Neutralinos, Big Bang Nucleosynthesis and $^6\text{Li}$ in Low-Metallicity Stars

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The synthesis of $^6\text{Li}$ during the epoch of Big Bang nucleosynthesis (BBN) due to residual annihilation of dark matter particles is considered. By comparing the predicted $^6\text{Li}$ to observations of this isotope in low-metallicity stars, generic constraints on s-wave dark matter annihilation rates into quarks, gauge bosons, and Higgs bosons are derived. It may be shown that, for example, wino dark matter in anomaly-mediated SUSY breaking scenarios with masses $m_\chi \lesssim 250 \text{ GeV}$ or light neutralinos with $m_\chi < 20 \text{ GeV}$ annihilating into light quarks are, taken face value, ruled out. These constraints may only be circumvented if significant $^6\text{Li}$ depletion has occurred in all three low-metallicity stars in which this isotope has been observed to date. In general, scenarios invoking non-thermally generated neutralinos with enhanced annihilation rates for a putative explanation of cosmic ray positron or galactic center as well as diffuse background gamma-ray signals by present-day neutralino annihilation will have to face a stringent $^6\text{Li}$ overproduction problem. On the other hand, it is possible that $^6\text{Li}$ as observed in low-metallicity stars is entirely due to residual dark matter annihilation during BBN, even for neutralinos undergoing a standard thermal freeze-out.

The nature of the ubiquitous cosmological dark matter is one of the outstanding questions in cosmology. Though there exist a multitude of proposed candidates, much consideration has been given to the supersymmetric (SUSY) neutralino, provided it is the lightest supersymmetric particle (LSP). SUSY extensions of the standard model are particularly successful in overcoming a number of shortfalls of the standard model, such as the hierarchy problem and grand unification. Neutralinos are appealing since neutral, likely stable, and endowed with annihilation/scattering cross sections which (a) makes it likely have the right cosmological abundance and (b) makes it be detectable in the not-to-distant future by either direct- (e.g. scattering in cryogenic detectors) or indirect- (e.g. observation of positrons or $\gamma$-rays due to residual neutralino annihilation in the Galaxy) detection means.

In general, the post-freeze-out number-to-radiation entropy $n_\chi/s$ of a stable and initially abundant particle subject to self-annihilation is given by

$$Y_\chi^f = (n+1) \left( \frac{H}{\langle \sigma v \rangle s} \right)_f.$$

where $\langle \sigma v \rangle$ denotes its thermally averaged cross section, $H$ the Hubble expansion rate at freeze-out, and $n=0(1)$ for s-wave (p-wave) annihilation, i.e. $\langle \sigma v \rangle = \sigma_0 x^{-n}$ with $x = m_\chi/T$, respectively, and is understood that quantities are evaluated at the moment of freeze-out (f) itself. Though Eq. (1) could have been obtained by simply equating a typical annihilation rate $1/Y_\chi dY_\chi/dt$ with the Hubble rate it turns out to be exact. The abundance of Eq. (1) yields a $\chi$ contribution to the present critical density $\Omega_\chi$ of

$$\Omega_\chi h^2 = 9.95 \times 10^{-3} (n+1) x_f^{(n+1)} \frac{g_{H}^f}{g_S^f} \langle \sigma v \rangle^{-25}_{-25}.$$

where $x_f = m_\chi/T$ at freeze-out, $\langle \sigma v \rangle_{-25}$ is the annihilation rate in units of $10^{-26} \text{cm}^3/\text{s}$ at $T = m_\chi$ and $g_{H}^f$, $g_S^f$ are energy- and entropy- radiation statistical weights at freeze-out, respectively.

