The Primordial Lithium Problem

Can We Avoid New Physics?

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What’s the problem?

Light elemental abundances constrain Big Bang cosmology
(Wagoner, Fowler and Hoyle, 1967; Steigman, Schramm and Gunn, 1977; Schramm and Turner, 1998)

Abundances set by
\[ \frac{n_B}{n_\gamma} = \eta \propto \Omega_b \]

WMAP gives \( \eta \)

Discrepancy between theory (Cyburt, Fields and Olive, 2008) and observation of \(^7\text{Li}\) (Spite and Spite, 1982; Smith et al., 1998)

“Law of trichotomy”
- Theory wrong
- Observation wrong (Richards et al., 2005; Melendez et al., 2010)
- Both wrong
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Cyburt, Fields and Olive, 2008
Theory Solutions

~ Assume observations right
⇒ Reduce \(^7\)Li or \(^7\)Be

~ Beyond Standard Model
- Dark matter decay (Bailly et al., 2009 and others)
- Bound states (Jittoh et al., 2010, Cyburt et al., 2006 and others)
- Varying fundamental constants (Berengut et al., 2010,...) etc.
Assume observations right
⇒ Reduce $^7$Li or $^7$Be

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OR

- Within Standard Model
  - Enhance nuclear reactions
    (Cyburt and Pospelov, 2009), Chakraborty, Fields and Olive (in prep)
Resonances
Resonances

- $A + B \rightarrow C + D$ vs $A + B \rightarrow X^* \rightarrow C + D$

Compound nucleus
Resonance parameters
Resonance parameters
Resonance parameters

[Graph showing the relationship between energy and cross-section, with the energy axis labeled and the cross-section axis labeled as 'Cross-Section'.]
Resonance Energy

Resonance parameters

$\text{Strength}$

$\Gamma_{\text{eff}}$

$E_{\text{res}}$

Cross-Section

Energy

Resonance Energy
Resonance parameters

- **Strength**
- **Width**
- **Resonance Energy**
- $\Gamma_{\text{eff}}$
- $\Gamma_{\text{tot}}$
- $E_{\text{res}}$
Resonance parameters

- **Strength**
- **Width**
- **Resonance Energy**
- **Narrow Resonance Approximation**

Symbols:
- $\Gamma_{\text{tot}}$
- $\Gamma_{\text{eff}}$
- $E_{\text{res}}$
Resonance parameters

- Resonance Energy
- Strength
- Width
- $\Gamma_{\text{eff}}$
- $\Gamma_{\text{tot}}$
- Cross-Section
- Energy
- $E_{\text{res}}$

Narrow Resonance Approximation
Resonance parameters

Energy

Cross-Section

Strength

Width

$\Gamma_{\text{eff}}$

$\Gamma_{\text{tot}}$

Resonance Energy

$E_{\text{res}}$

Narrow Resonance Approximation
Resonance parameters

- Resonance Energy
- Strength
- Effective Width ($\Gamma_{\text{eff}}$)
- Resonance Energy ($E_{\text{res}}$)
- Narrow Resonance Approximation
Cyburt and Pospelov, (2009)

- Recognised existing level
  \((16.7\text{ MeV in } ^9\text{B})\)
- \(^7\text{Be} + \text{d} \rightarrow \text{p} + 2\ \alpha\)
- Strength unknown
- Big error bars in \(E_{\text{res}}\)
- Potential solution?
- We agree
Cyburt and Pospelov, (2009)

- Recognised existing level (16.7 MeV in $^9$B)
- $^7$Be + d $\rightarrow$ p + 2 $\alpha$
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![Graph showing $E_{\text{res}}$ versus resonance energy $E_{\text{res}}$ in keV with lines for $^7$Li / H at 1.23e-10, 2.0e-10, 3.0e-10, 4.0e-10, and 5.0e-10.]

