Light Elements in the Universe
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The cosmic lithium problem and physics beyond the Standard Model

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Abstract. In this proceeding I briefly discuss the possibility of relic decaying or annihilating particles to explain the cosmological ^{7}Li anomaly and/or to be the source of significant amounts of pre-galactic ^{6}Li. The effect of relic massive charged particles through catalysis of nuclear reactions is also discussed. The possibility of a connection of the ^{7}Li problem to the cosmic dark matter and physics beyond the standard model of particle physics, such as supersymmetry, is noted.

Keywords. Cosmology: theory, early universe, cosmological parameters

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The standard scenario of Big Bang nucleosynthesis (BBN), with its minimalistic assumptions about the composition and state of the Universe at around one second, predicts light-element abundances generally in approximate agreement with those observed. However, after an independent precise observational determination of the baryon density through observations of the cosmic microwave background radiation by the WMAP satellite, a significant discrepancy between the predicted and observationally inferred ^{7}Li/H ratio has emerged (Cyburt *et al.* 2008). This discrepancy may not be due to seriously underestimated stellar surface temperatures and only very unlikely due to nuclear reaction rate uncertainties (Cyburt & Pospelov 2009). The mismatch may, however, be due to ^{7}Li depletion in low-metallicity halo stars (Richard *et al.* 2005, Korn *et al.* 2006), though the details of such depletion remain uncertain. Alternatively, the discrepancy may be due to physics operating during the BBN epoch itself. Such non-standard BBN scenarios also often lead to the production of considerable amounts of ^{6}Li. Interestingly, the existence of substantial ^{6}Li in low-metallicity stars has been claimed (Asplund *et al.* 2006), though due to the difficulty of these observations is currently controversial (Cayrel *et al.* 2007). A brief summary of BBN scenarios leading to a reduction of ^{7}Li and the production of ^{6}Li will be the main subject of this note.

^{7}Li is only produced in trace amounts during BBN the main reason being that its synthesis requires the presence of ^{4}He and by the time that neutrons are incorporated into ^{4}He the Coulomb barriers for the two main ^{7}Li producing reactions, i.e ^{3}H $+^4$He $\rightarrow^7$Li$+\gamma$ and ^{3}He $+^4$He$\rightarrow^7$Be$+\gamma$ are already substantial. Production of ^{6}Li in standard BBN is even further supressed compared to ^{7}Li by an additional factor $\sim 10^{-4}$ due to the weakness of the quadrupole reaction ^{2}H $+^4$He $\rightarrow^6$Li$+\gamma$. Most alternative BBN scenarios, such as inhomogeneous or with antimatter domains or with lepton chemical potentials, etc., do not lead to a reduction of the ^{7}Li abundance, rather usually the opposite happens. Attempting to reduce the ^{7}Li by later photodisintegration is highly problematic (Ellis *et al.* 2005) due to the concommitant ^{2}H photo-disintegration or ^{3}He/^{2}H overproduction due to ^{4}He photodisintegration. One known way of reducing ^{7}Li is by the assumption of varying fundamental constants, since ^{7}Li production is very sensitive to the ^{2}H and ^{7}Be

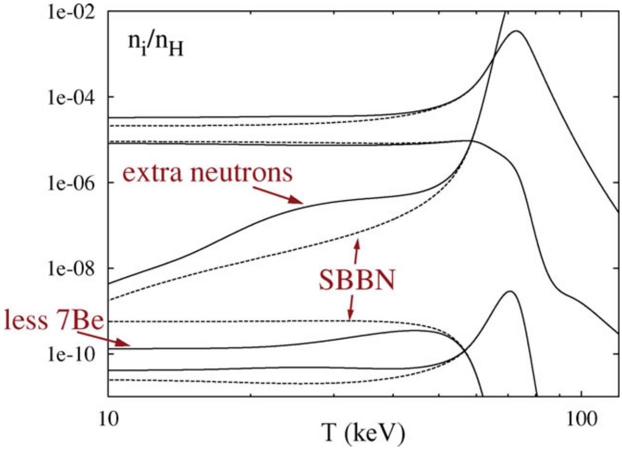

Figure 1. Evolution of light element abundances during BBN in a standard BBN scenario (solid) and in a BBN scenario with $\sim 10^{-5}$ additional neutrons/baryon injected at time $\tau \approx 1000\,\mathrm{sec}$ (dashed). From top to bottom (at low temperatures), the lines show ^{2}H/H, ^{3}He/H, n/p, ^{7}Be/H, and ^{7}Li/H, respectively. Figure taken from Jedamzik (2004a).

binding energies (Dmitriev *et al.* 2004). It is nevertheless very difficult to test for such a hypothesis by other means.

