Massive gravitino decays and the cosmological lithium problem

- BBN and the WMAP determination of $\eta, \Omega_B h^2$
- Observations and Comparison with Theory
  - D/H  - $^4\text{He}$  - $^7\text{Li}$
- The Li Problem
- Solutions?
Massive gravitino decays and the cosmological lithium problem

or

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- Observations and Comparison with Theory
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  - $^4\text{He}$
  - $^7\text{Li}$
- The Li Problem
- Solutions?
Massive gravitino decays and the cosmological lithium problem
or
How to best reconcile Big Bang Nucleosynthesis with Li abundance determinations

• BBN and the WMAP determination of $\eta$, $\Omega_B h^2$
• Observations and Comparison with Theory
  - D/H
  - $^4$He
  - $^7$Li

• The Li Problem

• Solutions?
WMAP best fit

\[ \Omega_B h^2 = 0.0226 \pm 0.0005 \]

\[ \eta_{10} = 6.19 \pm 0.15 \]
D/H abundances in Quasar absorption systems

BBN Prediction: \(10^5 \frac{D}{H} = 2.52 \pm 0.17\)

Obs Average: \(10^5 \frac{D}{H} = 2.82 \pm 0.21\)
\[ ^4\text{He} \]

Measured in low metallicity extragalactic HII regions (~100) together with O/H and N/H

\[ Y_p = 0.2561 \pm 0.0108, \quad \langle Y \rangle = 0.2566 \pm 0.0028 \]

\[ \frac{d(Y)}{d(O/H)} = 9.43 \pm 192 \]

Aver, Olive, Skillman
$^4\text{He}$ Prediction: 0.2487 ± 0.0002

Data: Regression: 0.2561 ± 0.0108

Mean: 0.2566 ± 0.0028
Li/H

Measured in low metallicity dwarf halo stars (over 100 observed)
17% increase in the cross section ⇒ 16% increase in Li
In addition, a 1.5% increase in $\eta$, leads to a 3% increase in Li ($Li \sim \eta^{2.12}$) plus another ~1% from pn

Net change in Li:
$4.26 \times 10^{-10}$ to $5.24 \times 10^{-10}$ or 23%
At the WMAP7 value for $\eta$:

$$\frac{\text{Li}}{H} = (5.12^{+0.71}_{-0.62}) \times 10^{-10}$$
Possible sources for the discrepancy

- Nuclear Rates
  - Restricted by solar neutrino flux

Coc et al.
Cyburt, Fields, KAO
BBN Li sensitivites

\[ \frac{^7\text{Li}}{^7\text{Li}_0} = \prod_i R_i^{\alpha_i} \]

Key Rates:

\[ ^3\text{He} (\alpha, \gamma) \quad ^7\text{Be} \]

<table>
<thead>
<tr>
<th>Reaction/Parameter</th>
<th>sensitivities ($\alpha_i$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\eta_{10}/6.14$</td>
<td>+2.04</td>
</tr>
<tr>
<td>$n(p, \gamma)d$</td>
<td>+1.31</td>
</tr>
<tr>
<td>$^3\text{He}(\alpha, \gamma)^7\text{Be}$</td>
<td>+0.95</td>
</tr>
<tr>
<td>$^3\text{He}(d, p)^4\text{He}$</td>
<td>−0.78</td>
</tr>
<tr>
<td>$d(d, n)^3\text{He}$</td>
<td>+0.72</td>
</tr>
<tr>
<td>$^7\text{Be}(n, p)^7\text{Li}$</td>
<td>−0.71</td>
</tr>
<tr>
<td>Newton’s $G_N$</td>
<td>−0.66</td>
</tr>
<tr>
<td>$d(p, \gamma)^3\text{He}$</td>
<td>+0.54</td>
</tr>
<tr>
<td>n-decay</td>
<td>+0.49</td>
</tr>
<tr>
<td>$N_{\nu,eff}/3.0$</td>
<td>−0.26</td>
</tr>
<tr>
<td>$^3\text{He}(n, p)t$</td>
<td>−0.25</td>
</tr>
<tr>
<td>$d(d, p)t$</td>
<td>+0.078</td>
</tr>
<tr>
<td>$^7\text{Li}(p, \alpha)^4\text{He}$</td>
<td>−0.072</td>
</tr>
<tr>
<td>$t(\alpha, \gamma)^7\text{Li}$</td>
<td>+0.040</td>
</tr>
<tr>
<td>$t(d, n)^4\text{He}$</td>
<td>−0.034</td>
</tr>
<tr>
<td>$t(p, \gamma)^4\text{He}$</td>
<td>+0.019</td>
</tr>
<tr>
<td>$^7\text{Be}(n, \alpha)^4\text{He}$</td>
<td>−0.014</td>
</tr>
<tr>
<td>$^7\text{Be}(d, p)^2^4\text{He}$</td>
<td>−0.0087</td>
</tr>
</tbody>
</table>
Require:

\[
S_{34}^{NEW}(0) = 0.267 \text{ keVb} \\
\frac{\Delta S_{34}}{S_{34}} = -0.47 \quad \text{globular cluster Li}
\]

or

\[
S_{34}^{NEW}(0) = 0.136 \text{ keVb} \\
\frac{\Delta S_{34}}{S_{34}} = -0.73 \quad \text{halo star Li}
\]
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Constrained from solar neutrinos

\[
S_{34} > 0.35 \text{ keV barn}
\] at 95\% CL
Coc et al. consider large variations of certain rates.

$^3\text{H} \ (p, \gamma) \ ^4\text{He}$ increase x1000 low $\eta$ XX

$^4\text{He} \ (\alpha, n) \ ^7\text{Be}$ small compared with destruction X

$^7\text{Li} \ (d, n) \ ^{24}\text{He}$ increase x100 low $\eta$ XX

$^7\text{Be} \ (d, p) \ ^{24}\text{He}$ increase $\geq x100$ high $\eta$ √? X
Resonant Reactions

Cyburt, Pospelov
Chakraborty, Fields, Olive

Is there a missing excited state providing a resonant reaction?

\[ {^7}\text{Be} + A \rightarrow C^* \rightarrow B + D. \]

If energy released in producing C* is

\[ Q_C = \Delta({^7}\text{Be}) + \Delta(A) - \Delta(C^{\text{g.s.}}) \]

Then the resonant energy is

\[ E_{\text{res}} \equiv E_{\text{ex}} - Q_C \]

\[ \Delta = m - Am_u \]

mass defect
Resonant enhancements will occur if $|E_{\text{res}}| \lessgtr \Gamma_{\text{init}}$

$$\sigma(E) = \frac{\omega}{8\pi \mu E} \frac{\Gamma_{\text{init}} \Gamma_{\text{fin}}}{(E - E_{\text{res}})^2 - (\Gamma_{\text{tot}}/2)^2}$$

leading to a thermally averaged cross section (in the narrow width approximation)

$$\langle \sigma v \rangle = \left( \frac{2\pi}{\mu T} \right)^{3/2} \hbar^2 (\omega \Gamma_{\text{eff}})_{\text{res}} \exp \left( -\frac{E_{\text{res}}}{T} \right)$$
The above figure shows the effect of the resonances in the $^9$B compound nucleus. In particular, the 16.71 MeV level is of interest. The proton channel as well as the $\alpha$ channel are exit channels of interest. The red contour indicates the observed mass $^7$A abundance.

As evaluated by [15], more than a factor of 2 destruction of $^7$A is achieved with a strength of 40 keV and resonance energy of 220 keV. The black solid line at 40 keV indicates the narrow resonance approximation limit. The vertical dashed line at 220 keV indicates the experimental central value of the resonance energy. The width for either channel is unknown experimentally and therefore, both the channels are potential solutions.
$^{7}\text{Be} + {^3}\text{He}$

eg. if a 1- or 2- excited state of $^{10}\text{C}$ were near 15.0 MeV .....
Possible sources for the discrepancy

- **Nuclear Rates**
  - Restricted by solar neutrino flux

- **Stellar Depletion**
  - lack of dispersion in the data, $^6$Li abundance
  - standard models (< .05 dex), models (0.2 - 0.4 dex)

Coc et al.
Cyburt, Fields, KAO

Vauclaire & Charbonnel
Pinsonneault et al.
Richard, Michaud, Richer
Korn et al.
Stellar Depletion in the Turbulence Model of Korn et al.