$^7$Be + d $\rightarrow$ p + 2 $\alpha$
Cyburt and Pospelov, (2009)

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$^7$Li / H = $1.23e-10$
$^7$Li / H = $2.0e-10$
$^7$Li / H = $3.0e-10$
$^7$Li / H = $4.0e-10$
$^7$Li / H = $5.0e-10$
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\[
\begin{align*}
^7\text{Li} / H &= 1.23 \times 10^{-10} \\
^7\text{Li} / H &= 2.0 \times 10^{-10} \\
^7\text{Li} / H &= 3.0 \times 10^{-10} \\
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\end{align*}
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What if experiment rules this out?
Fear not........there’s more options
Fear not..........there’s more options

Chakraborty, Fields and Olive (In prep)
- $^7$Li or $^7$Be can be destroyed with n, p, t, d, $^3$He, α and γ
- Resonances in compound nuclei with mass 8 to 11
- Systematically list them
- Parametrize solution space for any resonance
Fear not........there’s more options
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Fear not........there’s more options
Do we have any Standard Model solutions?

- Potentially yes → Nuclear resonances
- Complete or partial match
  - $^7\text{Be} + d \rightarrow p + 2\,\alpha$ (Cyburt and Pospelov, 2009) and competing channels
  - $^7\text{Be} + t \rightarrow \text{Inelastic}$ (Chakraborty, Fields and Olive, In prep)
  - Missed resonances / levels
- Testable by current nuclear experiments
- We may be able to avoid new physics
Thank you!!
Theory vs Observations - The Lithium problem

Cyburt, Fields and Olive, 2008
Nucleosynthetic History

Mukhanov (2004)
Nucleosynthetic History

\[ p \xrightarrow{\text{Weak}} n \]

Weak Equilibrium until 1 sec

Mukhanov (2004)
Nucleosynthetic History

Weak Equilibrium until 1 sec

Mukhanov (2004)
Nucleosynthetic History

- Weak
- $p, n$
- $p$
- $n$
- $\gamma$

Weak Equilibrium until 1 sec

D
Bottleneck ends at 100

Mukhanov (2004)
Mukhanov (2004)

Nucleosynthetic History

- Weak Equilibrium until 1 sec
- D Bottleneck ends at 100

Reactions:
- (p,n)
- (D,p)
- (D,n)
- (p,n)
- $^3$He
Nucleosynthetic History

Mukhanov (2004)

Weak Equilibrium until 1 sec

D Bottleneck ends at 100

All neutrons go into $^{4}\text{He}$
Nucleosynthetic History

- Weak Equilibrium until 1 sec
- D Bottleneck ends at 100
- All neutrons go into \( ^4\text{He} \)
- Ends in 3 min

Mukhanov (2004)
Theoretical Predictions

Theoretical Predictions

Observations

~ Need primordial abundance measurements

~ Light elements also formed in other ways

~ Look at low metallicity environments, avoid pollution

~ $^4$He - Metal poor compact dwarfs (Izotov and Thuan, 1999; Meurer et al., 1995)

~ D - Quasar absorption lines (O’Meara, 2006,2001)

~ $^3$He - Galactic HII (ionised hydrogen) regions (Bania et al., 2002)
What’s wrong ??

~ We dont know for sure !!
~ “Law of trichotomy”
  - either theory or observation is wrong or both !!
~ Theory
  - Holes in nuclear reaction network
    (Cyburt and Pospelov, 2009)
  - New physics !!
    (Dark matter decay
    (Bailly et al., 2009 and others),
    Bound states (Jittoh et al., 2010, Cyburt et al., 2006
    and others), varying fundamental
    constants (Berengut et al., 2010),....)
~ Observations
Nuclear Physics Solution

- Two main checks
  1. Completeness of nuclear database or missing reactions
  2. Improved reaction rates

- Can’t decrease production rates
  - well studied and constrained

- Increase destruction

- Resonances?
Let’s try resonances

http://pntpm3.ulb.ac.be/Nacre/barre_database.htm

http://en.wikipedia.org/wiki/Nuclear_reaction

\[ A + B \rightarrow C + D \] vs \[ A + B \rightarrow X^* \rightarrow C + D \]
Let’s try resonances