There exists, however, a very simple way of reducing the ^{7}Li yield (Jedamzik 2004a). At a baryon-to-photon ratio of $\eta \approx 6.2 \times 10^{-10}$ around 90% of all ^{7}Li is synthesized in form of ^{7}Be which after BBN electron captures to form ^{7}Li. In case this ^{7}Be is converted prematurely, already during BBN, to ^{7}Li, the resultant ^{7}Li will be destroyed by the reaction $^7\mathrm{Li}+p \rightarrow ^4\mathrm{He} + ^4\mathrm{He}$. The main reaction which converts ^{7}Be to ^{7}Li is $^7\mathrm{Be}+n \rightarrow ^7\mathrm{Li}+p$. The efficiency of such conversion depends on the ambient neutron density. Due to the large cross section for this reaction already a minute amount of extra neutrons $n/p \sim 10^{-5}$ injected at temperature $T \approx 30\,\mathrm{keV}$ may severely deplete the ^{7}Li. This is seen in Fig. 1 where the evolution of abundance yields of such a model with extra neutron injection is compared to standard BBN. Such neutron injection also leads to some additional ^{2}H.

^{6}Li is a sensitive probe of non-standard BBN scenarios and the evolution of the early Universe (Jedamzik 2000), since in a large number of non-standard scenarios, already small deviations from standard BBN (SBBN) lead to ^{6}Li synthesis beyond that in SBBN. All scenarios which include the injection of energetic hadrons or photons into the plasma, lead to either photodisintegration of ^{4}He or nuclear spallation of ^{4}He. The resultant energetic ^{3}H and ^{3}He nuclei may participate in the non-thermal nuclear reaction ^{3}H (^{3}He) + $^4\mathrm{He} \rightarrow {}^6\mathrm{Li} + n\ (p)$ (Dimopulos *et al.* 1988) to form ^{6}Li. Note that these reactions are not available to thermal BBN, due to the existence of energy thresholds.

When searching for scenarios which may lead to an injection of extra neutrons during BBN to solve the ^{7}Li problem, one immediate idea is the possibility of residual annihilation of cosmological particle dark matter during BBN (Jedamzik 2004b). It is well know that the correct cosmological dark matter density results when assuming a thermal freeze-out from equilibrium of a self-annihilating stable particle (e.g. a supersymmetric neutralino) with annihilation rate $< \sigma v > \approx 3 \times 10^{-26}\mathrm{cm}^3\mathrm{s}^{-1}$. Since such annihilation rates are typical for weak mass scale particles, an attractive possibility for the cosmological dark matter is a new stable particle of mass $m_\chi \sim 100\,\mathrm{GeV}$, potentially to be discovered at the LHC. Such particles would also be present during BBN with residual annihilations taking place. Since in many extensions of the standard model their annihilation products are quarks, the concommitant formation of baryons and anti-baryons

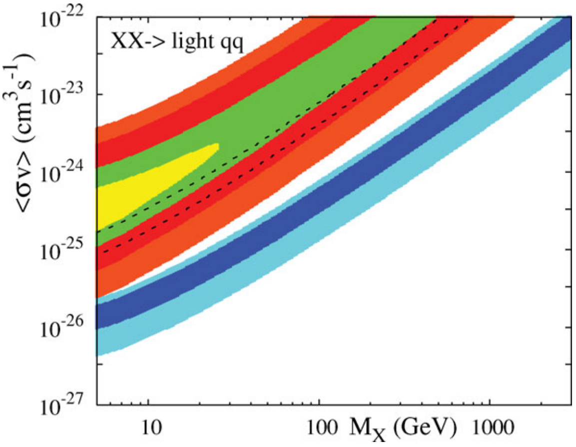

Figure 2. Dark matter annihilation rate versus dark matter mass. The blue band shows parameters where ^{6}Li due to residual dark matter annihilation may account for the ^{6}Li abundance as inferred in HD84937 (^{6}Li/^{7}Li$\approx 0.014-0.09$ at 2-σ), whereas the orange-red-green-yellow region shows where ^{7}Li is efficiently destroyed (e.g. green band - ^{7}Li/H$< 2\times 10^{-10}$). From Jedamzik & Pospelov (2009).

would lead to the injection of extra neutrons. In Fig. 2 the parameter space in the annihilation rate $<\sigma v>$ and particle mass m_χ is shown where annihilations significantly affect the ^{6}Li and ^{7}Li abundances. It is seen, however, that residual dark matter annihilation can only solve the ^{7}Li problem (the orange-red-green band) at the expense of overproducing ^{6}Li (the blue band). Annihilations are therefore most likely not at the heart of the ^{7}Li problem. However, it is intruiging that a dark matter particle of $m_\chi \sim 20-80\,\mathrm{GeV}$ annihilating into quarks at the required rate for the dark matter density may produce *all* the ^{6}Li as claimed to exist in the star HD84937. Note, that this already includes a factor ~ 3 stellar depletion of ^{7}Li (and ^{6}Li) to solve the ^{7}Li problem. Here it has been assumed that both isotopes are depleted by the same amount.

