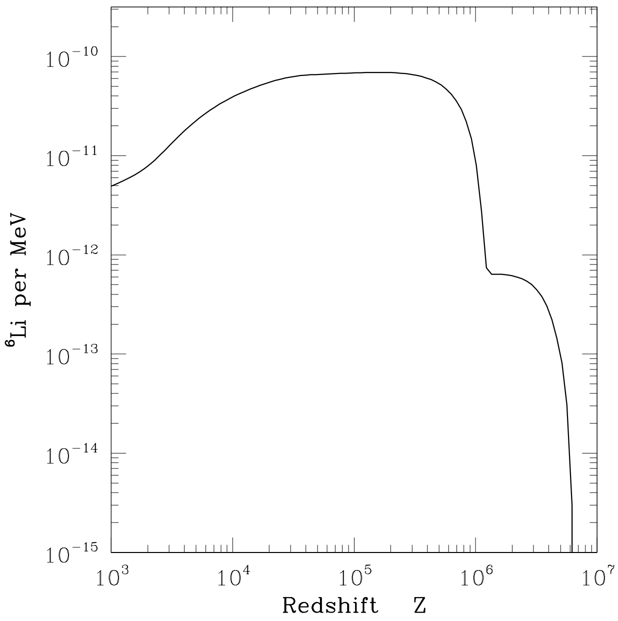

FIG. 1. Total number of ^{6}Li nuclei produced per MeV of energy in energetic electro-magnetically interacting particles injected at an epoch with redshift z.

The ^{6}Li isotope may be depleted during the pre-main sequence, as well as main sequence phase of stars, one of the very reasons to perform arduous ^{6}Li abundance determinations in stellar atmospheres, to (a) constrain stellar structure (such as the depth of the convective zone), and (b) the amount of depletion of the less fragile ^{7}Li on the Spite plateau. In fact, the models by Ref. [25] and [26] have been used to argue against significant (more than factor ~ 2) depletion of ^{6}Li (and ^{7}Li) in the PopII halo stars. The claim is, that by constructing models which reproduce the solar system ^{6}Li, the ^{9}Be versus iron relation, as well as the metallicity varying ^{6}Li/^{9}Be ratios ($\simeq$ 80 in PopII stars, and $\approx$ 5.9 in the solar system), it seems not possible to produce ^{6}Li by far more than that observed in the halo stars precluding significant astration of this isotope. Ramaty *et al.* [27] even claim, that whereas models of metal-enriched cosmic rays may reproduce the ^{9}Be data, *none* of the existing cosmic ray models are able to synthesize ^{6}Li in abundance as observed in the halo stars, an argument which is based on cosmic ray energetics.

In light of this it is intriguing to note that existing ^{6}Li observations, taken face value, are consistent with a "no evolution" hypothesis for metallicities below [Fe]$\lesssim -0.6$. Such a trend could be reconciled with a primordial origin of ^{6}Li, similar to the existence of a Spite plateau for ^{7}Li, though with ^{6}Li originating from a very different process. A very attractive explanation for the observed ^{6}Li would then be the non-thermal synthesis induced by the decay of relics after the BBN epoch, such as gravitinos produced during an epoch of reheating. This process could also lead to potentially observable chemical distortions in the spectrum of the microwave background radiation on the level $\mu \sim 10^{-5}$–10^{-7} for production of ^{6}Li/H $\sim 5\times10^{-12}$. Nevertheless, it is not possible to draw conclusions about a primordial origin of ^{6}Li at present. The most likely explanation for the relatively low ^{6}Li/H ratios in disk stars is astration. One may estimate the minimal cosmic ray ^{6}Li production up to [Fe] ~ -0.6, by employing observationally inferred ^{9}Be/H $\approx 6 - 10\times10^{-12}$ at this metallicity, and minimum theoretically anticipated cosmic ray ^{6}Li/^{9}Be production ratios of $\sim 3-5$ [23,27], which yields ^{6}Li/H $\sim 2-5\times10^{-11}$. This should be contrasted to the observed ^{6}Li/H $\approx 7\times10^{-12} - 1.4\times10^{-11}$, arguing for depletion. Similarly, the relatively high ^{6}Li/H ratios in Pop II stars ($\approx 5\times10^{-12} - 1\times10^{-11}$) may be associated with the action of so far unknown cosmic ray populations, or an increased cosmic ray flux with decreasing metallicity [28]. If one demands pre-galactic ^{6}Li synthesis not to exceed ^{6}Li/H $\approx 7\times10^{-12}$, one infers that not more than 0.1 MeV per proton of energetic, electro-magnetically interacting particles may be injected by relic decay in the redshift range $3\times10^4 \lesssim z \lesssim 3\times10^5$. This may be converted to $M_X n_X/n_\gamma \lesssim 4\times10^{-14}$GeV, where $M_X n_X$ is the energy density of the decaying relics and n_γ is CMBR photon number density. This should be compared to the commonly used limit $M_X n_X/n_\gamma \lesssim 2\times10^{-12}$GeV [2] at redshifts $\sim 10^5$ derived by demanding a pregalactic abundance of less than $(^2\mathrm{H} + {}^3\mathrm{He})/\mathrm{H} < 10^{-4}$.

In summary, I have shown that an era of non-thermal light-element nucleosynthesis following the BBN freeze-out and initiated by the electro-magnetic decay of massive particles, evaporation of primordial black holes, or radiating topological defects, not only leads to production of ^{3}He and ^{2}H as commonly known, but also results in efficient ^{6}Li synthesis. Here ^{6}Li is mainly synthesized via $^3\mathrm{H}(\alpha,n)^6\mathrm{Li}$ by energetic tritium nuclei resulting from the photodisintegration of ^{4}He. This result provides additional motivation for observations of ^{6}Li in low-metallicity stars, accompanied by an improved understanding of ^{6}Li cosmic ray production, and stellar depletion, since upper limits on the pregalactic abundance of ^{6}Li may be used to constrain non-equilibrium processes in the early universe. In the absence of stellar ^{6}Li astration, current observationally determined ^{6}Li/H ratios in low-metallicity stars, already provide a factor ~ 50 stronger constraint on the electro-magnetic decay of relics than consideration of production of $(^2\mathrm{H} + {}^3\mathrm{He})$ alone. Due to the small anticipated ^{6}Li abundance resulting from the BBN freeze-out, constraints could potentially be further strengthened by an additional factor of ~ 100, if it ever should become feasible to observe ^{6}Li/H ratios down to the level 5×10^{-14}. This underlines the importance of the study of ^{6}Li in metal-poor stars. On the other hand, if a relatively high plateau of ^{6}Li/H ratios in low-metallicity stars should be established, as there currently even may be some observational evidence for, invaluable new insight in the evolution of the very early universe might be gained.

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