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http://en.wikipedia.org/wiki/Nuclear_reaction
Let's try resonances

\[ S(E) = \sigma(E)E \exp(2\pi\eta) \]

\[ \text{Original data} \]

\[ \text{A} + \text{B} \rightarrow \text{C} + \text{D} \quad \text{vs} \quad \text{A} + \text{B} \rightarrow \text{X}^* \rightarrow \text{C} + \text{D} \]

http://pntpm3.ulb.ac.be/Nacre/barre_database.htm

http://en.wikipedia.org/wiki/Nuclear_reaction
Resonant Cross-section

- In nuclear physics,
  \[ \sigma \propto \frac{\Gamma_1 \Gamma_2}{(E - E_R)^2 + (\Gamma_{\text{tot}}/2)^2} \]

- (Breit-Wigner single level formula)

- Rate of reaction \( \sim n_A n_B \)
  \( < \sigma \; v > \)

\[ ^\dagger \text{Not position of the energy level in the compound nucleus, but extra energy required by reactants to get there over Q-value} \]
Carbon 12

There it is
Cyburt and Pospelov

- Identified a narrow level in $^9$B at 16.7 MeV
- Width of energy level unknown
- Enhancement of reaction $^7$Be(d,γ)$^9$B and $^7$Be(d,p)α α
  $(E_R,\Gamma_d) \sim (170-220, 10-40)$ keV , $^7$Li/H = $(2.5 - 6) \times 10^{-10}$

Observations
Looks encouraging but........

A. Experimental verification

B. More importantly, $^9$B has other decay channels

$^9$B $\rightarrow$ $^9$Be

Boesgaard et al., 1999
Looks encouraging but........

A. Experimental verification

B. More importantly, $^9\text{B}$ has other decay channels

$^9\text{B} \rightarrow ^9\text{Be}$

Boesgaard et al., 1999
They are fine
They are fine
Systematic Search

Need other options ready
Want to try all conceivable resonances
Not infinite choices !!

Lock on to our targets
- $^7$Li, $^7$Be

Ready our projectiles
- n,p,t, $^3$He, $^4$He, and photons
### A.2. Table of resonances