Whereas dark matter annihilation can not solve the ^{7}Li problem, the decay of meta-stable particles during BBN can. This may be seen in Fig. 3, which shows the parameter space in the $\Omega_X B_h$ and τ_X plane for which the ^{7}Li problem may be solved and/or significant ^{6}Li is synthesized. Here Ω_X would be the contribution of the X-particle to the present critical density if it wouldn't have decayed. It is seen that for decay times $\tau_X \sim 100-2000\,\mathrm{sec}$ the ^{7}Li abundance may be significantly reduced due to the injection of extra neutrons from the decay. For larger $\tau_X \gtrsim 10^3$sec large amounts, i.e. ^{6}Li/^{7}Li$\approx 0.015-0.3$, of ^{6}Li are synthesized. At $\tau_X \approx 10^3$, both, ^{7}Li and ^{6}Li, are in agreement with observations. In this area, additional ^{2}H production results as well.

It has been recently realized that significant amounts of ^{6}Li may also result simply due to the presence of negatively charged weak mass scale particles during BBN (Pospelov 2007). This is due to such particles entering into bound states with nuclei and thereby leading to catalysis of nuclear reactions. The most important of these reactions is (^{4}He-X^-)+^{2}H$\rightarrow$^{6}Li + X^-. Nevertheless, though interesting in its physics, and having received wide-spread attention, concerning ^{6}Li production, catalysis is only more important that the ^{6}Li production due to hadronic decay products, when the particle has a hadronic branching ratio smaller than $B_h \lesssim 10^{-2}$. Though this may occur (e.g. the supersymmetric partner of the stau lepton) it is often not the case. Catalysis may not present the solution to the ^{7}Li problem (Bird *et al.* 2007, Kanimura *et al.* 2009), unless the hadronic branching ratio of the charged weak mass scale particles is very small $B_h \lesssim 10^{-5}$ and its abundance

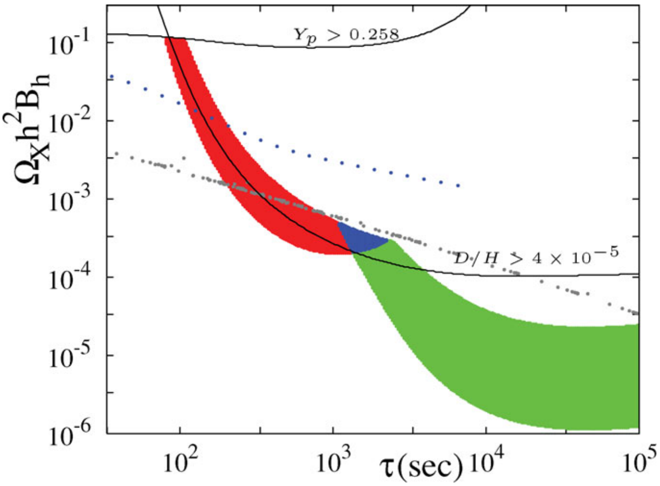

Figure 3. Parameter space in the relic decaying particle abundance times hadronic branching ratio B_h, i.e. $\Omega_X h^2 B_h$, and life time τ_X plane, where ^{7}Li is significantly reduced (red and blue) and ^{6}Li is efficiently produced (green and blue). See text for further details. From Bailly *et al.* (2009).

is very large, i.e. $\Omega_X \gtrsim 10$. However, though currently not certain, catalysis could lead to the formation of ^{9}Be in BBN (Pospelov 2008), something impossible to achieve with neutral decaying particles.

In summary, the decay of metastable relic particles during BBN may easily reduce the standard BBN predicted $^7\mathrm{Li/H} \sim 5 \times 10^{-10}$ to its observationally inferred value $^7\mathrm{Li/H} \sim 1 - 2 \times 10^{-10}$. When such decays occur around $\gtrsim 10^3$ seconds they are also associated with considerable ^{6}Li production. In contrast, residual annihilation of dark matter during BBN may account for all the ^{6}Li as claimed to exist in the star HD84937, but not solve the ^{7}Li problem without significant ^{6}Li overproduction. Catalysis of nuclear reactions due to electrically charged weak scale particles may lead to additional ^{6}Li, potentially produce ^{9}Be, but only very unlikely has impact on the cosmological ^{7}Li problem. It is the hope that many of these scenarios are testable at the LHC accelerator, either in form of production of light dark matter particles (e.g. a supersymmetric neutralinos) or metastable particles being stopped and decaying in the detector (e.g. a supersymmetric staus or gluinos). However, some particularly attractive scenarios are unfortunately not reachable in energy at the LHC (Jedamzik *et al.* 2006).

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