Note new BBN Li result pushes primordial value up from 2.63 to 2.72
from Gonzáles Hernández et al.
Possible sources for the discrepancy

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- **Stellar parameters**

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- **Stellar parameters**

\[
\frac{dLi}{d\ln g} = 0.09 \\
\frac{dLi}{dT} = \frac{0.08}{100K}
\]
Claim:

New evaluation of surface temperatures in 41 halo stars with systematically higher temperatures (100-300 K)

Melandez & Ramirez

\[ [\text{Li}] = 2.37 \pm 0.1 \]
\[ \text{Li}/\text{H} = 2.34 \pm 0.54 \times 10^{-10} \]

BBN Prediction: \( 10^{10} \text{Li}/\text{H} = (5.12^{+0.71}_{-0.62}) \times 10^{-10} \)
Recent dedicated temperature determinations
(excitation energy technique)

Use Fe I lines:
population of a given state $\propto \exp(-\chi_i/T)$
Comparison

![Comparison Graph](image-url)
Possible sources for the discrepancy

- Nuclear Rates
  - Restricted by solar neutrino flux

- Stellar parameters
  \[
  \frac{dL_i}{dl\eta g} = \frac{0.09}{0.5} \quad \frac{dL_i}{dT} = \frac{0.08}{100K}
  \]

- Particle Decays
Limits on Unstable particles due to
Electromagnetic/Hadronic Production and Destruction of Nuclei

3 free parameters

\[ \xi_X = n_X \frac{m_X}{n_\gamma} = m_X Y_X \eta, \quad m_X, \]
and \( \tau_X \)

- Start with non-thermal injection spectrum (Pythia)
- Evolve element abundances including thermal (BBN) and non-thermal processes.
E.g., Gravitino decay

\[ \tilde{G} \rightarrow \tilde{f} f, \tilde{G} \rightarrow \tilde{\chi}^+ W^- (H^-), \tilde{G} \rightarrow \tilde{\chi}_i^0 \gamma (Z), \tilde{G} \rightarrow \tilde{\chi}_i^0 H_i^0 \tilde{G} \rightarrow \tilde{g} g. \]

plus relevant 3-body decays
Based on $m_{1/2} = 300 \text{ GeV}, \tan \beta = 10$ ; $B_h \sim 0.2$
$m_0$ (GeV) vs $m_{1/2}$ (GeV)

- $\tan \beta = 10$, $\mu > 0$
  - $m_h = 114$ GeV
  - $m_{\chi^\pm} = 104$ GeV

- $\tan \beta = 50$, $\mu > 0$
  - $m_h = 114$ GeV

EOSS
co-annihilation strip, \( \tan \beta = 10 \); \( m_{3/2} = 250 \) GeV
co-annihilation strip, \( \tan \beta = 10 \); \( m_{3/2} = 1000 \) GeV
co-annihilation strip, $\tan \beta = 10$ ; $m_{3/2} = 5000$ GeV
Benchmark point C, $\tan \beta = 10$ ; $m_{1/2} = 400$ GeV
Uncertainties

There are only a few non-thermal rates which affect the result:

\[ p^{4}\text{He} \rightarrow np^{3}\text{He} \] 20%
\[ p^{4}\text{He} \rightarrow ddp \] 40%
\[ p^{4}\text{He} \rightarrow dnpp \] 40%
\[ t^{4}\text{He} \rightarrow ^{6}\text{Lin} \] 20%
\[ ^{3}\text{He}^{4}\text{He} \rightarrow ^{6}\text{Lip} \] 20%
\[ n^{4}\text{He} \rightarrow npt \] 20%
\[ n^{4}\text{He} \rightarrow ddn \] 40%
\[ n^{4}\text{He} \rightarrow dnnp \] 40%
\[ p^{4}\text{He} \rightarrow ppt \] 20%
\[ n^{4}\text{He} \rightarrow nn^{3}\text{He} \] 20%
How well can you do

$$\chi^2 \equiv \left( \frac{Y_p - 0.256}{0.011} \right)^2 + \left( \frac{D}{H} - \frac{2.82 \times 10^{-5}}{0.27 \times 10^{-5}} \right)^2 + \left( \frac{^7\text{Li}}{H} - \frac{1.23 \times 10^{-10}}{0.71 \times 10^{-10}} \right)^2 + \sum_i s_i^2,$$

SBBN: $\chi^2 = 31.7$ - field stars
SBBN: $\chi^2 = 21.8$ - GC stars
Table 2: Results for the best-fit points for CMSSM benchmarks C, E, L and M. The second set of results for C and M correspond to the globular cluster value for primordial $^7$Li/H. The third and fourth entries for point C correspond to the higher adopted uncertainty for D/H in field stars and to the globular cluster $^7$Li abundances, respectively.