<table>
<thead>
<tr>
<th>Resonance in Compound State</th>
<th>Reaction</th>
<th>$E_R$ (keV)</th>
<th>$\Gamma_{rzn}$</th>
<th>$\Gamma_{tot}$ (keV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^8$Be, $1^+$, 17.64 MeV</td>
<td>$^7$Li($p, \gamma$)$\alpha\alpha$</td>
<td>385</td>
<td>unknown</td>
<td>10.7</td>
</tr>
<tr>
<td>$^8$Be, $2^+$, 16.922 MeV</td>
<td>$^7$Li($p, \gamma$)$\alpha\alpha$</td>
<td>-333</td>
<td>unknown</td>
<td>74.0</td>
</tr>
<tr>
<td>$^8$Be, $2^-$, 18.91 MeV</td>
<td>$^7$Be($n, \gamma$)$\alpha\alpha$</td>
<td>10.3</td>
<td>0.168+0.099 eV</td>
<td>122</td>
</tr>
<tr>
<td>$^8$Be, $3^+$, 19.07 MeV</td>
<td>$^7$Be($n, \gamma$)$\alpha\alpha$</td>
<td>170.3</td>
<td>10.5 eV</td>
<td>270</td>
</tr>
<tr>
<td>$^8$B, $2^+$, Ground state</td>
<td>$^7$Be($p, \gamma$)$^8$B</td>
<td>-137.5</td>
<td>unknown</td>
<td>unknown</td>
</tr>
<tr>
<td>$^8$B, $1^+$, 0.7695 MeV</td>
<td>$^7$Be($p, \gamma$)$^8$B</td>
<td>49.5</td>
<td>$\approx$ 35.6</td>
<td>35.6</td>
</tr>
<tr>
<td>$^9$Be, (5/2$^+$), 16.671 MeV</td>
<td>$^7$Li($d, \gamma$)$^9$Be</td>
<td>-24.9</td>
<td>41 keV</td>
<td>41 eV</td>
</tr>
<tr>
<td>$^9$Be, 1/2$^-$, 16.9752 MeV</td>
<td>$^7$Li($d, \gamma$)$^9$Be</td>
<td>279.3</td>
<td>62 eV</td>
<td>389 eV</td>
</tr>
<tr>
<td>$^9$Be, 1/2$^-$, 16.9752 MeV</td>
<td>$^7$Li($d, p$)$^8$Li</td>
<td>87.0</td>
<td>$\approx$ 290</td>
<td>89 eV</td>
</tr>
<tr>
<td>$^9$Be, 1/2$^+$, 1.684 MeV</td>
<td>$^7$Li($d, n$)$^8$Be</td>
<td>18.6</td>
<td>$\approx$ 217</td>
<td>217</td>
</tr>
<tr>
<td>$^9$B, (5/2$^+$), 16.71 MeV</td>
<td>$^7$Be($d, ^3$He)$^9$Li</td>
<td>107.7</td>
<td>unknown</td>
<td>unknown</td>
</tr>
<tr>
<td>$^9$B, (5/2$^+$), 16.71 MeV</td>
<td>$^7$Be($d, ^3$He)$^9$Li</td>
<td>219.9</td>
<td>unknown</td>
<td>unknown</td>
</tr>
<tr>
<td>$^{10}$Be, (2$^-$), 17.12 MeV</td>
<td>$^7$Li($t, \gamma$)$^{10}$Be</td>
<td>-130.9</td>
<td>$\approx$ 150</td>
<td>unknown</td>
</tr>
<tr>
<td>$^{10}$Be, 17.79 MeV</td>
<td>$^7$Li($t, n$)$^{10}$Be</td>
<td>539.1</td>
<td>$\approx$ 112</td>
<td>unknown</td>
</tr>
<tr>
<td>$^{10}$B, $2^+$, 18.80 MeV</td>
<td>$^7$Be($t, \gamma$)$^{10}$B</td>
<td>130.9</td>
<td>$\approx$ 600</td>
<td>unknown</td>
</tr>
<tr>
<td>$^{10}$B, $2^+$, 18.80 MeV</td>
<td>$^7$Be($t, p$)$^{10}$Be</td>
<td>130.9</td>
<td>$\approx$ 600</td>
<td>unknown</td>
</tr>
<tr>
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<td>$^7$Be($t, ^3$He)$^7$Li</td>
<td>130.9</td>
<td>$\approx$ 600</td>
<td>unknown</td>
</tr>
<tr>
<td>$^{11}$B, (3/2$^-$), 8.56 MeV</td>
<td>$^7$Li($\alpha, \gamma$)$^{11}$B</td>
<td>-103.7</td>
<td>94 eV</td>
<td>unknown</td>
</tr>
<tr>
<td>$^{11}$C, 3/2$^+$, 7.50 MeV</td>
<td>$^7$Be($\alpha, \gamma$)$^{11}$C</td>
<td>-43.0</td>
<td>$&gt; 7.37 \times 10^{-3}$ eV</td>
<td>$&gt; 7.37 \times 10^{-3}$ eV</td>
</tr>
</tbody>
</table>

Table 2: This table lists the potential resonant reactions which may achieve required destruction of mass 7. These are all allowed by selection rules. The values of these parameters are taken from http://www.tunl.duke.edu/nucldata/
Result

Observations

width $\Gamma_{\text{eff}}$ [keV]

resonance energy $E_{\text{res}}$ [keV]

$^7\text{Be}(t,p)^9\text{Be}$

1.23e-10
2.0e-10
3.0e-10
4.0e-10
5.0e-10