Considering freeze-out from annihilations with thermal equilibrium initial conditions, a particle in the hundreds of GeV range with $\langle \sigma v \rangle_{-25} \approx 0.2$ freezing out at $x_f \approx 20$ when $g_{H}^f \approx g_S^f \approx 86.25$ due to the known standard model degrees of freedom comes close to the recently by WMAP determined matter density of $\Omega_m h^2 \approx 0.1126^{+0.0161}_{-0.0181}$ (with $h$ the Hubble constant in units of $100 \text{ km} \text{s}^{-1}\text{Mpc}^{-1}$ and excluding baryons). In the case of mSUGRA models, where the LSP is typically the bino, this may be the case in thin strips of parameter space when $m_\chi \lesssim 500 \text{ GeV}$ though the bino $\langle \sigma v \rangle_{-25}$ is typically smaller than 0.2 $^3$. Other parameter space with viable neutralino abundances $\Omega_m h^2 \lesssim 0.113$ (corresponding to $\langle \sigma v \rangle_{-25} > 0.2$) in mSUGRA exist in the so-called FOCUS point area at several TeV unifying scalar masses $m_\chi$, with the LSP having a large Higgsino component. Leaving the fairly restrictive limitation of mSUGRA a wider array of possibilities may occur. When gaugino mass unification at the GUT scale is dropped $^4$, the LSP is frequently the wino or higgsino, albeit often with an s-wave annihilation rate of the order $\langle \sigma v \rangle_{-25} \sim 1 - 100$. Similar large annihilation rates may occur in anomaly-mediated SUSY breaking schemes (AMSB) $^4$ where the LSP is likely the wino, or even in mSUGRA when annihilation may occur on Higgs poles (e.g. the so-called A-funnel region for annihilation on the CP-odd Higgs) for $m_\chi \approx m_H/2$ $^7$. It is also possible that the neutralino LSP is very light $^3$.

Many of these cases have in common that for $m_\chi$ not too high, thus avoiding fine-tuning for the electroweak symmetry breaking to occur, annihilation rates are too large to produce $\Omega_m h^2 \approx 0.113$ during thermal freeze-out. Nevertheless, there is a number of proposed scenarios generating neutralino dark matter either by non-thermal means or due to the existence of extra degrees of freedom in the early Universe. Q-balls $^3$, for example, non-topological solitons which occur in the spectrum of
SUSY theories, may be easily formed after an inflationary epoch of the Universe. As they are made of squarks, and are unstable in SUGRA and AMSB, their R-parity and baryon-number conserving evaporation at late times $T_D \lesssim 1$ GeV may not only generate many LSP’s but also the observed cosmic baryon asymmetry. The thus generated LSP’s may undergo further self-annihilation to reach an asymptotic final abundance dependent on $T_D$ \cite{10}. Similarly, in AMSB scenarios, gravitinos are typically heavy $m_G \gtrsim 50$ TeV, such that their decay occurs before BBN. In such scenarios, which circumvent the gravitino problem, neutralinos are produced in $G$ (and/or moduli) decays well after the conventional thermal freeze-out of neutralinos from equilibrium \cite{2, 4}. When additional substantial non-thermal injection of neutralinos at $T_D$ occurs, their final present day abundance may still be calculated via Eq. (1) and Eq. (2) with $x_f$ given by

$$x_f = \max [x_D, x_{1f}]$$  \hspace{1cm} (3)

where $x_D = m_\chi / T_D$, and $x_{1f}$ quantifies the appropriate freeze-out temperature during thermal freeze-out \cite{11}, and where it has been implicitly assumed that the pre-annihilation neutralino abundance exceeds that of Eq. (1) and Eq. (2). LSP abundance estimates may also be changed (i.e. increased) when compared to the standard evolution of the Universe, when additional degrees of freedom are present in the early Universe. This may be, for example, due to the existence of a quintessence field in the stage of kination, or quite generally, due to extra degrees of freedom $g_H$ (with $g_S$ unchanged) contributing to the Hubble expansion \cite{12}. There are currently no limits on $g_H$ at high $T$ other than those from the (much later) epoch at BBN $T \lesssim 1$ MeV.