<table>
<thead>
<tr>
<th>$m_{3/2}$ [GeV]</th>
<th>$\log_{10}(\zeta_{3/2}/[\text{GeV}])$</th>
<th>$Y_p$</th>
<th>D/H ($\times 10^{-5}$)</th>
<th>$^7$Li/H ($\times 10^{-10}$)</th>
<th>$\sum s_i^2$</th>
<th>$\chi^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>BBN</td>
<td>—</td>
<td>0.2487</td>
<td>2.52</td>
<td>5.12</td>
<td>—</td>
<td>31.7</td>
</tr>
<tr>
<td>C</td>
<td>4380</td>
<td>-9.69</td>
<td>0.2487</td>
<td>3.15</td>
<td>2.53</td>
<td>0.26</td>
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<tr>
<td>E</td>
<td>4850</td>
<td>-9.27</td>
<td>0.2487</td>
<td>3.20</td>
<td>2.42</td>
<td>0.29</td>
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<tr>
<td>L</td>
<td>4380</td>
<td>-9.69</td>
<td>0.2487</td>
<td>3.21</td>
<td>2.37</td>
<td>0.26</td>
</tr>
<tr>
<td>M</td>
<td>4860</td>
<td>-10.29</td>
<td>0.2487</td>
<td>3.23</td>
<td>2.51</td>
<td>1.06</td>
</tr>
<tr>
<td>C</td>
<td>4680</td>
<td>-9.39</td>
<td>0.2487</td>
<td>3.06</td>
<td>2.85</td>
<td>0.08</td>
</tr>
<tr>
<td>M</td>
<td>4850</td>
<td>-10.47</td>
<td>0.2487</td>
<td>3.11</td>
<td>2.97</td>
<td>0.09</td>
</tr>
<tr>
<td>C</td>
<td>3900</td>
<td>-10.05</td>
<td>0.2487</td>
<td>3.56</td>
<td>1.81</td>
<td>0.02</td>
</tr>
<tr>
<td>C</td>
<td>4660</td>
<td>-9.27</td>
<td>0.2487</td>
<td>3.20</td>
<td>2.45</td>
<td>0.16</td>
</tr>
</tbody>
</table>

As discussed earlier, one may also consider the effect of increasing the size of the uncertainty in the mean D/H abundance. Using an observed abundance of $(2.82 \pm 0.53) \times 10^{-5}$, we obtain the $\chi^2$ contours seen in the left panel of Fig. 10, corresponding to point C. In this case, we can obtain solutions with $\chi^2 = 2.8$ and a best-fit point with $^7$Li/H abundance of $1.81 \times 10^{-10}$ coming at the expense of a higher D/H abundance of $3.56 \times 10^{-5}$. When the globular cluster value of $^7$Li/H is used together with the higher D/H uncertainty, we can even find a best-fit solution with $\chi^2 = 1.1$: D/H = $3.20 \times 10^{-5}$ and $^7$Li/H = $2.45 \times 10^{-10}$, as seen in the right panel of Fig. 10.

Summary and Conclusions

We have presented in this paper an analysis of the modifications of the cosmological light-element abundances that would be induced by the late decays of massive particles, incorporating for the first time the uncertainties in relevant nuclear reaction rates. We have analyzed the possible effects of the 36 different nuclear reactions shown in Table 1, and identified three as the most important, namely $n^4\text{He} \rightarrow np$, $n^4\text{He} \rightarrow ddnp$ and $n^4\text{He} \rightarrow nn^3\text{He}$.