Though the post-freeze-out $Y_\chi^f$ stays essentially unchanged, residual $\chi$ annihilations occur up to the present day and may have considerable impact on the process of Big Bang nucleosynthesis (BBN). The effects of residual annihilation of $\chi$’s during BBN have been considered some time ago \cite{13, 14}. Nevertheless, whereas earlier studies were based on the isotopes $^2$H and $^4$He, it has been pointed out that $^6$Li production during electromagnetic \cite{15, 16} or hadronic \cite{17, 18, 19} energy injection during BBN is particularly efficient \cite{20}. The isotope of $^6$Li may be produced via non-thermal reactions (subject to energy threshold), such as $^3$H($\alpha, n$)$^6$Li or $^3$He($\alpha, p$)$^6$Li. Energetic $^3$H and $^3$He are readily produced via nuclear $^4$He spallation by energetic nucleons or $^4$He photodisintegration. Since the photodisintegration of $^4$He is only efficient for $T \lesssim 0.3$ keV particular importance in the annihilation case is due to hadronic spallation. This is because residual annihilation is stronger at earlier times. Resulting $^6$Li abundances are given formally by a time integral

$$n_{^6\text{Li}} / n_{^4\text{He}} = \int dt \left( \frac{d \text{Ann}}{dt} \right) \left( \frac{n_{p,n}}{\text{Ann}} \right) \left( \frac{n_3}{n_p} \right) \left( \frac{n_6}{n_3} \right)$$  \hspace{1cm} (4)

where the factors on the right-hand-side from left to right, denote (a) the $\chi$ annihilation rate

$$\frac{d \text{Ann}}{dt} = \frac{(\sigma v)}{2} \left( \frac{\rho_\chi}{m_\chi} \right)^2$$  \hspace{1cm} (5)

with $\rho_\chi$ neutralino density, (b) the generated energetic protons $p$ and neutrons $n$ per annihilation, (c) the produced energetic mass-three nuclei per generated energetic nucleon, and (d) the produced $^6$Li per energetic mass-three nucleus, respectively. Here the first factor is determined by the annihilation rate under the assumption that $\chi$ is the dark matter whereas the second factor may be obtained assuming a particular $\chi$ annihilation channel and computing the energetic nucleon spectrum via a hadronic flux tube Monte Carlo code such as PYTHIA \cite{21}. Concerning the third and fourth factors I have recently presented first \cite{18} results and a first description of a newly developed Monte-Carlo code describing the cascading of energetic nucleons and nuclei on background thermal nucleons, nuclei, and electromagnetically interacting particles which allows me to evaluate Eq. (3). This code includes, Coulomb and Thompson stopping of fast charged nucleons and nuclei, elastic- and inelastic- nucleon-nucleon scattering and elastic- and break-up- processes in nucleon-$^4$He scattering. Of all mass three nuclei produced a small fraction react on $^4$He to form $^6$Li. The probability to do so, may be approximated by

$$P_{^6\text{Li}} = \left( \frac{n_6}{n_3} \right) = \int dE_p dE_{^4\text{He}} \int dE_i \frac{1}{l_{^6\text{Li}}(dE/dx)_C} \times \exp \left( - \int dE_p dE' \frac{1}{l_{\text{nuc}}(dE/dx)_C} \right)$$  \hspace{1cm} (6)

a convolution over the initial energy distribution of mass-three nuclei, $dn_{^6\text{Li}} / dE_i$, - the probability that a mass-three nucleus during it’s passage through energy space due to the dominant multiple Coulomb interactions with energy loss per unit length $dE/dx$ undergoes a reaction to form $^6$Li (where $l_{^6\text{Li}} = 1/(\sigma v_{^6\text{Li}} n_{^4\text{He}})$ is the mean free path towards formation of $^6$Li) - while, the exponential factor, not having undergone already another nuclear interaction (mean free path due to all nuclear interactions is $l_{\text{nuc}}$) \cite{22}. Compared to the Coulomb losses other nuclear interactions in Eq. (6) are typically not very important, except for charge exchange between the mirror nuclei $^3$H($p,n$)$^3$He and to a lesser degree elastic p-$^3$H and p-$^3$He scattering, in only a narrow temperature range between several keV and $\approx 20$ keV. Nevertheless, though the freshly synthesized energetic $^6$Li typically survives almost completely p-spallation \cite{23} it may only survive $^6$Li($p, p$)$^3$He thermal reactions (after it’s rapid thermalization) when $T \lesssim 10$ keV. It has been realized \cite{13, 15} that in the above-given temperature window Coulomb losses loose some of their efficiency (by roughly a factor 3-10) for energetic 3-nuclei with velocities below the electron thermal velocities (but still above the lithium formation reaction thresholds of 8.39 and 7.05 MeV for $^3$H and

\begin{align*}
\frac{d \text{Ann}}{dt} = \frac{(\sigma v)}{2} \left( \frac{\rho_\chi}{m_\chi} \right)^2
\end{align*}
\( \text{FIG. 1: Final } ^6\text{Li yield functions defined via Eq. (7) as a function of neutralino mass for various annihilation channels as labeled in the key. The 1-}\sigma \text{ range of the } ^6\text{Li abundance in HD84937 is also shown.} \)

\( ^3\text{He, respectively). I have computed the energy transfer of a fast charged nucleon or nucleus due to Coulomb interactions with an electron-positron plasma at temperature } T, \text{ explicitly accounting for a thermal average and accounting for higher order terms. Details on this calculation will be presented elsewhere. Since } ^6\text{Li synthesis during/after BBN is dominated during those epoch where (a) the annihilation rate Eq. (5) is still large, (b) synthesized } ^6\text{Li survives the thermal } ^6\text{Li}(p,\alpha)^3\text{He reaction, and (c) } dE/dx|_C \text{ is at it’s minimum, the bulk of the } ^6\text{Li is synthesized at } T \approx 10\text{ keV and an exact evaluation of } dE/dx|_C \text{ is paramount to an evaluation of } ^6\text{Li abundances.} \)

\( \text{I have thus computed the } ^6\text{Li yield for annihilating particles and under the assumption of specific annihilation channels such as into } uu, dd, ss, bb, \text{ or } tt \text{ quark-antiquark pairs, as well as } W^-W^+ \text{ or } ZZ \text{ gauge bosons.} \)

\( \text{The results of these computations for varying neutralino masses } m_\chi \text{ are shown in Fig. 1. Here the annihilation-channel dependent yield functions } Y_{iLi}^i \text{ are defined via the equation} \)

\( n_{^6\text{Li}}/n_H = (\langle \sigma v \rangle - 25m_{^6\text{Li}}^{-3/2}) \left( \frac{\Omega_\chi h^2}{0.1126} \right)^2 \sum_i b_i Y_{iLi}^i \) (7)

\( \text{where the } b_i \text{ are branching ratios into channel } i \text{ and } m_{^6\text{Li}} \text{ is the neutralino mass in units of 100 GeV. Eq. (7) is remarkable as it allows a quite general evaluation of the final } ^6\text{Li abundance, independent of the nature of the annihilating particle, as well as applicable for essentially all relevant } \langle \sigma v \rangle \text{ and } m_\chi. \text{ Note that the } Y_{iLi}^i \text{‘s for leptonic channels, which are not shown, are essentially zero due to the absence of injected nucleons. Annihilation into Higgs bosons, on the other hand, yield } Y_{iLi}^i \text{ only somewhat smaller than those shown in Fig.1, since Higgs bosons typically decay into heavy quarks or mass-} \)

\( \text{sive gauge bosons. A simple scaling with } \langle \sigma v \rangle \text{ was possible due to the linearity in the } ^6\text{Li production and destruction mechanisms. Note that though for fixed dark matter density } d\text{ Ann}/dt \approx m_\chi^{-2} \text{ a scaling in Eq. (7) with } m_\chi^{-1.5} \text{ has been adopted. This is due to higher mass } \chi \text{ producing more energetic primary nucleons which, in turn, produce a larger number of secondary } p \text{ and } n, \text{ yielding a final } n_{^6\text{Li}}/n_H \approx m_\chi^{-1.5}. \)