It is well known that there is a problem with the cosmological abundance of $^7$Li in conventional BBN with no late-decaying particles, and a natural question is whether this problem could be mitigated by some suitable late-decaying particle. As an example of the possible applications of our uncertainty analysis, we have considered in this paper the late decays of massive gravitinos in various benchmark supersymmetric scenarios. It had been observed that increased uncertainty in D/H + GC value for Li...
Effects of Bound States

- In SUSY models with a $\tilde{\tau}$ NLSP, bound states form between $^4$He and $\tilde{\tau}$
- The $^4$He (D, $\gamma$) $^6$Li reaction is normally highly suppressed (production of low energy $\gamma$)
- Bound state reaction is not suppressed

![Diagram of the reaction $^4$He + D $\rightarrow$ $^6$Li + $\gamma$]

Pospelov
$m_{3/2} = 100 \text{ GeV}, \tan \beta = 10, \mu > 0$

$^{7}\text{Li} = 4.3, ^{3}\text{He}/D = 1$

$^{6}\text{Li}/^{7}\text{Li} = 0.15, 0.01$

$D = 4.0$

$^{3}\text{He}/D = 1$

$^{6}\text{Li}/^{7}\text{Li} = 0.15, 0.01$

$D = 4.0$

Cyburt, Ellis, Fields, KO, Spanos
m_3/2 = 0.2m_0, \tan \beta = 10, \mu > 0

Cyburt, Ellis, Fields, KO, Spanos
Possible sources for the discrepancy

• Stellar parameters

\[
\frac{dL_i}{dl_\text{mg}} = \frac{.09}{.5} \quad \frac{dL_i}{dT} = \frac{.08}{100K}
\]

• Particle Decays

• Variable Constants
Limits on $\alpha$ from BBN

Contributions to $Y$ come from n/p which in turn come from $\Delta m_N$

Contributions to $\Delta m_N$:

$$\Delta m_N \sim a\alpha_{em}\Lambda_{QCD} + bv$$

Changes in $\alpha$, $\Lambda_{QCD}$, and/or $\nu$
all induce changes in $\Delta m_N$ and hence $Y$

$$\frac{\Delta Y}{Y} \sim \frac{\Delta^2 m_N}{\Delta m_N} \sim \frac{\Delta \alpha}{\alpha} < 0.05$$

If $\Delta \alpha$ arises in a more complete theory
the effect may be greatly enhanced:

$$\frac{\Delta Y}{Y} \sim O(100)\frac{\Delta \alpha}{\alpha} \text{ and } \frac{\Delta \alpha}{\alpha} < \text{ few } \times 10^{-4}$$

Kolb, Perry, & Walker
Campbell & Olive
Bergstrom, Iguri, & Rubinstein
Approach:

Consider possible variation of Yukawa, h, or fine-structure constant, $\alpha$

Include dependence of $\Lambda$ on $\alpha$; of $\nu$ on $h$, etc.

Consider effects on: $Q = \Delta m_N, \tau_N, B_D$
Approach:

Consider possible variation of Yukawa, h, or fine-structure constant, \( \alpha \)

Include dependence of \( \Lambda \) on \( \alpha \); of \( v \) on \( h \), etc.

Consider effects on: \( Q = \Delta m_N, \tau_N, B_D \)

and with \( \frac{\Delta h}{h} = \frac{1}{2} \frac{\Delta \alpha_U}{\alpha_U} \)

\[
\frac{\Delta B_D}{B_D} = -[6.5(1 + S) - 18R] \frac{\Delta \alpha}{\alpha}
\]

\[
\frac{\Delta Q}{Q} = (0.1 + 0.7S - 0.6R) \frac{\Delta \alpha}{\alpha}
\]

\[
\frac{\Delta \tau_n}{\tau_n} = -[0.2 + 2S - 3.8R] \frac{\Delta \alpha}{\alpha},
\]

Coc, Nunes, Olive, Uzan, Vangioni
Dmitriev & Flambaum
Effect of variations of $h$ ($S = 160$)

Notice effect on $^7\text{Li}$
For $S = 240$, $R = 36$, $\Delta \alpha / \alpha = 2 \Delta h / h$,

$$-1.6 \times 10^{-5} < \frac{\Delta h}{h} < 2.1 \times 10^{-5}$$

FIG. 4: Primordial abundances of $^4$He, $^3$He, D, $^7$Li. The abundances are depicted for three values of the parameter: $R = 0, 36, 60$. Not considered are the uncertainties between observational data.
Summary

• D, He are ok -- issues to be resolved

• Li: Problematic
  – BBN $^7$Li high compared to observations

• Important to consider:
  – Nuclear considerations
    – Resonances $^{10}$C (15.04)!
  – Depletion (tuned)
  – Li Systematics - T scale - unlikely
  – Particle Decays?
  – Variable Constants???

• $^6$Li: Another Story