\( \text{Fig. 1 also shows the one-sigma range } ^6\text{Li}/H \approx 8.47 \pm 3.10 \times 10^{-12} \text{ of the observationally best determined } ^6\text{Li}/H \text{-ratio in a low-metallicity star, i.e. in HD84937, which has been analyzed by several groups [24, 28]. } ^6\text{Li detections have been currently claimed in three low-metallicity } [Z] \lesssim -2 \text{ [26, 28, 29] and two higher metallicity stars } [Z] \sim -0.6 \text{ [30] with their abundances coincidentally all in the same range, reminiscent of a unique cosmic abundance. In principle, } ^6\text{Li may be depleted in stars, in practice, however, those low } [Z] \text{ stars which show } ^6\text{Li have normal } ^4\text{He-plateau } ^6\text{Li abundances, and as this latter isotope would, in most circumstances, be depleted as well, substantial } ^6\text{Li depletion seems un-} \)
FIG. 3: S-wave annihilation rate required to produce within the $2 - \sigma$ limits the $^6\text{Li}$ abundance of HD84937. The heavy lines indicate the central value of HD84937, whereas lighter lines the $2 - \sigma$ ranges. For simplicity only the $u\bar{u}$ (solid) and $W^-W^+$ (dotted) channels are shown with results for other channels similar (cf. Fig. 1).

It is thus conceivable that the origin of the $^6\text{Li}$ is of entirely of primordial origin, though other alternative origins have also been proposed. As evident from Fig. 2, light neutralinos with mass $m_\chi \lesssim 20\text{ GeV}$ annihilating into light quarks are ruled out. Limits of this sort are also important in light of scenarios which invoke neutralino annihilation as putative explanations of, for example, the observed cosmic positron excess at $\sim 10 - 30\text{ GeV}$ as determined by HEAT, or the galactic-center diffuse gamma-ray fluxes as determined by EGRET, VERITAS, or CANGAROO. In order to explain anomalous components of such signals such as bumps in the spectrum a signal boost (enhancement) factor $B_\gamma$ of the order $\sim 50 - 10^3$ is essentially always required. Considering the most recent N-body simulations on substructures and halo profiles, such $B_\gamma$ is unlikely due to clumpy halos or singular halo profiles though, in principle, one could envision it due to an enhanced $\langle \sigma v \rangle$ with respect to its standard thermal freeze-out value. Nevertheless, already modest particle-physics motivated boost-factors of the order of $\sim 1 - 10$ will have to face a potential $^6\text{Li}$ overproduction problem.

Last but not least, it is possible that the entire observed $^6\text{Li}$ at low metallicity may be due to the residual annihilation of a dark matter particle. Fig. 3 shows the mass-dependent annihilation rate required to produce a $^6\text{Li}$ abundance within the $2\sigma$ range of those observed in HD84937. It is seen that this may be accomplished even by a standard thermal freeze-out with dominant s-wave component annihilation into light quarks, provided the neutralino mass is within the approximate range of $20 - 80\text{ GeV}$. The observed amount of $^6\text{Li}$ may be produced for even larger mass neutralinos when either coannihilation effects or annihilation on poles occur in the thermal freeze-out case or neutralinos are generated non-thermally. Coincidentally, the recently proposed specific dark matter neutralinos and Kaluza-Klein particles which could explain the claimed bump in the extra-galactic $\gamma$-ray background and/or the positron excess as observed by HEAT would have just the right properties to yield $^6\text{Li}$ abundances as observed in low-$[Z]$ stars. Such annihilation is also associated with some, albeit small, amount of observationally favored $^7\text{Li}$ depletion. It is intriguing that the observed abundances of $^6\text{Li}$ in low-metallicity stars may be entirely a product of dark matter annihilation.

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Note that results of analysis of the observational data are typically given as ${{}^6 Li}/{}^7 Li$ ratios. Conversion to a ${{}^6 Li}/H$-ratio requires thus a ${{}^7 Li}/H$ ratio. This latter value is given for HD84937 in Ref. 25 at ${{}^7 Li}/H \approx 1.3 \times 10^{-10}$, agrees with other ${{}^7 Li}/H$ ratios on the Spite-plateau but not with that predicted from standard BBN for $\Omega_{B} h^2 \approx 0.0218$, which is about a factor 3 larger. In case the observed value of ${{}^7 Li}$ is due to a significant factor ~3 stellar depletion, a factor > 3 stellar depletion of ${{}^6 Li}$ is predicted. In this case, observational constraints based on ${{}^6 Li}$ abundances are relaxed. On the other hand, the resulting uncomfortably large pre-depletion ${{}^6 Li}$ abundance seems unattainable within the context of galactic cosmic ray nucleosynthesis, arguing for an origin of ${{}^6 Li}$ which is likely primordial or at the least pre-galactic.

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